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The Potential of Structural Analysis in Archaeological Simulation and Interpretation:
A Case Study of Medieval Winchester Cathedral Precinct

by

James Edward Miles

Thesis for the degree of Doctor of Philosophy

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ABSTRACT

FACULTY OF HUMANITIES

Archaeology

Thesis for the degree of Doctor of Philosophy

THE POTENTIAL OF STRUCTURAL ANALYSIS IN ARCHAEOLOGICAL SIMULATION AND INTERPRETATION: A CASE STUDY OF MEDIEVAL WINCHESTER CATHEDRAL PRECINCT

James Edward Miles

This multidisciplinary PhD provides an integration of structural analysis and archaeological interpretation, focused on the implications of methods used to generate virtual models and the analytical frameworks within which new interpretations emerge. It builds on established connections between disciplines in the University of Southampton’s Faculties of Humanities, Physical Sciences and Engineering, Engineering and the Environment and on the AHRC funded Parnassus and Portus research projects, and on international collaborations developed by the author. The main aims are:

1. To explore the benefits of using structural analysis in an archaeological context;

2. To review different methodologies of archaeological virtual modelling;

3. To investigate how structural analysis can influence the way archaeological graphical simulations are produced;

4. To evaluate the impact of different surveying methods on the potential and practice of structural analysis.

Using Winchester cathedral and its precinct as a case study allows the examination of these aims in the context of:

1. a broad range of different architectural styles;

2. contrasting surveying and prospection methods;

3. varying information including archival data relating to demolished buildings;
Abstract

4. differing interpretations of the surviving remains.

A number of research questions are provided in relation to each of the buildings examined that fit within the overall research aims.

Structural analysis is widely used to determine static, dynamic, and thermal behaviour of physical systems and their components. Several methods can be employed to analyse building and non-building structures. The main purpose of structural analysis is to ensure the adequacy of the design from the viewpoint of safety and serviceability of the structure and to check the strength of existing systems. Although the method plays an important role within many different disciplines, it is rarely applied within archaeology. Therefore, the research presented here is based on the application of structural analysis within archaeology, specifically through archaeological interpretation and (archaeological) modelling of historic buildings and novel integration of voxel and surface techniques.

Archaeological modelling is used to reconstruct various interpretations of standing and ruined remains, but many of the models produced may have little or no structural basis and are limited to visual representations of hypotheses. The literature associated with structural analysis is considerable but is focused upon engineering principles, with very few investigations into its use within archaeology. The research bridges this gap between (the two) disciplines, tying in the emphasis of archaeological methods to record historic buildings, both standing and ruined, with structural investigations used within engineering. The thesis includes an up-to-date evaluation of the various tools used within recording, creating an overall analysis of laser scanning, photogrammetry, building surveying, and geophysics within the study of buildings.

The overall aim of the research is to develop a tool within the study of computational archaeology that will aid our understanding of how and why historic buildings were built and why some lie in ruins.

Archival data (provided by the Cathedral authorities) has been used as a basis to reconstruct the known structures and compare the structural properties to those that are standing. The standing buildings were recorded through terrestrial scanning and building surveying techniques. The models are examined through Finite Element Modelling with collapsed architecture. The work is supported by Winchester Cathedral who has given access to all archival data and buildings. The research has highlighted important issues within computational archaeology and through the basis of failure mechanism inherent within structural modelling; the analysis of archaeological models can be assessed to determine actual form. This provide answers that have until now been unknown.
The research has involved a considerable amount of fieldwork to record the necessary data and has comprised mostly the computational analysis needed to attain the structural properties of the standing buildings. These results are used as a basis to analyse the reconstructed models. Overall, the reliability of the precision of reconstructed models can be controversial due to absence of historical information and fabric loss; structural analysis from an archaeological perspective can be seen as an effective alternative tool to traditional reconstruction techniques. The study will lay the foundation for future work that can then be used within a wider aspect of archaeological interpretation that is not limited to buildings.
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Table 1. Files Submitted

Due to the file sizes of the recording completed at Winchester, none of these files are included in the accompanying materials
Acknowledgements

This thesis is dedicated to my parents, as without their continuous support, I would not be in the position that I am today. Whether it be difficulties at school, early morning starts for rugby and swimming events, financial help at university, or just someone to speak to you when things became too much to deal with, they have been there, going without to support my hopes and aspirations. I thank you from the bottom of my heart for the life that you have given me and I hope that this work provides some small return for the sacrifices that you have made to get me here.

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I would like to thank Winchester Cathedral for allowing access to my case study area, as well Dr John Crook for the support and guidance that he has given me whilst I was researching the cathedral and precinct buildings. Thanks must also be given to Dough Murphy at Opti-cal Survey Equipment for providing the necessary recording equipment used at Winchester. Without Elizabeth Richley, I would have been unable to capture and process the geophysics results. Thank you for the time and effort that you provided during those winter months of fieldwork, even if we did scare off the master students!

During my time at Southampton, I have worked on a number of different projects to help support my studies. Thanks must go to Penny Copeland (my academic mother), Kristian Strutt, Dom
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Last but not least, Kate what a first year together it has been! These last few months have been difficult and without you looking out for me, I doubt I would have coped. Thank you for everything that you have done and I look forward to doing the same for you when you submit.
### Definitions

Table 2. Definitions of key words and phrases

<table>
<thead>
<tr>
<th>Word, Phrase or Abbreviation</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>Applied Force</td>
<td>A force that is applied to an object by a person or another object</td>
</tr>
<tr>
<td>Compression</td>
<td>An inward pushing force to different points on a material or structure</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>The measurement of the stiffness of a solid material</td>
</tr>
<tr>
<td>Elasticity</td>
<td>The way a material initially reacts when it is subjected to stresses</td>
</tr>
<tr>
<td>Force</td>
<td>Any action applied to an object that would cause the object to move, change direction, or change its shape</td>
</tr>
<tr>
<td>Force vector</td>
<td>A graphical representation of a force</td>
</tr>
<tr>
<td>Gravitational load</td>
<td>A load that is of a constant magnitude and fixed positions that acts permanently on the structure</td>
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<tr>
<td>Internal Force</td>
<td>Forces that occur between objects found inside an object</td>
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<tr>
<td>Load</td>
<td>A collection of forces acting on an object</td>
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<tr>
<td>Mass</td>
<td>The amount of matter contained within an object</td>
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<tr>
<td>Member</td>
<td>A support that is a component part of any structure or building</td>
</tr>
<tr>
<td>Moment</td>
<td>The measurement a force that causes a rotation about an axis</td>
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<tr>
<td>Naked edges</td>
<td>Edges that have only one adjacent face</td>
</tr>
<tr>
<td>Word, Phrase or Abbreviation</td>
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<tr>
<td>Poisson Ratio</td>
<td>Is the measurement of the Poisson effect, an occurrence in which a material tends to expand in vertical directions to the direction of compression</td>
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<tr>
<td>Pressure</td>
<td>An external force that is applied over an area</td>
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<tr>
<td>Shear</td>
<td>A force that is parallel to the surface of an object or material</td>
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<tr>
<td>Static determinate</td>
<td>Structures that can be analysed by just the use of basic equilibrium equations</td>
</tr>
<tr>
<td>Static indeterminate</td>
<td>Structures that cannot be analysed by just the use of basic equilibrium equations. Further calculations are required.</td>
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<tr>
<td>Strain</td>
<td>The change in length of a stressed structural element divided by the original length of the unstressed element</td>
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<tr>
<td>Stress</td>
<td>The force per unit area that the force acts upon</td>
</tr>
<tr>
<td>Tension</td>
<td>An outward pulling force to different points on a material or structure</td>
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Chapter 1: Introduction

1.1 Contribution of This Thesis

The aim of this thesis is to provide a new approach to creating virtual reconstructions of archaeological sites. Structural analysis is the “predication of the performance of a given structure under prescribed loads and/or other external effects, such as support movements and temperature changes” (Kassimali, 2005: 3). The thesis will examine the use of this tool and will advocate structural analysis as a mechanism for creating realistic interpretations of the past. The intention is to create discussions in the field of virtual archaeology and to analyse how the past is reconstructed. Structural analysis imposes a broad area of cross-functional expertise and this thesis is meant only as an introduction to the subject; it is not intended as an instruction manual, but rather it acts as an introduction to how the method can be utilised within archaeological research. This may provide a way of stimulating further interest within engineering as it demonstrates existing overlaps between the two disciplines. Further work will be required in developing the principle within all aspects of virtual archaeology but the work presented here will provide a foundation for future work and development for collaborative research.

1.2 Aims and Objectives

The aims of this thesis are multi-faceted. A number of research questions will be considered throughout the thesis that relate to the following central aims:

1. To explore the benefits of using structural analysis in an archaeological context;

2. To review different methodologies of archaeological virtual modelling;

3. To investigate how structural analysis can influence the way archaeological graphical simulations are produced;

4. To evaluate the impact of different surveying methods on the potential and practice of structural analysis.

The main objective of this thesis is to provide a new validation tool within the interpretations used in graphical simulations. The aims of the thesis concentrate on the use of the method within
building simulations but structural analysis is applicable to most aspects of archaeological research.

1.3 Background

This thesis developed from my involvement in the Parnassus Project, a collaborative research project between University College London (UCL), University of Southampton and the University of Bristol. The Arts and Humanities Research Council (AHRC) and the Engineering and Physical Sciences Research Council (EPSRC) funded the project. The project focused on the protection of cultural heritage from flood and driven rain. The University of Southampton’s contribution to the project was the overall archaeological assessment of the buildings within the scope of the projects, most notably Winchester Cathedral, Hampshire; Odda’s Chapel in Deerhurst, Gloucestershire; and Bodiam Castle, East Sussex. The University of Bristol’s contribution was interdisciplinary: the Geography department performed simulations of flood and driving rain, and provided probability analyses of flooding, whilst their Civil Engineering department performed an analysis of the material characterisation and the effect of freeze-thaw on the residual strength of masonry composites. Both universities worked closely with UCL who led the on-site and lab analyses to define damage thresholds within the buildings; probabilistic modelling of the impacts of flood and wind-driven rain; and the development and validating of adaptation measures in a structural context. The work performed by UCL included the use of structural analysis within the probabilistic modelling and there were many overlaps in exploration of what the method could provide within a wider archaeological context.

Collaboration with UCL allowed me to develop a core understanding of how civil and geomatic engineering could aid archaeological knowledge. I worked with Dr Aykut Erkal whilst developing ideas for a thesis topic resulting in the selection of Winchester Cathedral due to my extant knowledge of the building drawn from my previous building surveys at the cathedral. Through working with Dr Erkal, and the creation of a series of different models for structural analysis testing, I began to learn more about the processes involved in creating suitable datasets. Furthermore, I began to expand my knowledge of how to analyse the results that were obtained. The project ran in parallel to the start of my research and this thesis has subsequently evolved from creating replicas of the cathedral and its precinct over time, to the evaluation of how structural analysis can aid archaeological investigation.

The Parnassus Project, along with The Portus Project, which is a multi-discipline research project studying the Port of Imperial Rome, funded by the AHRC, allowed me to develop my skills associated with three-dimensional recording. Involvement in both projects led to the...
enhancement of my understanding of the suite of technological approaches and the limits of each. This enabled me to create a systematic approach in recording a variety of objects, from small artefacts to large landscapes. With the level of skill that I had acquired in laser scanning (B.1) and photogrammetry (B.2), I felt that the methods could be adapted for use within structural analysis. The creation and process of generating a structural analysis model will be discussed in detail throughout this thesis. During the course of researching for the thesis, it was necessary to describe the integration of the recording methods used to establish a fuller understanding of how the methods could aid archaeological investigation using state-of-the-art recording processes. The work completed not only assesses how structural analysis can be used but it provides an assessment of the best ways to record the features using three-dimensional recording methods.

1.4 Case Study

The case study for the application of structural analysis and the assessment of the recording methods necessary is Winchester Cathedral and its surrounding precinct buildings. Church archaeology as a field of study was put on a more systematic basis due to the work performed by Martin Biddle at Winchester on the Anglo-Saxon Minster (4.2.2.1) between 1961 and 1971, providing the first detailed recording of the excavation process (Rodwell, 1989: 30). The Norman cathedral has since continued to be a source of investigation and is one of the most archaeologically documented cathedrals in England. The origins of the cathedral as it currently stands date from 1079 AD, partially overlying the Anglo-Saxon Old Minster and close to the New Minster (4.2.2.2). The Benedictine rule of this area was unbroken from 964 AD through to 1538 AD (Bussby, 1979: 6). In 1538 following the break from the Catholic Church by Henry VIII, the Benedictine monastery was dissolved and in 1541 changed into a church governed by the Dean and Chapter (Bussby, 1979: 89). The continued presence of episcopal activity has led to a great transformation of the cathedral and the surrounding buildings, with many different architectural styles. Its chequered history following decay during the civil war and post-Reformation destruction means the cathedral area provides a suitable case study to test the potential of structural analysis, not only through the standing remains but also through the assessment of its use within the reconstruction of past buildings that once stood in the Inner Close. The precinct is subject to subsidence caused by the changing level of the water table, and tests can be performed to verify how suitable structural analysis is for predicting known results based on the design of the original buildings. The site allows for a varied approach within the recording processes that enables a fuller assessment of the uses of three-dimensional recording within the construction of structural models.
Within this case study, a number of different buildings have been chosen. The entirety of the precinct has not been evaluated, but rather selected buildings that will provide useful results have been chosen. The surrounding buildings must be investigated along with the cathedral as any assessment could affect the dynamics of the main building under investigation. Each will be treated as a separate entity but in some instances the presence of the surrounding buildings will greatly affect the investigations that can be made due to their close proximity and the structural support provided.

The focus of the case study and the use of structural analysis within church archaeology is not new; Roca (2001) completed an investigation of three Gothic cathedrals, analysing their structural features and present conditions. The work completed was based solely on the engineering of the cathedrals and offered only an explanation of the variations in architectural styles. The case study completed for the current thesis will instead provide an archaeological assessment, for which the potential of structural analysis can be truly evaluated within an archaeological context.

1.5 Virtual Archaeology

The term “Virtual Archaeology” was brought into use by Reilly (1991) who introduced the concept of presenting archaeological data to “provide insights into the understanding of archaeological formations by the addition of the powerful resources of the computer” (Reilly, 1991: 134). Virtual reality, as the method has come to be known, began via the introduction of basic solid modelling. The models created were used to perform “theoretical reconstructions, three-dimensional recorded features and interfaces for data interrogation and navigation” (Reilly, 1991: 136). Its use has since evolved to encompass a wide-ranging suite of technologically based investigations (2.3), some of which are, it is asserted, inappropriately termed. Miller and Richards (1995), advocated that the techniques that were introduced were not intended to reveal new information but rather act as a way to present known information. This approach reduced the potential of what could be extracted; using these tools, correctly and efficiently, would allow for a system that utilises the archaeological data to provide scientifically centred results. Using this type of analysis within the virtual reconstruction of the past would create an archaeological record that is founded on more than interpretation, and possesses a greater rationality within the choices made. One such application of this scientific approach to modelling is the use of structural analysis as introduced within this thesis.

There exist a number of publications dedicated to the explanation of the fundamental aspects of virtual reality and archaeological reconstructions such as Barceló et al. (2000b), Bevan and Lake
(2013) and Wittur (2013). The papers presented and discussed in these publications examine a wide range of aspects currently used for the reconstruction of the past. This demonstrates a step change in the method from the original problems attached to the “projection of three-dimensional space onto a two-dimensional plane” (Reilly, 1991: 133). Barceló et al. (2000a: 3) termed virtual reality as being defined as those “environments where the human operator is transported into a new interactive environment by means of devices that display signals to the operator’s sense organs and devices that sense various actions”. Gillings (2000: 59-70), however, termed virtual reality as “the presentation of interactions between the modelled past, the reality attached and the authenticity that the model is based upon”. Authenticity plays an important role when understanding the past (2.4.4); its use within virtual reconstructions provides a footing for a model to be seen as genuine and realistic. Are these models realistic or are they proxies for reality? Is authenticity possible within recreating unknown aspects of the past using the limited data attached to the archaeological record? Modelling the past requires greater technological choices to be made, allowing for enhanced explanations as to why the models produced are useful to archaeological research.

Papers such as that by Wheatley and Gillings (2000) which focus on vision and perception (2.4.6) within a GIS (Geographic Information System) context provide further evaluations of the possibilities that can be gained by simulating the past, noting that “archaeologists must be encouraged to work towards the development of new approaches geared around the specific requirement of archaeology” through “direct implementation or the weaving together of techniques already present” (Wheatley and Gillings, 2000: 24). The interaction of technologies seen in the concepts put forward by Morgan (2009) suggest that the construction of virtual models of archaeological sites is an appropriate method for representing the past but only if archaeologists perform an active role and address issues of representational accuracy (Morgan, 2009: 468). The adoption of technological advances means that virtual modelling can reveal relations within an archaeological reconstruction more clearly; aid the visual aspect of understanding a site through spatial queries; and support the evaluation of theories of how the past was constructed through critical evaluation of hypotheses (Barceló et al., 2000a: 6).

Reilly and Beale (2015: 122) stated that the original intention of virtual reality in archaeology was to “describe a multi-dimensional approach to the modelling of the physical structures and process of field archaeology”. At the time when Reilly termed the virtual archaeology, a broad and wide range of technologies and processes were used within archaeological research, but examination of the past should now “focus on the practice of adapting technology as well as the technology itself” (Reilly and Beale, 2015: 125). Newer technologies allow for the augmentation of archaeological research rather than acting purely as visual tools. Amongst these newer
Chapter 1

technologies is the adoption of three-dimensional recording devices such as laser scanning (B.1), photogrammetry (B.2) and structured light scanning (B.5); together with image-based analysis tools such as Reflectance Transformation Imaging (RTI) and high-resolution photography that include visible and multispectral frequencies.

Virtually recorded data presented through three-dimensional visualisations allow for detailed documentation of architecture, which can be used to create three-dimensional vectors from which construction methods can be analysed and reconstructions based (Lambers et al., 2007: 1710). Three-dimensional recording provides high-speed operations that offer an approach for data acquisition of any “large scale, complex, irregular, standard or nonstandard object or scene” (Chen et al., 2005: 1). The recording devices provide a surface-based three-dimensional measurement technique, visualised through the production of point clouds with final results depicted in “line drawings, CAD models, three-dimensional surface models and video animations” (Boehler and Marbs, 2004: 292). Their use enables the digitisation of all three-dimensional information concerned with a real-world object, and provides a better communication and understanding of the past through the ability to visualise real-world objects in three-dimensional space (Xiao et al., 2007: 5791). The adoption of photography methods such as RTI as seen in the work of Mudge et al. (2006) enabled a further insight into surface differences which could be used in conjunction with three-dimensional recording, as seen in Miles et al. (2014). The combination of these different tools enables a more detailed examination and allows clearer interpretations to be made. Their use within virtual archaeology has gained unprecedented value but is largely concerned with the recording of the current state of archaeological data and is used within projects to validate reconstructed models due to their inclusion of ‘real data’.

If reconstructed models are produced based on having explanatory capabilities, the research that may be carried out is reduced to a puzzle-solving reinforcement of academic norms and leads to normative predictable conclusions (Glassie, 1979: 14). Regardless of how intellectually sound interpretations may be, dealing with only partial data restricts what can be achieved within archaeological research. The production of models of known buildings, for example, is straightforward: the data are analysed, other building types are looked at and a general overview of the building is produced. The understanding of buildings follows a language. Once the basics are known in terms of architectural styles, then the foundations for the modelling can take place. Although generic styles can be used, each building is unique in terms of its structural integrity. The differences in space, supports and materials affect how the building was built, and it can never be said that an interpretation is absolute. The buildings of the past provide an illustration of the mechanics of the development of architectural capabilities and the “context by which they were designed were constricted and driven by the available resources at the time” (Glassie, 1979: 114).
To understand a building there is an imperative firstly to seek to recognise the context in which it was constructed. Without this, any interpretation made within a wider sphere of virtual reality can be challenged.

The basis of our understanding of the past is limited to what is found during excavation and what is documented on similar sites. The excavation of an entire site would be a prohibitively expensive and time-consuming process, and despite rare exceptions such as Çatalhöyük (Hodder, 2013), where a large proportion has been uncovered, only partial areas of particular interest are generally dug. These can still be subjective due to the level of interest that an excavator may have in particular areas. The understanding of the past based on this limited information cannot be representative and decisions have to be made interpreting this to define the limits and proportions of what was once possible. The reconstructions that are produced should be based on “comprehensively reviewed archaeological records and well-studied comparators to provide a fertile basis for a faithful reconstruction” (Papadopoulos and Earl, 2009: 59). Within the world of deadlines versus computer power and rendering times, shortcuts are always engrained within the process to provide data that can produce representations that could be deemed inaccurate.

In order to create models of the past within virtual archaeology and analyse them correctly, the adaptation of newer technologies is needed. Focus, however, must be maintained on the modelling of the physical structures, thus staying faithful to the original intentions of virtual archaeology. The adoption of newer technologies within the field of archaeology has been significant; e.g. the excavation recording via photogrammetry at Çatalhöyük (Forte et al., In press) but it would appear that the adaptation has been targeted at enhancing insights gained from extant data, rather than extracting all new information. To provide insights into the understanding of archaeological formations, the basic construction of the modelling process has to be re-evaluated, applying greater emphasis to how the models are constructed. This probes the scientific nature of how the past is reconstructed, establishing a need for heightened physical understanding of how buildings and landscapes were used and interacted with by people due to their direct physical nature. One such example of this can be seen in the work by Chalmers and Debattista (2005) within their research on prehistoric Maltese temples, who suggested (but did not elaborate on), the use of structural analysis within archaeology as a way of producing structurally viable models for interpretation.

Many three-dimensional models are produced via raw site data, comparisons with standing structures and familiar architectural understandings. These have a frequent limitation of insufficient validation. For example, the study of the Holy Trinity Priory at Aldgate, London (Schofield and Lea, 2005), the study of Roman Imperial architecture (Packer, 2006) and the study...
on the ‘Rome Reborn’ project (Frischer, 2008) provide visually satisfactory interpretations of the past, but the validity of the models can be questioned when the production considerations, such as creating models based on comparable architecture, and validation aspects, through seemingly pleasing visual outputs, are taken into account. The examples described may provide a detailed archaeological investigation but the virtual outputs used to support the explanations and to visualise certain aspects should be based on more than just archaeological information (although this may also include architectural, historical, artistic and other information), as it can constrain perceptions of the data to set personal opinions. The data are used to evaluate and test various academic theories, in turn helping academics and researchers interpret archaeological sites and contribute to the education of the public (Eppich and Chappi, 2006). To ensure the correctness of the models, these interpretations need to be evaluated by considering other decisive aspects.

Examination of the structural stability of a building can be considered one of the reliable confirmation approaches, together with various other techniques that employ physical properties within modelling. Investigations as to whether reconstructed buildings can withstand the gravitational loads form the foundation of an additional layer of validation of the model. This layered approach allows for greater scrutiny and scientific rigour, creating a tool that is able to review the models produced. The current procedure of how models are deemed to be authentic does not certify archaeological integrity (Brown III and Chappell, 2004: 61). Creating models that follow physical rules will allow for a greater system of testing within the validation of hypothetical forms (2.5.4); these physical properties are governed by real-world physical laws and cannot be contested (2.5.5); only the choices made within the modelling can. If a model cannot be created under Newton’s laws of gravity and motion then the hypothesised forms require adjustment or a re-examination based on the archaeological data used. These laws are fundamental within engineering, physics and mathematical examinations of buildings, yet it has rarely been applied to archaeological evaluation (3.2.3). Virtual archaeology must adapt to create a system that is focused largely on the archaeological potentials within research rather than the “realistic” form currently used. Using structural analysis through the examination of a model’s physical properties allows for not only a critique of its form, but through wider structural tools, possible functions can be clarified and questioned with a greater certainty than is currently available.

Structures are designed to carry loads: first they must carry their own weight; second they must support vertical loads that are imposed upon them, such as roof coverings and weight on floors; and third they must support external horizontal loads such as wind (Cowan, 1976: 1). When designing a building its safety is not so much a matter of opinion as of “ascertainable fact” (Cowan, 1976: 39). The same assessments should therefore be carried out within the modelling of these buildings virtually to add the element of realism (2.4.2). This thesis is based on the
application of structural analysis within virtual modelling, providing an assessment of how the past is reconstructed, and how the method should be adapted within the original outline of what virtual archaeology should have been. The work that will be carried out is focused on the application of this technique and what it can offer, through the adaptation of traditional recording and modelling processes within archaeology (Appendix B). Its aim is not to provide a full record and review of the modelling procedure, but rather to assess how structural analysis can be introduced practically and to inform archaeologists of the possibilities that the method could have within the interpretative process.

1.6 The Potential of Structural Analysis

“Structural analysis of historical structures constitutes a multidisciplinary, multifaceted activity through the integration of different approaches and sources of evidence” (Roca et al., 2010: 300). The main issue when discussing the potential of structural analysis within historic structures is not so much based on the technique but rather the geometry of the building in question. Engineers, when compared to trained archaeological surveyors, may lack the technical knowledge and skills to understand and highlight features of interest in historical structures. The conclusions that are made are technically competent but are based on generic investigations of building types rather than the separation of distinct features that historical structures require when analysing their construction. The work that will be shown will highlight the differences between the engineering principles used within modern analyses and the methods that should be extracted and altered to the betterment of archaeological methods currently used. The key part of this is the way in which the structures are recorded and how they are then assessed.

There are several methods and computational tools available for the assessment of the mechanical behaviour of historical constructions (3.3). Each provides different sets of theories and approaches creating differing levels of complexity together with factors such as time, cost and specialism (Lourenço, 2001: 92). The research that will be assessed throughout is the introduction of Finite Element Modelling within an archaeological context (3.3.3). Finite Element Modelling is a “sophisticated series of simulations of structural behaviour that are viewed through the mathematical description of the material behaviour of the building elements used” (Lourenço, 2001: 98). Other methods will be discussed and evaluated but the potential of structural analysis should follow that which takes place within engineering, with the most common form of Finite Element Modelling used. The potential of the method for archaeological investigation is multifaceted. A wide range of methods can be adopted within this field, with each being separately chosen to best answer the archaeological questions posed. The analysis within this thesis will concentrate on the assessment of the relationship between stress and strain, most notably within
gravitational loading. After forming a basic impression of what hypothetical reconstructions are possible, based on the identification of gravitational loads, the study will lead to further examinations enabling questions that are more specific to be asked. The potential of the method is great. It is hoped that this thesis will examine all possibilities that will assist archaeological understanding, particularly as the method falls within the realm of Barceló’s (2007: 439) direct solution within virtual reality, whereby solutions are based on the complete description of their causes, allowing for the model to predict resultant effects rather than being used as visual tools of examination (Chapter Six).

1.7 Thesis Outline

This thesis is separated into seven chapters with two appendices used to add to the methodological approach developed. The first chapter has already been introduced (1.6). The second chapter, titled “Virtual Modelling within Archaeology”, will give an overview of the current uses of virtual modelling within archaeology. It offers an assessment of current methods in modelling and will make suggestions as to how structural analysis can be integrated into the practical application of virtual modelling, based on the original purpose for which virtual archaeology was intended.

The third chapter, “Structural Analysis”, continues this assessment by providing a historical contextualisation of what structural analysis is and how it has developed into a leading engineering practice. Included will be the fundamental aspects of Finite Element Modelling, including relevant case studies of engineering-based investigations. The aim of the chapter is to describe these methods and to provide an archaeologist with the (basic) understanding of how they could be utilised within archaeological investigation. It is not the aim of the chapter to provide a comprehensive in-depth analysis, but rather an awareness of what is possible, as to discuss all aspects would fall outside the scope of archaeological interest.

The fourth chapter, titled “The History and Archaeology of Winchester Cathedral”, focuses on the archaeological and historical development of the cathedral. It follows the one-thousand-year history of the building, noting any significant changes that may have altered its structural integrity, with comparisons made to the points raised within Chapter Three. It provides an overview of why structural analysis investigation has provided a significant contribution to the study of the building. In this chapter, research questions are considered based on the changes within the architecture present and the conjectured original.

Chapter Five, “Winchester Cathedral Precinct”, will continue the desk-based assessment of Chapter Four with more focus given to the precinct buildings. Short reviews of the architectural
condition and history of the buildings will be presented; the recording methods used to record these buildings will be discussed in more detail than in the previous chapter; and the results from the extensive survey carried out at Winchester will be shown. Research questions will be addressed at the end of each building discussed, outlining queries that will be resolved within Chapter Six.

Chapter Six, “Results: Structural Analysis at Winchester Cathedral Precinct”, will discuss the Finite Element models produced for all aspects of the cathedral based on the research questions outlined in the previous chapters. This evaluation is continued as an appendix and focuses on the precinct buildings. The work discussed will examine the current building activity and highlight how the virtual reconstructions through simulating the changes that have occurred, will imitate the subsidence seen. This will form the basis for reconstructed models of the destroyed buildings, with hypothesized models created for each. The identification and modelling of these hypothesized buildings will be discussed in more detail through relevant documentary analysis and comparisons with ten other English cathedrals.

The final chapter will provide conclusions of the work completed and will assess the overall aims and objectives of the thesis. The chapter will show the potential of structural analysis within archaeological simulation and interpretation. Included will be future suggestions for what is possible within archaeological structural analysis.

As an appendix, the “Introduction to Survey Methods” will focus on highlighting and explaining the available tools that are currently being used within archaeology to record historic buildings. The focus within this appendix will be on two types of recording methods, but general comments will be made with regard to other possible techniques. Within this appendix, the methods will be reviewed based on the utility of the technologies and the possibilities of each. The technologies that will be outlined are all of use within the modelling of structural analysis; some, however, will be shown to offer greater benefits. The potential of their use within the archaeological process will depend greatly on the results that can be gained. Therefore, the purpose of this appendix is to outline the positives and negatives and discuss which methods should be utilised for future recording for use within structural analysis assessments. It is included as an appendix rather than as a chapter of this thesis due to the depth of detail provided, enabling a specialist and non-specialist to understand the methods discussed.
Chapter 2: Virtual Modelling Within Archaeology

2.1 Introduction

Virtual modelling is the process by which the past is reconstructed via three-dimensional graphical simulations. They are produced to aid our knowledge of the past and to gain interpretations from the archaeological material recovered. It is not the aim of this chapter to discuss the history of the technique (see Barceló et al. (2000b) and Wittur (2013) for a more in-depth review) but rather to provide a footing that shows the current procedures and practises used. It will discuss the previous applications of illustrations pointing out the issues that surround their use within archaeological interpretation and will focus on their artistic nature and the problems associated with these simple representations.

The chapter will assess the early developments of computational modelling in archaeology, providing examples of the first models produced. The chapter will develop and discuss the issues that have resulted from these models and considers the current limitations that the method provides. Attached to this is the discussion of theoretical implications, aimed predominantly at the accuracy and realism attached to the models produced. Uncertainty, as well as authority and interaction, plays a prominent feature in the arguments made.

The chapter will conclude with how virtual reality could be used within archaeology, using current software solutions. It will suggest that virtual modelling should be more than an illustrative medium, whereby hypotheses tests are incorporated through the use of structural analysis, as the method can validate interpretations based on physical possibilities, leading to a greater inclusion of information within the overall modelling process.

2.2 The Early Development of Computational Methods via Virtual Reality

The first computer-generated visualisations in archaeology were created in the 1980s and were based on architectural representations. The first that can be seen was by Cornforth and Davidson (1989) who reconstructed the dining room and courtyard at the Roman Palace of Fishbourne. The next can be seen in the early work by IBM in their reconstruction of the Old Saxon Minster at Winchester (Burridge et al., 1989) as shown in Figure 1. Its purpose was to show the visual spatial relationship between the architectural elements (Reilly, 1992) and its production used the best method for this at the time. Another example can be seen in the Roman Temple of Sulis Minerva.
in Bath (Woodwark, 1991: 19) (Figure 2) where the Roman civic bath complex was reconstructed based on surviving remains. These remains were a loose resemblance of the original and the visualisation created is hard to understand from an uninformed stand point (Reilly, 1992: 150).

Image represents an early reconstruction of the Old Minster at Winchester.
Copyright permission was not gained.
The image can be found on page 35, figure 14 of W. Rodwell. 1989. Book of church archaeology. Published by Batsford Ltd, now Pavilion Books

Figure 1. Possible reconstruction of the Old Minster, Winchester (Rodwell, 1989: 35). © Pavilion Books

Figure 2. Aerial view of the Temple of Sulis Minerva and its precinct, along with the bathhouse that enclosed the King’s Bath in Roman Bath, England (Woodwark, 1991: 18). © 1991 IEEE

The media attention generated by these types of images create a form of public understanding of archaeology (Reilly and Rahtz, 1992: 7) and required archaeologists to consider the implications of
how the public perceived the data. Moser (2001: 263) argued that there was an incorrect
assumption that popular representations played a primary role in shaping the public’s perception
of archaeology (2.4.6). The past is represented in archaeology as a visual language of
communication and thus the past is created through pictorial conventions that have symbolic
content (Moser, 2001: 266). Their early development and lack of academic validation (although
accepted through publications) highlighted the potential damage that the technique could create
within the discipline, with many of the models produced falling short of the scrutiny that is now
placed upon their creation (2.3).

Within the early introduction of virtual reconstructions Reilly (1991: 136) advocated that the
three-dimensional methodologies, through the large volumes of complex data, should have been
able to explain the interpretations clearly. This was not the case as it is now a system that is more
of the “illusion that a model, a replica, or even the note of something can act as a surrogate or
replacement of an original” (Reilly, 1991: 133). The earliest examples of its use within archaeology
were based around the exploration of what was possible rather than following set methodologies.
They provided a significant development in how we communicate our interpretations and if
appropriately constructed, they have the potential to provide a range of features that other
media cannot (Wittur, 2013: 3).

The stages between what could be misleading and visually accurate are where the substantive
issues exist relating to how the past has been reconstructed and how the discipline has moved
forward (2.4). How were these models used? In what ways were they presented? Were they
viewed as the only interpretation or were they presented as one possible idea among many?
These issues, as with others, have been discussed in detail by James (1997). Several models can be
seen by the public as being “true” regardless of what information is stored within them. It opens
up a number of important questions into how the past is reconstructed. What decisions are made
in the modelling process? What archaeological information is used? How do the public engage
with the images presented? Wittur (2013: 3) suggested that models were created to present
complete, photorealistic visualisations to the public and these reconstructions could be seen as
being perfect with no uncertainty raised (2.4.3). When questions were raised about their
reliability, “alternative views” were given as a way to counteract differing methodological
approaches in visualising the past. This “alternative view” is still inherent within many of the
models that are deemed ‘real’ as seen in general papers given at conferences such as those seen
at the 2015 CAA Conference. The catalyst for visualisation, however, was not so much engrained
in improving ways of discovering new knowledge but rather within the process of presenting
established knowledge to the public (Miller and Richards, 1995: 19; Reilly, 1996: 43). The basis for
its use was a medium of representation and a tool for dissemination (2.3).
Reilly (1996) implied that the visualisations produced, which have the largest exposure, are presented as static images that do not contain the academic discussions associated with their production. The audience is compelled to respond only to the data given and to contextualise different views from those obtained from specialists (Reilly, 1996: 47). This leads to the argument of what should be produced for public dissemination in terms of academic credibility versus artistic embellishment. Integrating different data types prevents archaeology from falling into interpretive pitfalls within the virtual modelling of the past. The process relies on recreating these untested interpretations. To create a virtual reconstruction and to produce a view in three dimensions does not equate to a conclusive assessment of a hypothetical reconstruction (Reilly, 1989: 572); the basis of the evidence used does. The key aspect of virtual archaeology is the ‘virtual’ part of it, in that it should act as a replica, as a surrogate or as a replacement for the original (Reilly, 1992: 162). Although Reilly’s early work was based around excavation, the virtual implications are applicable throughout.

The same problems can be seen within disciplines outside of archaeology, most notably in palaeontology and the representations of dinosaurs. In films such as Jurassic Park (Spielberg, 1993) dinosaurs are seen as being realistic due to the environment, appearance and sound in which they are placed and used. The issue of realism and accuracy, in relation to this film, is discussed in depth by Barnett et al. (2006: 180) who argued that these “images have plausibility and explanatory power” and are able to influence concepts of scientific phenomena. The representations of the dinosaurs used are unsubstantiated: the biomechanics of the velociraptors have been disproved (Manning et al., 2009), as have the skull morphology of the Tyrannosaurus Rex (Rayfield, 2007). The use of these media to represent unknowns is challenging and great care must be given in how the data used are produced. Representations allow for an insight into the past but if created with set aims and agendas, the data can be miscommunicated and accepted as ‘real’ without any form of validation, both within archaeology and wider disciplines.

### 2.3 The Problems Associated with Virtual Reconstructions within Archaeology

The way archaeological data is recorded and how it is presented follows guidelines. There exists the Archaeological Data Service (ADS) (2014) and their Guides to Good Practice and Historic England (Menuge, 2006; Bryan et al., 2013) with specific guidelines. Nothing however exists for the creation of virtual models save for The London Charter (2009) which provided recommendations for how best to model the past. The meeting in which these were agreed took place in 2006 and the application of these guidelines are now out of date due to the tools that are
currently available. The problem associated with the London Charter was that they dealt unambiguously with a process from data to a three-dimensional model, from the field to the lab. This meant that not all of the information could be contained within the models produced. It can be argued that virtual modelling encompasses many areas of specialism and this makes it extremely hard to manage and control. It has evolved from the statistical approaches created in the 1950s and 1960s (Reilly and Rahtz, 1992: 1) into a system that is multifaceted, and one that requires greater regulations and more defined guidelines that fit the purpose of modern-day modelling solutions.

In essence, anyone with some form of knowledge of a three-dimensional software package has the ability to create a rendered image and place it online, and the public could perceive it as genuine and real due to its photorealistic qualities. An example of this can be seen in Altair 4’s work at Portus (Altair 4, 2012) where their reconstructions (from personal experience on working at the site) are structurally incorrect. In academia, models or images were originally promoted through peer-reviewed journals, books and articles but their evaluation in academic circles was based more on the archaeological investigation that took place via the use of a virtual model, rather than how the model was constructed. Examples of this are Kenderdine’s (2001) work on Olympia, Athens in 200 BC and Pollefeys’s (2001) virtual modelling at Sagalassos, Greece. Reconstructed pasts are now no longer published through academic means alone, with online blog posts becoming a standard tool in public communication of work. A virtual replica of any known archaeological site, based on very small amounts of information, or none at all, can easily have overstated fictitious features added. These models can be made available via an online blog post, and if marketed for the public audience, could lead to the public believing that the produced models are true. In academia, the models might be discredited, but this does not stop the public having in their mind that the images were factually based and an authentic representation (2.4.4). In order to understand the reconstructed models, the public should in some way have access to education and training to be able to read and comprehend the completed work (Reilly, 1996: 39) and the key question related to this is why the model was simulated in the first place. Online systems such as the Portus MOOC (Future Learn, 2016) are now introducing this breakdown and if this continues, a form of training and education can be generated in how to comprehend the interpretations made.

To understand virtual reconstructions, the public are guided by visual media seen on television, in magazines and in numerous Hollywood films, many of which already contain archaeological inaccuracies. One example of this is the film *Gladiator* (Scott, 2000) where architectural elements were added to the city of Rome and the buildings were mainly portrayed as being white, whereas in truth, colour was a prominent feature (Clarke, 1991). Although small in detail, the use of white
rather than colour limits the focus on the surrounding areas and allows the viewer to concentrate on the actor. This small cinematic variation manipulates the viewer in a subconscious way that may be transferred to other virtual models. In more recent films, such as the 2014 film *Pompeii* (Anderson, 2014), archaeological recording methods and excavation data are used to map accurately the layout of the city to add an impression of realism. Although real data were used, the representation contradicts archaeological and architectural fact, such as the relocation of the amphitheatre from the southwest part of the city to the centre. Likewise, the amphitheatre is shown within a fight sequence to have a sequence of floors even though it is known that no substructure existed.

The artistic nature of this media is problematic when the term ‘realism’ (2.4.2) is discussed and how its use can deceive viewers into believing something is genuine. The viewer may not care about this but the way the data are presented may be of importance to archaeologists as it affects the way in which the public views archaeological data. The critiques given can be defined by the aesthetic choices made, with further manipulations also possible in camera positions and different lens choices. Although these issues are relevant to all archaeological research, they are more prominent in the visual outputs used within dissemination. Ultimately, these cases illustrate the contradictory nature of this exchange: in which archaeological truths are manipulated in the service of cinematic truths, to the detriment of archaeological accuracy.

Physical reconstructions of the past can also influence historical perceptions (2.4.6). Berlin and the reunification is one example of this, where the city was redeveloped to remove as many elements of the Nazi reign as possible, thus creating an inauthentic representation of the recent past (2.4.4). Rebuilding something that is destroyed or damaged can never be represented in its original context, “it is a mediated, discursive construct” (Goebel, 2003: 1270). The rebuilding of Berlin included new designs as a way to improve the engineering of the buildings following the Soviet destruction but it added to the historical discontinuity of the city, through an attempt to disassociate the country with Hitler’s reign, creating a deceptive view of the past. The Reichstag for example was rebuilt after World War Two, with the original façade remaining and a new dome and other building parts added, creating a symbolic foundation between the past and present, showing that Germany was stronger united. Creating a new building using the shell of the previous, especially when considering that it houses the German Parliament, provides a need to be reflective about the historical value that a property can contain, especially when the original design showed a different Germany (Goebel, 2003: 1275). Modifications such as this, shown throughout Berlin, provide intricacies of post-modernist uses; it abuses the historical original and removes the wartime wreckage; this provides a crisis of consciousness that provides visionary ideologies and disrespects the historical value before the wars (Goebel, 2003: 1287). Historical
authenticity is more than just reconstructing a building following old and new methods; it should create a memory of the past, whilst aiming to provide a sensory experience. Berlin, as an example, provides a political influence but further issues such as funding and personal choices can add to these idealised forms of the past (Linebaugh, 2004: 32)

Realism versus reality is problematical within virtual modelling due to the number of compromises that have to be made within the modelling process (2.4). As Kantner (2000: 47) suggested, “realism inherent within three-dimensional modelling is easy to construe as past reality when a large proportion of what the viewer sees is dependent on the numerous inferences made by the modeller in the absence of real data”. Although this statement is sixteen years old, and the consumption of technology by the public has increased, the same control in the production of models is prevalent. The audience may have a firmer grasp of the technology, but the choices made in the modelling process are still unknown unless these choices are explained. Simply using a new form of modelling software with greater digital visual outputs does not equate to an enhanced realism, as the models produced could still be inferred as being real and genuine.

When looking at work before virtual reality, such as sketches, the viewer understands that there is always a level of artistic licence within its production (2.4.3). The unknown aspects can easily be represented as such, through blank spaces or different colours. To do this within three-dimensional modelling leaves gaps in the data, and with most consumers wanting photorealistic representations, the unknown aspects are represented as being realistic due to the level of completeness required. The observer therefore may not be fully aware that a rendered image is conjectural as the image may appear to be perfect (Fletcher and Spicer, 1992: 98). When dealing with gaps, the stylistic choices used in these recreated models are important: clouds, smoke, choice of camera setup, perspective, depth of field and the inclusion of props to block set views do allow a physical realism to be included, but these can be used to exclude uncertain parts. Although this creates the appearance of gaps, the inclusion of these elements are not explicit and could instead be seen as a creative way to view the data.

Wittur (2013: 8) theorised that the modelling process is broken down into the following:
− All information based on observation and interpretations;
− Data basis that are centred on information considered relevant to the topic;
− Model basis based on information used for visualisation

She identified that data used in the visualisation are not necessarily all of the information available but instead are based on specific choices. It can be argued that the model basis that she outlines should not be a subjective choice and regardless of the person who builds the reconstruction (2.4.5), all of the data can and should be used. Modelling should be centred on
complete data sets and not just elements that are felt to be important. Three-dimensional recording is a vital element in this process as all data are provided rather than specific parts, as seen through the subjective nature of topographical and building surveys (B.3). Papadopoulos and Earl (2009: 57) suggested that these processes provide direct answers to research questions, but these questions need to be explicit; the current modelling process instead follows the testing of various ideas, the majority of which provide unverifiable results.

The majority of current work has been shown to concentrate more on the technical side than on issues of archaeological importance (Wittur, 2013: 10). The practice of reconstructing the past has been relatively simplistic and can be seen to be the production of visually appealing pictures. This can be seen in the images created by Wessex Archaeology to help explain the Neolithic houses at Horton, Berkshire (Wessex Archaeology, 2013). The only remains found were post-holes of the original timber-framed structure and hypotheses (although based on significant archaeology experience) were included in the reconstruction (Figure 3) to try and illustrate the original appearance of the house. Miller and Richards (1995: 20) emphasised that the main issue within any virtual reconstruction was that it was a collaboration between computer scientists and archaeologists and was therefore out of the control of the person who knew the most about the subject. They argued that uncertainties should not be hidden in the final model and that all aspects should be open to inspection as it misleads the public into thinking that the models represent a past reality (Miller and Richards, 1995: 21). Although many aspects of this modelling process have changed since this paper, the same issues still apply, not only in terms of public acceptance but also in the way academics wish to express their views and ideas. More and more academics are turning to computer modelling processes to show their interpretations of the past, but these models follow the same methodological approaches and are usually completed by computing experts, rather than the specialist of a given period or site.

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1 Although this statement refers to a model produced by Wessex Archaeology, key individuals such as Tom Goskar and Paul Cripps were influential in creating excellent examples of evidence-based reconstructions, such as their prehistoric landscape of the palaeo-Arun now submerged in the English Channel - available at https://vimeo.com/654575
It is argued by many, such as Forte (2000), Frischer et al. (2002) and Reilly (1996), that the modelling process can be applied with interactive (2.4.1) and analytical possibilities for exploration, interpretation and hypothesis testing (Wittur, 2013: 11) (2.5.4). Although current modelling processes now follow these possibilities, the results can only be deemed worthwhile if the model is structurally correct (such as when creating a reconstruction of a complete building that is still intact), although some can lead to alternative interpretations from the hypotheses created. Reconstructing archaeological sites is one part of archaeological research. It is more important to understand the subtleties of the raw data, as this leads to the insights into what the archaeological record shows. A greater understanding leads to the potential of greater interpretation (Reilly, 1991: 135). Virtual models, as Frischer (2006: 169) stated, are powerful means of communication; are one of the best tools for documenting the state of a given monument (laser scanning (B.1) is now a better tool for this); and allow for the study of problems that would otherwise not be possible.

Wood and Chapman (1992: 144) stated that there are different levels of models within virtual reality. The first deals with creating attractive models for publicity; the second for accurate testing of theories and communication devices; the third through scientific working models; and the fourth for education as interactive tools. Kantner (2000: 48-49) elaborated in his work that three-dimensional modelling requires research, pedagogy and public consumption to be in mind when creating models of the past. Models that focus on research act as a way to answer specific questions. Models that deal with pedagogy need to include a full representation rather than a
selective process as it may risk or undermine the imagination and interpretation of the viewer (2.4). Selective views can be shown when referring to selected parts, but when trying to understand this selected feature within a given context, greater complexity of data is required to provide a general overall understanding. Models that concentrate explicitly within public consumption contain the greatest level of interpretative steps from known to unknown due to the way they are consumed. With the public having a perception of how the past was created through original model, illustrative drawings and films, the application of creating academically credible models could be restricted. The belief of what a specific building type should look like is engrained through early representations; creating newer, updated models could provoke the rejection of more credible ideas due to the associations with these unfaithful representations. To understand the problems associated with this requires a firmer understanding of what these earlier models were meant to represent. If they were created through detailed archaeological research then perhaps they have some credibility, but if they were created to test ideas or to provide a simple overview, these models are more hypothetical in nature and could be untrustworthy when compared to models that contain greater archaeological evidence.

Papadopoulos and Earl (2014: 137) argued that there are two forms of three-dimensional models. The first deals with the modelling process that is structured around an expected visual product, such as those used in film. The second addresses models that focus on physical realism (2.4.2), that deal with light, colour and shade. Light plays an important part within the understanding of architecture, and an accurate simulation of illumination is needed within a virtual reconstruction (Lucet, 2000: 87), as light can determine how a model or scene is viewed and understood. Light after all controls the visual impact that a user may have, with the ability to draw attention to key areas of interest (predefined by the modeller). If the objects created look real but also allow for a valid perception of the built ambience, which may be achieved through simulating elements that participate in the space definition, then application of physical interfaces may lead to a greater physical realism. Papadopoulos and Earl (2014: 135) go on to argue that “architectural design software is able to calculate exact movement and transformations of natural light around built spaces” which then allows for an insight and analysis of movement based on illumination. They add that it is important to distinguish lighted areas as these add to the hypothesis of function (Papadopoulos and Earl, 2014: 136). Although this may be the case, models need to be created in a way that accurately and precisely replicate the structural properties, as any inaccuracies create an incorrect analysis of light due to the variation possible.

Models, as questioned by Barceló (2000) and Earl and Wheatley (2002), are subjective as they are based on interpretation. This interpretation is part of archaeological research and thus subjectivity will always be engrained within the model in some format. When creating an
interpretation, it is useful to visualise ideas through a reconstruction as it may identify weaknesses in the arguments made, but as these features are defined by the modeller, the interpretations may be modelled incorrectly (Reilly, 1989). They will in some cases force the researcher to change their ideas and reconsider the original data. Indeed different people have different ways of learning; visualising ideas is one process for this. A virtual model can be classified as a representation of some (not necessarily all) features of a concrete or abstract entity. Its purpose is to allow for an understanding of a structure or its behaviour and to provide a tool for experimentation of ideas (Barceló, 2000: 9). Within architecture the aims of its use should be in the extraction of new information that contributes to the understanding of cultural expression and historical experiences (Lucet, 2000: 88).

To avoid prejudice of a given view, the processes behind the use of these interpreted views and how they were modelled needs to be reconsidered, as the views of one individual and the choices made are what are effectively shown and developed. The subjectivity of models ties in with the idea of accuracy and although the peer-reviewed modelling processes suggested by Frischer et al. (2002) are a good idea, the logistics behind them are impossible to control. Who is qualified to peer-review the models? What makes their ideas any more valid than those already suggested? Very few publications focus on the critical scrutiny of virtual models (Gillings, 2005: 224) and instead work has focused on specific elements such as metadata, uncertainty and realism (Wittur, 2013: 14). One example of updating this workflow can be seen at the Portus Project (2014), where researchers have tried to incorporate all aspects of the archaeological record within the modelling process. Reviewing the models is however an important part in the creation of ‘realistic’ reconstructions and the internet can play a significant part in this. Online model repositories such as Sketchfab allow comments to be added to the reconstructed models, providing a tool for dissemination and appraisal from those who may not have been included in their original construction. Any comments that are made can be considered by the modeller and incorporated into the modelling process through subsequent edits. This removes the issue of defining who is qualified to review the models, as the onus is placed on the modeller. Some comments could be incorrect but if valid reasons and justifications are given as to possible changes, their inclusion is a possibility.

The primary arguments and issues in modelling lie within their authenticity (2.4.4) and the uncertainty (2.4.3) included. These arguments are based on theoretical ideas and do not provide an insight into how the models can be fixed, simply stating that realism is a problem and that it must be discussed. An example of this can be seen in the work completed by the University of Portsmouth and their Computer Games Technology course (2013), who created an ‘accurate’ model of Winchester Cathedral in its original form based on the archaeological information.
Chapter 2

gathered by John Crook. The model can be seen in Figure 4 and although realistic in its nature, is
incorrect in terms of the architecture modelled due to the conjectural information that the data
are based upon. The addition of seven towers is one that has been suggested by several scholars
(Willis, 1845; Gem, 1983; Crook, 1993c) but their claims are only supported by limited data. The
interior, as seen in Figure 5, is similarly problematic, with the columns positioned incorrectly as
shown in the survey conducted for this thesis. The modelling of the nave roof has a pitch that is
contested (Crook, 1993b; Hare, 2012) and following the advice of Crook, the model has been
created based on his views. The cloister and attached buildings are also hypothetical due to the
lack of detailed excavation or other material related to their formation and layout. Furthermore,
the cloister roof supports within the model are added in unknown positions. Due to its
destruction by Bishop Horne the only evidence to support the angle of the roof presented is
scarring found on the exterior walls of the cathedral. It is unknown how probable these supports
are, especially with the varying height of the surrounding walled features.

The model was created by undergraduate students with no archaeological background and it was
created over successive years as a training resource where the focus was on the modelling
process, rather than the accurate representations needed. The model does follow some known
archaeological information but there remain questions as to why certain parts of the building
have been modelled in the way that they were. For many, an image like this, placed within the
cathedral, would be deemed accurate. The erroneous details included are only known due to the
documentary research and building examination that has been carried out by the author (Chapter
Four). For others it may be impossible to tell. This highlights the difficulty within the modelling of
the past, in that virtual models will always contain some form of data that will mislead due to the
unknowns included. Many of these misleading features are overlooked by the viewer and affect
the understanding that many will have.

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2 The students who created this model may not have been aware of this issue, as they most likely had no
access to onsite measurements, save for the data provide by John Crook.
The act of creating something usable requires theoretical thought processes. This allows for an analysis of how virtual models can be used within archaeological research. With varying
theoretical implications, the application and use of virtual reality within archaeology varies greatly and the important areas of interest are discussed below.

2.4 The Theoretical Implications of Virtual Reality within Archaeology

Theory provides scope for understanding how the past was created but following pedagogical concepts within archaeological reconstructions can lead to representations that contain less physical evidence, thus affecting the realism and validity that these theories are meant to represent (Brown III and Chappell, 2004: 52). Noble (2004: 284) believed that reconstructions need not be painstakingly true to the historical reality in order to be authentic or successful; they should instead be based on what we want to accomplish and what is realistic. Higgins et al. (1996), Forte and Siliotti (1997), and Dingwall et al. (1999) have discussed in great detail the early theoretical implications that virtual reality had within archaeology. The aim of this section is not to provide an overview of these theoretical discussions but rather act as a footing on which discussions can be based.

Virtual reality allows for a selective emphasis, a transformation and a contextualisation of data. Selective emphasis provides a means to detect hidden patterns; transformation allows for the transfer of ideas from paper to a virtual environment; and contextualisation allows for the visualisation of the context (Erickson, 1993: 5). It is a tool with which to manufacture and convey different elements, each with different levels of reliability (Demetrescu, 2015: 44). Within archaeology, the analyses of material and cultural entities are selective. We perceive and act within set material and social situations that create a system whereby the viewer connects with the data in an ideological way (Molyneaux, 1992: 313). There are two variations of modelling, implicit and explicit. The former has hidden and untested assumptions, with the latter providing detailed greater sources of information, one that has the feasibility of sensitivity analysis (Epstein, 2008: 12). Virtual reality in cultural heritage is a useful tool when formulating abstract concepts and ideas; when dealing with spaces that are unreachable or no longer exist; and to provide diverse and unique viewpoints (Roussou, 2002: 93). Within interpretation, there are two main approaches, re-creation and reconstruction. Re-creation brings the past to life and ought to be based on the knowledge and values of the present (Lynch, 1972: 53); reconstruction provides a historical recollection in relation to and in the context of the present (Affleck and Kvan, 2005: 171). Within virtual heritage, the differences between the two are never truly examined, and whilst they allow for a reinterpretation of the data per model to be created, the descriptive and discursive methods adopted follow the reconstruction approach more closely.
Moser (2012: 294) argued that there are many levels of decision-making engrained within the creation of an archaeological image. These are based on the observation of the object or site represented. What is generally overlooked is the subjective nature of the interpretations made. Images create a “powerful effect on the way in which we subsequently engage with other archaeological artefacts” (Jones, 2001: 338); although referring to artefact drawings, the same is applicable within all archaeological representations. Virtual reality is an orthodox process in that the models are “sophisticated end products that are in a continued state of becoming rather than being a useful heuristic that already exists”, and may be confused with the real thing rather than be seen as an interpretation (Gillings, 2005: 227). The past is after all largely an artefact of the present, shaped by today’s predications, understood through ways of being and believing that are comparable with our own (Lowenthal, 2015: xvi). The majority of audiences are left to discover the limitations of these models on their own, with most being ill-equipped to do so (Sterman, 2002: 519).

Visual interaction with the past is one of the most prominent features in virtual archaeology and its role is often discussed in relation to theoretical debates that focus on bodily experience and its understanding (Wheatley and Gillings, 2000: 1). The focus of this debate surrounds GIS (Geographic Information System) but the application of vision is not restricted to this medium. Vision is an important aspect that is used to convey the past but this is one aspect. The fundamental characteristic of three-dimensional modelling is the production of visually pleasing images to convey theoretical discussions and to represent possible scenarios. The basis for the model must be more reliable than is currently presented. Box (1976: 792), writing from a statistician’s point of view, postulated that all models are wrong. A model cannot be created without a description of the natural phenomena included. Creating models based on assumptions of data that are known to be false, but believed to be important, creates a system that is based on incorrect and false ideals. To create models that are correct there must be an awareness of what is wrong with the model produced. Box’s experimental design (Figure 6), whereby randomisation of data is used to achieve validation; replication of the model by others to provide valid estimate of errors; and the blocking of unnecessary sources of disturbance to achieve accuracy provides a system from which virtual modelling can be created (Box, 1976: 797). Creating a feedback loop combines both theory and practice that leads to resolving uncertainties within our data rather than redefining unknowns.
When dealing with complicated data, Box (1979: 202) suggested the use of robustness and parsimony where scientists attempt to express data in a simple way. Simplicity within a model provides a clarification of data whereas complicated features obscure the results. In his earlier paper (Box, 1976), all models were wrong but he later agreed that some were useful (Box, 1979: 202). He noted that a model could not exactly replicate the real world, but through a parsimonious model, useful approximations could be gained. If searching for genuine and precise answers about the past, none can be gained through the generation of models, regardless of how accurate they are deemed to be. Instead, an interaction between what should be included and what should be omitted is required. This is regularly completed within model production but the interaction between the model and analyses are sometimes overlooked in relation to the criticism attached to the model production (Figure 7). Wit et al. (2012: 224) discussed this concept further by suggesting that all models are wrong, in the sense that models can never tell the whole truth, but at best, represent fragments of it. These fragments should not be based on procedures and inferences but rather on the assumptions and starting points on which the data are interpreted.
Uncertainty then is not based solely on internal differences of understanding, but also how the data relate to the rest of the world (Wit et al., 2012: 229).

Figure 7. Interative Model Building (Box, 1979: 203). Reproduced with permission of Elsevier, www.elsevier.com.

Following Box’s (1979: 204) interative process, tentative analysis and tentative modelling require modification and repeated steps until the model is deemed to be correct. The idea of interative fixing of a model provides an early idea of creating genuine results from complex systems through a simplification of necessary information. To create a genuine and more truthful representation within archaeology, the introduction of outliers and limited information is necessary. Interative fixing is necessary but requires a reassessment of what tentative analyses are performed. Using scientific approaches, such as structural analysis, provides a footing on which the tentative models are created, based on logical tentative analyses. Although Box (1979: 230) admits that “attempting to allow for every contingency is impractical”, the introduction of superior computing systems allows for more complex data to be included within the final results. This process moves away from the simplistic models that are created, generating residual quantities that allow for the removal of discrepancies in the reconstructions that archaeologists create. Watterson (2015: 122) however believed that using scientific approaches masked the subjectivity that is included within modelling, as it provides a generalised objectification that distances those who interact with it. Creativity and artistic processes allow for the generation of these virtual models, but problems with accuracy and authenticity can result.

Accuracy and authenticity within reconstructions need not distort our sense of the past, as long as these are presented and understood to be an attempt to view a past generation, where the truth can never be truly known. Instead these models should give an impression to help understand and relate the context, meaning and significance rather than be an exact copy (Jameson, 2004a: 13). This raises an issue of how the reconstruction is evaluated and if the public who experience it share the understanding of the creator. Watterson’s (2015) paper raises interesting points attached to how reconstructions should be created. Watterson follows a creative approach in her modelling, through the addition of creative features that enhance the reconstruction. Using archaeological data should define the limits of what creativity should and can be used. To use creativity requires artistic license, which is dangerous when used on untested representations due to the level of expectation that is already seen from the audience. Creativity is needed to create
the reconstruction in the first instance but using scientific testing allows the interpretations to have validation, not just a specific view from the originator.

Epstein (2008: 12) noted that the understanding of simple models as being invaluable without being ‘right’ is flawed, as they only provide illuminating abstractions. Their uses provide idealisations of the given data, as “all scientific knowledge is uncertain, contingent, subject to revision, and falsifiable in principal”. The knowledge gained is founded within the observations that can be made. Lynch (1972: 53) believed that knowledge of the past should change as our present knowledge and values change, mimicking the way history is rewritten. Following this is necessary but great care must be given in validating these changes. Using technology is one form of this and technologists that deal with visualisation are generally more concerned with the technical issues of implementing the visualisation rather than the authenticity and accuracy attached (Roussou, 2002: 93). The use of material residues and the accounts of those who experienced it provides no evidence that can tell us about the past with absolute certainty; its survival is selective and will contain residual doubts based around our eagerness to accept it (Lowenthal, 2015: xxii). The past is therefore subjectively biased by both the narrator and audience. When dealing with physical remains, the survival invokes a past that is static, that confirms or denies what we think, thus creating a system where authenticity is based around the views of what the past ought to have looked like rather than on what the original shows (Lowenthal, 2015: xxiii).

Earl (2004: 173) stated that to interact with a site, object, or landscape from a user’s point of view is to be physically and emotionally involved. This is applicable to all forms of archaeology but is relevant within the theoretical application of virtual reality, especially when dealing with the use of augmented reality such as the work of Chrysanthi et al. (2013) which allows for an engagement within simple interactive displays. The important aspect of three-dimensional graphics is the ability to convey the sense of three dimensions and is best suited to direct interaction within a virtual space (Papadopoulos, 2013: 135). Paliou (2013: 258) discussed this three-dimensional application in respect of viewsheds within a GIS context, much in the same way as Higuchi (1983) does in point seven and eight of his adapted viewshed. The addition of a third dimension allows for a greater number of outputs. This moves away from the limiting factor of technological reconstructions restricted to dealing with two dimensions. The integration of human perception (2.4.6) and behaviours requires more work to be included but it can be modelled. To understand visibility in a way that is independent from interpretation of theoretical and methodological similarities, the use of three dimensions is required.
This creates a medium on which vision can play a more prominent part but it also allows our other senses to be incorporated. Work within computational senses already exists as shown in Mlekuz’s (2004) investigation of the sounds of church bells and the social construction of the landscape; Tschan et al.’s (2000) work on smell with flora and plant distribution patterns; Gaugne et al.’s (2014) work within haptic feedback systems to create a level of touch within virtual reality; and Eve’s (2014) work within mixed reality. The notion of experiencing taste virtually is difficult but systems could be created that follow Heston Blumenthal’s sensory experiment with food and smell (Jamieson, 2012). In his work, Blumenthal introduced a food menu and a series of smells to stimulate senses within a cinematic experience. The same stimuli could be applied via a system similar to haptic feedback and would add to the communication of virtual models as seen in the phenomenological study by Eve (2016).

2.4.1 Interaction in Archaeological Virtual Reality

Models fail because basic questions about their suitability to the purpose they were intended for are not asked (Sterman, 2002: 521). Interaction may be a result of this but the interaction follows nonspecific research questions; if modelled incorrectly they create a sensory experience that is deceptive. If dealing with interaction on pre-existing data, such as buildings that have been laser scanned (B.1), the interaction allows for a contextual and social interpretation; if the model is hypothetical, the interpretation gained from the interaction limits the interpretations that can be made due to control engrained within the original reproduction. Bogdanovych et al. (2010: 618) believed that the primary focus of traditional methods of preservation are based more on the significant events, the technological advances, the buildings and the customs, as shown through rituals, movement of people, social norms and etiquette. Through the use of three-dimensional technologies that include interaction, they felt that a more accurate preservation could be created such as Roussou’s (2007) work at Pompeii using artificial intelligence for virtual crowd movements. The work presented followed an agent based study, that of allowing users to interact within a given framework in Second Life. A social influence was key within understanding the cultural setting related to the movement of the artefacts. The interpretations gained however are generated by individual thought processes and are not constrained by static images. This can still be deemed false if the interpreted reconstructions are designed around a basic form of knowledge. Earl (2013: 234) believed that movement within an archaeological site is mediated by the extent of preservation and the rules of access, rather than by the original structure of the space; creating a model that incorporates a wider area associated with the site in question allows for greater experience.
Adding interactive elements provides a system that allows for immersion and co-presence that gives suggestive and emotional effects through direct experience of the past. It is believed that the more immersive the model is the more effect the symbolic content would have (El Antably, 2010: 4). Although immersion through interaction provides some level of experience, this experience can be tainted. It is synthetic perception, one that is specific to the society in which the environment was created and deployed, leading to the possibility of misinterpretation when viewed outside of this society (El Antably, 2010: 7). Simply adding interaction is not enough, the model has to be built in a way that provides an authentic experience, one that is hard to complete when dealing with hypothesised views. We measure what we care about, and those measurements alter what we believe is important (Sterman, 2002: 524). Regardless of a site’s history or a person’s experience and knowledge, sensitivity in understanding specific elements allows for specific areas to be investigated without prior assumptions that affect the interpretations made (Jones and Yarrow, 2013: 14). Through sensitivity, the authenticity is protected and contextualised and should not, as Bakar et al. (2013: 42) suggested, be based on individual opinion but rather is a system that combines several ideas and hypothesis.

2.4.2 Realism in Archaeological Virtual Reality

The relationship between material authenticity, site-specific interpretation, and the objective is key in reconstruction understanding (Brown III and Chappell, 2004: 47). The majority of virtual heritage follows a descriptive approach to interpretation. With the greater use of gaming, a successful project is defined by the photorealistic nature it produces; the degree of realism directly maps the degree of authenticity and is generally poorly done (Affleck and Kvan, 2005: 169-170). In Rua and Alvito’s paper (2011: 3298-3299) the reconstruction of the Roman villa of *Casal de Freiria* used a mixture of topographic, archaeological and photographic records to virtually reconstruct the villa as it once was. An emphasis was given to the photorealistic quality of the final rendered image but it was believed that physical reconstruction would be too difficult to achieve due to the many hypotheses of form that existed. Their work was based on the extant remains; the data present on site was first modelled, as shown in Figure 8. A game engine was used to add a form of realism in terms of interaction and the model included involvement from architects and structural engineers. Although included, a simplified model was produced, using all known information to remove uncertainty. The hypothesised virtual model was built directly onto the modelled archaeological data, and was believed by the authors to be realistic; there are issues however as the final model was based on comparative studies. Figure 9 may seem realistic from its photorealism but when each element of the building is broken into parts (Figure 10), the justifications given in the text are insubstantial, especially if tested under structural deformation;
the individual timber frames would most likely collapse due to there being no beams to connect each element together.

Figure 8. Reconstruction of the present day archaeological site of Casal de Freiria (Rua and Alvito, 2011: 3301) (http://www.sciencedirect.com/science/journal/03054403)

Figure 9. Textured model of the Freiria Granary (Rua and Alvito, 2011: 3302) (http://www.sciencedirect.com/science/journal/03054403)
When converting two-dimensional entities to three-dimensional models, and when representing three-dimensional models as two-dimensional images, the system creates partial information. The process needs to change but at a basic level provides “perceptual, physiological and technical factors within the interpretation, visualisation and reconstruction” (Papadopoulos and Earl, 2014: 157). The desire to create photorealistic models has produced a system that relies on these two-dimensional photographs that marginalise the capability of what can be done using virtual reality. The method of creating images outweighs the interpretative uses that models could be used for. The perception and classification assigned to images can create a system that adds a disproportional credibility to the results gathered because they were created on a machine (Reilly and Rahtz, 1992: 21). Although this statement was from 1992, this credibility is still prominent in archaeology as virtual models still provide a ‘wow’ factor that can enrich perceptions of the archaeological evidence. In this notion, creating an image of a virtual model allows for an inference by viewers of the image being ‘truthful’ due to the sophisticated software used to create it.

In order for the public to understand more about the past, there is a need to first help them see the limitations that exist within their current beliefs (Sterman, 2002: 526). A well designed virtual heritage application within a museum setting is one that visualises and provides access; one that presents multiple and alternative representations and visualises different theories; keeps interest alive; and aids distance learning (Roussou, 2002: 94). Whilst these are important, only one representation is usually shown and the different theories attached are not explained, rather representations are evaluated based on their photorealistic quality. Photorealism allows for a
greater interface but this must be done in a meaningful and engaging way that includes greater data and greater complexity. Research should address issues beyond photorealism, whereby interpreting and communicating the complexity of tangible and intangible heritage in a more meaningful way will provide a greater basis. There needs to be a shift in focus, where any understanding is based more on the relation to a contemporary perspective (Affleck and Kvan, 2005: 170) as most visitors do not distinguish between the original and reconstructed parts but yet are still concerned about authenticity contained within the reconstructions (Lowenthal, 2015: 355).

Within archaeology and the way the public understand the data transmitted, there is a need to create a learner-centric approach, whereby each step of a reconstruction is taught and understood. When examining images, either in two dimensions or three dimensions, requires experience in the required way of seeing (Mosaker, 2001: 19). Without a more concrete learning approach, any ideas and interpretations that are created from flawed understandings will inevitably result in a flawed problem-solving process. This affects the realism included within the processed reconstruction and thus changes the authenticity that is perceived. Greater familiarity will alter our experience and with more reconstructions being created, what seems authentic is based on what is shown in such faithful detail rather than on the uniqueness that every reconstruction should follow. Realism heightens the appeal of virtual reconstructions but these are never truly tested beyond academic perceived norms.

2.4.3 Uncertainty in Archaeological Virtual Reality

Uncertainty and accuracy are genuine issues within virtual reconstruction. They can imply a level of interpretive certainty which is largely unobtainable due to the implicit assumptions and explicit choices that are made (Watterson, 2015: 120) and are more an interpretive process than anything else (Russell, 2013: 298). Digital media is accused of lacking accuracy due to the results of the abstraction and the assumptions included going against what is recorded (Roussou, 2007: 267). Much has been said on how interpretations and understandings are affected based on the data that are included and shown within these virtual representations. The same can be applied to physical reconstructions as demonstrated through Jameson’s (2004b) edited volume on The Reconstructed Past. Jameson (2004a: 2-3) suggested that the public was unnecessarily misled by reconstructions that have not been verified by archaeological and documentary research. The physical reconstructions produced do provide a three-dimensional encounter with history, to which people relate and can comprehend with their own experiences. However, contemporary cultural perceptions and norms influence the reconstruction process, and due to the incomplete nature of the data that can never be truly recovered, a true representation can never be achieved,
Chapter 2

thus affecting the experiences of the public and their comprehension of what is shown. Jameson (2004a: 7) highlighted this through the physical reconstruction of Jamestown, Virginia where none of the reconstructed buildings are completely justified. In North America the reconstruction process since the 1970’s have been subjected to higher levels of scrutiny in terms of archaeological authenticity and truth for public perception, such as the reconstruction of the Mission San Luis in Florida that was completed by Hann and McEwan (1998) (Figure 11). The representation and experience that can be gained is superior as the archaeological investigations were more detailed (Jameson, 2004a: 13). This is not evident across all of the states and indeed any reconstruction created using set contexts can be obscured through its eventual consumption.

Image represents the Reconstructed council house at the Mission San Luis de Apalachee State Park.
Copyright permission was not gained.
The image can be found on page 15, figure 12 of J.H. Jameson. 2004. The Reconstructed Past: Reconstructions in the Public Interpretation of Archaeology and History. Published by AltaMira Press

Figure 11. Reconstructed council house at the Mission San Luis de Apalachee State Park (Jameson, 2004a: 15). © Altamira Press 2004

Representations, like the one above, may communicate meanings that we may not be aware of or wish to convey (Moser, 2001: 268). They are used as persuasive tools that appeal to our senses but the key aspect of their success lies within the authenticity that they present. When dealing with community based archaeology, different perspectives can be generated through these representations; the views of archaeologists may differ to those within the local community and understanding whose view should be included is problematical. As an example, Australian aboriginals may have alternative ideas or views of a given settlement to those archaeologists who specialise in aboriginal archaeology; simply studying the site is not enough, as the aboriginals have a different association to the site and may wish for these representations to be expressed in another way. This difficulty is discussed further by Byrne (2013). If both views are incorporated, the accuracy of the presentation can be deemed to be greater but can still be seen as a superficial device, as the representations may be biased to the archaeological perspective, rather than the community whose cultural life are engrained within it. As these are persuasive tools, representations and illustrations can create a greater sense of authenticity and these become “engrained in our consciousness”, creating a system whereby visualisation become “intimately linked with knowing or understanding the past” (Moser, 2001: 280). We can never know the past,
we can only speculate based on the information given. If the representations of the past do not follow a firm basis for communication, then the understanding of the past through academic and non-academic means is restricted. To communicate with partial information or a one-sided opinion creates an understanding of the past that is predicated on deception whether consciously or not. We accept or reject any account of the past on the basis of our own internal acceptance (Lowenthal, 2015: 215), defined by the material clues which characterise age; the audience expectations through preconceptions; and plausibility and meaning through the historical story told (Holtorf, 2013: 432-434).

2.4.4 Authenticity in Archaeological Virtual Reality

Authenticity is the central pillar within cultural heritage whereby the data presented claim to be real, scientifically truthful and historically validated (Flynn, 2007: 349). Instead of seeing virtual reality as an objective simulation that replicates the past, they should be seen as a construct which can never be wholly authentic; “they are not the past and they can never be” (Gillings, 2005: 230). Thus, authenticity plays an important role within how the past is modelled, but to say that something is inauthentic is not to say that it is trying to deceive, but rather that it is acting as an interpretive tool that misrepresents the past. The processes are however the primary issue with what can be termed misleading and it is these that need altering, as seen in the work of Eiteljorg (2000), James (1997), Miller and Richards (1995), and Moser (1998) who discuss this issue further.

Reisinger and Steiner (2006: 66) believed that the term authenticity should be removed when discussing the genuineness of objects or activities due to the different concepts and perceptions that exist of what authenticity is, as there are many that contradict each other. Jones (2010: 182) argued that culture and object authenticity overlapped one another and a combination of both was necessary. The essential element however is in removing the assumptions that lead to the classification of authenticity when discussing reconstructions as real imitations. The perception of authenticity can be gained from the credible determination of what the object or site represents, but this can also be gained from other experiences and information, such as associated descriptions (Holtorf, 2013: 431). Authenticity is not restricted to reconstructions but is applied throughout archaeology. The reason authenticity becomes an important issue within the virtual reconstructions is due to the nature of how it is represented. This can stem from the inclusion of photographs to capture and present archaeological data. Photographs captured in the past are generally regarded as being truthful copies and were believed to depict remains in an authentic manner (Weiler, 2013: 40).
Photographs are treated as being important supporting pieces of evidence within the interpretation process of archaeology. They are however often used out of context within the wider sphere of public awareness and thus are manipulated to represent an unbiased representation (Papadopoulos, 2013: 46). These representations are restricted to a given time but their use as a tool to record features led to the adoption of more photorealistic renders of reconstructions being made. The same out-of-context representations are seen within virtual archaeology.

Earl (2004: 178) argued that photographs should be used within the reconstruction process to add the feeling and knowledge that is found within them but as Moser (2012: 297) pointed out, “we are yet to consider the extent to which imaging technologies might alter our perception of the past” through the use of photorealistic reconstructions. The only work of consequence that deals with this is by Frankland (2012) who studied how archaeological visualisations are consumed by professionals and non-professionals via different styles of computer-generated reconstructions that included non-photorealistic rendering, depicting three-dimensional graphics in artistic and expressive styles. In his work, it was found that the public interpreted the data with different expectations, meaning that the viewers created their own interpretations based on the same information given. This creates a need for all information to be included to remove the hidden nature of limited understanding through the camouflage of realistic representations. The overall problem that lies within photorealism is that it leaves little in the way of thought to produce different hypotheses.

The issues that surround photorealism versus non-photorealism are the validity of the information shown and the importance of accuracy in the representation. The reconstruction must reflect as truly as possible the situation of the surrounding environment where the senses, other than vision, are simulated (Roussou and Drettakis, 2003: 52). Roussou and Drettakis’s work was meant to provide a comparison between the two representational tools, but concluded by saying both were good but their use should depend on the intention of their end use (ibid:57). The introduction of non-photorealistic reconstructions provided a way for selective understandings to be gained, but they are subjective in their nature. Its use is to show what areas are deemed more correct and are based on personal decisions, unless archaeological data still exist. This was an approach suggested by Mosaker (2001: 17) in showing areas that have known aspects and one that is highlighted by Earl (2013: 232). Similar is the layering system promoted by Demetrescu (2015: 45) where the original archaeological data could be seen in the final image. This can be seen in Figure 12 and although it offers an understanding of how the model was created, no choices of the model process are included. Demetrescu treated the reconstruction process as an excavation and stratigraphic examination, where the original sources are inspected,
the used data are scrutinised and the properties of the material are given. These properties include location, shape, material and dimensions and focus on known source data (SU) and hypothesised ideas (USV). This process can be seen in Figure 13 and provides a complicated procedure to follow and one that may provide too much information for archaeological practice.

Figure 12. An exploded view of a reconstruction showing the archaeological data and the resultant virtual model (Demetrescu, 2015: 46)
(http://www.sciencedirect.com/science/journal/03054403)
Figure 13. The stratigraphic sequence of tangible and source-based actions with USV highlight hypothesised ideas and SU representing source data (Demetrescu, 2015: 48) (http://www.sciencedirect.com/science/journal/03054403)
2.4.5 Authority in Archaeological Virtual Reality

The value that is placed on a reconstruction is one that is an ambivalent concept that is ascribed to both tangible and intangible things, ones that are not objective and innate (Bevan, 2012: 2). The values that are assigned to archaeology are sometimes wrong and others feel differently about their use; their application is defined by the positive feedback associated with the creator’s authority. This often comes from individuals who have authority within a field of expertise; although powerful, the trust that is given is one that exceeds what should be granted. Authority is however a statement (Niccolucci and Hermon, 2010: 28) and when dealing with the reconstruction process the interpretative and expressive qualities must be examined, as the former can clarify concepts, with the latter providing a means to visually convey and communicate them (Hermon and Fabian, 2002: 103). The authority attached differs depending on what the original purpose of the model was. As interpretation through visual means replaces direct experience with the cultural object in question, the information gathered replaces the presence of the past (Flynn, 2007: 350) and the use of virtual reality forces space to be seen as a mathematical division and a simple container for the object examined.

Earl (2013: 228) suggested that three-dimensional analysis allowed complex components to be studied concurrently, in turn abdicating authority to the simulations created. His acknowledgement of computer modelling enabling infinite experimentation set by physical characteristics of surviving data and knowledge is true, as is the multiplicity of meaning attached to the accuracy contained, but more is needed to ascertain what is accurate than the examples of material recovered, changing nature of interpretation, and the engagement with the model (Earl, 2013: 230). The historical value and the authenticity that is seen in the material fabric is intrinsically inherent and is essential in any analysis (Jones, 2010: 184; Bell, 2011: 225). To create a virtual reconstruction without including this material fabric conceals the originality of the building under investigation and any attempt to analyse is limited. Complexity is therefore needed, otherwise the reconstruction can be seen as being an “objective truth” where there is no space for analysis or criticism as the accuracy contained is skewed (Niccolucci and Hermon, 2010: 28).

2.4.6 Perception in Archaeological Virtual Reality

The representation of archaeology has different modes of presentation, split between academic and non-academic means (Moser, 2001: 262). These are not unproblematic as they can make their own statements and create ideas about the past (Moser, 2001: 264). The issue surrounding perception is that it is inevitably influenced by idiosyncratic prejudice, knowledge and experience, with each having a number of different understandings of how visual perception works.
The archaeological use is mainly based on the work performed by Gibson but the concept of perception is valid only when the model created is genuine and useful.

Gibson (1950, 1968) believed that visual perception does not proceed from the interpretation of a static image but begins with the situation of the perceiver. He recognised that visual perception could not be understood unless movement was taken into account, as can be modelled virtually. Although discussing people, the same can be applied to buildings and how they moved and reacted within a physical environment. The adoption of virtual reality for user participation is centred upon the separation of perception between real and virtual. Following his view of perception, Molyneaux (1992: 315) suggested that the viewer was able to engage with the material via computer simulations as they act as the environment, thereby creating real-life activities that make archaeological problem-solving possible via conceptual inhabitants. Although this understanding of perception is one that should be followed, the applications of it depend greatly on the model produced, as, if incorrect, the perception of the model will be wrong and any statements will be erroneous.

The inclusion of light simulations within the realm of perception is important but the physical properties of its colour information are limited by the computer hardware and the variance in different retina displays. The analysis of light as a method of identifying design properties within historical constructions is limited by each individual’s sight, therefore making the interpretation of the data unique to each user (Lucet, 2000: 94). This is further supported by Pope and Chalmers (2000: 110) who add that lighting simulations provide an acceptable approximation but the images produced are restricted by the viewing frustum. Earl (2004: 183) considered perspective as being generalised via the computer modelling process. The painted image however is defined by its varied adherence to the set rules (Moser, 2001). Our perception and experiences of these data are situated within given cultural contexts, defined by their materiality (Holtorf, 2013: 431,440). Thus with a combination of computational and illustrative rules, virtual reality has the ability to cope with a wider spectrum of issues if these differing positions are taken into account. Arbace et al. (2013: 333) believed that most of the true potential of digital technology reside more in being able to address specific needs and specific questions. There have to be reasons attached to why the artefacts or sites are recorded or modelled. Theoretical discussions play a part in this process. Virtual reality has the ability to provide a greater resource to remove these discussed issues, especially with the familiarity that the public have with the technology, through
games, online repositories, and the ability to interact virtually with models and sites for free through VR applications generated through Facebook’s purchase of Oculus Rift.  

2.5 Possible Uses of Virtual Reality

2.5.1 Virtual Reality as Realism

Barceló (2000: 21) stated that realistic models are ones that feel and look like real-world objects; in other words, ones that include the effects of light interacting with the physical object. To create realistic models there is a need to imitate the real world in more than just shape and Barceló recommends the addition of colour, texture, topology and motion. The combinations of these different sources act together to simulate the real but the effect that this has is based more on the visual appearance than the realistic nature of the physical properties. Although he later discusses dynamic models that change around user input by specifying physical properties such as mass, weight, inertia, texture and deformation (Barceló, 2000: 23), the results are restricted to animated sequences that are hypothetical. The hypothetical system together with light reflection and edge detail are important and can suggest details that may be overlooked in general analysis, but the basic elements of the model have to be correct in order to discuss their possible application. If these elements are incorrect then no visual hypothesis can be validated. Barceló (2000: 26) did mention that the future of visual reconstructions should be systems that compute physical laws but like many others who mention it, failed to follow through with its application.

Realism is a term that may be applied in respect to a reconstruction’s photorealistic quality with the rendered images seeming to fit the purpose of the study. Moser (2012: 316) provided an insight into realism and highlighted that the issue of realism has always been prevalent within archaeology. One example she used is that of the dal Pozzo images (The Warburg Institute, 2015) where a lack of ornaments within the illustrations provided an unrepresentative view of the artefacts drawn. Although these are simple drawings and are important in representing the items, the work provides only partial information. Likewise Terras’s (1999) model of the Kelvingrove tomb, created a sense of realism, but the digital removal of several structural elements created an invalid model, even though it was seen as being genuine by the public.

3 https://www.theguardian.com/technology/2014/jul/22/facebook-oculus-rift-acquisition-virtual-reality
2.5.2 Virtual Reality as an Analytical Tool

Modelling is not a simple process, incorporating many aspects that are often unnoticed and the archaeological investigations that are placed upon models fail to use them fully. Discussions as to how best to use models can be seen in Earl and Wheatley (2002: 8) who suggested that virtual models should be used for research whereas Krasniewicz (2000: 164) believed that reconstructions were unsuitable for archaeological research. In the early productions of virtual reconstructions Reilly and Rahtz (1992: 170) suggested that solid models could help investigate the realm of low-level theory as seen in the physical properties of extant remains (Wittur, 2013: 30). Reilly’s original idea of virtual reconstructions within archaeology was meant as a way to interact with the archaeological data rather than to use them as a means to create new understandings of the past (Reilly, 2014). The concept was meant as an analytical tool to create replicas of the excavated material and yet twenty-two years on from his original idea of models helping within the investigation of low-level theory, the discipline has instead delved into other areas of research with the advance of computing. The majority of what is now termed “virtual archaeology” goes against Reilly’s suggested intention. The early concept of virtual modelling provided a “wow factor” within the discipline and for many it was important to include it within their research, as seen in Daniels (1997) who wanted to add a third dimension to his dataset to help conceptualise and understand it better. The understanding of these models seems to have fallen away with the acceleration of the discipline and instead, rather than focus on how to correct the mistakes made, the discipline moved into a new direction by integrating new variations of graphical simulation within erroneous datasets, especially with the introduction of historically based TV shows and films.

Within a GIS context, the statistical representations are often limited to point data, that in turn are presented via a subset of points which can distort the interpretations possible (Lock and Harris, 1992: 85). The same can be applied within all aspects of archaeology and rather than limit this to quantitative analysis, the inclusion of a subset of data within a virtual reconstruction can again offer distorted interpretations. There is a need to recognise that there are limitations within the application of both GIS and virtual reality, and there is a need to represent these failings in both the raw data and the way in which they are displayed. If for example a digital elevation model is produced via a topographic survey of one hundred points, the results gathered offer very little when compared to a model produced via one hundred thousand points. The representation is the same, but the raw data have greater integrity. Likewise within a GIS context, the production of meaningless and misleading map data is prevalent via the use of untrained archaeologists who do not have the background expertise in the software or in the subject matter (Miller and Richards, 1995: 21). When dealing with the finer points of GIS and producing elevation models,
the accuracy is not related in a simple way to the accuracy of visibility predictions, as the edges produced for the elevations are of more importance than the flat areas (Gillings and Wheatley, 2001: 30). It is impossible to know areas of trees and bushes when modelling the past and as Tilley (1994: 74) stated, the views can change as the user interacts with the environment; thus the exact modelling of the past in terms of visibility is impossible. The issues surrounding this are also prevalent in three-dimensional reconstructions but there are ways to simulate the buildings or landscapes to aid the understanding and give the reconstruction more probability.

2.5.3 Virtual Reality as a Physical Interaction

The majority of models are based on theoretical or simulated beliefs that follow general knowledge about the most probable design or are based on existing archaeological knowledge (Barceló, 2000: 18). Geometry within a virtual environment is used as a visual language to represent a theoretical model shown through the pattern of contrast and luminance (Barceló, 2000: 9). However, solid modelling will usually entail a high ratio of subjective judgement, as colour, texture and dimensions are based on assumptions or knowledge obtained from other sources (Fletcher and Spicer, 1992: 98). The issue, as Reilly (1992: 159) suggested with photorealism, is how to inform the viewer on how much confidence the archaeologists have in each reconstructed element. As photographs are an essential part of our everyday lives, the connection to judge real-world entities are based more on the photographic detail available. Photographs however teach a particular way of seeing and as Gillings (2005: 229) stated, we have to be careful how we read them. One aspect that could be explored is the continuation of the physical components that make up a reconstruction and the physics that are engrained within real-life examples. Physics is applied to everything in the known world; one example can be seen with forces that can be created based on the gravitational energy that an object exerts. Within archaeological research, the majority of these physical interactions and boundaries pertain only to lighting. Within three-dimensional programmes such as 3DS Max and game engines; physical properties such as gravity can be applied. These physical properties pertain to unknown weights and deal with the scattering, dropping or draping of objects that simulate movement, rather than computing them. Our understanding of the past is made up by what we know today and part of that is how objects interact when forces are applied to them. The application of the physical properties within how the past is reconstructed must therefore be used as a way to add to a scientific approach within which models are produced. It is only through these means that archaeological modelling can adapt and create authentic reconstructions.

One of the only methods of physical interaction to have been undertaken to date is the study of how light interacts within a given space. The method can be applied to all forms of archaeological
research but it is mostly used in relation to buildings. Examples of light analysis within archaeological reconstructions can be seen in Chalmers (2002) who focused on accurate simulations of ancient lighting; Sundstedt et al. (2004) who used lighting analysis as an additional examination tool, although they did not offer a true lighting analysis as it is perceived today; Dawson et al. (2007) who used light within Arctic dwellings to identify the tasks performed within the buildings; and Callet et al. (2010) who used natural lighting analysis within Notre Dame Cathedral, Paris, to analyse the gilds and polychrome present. This last example provided the most accurate simulation of light, because the structure was known. A further case study can be seen in the work of Papadopoulos and Earl (2014) who focused on the Minoan cemetery at Phourni. They created models based on theories surrounding the orientation and the natural illumination within the mausoleums. The outlines of the buildings were known but their form, in terms of the roof, was not. They stated that in order for a lighting analysis to be accurate the geometry must be carefully and accurately produced; that the orientation and location of luminaries must be correct; the energy and distribution pattern must be based on real-world values; the quality of lighting solution must be high; and the material used must be truthful (Papadopoulos and Earl, 2014: 140-141). Within their results they gave a general overview of the lighting analysis based on the reconstructions created, but their results must be queried, as they themselves say that approximations of the building work will have a direct impact on the physical accuracy possible (ibid:140). Although this was aimed more at the light pattern, the same can be said of the model produced with uncertainties in architectural form meaning that uncertainties relating to the lighting analysis will exist (ibid:142).

The results gathered from light analysis can provide an idea about human interaction and in turn can provide reasoning as to why the buildings were constructed in the way that they were. Lighting analysis can focus on specific elements within a structure providing answers to different archaeological questions that relate to the positioning of artefacts based on human interaction. The foundation for these results is the known movement of sunlight in a virtually replicated past building. The visualisation of space may be more accurate through this method but the fundamental part of modelling is still based on unknowns. The production of qualitative and quantitative representations through light can be true in known buildings but are not as definitive in hypothesized reconstructions. One variation of this can be seen through hypothesis testing.

2.5.4 Virtual Reality for Hypothesis Testing

Wittur (2013: 33-34) stated that hypothesis testing is an exceptional form of analysis used in archaeology but ignored that hypothesis tests are never truly answered. Frischer et al. (2000) used hypothesis testing in their Santa Maria Maggiore model, which highlights the changing
pattern of the building over time. In it, they included different interpretations to assess which ones were true, and whilst different entrances to the nave were modelled, the answers relate only to the visual appeal and thus provide no scientific answer that could be validated. To arrive at a complete or even partial picture we need to depart from observations and advance into a more complete interpretation (Wittur, 2013: 44); this is difficult when differing interpretations and observations can be made of the same raw information. Hodder (2000: 94) warned us that possible distortions of the data could be used to fit a hypothesis and although frequent within archaeological investigations, he chose to look at the hypothesis that incorporated the majority of the data gathered. This rule leads to the research carried out in this thesis.

Ideas that contain all of the information gathered, even if the interpretations seem to be untrue, will in turn create a more complete model on which analyses can be based. Whatever type of analysis takes place, it must be based on a model that is physically accurate; the only way to do this is to rigorously test the physical applications of the structure created. Interpretations of archaeological data will always differ but the testing of structural feasibility enables these interpretations to be seen as valid, as they will provide answers to whether or not a structure is physically practicable via straightforward positive or negative answers.

Work by Harrison (2011) and Earl et al. (2013) observes the continuance of hypothesis testing via the application of procedural modelling. Their work focused on the reconstructions of buildings at Portus, Italy and used procedural modelling techniques to provide various hypothetical forms of the buildings under investigation. The work included the identification of structurally important features with various measurements taken from survey, excavation and known architectural lengths to create the models. The production of the models created new ideas about what was possible within the parameters input, but the results are still based on interpretations restricted by the limits of the inputted information, which may be incorrect. Although various hypothetical tests can be created, which in turn allow for a visual interaction, the data are no more than an automatic interpretation based on numbers inputted into a software package. More is required to validate a chosen response and it then leads onto the possibility of continuing this application by scientifically testing the automated models.

A key purpose of digital modelling as extracted from Gomes et al. (2014), is to ensure that the information about the shape and appearance is not lost, so that it can act as a dissemination tool and to create replicas of the past. To reduce a scene’s complexity is a common approach within virtual reconstruction and limits the modelling to only visible components (Papadopoulos, 2013: 149). When dealing with different varying sources of information, the modeller will filter this to produce a model that is based on what they believe to be the key information.
(2013: 224) goes on to say that he has never seen a publication that openly discusses the choices made from these. I would go one stage further and suggest that these are hidden from public view as the models produced have varying levels of confidence attached. Importantly Papadopoulos further suggested that this was due to the way in which archaeology presents interpretations. When looking at mainstream interpretations, an analytical review of their data is not required, yet within virtual archaeology it is imperative that this be done. Since reconstructions are used as a visual form of communication, a level of transparency is required, as the debate and sources used are often not elaborated on. Using complex systems by users who do not fully understand the technological solution can create a system that abdicates authority, as users can create results using generic commands. These can be taken out of context, where arguments are separated from evidence, and the interpretations made are treated as fact (Huggett, 2004: 84). Within mainstream publications, the source data are usually provided and an analytical review of the work can be completed. For virtual archaeology there is a greater risk of these reconstructions being used out of context due to their digital nature, and once removed from the associated text, may become misrepresentations that detract from the understanding of the past.

If the model is managed in a precise and complete way whereby each element is thought about and evaluated, then archaeology is better equipped to obtain images that are closer to reality (Lucet, 2000: 88). The reconstructions can either be a product of a complete or finished image that is based on minimal data or it can be seen as an innocent representation that is based more on surveyed data (Fletcher and Spicer, 1992: 99). However there is a danger of “convincing the uncritical viewer that the model presented shows what the original would have looked like” (Reilly, 1992: 159), especially as what is simulated is not necessarily the same as what it simulates, as models can be built to follow set ideas and to answer specific questions of research (Molyneaux, 1992: 313).

There is a “need to create a generalised structure in which cultural heritage is communicated and utilised in a way that is clear to both simulator and the simulator’s audience” (Biskowski, 1992: 212). Gillings (2005: 228) suggested that the ability to create a model using stone-by-stone data sterilises the information gathered as questions in relation to volume, mass, gravity and economics become more important, and the outputs gathered are not equal to the time invested. Although it may be accepted that the outputs in creating a model based on stone-by-stone data are not worth the time invested, it has to be argued that the questions that surround the physical elements do not limit the investigations that can be placed upon it; rather it can create a more solid foundation from which to argue. Gillings goes on to say that mass and centre of gravity are not important compared to being able to experience and dwell within the model. What Gillings
overlooks is that the fundamental part of a building is how it is constructed, and the models need to follow this use of mass and gravity to be able to provide the correct lived experience.

2.5.5 Introduction of Forces

The application of structural analysis within computational modelling is a method that will allow for the analysis of construction methods and provides a means to test authenticity and accuracy. Structural analysis is the study of the physical properties of a given structure. In simple terms, it provides calculations via the mass of an object and its interaction with other structural bodies that are expressed through the gravitational forces that are exerted upon them. From the forces built up with the multiplication of the objects used, such as stone or timber, and in given shapes, calculations can be made on whether or not a certain form is viable and acts as a model predicated by force. In real terms a building, if correctly built, is able to cope with the stresses that are placed upon it and are usually represented through the completeness of the building. If for example a timber lintel is created in a virtual model that supports an upper brick window, the forces exerted by the brick have to be countered by the timber. If the lintel was virtually modelled as being paper thin, the stresses on the relieving arch of the window would lack the support necessary but would appear to be correct visually. Within a physical building, this window would collapse if the lintel were load bearing, as it would be unable to support itself and the forces applied to it.

The application of engineering within an archaeological reconstructed past is something that has not been mentioned save for a few papers by Renato Perucchio, such as his work on the concrete vaulting of the Great Hall of Trajan’s Markets (Perucchio and Brune, 2008). Chalmers and Debattista (2005) do provide an early case study but, as with others, the engineering principles are only mentioned as suggestions for further work. Perucchio however provides answers to the possible reasons as to the destruction of Trajan’s Market and allows a footing to examine in more detail why parts are still standing. Nothing has been provided in using these data to confirm a virtual reconstruction of a past building, rather the focus of the technique has been within the answering of engineering-based questions in relation to still-standing buildings. To provide scientific data through the physical implications of a building allows for further examinations that can be placed around more than just providing answers that validate forms. Instead, they can be used to simulate all aspects of archaeological knowledge.

In computational modelling this is never taken into account. The application of structural analysis therefore allows for the virtual testing of these different types of stresses. The method provides answers to whether or not a reconstructed building would stay upright or whether it would
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collapse. It will provide ‘yes or no’ answers that are used within engineering planning, to the various hypothetical forms that can be created from the same data, providing a more certain basis on which further hypothetical questions can be asked. The application therefore moves away from the problems that are inherent within current research by providing clear responses to questions asked on how well the original archaeological data have been understood and used. In creating a model that follows scientific procedures the basis for the discipline will change, as it will create something that is tangible and real, meaning that the terms “realistic” and “authentic” can be used correctly within the explanation of the data gathered. It moves towards a system that was originally intended by creating something that can be used to study the past more accurately and to help within the investigation of low-level theory as suggested by Reilly and Rahtz (1992). It is not, as suggested by Gillings (2000: 59) in his earlier work, a system that focuses on asking how rather than asking why, but one that instead leads to the potential future of the discipline.

The application of virtual modelling has moved to a system whereby the model has to be deemed realistic by its textural quality rather than its architectural form. The application of structural analysis creates a combination of the available technological advances whilst still administering the archaeological interpretation required. Instead of trying to use the newest modelling software or type of analytical investigation available, the technique steps back to the basic archaeological queries that the discipline should have employed, in proving that the interpretations made are genuine. The technique is demanding and will be difficult to implement but the benefits that can be gained will alter the way in which the past is studied, creating a system that is more scientific, more systematic and more precise in the validations that are made. The system can be used on its own but it would be wrong to focus on just the structural detail. Rather the method should be used in conjunction with the virtual applications that are currently used to add an insight into whether or not the possible reconstructions are true. Applications like procedural modelling, lighting analysis, the simulation of people and many others have their place within this archaeological framework, but they do not provide the basic principle of what artefacts, buildings and landscapes are. To model a replica or interpretation of an entity is one thing but the modelling of the true physicality of something creates a system that is more scientific. The method provides a more rational and more enhanced understanding that then allows for the validation of ideas that are put forward by those who deal with the fundamental aspects of the past. In turn, this will create the interpretations on which our knowledge is based on which archaeological research can be based.

“Reconstructions demand that you know the correct answer to every engineering and architectural question” (Noël Hume, 1979: 232). This provides a reconstruction that would be unachievable to create and which Noël Hume, rightly, ignores as he felt that there was an
obligation to keep faith with the past and to inform (Brown III and Chappell, 2004: 48). It is never clear however how accurate the information used was and how legitimate the subsequent visualisation is; “the level of accuracy, legitimacy and realism of context is analogous to the level of perceived authenticity” (Affleck and Kvan, 2005: 170). If the perceived authenticity is greater than the real, than the accuracy, legitimacy and realism that follow are inappropriate.

Sidiropoulos and Sideris (2003) suggested in their work that virtual reality was a tool that could be used to solve archaeological controversies, where the final model would show no assumptions. Although unrealistic following modern methods, the idea of creating something without assumption is needed. This cannot be done without a more focussed and scientific approach, one where the final data provide enough complexity of information for both experts and amateurs. Almagro (2007: 165) believed that providing greater documentary research meant that the model he created had a higher certainty of being genuine. A model that contains more information may be more factual but uncertainties in proportion to the exactitude of its research may remain. To create something that is accurate means having to examine all aspects of the reconstruction, documentary evidence is necessary but each building is unique and explanation and justification of the decisions made must be given.

### 2.6 Conclusion

This chapter has provided an overview of some of the concerns contained within archaeological virtual reconstructions. At the forefront is the interpretative nature of what can be deemed authentic and realistic. To produce something that is based on interpretation is to create hypothesised visual views that can help to understand the past. These visual media allow interpreters to understand the process of ideas but when taken out of context, the process creates a system that could be seen as being invalid. Each user has the ability to visualise a reconstruction and create unique interpretations based on the information provided. This information can include minimal or all forms of archaeological knowledge and it is the variation in this that leads to the complicated nature of how we understand the past.

The application of structural analysis is one element and should be used within a structure that defines and regulates the choices that can be made. Through this method, the application of virtual reality, rather than using the most up-to-date software packages for the most photorealistic representations, will instead return to the original purpose of what virtual reality was meant to be: a tool that helps to examine the past. Through more factual reconstructions that are based on the physical properties and the physics inherent within the models produced, the system would allow for this to take place and instead of having a system that involves
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untested interpretations, will instead create a system that validates or discredits the interpretations made, leading to greater inclusion of information that contains less uncertainty.

The following chapter will discuss structural analysis in detail and will highlight the limits and proportions that can be utilised within the reconstruction of the past. The chapter will identify working case studies and will point out the advantages that structural analysis offers in relation to virtual reconstructions. It will act as an introduction to the engineering method and will relate to Chapter Five through the examination of Winchester Cathedral and its ever-changing architectural form.
Chapter 3: Structural Analysis

3.1 Introduction

The introduction to virtual modelling in the previous chapter highlighted the problems and possibilities that exist with the current methodological approaches used within archaeology. The application of structural analysis was proposed as a technique that could aid archaeological reconstruction. This chapter will focus on what structural analysis is and how the method can influence archaeological processes. The chapter will begin with an introduction to the technique through early archaeological examples, pointing out the limited understanding that the method currently has within archaeological investigation.

The chapter will develop arguments based around the fundamentals of the application in relation to engineering processes. It will highlight the early development and background of structural analysis and will include the basic functionality of the method. This will focus on the two-dimensional tools, calculations and applications that were originally used prior to the introduction of the computer. The analysis will continue with how the technique has been applied within engineering by introducing the different systems, methods and analyses that are available.

Once these parameters have been explained, the chapter will turn to the computational methods that are currently used, namely the Discrete Element Method, the Boundary Element Method and the application of the Finite Element Method. The Finite Element Method will be discussed in detail and will be utilised in the research conducted within this thesis. The chapter will elaborate on the application of the Finite Element Method, and will discuss its history, as well as the applications of its use in engineering and how it can be included within archaeology. This will develop into the fundamental aspects of the technique through the displacement approach and will discuss how a Finite Element model can be created. It will identify the benefits and drawbacks of the technique and.

The chapter is not meant as an overarching review of the technique as there is too much information that could be included (see Brohn (2005), Kassimali (2005), and Hibbeler (2012) for more detailed reviews), but will focus on the important areas that need reviewing in relation to archaeological practice. The methods that will be explained are detailed but are in a simpler terminology than engineering provides and case studies will point out working examples in relation to cultural heritage based investigations within engineering.
Chapter 3

3.2 The Fundamentals of Structural Analysis

3.2.1 Early Archaeological Applications

To understand the possibilities of what structural analysis can offer to archaeology, there must first be a breakdown of what work has already taken place within the discipline. The first archaeological example relates to typical building surveys (B.3) that identify structural elements as shown through Phillips’s (1975) structural investigation of both the interior and exterior of York Minster. This study overhauled previous hypotheses about the early development of the building (Rodwell, 1989: 35) and identified how structural features can play an important role in our understanding of the past. It was Reilly (1989: 578; 1992: 159) who first suggested the use of structural analysis within archaeology, through his discussion of models being used to test forces to see how ruined structures were destroyed. He concluded that most three-dimensional software packages at the time could not simulate physical behaviours. This work was continued by Delooze and Wood (1991: 144) who further suggested that modelling should allow for the simulation of structural stresses. Daniels (1997) introduced a more systematic analysis through Finite Element Modelling to try to understand more about a building’s labour costs and construction by knowing more about its volume and mass. This was continued in the work by Chalmers and Debattista (2005: 109) who postulated its use within their investigation of Maltese temples; and by Hermon (2008: 39) who suggested that modelling could test structural feasibility.

None of these examples provided concrete methodologies but rather advocated the use of structural analysis within future research. Although not completed their work showed that ideas of force testing were inherent within the early application of virtual modelling and continued with the development of virtual archaeology. Despite the possibilities of what could have been gained using this method, very little has since been completed.

Archaeology has and will always be a field that depends on other scientific work, as can be seen in all aspects of archaeological computing and scientific study. The original and now well used software or investigative analyses within archaeology were developed from further afield. The absence of structural analysis as a technique within archaeological investigation is most likely due to the problems related to the understanding of the technology. Papadopoulos (2013: 140), as an example, suggested that even advanced structural analysis software was unable to simulate and test structures made of irregular stone and differing bonding materials. In fact, the method is capable of doing this if the model is correctly set up. To understand the method and to establish its use within archaeology an outline of the basic principles of what the method is will follow and the chapter will show how structural analysis can be beneficial to the discipline.
3.2.2 The Archaeological Understanding of Structural Analysis

Structural analysis and the understanding of the forces that work within the method is not new. The method was developed first by seventeenth-century engineers who began applying knowledge of mechanics to the design of structures. The majority of earlier buildings, from the time of the Egyptians, are based on a system of trial-and-error and past experiences with many Greek, Roman and Egyptian buildings still standing (Kassimali, 2005: 4). The trial-and-error approach was passed down through each generation of builders, with small adaptations, changing architectural styles. Indeed “the art of building in the Middle Ages was transmitted from one generation to the next, not through books, mathematical tables, architectural plans and pictures, but rather through the direct teaching of the younger masons by the masters experienced in the craft” (Shelby, 1964: 388). This is a continuance of deploying capacities of attention and responses through the embodiment of practice and experience discussed by Ingold (2011: 11); the general apprenticeships within archaeological practice seen in the work by Kelly-Buccellati (2013: 208); and the training associated with apprenticeships within the construction of buildings as discussed by Salzman (1952: 41).

Each style of architectural form had unique strengths and weaknesses. Following the guidelines that have been passed down has led to a system that allows for the interpretations of past buildings by architectural historians and archaeologists. Knowing these rules creates a system of interpretations based upon the known general construction of past buildings at set periods. The understanding however of how these architectural styles affect buildings is generally overlooked. With the introduction of structural analysis, these changing patterns of architecture can be examined and allow for hypothesised views and queries to be tested and verified. This not only allows for an overview of their structural reliability but also enables an evaluation of how alterations to these styles affected overall form and function.

One common misconception within archaeology is the definition of structural analysis. For engineers it is a clear outline of the determination of the effects of loads on physical structures and their components. Within archaeology one of the earliest references to “structural analysis” as a form of investigation is that of Rahtz et al. (1997: 12-124), who examined the architectural styles at Deerhurst Church between 1971 and 1984. Their book title stated that structural analysis was one of the main focuses of research and Chapter Two refers to the “structural analysis of walls below and above ground level” (Rahtz et al., 1997: 12). No explanation or investigation of the determination of the effects of loads was included. Rather, the structural analysis element followed an analysis of the structure, providing a commentary on the stone-by-stone detail that remains to show the different phasing, and it offers an insight into the building following a simple
architectural investigation. Based on this early example the use of structural analysis within archaeological research, as the method is today, is one that is greatly exaggerated and a clearer outline of what it is needs to be provided. The application and adoption of the technique has changed since 1997, with some papers outlining the most commonly used methods, but nothing has been provided in terms of what it is and how best it can be applied to archaeological research.

Although published earlier, the work by Rackham et al. (1978), showed one of the first examples of the analysis of timber in relation to deformation. No mention of structural analysis was used within the paper but it did provide the fundamentals of force analysis. This focus related to the timber-framed roof of the thirteenth-century Blackfriars Priory in Gloucester, where the surviving buildings are the only reasonably complete Dominican examples in Britain (Rackham et al., 1978: 106). During a refurbishment period the timber frames were dismantled which allowed for the recording of the measurements of the permanent distortions of the timbers. The results gave an idea about the disruption of the stresses, which at the time were hard to understand analytically. This was due to the varying levels of support that the structure could provide through alternative systems of stress distribution. It was found that the curvature at any one point was proportional to the bending moment present. The largest bending moment was seen in the outwards push of the ashlars and the inwards pull of the scissor-heads (3.2.5.2). This suggested that the ashlars were strong in compression and the scissors were strong in tension (Rackham et al., 1978: 115).

Figure 14 represents the distortion levels and shows the exaggerated form of the scissor truss when in use. This early example, although reliant on the dismantling of the timber, shows how important engineering principles can be in understanding the form of current building work and points out the benefit of detailed stress analysis. Through a complete digital survey, results can now be manipulated to allow for a more comprehensive insight, without the need for the timbers to be removed. This can provide further understandings of how the inherent forces would have affected a structure in question.
3.2.3 Early History and Development of Structural Analysis in Engineering

It is generally thought that Galileo Galilei (1564-1642) was the originator of the theory of structures in his 1638 work entitled “Two New Sciences” (1974) where he tested the failure of simple structures. His published work laid the foundations for the future developments of the discipline into what it is today, with the second half of the seventeenth and the eighteenth centuries providing a rapid advance in the understanding of structures (Kassimali, 2005: 5). This is demonstrated through the work of Robert Hooke (1635-1703) who developed the law of linear relationships between force and deformation of materials and created the basis of the theory of elasticity (Lourenço, 2001: 94), Sir Isaac Newton (1642-1748) who formulated the principle of virtual work (3.2.10), and Charles-Augustin de Coulomb (1736-1806) who presented analyses of the bending of elastic beams (Kassimali, 2005: 5). The first textbook on the modern theory of the strength of materials was published by Claude-Louis Navier (1826) who focused on the elastic
behaviour of structures. This first textbook led to a rapid expansion of technical understanding in the nineteenth and early part of the twentieth centuries with the majority of classical methods being developed. Examples of this can be seen in Otto Mohr’s (1835-1918) examination of stress and strain and Hardy Cross’s (1885-1959) development of moment-distribution in 1924 which became the most used form of analysis from 1930 to 1970 (Kassimali, 2005: 5). From 1970 onwards, the computer age developed the discipline greatly, changing the way in which the classical methods were used and calculated. The following sections outline these changes and provide an insight into the most commonly used form of analysis that best suits archaeological research.

3.2.4 The Use of Structural Analysis within Engineering

There are two variations in the structural understanding of buildings. The first is structural engineering which is the “science and art of planning, designing and constructing safe and economical structures that will serve their intended purpose”; the second refers to structural analysis and is the “predication of the performance of the proposed structure” (Kassimali, 2005: 5). In the construction of modern buildings, several elements are examined before they are deemed safe. This includes planning, which examines the general layout of the building, and is followed by the preliminary structural design and estimation of loads. Structural analysis is performed on this to determine the stress and strain that these loads will provide. This results in the safety and serviceability checks that determine the structure’s safety based on the result given (Kassimali, 2005: 6).

The classification of structures is based on the different types of stresses that may develop in a structure’s members. The first type is that of tension structures (Figure 15) where members are subjected to pure tension under the action of external loads. Within this category, the tensile stresses are distributed uniformly over cross-section areas of members and are usually seen in bridges and long-span roofs made of flexible steel cables. The second refers to compression structures (Figure 16). These structures develop compressive stresses under external loads and are generally seen in column and arch-based systems. Columns as straight members are subjected to axially compressive loads whereas arches, through a redistribution effect, are usually designed to support the compressive stresses applied from other areas of the building. These types of structures are usually subject to buckling issues and instability problems. The third type of structure is trusses (Figure 17). These usually straight members are connected at their ends by moveable connections to form a stable configuration. These are usually seen supporting roof constructions. Trusses as structural features are intended to be in uniform tension or compression depending on the loads applied with the members elongating or shortening as required. The
fourth type is that of shear (Figure 18), used to reduce lateral movements in a structure via small amounts of bending stresses. These are regularly seen in reinforced concrete assemblies. The final type is that of bending (Figure 19) and deals with structures that contain bending stresses under loading and are usually found in beams, rigid frames and plate-based buildings (Kassimali, 2005: 8-11).

Figure 15. Tension Structure as seen in the Jackfield Free bridge, Shropshire, England where the cables are in tension and the supporting pillars are in compression (Pope, 2015). CC BY-NC-ND 2.0 Harry Pope.
Figure 16. Compression Structure as seen in the Pension Building, Washington (Roeder, 2017). CC BY 2.0 Phil Roeder

Figure 17. Truss Structure as seen in the roof of the Basilica di Santa Croce, Florence (Sailko, 2009). CC BY-SA 3.0 Sailko.
Figure 18. Shear Stress as seen in a reinforced concrete column for a bridge (Störfix, 2005). CC BY-SA 3.0 Störfix.

3.2.5 Methods of Analysis

3.2.5.1 Plane analysis

When discussing buildings and the use of structural analysis, the easiest method in the past to show analytical data was to represent it as an analytical model based on simplified representations of the structure. Using analytical models allowed the intended analysis to be broken down into sections. These provided the behavioural characteristics whilst removing much of the detail about the members or connections that have little effect within the analysis (Kassimali, 2005: 12). One form of analytical model can be seen in the use of plane structures as shown in Figure 20. An analysis of a building is completed through planes or two-dimensional views. The two-dimensional separation provides a way to break the building up into sections making it simpler to calculate the stresses and strains. Three-dimensional analysis via planes is much harder to complete. This is due to the maths involved and the way in which the analysis is completed via line diagrams that show simplified versions of the structure in question.

Plane stress and plane strain are those stresses and strains that are considered only in the XY axis. These are analysed using a basic element shape of triangles, which guarantees continuity of displacement with adjacent elements. “The displacements vary linearly along any side of a triangle, creating a constant displacement along the entire interface” (Zienkiewicz and Taylor, 2000: 89) thus providing a constant strain. Within plane analysis, the displacement functions, strain, elasticity matrix and initial strain are all examined to provide results of the stiffness matrix, forces, distributed body forces and the body force potential. As the analyses are based on two-dimensional representations on the X and Y plane, the stresses given are a basic assumption. The elastic properties should be identical in all directions at any given point. As these calculations are
based on assumptions, the results mean little when used to predict the outcome of stress and strain under changing forces.

Plane stress analysis was once an experimental tool and provided very little in the way of useful data. The removal of the Z plane limits any analysis; a real-life structure is three-dimensional and should be treated as such when analysed. Using a three-dimensional modelling technique moves away from any known problem associated with plane analysis. This is due to superior accuracy in the calculations, as options that are more versatile can be employed, such as the results shown in Gonçalves et al’s (2002) work on stress analysis of adhesive joints. Plane analysis was once a useful tool when computing power was limited. With the increase in available options, the use of the method should be limited to plane representations that are based on a three-dimensional analysis. This creates a system that can show how structures will act differently in relation to the rest of the body. The application of plane-based analysis may be beneficial to archaeological practice by an understanding of basic forms, but as all artefacts, buildings and landscapes are three-dimensional in nature, its application is best suited to simple investigations that require limited outputs.

3.2.5.2 Bending Moment, Shear and Rotation

Within structural analysis, there are three main tests of investigation that a structure must meet in order for it to be deemed safe and these are always applicable. These are bending moments (Figure 21), shear forces (Figure 22) and possible rotations (Cowan, 1976: 2). Bending moments are seen through the “weight of a given subject via a load and the reaction achieved should be equal and opposite, creating a stabilising moment whereby force equals reaction” (Cowan, 1976: 4). The analysis of bending moments is seen through bending moment diagrams that outline the distribution of these loads and the bending moments that are most likely to occur. These diagrams “cross the base line at points of contraflexure” (Brohn, 2005: 43), which, when a load is applied, are the points at which no bending takes place. Shear forces are those forces that act perpendicular to erected structure and vary “under the slightest provocation from changing circumstances” (Brohn, 2005: 1). Rotations are the movements of these members along set axes that affect the possible bending moments and stress and strain relationships. All three play an important role, but it is the concept of stress and strain that affects the overall strength of a building more than others do. Within this, there are three different performance characteristics. The first are the stresses or stress resultants that are imposed upon the subject; the second refers to any deflections that occur; and the third relates to the support reactions required (Kassimali, 2005: 3). With stress and strain, there are two possible variations. The first is shear and the second is direct. Shear refers to the distortion of the structural element. Direct deals with the
change of length of the element divided by its original length (Cowan, 1976: 158). The calculations of these tests are the fundamental products on which structural analysis is based. The knowledge of what they represent must be known within all studies to identify the structural feasibility of a given structure and is important within archaeological practice, as this is to know the limits and proportions of what is conceivable within a reconstruction process.


Figure 22. Shear forces diagram. The left shows an upward force, with the right showing a downward force (McKenzie, 2006: 159). Reproduced with permission of Taylor & Francis, www.tandf.co.uk.

3.2.6 Structural Elements

When considering three-dimensional analysis, the basis of investigation is through the structural element sizes, their number, the supports in place and their material strength. Overstressing the structural material can lead to the failure of a structure regardless of the frequency in number of elements. If the material is loaded in tension, compression, bending or torsion, or through a combination, then it will fail either through permanent deformation or through fractures or cracks (Cowan, 1976: 41). With a crack, although the material has failed, the building may still stand, whereas a permanent deformation will result in total irrecoverable damage as seen in Figure 23. This separation is critical in understanding buildings structurally within archaeology. The numerical results may suggest failure but this may not be evident in its physical counterpart, as is
seen in many still-standing archaeologically important buildings that feature cracks and deformation. Masonry structures are supposed to crack and indicate that a building has at some point been subjected to imposed movements from the external environment (Heyman, 1997: 23). Understanding visually how the material works under tension, compression, bending and torsion will allow for the identification of these points of failure and will create a firmer idea about the potential at which permanent deformation occurs.

Figure 23. Failure in material due to stress. A) Stress produces a crack that leaves the arch in the same position. B) permanent deformation through a complete movement of the arch, unrecoverable in its form (Cowan, 1976: 43). Reproduced with permission of Elsevier, www.elsevier.com

3.2.7 Loading

Every material deforms elastically under loading. Every building has deformed in one way or another and whereas the material would normally recover once the load is removed, the point of deformation is that where the “tensile stress of the material reaches its limit of fracture” (Cowan, 1976: 44). This limit does not necessarily damage the material, but is seen as a structural failure. The way in which stress is viewed is via the relative strength of the structure and should not be confused with the stiffness variances as these, rather than the elasticity of the structure, are measured by Young’s Modulus (Lourenço, 2001: 97). Young’s Modulus is the “stress required to produce elastic deformation equal to the original length” and is normally seen as one thousand times the maximum stress value allowed (Cowan, 1976: 157). Each material has different qualities and different strengths. Stone is highly compressive and has a low tensile strength whereas
timber has a low compressive rate and yet a very high tensile strength. The separation of the different pros and cons of material strengths and weaknesses provide an idea as to how they should be used. Stone for example is not usually a suitable support structure for exceptionally large gaps, unless reinforced with metal, as the material cannot support the tensile forces applied to it via gravitational force. This gap is more suited to timber, which has a high tensile strength property.

Choosing the correct materials based on their structural properties will ultimately affect the overall design. Material type is the most important choice that has to be made when building a structure, as regardless of the number of elements used, if these are unable to support the weight of the structure, it will fail. The choice of material types within historic buildings can play an important part in the building’s longevity; indeed, if a high-quality stone that was structurally strong was used within the construction process, but a weak lime mortar was utilised as a bonding agent, then the structural integrity of the building would be affected due to weakness inherent within the mortar. The use of a material available at the time of construction may therefore result in failure. Questions can be raised as to why certain building materials have been used within building types and how useful they are in relation to the structural strength of the building can be identified, enabling a more precise understanding within the interpretation process.

3.2.7.1 Dead, Live and Environmental Loads

Materials are affected by the loads that are applied to them. These are usually in the form of dead loads, which are the structure’s own weight and permanent non-structural parts; and live loads which refer to the removable features contained within them (Cowan, 1976: 47). A third loading type can be seen in environmental loads that are based on the environmental effects that could affect the structure (Kassimali, 2005: 17). Dead loads refer to gravitational loads that are of a constant magnitude and at a fixed position that act permanently on the structure. These are the weight of the structure and the material and equipment permanently attached to it, such as electrical cabling. Live loads are of varying magnitude and/or position and are always changing. Usually these loads are distributed uniformly across the surface of the structure, such as vehicles driving over bridges. Environmental loads include a number of environmental possibilities that could affect a structure. This loading type is often overlooked when reconstructing archaeological buildings. Conditions such as wind, snow, earthquake, hydrostatic and soil pressures along with thermal changes will affect how a building acts and these must be taken into account when accurately reconstructing the past. Undeniably all of these load types must be met (if applicable) in order for a building to meet its purpose, as if it fails under its conventional loading, then it can
be deemed imperfect and unfit for use. The same can then be applied within archaeological research as the method enables the identification of changing patterns of use, as well as conceivably uncovering a building’s purpose if little is known of its original consumption.

Wind loads refer to the loads applied from the wind around the structure and are dependent on the location of the building, the obstructions around it and the surrounding terrain, geometry and vibrational characteristics of the building. Within engineering, earthquake analysis is the most used form of environmental loading technique. Ground surfaces move in both horizontal and vertical directions during an earthquake. The magnitude of the vertical component is usually so small that it does not affect the structure. Horizontal ground motion however goes against this vertical component. If the motion is great enough, structural damage can result. During an earthquake, the foundation of the structure moves with the ground, as does the superstructure, which results in some form of shear damage through fracturing or complete separation of the structure. This damage occurs due to the inertia of the structure’s mass resisting the horizontal force applied, creating a form of vibration in the horizontal direction, which in turn create the horizontal shear forces.

Earthquake loading deals with the mass and stiffness characteristic of the structure. These have to be strong enough to support varied magnitudes of earthquake. Because earthquakes are considered unlikely to occur in the UK, the majority of buildings are not designed to support this type of force, but areas such as Nottinghamshire (BBC, 2014) and more recently Winchester (BBC, 2015) have been affected. There is a need therefore for this type of analysis to be included within future UK-based archaeological research. Earthquake analysis is a prominent feature within common earthquake areas, such as Italy, and is used within engineering to understand a building’s deformation. A continuation of this within archaeological research is needed to accurately reconstruct these different buildings, as small changes in an earthquake’s magnitude could prove costly to the overall form of a building. To recreate an earthquake digitally allows for a further insight into the damage produced, in turn creating a virtual model that is based on a building’s use, not only within function but also within the environmental setting.

Hydrostatic and soil pressures are of importance within archaeology. Hydrostatic pressure acts against the submerged surface of the structure. This is affected by varying geological depths. The lower the foundation, the greater the force that is applied. Soil being a constant within any building foundation, its pressure, being in a lateral form, is dependent on the soil type found. If this is disturbed or removed via excavation or for geological reasons, then the hydrostatic pressure could prove destructive (Kassimali, 2005: 19-37). Any structure must be designed to withstand the most unfavourable combination of these different load types that they are likely to
encounter. Within modern architecture minimum design loads must comply to set guidelines such as the American Society of Civil Engineers ASCE 7 (ASCE, 2014). Within historic buildings, the understanding of these different loading types will allow for a further insight into their original construction, and provides suitable data on which to conserve and protect historically important structures from general decay and use.

3.2.8 Forces

The load types discussed above are known within engineering as forces. Force can be seen as “anything that changes or tends to change the state of rest of a body or its uniform motion in a straight line” (Cowan, 1976: 53). In buildings, force is normally shown through gravitational weight and reactions from the elements within are required to support this and must be equal or opposite. When this occurs and the force applied is equalled by the reaction, the two are said to be in a stage of equilibrium, as seen in Figure 24. This is fundamental in the examination of the past, specifically within the reconstruction process, as the building or object under examination must meet this equilibrium in order for it to serve its purpose. As an example, if a medieval naval ship was constructed that was unable to support the weights of the intended cannons, then the equilibrium would not be met, and the structure would not meet its purpose.

![Force versus reaction](https://www.elsevier.com)

**Figure 24.** Force versus reaction (Cowan, 1976: 53). Reproduced with permission of Elsevier, www.elsevier.com

3.2.8.1 Equilibrium

Before modern computational methods, structural integrity models were examined via graphical representations. The drawings produced had to show that the building could meet the condition of static equilibrium. Static equilibrium is broken into two parts: those that are statically determinate which are “isostatic structures that cannot be solved purely on statics”; and those
that are statically indeterminate which are “hyperstatic structures that require more laws of physics and equations to solve them” (Cowan, 1976: 63). A structure is considered to be in equilibrium if, initially at rest, it remains at rest when subjected to a system of forces. These forces acting on the structure must balance one another out and are classified as external and internal forces (Kassimali, 2005: 44-46). External forces are actions of other bodies on the structure under consideration typically via loads with the reactions being forces exerted by the supports of the structure to prevent movement. Internal forces are those exerted on a member or section of the structure by the rest of the structure in question. This should occur in equal and opposite pairs where members exert the same force that is applied to it, but if poorly designed, these members may exert a greater or lesser force creating a shear stress that causes the building to fail.

3.2.8.1.1 Statically Determinate and Indeterminate

Before any analysis takes place, there is a need to understand whether a structure is statically determinate or indeterminate, as it will affect the choice of what structural analysis examination takes place. Each variation requires different equations to solve whether or not a structure is safe. Statically determinate structures are said to be statically determinate externally if all of their support reactions can be determined by solving the equations of equilibrium of which only three reactions are allowed. If more equations are required then the structure is deemed externally statically indeterminate. Internally this is different, with the determinate structures needing to be made stable by external supports of which a minimum of four are needed (Kassimali, 2005: 49-54). With two-dimensional analysis, there are three different equations of equilibrium that must be calculated, as seen in Figure 25, with three-dimensional analysis requiring six, as seen in Figure 26. The two-dimensional analysis is based on force reactions in the X and Y plane, with clockwise or counter clockwise rotations in the Z plane. With three-dimensional models, these forces are examined further with the inclusion of the Z plane and the rotations are likewise extended to all axes.
When deciphering equilibrium equations it is important to note that in the XYZ directions all of the forces and moments that are applied to the structure must equal zero. If the results are below this then the building is overengineered; if it is greater, the structure is structurally weak. Over engineering is not necessarily bad as it provides a greater support structure, but with over engineering comes a need for greater supplies of material and cost. If structurally weak, the building may require the insertion of support members to counter the reactions present.

3.2.9 Laws of Static

The principle behind structural analysis and the results gathered are based on the laws of static where buildings must be stable in a static state. This applies to the gravitational forces that are exerted on the building under no other loading types. The later vertical and horizontal forces that are then added on top of this provide answers as to the potential usability of the building, but the underlying factor that is most important is that of the gravitational load with which it is capable of dealing. If it suffers a fault under the basic parameters of its own weight then it will be unable to perform another function. This function forms the basis of initial research within this thesis and has been used within the hypothesised reconstructed models of the past buildings of Winchester Cathedral’s precinct.

Statically determinate structures are the easiest form of analysis within structural analysis but today most real-life structures are not statically determinate due to secondary loading paths
within each of the structure’s members (Brohn, 2005: 3). With several forms of analysis that are required, statically indeterminate structures form the base of most modern analyses but when dealing with structures from the past, only the basic level of investigation is needed. Statically indeterminate analysis deals with structures that have more unknowns that cannot be solved by the three equations of equilibrium alone (Brohn, 2005: 21). The bending moments and shear forces generated are dependent on the material used and additional calculations are needed within the extra forces applied via displacements. This is completed through either statical indeterminacy or through kinematical indeterminacy (3.3.3.4). Both forms allow for an analysis based on no fixed number of equations, allowing several unknowns to be solved. Their use should be limited to small factors that are based around the changing distribution of force. This is seen through additional external reactions that may take place due to the increased internal rigidity of the structure and the additional members found. The increased supports that are needed to maintain these three factors result in indeterminacy being key within their design.

Statically indeterminate analyses are not generally needed when examining the ‘basic’ architectural patterns of the past. Complicated features can of course be seen in Gothic architecture but these are mainly based on appearance and the underlying architectural elements fit within the statically determinate form of analysis. The only part of a structure that would benefit from using indeterminacy under normal loading conditions would be that of complicated timber frames where extra members are needed to redirect the forces applied to the structure. This can be seen at Lincoln Cathedral’s Chapter House where a number of added connections have been included in the main truss beams (Figure 27). An analysis of this truss system under statically determinate calculations would provide little with respect to archaeological research; the results gained would be erroneous due to an incorrect number of equations used to solve the unknowns. Considerations then have to be given as to what calculations are needed within archaeological research. Using statically determinate analysis in statically indeterminate structures will still provide results but these calculations need to be assessed to see how appropriate they are.
3.2.9.1  The Calculation of Statically Determinate or Indeterminate Structures

When dealing with historic buildings, in order to ascertain if they are statically determinate or indeterminate, the number of joints and members must be counted. The equation used to test this is based on “two times the number of joints being equal to the number of members plus three” (Brohn, 2005: 33). If the number of either of these is greater, then the structure is said to be statically indeterminate. In the analysis of indeterminate structures, equilibrium equations must be met to ensure that the structure remains in equilibrium. The same can be said for the compatibility conditions and member-force deformation reactions. Indeterminate structures contain unknown forces and cannot be solved directly with equilibrium equations. Thus the “compatibility conditions examine the displacements and the member-force deformation reactions express the unknown forces in terms of unknown displacements or as unknown displacement in terms of unknown forces” (Kassimali, 2005: 469). This is completed via the general methods of analysis through force methods and displacement methods, with the former dealing with the flexibility and the latter dealing with the stiffness of the structure.

An advantage of designing statically indeterminate structures is based on the structure having smaller stresses as the members will have a greater stiffness due to the redistribution of loads through the increase in member numbers. The stresses that are evident are due to the support settlements, which are able to move more easily in statically determinate structures. The stresses
that would still be evident would relate to changes in temperature and manufacture errors. In statically indeterminate structures, the use of material such as wood, which was and still is a common building material, would not be allowed as it expands when temperature rises. In determinate structures this expansion is allowed (Kassimali, 2005: 464-466) and the analysis of determinate structures, through mathematical equations, is more suited to historical structures. This is important as the shape of timber beams may change over time due to drying or other external influences, and although the form may stay consistent due to the joints in place, greater stresses may result in the material.

### 3.2.10 Deformation

In terms of analysing deformation, there are two types of analysis that can take place; the first is based on linear elastic deformation and the other is based on non-linear elastic deformation. In linear elastic analysis, when the load doubles, so does the deformation, as the relationship between them is proportional. Using non-linear analysis requires knowing non-linear material properties which are hard to obtain and the maths involved is far more complicated as the relationship is non-proportional (Lourenço, 2001: 95). Linear elastic deformation follows rules that do not do this and thus creates a numerical dataset that is more reliable based on the knowledge pertained within the initial investigation. The choice of determinacy and elastic analysis plays a crucial role in the types of analysis that can be performed. Choosing the correct method based on the questions asked is of more importance than the modelling of the intended structure, as choosing poorly will result in a dataset that is incorrect.

A structure is deemed safe or unsafe based on the stresses caused by forces and moments. If the stress is greater than those permissible then the structure will fail. Although this elastic limit is reached at the point of failure, a structure can support itself until this point of failure is exceeded as shown in Figure 28. A more general approach to the elastic deflection of trusses, beams and frames can be seen in various different types of analysis. One example is the work-energy method, and is calculated by the work done by a force acting on a structure. It is defined as a force times the displacement at the point of application in the direction of the force and can be used to identify how structural elements carry the loads applied. If results are positive, the force and displacement are said to be equal to one another (Kassimali, 2005: 278). Another form of general application to deformation can be seen in the principle of conservation energy. Within this the energy of the structure, which is the capacity that it has for doing work, is measured directly against the strain energy, which is the energy that the structure has because of its deformation. The work performed on the elastic structure by an external force should be equal to the work done by the internal forces, or strain energy stored in the structure. Once calculated, if
the strain energy is greater than the structure it can be associated with a general deformation (Kassimali, 2005: 314) and is useful within archaeological research in identifying areas of weaknesses or strengths. This helps to understand how each structural element works with others, and can lead to alternative interpretations that are based around function, use and size in relation to known archaeological information.

Another example of deformation can be seen in Castigliano’s second theorem where the “partial derivative of the strain energy with respect to an applied force is equal to the displacement of the force along the line of action” (Kassimali, 2005: 318). Any of these above instances provide an insight into what is possible within structural analysis, with one or all of these different equations needing to be solved for a structure to be safe. There are many varying principles within structural analysis that which can be applied to test the feasibility of a given subject, with the most recent being “virtual work” which deals with rigid bodies and deformable bodies. This is not to be confused with what the term virtual stands for in archaeology, as the principles are still completed on paper and involve no visual computer-simulated application of the analysis.

Figure 28. Load deformation diagram A) shows the start of test; B) shows the Elastic Limit; and D) shows the point of failure (Cowan, 1976: 157). Reproduced with permission of Elsevier, www.elsevier.com
Foundations are key within this structural deformation as they serve to distribute the concentrated loads to the ground, providing a pressure that is uniformly distributed as seen in Figure 29.

![Foundation pressure](image)

**Figure 29.** Foundation pressure (Cowan, 1976: 71). Reproduced with permission of Elsevier, www.elsevier.com

When discussing foundations and the support that they provide when designing a building, the middle-third rule has to be taken into account. This middle-third rule is where a wall or other structure is held in equilibrium by its weight, horizontal pressure from the surrounding area and the reaction created by the material underneath it. With the wall as an example, it is held in its position by its own weight, the horizontal pressure of the soil around it and the reaction from the foundations. The rule within structural analysis states that no tension is developed within a wall or foundation if the resultant force lies within the middle third of the structure in question. A good example of this can be seen in Gothic flying buttresses where the thrust is turned downward by the weight of the pinnacle and by the weight of the masonry used. In order to avoid breaking the middle-third rule, the buttress has to be built wide enough for the thrust of the force from the joints to be limited to the middle third. If the buttress is not wide enough then the force will be directed elsewhere, creating a state of tension that will ultimately create a structurally weak building as seen in Figure 30.
Figure 30. The thrust of a correctly built flying buttress. It is seen as being wide enough as the force is directed into the middle third therefore avoiding tension (Cowan, 1976: 76). Reproduced with permission of Elsevier, www.elsevier.com

Connected to the idea of thrust lines and that of the middle-third rule, is the work completed by Heyman (1997) and his structural theory of stability. Within this, the idea of buildings is reanalysed through an understanding of plastic theorem, which incorporates the geometry of the building, not just the material strengths of the structural elements. All modern structures are designed to be viewed in terms of limit states and are defined by their overall strength, stiffness and stability (Heyman, 1997: 3). Applying the same to historic buildings is suitable but Heyman makes note that extra care should be given in understanding the limits of these three structural criteria, by also analysing the rules of proportion of a given building, as this can give a fundamentally more correct understanding of the design and behaviour of the masonry used (Heyman, 1997: 5). The inclusion of the proportional understanding includes the equations of equilibrium but these alone are not enough to determine the limits of stability, as these are defined by the strengths of the material, as well as the geometrical forms used. This is because the forces and thrust lines found within these structural elements must lie within the boundary of the material.

If movement does take place within a building, cracking may be evident and this is not a sign of failure, but rather should be seen as the structure adapting to the stresses placed upon it (Heyman, 1997: 15). Small variations in stress locations will always be evident as a building is
active and is always changing the responses based on the forces applied. With the building adapting to these changes, failures may result, but these may not be due to the material strength of the building work, rather, the thrust lines of moving stresses no longer fit within the boundary of the structure and signify the importance that should also be placed on the geometry and overall shape and thicknesses of structural elements (Heyman, 1997: 18). The overall stability of a building would have been assured by the original builders through the compaction under gravity of the various elements (Heyman, 1997: 12) and the shape of these elements are suggested by Heyman as being more important. When looking at the Roman Pantheon, it is known that the building is strong, as it is still standing but by modern analyses, it would not have been built due to safety conditions predefined by the strengths of the material: the building stands through the differences found in the thickness of the dome, allowing for the increased thrust lines to be included within the overall shape of the material.

Although understanding the geometry of the building is an essential part in an archaeological investigation, the understanding of thrust lines may also be required to fully understand how a past building was constructed. Including geometrical analyses, based on the overall stress possibilities and responses needed may prove too much to be included within a set archaeological structural examination, as this requires a greater understanding of the mathematical solutions provided. This is however something that could be inspected when examining the overall results as a validation tool to the structural results. The ability to scale a structure is dependent on this condition but in order for a building to be deemed stable, the geometry, dimension and proportion of each part can all affect the overall possibility of stability. Heyman’s theory of structural stability is important to include, as engineers often overlook the geometrical limits of a building, as modern building material is stronger and able to support greater loads. When examining the past, the same cannot be said and slight changes in the movement of a building would have occurred. Applying examinations based on just material strengths will provide results that are valid, but in order to understand the full capabilities of a model, we too have to take into account how the builders would have created the structure and assess how creating different geometrical shapes affected the overall stability, as minimum thicknesses would be needed based on set shapes.

Analysing a structural result is therefore a complex process and one that requires an understanding of the maths involved. The applications shown above provide a footing on which archaeologically important questions can be asked. Their applications were limited to two-dimensional approaches but now form the basis of modern structural analysis through the addition of computational methods. Their basic parameters allow for further insight into the
mechanics of historically important structures and in turn provide a firmer basis on which our hypothetical reconstructions can be based.

### 3.3 Computational Methods

The methods described above are based on the classical approaches used in structural analysis but there exist many other forms of analysis for understanding structural behaviour. The majority of the classical methods are labour intensive when calculating by hand and are better suited to computational analysis. Examples of computational analysis differ but are based on shell elements, which deal with out-of-plane analysis, discreet element modelling programmes and volumetric based analysis. The most valuable to archaeology is that of matrix structural analysis. This method is the combination of the relationships of equilibrium, compatibility and member-force displacement reactions in statically indeterminate structures. Within the analytical model, the structure is considered an assemblage of straight members connected at their ends by joints, and thus calculations of force displacements are able to take place as everything is connected. In theory, the number of members and joints should be equal to the elements and nodes. The majority of software that deals with this form of analysis focuses on the stiffness method as it is easier to compute and most require line drawings with a XYZ plane outlined to provide force displacement reactions along given directions (Kassimali, 2005: 769-771). Matrix analysis, although dealing with indeterminate structures, proved a success and it was a stepping-stone to something that has revolutionised structural analysis in the way of Finite Element Modelling (3.3.3).

The data gathered within structural analysis is represented by numerical methods, which are then modelled to act as a visual aid. The main areas of interest lie within the resulting behaviour that the structure has undergone based on the load applied. Questions have to be asked of the results gained to see if they are practicable. What was the load applied? Are the loads applied likely to be achieved in real terms? What is the resultant deflected shape? Is the deflection gained still permissible as a viable option? What are the resulting reactions? Other than shape, are the elements in question able to function and support the reactions needed based on the load applied? These questions are the basis on which any examination must be made and it is important to note that not all results are wrong, even if they are suggested to be so by the

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4 Matrix analysis is a mathematical process which involves the investigation of matrices and their algebraic properties
software. With the movement of the structure to counter the loads, even if shear forces create damage, such as cracking, the structure may still be viable, as is seen in countless historic buildings across the world that have evidential cracks and substantial parts missing. Mathematically these may not be practical but when the nature of the elasticity of a structure is taken into account, where “stress is directly proportional to strain and the deflections gained are directly proportional to load” (Brohn, 2005: 39), the real-term data will sometimes prove that the strain and deflections gathered will be possible if the members are appropriately positioned.

3.3.1 Discrete Element Method

The first common type of computational method that will be discussed is the Discrete Element Method. This is a modelling technique that models material as an assemblage of distinct blocks interacting along boundaries, whereby finite displacements and rotations are needed on the discrete bodies. The results are based on the automatic identification of new contacts between the different blocks (Roca et al., 2010: 320). The Discrete Element method is a “numerical scheme for simulating the behaviour of discrete, interacting bodies” (Mishra and Rajamani, 1992: 598). The process usually involves a large number of distinct bodies within the processing of the calculations which creates a system that includes longer modelling and processing times (Mishra and Rajamani, 1992: 599). The introduction of the three-dimensional rather than two-dimensional Discrete Element Method began in the early part of the twenty-first century with an example seen in Hentz et al. (2004) whose work focused on the fracture and fragmentation of concrete. The results provided good qualitative solutions but due to the nature of the method, it required twenty iterations of the model to produce something usable. As Fakhimi and Villegas (2007: 195) suggested, the method, although allowing for interactions explicitly within the models, needs to be calibrated via a system of trial and error. The results are dependent on the process that the examiner follows and needs to be analysed in detail in order to test the accuracy of the results gained. This is again mentioned in the work of Chung and Ooi (2007: 83) and is seen as a promising tool but requires careful validation.

The calculations inherent are data intensive and considerations have to be made surrounding the model size, with compromises made to the areas of the model that are understood to require less precise calculations such as flat walls. The calculation time still proved to be extensive in the 2014 case study by Mechtcherine et al. (2014) and for this reason it is infeasible for use within archaeological research. Not only will the calculations needed take a greater time than is possible but also the simulations required follow a more linear process. Although the discreet method allows the opportunity to see discrete movements as a whole, as well as the individual
components, so too do other computational methods that can calculate the results at a much faster rate.

In general, the method allows for a more in-depth analysis than other computational methods, but requires each part to be modelled separately, which may lead to errors in the modelling stage of each element, creating unrealistic solutions. An example can be seen in the work completed by Roberti and Spina (2001) who modelled the typology of Nuraghe masonry in Sardinia. Using this method provided results but the models needed to be heavily calibrated and the results were poor. To this end, the method is unsuited to archaeological research as it requires too much attention to each part when modelled, as the shape and the physical properties of every element have to be known. This falls outside the scope of what is realistic for the integration of structural analysis within archaeological reconstructions, as we are unable to accurately define the shape and properties of each building element; we can only speculate from the evidence available.

### 3.3.2 Boundary Element Method

The second most common method is the Boundary Element Method, which is a technique that approximates the numerical solutions of the boundary integral equations within a structure. This method provides an exact solution to the differential equations within the domain that the boundary encloses and is parameterised by a finite set of constraints that are enclosed within the boundary (Costabel, 1987: 243). The method requires the boundary of the domain to be calculated and is especially useful when considering datasets that are of two dimensions. The method provides more accurate data when compared to other computational analyses of boundary values from the solutions of the boundary integral equations, but requires an approximation of the interior solutions. Unlike other methods, the Boundary Element Method requires a precise knowledge of the solutions of the differential equations needed, and even if these are known, several choices have to be made for the varying number of boundary integral equations and the numerical approximations derived. Not only does this require more knowledge about engineering and further computational resources to model the variances, but if the boundaries contain corners and edges, then the solution provided would “contain errors due to the singularities at the boundary that would be ignored” (Costabel, 1987: 244).

Although the method is more efficient when compared to others, the method is best suited to small areas of interest due to the problems of solving the differential equations and the calculations needed to derive the boundary solutions within complicated geometry. As such the method provides very little use for structural analysis within archaeology, especially when considering buildings three-dimensionally. The method could prove useful when dealing with
arтеfacts or small building elements of a structure, as the result that can be gained will be superior if these boundary conditions are performed correctly.

3.3.3 Finite Element Method

Finite Element Methods are the procedures whereby an approximation of the differential equations that govern a continuous system are solved based on the algebraic equations relating to a finite number of variables” (Brebbia and Connor, 1973: 11). The process involves the subdivision of a solid model into subdomains, known as “finite elements”. The method is applicable to all forms of analysis including stress, heat and magnetic forces; there are no geometric restrictions as any shape can be modelled and tested; and it allows for a combination of different structural behaviours (Cooke et al., 2001: 2). The analysis that takes place is done through the displacement and force measurements at the nodes of the mesh, which are then used to govern the discrete equations used. The displacement method, which is measured as discrete points in the body, are taken as the unknowns and the displacement field necessary is defined in terms of the discrete variables allowed, such as a range of permitted movements. The displacements, once calculated, become known and it is from these that Finite Element Analysis can calculate the strain and stresses.

Within Finite Element Analysis, the basic method used is that of the linear theory of elasticity. Within this, the analysis assumes that the change in orientation of a body to displacement is negligible and the focus instead is placed upon the resulting linear strain displacement. This strain develops from the material properties that are inputted into the overall properties of the analysis (Brebbia and Connor, 1973: 12). Strain forms one part of the initial investigation, with the other seen through stress tests that are defined by the stress tensor of the structure through the stress strain relations. These, like the previous methods, must satisfy the equilibrium equations necessary. In total a complete set of equations is used to govern an elastic solid and these consist of the three equilibrium equations, six strain displacement relations, six stress-strain relations, stress boundary conditions and the primary geometrical boundary conditions (Brebbia and Connor, 1973: 16). The introduction of structural analysis in archaeology should therefore not follow the two methods discussed above but should instead limit the application of modelling to the Finite Element Method.

3.3.3.1 History of the Finite Element Method

The history of the development of the Finite Element Method is hard to define due to the way the method was created through different disciplines and approaches. It first begun in mathematics, with the discipline having developed general techniques that were applicable to differential
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equations governing problems such as finite difference approximations, as seen in the research into Relaxation Methods by Southwell (1946) and Allen (1955). These early developments then led onto various weighted residual procedures as seen in the work conducted by Crandall (1956) and Finlayson (1972) which in turn developed into the approximate techniques for determining the statements of properly defined functions. With mathematical foundations, use within engineering began to develop. The earliest application of the Finite Element Method began in 1941 through the work of Hrennikoff (1941) where the solution to the elastic continuum problem was replaced through the use of an arrangement of simple elastic bars. Within engineering, the process of solving the elastic continuum involved creating an analogy between real discrete elements and finite portions of a continuum domain. These were further developed by Argyris (1954) through the reasoning that small elements behave in a simplified manner and thus must be treated as such within any form of analysis. The understanding of elements behaving in a simple way led to the first use of the Finite Element Method by Clough (1960) where he used a standard methodology applicable to discrete systems. In his work, he noted that conceptually, the discipline needed to improve its understanding of the finite element, and computationally there was a need to unify approaches to the variety of problems within one system.

As with the majority of disciplines, the introduction of the computer greatly enhanced understanding and use of structural analysis. Since the 1960s, much work has taken place on the Finite Element Method. The Finite Element Method now forms a general discretisation procedure of continuum problems posed by mathematically defined statements and is a standard methodology for problems of a discrete nature. Since the 1960s, civil engineers have made much use of this method within calculations of the force-displacement relationship of each element within a structure. These elements are then assembled by establishing the local equilibrium at each node or connecting part. Treating each element as a separate entity and then assembling these different parts by equilibrium equations means that the continuum is divided into a finite number of parts: a finite number of parameters therefore specifies the behaviour. The solution to these provides a complete assemblage of elements that follow the same rules as standard discrete problems (Zienkiewicz and Taylor, 2000: 1-3).

3.3.3.2 The Application of the Finite Element Method within Engineering

The majority of engineering problems fall within mathematical approximation procedures and thus the use of the Finite Element Method has created a system that is universal and can be applied to the majority of engineering questions about structural integrity. As noted above (3.3), the matrix analysis was key in the development of this technique and the present-day method combines all of the key advances already mentioned. The introduction of Finite Element
Modelling allowed for the first time a truly three-dimensional form of analysis within engineering as it allowed all practical cases to be examined. In comparison to two-dimensional approximations the results that could be gathered were “more adequate and more economical”, giving better results (Zienkiewicz and Taylor, 2000: 127). Differing from two-dimensional analysis, the basic form of an element, rather than being a triangle, is a tetrahedron. This three-dimensional element was first used by Rashid and Rockenhauser (1969) after being suggested for many years. In order to make the analysis reliable a large number of tetrahedron elements are needed which requires a large number of simultaneous equations to be solved, as each tetrahedron element contains four nodes. If a model has three displacement variables and is represented through a two-dimensional mesh that contains twenty elements, the number of nodes present will be four hundred. This creates one thousand two hundred simultaneous equations. The three-dimensional model in comparison to the same model under the same displacement variable will contain eight thousand nodes equating to twenty-four thousand simultaneous equations represented in the form of a strain matrix. Under a three-displacement variable, three simultaneous equations are required per node. If a four-displacement variable is applied then the equations per node would increase to four and the number of simultaneous equations would increase, as shown in Figure 31. Choosing the correct displacement will greatly aid the way in which the model is analysed. If this is too high and too precise it will result in hundreds of thousands, if not millions, of simultaneous equations needing to be solved, exceeding the computing power of most computers.

![Simultaneous equation calculation](image)

**Figure 31.** A graph showing the number of simultaneous equations based on varying displacement variables and node numbers

With the inclusion of the tetrahedral elements within three-dimensional analysis, the results gained may still be limited due to the detail required in certain areas of a structure. Limiting
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elements to four nodes means that subtle movements may be overlooked. To counter this, the preferred element choice within any analysis requires a greater number of nodes. This creates a larger number of blocks within the elements; these are usually seen through eight-node brick elements known as quadrilaterals, which can be subdivided into twenty and thirty-two node elements. Increasing the number of nodes results in a higher number of degrees of freedom that an element can move, with Figure 32 showing the way in which the node can be inserted into an element. Creating more nodes results in a larger number of tetrahedral elements, which are grouped together. The model can then be broken into greater parts to be analysed in finer detail. This is essential within Finite Element Modelling, as the basic principle of the tool is to find the approximation of the unknown; with a greater number of elements to analyse, the unknown can be turned into the known through careful examination of subtle movements under stress that would have been missed in previous forms of structural analysis.

Figure 32. Increasing the number of nodes for quadrilateral elements (Zienkiewicz and Taylor, 2000: 185). Reproduced with permission of Elsevier, www.elsevier.com
Figure 32 represents the way in which the quadrilateral elements can be created, increasing the number of nodes to twenty and thirty-two. This is not possible when using the basic form of tetrahedron elements which contain six nodes. Rather than producing twenty and thirty-two, the element can be subdivided into fifteen and twenty-six as seen in Figure 33. This subdivision allows for a more detailed analysis and can be generated for either type of generic three-dimensional element types.

![Figure 33. Tetrahedron subdivision of nodes (Zienkiewicz and Taylor, 2000: 189). Reproduced with permission of Elsevier, www.elsevier.com](image)

Although Finite Element Modelling deals with the unknown, the results often have arbitrary boundary conditions that will differ slightly to real-life scenarios. Generally, a structure can be moved in an infinite number of ways unless it is constrained to particular locations, with the most common form being foundations and supporting walls. Within Finite Element Modelling, the software can produce infinite boundary conditions, which allow the material to stretch in an infinite way. This slight difference produces results that differ, as the resultant forces are not limited to set boundaries. Unlike the usual form of structural analysis, the inclusion of infinite boundaries means that the model does not have to be modelled in its entirety and the results gathered are usually representative of the true characteristics of how a structure would move under loading. An overview of this method is discussed by Babuška and Melenk (1997), but as an
example, a building that contains twenty repetitive columns arches of the same size and shape would only require a subset of the building to be tested, thus saving valuable processing time.

The choice then of element sizes is of importance when studying buildings, especially historic buildings that are of an irregular shape. The ability to model the geometry of the structure in detail and to analyse particular parts allows for a great insight into the understanding of their original construction and subsequent use. Choosing the incorrect size element will provide limited information and may falsify the results given. This is important when dealing with hypothesised reconstructed buildings, as to understand and evaluate their form, the analysis has to be correct in the first instance.

3.3.3 Materials

In order to create structural results that are valid, there is a necessity first to understand the examination that takes place, based on the material properties of given structural element. The two main forms of analysis are those of linear and non-linear elastic behaviours. Examples of these two different approaches within archaeology based engineering studies are given in 3.4. Essentially, these two forms of analysis provide different numerical results based on the generated forces of a given structure. Linear elastic behaviour focuses on rules that are known within the defined laws of static but the analyses that can be placed on their behaviour are limited to deformation results. Non-linear elastic behaviour moves away from this, requiring unknowns to be calculated, thus adding to the potential numerical results generated.

When examining masonry, the material is heterogeneous and consists of units and joints. With the number of different possible arrangements that could be generated through this heterogeneous material by the geometry, type, and the arrangement of the different units, it raises doubts about the accuracy that could be generated under structural loading (Lourenço et al., 2007b: 1443). It is not realistic to try and formulate models that fully incorporate all interacting mechanisms of a specific material, as any created model or theory is a simplified representation of reality (Lourenço, 2001: 98). Creating models based on linear elastic behaviour will provide representative results of the applied loading, but this only takes into account a specific range of structural forces. The inclusion of non-linear elastic behaviour moves away from this by including the unknowns. Non-linear analysis is the most powerful method of analysis available within Finite Element Analysis, as it is able to outline the complete response of a structure from the elastic through to the inelastic range (Lourenço, 2001: 101).

Understanding non-linear behaviour does however add a greater complexity to the numerical results and requires structural analysts to fully comprehend them. “The inherent complexity of
the subject precludes mass teaching in civil engineering” (Lourenço, 2001: 101) and thus would be difficult to implement within archaeological assessments. Whilst this does allow for the complete behaviour of a structure, including linear elastic behaviour to be produced, further material properties are required. These extra properties include the known elastic properties, as well as the strength of the materials and the additional inelastic information to create deformational behaviour, stress distribution and the failure mechanism of the structure (Lourenço, 2001: 107).

Providing these properties are however difficult without first testing the original material through laboratory based tests, which require specific machinery, money, as well as the raw material from the building.

Although non-linear analysis represents the most sophisticated tool for structural analysis and allows for the validation and proposition of simple design techniques and solutions for engineering applications to be completed (Lourenço et al., 2007b: 1448), the inclusion within archaeology is unfeasible until the material can be fully tested to generate the properties needed. Generating non-linear results is an important process within historic buildings that needs to be completed, as greater overall analyses can be generated, but analysing the past through linear elastic behaviour will still provide results necessary within archaeological simulation. Linear based analysis is therefore more suited to the approach adopted within this thesis, as well as for archaeology overall, unless specific investigations are required or greater complexity of the material qualities are need.

3.3.3.4 The Application of the Finite Element Method within Archaeology

Dealing with three-dimensional data moves away from the generic errors that were persistent in the standard methods of analysis. Although these have been removed, the results have led on to the formation of different faults that must also be removed or taken into account when looking at the results gathered. Error is the difference between the exact solution and the approximate one and within Finite Element Modelling, these differences are due to the way in which the model was meshed into the brick elements. As archaeologically important buildings are generally of an irregular shape, one has to produce an irregular mesh and this is where errors are normally generated. Irregular meshes contain nodes that are placed in positions that may not be best suited to the overall analysis of the structure. Having elements of different sizes through this irregular mesh provides differing levels of degrees of freedom for the nodes to move upon. When an area of interest is geometrically complicated, a large number of elements are needed to simulate the movement, but it may not necessarily mean that the rest of the mesh has to follow suit in the areas that are generic and simple. One method of removing these errors relates to a mesh simplification to refine the mesh to a set tolerance of accuracy, which creates a reduction in
the average displacement errors in each element. The software is then able to provide complete control over the production of this mesh and areas can be specified where more or less detail is required. The localisation of mesh detail allows faster calculations to be made. The displacement errors reduced to a uniform mesh over an entire body may be too simple or too complicated to calculate precise movement. The generation of a constructed mesh that is suitable to the body under investigation is the method that should be used, as it allows for a focus on the irregular areas, such as curvatures, to be examined in closer detail. Figure 34 demonstrates this by the process of element subdivision, a mesh regeneration, and a refinement via the movement of nodes to change the shape of the element. This mesh refinement can be controlled by the user and although generic in its reproduction, can be set up in any way that benefits the end results of the analysis performed.
When dealing with non-linear analysis mesh refinement, the process is known for “its instability and computational inefficiencies” (González and Bussler, 2000: 1). To move away from this instability (change in node value) González and Bussler (2000) suggested the implementation of a new finite element known as a kinematic element via mechanical event simulation. This allows for the simulation of large-scale motions and their consequences. This, unlike linear analysis, does not estimate the loads interacting with the different members and creates a better system on which inertia forces can be calculated. This non-linear analysis proves useful in the simulation of
earthquakes, especially as the time constraints inherent are reduced, but within the analysis of buildings, the evaluation of motion is not needed. Parts, however, such as glass, may need to be analysed using this method but this is only useful if the fracture point has not been rendered during normal linear analysis (González and Bussler, 2000: 7). Within archaeological research, it may be of importance to separate the analyses performed and to focus on different areas of interest to gain a fuller comprehension of the building or its reconstructed counterpart.

3.3.3.5 The Displacement Approach

The displacement approach is one of the most popular and easily understood forms of analysis within elastic solids and is commonly applied when dealing with linearly elastic structures. This function of displacement should be able to represent the true displacement distribution as closely as desired. This is achieved through the selection of suitable sized elements within the modelling process. Within this, having too large an element size will reduce the level of strain analysis possible thereby making the displacement function incorrect. Having elements that are too small will affect the end results, with further calculations needed per node, therefore increasing the time spent computing the results. Having too small an element will more often than not overcomplicate the interaction between elements, and erroneous results can be gained in this way. In order to create an analysis that provides the necessary answers, the displacement function used has to be of “such a form that the nodal displacements are compatible with the constant strain that will be obtained” (Zienkiewicz and Taylor, 2000: 31). Creating this parallel system requires the calculation of unknown function or functions that satisfy the differential equations needed per node. This is hard to calculate when dealing with the usual methods such as plane-based analysis and this is where Finite Element Modelling gains superiority over other forms of investigation.

Following the principle of virtual work, on which the method is based, the analysis works not only on a global scale but can be localised around selected features. Allowing local calculations creates a far simpler form of analysis on which the displacement approach can be performed. Within a local examination, the model can be split up into key sections and each can be analysed individually. This local examination works well on structures that follow a constant form, or close to constant. The reactions that take place throughout can be defined on a smaller scale. Instead of using a whole model, where a number of calculations will be needed to solve the differential equations per node, a section with applied boundary conditions can be used instead. These boundary conditions represent the rest of the structure that has been cut away and are used to simulate the forces that would be applied if they existed in the model. These boundary conditions are often used on the floor of the structure to simulate the foundations. The maths involved is
less but the results provided are the same nonetheless. These types of analyses cannot always be applied to structures and must be used when a model is extremely complicated geometrically or if a constant is involved such as arches within a hall. The method then is applicable to historical buildings such as cathedrals and a linear approach will be used in the case study at Winchester.

3.3.3.6 The Production of a Finite Element Model

The generic method of producing Finite Element models is based on two main steps, that of data input and that of the solution it provides. Data input varies depending on the software used but the generic method requires a level of storage for the model; in turn the element and coordinate data application is inputted via the analysis of the model; the material properties are inputted and assigned to the different elements; and boundary conditions are applied to control the set node displacements. Within this process, the level of the degree of freedom that these boundaries have is also inputted with movement and rotation in each of the XYZ planes outlined. Following the generic input of the model and material types, the loading type and the level of forces that should be applied are then added to the elements. This leads to the second stage where the forces and loads are solved. In most software packages, the operations that are carried out are unknown to the user as the system follows a generic framework of what it should analyse. These are based on the analyses that were chosen within the previous step based around linear or nonlinear functions. The software solves the simultaneous equations needed, through either a direct solution or an iterative solution. The direct solution is restricted to the problems outlined in the coefficient matrix and is the type most often used. The iterative solution works based on the stiffness matrix and requires the reprocessing of a set of equations until the residual equations become less than the specified tolerance. The iterative solution therefore reduces the level of analysis performed and although it is satisfactory for modern buildings, the level of detail required in historic structures entails the solution to be solved via the direct method. As such, the direct method will be utilised within this research as it increases the level of analysis that would be applicable to historic structures.

There are a number of different software packages that deal with Finite Element Modelling; each has different ways to process the data. Generally, four main steps are used. The first is the determination of element properties from the geometric material and loading data. These are applied to each individual element as each has a unique number and nodal connections, meaning that each element will differ under loading stresses. The second major step is the production of equations based on the number of members. The third is setting out boundary conditions of the assembled elements, so as to restrict movement and the last is to solve the equations generated to find the determined structural properties of the structure under investigation (Zienkiewicz and
Within this, the focus of analysis is usually based on the standard discrete system and elasticity properties of the material used. The standard discrete system is based on the behaviour of each element that is outlined, with each then given a set of quantities whereby the equations needed are based on the addition of the number of elements.

The elasticity, whereby the stress and strain distributions in the elastic continuum are solved, are often needed within different phases of distribution and these range from two-dimensional plane stress to full three-dimensional modelling. Within Finite Element Modelling, the principal investigation behind its use, between each element, requires an infinite number of movements so that it can move in any direction. Finite Element Modelling allows the continuum to be separated into finite elements, whereby the assumed elements are interconnected. The functions then define the state of displacement within each finite element based on the nodal displacement. This displaces the elements through the defined strain that is applied allowing the stress to be calculated. The forces that are applied at the nodes can then be determined and are based on the stiffness relations, which give the elasticity properties of the structure in question. This allows for the minimisation of the total potential energy of the system in terms of the displacement field that is to be calculated (Zienkiewicz and Taylor, 2000: 18-19). In turn, the method provides the basic functionality for the examination of buildings and this methodological approach has been tested in the working case study (Chapter Six).

### 3.3.3.7 The Benefits and Drawbacks of Using the Finite Element Method

Although the method is used within modern buildings before construction takes place, it can be applied to all forms of modelled buildings to understand how they were constructed. The calculations involved are often complex and time-consuming to complete. Using Finite Element Modelling means that repeated calculations of the different planes are not needed as the equations can be applied to the whole model. This process allows for the calculation of the displacement that will vary with set undefined parameters per nodal parameter, therefore allowing for analysis of more complex shapes and geometry. Subsequently this creates a greater understanding of past buildings, through the modelling of more complex structures that are often more irregular, through either original construction, or structural changes over time. This fits more with the archaeological way of recording; rather than the modelling of simple “straight” outlines that are often extracted from real data, real recorded geometry can be used. The method then creates a system that is more accurate, in terms of not only geometry but also the structural forces that are applied to the structure in question.

Errors within the extraction of results do occur. The first and most usual error within the results gained, except for geometric simplification of faults, is that of rounding off errors (Zienkiewicz and
Taylor, 2000: 33). This relates to the rounding up or down of the numbers included within the equations that solve the unknown functions per node. This rounding creates very small errors in the accuracy of the results. These errors will always be present as there will always be a limit on the number of decimal places allowed within the differential equations. As a result, the exact solution to the questions asked can never be attained. Instead, the calculations produced provide almost certain answers. The only other errors that may be attainable relate more to the modelling stage with the correct number and size elements needed.

The discretisation of the models, which is the process of transferring continuous functions, models, and equations into discrete counterparts, is done by dividing the body into volume elements that have finite dimensions. The number of elements chosen depends on the analysis and geometric shape of the object in question. In areas that are assumed to have a range of high stress values, a larger number of elements are needed to map the subtle displacements that will take place. The node connectivity within this is vital and influences how many elements and nodes are interconnected. An overall finer grid in relation to specific parts of complex structural features will produce more accurate results, as seen in Turon et al.’s (2007: 1673) work on mesh refinement, but the equations needed to be solved will increase greatly due to each node having to be solved. Choosing correctly and defining the nodal displacements allowed based on their X, Y, Z position along with their rotation around U, V, and W will help limit the time and computing power needed. For some structures, a generalisation of the elements will be needed to give a general impression, but for some, time and precise modelling will be needed. If the results gained are acceptable then the data shown will represent the upper boundary of what is possible within the building (Brebbia and Connor, 1973: 87).

3.3.3.8 The Different Types of Finite Element Modelling

There are two different ways the application of Finite Element Modelling can be used. The first is macro-modelling, where there exist no distinctions between the units or joints, unless there are specific modelling requirements. The second is micro-modelling where each individual component is modelled, including mortar which is treated as joints (Roca et al., 2010: 314-316). Although the micro-modelling may provide slightly more accurate results, the time associated with modelling each individual component is a laborious task. The results gathered from the macro-model for all types of analysis provide satisfactory results as long as the material properties include all parts of a wall. Likewise, the modelling of joints is often problematical, as intact connections cannot always be seen unless the structure is taken apart. The method of joining different elements within the software means that assumptions are made within the integrity of these parts. In
theory, if a structure is standing, or if it is to be built successfully, the joints used will always be those needed.

In archaeological research, the use of micro-modelling in specific analyses, such as the stress variances in different single truss timber joint types, may be of use, as this modelling approach requires greater scrutiny. When dealing with a complicated structures such as a cathedral, the macro-method proves to be more successful, not only in terms of modelling, but also in providing numerical data in much faster ways, as fewer calculations are needed to see how each component interacts. The focus of this analysis is not so much the joining parts of the structural elements, but rather their overall form and material properties (6.3). An example of this can be seen in Wolfe’s (2004: 124) research, where macro-modelling reduced the processing time by 40,000.

Within Finite Element Analysis, the calculations discussed above are only a subset of what is available: there many more processes that can be completed. Using the summary above, Finite Element Analysis has been shown to be a tool that can offer a unique insight into the documentation and analysis of historic buildings within archaeology, and can be used as a tool within the other computational methods discussed in the previous chapter (2.5). As the method is purely virtual, the application within the modelling of former buildings will add to the scientific approach within the study of the past, creating models that are more genuine and more precise. Although these are still conjectural due to the many variations of building types and forms possible, the application will be able to reduce the number of possible variations and it will allow for conclusive answers to some archaeological questions through scientific means.

Using structural analysis will consequently provide a final model that follows set physical rules and moves away from the unambiguous hypotheses (related to structural form and composition) that are currently established within archaeological research and archaeological modelling (2.4). This will be demonstrated in Chapter Six and will be discussed in the case studies below. The introduction of the Finite Element Method is one subset of many possibilities. It will be used within this thesis and it provides the best available solution to answer the archaeological questions imposed. The introduction of the methods described in 3.2 provides the parameters on which the Finite Element Method works. The digital application creates a system whereby all forms of analysis are used. The results provide definitive answers related to the physical properties of given elements based on the loading types allowed per material. These are defined by the limits of stress through compression and tension values. Each material has unique values that cannot be changed. To create a model that is structurally viable, these material parameters have to be met. If they exceed the material properties’ maximum, then the model will fail
structurally. Through the Finite Element Method, those untrained in engineering can calculate these values quickly and efficiently. Its application then is suitable to archaeological research, as the method can easily be incorporated within current computational analysis used within the discipline (2.5).

### 3.4 Archaeological Structural Analysis Case Studies

The purpose of these case studies were to evaluate structural analysis in relation to archaeological practice. These will act as a way to identify how these past applications can be used in relation to modern recording processes and modelling techniques. They include the limited examples that exist within archaeology and focus mainly on engineering work relating to cultural heritage buildings.

An early example of structural analysis within archaeology can be seen in the work of Wood and Chapman (1992) who utilised their Plant Design Management System (PDMS) software package via Enhanced Visualisation Software (EVS) that linked stress analysis via a database system to visualise data in three dimensions. The software is usually used within the modelling of process plants to ensure clash-free designs and has the ability to include all elements of a fabricated building, including cabling and piping (within process plants). The PDMS system is now far more advanced, but it enabled the modelling of archaeological data for structural examination, with the rendered images produced via the EVS system. The example of Furness Abbey in Cumbria (Figure 35) showed a model that was used as a research tool for reconstruction ideas, interpretation and the simulation of structural stress. Wood and Chapmen went on to discuss how the virtual model created of the Langcliffe Kiln showed what was once there, but no aspect of what data incorporated within the reconstructed model was included. Although able to view and interpret the model, there is a necessity within public dissemination to emphasise how archaeological data was used within its construction. The PDMS software used in 1992 was extremely limited and the authors suggest the use of Finite Element Modelling to identify how the different elements would have withstood loads placed on them (Wood and Chapman, 1992: 143) but like so many others, the suggestion was not followed through.

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5 Multiple permutations of the same model under different loading conditions can be completed quickly. Permutations of different variables (structural elements) require edits to the generated CAD models that are tested.
Levy and Dawson (2008) continued this research with their archaeological examination of a Whalebone house in Canada. In their paper, they used structural analysis to determine the stability of the house with dead loads applied, such as skin. Whilst an assumption of the material property of the whale was used, the study also incorporated environmental effects such as wind on the buildings, adding to the overall evaluation. The buildings are of a simple design and the analysis was easy to complete but even at this rudimentary level, it showed potential in the use of structural analysis within archaeology. An earlier example of this type of work was by Scagliarini Corlàita et al. (2003: 244) who used structural analysis in their research. This approach was limited and the overall application was poor but combined with Levy and Dawson it created a footing for potential work within archaeology.

Although archaeological applications are limited there do exist a large number of cultural heritage related research projects based on engineering applications. The majority of these examples relate in some format to earthquakes and the effects that they have on historic buildings. An example of this can be seen in the work completed by Brandonisio et al. (2013) who focused on four basilica churches affected by the 2009 L’Aquila earthquake in Italy. A linear range of tests was performed to provide the static and dynamic properties of these buildings through the identification of how horizontal forces would affect them. Past seismic activities were used as a comparison and the differing elements of the structures were tested to the point of collapse (Brandonisio et al., 2013: 694). The results identified that the façade, domes, triumphal arches and projections were the most vulnerable areas of these buildings. Although the case study was
more concerned with the macro elements, the results show movement in the building’s out-of-plane capacities (vertical sections) and have been compared with the real seismic data as shown in Figure 36.

![Figure 36](http://www.sciencedirect.com/science/journal/13506307)

Figure 36. Comparison between the real seismic damage and the Finite Element Analysis results for the triumphal arch and the arcade in the Santa Giusta church, L’Aquila

(Brandonisio et al., 2013: 711)

The work by Binda and Saisi (2005) outlined the use of structural analysis in interpreting and predicting observed damaged and collapse modes in areas of high seismic activity in Italy. In their work they outline that the modelling of masonry structures is difficult as the material does not always obey the usual isotropy, elastic behaviour and homogeneity rules seen in other materials (Binda and Saisi, 2005: 72). When dealing with complex structures, Binda and Saisi suggest that it is best to only use linear elastic analysis as the constitutive laws for material under non-linear stress rarely exist unless the material is tested within controlled environments. As such, the elastic models give only an interpretation of the mechanical behaviour of the structure in question. They cannot be truly relied upon when other behaviours beyond the elastic range are needed. To counter this, non-linear analysis can be used, as seen in work by Macchi et al. (1993) on the Leaning Tower of Pisa (Figure 37), as the method allows for more detailed and varied questions to be asked. Although the Pisa model is simple in terms of its element sizes, the application of a more specific analysis allowed for a better understanding of how this important historic building would react under varying seismic actions. Macchi, along with the work completed by Chiarugi et al. (1993) on the Brunelleschi dome, Florence, Croci (1995) on the Colosseum, Rome, and Mola et
al. (1995) on the inspection of the soil and foundation deformation of St. Mark's Basilica, Venice, proved to be the catalyst for the development of the analysis within historical structures, thanks largely to the advanced computer methods that were available by then.

A key example in the field of engineering is that of Muñoz et al. (2014) who proposed that the processing and interpretation of the numerical results of Finite Element Analysis are difficult due to the large volume of information that is generated. The paper provided a useful reference to the popularity of using virtual reality models within engineering via Finite Element Analysis. Virtual reality as stated by Muñoz et al. (2014: 784) is the “computer-simulated environment that can simulate physical presence in real or imaginary worlds”. The usefulness of virtual modelling within structural engineering has yet to be fully recognised. It can be argued that the models produced in engineering do not offer their full potential; rather they are concerned with producing the numerical data needed in outlining the potential of a building. Muñoz went on to suggest that virtual models can be created that use the numerical results where stresses, strains and damages can be incorporated, more so to add to a visual representation of what the numerical data state. Nonetheless, the application and thought about how these data can be used fits within the outline of this research, through the production of virtual models that imitate the real, not only through visual means but also through the addition of simulated physical properties. The model that was produced within their case study did not use any new software functionality as the
system used already exists within commercial software packages. Their main aim was to convert
the numbered data to graphical representations whereby the results could be interpreted
visually. The base model that is now generated in the more up-to-date software packages
provides this already. The results gained offer little in the way of new data but the idea of how
these models are used is one that has already taken place in engineering. The ideas put forward
are applicable within the field of archaeology.

The example by Guarnieri et al. (2013) discusses work that took place before 2010, in which they
discuss the combination of laser scanning (B.1) and photogrammetry (B.2) within the recording
and processing of a Finite Element Model. As with the recording methods, the technology and
software packages that exist within Finite Element Analysis have greatly changed, meaning that
the example is slightly out of date when compared to recent work. Nonetheless, the Olympic
Theatre in Vicenza, Italy, was captured and processed, first via a photogrammetry model, with
images taken from five to forty metres away from the stage to give an overview of the structure in
its simplest form. Laser scan data were then added, with a point spacing on the statues being five
millimetres and that of the structural elements being fifty millimetres. These two models were
then merged and decimated with the final product having a fifty-millimetre spacing, making the
capture of the statues at the much higher resolution inconsequential. The data were meshed in
Geomagic and imported into the relevant Finite Element Analysis software, the results of which
can be seen in Figure 38. As the scan data produced only the interior shell of the theatre, the
analysis that took place was inadequate as the limits placed on the model are on the roof and
floor level. In any building the thickness of the roof and the walls influence the building greatly
and these were not included. This makes the result of the static and dynamic analysis
meaningless. Within the paper no real explanation is provided but the final images, one of which
is shown in Figure 39, highlight the incompleteness of the Finite Element Model. This is due to the
gaps that are present in the survey from the partial surface capture completed within the initial
recording. This highlights a problem that is contained within archaeology and engineering, with
the data collection of the original structure needing to be more accurate. This can be corrected
with a more precise recording methodology. With more emphasis and more experience in the
recording process, a better model at a much higher resolution can be gathered and used within
the structural analysis as will be completed for the Winchester case study (Chapter Six).
Following the previous case study, the work by Arias et al. (2007) provides an example where photogrammetry and ground penetrating radar (GPR) (B.4.3) were used in combination to produce analytical models through linear stress analysis of a medieval bridge in Spain. The paper provided an overview of what documentation methods were used within conservation, where measurements were made by hand, transferred to two-dimensional plans, and added to by photographs and notes. This method was highly inaccurate and the majority of structural
elements that could affect a structure of this kind, such as current cracks, were poorly recorded.
The use of three-dimensional recording through photogrammetry allowed for a virtual model to
be made with all of the necessary data included; the introduction of the GPR allowed for the
depth properties of the stone within the bridge to be found as the infill thickness could be
identified. The GPR was likewise able to identify the depths of the foundation. The bridge’s own
weight, filling weight and possible traffic weight were all combined and tested to show the
compression principal stresses that are contained when it is in use, the result of which is seen in
Figure 40.

The results suggest that the central piers were sinking and this was confirmed when the ground
under the piers was examined. The results show how invaluable these digital methods were in
recording all of the minute detail required, and although a simple survey would have sufficed to
gain the outlines of the structure, the introduction of the GPR proved how vital the method is in
understanding the internal properties of structural material.

Figure 40. Compression principal stress in the wall. The blue lines shown represent the direction
of the compression, with the largest compression distribution seen in the widest
span (Arias et al., 2007: 1453). Reproduced with permission from Elsevier,

Another example of photogrammetry and the use of Finite Element Modelling can be seen in the
work completed by Lubowiecka et al. (2007) who evaluated its use with timbers of a roof made up
of twelve trusses. Within the paper, they discuss the past limits of recording the timbers by hand
and due to the inaccuracy engrained in the methodology, preferred to use photogrammetry to
record the overall structure. Although the method had potential, only one truss was used within
the calculations, which limited the conclusions made. Each separate element within a truss should
be unique, whether it be age, thickness, length or level of deterioration. The calculations that
were made were based on extracted features from the model through polylines and did not
incorporate the changing pattern of each timber. The material properties that are given within
the calculation are isotropic in nature and the calculations used are based on the approximation
of the cross section of the changing truss elements. The results therefore avoid the environmental
erosion that is caused by the degradation of the wood and are unrepresentative of the nature
that wood has. Despite this, the results, which are based on a medium brick-sized element, show
Chapter 3

extreme locking within the dead load test applied to the timber truss. This suggested potential damage if further loading was applied.

The results have to be contested as the use of a smaller brick-sized element, which would increase the number of finite elements used, could have provided a different answer due to the increased calculations per node within the bending of the truss. Of importance within this case study is the realisation that no changes were made to the already deformed shape of the timber when it was analysed. The truss used is based on real data through three-dimensional recording, which means that the truss already contained some form of loading based on the gravitational force and the load of the roof that it supports. Applying a further dead load test to a modelled replica of a deformed truss will provide different results from those tests performed on a truss that has just been built. Great care must therefore be given when analysing different buildings and a key identification of what structural forces are already applied must be considered. If there is an interest to test the original state of a building, the recorded replica has to be modified to see how the forces and interactions over time have led to the building being the way that it is. If questions arise as to how well a structure will perform if a new load is introduced then the use of the raw three-dimensional recorded elements will be sufficient.

Continuing their research Lubowiecka et al. (2009) further discuss the combination of three-dimensional recording and GPR in the analysis of an historic bridge in the Mondariz region in North-West Spain. Rather than photogrammetry, the recording process utilised laser scanning, providing a much higher resolution dataset upon which the finite model could be built. The point cloud provided was meshed using a two-dimensional Delaunay flat triangle setting with the size of each being a maximum of one metre. This size is still too large to mesh the small surface changes, but nonetheless, the surface detail, in combination with the GPR data, which showed a course infill of material inside the bridge, allowed an accurate model to be created. Ideally, the model produced would have contained all known interacting components such as mortar but to save time and computing power, the model is that of a continuous watertight mesh that contains a very fine mesh size. The solution is far superior to their previous photogrammetry method, not only due to the virtual model used, but also through the size of the mesh. Creating smaller elements might have increased the time taken to process the data, but the mesh movement is more realistic because of it.

Although the technology behind the recording of archaeological objects is an important stage within the production of Finite Element Models, there must always be a consideration of how the data provided will aid archaeological understanding, rather than simply outlining the possibilities of the structure in question. An example of this is the work by Chalmers University of Technology,
Sweden, where Thelin and Olsson (2005) attempted to demonstrate how Finite Element Modelling and visualisation could provide a means of creating a platform between engineers and other persons related to restoration. The idea that non-engineers should use the technology is welcome, and although their focus is engineering-related, it suggests the potential for collaboration between engineering and other disciplines. This will ultimately allow variations and hypotheses regarding form and function to be tested.

Thelin and Olsson’s work also provided detailed examples of how the modelling technique could be best used within the study of roof trusses, specifically the Glimmingehus building in Sweden. The data were processed in Matlab rather than a standalone Finite Element software package and a linear elastic material of pine and oak at a twelve gigapascals (GPa) modulus of elasticity was used. Within the testing, a dead load of the roof’s weight was examined, as were the horizontal forces of wind on the structure. The results were generally poor due to the simplified nature of the modelled timber frame, but showed that the timber rafters under a dead load provided the main support to the king posts rather than the trestles, which had been assumed the main support mechanism. The analysis also showed the variance between the two loading types and it predicted that a greater support mechanism was needed to counter the wind. The work outlined was intended to show how external disciplines could use this method within their own, but the data provided was purely numerical and offered little in the way of external influences and contributions. The only way to do this is to visualise the dataset, and this is mentioned in the concluding remarks of the paper (Thelin and Olsson, 2005: 49). Rather than allowing an engineer to model the building following the advice of historians and architects, it would make more sense for the specialists themselves to do this, as explaining key architectural styles and features to a general practitioner would be a laborious task. Several renditions of the model would be needed before all parties were happy with the realism (2.4.2) of the model shown.

This process can be seen in the reconstruction of the Dresden Frauenkirche, Germany, and provides a good example of how a research project can create a more accurate representation. The work completed by Collins et al. (1995) focussed on the digital reconstruction of the destroyed church following WW2 bombings. As the building was a focal point in the area, a number of archaeological and architectural drawings existed prior to its destruction, including an extensive photographic record, such as Figure 41. The reconstruction process followed these

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*A pascal is a form of measurement used to quantify pressure, stress, Young’s modulus and tensile strength, defined as one newton per square metre; one gigapascal represents one million newtons of pressure.*
photographic records and included the extensive extant features found after the bombings (Figure 42). Where details were missing, data were extracted from photographs and compared with contemporary churches. The reconstructed model, as shown in Figure 43, provides a realistic interpretation of the exterior of the church, mainly due to the level of information that was engrained within the study. The internal and external parts were modelled separately, resulting in slight structural reliability issues but the overall form is authentic (2.4.4). Not every model has this information available, but with this being one of the first detailed virtual reconstructions within archaeological research, it showed that emphasis on reliability and accurate portrayal of data were evident. This unfortunately cannot be said with every case study, both in terms of raw data and in terms of its subsequent use. This example is of importance as it shows a clear outline of how the model was created and it was later confirmed by Jäger and Burkert (2001) in their structural investigation.

Figure 42. A photograph of the ruins of the Dresden Frauenkirche taken after 15th February 1945 (Collins et al., 1995: 20). Reproduced with permission of the Deutsche Fotothek Dresden, http://www.deutschefotothek.de.


The structural paper focussed on how the church collapsed during the bombing, with the results indicating that the original design led to a very high load on the interior columns, with fire increasing the tension and expansions found in the masonry (Jäger and Burkert, 2001: 170). The model created by Collins et al. (1995) provided an interpretation of how it once looked and a real life counterpart was commissioned. This was based on the plans of the original building, using the same building principles, reuse of material including the extant remains, but following updated engineering standards. The structural examination focussed on the soil, the building and soil interaction; the foundation supports; the testing of different stone materials; and how the weather would ultimately affect the building. With the general weakness found within the interior columns, the building was adapted to remove the overloading and created a more stable building.
This differs from the virtual reconstruction and the newly built church provides a misleading representation of the past (although superficially this looks the similar). The building is not how it was once created, but rather follows an updated safety mechanism.

With the slight alteration to the building work, a new understanding is created and the experience of interaction that is gained is false. Whilst testing was conducted using the original material (Figure 44) and although the building follows the original very closely, there has be to great care given when we alter the past. On one hand, buildings are always adapted to make them better, stronger and more current; but on the other hand, the intention of this reconstruction was to create a replica of the original. The new ideas postulated were tested as Finite Element Models following compressive, shear loads as well as how the fire interacted with the building (Pohle and Jäger, 2003: 654-656) and it proved how engineering and archaeology are able to function using the same processes. The model created by Collins et al. (1995) highlighted that structural properties were important but this has not been adapted to wider modelling processes within archaeology. Using structural testing within the creation of the physical restoration proved how reliable the virtual model was, allowing the model to be seen as realistic. The example then provides a footing on which to work, by combining the analytically tools available to create virtual models that are genuine.

Figure 44. Load bearing tests performed on the original masonry of the Dresden Frauenkirche (Jäger and Burkert, 2001). © University of Minho 2001.

The application of these different case studies leads onto the final example that has an archaeological context. The Parnassus Project was a joint collaboration between the Engineering department at UCL and Archaeology at Southampton. The archaeology department surveyed and
modelled a number of buildings for use within Finite Element Modelling software, as seen in Figure 45, to test and analyse the effects of water on historic buildings. Part of the overall research outlined in this thesis originates from this project due to the author’s involvement and it was one of the first to combine archaeological research with engineering principles at its core.

Figure 45. Three-dimensional model of the Avon Mill at Tewkesbury, Gloucestershire (D’Ayala et al., 2017: 138)

Separate models of each building recorded at Tewkesbury, Gloucestershire, were made and converted to Finite Element Models for use in Autodesk Simulation (now Autodesk Simulation Mechanical). Their purpose was to consider the strength of the structures of the buildings, and how they would respond to any weakness caused by flooding and worsening weather in the future. In addition to the geometrical features, the research attempted to reflect the nonlinearity of material properties as closely as possible with the timber-frame skeleton and the brick infill. Unlike most material properties used in structural tests, the compressive strength values of the brick and mortar were determined by laboratory tests. The preliminary analyses were carried out by using a Mechanical Event Simulation analysis type (3.3.3.4). In addition to first-floor live loads and the roof load, the model was hydrostatically loaded to simulate flooding for the full height of the ground floor as seen in Figure 46. In order to identify the damage mechanisms the contact surfaces between the timber-frame and masonry infill were defined as partially bonded on the front and side façades of the ground floor, while the other contact surfaces were taken to be fully bonded to decrease computation time.
The results showed that the brick infill in the frames tends to bend under hydrostatic loading and cracks due to excessive tensile stress as seen in Figure 47. In addition to this, gaps appeared between the timber framing and brick infill suggesting structural damage may occur with flooding. These results show that the separation between timber framing and masonry infill can be simulated using an appropriate method, which can be used to understand the structural problems of heritage buildings in the future. Using this case study as a basis for future work allows the expertise of two different fields to be combined leading to a fuller and more complete understanding of the buildings in question.
The outline of the case studies above provides an insight into what is possible with structural analysis within an archaeological context. Little in the way of primary archaeological research has been completed using this method. The University of Rochester provided newer case studies through their interdepartmental course on Mechanical Engineering and Anthropology during which students and staff focused their attention on Roman buildings such as the work by Mittleman et al. (N.D.) on the Pantheon, McCrossen and Perucchio (N.D.) on the Baths of Caracalla and by Simpson et al. (N.D.) on the Baths of Diocletian. Their works provide a combination of interpretation with real data from archaeological remains but the focus has been on the implication of their engineering and the questions asked are limited to key sections of the building types. No work exists using structural analysis within the validation of reconstructed hypothetical models, based on archaeological research. Those limited archaeological investigations that have used this method have only suggested that Finite Element Modelling could be used as a future tool within archaeological research (Meschini et al., 2014: 420). The potential that the technique has is countless and there exist many applications of its possible use.
The production of Finite Element models are determined by the data available and can be utilised in archaeological research to provide answers as to the hypothetical reconstruction discussed in the Virtual Modelling chapter. The introduction of the application will be studied in detail through the working example of Winchester Cathedral in Chapter Six. This will follow the examination of the structural detail of the cathedral in Chapter Four and the precinct buildings in Chapter Five. The tools shown in the case studies will be utilised throughout as will the fundamental application of structural analysis (3.2). This will provide scientific answers as to the possibilities and limitations that could exist around the known information provided from archaeological research.

3.5 Conclusions

It has been shown in this chapter that structural analysis is a wide and encompassing technique that is used within engineering to create safe and reliable structures. Its application within archaeological study is limited, most likely by the amount of information that has to be incorporated. The chapter has attempted to explain some of the more important features of this technique that are applicable within the general practice of structural analysis to archaeological investigation. It has been argued that the computational methods utilised vary in terms of the results that can be gained and that the Finite Element Method using linear elastic investigations should be used within archaeological research. Using this method allows known rules to be followed and creates a numerical dataset that is more reliable based on the knowledge gained from archaeological research. The predominant focus of this investigation will surround the displacement function of historical buildings to identify their original form with further functionality tests provided via differing load variables. The understanding of structural analysis within the still-standing Winchester Cathedral will be used as a basis to understand the functionality of the software. The ability to model the original construction from the archaeological research will be shown in Chapter Four and Chapter Five and will allow for a more detailed understanding of the changes that have occurred over time. The changing pattern will then be analysed and the results gained will be used in relation to the hypothetical reconstructions of the precinct buildings that no longer exist.

The following chapter will deal with the structural changes of Winchester Cathedral with reference to the structural analysis results that will be produced in Chapter Six. The chapter will focus on the history and development of the cathedral and the surrounding area and will refer to the changes that would affect the structural integrity of the building. This information will then be used in relation to the building survey carried out. Known and hypothetical reconstructions will be created to allow for the simulation of this historically important area to be analysed using the Finite Element Method discussed.
Chapter 4: The History and Archaeology of Winchester Cathedral

4.1 Introduction

This chapter provides an overview of the history and archaeology of Winchester Cathedral. It outlines the major developments that have occurred throughout the history of the building, with much of the emphasis being on the modifications that have taken place. The Inner Close has been touched upon but the individual houses and buildings in the precinct will be discussed in Chapter Five when outlining the investigations that have taken place.

This chapter focuses on the identification of structural features within Winchester Cathedral. The purpose of the chapter is to provide contextual background for the research, which will act as the basis for the individual aims within the investigations. It begins with an examination of the origins of the city and includes the developments that occurred during the Roman and Saxon periods. This is continued with the introduction of Norman builders who greatly changed the ecclesiastical layout of the whole precinct. Following the work completed by Bishops Walkelin (1070-1098 AD), de Lucy (1189-1204 AD), Edington (1345-1366 AD), Wykeham (1366-1404 AD) and Fox (1501-1528 AD), the changing pattern of architecture will be examined and features of importance, in relation to structural developments, will be discussed in more detail.

The major redevelopments of the cathedral will be focused upon the changing architectural features and will be discussed in detail. One significant part of this chapter is how the original layout of the Norman cathedral is conjectural and how the architectural examination that will follow allows for the analysis of this information. It will go on to discuss how later modifications, as seen through the complete or partial redevelopments of the west front, nave, transepts, central tower, crypt, Lady Chapel and roof system, have greatly changed the building. Focus will be on understanding the structural faults associated with each part of the building. The areas that are unknown in terms of origins will be discussed in further detail and research questions will be extracted that are based upon the information provided in Chapter Three, and that address the issues mentioned in Chapter Two.

The chapter will then discuss the underpinning programme that occurred in the twentieth century and how it saved the cathedral from complete destruction. The underpinning programme led to a greater awareness of the structural faults that are found within the cathedral and the discussion points out how these affected its overall development. In relation to this, the chapter will
consider the issues that surround the cathedral’s precinct and how the area is under subsidence strain.

4.2  Winchester Cathedral

4.2.1  Roman Winchester

Winchester occupies one of the narrowest parts of the Itchen Valley, and it dates its origin to the pre-Roman period with the Iron Age earthwork found at St Catherine’s Hill outside the southeast part of the city and at Oram's Arbour which is partly within the west part of the later Roman boundary wall (Biddle, 1966, 1967). Roman Winchester, which was the fifth-largest Roman city in Britain (Biddle and Kjølbye-Biddle, 2007: 203); was referred to as Venta Belgarum and dates to the first century AD. Little in the way of documentary evidence exists (James, 2006: 11). Scobie (1995) suggested that its location was because of access to flowing water, with the River Itchen found in the central part of the city. Excavation in relation to the Roman period was undertaken by Cunliffe (1964) at St George Street in 1955-7; Biddle at the Cathedral Green from 1961-70; Biddle and Clarke at Lankhills in 1967-72; and Biddle in 1963-71 and 1974 at Wolvesey (James, 2006: 24-25). The work by Biddle has revolutionised our understanding of Winchester, particularly in relation to the cathedral, with more to be discussed in the forthcoming volume by the Winchester Excavation Committee (In prep).

Within the car park excavation of the Wessex Hotel north of the Cathedral Green, Roman levels identify that the area once contained Roman roads that now lead under the north transept, with Figure 48 highlighting the extensive grid pattern used in the city. East of the road under the north transept was a Roman house and to the west a large building (Biddle, 1970: 2). To the north west, the Roman Forum was found during the 1960s excavations, revealing large buildings that surrounded the area (Biddle, 1970: 33; James, 2006: 36). The forum was a central hub of activity and the dominant influence within the local landscape. In Biddle and Kjølbye-Biddle’s (2007: 189) most recent work they state the Roman city underwent a great change in the fourth century with the demolition of housing, seen via the reuse of their material in later construction across Winchester. The general increase in housing, as shown through the coins found up to the fourth century (James, 2006: 44), suggest a steady rise in population until c. 350. After this period the defences were strengthened and enlarged cemeteries were added to cope with the increased death rate associated with a plague (James, 2006: 45). Roman Winchester began to decline and following the Roman collapse in the fifth century Winchester was altered in the Anglo-Saxon period (Biddle and Kjølbye-Biddle, 2007: 189).
Anglo-Saxon Winchester

Anglo-Saxon Winchester, named Wintanceaster, denotes an area that was once a Roman walled site. The evidence of this wall is limited, but from the excavation completed at Pilgrim’s School, Champness et al. (2012: 45) suggested that it was destroyed and a replacement was built on its foundations. It is unknown whether this wall relates to the Anglo-Saxon period directly, but it is known that Vikings attacked the city in AD 860 and that the defences were restored, as found in the West Saxon Charters (James, 2006: 51). The present wall suggests a continuous form from Roman to Norman occupation. The most noted work of Anglo-Saxon origins within Winchester relates to the building work completed within what is now the Cathedral Green, as shown through the Old Minster, New Minster, Nunnaminster and Royal Palace.

4.2.2.1 Old Minster

The Old Minster was dedicated to St Peter and St Paul and was built just south of the Roman forum across the east to west street of the Roman town (Barlow and Biddle, 1976: 306). It was a creation of different architectural and religious influences four hundred and fifty years before the Norman invasion and Brooke (1993: 3) suggested that it was a “collection of houses, built up of cells small and large”. The Old Minster was seventy-six metres in length and most likely forty to fifty metres high (Barlow and Biddle, 1976: 307). It has been argued by Yorke (1982: 79-81) that the Old Minster was constructed in 660 but this has been disputed by Biddle and Kjølbye-Biddle (2007: 205) who advocated a 648 construction. Despite these different dates, both publications relate the construction to Cenwalh of Wessex, who ruled from AD 643 to 674. The Old Minster appears to be based on the North Italian architectural style (Biddle and Kjølbye-Biddle, 2007: 207) and stood alone until, under the instruction of King Edward the Elder, a new monastery in 901 was built, now known as the “New Minster”. Little is known of the history of the immediate area during the seventh to ninth centuries.

4.2.2.2 New Minster and Nunnaminster

The New Minster was founded, according to tradition, at the request of King Alfred who bought the land north of the Old Minster, and it became associated with royal interest. It was built directly next to the Old Minster and was relocated to Hyde in 1100 following the construction of the cathedral (Barlow and Biddle, 1976: 312). In association with the New Minster, which stood to its east, was the abbey of St. Mary, known as the Nunnaminster. It was founded jointly by King Alfred and his queen Eahlswith at around the same period as the New Minster. The Nunnaminster was constructed by Edward the Elder (Doubleday and Page, 1903: 122). The abbey followed Benedictine rule and was closely connected with the royal household. It was refounded in 963 AD.
by Bishop Æthalwold (Doubleday and Page, 1903: 122) and was rebuilt in the twelfth century following its destruction in a fire. It stood until its demolition under Henry VIII and like the New Minster, little is known save for the interim reports produced by Biddle following the 1960s and 1970s excavation, and a pamphlet produced after the excavation in the 1980s (Qualmann, 1984). Kjølbye-Biddle et al. (Forthcoming) will be releasing a long-awaited volume with information regarding these two buildings as well as detailed information with regard to the Old Minster.

4.2.2.3 Later Redevelopment of Old Minster

The continuation and rise of the church, and the Benedictine Reform, led by Æthalwold in AD 963-84, created a system of reformed building work mostly associated with the redevelopment of the Old Minster. St Swithun, Bishop of Winchester between 862 and 865 AD, was translated from his exterior burial at the entrance to the Old Minster, to a newly formed shrine associated with the regeneration of the building (Barlow and Biddle, 1976: 307). This regeneration was seen between 971 and 980 AD with the Old Minster expanded westwards over the site of St Swithun’s grave. After its dedication, the church was extended eastwards with the east end remodelled to form the principal crossing and high altar (Barlow and Biddle, 1976: 307). There was likewise a structural change within the Old Minster due to the addition of a chair for the king, placed in the west at an elevated height, in order for the view of the king to be unobstructed towards the east (Kjølbye-Biddle, 1993: 16). An architectural reconstruction of both the Old and New Minsters can be seen in Figure 49. The reconstructions are based on the structural developments found through the excavation data of the 1960s, text from poems of the time and the limited text from the Cathedral Annals (Kjølbye-Biddle, 1993: 20). The reconstruction is conjectural and it has no other basis for its construction. The model includes four towers, three apses and twenty-four small chapels; three crypts are also mentioned by Kjølbye-Biddle but are not included within Figure 49.
4.2.2.4 Royal Palace

West of the Old Minster was once a royal residence. Again little is known of this except that it was expanded under Norman rule, being doubled in size in 1070 AD. This is noted in documentary evidence but no archaeological remains have been found (James, 2006: 66). More on this will discussed in The Cathedral Precinct section (5.2) but it must be noted that the location is unknown but it is considered to be west of Great Minster Street, which now forms the western boundary of them current cemetery.

By the end of the tenth century, the Old Minster and the surrounding ecclesiastical quarter, which included the above-mentioned buildings, as well the New Minster’s own precinct, had taken its final form. The development of what is now the Cathedral Green can be seen in Figure 50 and is based on the excavations completed by Biddle from 1961 through to 1970, which revolutionised our understanding of the area. At the time of completion, what is now the Outer Close (northeast of the cathedral) would have been an area of high importance and the power of the area would have been perceived through the number of buildings present. The prestige of this ecclesiastical area was continued after the Norman invasion and it led to the development of the church that can be seen today. Indeed the precinct in 1093, after the Norman invasion, consisted of the Old Minster, the New Minster, the Royal Palace, the Nunnaminster and the newly formed Bishops Palace at Wolvesey, as well as the east part of the new cathedral that was developed under Norman influence (Kjølbye-Biddle, 1993: 13) as shown in Figure 51.
Figure 50. Winchester Cathedral in relation to the Old and New Minsters (Biddle, 1972: 116). Reproduced with permission of Cambridge University Press, www.cambridge.org.

Figure 51. Plan of the cathedral precinct c.1065-1093 (Kjølbye-Biddle, 1993: 14). Reproduced by kind permission of The History Press, www.thehistorypress.co.uk.
Chapter 4

4.2.3 Norman Winchester

The development of Norman Winchester took three stages. It consisted of a continuity of form and function, whereby defences, streets and houses were adapted, with Biddle (1984: 119-126) suggesting that the street plan found within the city is of Saxon origin; a major architectural transformation for royal and ecclesiastical activities; and a growth in population via the expansion of suburbs (Biddle, 1987: 325) as shown in the survey of 1148 (Barlow and Biddle, 1976: 69). The major architectural transformation followed a practice of the Normans to build great Norman churches to replace Saxon minsters (Bussby, 1979: 1). The evidence of the cathedral from the twelfth and thirteenth centuries is based on the documentary evidence of annals, chronicles, deeds and charters. The fourteenth and fifteenth centuries have further sources and include monastic and episcopal act books and registers, correspondences, financial reports and government records (Greatrex, 1993: 141).

The following sections provide an outline of the work that has been completed at the cathedral since its consecration. It will highlight important alterations and will discuss the archaeological changes that have affected the structural integrity of the building. All of this material will be used within the structural tests that will be performed in Chapter Six. Figure 52 points out the successive changes of the cathedral and will be used within the text to refer to the areas discussed.
4.2.4 The Constructions of Bishop Walkelin (1070 -1098 AD)

In 1070 William Walkelin was appointed the first Norman Bishop of Winchester and set about the redevelopment the area (Gem, 1983: 1). In 1079 cathedral construction began under the direction of Walkelin by Hugh Caementarius, the mason (Harvey, 1972: 61), with the church being consecrated in 1093. The stone used in its construction was Quarr Stone with a thick rubble core (Crook, 1993a: 29), with parts of the original walls also being made up of other forms of Oolitic limestone.

The cathedral took a relatively long time to be constructed, when compared to the four years it took to build Ely cathedral. The most important part, the foundations of the building, took seven years to complete (Bussby, 1979: 1). The Old Minster was pulled down after the consecration of the east end to allow for the northwest part of the building to be finalised and this was completed by the end of 1093 (Crook, 1993a: 22) meaning that the cathedral was not yet complete when it was consecrated. Once the cathedral was completed and dedicated, the only work that exists that describes the building at the time is that of Durand (translated in 1843) who was alive in the thirteenth century. It is speculated that the cathedral was dedicated when the eastern arm, crossing and transepts, and the eastern three bays of the nave were completed (Bussby, 1979: 3).

Churches have always been placed on an east to west orientation in alignment with the sunrise on the feast day of a church’s patronal saint. The work of Hinton (2006; 2012) focuses on this alignment by comparing 1444 churches across the country. His findings suggest that there are three main issues associated with this alignment. The first is through the height of the eastern horizon, which would affect the relative position of the sun’s location. The second deals with calendar drifts, with the third being church re-dedications to different saints. It was found that across the country the mean alignment of churches varies between 80.4⁰ and 92.4⁰ with 61.1% aligned north of east (Hinton, 2006: 214). This could relate to a variance with the earth’s magnetic field, seasonal issues, sunrise at specific times of the year and the chronology of churches that were built on previous foundations. With the majority of churches aligned north of east, it suggests that the foundations were most likely completed during the winter months, as if completed earlier in the year, the alignment would be further south (Hinton, 2006: 217). Hinton concludes that the intention to align churches was completed roughly to an east orientation and accuracy was not key (Hinton, 2006: 223). At Winchester, the orientation follows the general pattern of alignment and suggests that its location was not restricted by the alignment of the Old Minster (Figure 52 A) but rather followed the general pattern found across the country, which would have also been restricted by the layout of the street plan.
When looking at Old Minster, Hoare and Sweet (2000: 162-173) also comment that the general pattern of Anglo-Saxon churches across the country was $88^\circ$ and follows the orientation of Old Minster which likewise does not have a true east to west alignment (Biddle and Kjølbye-Biddle, 2007: 192). The orientation of the cathedral proved significant through its development and more on this will be discussed below (4.2.4).

It can be considered that Winchester Cathedral was one of the most remarkable buildings of its age in England and Europe in terms of the scale and the diversity of influences in its design (Gem, 1983: 1). The length of the nave, which Crook (1993a: 22) suggested was due to the cathedral having the same west location as the Old Minster, and the transepts needing to be built in an open area. Fernie (1979) saw Winchester’s great length as being an indication of an attempt to emulate the size of the largest early Christian basilicas in Rome. This was due to the cathedral having the resemblance of a basilica, the design of which was based on an oblong building with rows of columns to divide the nave from the aisles, with one end forming a semi-circular apse (Bussby, 1979: 2). The transepts (Figure 52 E and F) add to this shape by creating a cruciform appearance. The cathedral as a whole however has one of the simplest designs in the country. The nave has a length of thirty metres, the transepts twenty-four metres, and the tower had a height of twenty-three metres (unconfirmed height), which made it taller than Peterborough and Ely. The total length of the cathedral is one hundred and sixty nine metres and the north to south distance of the transepts equates to seventy metres. In comparisons to other cathedrals of similar design and age, the cathedral is known as being the longest in England and across Europe. Ely cathedral, which was built in 1109, was most likely based on Winchester in some format due to Walkelin’s brother, the Abbot of Ely, being given the task of constructing it (Crook, 1993a: 21) and it closely resembles Winchester. It has a length of one hundred sixty three metres, whereas others such as Lincoln and Canterbury have lengths of one hundred and fifty nine metres and one hundred and fifty seven metres respectively. Although Winchester had a longer cathedral, the plainness in its design means that the length is not apparent, unlike Canterbury, which seems to have a much wider span.

4.2.5 The Constructions of Bishop de Lucy (1189 -1204 AD) And Bishop Edington (1345-1366 AD)

Documentary evidence for the earliest construction of the cathedral is limited and the major evidence used is from the Cathedral Annals which were compiled a century after the cathedral was built (Crook, 1993a: 21). The original Walkelin construction proved to be strong and durable enough over time so that the majority of it forms much of the core of the cathedral as it is viewed today. After Walkelin’s death, the history of the building is limited. Bishop de Lucy added to the
cathedral greatly in 1189, mainly evident in the retrochoir (Figure 52 H) and the Lady Chapel (Figure 52 I). The thirteenth-century work completed by Edington at the east end would have been governed by the original eleventh-century construction. This can be seen in the regularity and continuity of the external plinths that suggest it was constructed as one single design built from east to west (Draper and Morris, 1993: 180). Draper and Morris (1993: 180) also suggested that the retrochoir may have originally been intended to have an extra pier due to the out-of-line pier next to the two chantry chapels (Figure 52 L) but that was left to support the arcade. The south and north piers of the presbytery and retrochoir are different, as seen in Figure 53, suggesting that the south was either under structural damage or different builders were used (Draper and Morris, 1993: 183). Although structural faults are now seen in this area, it is more likely that different builders were used as there is evidence that they were built around the same time (Draper and Morris, 1993: 184). Furthermore, if the same builders were used, it is strange to see different forms of mouldings used as shown in Figure 54 and Figure 55. The area was once the end of the Norman apse created by Walkelin, with the piers in question showing this point. Figure 56 highlights this and demonstrates that the piers in questions were built on new ground.

Figure 53. North-east arch of the presbytery and retrochoir showing the north arch of the arcade and the south presbytery gable (facing west) (Draper and Morris, 1993: 184). Reproduced by kind permission of The History Press, www.thehistorypress.co.uk.
Figure 54. Piers around the feretory in the retrochoir (north of Figure 52 L). The mouldings found in the east are of two different constructions and can be explained by different building strategies (Draper and Morris, 1993: 186). Reproduced by kind permission of The History Press, www.thehistorypress.co.uk.

Figure 55. Moulding profiles of the presbytery arcades. A) East Bay, northeast arch. B) East Bay, southeast arch. C) Main arch type of found in bays two to four (Draper and Morris, 1993: 187). Reproduced by kind permission of The History Press, www.thehistorypress.co.uk.
Figure 56. The end of the Norman apse superimposed on the feretory area (north of Figure 52 L) (Crook, 1993c: 58). Reproduced by kind permission of The History Press, www.thehistorypress.co.uk.
Until the fourteenth century, the main concentration of reworking took place at the western end of the cathedral. During Bishop Edington’s time the towers at the western front, Bussby (1979: 37) has suggested, had become insecure or had collapsed and rebuilding was necessary. Although this is plausible, the reworking of the west front was mostly related to updating the style of the cathedral to a more modern appearance. It is because of this that the west end as it now stands was built. The west front of the Norman Cathedral is however disputed and will be discussed below (4.2.9).

4.2.6 The Constructions of Bishop Wykeham (1366 -1404)

William of Wykeham is the most celebrated bishop and builder in Winchester Cathedral’s history. His other works include New College at Oxford and Winchester College. The master-mason associated with Wykeham was William Wynford who had also worked at Windsor, Wells, Abingdon, Southampton, Oxford and Corfe Castle (Bussby, 1979: 40) and thus the work followed experienced guidance. Under Wykeham, although disputed by Hare (2012), the cathedral changed greatly (4.2.9). The double tier arches in the Peristyle were turned into one. His most celebrated work however lies within the nave. Wykeham had the original Norman columns in the nave converted to the Perpendicular style by encasing the masonry, and converted the Norman arches to pointed arches (Bussby, 1979: 40). The conversion of the piers began by altering the mouldings by cutting Perpendicular mouldings in the stone in situ and is evident in the first eight piers from the west on the south of the nave with thicker joints (Henderson and Crook, 1984: 29) (Figure 52 C). The piers on the north of the nave, with the Norman stone being much coarser and having uneven mortar joints, were skinned of their ashlar and new masonry was added (Woodland, 1932: 123). The triforium arches were left in their original position and were covered by a Perpendicular balcony (Woodland, 1932: 121). Wykeham also added the buttresses that can be seen on the north of the nave whose foundations, being higher than the main walls, gave very little in the way of support (Henderson and Crook, 1984) (3.2.5.2) 7.

4.2.7 The Constructions of Bishop Fox (1501 – 1528)

Wykeham was one of the last medieval Bishops who undertook any major redevelopment with his successor Beaufort doing very little. An extension to de Lucy’s Lady Chapel (Figure 52 I) was

7 Structural analysis could be used to test the validity of Henderson and Crook’s views by examining how effective the north buttresses were as a support mechanism.
completed by Bishop Fox, who also, in 1519-1524, added the flying buttresses to the presbytery (Figure 52 G) (to act as a springer for the flying buttresses that run to the clerestory above), a wooden choir roof with bosses (Figure 52 G), choir screens and his own chantry chapel (Bussby, 1979: 90). This redesign converted the choir and presbytery into the Decorated style, leaving the Norman aisles as they were originally built. The work attached to Fox’s reworking of the retrochoir area, as suggested by Harvey (1978: 27), was completed by Thomas Bertie who also worked at Christchurch Priory and Warblington for Margaret Pole (Riall, 2015: 215). Bertie was responsible for the carved corbels in the choir and most likely oversaw the rebuild of the presbytery aisles before 1518 (Riall, 2015: 216) (Figure 52 N). Harvey (1978: 27) attributed to Bertie the 1532 stone vaulting in these aisles, but argued against Riall (2015: 235) that this was already accomplished due to the inclusion Fox’s Chantry Chapel between 1513 and 1518, which would have had to have been completed prior to the vaulting being put in.

Riall (2015: 236-245) commented that due to the lack of Fox’s badge of arms, except for within the presbytery aisles and retrochoir vaulting, and due to there being no evidence of stone being bought, a new build was not completed. He concluded that Fox was not responsible for the rebuild of the retrochoir but rather only for repairs to the vaulting and walls. Draper and Morris (1993: 189) however suggested that the reworking of the presbytery piers in the sixteenth century was completed as one build. This is due to the different-sized bays that would have affected the length of Norman vaults above. They further suggested that the windows found in this area were built at a different time to the original construction as they are unlike the others found in the cathedral. This suggests that Fox added them in the sixteenth century along with the Choir screen or when the vault was added (Draper and Morris, 1993: 189), contrary to Riall’s view.

This general redevelopment was the last major structural work that took place before the great work of the nineteenth century. In 1558, all building work ceased and it was under the guidance of Bishop Robert Horne that the cathedral and all of its precinct buildings fell into neglect. This included the Chapter House, along with some of the stained glass windows and architectural decorations of cathedral being destroyed.

4.2.8 The Original Construction of the Cathedral

When the present cathedral is examined, many different phases of construction can be seen; due to the combination and inclusions of different architectural features, dating is challenging. From documentary evidence and from architectural inspection it is evident that the majority of Walkelin’s cathedral remains. This is seen in the foundations, transepts, outer face of the south wall, the core of the nave columns (the stone of columns have been removed in places), the crypt
and part of the west wall. The original form however is conjectural and is based on this information. It is suggested by Gem (1983: 2) that the cathedral was originally meant to have seven towers, four of which were intended for each corner of both transepts (Figure 52 E and F). Evidence for the transepts having towers can be seen in the ground-level piers, which are larger in the corners to support the weight of these towers. The transverse arches that were built in the gallery (Figure 57) seem to be able to support the walls of each of these towers. The double bay system (Figure 58) that can be seen in the relieving arches in the clerestory, as well as indications of an external doorway (Figure 59) in the outer bays suggests that access to the third storey of the tower would have been provided (Crook, 1993a: 30). The unfinished turret at the northeast corner of the north transept remains but its incomplete nature suggests that the turrets were never fully constructed. This incomplete nature is most likely due to the central tower collapse on October 7th 1107 AD (Bussby, 1979: 8) (4.2.11) and could be tested using structural analysis.

Figure 57. The triforium and clerestory of the east wall of the south transept (Figure 52 F). A wider column span (a), in comparison to the rest of the transept (b), allows for an enhanced downward thrust redistribution of the building work.
Figure 58. The double bay system within the southwest corner of south transept (Figure 52 F).

Figure 59. On the right is a possible indication of an external doorway found on the clerestory level of the west wall of the south transept (Figure 52 F). This is larger than the left-hand window and shows signs of deformation.

The addition of these towers would fit with the style of the cathedral as supported by the 1960s excavations by Biddle (1970: 87) when the original west front (Figure 52 B), with two flanking
towers discovered (Figure 60). Barlow and Biddle (1976: 310) suggested that the possible twin towers that were on the west front of Winchester cathedral were similar to King William’s Abbey of Sainte-Trinité in Caen as seen in Figure 61. This former monastery is of Romanesque construction and is more advanced than anything else built in Normandy. In association with this is the Abbey of Jumièges in the upper region of Normandy. This abbey had a similar twin tower design, as shown in Figure 62 (foreground), but differs slightly with the addition of turrets. As Winchester was seen as William’s new royal centre, the association with the great architecture found in Normandy can be made. Comparisons however in identifying Winchester’s form must be made in relation to those found within England. Lincoln and Durham Cathedrals, built from 1088 and 1090, have a similar twin tower design with their current towers showing Romanesque features. Canterbury likewise would originally have been designed in a similar fashion (Rogers, 2013: Catheral Guide) but has since been converted to the Gothic style. If Winchester adopted this advance in architectural design at the time, then it cannot be found elsewhere within England that relates to the same period due to the level of transformation that has taken place across the country. Comparisons therefore have to be made around the central tower of Winchester cathedral. A reconstruction of these towers can be seen in Figure 63 but it must be noted that the towers, along with the design of the western front, is conjectural. To create a system that is more precise, more information has to be drawn from what remains and a system of models will be examined in identifying the true original form.

Figure 60. The original west front foundations as shown in the Biddle excavations of the 1970s (Biddle, 1970: 88). © Warren & Son 1970.
Figure 61. West front of the Abbey of Sainte-Trinité (Pradigue, 2014). CC BY-SA 3.0 Pradigue.

Figure 62. Abbey of Jumièges (Urban, 2004). CC BY-SA 3.0 Urban.
4.2.9 The West Front and Nave Conversion

In 1607 Camden (2004: 191) noted the remains of the late sixteenth century solid walls of the original western front that were later discovered by Biddle. Willis (1845), whose works forms a significant part of our understanding of the cathedral, developed Camden’s notion and directed excavation work that was completed by Owen Carter. Willis created a plan (Figure 64) based on this and Crook (2010: 221) comments that the misalignment of the walls within it suggests that it was genuine and based on real data. On this plan, small lines can be seen on top of the foundations, pointing out the bases of walls, with the black areas highlighting the standing rubble that existed during the original survey.
Based on the work completed by Willis, Crook (2010: 228-235) suggested that there was once a solid east-to-west wall present where the current west wall is placed. This would have acted as a support mechanism for the towers mentioned above. The idea of there being a central tower on the west front, as proposed by Peers and Brakspear (1912: 52), in comparison to Ely and Bury St Edmunds, has been disputed by Crook (1992: 15-17), as the central cell contains a thin wall only 3.5 metres thick whereas the outer walls have a thickness of 4.52 metres (Crook, 2010: 232). The outer walls being thicker suggest that they supported something more substantial. These two flanking towers would have measured 10.7 metres by 7.5 metres, similar to Durham’s 10.36 metre by 6.1 metre towers created in 1090 AD. At Durham a spring vaulting is used if there were a similar form of construction at Winchester it would have had springing from three metres above the ground (the nave springing starts at five metres) (Crook, 2010: 232). Crook (2010: 233) added that the central cell would have had a similar tribunal platform to that seen in the transepts but rather than have the double portal for a two-cell vault, the more logical conclusion is that it consisted of one. These would have been accessed from the exterior with the towers being accessed via an internal doorway. Crook’s (2010) updated plan can be seen in Figure 65 and
follows the most logical layout based on the known data. Little has changed from the original plan submitted by Willis and it highlights that some of his original reports are valid in their interpretation. This material could be used in understanding the structural form and could be assessed via structural analysis to confirm the conjectural form of the original west front.


Crook (1993b: 217) suggested that the construction of the Perpendicular remodelling of the nave was completed due to it being stylistically outmoded. He pointed out the arguments for structural deformation are unlikely, as the foundations of the tower located in excavation appeared
extremely strong. He believed in 1993 that the reworking of the west end was a twofold programme that Edington began and Wykeham completed, with the majority belonging to Wykeham. This consisted of three phases. The first was the construction of the triple porch block (Figure 66) now found on the west front that was built before the Norman west wall was destroyed.

Figure 66. Present-day west front of Winchester Cathedral with the triple porch system found on the ground floor

The second phase consisted of the interior and upper parts of the west front and can be seen in the disjunctions between the coursing of the outer and inner walls of the three-porch system signifying a different construction period. Figure 67 shows that the interior part of the west end of the nave which suggests a third phase of construction as the bay shown has an uneven height compared to the top of the porch disjunction and was added to support the vaulting. This uneven height signifies a different construction pattern as, if built as one, everything would have aligned equally (Crook, 1993b: 218-220). The buttresses on the exterior of the nave (Figure 69) appear to be of the same construction as the second phase and suggest that the height of the west wall,
windows and gables were constructed as one unit along with the stair turrets in the west elevation. Crook (1993b: 222) added that the remodelling of the aisles in the nave was part of the second phase of remodelling due to the clasping buttresses. The third phase focused on the remodelling of the main elevation and was completed first on the south side piers (Figure 52 C) from west to east, and secondly on the north piers (Crook, 1993b: 225). Crook attributed the second and third phases to Wykeham and the first to Edington.

Figure 67. Interior panelled band at the west end of the north aisle wall pointing out the uneven height of the bay in conjunction with the porch system (Crook, 1993b: 220).

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Hare (2012) questioned the three phases suggested by Crook and proposes instead a four-phase construction, two under Edington and two under Wykeham. It is agreed that Edington began with the construction of the western porches but it is suggested that he began to rebuild the nave before his death (Hare, 2012: 278). Wykeham halted the work as it was too ambitious and was redesigned under a separate three-phase plan. Hare (2012: 279) believed that Wykeham’s work began in 1372 and restarted in 1394 after funds were secured for its completion. Hare associates the hiatus between these two redevelopments as related to Wykeham being engaged in other building work.
Chapter 4

Part of Hare’s assessment of the different building patterns is based on the carved decorations within the string course (Figure 68) which are of different sizes suggesting different craftsmanship (Hare, 2012: 282). In association with this are the coat of arms of Richard II found on the north part of the nave but not on the south, indicating possible different periods of craftsmanship. Hare (2012: 282) took this one stage further by associating the refacing and re-cutting of the nave piers in line with these coats of arms. He suggests that rather than being completed as one development, the transformation of the nave was completed in stages, by the same architect but with a modified approach.

![Figure 68. Two phases of stringcourse found within the nave. On the right (a) is the 1370s work and on the left (b) the work completed in 1394 (Hare, 2012: 282). Although small in detail, the heraldic badges found differ in size and spacing](image)

Hare (2012: 291-294) suggested that the first phase consisted of the triple porch construction. The incompleteness of the west front, rather than being associated with the Black Death, was a consequence of a shift of focus onto Edington’s own monastery. The second phase therefore includes the demolition of the Romanesque west wall that remained and the replacement of a thinner fourteenth-century one. The first two bays were rebuilt at this period in the north aisle, as was the first bay in the south. The windows found here differ from the rest in the nave (Figure 69) and follow a similar design to Edington’s west end window (Figure 66). These two bays signify that there was an intention to redevelop the whole nave in similar fashion before Edington’s death. The third phase therefore consisted of the completion of the west wall by Wykeham along with
the extension of the stair turrets and balustrades that hide Edington’s original bay redevelopment. The nave aisles were also increased in height during the fourth phase, which included the completion of the nave arcade, the remodelling of the clerestory and the addition of the stone vault (Figure 70). The aisle were raised to add support to the vaults as shown in Figure 69 and the remodelling of the clerestory and vault system was completed in one phase which is evidenced by the hidden Romanesque features behind the panelling. This fourth phase was completed after the death of Wykeham who left money in his will and consequently, although assigned to Wykeham, was completed by Bishop Beaufort (Hare, 2012: 295).

Figure 69. North exterior of the nave aisle facing south, showing Edington’s window on the left (a) and Wykeham’s later windows on the right (b). The increase of the height of the bays can be seen directly above each window (Hare, 2012: 292). Reproduced with permission of Cambridge University Press www.cambridge.org.
Crook (2010: 225) added that his original second phase should be reassigned to Edington rather than Wykeham due to money being left in his will to finish the work he started. As the west front was already completed this led Crook to suggest that Edington had begun to build the west wall on top of the porch system. He argues against the four phases mentioned by Hare and agrees with his first comments that the Black Death was responsible for the gaps between the first and second phase, but admits that it would require a four-year build of the porch and demolition of the original west front before Edington’s death (Crook, 2010: 227).

The conjectural nature of the building work could be studied in this thesis to verify what levels of building work were required within the function of its form. With the conversion of the Walkelin style to the new Gothic style, evidence of its original form can be seen in the Norman columns that were halved in height. Some of the original parts in the roof space above the vaults remain as seen in Figure 71. The removal of the bases and capitals of these grouped shafts provided remains of masonry or scars that can be used to give an insight into the spacing of the original columns, which suggests that their spacing was uniform and consistent with what is found today. Although removed, the north end of the nave contains part of the original columns, which have been incorporated into the later ones, and the Norman relief shafts on the south side are still evident, as seen in Figure 72. Using this information and relying on architectural investigations, the remains of the original piers can be extracted and used in reconstructing the original form.
Figure 71. Remains of the Norman columns above the gothic vaulting in the nave

Figure 72. Remains of the Norman shafts in the south wall of the south nave. These have been cut back to create demi-columns
4.2.10 The Transepts

The transepts are made up of the main arcade, gallery and clerestory, which are equal in height. They contain a mixture of half shafts, which are for aesthetics, and full-length shafts, which were used as structural supports for the original tie beams of the roof. The transepts remain mostly in their original form, and the presence of these Norman aspects is strange considering the rest of the redevelopment that took place within the cathedral. Work had been planned in this area but an expense dispute between the monks and bishop in keeping the Lockbourne system (5.2.4), which would have been removed if the south transept was extended, led to the work being postponed. With the death of Wykeham shortly after the restoration began, no further remodelling took place (Vaughan, 1914:91; although this is an out-dated reference, it provides the only indication that can be found in relation to the Norman features’ survival).

The north transept is similar in many ways to its counterpart but two of the piers on the eastern side have been modified. In the south transept, the aisles have been divided into six chambers with the southernmost acting as the entrance to the seventeenth-century slype and the library above (Figure 52 J). On the north, these aisles remain open except for the western part, which has been turned into a chapel that retains its original Norman construction (Figure 73). The ceilings of both these transepts would originally have been open, displaying the timber-framed roof structure but in 1825 a wooden ceiling was installed (Barrett, 1993: 318).
Figure 73. Converted chapel in the west part of the North transept showing original Romanesque features

The survival of the Norman features is of the utmost importance for discovering the original design of the cathedral. The transepts are of a thick coarse stone and the most significant change can be seen in the crossing, which was rebuilt due to the collapse of the central tower. After the tower collapse, it can be seen in Figure 74 that a much better quality of stone was used in the building work, signifying that the modifications were done at a later period and not in the original construction.
Within the transepts, the arches in the triforium and clerestory are square-edged unlike Ely, which has smooth continuous arches. This added effect of square edges provides a simple construction method and adds considerably to the structure’s strength. Each transept level was separated into four compartments. At the east end, the upper levels that rise to the pier arch level consist of two arches with shaft supports in the centre. These act not only as supports for the roof structure but with the added strength of the shaft supports present a way to create a form of gallery that was built as passageways for the monks to pass around at the triforium level (Sergeant, 1903: 62).

4.2.11 The Central Tower Modification

The later central piers that were built after the tower collapse (Figure 52 M) had to be strong to support the redeveloped main tower. There is reason however to suggest that their size never needed to be as large as they are. The piers appear to be strong enough to support much more than the current tower and are in stark contrast to those in the transepts. With the tower being reduced in height and with it the forces applied being less, there is no structural reason for their size. Henderson and Crook (1984: 24) noted that the piers of the four corners of the crossing are...
exaggerated. They would originally have been constructed in a plainer fashion, fitting in with the original design seen in the rest of the nave. With the tower collapse, it suggests that the builders were worried about further structural faults and overengineered the redesign, or had envisaged building a taller tower. The size of these piers has been tested to confirm this. These enlarged piers, have proved to be strong enough to support the later nave vaulting. This adds to the suggestion that they were overengineered. In comparison to Canterbury Cathedral, which required the addition of flying buttresses to support the stone vaulting of the nave, the overengineered state of the central piers seems to have necessitated fewer modifications within Winchester Cathedral.

The rebuilt tower (Figure 75) now has its coping 10.66 metres above the ridge of the transept roof and is in a simple square form that is 45.72 metres tall and 15.24 metres wide. After the twelfth century Caen stone began to be used, as it was easier to work with. Figure 76 highlights its introduction within the tower as shown through the shaded elements in the parapet. Caen stone can also be seen at the east end of the cathedral within the internal walls, which were faced externally with Quarr stone. The capital, bases, shaft rising and moulded string courses are of Purbeck marble (Tatton-Brown, 1993: 41) and the tower now contains a wooden ceiling that was installed in 1634 (Cobb, 1981: 124).

Figure 75. Winchester cathedral viewed from the south with the modified tower shown in the centre
4.2.12 The Crypt

The crypt of the cathedral plays a very significant part in the understanding of the original construction of the cathedral. As shown in Figure 77 there are three chambers in the crypt. The first (Figure 77 A) runs under the eastern tower piers as far as the first piers of the retrochoir, and includes a central room divided by a row of three columns (two survive) with an apsidal eastern termination. Two aisles that have square eastern ends, which stop in line with the entrance to the second chamber, flank this central room. The second chamber (Figure 77 B) is narrower and has five columns that finish under the end of the retrochoir (Figure 78). This termination shows the original design of the Romanesque cathedral as seen in the masonry that has been cut through (Figure 79). The last chamber (Figure 77 C) is a narrow rectangular vaulted room of Gothic design below the Lady Chapel. The two previous chambers are of the original Romanesque design as the rest of the cathedral would have been. The crypt regularly floods and at some point in its history
(which remains unknown), the floor level was raised to stop the continuing effects of water within the daily routine of the monks that used it. In 1886 the crypt was cleared (Sergeant, 1903: 94) and the present floor level was based on the original.

Figure 77. Results of the 2013 crypt survey (Sweda, 2013: 77)

Figure 78. Romanesque features found within the crypt (Figure 77 B)
Figure 79. Evidence of the original Norman Apse in front of the entrance to the Lady Chapel area in the crypt (eastern termination of Figure 77 B)

The crypt acts as a support mechanism for the majority of the cathedral and is reminiscent of the 1063 Rouen Cathedral and its crypt. The style of the apsidal crypt can also be seen in the Abbey of St Augustine at Canterbury built in 1070 AD (Figure 80) and both could be used for the reconstruction of the original cathedral at Winchester as sources of comparison.
4.2.13 The Lady Chapel and Retrochoir

The original Norman cathedral was designed with an apse, as found in the crypt level. With the reworking of the retrochoir area (Figure 52 H), the cathedral’s form changed to incorporate a Lady Chapel. The addition of the Lady Chapel to the east end of the cathedral extended the length of the building by 33.5 metres, and was built using new foundations.

The windows within the Lady Chapel contain seven lights and resemble Wykeham’s design. Within this area, there is a mix of architectural styles with Gothic, Decorated and Perpendicular all present. The rebuild of the area allowed for more space, more chapels and superior engineering to make the area more stable. The area is under significant strain following recent subsidence, as shown in Figure 81. It was noted by Walker (1993: 335) that the retrochoir had “moved five inches to the east of the south wall and that the presbytery was eight inches out of plumb” and that daylight was visible through the wall of the north transept in the twentieth century.
Figure 81. Subsidence issues in the retrochoir looking east. Notice the significant dipping on the right hand side and the lean of the southern wall.

The Lady Chapel has four great buttresses with four shallow arched recesses on the east end (Figure 82). Each arch within this section unites two minor ones. A blank façade can be seen on the south of the Lady Chapel but not on the north. Connected to the Lady Chapel to the north is the chapel of the Guardian of Angels and to the south Bishop Langton’s chantry chapel. The north and south walls of the Lady Chapel are Gothic in design but the east wall is Perpendicular like the work at Rochester Cathedral and Lincoln Minster (Gem, 1983: 5).
The retrochoir was once the area of the original apse (Figure 52 L). It is west of the Lady Chapel and has a plain stringcourse within each compartment under a level parapet with an arcade of four narrow pointed arches. The rooms above can be accessed by the octagonal turret towers on each corner of the retrochoir and again are of Perpendicular design unlike the towers, which contain complicated geometry. The changing pattern of architecture therefore may have added to the strain and the variation in design could be tested.

4.2.14 The Cathedral Roof

The roof, specifically the timber frame, has undergone four main alterations. A dubious reference as noted by Crook (1993a: 21), has the original timber for the cathedral taken from Hempage wood following Royal order, where Walkelin was allowed to use as much wood as he could gather in a day (Woodland, 1932: 60). Munby and Fletcher (1983: 101) believed that none of the original Walkelin roof remained in situ, parts of the Norman timber may however have been reused. In the early fifteenth century, the nave roof was redesigned, as seen in the pitch alteration and the weathered course in the west wall of the tower (Crook, 1993b: 226). In 1896, repairs to the roof also took place with the western end of the nave roof remodelled to relieve the downward thrust of the timber frame on the vaulting. This was completed by elevating it slightly through the introduction of new timber beams that weighed 198.25 tonnes (Bussby, 1979: 249), as shown in Figure 83. The full weight of the timber beams are unknown.
With the redevelopment of the retrochoir, a modified timber-framed structure was also installed and as seen in Figure 84; there exists little space for relieving stresses that are inherent. The addition and redesign of this roofing therefore play an important role within the investigation that will take place and it is interesting to see how the building reacted to these changes.
4.2.15 Royal Influences

The architectural interests of the reigning monarch influenced Winchester, following a royal association, greatly. Many differing architectural designs, as was the case at Westminster, were incorporated into the development of Winchester cathedral. Architecture represents power and importance and with the movement of the Treasury to London in the second half of the twelfth century, the development of different designs within the cathedral halted and little in the way of modification occurred until the fourteenth century (Gem, 1983: 10). The combination of the designs that make up the building created a system that was somewhat structurally weak (as seen in the retrochoir). This conceivably led to the inconsistencies in design that are found due to other possible structural weaknesses.

4.2.16 Civil War

The Civil War between 1642 and 1651 broke out between Charles I and his parliament; with Portsmouth being in the hands of the parliament, Winchester was seen as an important stronghold for the Royalists. Winchester was repeatedly attacked and in December of 1642, the cathedral windows were broken. Captain Fiennes, who was in command of the 36th Troop of Parliamentarian Horse, saved the cathedral from total destruction. His family being “Founders Kin” of Winchester College, and Wykeham being its founder, Captain Fiennes is said to have saved all of Wykeham’s work (Woodland, 1932: 192) within the cathedral but could do nothing to save the cathedral library and its records. A second attack that took place in March 1643 further added to this destruction, with everything that was saved previously being taken and destroyed (Woodland, 1932: 195). The archives of the Dean and Chapter of Winchester now show an uneven and disappointing rate of survival. The majority of the pre-commonwealth collection, except for ledger books, were ransacked by the Puritan soldiers and provisions were outlined in preserving minor documents of interest, as seen at Winchester College during the same period (Crook, 1984: xiii).

During the Civil War, control of Winchester changed many times, with the Royalists gaining control again in September 1643, only to then lose it in October 1644. This culminated in 1645 with the Dean and the prebendaries being deprived of their houses and their financial support from the cathedral properties (Bussby, 1979: 138). A parliamentary survey of the houses was completed in 1649 with the houses being sold to the supporters of the new regime (Bussby, 1979: 138). Following a public petition in 1652 some of these buildings received some small repairs (Bussby, 1979: 141). After the civil war the Dean and Chapter were involved in an extensive rebuilding programme to replace houses which had been pulled down during parliamentary
occupation of the precinct, with only three of the twelve prebendal houses and the Deanery in 1675 surviving without any damage occurring to them (Crook, 1984: xv). Two other houses were partially damaged and the rest were demolished for building material. As well as these, and because of Richard Horne (who was the first Bishop of Winchester in the Post-Reformation period), important secular buildings such as the Chapter House and cloisters were also demolished. 1660 saw the end of the overall destruction due to the return to power of Charles II and the restoration of the church system.

Further rebuilding of the precinct did occur, in particular, the Dome alley around 1660, where houses were built on previously open gardens. This took forty years to compete and in comparison to the twenty years associated with building the cathedral, shows that the Chapter had limited resources following the civil war. In 1775 the Dean and Chapter passed a resolution that the cathedral should regularly undergo a professional inspection (Bussby, 1979: 193) and it is because of this that the cathedral was saved from severe damage in the early nineteenth century. The inspectors hired to perform these duties were James Essex (1775), William Garbett (1809), William Porend (1813), John Nash (1820) and Edward Blore (1820) who all agreed on the weakness of the building, especially in the south transept (Bussby, 1979: 193). Differing report systems were sometimes conflicting in their nature, with each having different views on the structural integrity of the building; in particular, Nash and Garbett wrote a series of conflicting reports about one another’s ideas, which must have been confusing for the Dean and Chapter. No view was supported by all parties until Edward Blore provided a full critique of the work carried out. In his report in the Cathedral’s Chronicle, he added his approval and disapproval of several modifications and suggestions; one such disapproval was the closing of the two east and west doors in the south nave and the introduction of the present central doorway. Blore also detested the introduction of the transept roof covering by Prebendary Nott in 1825 and commented that it was a “gross violation of good taste and propriety” (Bussby, 1979: 195).

In the eighteenth century, the cathedral was in a poor state. With the publishing of Reverend Milner’s work (5.2.1) (a visiting Catholic priest) came a renewed interest in the cathedral and repairs began. From 1809-1815 the architect of the time, William Garbett, published nine reports on the repairs completed. This included the renewal of two flying buttresses on the south presbytery aisle and the reworking of the vaulting in the retrochoir (Barrett, 1993: 320). In 1825 the transept ceiling was replaced and repair was completed of the nave piers (Barrett, 1993: 317-319). In addition to this, the west front was repaired in 1860. Between 1896 and 1898 the internal and external nave roof was restored with the addition of timber and lead that amounted to additional weight of 198 tonnes of oak, 326 tonnes of pitch pine, 40 tonnes of iron and 197.5 tonnes of lead (Bussby, 1979: 249). At the same time the nave vaulting was repaired as were the
choir roof, the east and west aisle roofs of the north transept and the great window of the west
front (Barrett, 1993: 325).

In 1841, with little income following the extensive repairs that were carried out on the west front
the year previously, a loss of manpower and poor finances led to the reduction in the number of
the clergy from twelve to five canons (Bussby, 1979: 230). With the canons reduced to five, some
of the precinct houses were not needed and a general tidy up of the precinct was conducted. The
building known as Ken’s House was knocked down and the deanery garden was extended, with
the boundary lines of Number 1 being redrawn. The Chapter House was cleared and made into a
lawn in front of Number 1, with the wall on the west side of the arches at the entrance of the
Chapter House removed (Bussby, 1979: 232). Furthermore, Number 11 was partly demolished
and partly added to Number 10.

4.2.17 The Twentieth-Century Underpinning

4.2.17.1 Engineering Advice

During the period between 1905 and 1912, the cathedral undertook a substantial remodelling
process to save itself from complete destruction following years of subsidence. The subsidence
had caused irregular settling arches in the interior of the southern retrochoir aisle as noted by
Sergeant in 1903 (30), writing before the 1905 underpinning programme (4.2.17.3), he offered an
insight into how prominent the subsidence was prior to renovation. On the south-eastern corner
the angle out of the perpendicular led to one of the vaulting shafts bending backwards and
cracking in half (Sergeant, 1903: 79). This subsidence is still evident in the retrochoir area and,
according to J.B. Colson, the cathedral architect in the 1890s, was leaning at an alarming rate,
most likely due to the flooding that occurred during the winter periods (Bussby, 1979: 257).

The engineering advice given by Francis Fox in 1905 was that the building should be shored up on
the outside; that the arch vaulting of the retrochoir be centred to avoid collapse; that steel tie-
rods be added where necessary; that the walls be grouted where necessary; and that the walls be
underpinned to the hard gravel (Bussby, 1979: 259). What was originally designed to incorporate
only one mason, two carpenters and five labourers ended up having over one hundred working
men at its peak, with forty-three workers being present in 1906 (Bussby, 1979: 259).

4.2.17.2 Geology

Local legend suggested that the structural problems with the cathedral were due to the
nineteenth-century mains drainage, with the system lowering the water table in the area. The real
reason related to the site’s location was the local geology of the area (Henderson and Crook,
1984: 13). In 1905 the foundations of the cathedral were thought to be at risk from collapse after T.G. Jackson and Francis Fox examined them and confirmed that the cathedral had been built on a bog and was subsiding (Henderson and Crook, 1984: 10). Questions may be asked as to why the original Old Minster and New Minster, as well as parts of the cathedral were not affected by these geological issues. Although the Old and New Minsters were removed, no reference can be found to any subsidence issues. To the east of these minsters, where the southeast part now rests, existed a marshy area with a layer of chalky marl and a layer of peat. This peat had a thickness of up to three feet before reaching the solid river gravel (Henderson and Crook, 1984: 14). When compared to the work completed by Champness et al. (2012: 27) at Pilgrim’s school to the south of the cathedral, a variation in depth of the strata can be seen.

The peat layer is the source of the problems associated with the cathedral and is found five metres below the surface of the nave but is deeper to the south and to the east (Henderson and Crook, 1984: 14). These structural problems were not new and it is noted by Henderson and Crook (1984: 31) that during the eighteenth and nineteenth centuries, the cathedral had severe subsidence issues prior to the 1905 renovation. The Dean and Chapter were informed in the late eighteenth-century that no work was required related to the filling of cracks, making good the masonry or replacing rotting timbers in the roof and the building was therefore left as it was.

The orientation of the cathedral (4.2.4) may have been an important factor in its development. The Old Minster was spared from demolition until the east end of the cathedral was completed with the west end overlying part of the west end of the Old Minster. The north transept was built in a way that would not encroach on the New Minster (Henderson and Crook, 1984: 17) (4.2.4). The problems associated with the cathedral were not so much related to its original construction. They were instead based on the choices made by the Normans in preserving the Saxon minsters until the cathedral was fully built. If the Old and New Minsters had been demolished in the first instance then the cathedral could have been placed on a different orientation, in a larger and more open space, possibly avoiding the subsidence issues that now prevail. The subsidence that is evident in the surrounding precinct buildings shows, however, that these issues are not limited to the cathedral. Relocation could have still affected the cathedral, as some of the buildings, such as No 10, are still descending. It is unknown how greatly this would have affected the structural integrity of the building and this could be examined through a system of differing foundation supports and stresses in structural analysis testing.

As described by T.G. Jackson, the Norman builders dug to the water level, removed the soil and peat and placed a layer of loose flints and chalk until they were above the water level. A rubble masonry mortar layer was then placed for the beginnings of the foundation with some areas
further supported by short upright piles of oak that were about two to three feet in length (Henderson and Crook, 1984: 21). It must be noted that the peat layer, which is a layer of hard mass of vegetable matter in the first stages of conversion into coal, is not weak and successfully supported the cathedral for over 850 years due to its compressive material properties. The peat layer is extremely strong (if it remains undried), as shown in Francis Fox’s tests where he compressed the peat under seven tonnes per square foot pressure. The change in height was only one tenth of an inch (2.54mm) (Henderson and Crook, 1984: 23).

It has been found that the gravel layer is deeper to the west of the south transept and south-east of the original east end (Henderson and Crook, 1984: 21). As the cathedral is not positioned on these areas, it has not caused further problems for the cathedral. Nonetheless, areas such as the Dean’s house, with a seventeenth-century extension, are now under serious strain from numerous points of subsidence. The cathedral foundations are made of flint and rubble in mortar as can still be seen in the crypt below the Lady Chapel. This flint and rubble mortar was known for its strength and was used for the walls of the cathedral, with the Quarr stone being facing only. This suggests that the building is extremely strong, which is fortunate, as the subsidence could have completely torn apart a weaker structure.

It has been noted by Henderson and Crook (1984: 26) that de Lucy’s extension was originally seen as repair working. With the east end rebuilt and extended, the original foundations were extended onto the peat area. The gravel for this area is a foot lower and there is evidence of continued subsidence in the exterior of the Lady Chapel because of this. As the gravel layer was a foot lower, the builders at the time could not dig to it. Struggling to reach the peat, the builders instead used a double layer of massive beech logs as a base in the bottom of their trenches at right angles to the wall (Henderson and Crook, 1984: 26). The peat level being five foot thick (1.5m) in this area was subject to a greater compression as elsewhere the geological layer is thinner. It is because of this and because of the rotting wood that the subsidence of this magnitude exists.

4.2.17.3 Underpinning and Modification

Although the structural problems of the cathedral are mostly evident at the east end, other areas are also at risk. Some of this was seen in 1895 when the nave roof caused significant problems. J.N. and J.A. Barry surveyed the roof and found that the feet and roof rafters were spreading and bearing down on the nave vault. This was corrected by J.B. Colson who raised the tie-beams by lifting the trusses (Henderson and Crook, 1984: 34) (4.2.14). The crypt was also under serious strain at this time and the vaulting within was collapsing, as shown in the brick supports currently found in the crypt.
In 1905 both the exterior and interior of the stonework throughout was a mass of cracks with some being minor and some being serious structural faults. This combined with walls that leaned at alarming angles and vaulting in the retrochoir being seriously deformed (Henderson and Crook, 1984: 1905), led to the cathedral being in a state of decay and near to destruction. The retrochoir was a significant part of the structural decay and its buttresses were not on solid foundations and were acting as an extra weight, adding to the subsidence (Henderson and Crook, 1984: 38). In order to understand the problems that the subsidence was causing to the cathedral, excavation work was carried out next to a buttress on the south of the retrochoir. This was dug to about sixteen feet (4.8 m) to the gravel layer and it was decided by the 1905 investigators that an underpinning of the building was needed (Henderson and Crook, 1984: 45). With the walls leaning at precarious angles, tie rods were needed across the south wall of the retrochoir to the north side to avoid further movement.

The underpinning of the cathedral was mostly completed by William Walker who was a diver trained at Portsmouth Docks and worked for Sieve Gorman, a British company that developed diving equipment. Walker was directed by his company, along with a reserve diver, to help the cathedral in the restoration work. This was completed by a series of “dives” underneath the foundations and water level. The process included digging trenches under predefined parts of the cathedral and for Walker to remove remaining peat and rotted wood until the gravel layer was reached. Dry cement bags were placed on top of the gravel and a grout machine was used to fill in the gaps between the bags. The bags were opened to allow the ground water to solidify the cement. The excess water was pumped out to allow bricks to be laid on the cement with cement blocks added to act as a further base. This was finished with hard bricks at the top of the original footings (Henderson and Crook, 1984: 69). As the cathedral was still in use, and because the foundations were being removed, the underpinning section by section took seven years to complete. Large scaffolding poles and supports were used whilst this took place. It meant that the archaeology of the surrounding area was affected by having large concrete blocks set in the ground to support lateral forces as seen in Figure 85. Although the locations of the these blocks are unknown, there is documentary evidence that shows that some of them were located in the area of the Chapter House (Henderson and Crook, 1984: 86).
Every section of wall that was to be underpinned also had to be grouted from the ground level upwards by injecting liquid cement into the cracks using compressed air (Henderson and Crook, 1984: 46). Injecting the grouting into the walls rather than covering the surface provided more structural integrity. A total of twenty-five tonnes of grout was introduced into the north-west corner of the north transept alone (Henderson and Crook, 1984: 100). In the Lady Chapel crypt the subsiding column was removed, the foundations were extended to the gravel layer with cement poured on top of it for a more secure base, and the column was replaced on the firmer foundation (Henderson and Crook, 1984: 69). The underpinning, as well as using concrete, utilised Portland stone for the cracks in the transepts and the eastern arm of the cathedral. The major repairs of the east end were created out of Doulting stone (Tatton-Brown, 1993: 44).

4.2.17.4 The Addition of Supports

The cloisters originally supported the south wall of the nave. All that was left after their removal by Bishop Horne was the Norman flat buttresses. As the underpinning process had cost a considerable amount, the decision was made in 1911 to add new buttresses to act as support mechanisms rather than to underpin the entire south wall. Figure 86 represents the exterior of the cathedral in 1880 prior to the addition of these buttresses and shows that the Norman buttresses terminate at the parapet level.
Two choices of buttresses were discussed by the architects and engineers, that of the eventually chosen flying buttress made of Weldon stone and a single substantial buttress directly against the wall of each pier (Henderson and Crook, 1984: 103). The flying buttresses, along with their opposite south wall counterparts, were underpinned to secure their arrangement in the same fashion as the rest of the building. Partially securing these sections helped reduce costs and provided structural support to the south nave wall. The choice of flying buttresses must be examined however to see if these were the best option as the single buttress design against each pier could have been sufficient. The testing of these buttresses have also be used in conjunction with the remodelling of the cloisters to examine how their removal would affect the overall structural form of the nave.

Figure 86. Winchester cathedral exterior on the south side of the nave in the 1880s (Cobb, 1981: 132). Photographer unknown.

4.3 Recording Winchester Cathedral

Laser scanning as seen (B.1) is a viable option for recording the majority of Winchester Cathedral and the surrounding buildings; the technique provides a high-resolution dataset to work from and reduces the time-spent recording the complicated architectural features found. This is completed at a faster rate and higher quality record than standard total station survey. The data produced using this method allow for a more precise analysis and feature detections that can be used within structural analysis as all aspects can be incorporated within the testing, rather than selected areas of interest. The scanning (Figure 87) took place over subsequent field seasons between 2013 and 2014 with two different scanning techniques used for the cathedral building; phase scanning through a Faro Focus 3D x130 and x330; and time-of-flight through a Leica
Scanstation 2. The Leica system used was outdated when capturing occurred, providing a slower rate of capture but was the only method available.

Figure 87. A Leica Scanstation 2 scan position within the cathedral

The recording methodology was adapted from B.1, with alterations made to the way in which the point spacings were calculated. Rather than selecting a vertical plane on which point distances were calculated, the horizontal plane was used. This allowed the ceilings to act as the furthest point on which the calculations for the point spacings were based. This meant that all areas that were shorter in distance to the ceiling had a greater number of points.

Each scan was taken in roughly equal distances to allow for a generic overlap in data and colour, with the interior shell seen in Figure 88. Parts of the cathedral, such as the library, were overlooked within the initial scanning due to building work. These areas, including the roof and other external areas, were subsequently collected in collaboration with Russell Geomatics (2014) through the use of a Faro Focus x330. The quicker data collection and small size of scanner were easier to use in the roof spaces that are difficult to access, with a number of scan positions needed to capture the individual timbers. Rather than use the Scanstation, the exterior of the
cathedral was captured with the Faro. With the updated x330, further scanning distances could be captured through the updated laser system. The time taken to complete the interior scans was six days, with the exterior and roof taking three. These were processed and stitched via targets to allow for a faster processing time. The data have been edited to remove all aspects of the captured movement of people and what remains is a detailed record of the interior of the cathedral from 2012.

Photogrammetry (B.2) of the external east end of the cathedral was completed in 1999 as part of a survey completed by Gifford Survey. The process involved an earlier format of photogrammetry that utilised stereo photographs rather than the currently used structure from motion (B.2). Rather than provide visually pleasing results, the method allows for the drawing of three-dimensional measurements based on two photographs from known positions. The method was seen as an alternative to total station building surveying with the results produced being comparable. The virtual replica that is created is line based and has to be digitised as a solid model to create the necessary CAD data for structural tests.
The method is used within this research as a way to highlight the differences between the two photogrammetric approaches. The results will not be used for structural testing but rather will be utilised for comparison only. The files that were provided from the cathedral were unreferenced, and work had to be completed to fix the spatial positioning inherent to create the three-dimensional model, which can be seen in Figure 89.

![Photogrammetric model of the east end of Winchester Cathedral based on stereo photographs](image)

**Figure 89.** Photogrammetric model of the east end of Winchester Cathedral based on stereo photographs

The crypt of the cathedral was recorded via a total station survey as part of Natalie Sweda’s (2013) Masters dissertation. The focus of her work was on the application of building survey (B.3) within archaeology and I was involved in the data capture process. The results provided are of a CAD drawing and show only outlines of the features present. Although limited in detail, it provides an overview of the depth of the crypt and identified the Norman remains. A building survey was also completed in 2010 of the rooms above the Lady Chapel area (Figure 52 I) as part of my Master’s research and has been used as part of the overall record of the cathedral. A combination of different survey methods has been used in the digitisation of the cathedral. These include the most up-to-date survey of the building possible and all aspects have been included in the structural analysis tests performed.

### 4.3.1.1 Other Recording Methods

Electrical Resistance Tomography (ERT), which was completed on sections of the exterior and interior walls of the cathedral as part of the Parnassus Project, will be included within this thesis. ERT, which is similar to resistivity (B.4.1), through the passing of an electrical current through the earth, takes a series of measurement at increased probe spacing intervals to build a profile of the changing material below the surface of the ground. These measure the varying apparent resistivity in ohm-metres (Ωm) and enable the detection of localised anomalies and features at increased depths. These are normally conducted on large landscapes, but were miniaturised and
attached to the walls of the building. Through the addition of water moisture, the varying depths between the probes could be measured. This created a series of profiles that allowed for the thickness of the wall to be calculated. This thickness variation is of importance in understanding the structural form of the building, with large gaps being present in the data. ERT was recorded via an Allied Associates Tigre 64-probe resistivity system (Allied Associates, 2006) with the probes placed at 5 centimetre positions. Measurements were then taken using an expanding Wenner array (Morris et al., 1996), with readings taken with the probes at differing intervals. This allowed for a full profile according to the length and depth required and the results can be seen in Figure 90 and Figure 91.

Figure 90. ERT results from Winchester Cathedral showing a variation in depth of an external and internal wall (D’Ayala et al., 2017: 135). The recording took place south of Figure 52 L, with the interior readings captured in the crypt
A number of other methods could have been employed within the research, such as computed tomography (B.5) scans of individual stones to identify internal structural faults, similar to Liu et al.’s (2007) work on subsurface crack propagation; as well as RTI which could have been used to identify subtle scarring on extant building work. Due to a lack of funding and time allowed on site, as well with the amount of technology already used within the research, it was decided not to incorporate these within the work. Rather, they will be discussed in 7.2.2, which examines future applications in structural analysis.

4.4 Research Questions Surrounding Winchester Cathedral

The research questions outlined throughout the text provide some form of investigation into how structural analysis can be applied to archaeological critique. One of the main aims of the research is to test the reliability of structural analysis by simulating known decay. Comparing modelled deformation to genuine decay creates validation of the technique and if correctly simulated provides a confirmation that Finite Element Modelling is suitable in predicating structural results for use within virtual reconstructions of unknown parts. The majority of the original cathedral can be identified through the architectural investigation above but there are a number of
uncertainties; the cathedral was modelled in its current form without any structural faults and tests have been performed to simulate the damages seen in the building work through subsidence. The results will be discussed in Chapter Six but should simulate the current condition of the cathedral. This will prove that the method is capable of providing results that can be used for purely virtual models.

There are a number of research questions about the cathedral using the data collected, which are listed below.

- How have the modifications over time affected the structural integrity of the cathedral?
- What led to the collapse of the Romanesque central tower?
- Could the original Romanesque cathedral have supported all of the towers proposed?
- Do the remodelled nave piers affect the structural integrity of the building?
- How have the addition of the gothic vaulted ceilings in the nave affected the building?
- Are the additions of the early twentieth-century flying buttresses on the south exterior nave wall supporting the cathedral? If so, could the second option of buttress have been chosen as an alternative?
- Would the cloisters have provided enough structural support to the cathedral if they still existed?
- How have the changes in roofing style affected the building?
- Can structural analysis be used to correctly emulate known structural decay?

Each of these questions provides a greater understanding of the cathedral, as well providing evidence of how structural analysis can play a part within archaeological research.

### 4.5 Conclusion

This chapter has shown the varied amount of work that has taken place at Winchester Cathedral. It has provided information with regard to the city’s Roman origins, its Saxon redevelopment, and the churches’ subsequent rebuild and renovation since the Norman period. Rather than discuss all of the work that has taken place since the cathedral was built, it has instead offered insights into the major developments that have occurred. The work completed by Walkelin, de Lucy, Edington, Wykeham and Fox greatly changed the visual appearance of the cathedral, but it is unknown how these changes affected the structural integrity of the building. With the deterioration of the cathedral and the surrounding precinct buildings, the cathedral fell into a state of disrepair that nearly led to its total destruction. The cathedral still needs to be structurally examined.
Analyses will be performed and discussed in Chapter Six that relate to the questions asked within this chapter, and will be created based on the material provided within Chapter Three. A focus has been the limited knowledge about the precinct buildings and structural analysis will be utilised to create a firmer basis on which reconstructions can be generated. The interpretation of the evidence provided is conjectural in its nature and further research has been carried out in relation to the buildings that are under investigation within the research, and is discussed in detail in the next chapter.

The following chapter will provide a continued discussion of the architectural developments within the precinct. It will introduce the survey methods used on site in greater detail and will follow the explanations provided in Appendix B, which outlines the differing survey methods available. Chapter Five is a continuation of Chapter Four, and specific research questions have been assigned to each of the buildings under investigation.
Chapter 5: Winchester Cathedral Precinct

5.1 Introduction

Chapter Four provided a detailed review of the archaeological research that has been completed on Winchester Cathedral church. Chapter Five continues this with an assessment of the archaeological research of the cathedral precinct. The space that surrounds the cathedral is known as the precinct and consists of an Inner and Outer Close, but can incorporate further monastic land that falls outside of these “defined” spaces. The purpose of this chapter is to provide contextual information in relation to the buildings that are used as case studies within the thesis. Archaeological assessments of each building will be provided and the surveys carried out on site will be discussed.

The chapter beings within an overview of the conjectural nature of the cathedral precinct and the buildings contained within it. A number of buildings will be discussed and include Numbers 10 and 10a; the Pilgrim Range; the Stables; and the Chapter House. Also evaluated are those structures and features that have been removed and demolished and will include the Cloisters, the Refectory and the Lavatorium. The overall geophysical results of the precinct will also be discussed and highlight areas of interest that relate to the buildings under investigation.

5.2 The Cathedral Precinct

5.2.1 The Layout of the Precinct

The history of the precinct can be divided into two phases. The first relates to the six hundred years as a precinct for the Benedictine community. The second to the period after the dissolution of the monastery by Henry VIII. The precinct, for its first six hundred years, contained an Outer Close, found on the north part of the cathedral, and an Inner Close, found on the south. These have since been expanded to incorporate further building work. The Inner Close was associated with the internal workings of the Benedictine community that served the church and it was the private area for its brethren. Within the research carried out, the focus of attention has been on this Inner Close, due to the number of different monastic buildings that were once situated in this space; its layout however is conjectural. Although some buildings are still in use today, there is evidence of other buildings that once stood here. A great deal of the current understanding of the building incorporated within the Inner Close is based on the medieval Lockbourne system (5.2.4).
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that acted as a drainage system for the precinct, and the accounts of a visiting Roman Catholic priest, John Milner, who produced the cathedral’s first authoritative descriptive history in 1808.

The Inner Close was presumably one of the finest and most extensive that existed in England when it was first constructed due to the level of detail in the surviving features found. The dates of the buildings are however unknown and even less is known of their structural history. The earliest record dates to 1124: there are mentions of the cloister, refectory, dormitory, infirmary and Chapter House for the year 1124 in the Winchester annal of 1128 (Barlow and Biddle, 1976: 310). The annals suggest that the building work took place during and most likely just after the time at which the cathedral was completed. As Walkelin died five years after the consecration of the church, with the building work of the cathedral not completed, the buildings of the Inner Close were presumably started by him but continued by Bishop Giffard.

The precinct was and is still surrounded by a high wall, which marks the limits of the old Benedictine monastery and the buildings that are now contained within it. From excavation carried out by Champness et al. (2012) it is evident that the surrounding walls formed the basis of the original layout of the precinct. There is nothing to suggest that the precinct spread any further beyond this. Figure 92 to Figure 94 show the extensive changes that were made to the ecclesiastical landscape from 963 AD through to 1148 AD, but the boundary wall remained constant.
Figure 92. Conjectural plan of Winchester between 963-1066 AD (Barlow and Biddle, 1976: 328).
Reproduced by kind permission of Oxford University Press, [www.oup.com](http://www.oup.com).
Figure 93. Conjectural plan of Winchester in 1110 AD (Barlow and Biddle, 1976: 328). Reproduced by kind permission of Oxford University Press, www.oup.com.
The buildings in the precinct would have been greatly affected by documented fires. The movement of the New Minster to Hyde in 1110 AD (4.2.2.2) allowed for the land north of the cathedral to be acquired, extending the precinct for use as a town cemetery (Barlow and Biddle, 1976: 312). Winchester, being a major Royal centre, also had a palace (4.2.2.4) close to the cathedral to allow for easy access to the cathedral for the King. This palace was immediately west of the Old Minster, east of Little Minster Street and south of the New Minster cemetery (Barlow and Biddle, 1976: 289). James (2006: 76) attributed the destruction of this royal palace to a fire in 1141 during the civil war between Matilda and Stephen over the rights to the crown. It was subsequently torn down by Henry de Blois who then used the area for his own property and included it within the overall Outer Close (Barlow and Biddle, 1976: 299). This was then cleared in its entirety and the area was converted to an open space that has since been used as cemetery. Other fires have also been recorded on site and have played an important role in removing the archaeological record and unless excavation is conducted in the area, the majority of interpretations of the size, shape, material and exact location of these buildings are conjectural.
There would have been three types of visitor to the precinct: the first would have been higher
gentry who were attended to by those working in the priory guest house; the second would have
been other monks or those from families other than royalty who would have been attended to by
the cellarer’s department; the third were pilgrims who were attended to in the Pilgrim Hall. This
created a further separation within the Precinct and these different visitors need to be examined
in order to understand the layout of the buildings on site. How they moved around without
entering restricted areas, such as the Chapter House, needs to be considered, as does their
lodgings. Understanding this separation will allow for a further awareness of locating individual
buildings. Although the landscape has changed greatly since the Norman construction, the outline
of the precinct has not. This therefore allows for only a limited number of places where these
buildings were situated, with many most likely being in the locations of the present day trees,
roads and grassed areas. To understand more and to help with understanding where each
building was located, a large geophysical survey was conducted within this research (5.9). This will
form the basis on which a more reliable reconstruction and plan can be created.

5.2.2 Plans of the Precinct

Understanding the layout of the precinct is extremely hard. Although conjectural plans do exist,
an example of which can be seen in Figure 95, none of these can be relied upon, as discussed in
5.2.3. When comparing the site to others around England, the precinct had to have contained
 certain buildings in order to function. From on-site inspection and from documentary evidence,
 the domestic buildings were organised around two cloisters. The first was the great cloister (Inner
 Close) which was bordered by the Chapter House, the dorter, the refectory and the cellarer’s
 range; this area acted as the main cloister for the precinct until its destruction by Bishop Horne
 after the dissolution of the monasteries (Crook, 2009: 6). The second cloister (south range), as
 suggested by Crook (2009: 6), was smaller and was attached south of the refectory, to the west of
 the Prior’s house, and to the north of the infirmary and chapel. Although Crook suggested this
 smaller cloister, its inclusion remains unproven.
The earliest and most reliable visual representation of Winchester is found in Speed’s 1611 map (Figure 96) of Hampshire, which includes an inset of Winchester. In this early representation, streets, houses, the cathedral and the river course can be seen. Although the most reliable early representation of the city it contains many errors and a more precise illustration can be seen in Gosdon’s 1750 map which was the first accurately measured plan (Figure 97) (Keene, 1985: 34). Other maps show the changing layout of the cathedral precinct, such as the military maps of 1776 and 1778; Thomas Milner’s 1791 smaller reproduction of Godson’s 1750 map (Figure 98); and R.C Gale’s Tithe maps and the Ordnance Survey map of 1895 (Figure 99) provide a comparison between the physical boundaries and measurements recorded in deeds and property plans (Keene, 1985: 35). Of importance, however, is the 1649 parliamentary survey which gave an overview of the cathedral precinct and its properties, providing a list of different rooms, the nature of their structure and the repairs that were needed (Keene, 1985: 34). This description allows for some understanding of the site as it was at the end of the Civil War.
Figure 96. Speed’s Map of 1611 (Norgate and Norgate, 2003b). Reproduced with permission of Jean and Martin Norgate.
Figure 97. Godson’s 1750 map (Atkinson, 1932: Plate III). Reproduced with permission of Friends of Winchester Cathedral.
Figure 98. Thomas Milner’s 1791 map of Hampshire showing the area around Winchester (Norgate and Norgate, 2003a). Reproduced with permission of Jean and Martin Norgate.

Figure 99. 1895 Ordnance Survey Map of Winchester (National Library of Scotland, 2014). Reproduced with the permission of the National Library of Scotland, www.nls.uk.
5.2.3 The Inner Close

An extensive architectural history and evaluation of the individual buildings within the Inner Close is discussed below. The buildings that survive have been analysed by John Crook but little documentary evidence survives to complement his research. The possible arrangement of the original Benedictine precinct can be seen in Figure 100, based on limited excavation data and comparisons to other cloisters that have since been rebuilt on Norman originals, such as Gloucester, Norwich and Lincoln. The form of these buildings would have conformed to the Benedictine plan discussed above (5.2.2), with a central cloister and surrounding buildings including the bursary, bakers, brewery, laundry, dormitory, infirmity, scriptorium, library and workshops (Kitchin, 1940: 8). Changes to the landscape of the precinct can be seen in Figure 101 and Figure 102. Figure 103 provides an overview of the buildings that are discussed in the following sections.
Figure 100. Conjectural plan of Winchester cathedral precinct (Kitchin, 1940: 9). Reproduced with permission of Friends of Winchester Cathedral.
Figure 101. Conjectural plan of Winchester Cathedral precinct in the first half of the 17th century based on the 1649 parliamentary survey (Crook, 1984: viii). Reproduced with permission of the Hampshire Record Office for Hampshire County Council.
Figure 102. Updated plan of the cathedral and the precinct c.1914. Outlines of the buildings are more clear, especially the east section of the Chapter House (Vaughan, 1914: 165)

The maps shown above provide the only real evidence of the layout of the cathedral precinct. Very few of its buildings have been visually documented because artists of the late eighteenth and early nineteenth centuries were attracted more to the cathedral and college (Keene, 1985: 35). Little of the tenement history can be utilised due to the maps’ topographical omissions and the cathedral records offer very little information. Furthermore, the landscape surrounding the cathedral just after the Norman invasion is problematical to understand, as no record exists until the 1110 AD Winton Domesday survey as studied by Barlow and Biddle (1976). Understanding the
archaeological record therefore becomes more challenging and is important for reconstructing the original ecclesiastical buildings in the precinct.

5.2.4 The Lockbourne System

King Æthelwold in 970 created a fresh running water system, now known as the Lockbourne system, to the monastic buildings for sanitary purposes (Vaughan, 1914). This system ran from Colebrooke Street (east of the Cathedral) through the reredorter (communal latrine) found in the Inner Close, and onwards past the area that now houses the college to the south of the city (Barlow and Biddle, 1976: 284). In more detail, the Lockbourne system drew its supply from the river above the city and passed to the east of the cathedral turning west to run under the Chapter House. It crossed the cloister garth and passed under the range of buildings on the west side, later turning south to join the river again (Atkinson, 1932: 15). In the tenth century, this would have been in the form of an open ditch but with the inclusion of this system running underneath the Chapter House, it was converted to form a culvert (Atkinson, 1932: 15). In areas where this is accessible, the masonry appears to be of Norman construction, similar to Gloucester cathedral and its water supply. Although the Lockbourne system still exists, the majority of the known channel is speculative and is based on small excavations around the precinct. Many of the conjectural building plans have been based on this.

5.2.5 Recording the Precinct

Laser scanning (B.1) and photogrammetry (B.2) have been used within the cathedral documentation; the same methods are applied to the precinct. Laser scanning provides a high resolution model from which to work from but is expensive to use and operate. Photogrammetry is a cheaper alternative and is used in the recording process of the precinct to test its application within a structural analysis context. Although laser scanning and photogrammetry have been carried out on site, there was a need to use the standard method of recording within building surveying with a total station. The method offers limited data in comparison to the two three-dimensional counterparts, as the recording process is dependent on the operator; only necessary features for structural modelling were recorded. The method is limited but the basic CAD models that are created using this method provide the necessary information required for structural testing and comparisons can be made between the different datasets. The combination of these three methods allow for the precinct to be documented in a short period whereby elevation drawings, contours, external plans and sections, angles of deformation and drawings can be created, as well the necessary structural models.
The thesis also aims to identify and examine the buildings that once stood in the precinct. Evidence of these building locations is limited and a geophysical survey was conducted to identify these features. The results, in conjunction with known documentary data; the architectural survey of the precinct; and comparisons with ten other cathedrals across the country which have been visited and studied, allow different hypothetical forms to be modelled. The geophysical survey forms the basis for these models, with each being tested for its structural validity.

5.3 The Cloisters Garth

5.3.1 Assessment of the Cloisters

The cloisters (Figure 103 A) were once part of the original Norman cathedral and were located on the south side of the cathedral’s nave. The buildings were pulled down at the same time as the Chapter House and very little is known of the original construction. The only report that deals with its architectural features comes from Milner (1798: 93) who reported that the south cloister wall was four feet thick and had several circular arches (recording prior to the building being covered). These were half of the depth of the wall at two feet wide with one wide arch in the centre. This design is similar to the blind arcading seen at the Chapter House (Figure 158) and is suggestive, as with evidence seen in the cathedral (Figure 104), that the same style was used throughout during the original construction.

![Figure 104. A small chapel attached to the north transept of Winchester Cathedral with original Norman construction comparable in design to that found within the Chapter House](image-url)
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The location of the cloisters is known through general comparisons with other Benedictine cathedrals and ideas have been suggested by Crook (2013) of its exact size. There is evidence of the doorway of Number 10 (Figure 103 E) and the doorway at the side of the deanery (Figure 103 D) being perfectly aligned. Crook (2009: 6) commented that these were originally connected to the cloister passageway at the end of the main cloister. This is further supported by Godson’s 1750 plan where the rectilinear outline follows the position of the two doorways. Figure 105 shows the view from Number 10 and Figure 106 shows the same view from the Deanery doorway.

![Figure 105. View from Number 10 doorway](image-url)
As the wall of Number 10 has been rebuilt (5.4.1), there is little except for a doorway that could be used to support this proposal by Crook. Supporting evidence can be found in the scarring above and next to the Deanery door, as shown in Figure 107. In this image, there is a separation in the form, marking out two separate buildings. These data can be used in relation to the survey results and give a potential height value of the cloisters through the stringcourse.
It is unclear how the overall building work was modified. The suggestion by Crook of this being the southernmost part of the cloister is plausible, particularly with test excavation pits for drainage showing some masonry elements that do align. It is unclear if these relate to the cloister or other monastic buildings.

The stringcourse mentioned can be seen in the phased drawing by Crook (Figure 108) further north of this doorway. In this image, Crook suggested that there were also two different heights within the cloisters; one general pattern found throughout and one specific to the increased height of the Chapter House. The idea of the height for the surrounding area is based on the scarring that is found on the south wall of the cathedral and the west wall of the south transept. Figure 109 shows a clear continuous line that is evident throughout this section. This is not found anywhere else within the building. The height for these scars is not enough to be the full height of the cloisters but rather is suggestive that they acted as support mechanisms for the roof.
Figure 108. East cloister wall showing phased detail. The height of the cloister roof stringcourse can be seen at the top. Reproduced with permission of John Crook.

Figure 109. Scarring on the South wall of the Winchester Cathedral

The full height of the cloisters in this area can be seen in the doorways that have since been closed and sealed on the east section of the south nave wall (Figure 110). As these were the main access points to the cathedral for the monks, the roof of the cloister had to be at the level of the tops of the doorways. Figure 110 shows that the scarring found on the surrounding walls are halfway between the floor and the door tops, suggesting an angled roof support, as shown in Figure 111. The image produced by Crook highlights the differences in heights in the cloister and this could be tested by structural analysis to establish how feasible Crook’s interpretation was.
Figure 110. East entrance from the cloister to the south aisle of the cathedral

Figure 111. Hypothetical form of the cloister. Reproduced with permission of John Crook.

Although the roofing style suggested by Crook in Figure 111 is conceivable, the angle shown is dependent on the width of the cloisters. A width of 4.6 metres has been suggested by Crook and this has been reviewed through the geophysical survey completed on site. Any variation...
of this width will greatly affect the angle of the roof support and will affect the structural integrity of the building work.

5.3.2 Research Questions Surrounding the Cloisters

The following research questions are based on the virtual modelling of the cloisters.

- What was the original form of the cloisters?
- What roofing types were possible?
- Were different heights possible?

5.4 Number 10 and Number 10a

5.4.1 Assessment of Number 10

Number 10 (Figure 103 F) is a Grade I listed building that has an eighteenth-and nineteenth-century façade (as shown in Figure 112) with medieval internal features. The earliest part of the building is a vaulted undercroft dating to the first half of the thirteenth century, often referred to as the house of the Hordarian (Crook, 2009: 3). Number 10a (Figure 103 G) which is connected to Number 10 (as shown in Figure 113), similarly once contained a vaulted undercroft and was most likely used as a hall area above the priory kitchen for the refectory. These buildings were separate until they were combined in the eighteenth-century when additional floors were added. At the same time Number 10 was reroofed and the east-west wing of Number 10a was reconstructed (Crook, 2009: 3). The location of the buildings, following traditional Benedictine rules, indicates that these buildings were most likely used as a cellarage for storage of food and wine. Kitchin (281) noted in 1892 that the Hordarian’s house and kitchen were situated next to one another. With Number 10 and 10a being the only suitable option, it is sensible to assign these roles to their function. This is supported with the understanding of the surrounding buildings, as the Hordarian would have overseen the purchasing of food and its preparation in the monastic kitchens. This would have required access to the refectory, as is the case at Norwich and Ely. The refectory is known to have been east of Number 10 and so both buildings fit within the idea proposed.
The building is one of the most important survivals of monastic architecture that remains in the precinct following the episcopacy of Bishop Horne and the general decay during the Civil War. Regrettably the 1649 parliamentary survey offers little, except that it was “well timbered”, in contrast to the Lincoln and Gloucester surveys (Crook, 1984: 101). From architectural surveying, 10 and 10a appear to have been constructed at the same time due to the masonry found in Number 10a, as shown in Figure 114. The internal sections of the buildings have been greatly
altered with a complete refurbishment taking place in 1804 (Crook, 2009: 23). The only surviving original features can be seen on the west exterior wall and parts of the southern wall connecting the building to number 9. Number 10 now acts as private housing and 10a incorporates the education centre for the cathedral. Number 10, like the cathedral, suffers from subsidence with a central pillar in the undercroft sinking, causing significant damage to the building. The majority of reworking follows stylistic changes but includes the addition of structural supports. General deterioration and modifications have left the building unrecognisable from its first construction. The original construction would have consisted of two storeys. The first floor, which has thirteenth-century remains (window scarring), would have formed an upper hall or chamber above the undercroft. The present second floor dates to the fifteenth-century (when the roof was raised) and would originally have been an open space rising to the timber roof (Crook, 2009: 13).

Figure 114. Surviving vaulting shaft in Number 10a that dates to the same period as Number 10

5.4.1.1 Undercroft

The undercroft that now remains in Number 10 was originally divided into three bays, each 3.75 metres long with two equal aisles with a total internal width of 7.5 metres. It has a quadripartite
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vault with chamfered ribs and plain cruciform keystones and was supported by three central pillars (Crook, 2009: 9). Due to the subsidence, the continuation of the vaulted undercroft has since been removed and modified via the introduction of a fireplace that replaced the northern most pillar (Figure 115).

Figure 115. Number 10’s fireplace replacing the original column (facing north-west)

The supporting pillars that remain are formed of coarse masonry that sit on moulded bases and have moulded capitals. The bases are now mostly hidden below modern flooring, as shown in Figure 116.
As shown in Figure 116 the vaulted structure is further supported by semi-circular responds that can be found against the east, south and west walls. Each of these responds has a moulded base above ground level (Crook, 2009: 9). The responds point show that the construction of the pillars coincided with the vaulting. Their presence suggests some form of structural importance within the building and this could be tested to identify whether the building would have been stable if only a corbel had been moulded.
Figure 117. Semi-circular responds found in Number 10’s west wall. The walls also appear to be leaning at an alarming angle.

The east wall of Number 10 was rebuilt in the eighteenth century and is now of a thicker construction to support the deformation of the building (Crook, 2009: 3) as shown in Figure 117. The deformation is of vital importance to the understanding of this building as it has greatly affected its structural integrity. Structural evidence alone, through the different heights of the responds and pillars, suggests varied areas of weakness, mostly constrained next to the central pillar through the flattening profiles of the rib vaults. “Cracks in these ribs were evident in 2004 and were covered, only to be exposed again at a later point” (Crook, 2009: 11). This suggests that the subsidence remains a continuous issue that has not been resolved with the later modifications. Modifications can be seen in the northernmost part of the vaulted area that had collapsed and was replaced by a wooden arch-braced timber which dates to 1392 (Crook, 2009: 11). The modification after only 140 years shows that deformation in the area was already occurring and hints towards further possible changes that have gone unnoticed. The bay in which
this arch brace is located is four metres wide in length, twenty five centimetres more than the others, and the truss has subsided on the north by 240 millimetres as shown in Figure 118.

Figure 118. Longitudinal section of Number 10 looking west showing the deformation of the building (Crook, 2009: 10). Reproduced with permission of John Crook.

It would be interesting to identify from the original construction how the subsidence of the main central pillar affected the building. If the introduction of the brace had not occurred, would the building still be standing? Furthermore, with the removal of the vault and the introduction of a chimneystack, formed of solid masonry, how much does this add to the support of the vaults? Was this simply used a decorative feature for the room or was it purposely added to create some form of structural resistance?

It is unlikely that the deformation is a result of poor foundations as suggested by Crook (2009: 10), but rather is a result of the local geology. Stratigraphy from excavation shows a chalky loam top section, above six metres of fen peat over the valley gravels (Crook, 2009: 10). As discussed in (4.2.17.2) the variation of this peat layer across the precinct affected what levels of hard gravel could be reached. The original builders, as is found in the east end of the cathedral, would not have been able to reach the original gravel, as this would have been below the thirteenth-century water table. The peat layer is known to be strong in compression (4.2.17.3) and if the foundations were placed on this, it suggests that the change in geology caused the deformation. The foundations would still have been strong enough to support the building, but if the area below
The central pillar has changed in height, that would explain how and why the deformation is localised to specific areas of the building. Importantly, within the excavation completed in 2003 (Crook, 2009: 6), it was found that Quarr limestone was used as a footing for the original wall of Number 10 (Crook, 2009: 6) and is indicative of the other buildings in the precinct. This suggests that the original wall would have been structurally strong as is the case with the cathedral.

5.4.1.2 Exterior

The exterior of Number 10 contains scars from the original construction and much detail can be gathered to formulate an idea around the first constructed phase. From the exterior sections in the courtyard between Number 10 and 10a (Figure 119), the chamfer stops of the doorway identify the original floor level and shows that floor of the undercroft remains at a similar level to when it was constructed.

![Figure 119. Entrance to Number 10 from the external courtyard](image)

5.4.1.2.1 South Wall

The window seen on the exterior section (Figure 120) shows reworking with the six-bay rectangular windows dating to the sixteenth-century (Vaughan, 1914). Above these windows are the remains of a previous window that would have once extended downwards towards the lower part of the newer window, as seen in the conjectural drawing shown in Figure 121. Figure 120 also indicates several lines within the façade that show the original roofline had a 22.5° angle
pitch, with the areas above the flint appearing to be worked in an uneven way, suggesting a
different construction phase. One important part of the research for this building is the
identification of how the roof pitch affected the structural integrity of the building. In Figure 122
different angles are seen which highlight small variations in the pitch.

Figure 120. South Exterior of Number 10; the ground floor elevation is hidden by a garden wall
Figure 121. Conjectural reconstruction of the south elevation of Number 10 (Crook, 2009: 17).
Reproduced with permission of John Crook.

Figure 122. Scars on the south elevation of Number 10 that point out the original roofline.
5.4.1.2.2 Roof

Dendrochronology shows that the roof of Number 10 was first raised in 1435 (Crook, 2009: 35), but retained the same 22.5° angle pitch shown on the external scarring. Whilst access to the upper levels of Number 10 was restricted due to the tenants occupying the apartment, Crook has made available the timber-framed construction recorded, as shown in Figure 123. He discovered that there exist seven surviving tie-beams and suggested that these were based on the original thirteenth-century positions (Crook, 2009: 37). They have been greatly modified over time with the fifth tie-beam having been moved with the introduction of the chimneystack. Figure 124 identifies the different tie-beams and shows the conjectural view of the possible moved tie-beam.

Figure 123. Longitudinal section of the present roof of Number 10 (Crook, 2009: 38). Reproduced with permission of John Crook.
Archaeological evidence in the roof structure suggests that the tie-beams have similar patterns of mortises, which were cut at the same time as the second reconstructed roof in 1436. These have been reinforced with wall posts, arch braces, two queen-struts and a central king-strut (Crook, 2009: 39) as shown in Figure 125. On these tie-beams were seven common rafters, with six currently being present. The measurements of these rafters are 49 centimetres with 17.3 centimetres spacing between them. Wall-plates are evident on the inner west wall to prevent
structural force directly on the wall and are placed at 38.5 centimetres spacing, that cover a 13.2 centimetres squared area (Crook, 2009: 39). The removal of these wall plates have been tested in the structural models to see how important they are to the structural form of the timber frame.

![Figure 125. Conjectural plan of 1436 roof of Number 10 (Crook, 2009: 39). Reproduced with permission of John Crook.](image)

With the dissolution of the Priory in 1539 came a series of new features that were added to Number 10. These included the addition of a second floor and the change of the roof to its current 49° degree angled pitch with the collars nailed to the face rather than tenoned. Further reinforcements were made to the building but these were poorly executed and were rebuilt in 1804 in line with the continual structural deformation of the building. This was in the form of reducing the wall thickness internally from the first floor upwards and extending the tie-beams to create a further supporting mechanism (Crook, 2009: 58). The changing pattern of the timber roof has been modelled and simulations of structural change have been created based on the data provided by Crook.

5.4.1.2.3 West Wall

The south elevation, with its more modern features, is often discussed in detail but the little studied west elevation reveals much more about the possible construction of the building. Figure 126 provides an overview of the building and shows possible features that could have once been windows. This is shown in Figure 126 with the remains of a window and the base of the thirteenth-century roof being obvious on the south side. Also revealed are small areas in the
north part of the wall that show a continuation of now infilled windows along the same alignment, with the possible date relating to the period of dissolution.

Figure 126. West elevation of Number 10 and close-up detail of scarred window remains and the height of the base of the thirteenth-century roof. A) represents a possible window. B) represents the original roof. (Crook, 2009: 19). Reproduced with permission of John Crook.

One phase of construction that is often missed is the access to the first floor in the thirteenth century. There is no evidence in the vaulting for a staircase and it is plausible that access was granted via an external staircase on the east elevation. This is supported by Godson’s 1750 plan, which shows an exterior feature. This could relate to the external stairs or to the ruins of another building such as the lavatorium. It is recorded in the Chapter minute books that an external stone staircase, along with the eastern wall, was removed in 1796 with the consent of the occupier (Crook, 2009: 20) which supports the theory of external access to the upper floor. Importantly, as this area was close to the edge of the cloister, it seems logical that this was somehow linked to the attached building work and it would be important to test different hypothesised ideas around this. It has also been noted by Crook (2009: 21-22) that a second external staircase on the west wall is possible, with three steps being revealed in an excavation that took place in 2003. This would have been limited to the area of the northern most buttress seen in the building work and the projected angle reveals a somewhat short height. If this external staircase existed then it would have had two separate flights, connected just below the current window where a possible door may have once existed, as seen on the left of Figure 126. This forms part of the ongoing research into this building and the result gathered in the original construction could be used to identify if this external feature was plausible.

5.4.1.2.4 North Wall

Attached to the north wall of Number 10 was once Number 11. Number 11 fell into a poor state of repair due to the reduction from twelve canons to five canons after the conversion of the
priory to a Dean and Chapter, with an 1842 ruling stating that it should be pulled down (Crook, 1984: 107). The 1649 parliamentary survey of the building contains little save “that it once contained a catalogue of rooms and was built of stone walls and covered in lead” (Crook, 1984: 108). It suggested that this was part of the original monastic construction as lead was used rather than tiles for the roof. The building being torn down between 1842 -5 led to the north end wall of Number 10 being rebuilt due to the destruction of the building attached to it (Crook, 2009: 4) with none of the original surviving. The original north wall has been included in the structural tests, with its original position taken from the exterior wall that runs parallel to Number 10 and the cathedral.

5.4.2 Assessment of Number 10a

5.4.2.1 Exterior

From the west elevation of Number 10a, as shown in Figure 127, it is clear that there existed two separate bays, separated by a wide pilaster buttress. The lower part of the wall is made of Caen stone ashlar blocks and the second storey is made out of flint rubble (Crook, 2009: 24). It has a door on the left hand side, a window on the right of the door and a light well above. All are of original construction. The light well indicates the line of the first floor and suggests that it was used a drainage system prompting further evidence that the original use of the building was a kitchen. Above the light well remains scarring of a window and it can be proposed that a similar window would have been present on the right hand side of the building preceding the current sash window.
The remaining walls of Number 10a have been redeveloped and rebuilt. To understand the original, Milner and Warton must be considered as they provided some information to its form before redevelopment occurred. Milner (1798: 94) recorded that the east wall contained two separate long narrow windows, in the style of Henry III, most likely with one at the end of each bay of vaulting. This suggests that an open area existed to the east of the building to allow for light. The north wall contained four rounded windows, in the style of Bishop Walkelin, and it is suggested that the cloister abutted directly to 10a. The identification of the exterior section of the cloister wall is of the utmost importance within the overall investigation of this work, as it will allow for a clarification as to the original length of Number 10a. As Milner pointed out, the north
wall of 10a had Romanesque style windows; as it is of a later construction than the cathedral, it
must have been built directly on to an already standing feature. From archaeological evidence, it
can be seen that the cloister wall stopped in line with the doorways of Number 10 (Figure 103 E)
and the Deanery side entrance (Figure 103 D). If Milner’s records are true then they support the
idea of another building being present between the walls of Number 10 and 10a. From the 2003
excavation records (Figure 128), a south wall, measuring 1.93 metres in width, was identified and
Crook (2009: 30) believed this to be the refectory associated with the Hordarian.

As the exterior has changed greatly, the identification of the unknown architectural features are
all conjectural. An example of this can be seen in the roofing style of the original. Currently 10a
has a different formation of roof due to the extension of the building work. It is unknown what
pitch the roof was originally designed with and the use of structural analysis can be used to test
different hypothesised styles based on the original Number 10 roofing style.

5.4.2.2 Interior

The identification of the possible refectory provides an understanding of how the internal
structure of Number 10a was designed. It is believed that the refectory was positioned abutting
both Number 10 and 10a which implies that access to the upper floors was restricted between the
two buildings. Currently a small extension connects them together for access to the undercroft.
Originally, the two buildings would have been constructed with only their corners meeting. If the
refectory did not abut the two then it suggests, through the discovery of the wall, that a further
part of Number 10a existed. The identification of the refectory, as proved through a GPR survey
(5.9.1.2) of the Inner Close, identifies the true nature of Number 10a. This provides an insight into
how the first floor was accessed, with the most logical being an external staircase accessed on the
north or east side, similar to the stone stairs noted above for Number 10. The location of the
refectory suggests that this staircase was directly incorporated into the building work. If this is
true than it means the conjectural plan by Godson, on which most of the understanding of the
precinct is based, is wrong.

The interior, as has been noted already, has been greatly modified. Evidence exists, in the form of
a vaulting shaft (Figure 114), that the interior was once vaulted in a similar manner to Number 10.
From the exterior buttress and the two bays identified, it can be seen that the vaulting would
have been separated into two separate vaulted cells. The span of the interior would have been
too wide for a single vault and would have required the addition of a central column for support.
In comparing the proposed vaulting to Number 10, the bays of the vaulting for 10a are smaller,
equating to a width of 3.48 metres. The arrangement of the possible vaulting has already been
outlined and conjectural plans of the vaults are shown in Figure 128.
Figure 128. Plan of the current building work of Number 10 and 10a with the thirteenth-century features highlighted in green. The undercroft of Number 10 has been extended and the three bay undercroft of 10a has been added to the drawing. A longitudinal arrangement of Number 10a’s potential undercroft can also be seen at the bottom of the image (Crook, 2009: 27). Reproduced with permission of John Crook.

5.4.3 Survey

A laser scan survey was conducted using a Faro Focus 3D x130 of the interior of the undercroft. In total eight scans were used to create the model, with the methodology in B.1 adapted to fit in with the close proximity of the architectural features. An overview of the interior scan can be
seen in Figure 129, with Figure 130 representing the different measurements associated with the subsidence.

Figure 129. Laser Scan model of the interior of the undercroft of Number 10

Figure 130. Laser scan model of the interior of Number 10 with measurements attached to each column

Laser scanning was the only suitable method for this area due to the complicated rib vaulting. The time taken to record this area with a total station would have taken in excess of a week and photogrammetry would have required a large number of images to capture the curvature of the columns correctly; laser scanning was completed in two hours.
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The two floors above the undercroft, along with the timber roofing, were inaccessible for recording due to their private occupancy, although the area could have been captured using laser scanning. Instead, the survey completed by John Crook was digitised to model the remaining sections of the interior. The modelled drawings were then combined with the laser scan data of the undercroft to create a replica of the current building work. This methodology proves useful within archaeology as it allows for a detailed examination of previous surveys, creating a tool for structural deterioration examination through subsequent years. With the building being a private residence, the exterior recording was also limited due to the permission required to access certain parts. Sections, such as the courtyard between Numbers 10 and 10a were owned by the cathedral, but had limited space to work in. It was felt that a total station survey was more suited to recording the external features of the south wall of Number 10 and the west wall of 10a. Laser scanning could have been employed but the results would have been poor due to the errors associated with angled data (B.1.5.6), which would have included partial data. Likewise, the use of photogrammetry would have produced poor results, as the required angles would have been unattainable to capture without a large stepladder or UAV.

The accessible east and north walls of both buildings were surveyed using the external scans of the cathedral taken with the x330. This allowed the overall scan data to be georeferenced with the other surveys conducted in the precinct. Access to the west wall of Number 10 was restricted with permission only gained after the hire of the scanner had ended. The survey of this area was therefore captured using a total station survey. Although this limited the amount of data achievable and greatly increased the time involved, it was the only possible method for the recording of the wall. Due to the vegetation, photogrammetry would have produced a dataset that contained missing information and a survey would have had to be conducted to fill in the gaps.

Despite the problems of access, the varied surveys that have been conducted of these two buildings allow for a greater comparison between what is possible within structural analysis; combining laser scan, building survey and CAD extracted models creates a system whereby all necessary information can be included. A full dataset now exists that provides enough information about the layout of the buildings and the focus of analysis will be based on the pre-1800 modifications rather than the more recent additions.
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5.4.4 Research Questions Surrounding Number 10 and 10a

There are a number of research questions attached to the buildings and are listed below. Without the data provided by John Crook, these could not be answered, and it provides a suitable case study within the use of different survey techniques for structural analysis testing.

- How has the subsidence affected building 10?
- How has the development of building 10 affected its structural integrity?
- If the undercroft was designed without corbels, how would the vaulting have coped?
- Could external stairs have been a viable option based around the limited space available?
- What was the original form of the roof of Number 10?
- Could a vaulted undercroft have been present in 10a?
- What possible roofing types could have been present in 10a?

5.5 Pilgrim Range

5.5.1 Assessment of Pilgrim Range

The Pilgrim range (Figure 103 J) dates its origins to the thirteenth century (based on the below dendrochronology readings) and contains one of the earliest hammer beam timber frames in Europe. The building has undergone many different uses since its first construction, most notably with its conversion to the Pilgrim School in 1931. This separated the building into two parts, the school, and the hammer-beam area known as Pilgrims’ Hall, as shown in Figure 131. The original purpose of the building is unknown but it is often seen as a guesthouse for the Priory. In the early seventeenth century the Pilgrims’ Hall area was used as a common brew house; the adjoining two bay hall which is now part of the school was converted into a dwelling house in 1626 and the single bay at the southern end was used as the Dean’s stable (Crook, 1991: 129). Shortly after its conversion, the brew house was converted to a larger stable and coach house for the Dean and by 1739 the southern bays were added to Number 3 to form a “first floor closet, with a brick wall built to mark the division between the stable and the house” (Crook, 1984: 41).

The earliest description, by Milner (1798), refers to the construction as being similar to ancient eating halls and as a refectory existed on site for the church hierarchy and important guests, it is
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sensible to assume, with its name, that the area was used predominantly by pilgrims. With the parliamentary occupation during the civil war, any indication of its use before the seventeenth century has been destroyed and as Crook (1991: 155) mentions, “there exists no medieval reference to the range complex”. The understanding of the building must therefore rely on the archaeological evidence found.

Figure 131. Exterior view of Pilgrims’ Hall with the Pilgrims’ school attached to the right of the image (facing east)

The length of the Pilgrim range complex is 29.9 metres long by 10.91 metres wide (Crook, 1991: 130) and consists of Quarr and Caen stone with coarse flint (Crook, 1991: 132). The archaeological evidence supports the idea of a single construction; with continuous longitudinal members and a uniform roof structure both being present. The single construction includes four separate types of truss, namely a true aisle truss, a base cruck truss, two hammer-beam trusses and one raised aisle (Crook, 1991: 129). The layout of this truss system can be seen in Figure 132. These trusses, through dendrochronology, date back to c.1308 and have undergone extensive research through the work of John Crook (1991).

8 The introduction of this name is unknown
From the archaeological assessment completed, it can be seen that the redevelopment of the building was accomplished in several stages during the seventeenth century. The range complex was divided into three bays rather than the original two halls that were built end-to-end that once consisted of a three-, two- and one-bay system (Crook, 1984: 39). The two halls mentioned would have consisted of the hammer-beam hall and a southern hall that was subdivided into a “second two-bay hall with a central base cruck truss and single bay at the south” (Crook, 1991: 129). Part of these trusses can be seen in Pilgrims’ school and a detailed report will be given on them. The
understanding of these trusses will provide a hypothesis of how the two-hall range was built and through structural analysis; these conjectural plans could be tested and validated.

5.5.1.1 Interior

Much of the interior has changed because of the seventeenth-century redevelopment but with the already mentioned work of John Crook, an indication of the layout of the original complex can be seen, and is shown in Figure 133. The exterior shown on the northern part of this image is conjectural and more on this will be discussed in the exterior review (5.5.1.3).

Figure 133. Reconstruction of the Pilgrims’ range as viewed from the north west (Crook, 1991: 130). Reproduced by kind permission of Cambridge University Press, www.cambridge.org.

To understand the interior of the building, the individual trusses have been separated into different parts. Although little survives, there are references that bays one to three, as shown in Figure 133 (to the right of the middle wall), suffered severe subsidence from an early date as mentioned by Crook (1991: 130). The cause of this could relate to poor foundation work or as seen elsewhere within the precinct, is most likely due to the geology of the area. Structural testing therefore plays an important role in the identification of the form, as well as its function and use. The timber frames that will be discussed have been removed or damaged and the
evidence is based on excavation work in the current building. The building has had two major alterations that have affected the interior, the rebuilding of the east wall in the mid seventeenth century, and the demolition of the west wall in the 1680s (Crook, 1991: 130). The understanding of the interior width can be extracted from the buttresses that remain on the exterior in the north of the building.

5.5.1.1.1 Truss I

Truss I is a true aisled truss and forms the basis from which the others have been constructed. The position of the truss relates to the first and second bays that were in the south of the range. The truss was investigated fully in 1986-7 during building works. Figure 134 shows that the surviving evidence of the timber is minimal and the image produced by Crook includes considerable interpretation. There exists nothing to show how the arcade post was originally supported at its base and hypothesised arch braces have been extracted from lap-mortices to provide structural support to the frame along with the tie-beam. In the seventeenth century the truss subsided and

Figure 134. Truss I from the South (Crook, 1991: 137). Reproduced by kind permission of Cambridge University Press, www.cambridge.org.
“took with it the arcade plates that formed the base of the upper roof triangle” (Crook, 1991: 135). Little is known about how this was connected to trusses II and VI to form the continual roof noted. With the angle of the roof fixed, the wall post of the truss must have once been exposed on the outside of the wall. The thickness that can be identified from the extant remains indicate that it matches the external width of the Pilgrims’ Hall (Crook, 1991: 138). It is doubtful, considering that the wall now connecting Pilgrims’ Hall to the school is straight, that the original would have differed. With the hypothesised truss being conjectural in its nature, the plan shown in Figure 132 can be modelled and various tests can be placed on its structural integrity to show how realistic it is. Individual sections of the truss, such as the studs evidenced in the mortices of the brace, can be removed and added to test the probability that they were a permanent fixture. With the subsidence taking place, the addition of the studs most likely relate to a support mechanism and again this can be tested through artificial subsidence of the left-hand arcade post. This will provide a fuller understanding of the interpretation made and provide an insight into what its original construction was.

5.5.1.1.2 Truss II

![Figure 135. Truss II from the South (Crook, 1991: 139). Reproduced by kind permission of Cambridge University Press, www.cambridge.org.](image-url)
Truss II is the next most northern. It consists of a base cruck attached to bays two and three. More of this truss survives in its original form than of truss I, although the lower parts of the two crucks have been removed. The identification of the angle of the two crucks is conjectural but there is evidence in the ceiling line of the seventeenth-century room, which now occupies the lower ground level, and provides some insight into the possible angle of the original. As with truss I, the support mechanism for the truss has been removed and tests could be performed to identify if the framing was placed directly in or on the ground, or on a stone pedestal for support. Figure 135 represents the conjectural plan of truss II and this could be tested to identify how reliable it is. Both knee braces remain, as does the collar beam, limiting the possibilities for modelling alternative forms of the truss. The beam is cambered and is similar in design to the hammer beams. The conceived scissor bracing that has been included is based on the design found within the other trusses, as well the mortices in the found on the beam. The layout of the truss is simple in design and is straightforward to replicate within a CAD model. Measurements of each part are known through the work of Crook (1991) and this conjectural plan could be used in relation to the other trusses to test how valid the form is.

5.5.1.1.3 Truss III

Figure 136. Truss III from the North (Crook, 1991: 141). Reproduced by kind permission of Cambridge University Press, www.cambridge.org.
Truss III now forms the partition between Pilgrims’ hall and the school. The only surviving parts of the original construction are the tie-beam and the scissor bracing with crown post. The plan of the conjectural truss can be seen in Figure 136 with evidence existing to suggest that it is similar in design to Truss I (Crook, 1991: 140). The partition wall that was removed in 1959 existed in the original construction due to the 40-millimetre cutting that is marked in the tie-beam ends. In the thirteenth century there existed a hearth in the middle of the Pilgrims’ Hall section, as supported by smoke damage that can be found on the timbers above (Vaughan, 1914: 62). This smoke damage cannot be seen on the south side of truss III and suggests possible infilling closer to the scissor bracing than is suggested by Crook (1991: 140).

Unlike the others within the range, the truss is not a true aisle as there exists no evidence of full-length timber posts and no plinths are evident for them to rest on. From the rebuilt brick wall that was built to divide the two halls in the seventeenth century it seems logical to assume that the original construction consisted of a flint or Quarr stone-based wall. There exists no indication that this was the case (Crook, 1991: 141) except for a flint base which could indicate that the wall was completely removed following the renovation work. Structural analysis could be used to test the possibilities of whether a wall was originally used within the construction of the truss. If the truss were able to support its weight on the two exterior walls of the building then it would suggest that an internal wall was not needed. If however it fails under its own loading, the idea of the wall being present would be supported. Although the truss may support itself without a wall being present, one could still have existed. The wall could have also have been part of a larger structural support system and this could be tested via structural analysis.
5.5.1.4 Trusses IV and V

Trusses IV and V (Figure 137) are in the north part of the Pilgrims’ Hall complex and contain the earliest form of hammer beam trusses in Europe. The hammer beams are tilted up slightly and are gently tapered with the opposite hammer beam to form a curved trefoil arch (Munby and Fletcher, 1983: 108). The design of the trusses is in stark contrast to the simple arches used elsewhere in the range and suggests that the area was of importance. The separation between this hall and the southern hall was accomplished via the partitioned wall providing limited access between the two. The separation and decorative design of the trusses suggest a high status area, perhaps for those who were unable to stay in the Deanery or those who attended the priory as pilgrims who had wealth. The hall could have been used by other individuals but the inclusion of carved figures show that great time and care was taken in their design, implying that it was intended for important persons or occasions.

The truss timbers, from the dendrochronology readings, date to 1290 ± 5 AD (Fletcher and Crook, 1984); with the carved heads of Edward II and Edward III and other unidentifiable characters on
the four hammer beams, the original construction of the range complex can be dated to the turn of the fourteenth-century. All of the timbers from the original construction remain and are in similar format to the other trusses and include a crown post to support the scissor brace. This crown sits on top of the collar beam, which is braced by large arch braces. The truss is further reinforced by “short struts from each brace to the soffit of the beam” (Crook, 1991: 142) with mortice and tenon joints. The hammer posts are aisle-posts, supported on hammer beams that fit directly onto the wall and are supported by an arch brace, as is the case at the later Westminster Hall. It has been noted by Vaughan (1914: 62) that the timber used for the framing and rafters are stout oak which suggests that the timber is extremely strong. The choice of oak can be seen elsewhere in the precinct and was most likely used because of its strength. Other timber such as chestnut could have been used and these variations in material properties could be tested to identify their structural performances. Was oak the best timber to use or could cheaper alternatives have been used?

Comparisons of the hammer beam truss can be made with that found at Tiptoft Farm in Wimbush, Essex which dates to the mid fourteenth century (Munby and Fletcher, 1983: 108); Upton Court in Slough which dates to the thirteenth century (Thornes and Fradgley, 1988); Plume of Feathers (fifteenth century) (RCHME, 1977a) and Three Cup Chequer (thirteenth century) (RCHME, 1977b) both of which are found in Salisbury but are not ‘true’ hammer-beam frames. The closest comparison can be seen in the kitchen of the Bishop’s Palace at Chichester which dates to the same period as Pilgrims Range (Crook, 1991: 150) as seen in Figure 138. The roofing style incorporates the same tilted and tapered beam, along with a similar chamfering style. Other comparison could be made in understanding the structural properties of this truss system but no others have survived. Part of the structural understanding is based around its current condition and it would be interesting to change the structural supports to see how necessary the elements were. By removing parts of the truss, would trusses I, II, III and VI be able to support themselves?
5.5.1.1.5 Truss VI

Truss VI is a true aisled truss found at the southernmost part of the range complex. Little evidence exists to suggest what the original design was like but as a true aisle, it would have been similar in construction to Truss I. The truss was a support mechanism for the end of the building and following the design of the southern bays of the range, it is plausible that it had full timber posts, supported by aisle ties and with the scissor bracing found throughout. The design of the truss can be based on structures that are of similar design, such as Purton Green Farm in Suffolk. The modelling of this truss could be evaluated through structural analysis with variations of design created.
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5.5.1.1.6 Truss VII

Like Trusses IV and V, Truss VII is raised and forms a raised aisle truss similar in design to Truss I. Like Truss VI, it was used as a support mechanism for the arcade plate that is inserted into the end wall found in the northern most part of the range. Although similar in style, the majority of its components relate to Truss III, having been secured to the masonry wall. Having a raised aisle construction for an end truss is rare with a normal system having a “full height gable or short posts set against the wall resting on corbels” (Crook, 1991: 147). The inclusion of this raised truss in terms of the structural integrity of the building is unclear. The framing is supported by the wall to stop any lateral movement and it would be suitable to test variations of this truss system, especially with the removal of the wall and the addition of a full height gable.

There are a number of different truss systems used within the range complex and it is puzzling as to why this is the case. With the variations in form, the structural integrity should vary within the building and it would be advantageous to test how one truss type could have been used throughout. Except for the change in social status with the hammer beam trusses there appears to be no reason why the alternative styles have been used. If it can be proved that one type was not a valid structural entity, then it may suggest why the differences can be seen.

5.5.1.2 Roof

The roof structure of this building was constructed as one with continuous longitudinal timbers (Crook, 1984: 39). It has an aisled form which can be identified through two arcade plates found in the two end trusses (VI and VII) both of which are “set square rather than in the plane of the roof” (Crook, 1991: 134). These would have then extended onto the five trusses discussed above and are seen in the stop tapering in each existing truss and the scarf joints at either side of the building complex. The rafters above the main trusses are tenoned directly into the support beam and are hooked over the arcade plate to allow for a continuous joint. Connected to these rafters are the scissor braces mentioned already with the addition of a central purlin to allow for an irregular shape. Stiffness is given to the upper roof by this purlin but it is the scissor brace that acts as a support mechanism for the long roof. Part of the investigation could include the removal of these scissor braces and central purlin to assess how well the roof is able to cope without the additional support mechanisms. Are they important to the structural integrity of the building or were the truss designs enough to cope with the forces applied? With oak used for the construction of the building and with its high tensile strength, the addition of the structural elements may not have been needed.
For the correct forces to be applied to the original constructed model, loading types have to be added to simulate the roof’s covering. Excavation in 1959 revealed slate pieces (Crook, 1991: 143) which would have been used for the roof covering and its presence is further supported by documentary evidence that the roof was rebuilt and slated in 1334-5 (Kitchin, 1892: 230). This follows a general use of the material in royal and monastic buildings in the twelfth century (Wood, 1968: 295). The form has changed and there is some level of inclination within the roofing, but is mostly likely due to the conversion of the range complex (5.5.1) and lack of structural support during the in-between phases of conversion. The current form of the southern end of the range is of a hip end roofing style that was added in 1946. It is suggested by Crook (1991: 136) that the “style would be reminiscent of that found in Pilgrims’ Hall” which has only been slightly adapted, with most of the reworking found based on the exterior characteristics of the building.

5.5.1.3 Exterior

Due to the conversion of the building, much of the external material has been replaced, although the general layout of the original was followed. The flint and rubble wall in the north section of the range has an average thickness of one metre. The two northeast buttresses, as well as the east buttresses, are original with the west side buttresses being replacements from 1959 (Crook, 1991: 132). The alignment of these buttresses fits in with the timber frames and it is thought, following fragmentary remains from excavation, that bays one to three (southern part of the range) differed in form and were once timber-framed walls due to plinths for the base of timber frames being found (Crook, 1991: 138). Although unlikely, modifications in form could be tested if structural results indicate that a timber frame was not strong enough to support the forces applied within the southern part.

Splayed openings suggest that the Pilgrims’ Hall bays originally had windows except one that was a possible door (Crook, 1991: 134). The doorway that Crook (1991: 133) suggested may have existed in bay four; with the current window off-centre, it could indicate that it was once a doorway (Figure 139).
In 1914 (Figure 140 and Figure 141) the present-day windows in Figure 139 did not exist, suggesting that they were fitted in the 1931 rebuild. No scarring can be found on the building that indicate previous openings and it is reasonable to suggest that the window openings were reworked from infilled sections.
Figure 140. A 1914 view of the Pilgrim Hall with number 3 built into it. Notice the lack of windows on the west side of the building (Vaughan, 1914: 70)

The identification of alignment of these current windows are seen in the laser scan model recorded. The most logical conclusion is that the southern part of bay four was once the access point to the hall. With the off-centre nature of the doorway, so close to the edge of the wall and buttress, would this affect the structural integrity of the area? If the test prove favourable, it would be indicative that the entrance point was here. This would move away from the idea put forward by Vaughan (1914: 63), who suggested that the doors present in 1914 were in their original positions. Figure 141 shows that a door is evident on the east side of the hall rather than the west. As the building was a public area, and as every other building in the precinct has access points that face inwards towards the precinct, it is compelling to suggest that the doorway Vaughan mentions was a later reworking of an original window, completed during the conversion to a stable. Also seen in this image is a double door system in the north, which again most likely relates to the time when it was a stable. This doorway can no longer be seen due to the extension of the building that has seen the addition of an alcove and a large first floor window but it does support the idea that access became more private following the Dean’s personal use. The addition of the northern window would have been introduced to allow more light but it would have affected the building through the introduction of structural stress points. Stress points affect the structural integrity of a building and are found on the corner points of openings; creating a doorway next to a supporting wall will create new stress points. Adding doorways in differing positionings in the structural models will allow these stress points to be analysed, giving an indication of where the central access point was.
5.5.2 Survey

A laser scan survey was completed of the Pilgrims’ Hall using the Leica Scanstation 2. Due to limited funding options, this was the only scanner available during the time of data collection. The results contain a low number of points, with the total scan data containing only twenty million points. It would have been suitable to use the updated Leica C10 or P20 for the interior of this building but access to the school was limited and they would not allow a subsequent scan. The interior of the hall was recorded using six scans, capturing an outline of the building work, the hammer beam trusses and the roofing style. The exterior was captured using eight scanning locations, one of which is shown in Figure 142. The scanning positions that were chosen enabled
the best coverage of the building, and with the buttresses providing limited field of views, a scan was taken in between each pair.

Figure 142. Laser scan station outside Pilgrims' Hall. The black and white reference targets are shown on the left buttress

The interior and exterior sections were aligned with one another in Cyclone (Leica, 2014) via a cloud-to-cloud comparison after being aligned separately via the reference target positions that are seen in Figure 142. The data provided have enabled a replica of the current building to examine the arrangement of the interior with the exterior. The interior and exterior sections were treated as separate scanning entities as this process enabled a simpler digitising of the results. The interior scan data can be seen in Figure 143, with the exterior seen in Figure 144 and the combined result in Figure 145.
Figure 143. Interior scan of the Pilgrims' Hall

Figure 144. Exterior scan of the Pilgrims' Hall
Unlike other methods, laser scanning was the only technique that could have been used for the complicated timber roofing in the building. Photogrammetry would not have provided useable results due to the number of angled photographs needed. A total station survey could have been undertaken but it would have resulted in several weeks of recording due to the large number of stations required to record each timber. Laser scanning has offered greater visual results and it has provided far greater information that can be used to test the statements made above by Crook and Vaughan.

Figure 146 provides an understanding of the timber roofing. Through a slice box system seen in Figure 147, each timber can be selected and drawn for conversion for use within a Finite Element Model. The scan data will be modelled in this way, and used in conjunction with drawings produced by Crook for the rest of the range complex. It is known that the timber roof continues throughout the building but access to record these features was restricted due to children being on site and the areas needing to be accessed being private residences. Although access would have been beneficial, data can be extracted from the Pilgrims’ Hall scan and will be used in conjunction with Crook’s work. The conjectural drawings of each truss will be modelled and scaled to fit the floor level within the scan data (Figure 148) allowing for a full structural analysis to be performed on the range complex.
Figure 146. Interior scan of Pilgrims' Hall highlighting the timber roof

Figure 147. Sliced scan data of Pilgrims' Hall showing the scissor bracing and hammer beam truss
Figure 148. Side on view of the scan data of Pilgrims’ Hall showing the height variance of the exterior ground surface and the original interior floor

Although the scans could have been recorded with a higher resolution scanner, the data that have been provided are adequate for use within structural analysis. A higher number of points would have been advantageous to remove some of the transparency issues within the data as seen in Figure 149, but with limited time on site, the scans had to be completed at a lower point spacing than was ideal. Nonetheless, the scan is of a good enough quality and is far superior to what is achievable with other recording methods.
Figure 149. An internal render of the laser scan data of Pilgrims' Hall. The points seen have been enlarged to remove most of the transparency issues but areas of transparency can still be seen.

5.5.3 Research Questions Surrounding Pilgrims’ Hall

Research questions can be summarised as:

- How accurate is John Crook’s conjectural plan of the Pilgrim Range in relation to its structural properties?
- How do the different truss systems affect the overall building?
- Would the use of one truss system throughout the range have been strong enough to support the building?
- Is a hip end roof plausible in the south range?
- Are the buttresses found in the north of the building necessary?
- How have the later modifications affected Pilgrims’ Hall?

5.6 Stables

5.6.1 Assessment of the Stable

The stables (Figure 103 K) as seen in Figure 150 are of a sixteenth-century design and now form the music room for the Pilgrims’ School. It is located near to the precinct gate and was used as the common stable for the Dean and Chapter by those who had houses within the precinct (Crook, 2013). The building is 31 metres long by 7.62 metres wide and consists of a ten-bay-timber
framed system. It has two storeys and the beams tenoned to the main wall posts suggest that this was part of the original design. The roofing is of an open form and has a clasped purlin design (Munby and Fletcher, 1983: 108) with queen posts and a central crown post as seen in Figure 151. The roof that covers it contains red brick tiles.

Figure 150. The common stables in the cathedral precinct facing south
Access to the first floor of the building was via an internal staircase that has since been modified. The access point is to the north end of the building in the two most northern bays with the carpentry suggesting that the upper floor was designed as living quarters. The building was remodelled in 1938 (Crook, 2013) but it can be seen that the seven bays separating the north and south ends were originally divided into two rooms at both ground and first floor levels. These two rooms were later subdivided into smaller spaces to form the stables as noted in the 1649 Parliamentary survey (Crook, 2013). The south part was forty feet long, divided into two twenty-foot rooms; the north section was originally thirty feet long, divided into a ten-foot and twenty-foot room system (Crook, 2013). The first floor was similarly redesigned and it provided, with the addition of the north and south bays, six separate stables that varied in size. The conversion of these rooms is of interest and it could be tested to show how this affected the building structurally.

The ground floor walls now consist of close studded frames (Figure 152). The entrance point to the stables was from the east, as seen in Figure 153, which depicts the modification and conversion of the building in 1938. This modification removed most of the bottom ends of the wall posts but Crook (2013) suggested that there were original doors in bay VIII and between bays V to VI. Their identification could be tested via stress points of the studding mentioned.
The present windows are mostly modern with the light originally being introduced to the building via the east. The first-floor small windows are original as are the northern end windows found in the habitable bay. The later dormers that were introduced would have affected the structural integrity of the roof and this could also be tested.
The building has undergone a number of modifications including the introduction of brick infilling in places (Figure 154). The introduction of brick within the building is one of the earliest example by English builders (Woodland, 1932: 266) and was likely used to add support to the building with cheaper material than the stone found elsewhere in the precinct. The infilling can be found on all of the west and north side of the building, and was introduced on the east when it was converted. One research area could be the removal of this infill to see how the plaster used on the upper level could have supported the lower level forces applied to the building. It is important to test whether the brick infill was necessary or whether it was used as a design feature. The floor level for the building will be modified in the model so that it matches the west side of the building.

5.6.2 Survey

A building survey was carried out using a Leica TCR805 total station via TheoLT (Latimer CAD, 2010). This command program interacts with AutoCAD directly. This allows for a visual recording process rather than through unknown measurements being recorded directly to the instrument. The setup can be seen in Figure 155 and it took four days to record the exterior and interior sections.
Figure 155. Total station survey of the stables using TheoLT

The process involved setting up a number of stations that allowed for all aspects of the building work to be seen and was recorded via the on-board laser. Rather than use a staff and prism, this method allowed for direct control of where the single readings would take place due to the laser guide. Using a prism would have introduce a varied amount of error due to height and angle differences and is unsuitable for building recording. The method is the same as laser scanning and photogrammetry in that it produces three-dimensional point data in a virtual environment but it is of much lower resolution. In comparison to laser scanning, the building survey completed of the stables contained over two thousands points; most laser scan models would be in their millions. Using TheoLT allowed the points to be processed via a laptop and each point could be linked to form lines.

The data collected for the stable involved four external and three internal stations. The survey is a continuation of the supplementary building survey completed of the precinct and allowed for the
data to be coupled with the other surveys collected on site. The results from the building survey of the stable can be seen in Figure 156 and show how hard it is to understand the contextual detail.

Figure 156. Building survey results of the Stable using a total station. The top is facing southeast, the lower left is facing south, and the right is facing west.

As the model is visualised via line data, it can be difficult to identify from initial viewing where certain elements are. Using AutoCAD within the survey enabled this difficulty to be removed as the model was manipulated to show set views and partial information. If the data were stored via the instrument, then the point data would have to be converted and some areas may have been recorded in the wrong place due to human error in the recording process. Although laser scanning and a photogrammetry model would have provided much better results in a shorter time, the use of total station surveying provides an outline of the required information at a lower memory capacity, making the process more efficient in recording simple details. Using a total station survey on this building was straightforward due to the straight edges present and the ease with which these could be recorded. Using this method on geometry that is more complicated would have been problematic and not all of the features necessary would have been recorded, with the majority containing partial information. The results for the full survey of the Inner Close can be seen in Figure 157. The full time associated with recording these features was over three weeks and only partial data were collected; other building features were captured using laser scanning.
and photogrammetry. These models form the basis for the structural analysis tests and will be converted to solid models for use within Finite Element Modelling software.

![Figure 157. The overall building survey of the Inner Close facing north east](image)

### 5.6.3 Research Questions Surrounding the Stable

The research questions attached to the stables are limited but are as follows:

- How was the original building designed?
- Was the brick infill that is used necessary in the construction of the building? Could the plaster used on the first floor have been used throughout?
- How does a full total station affect the accuracy of the structural analysis tests performed?

### 5.7 The Chapter House

#### 5.7.1 Assessment of the Chapter House

The Chapter House (Figure 103 C) in the east range of the Inner Close was built by Walkelin and was used as the centre for the daily business of the church, dealing with all affairs of the cathedral and monastery. The Chapter House was pulled down by Bishop Horne in 1570 and nothing survives save for the entrance arches and a blank arcading on the north wall (Figure 158).
The Chapter House has an open arcade at the front, with the central arch used as the main entrance with a width of 1.8 metres. Understanding the layout of the building seems simple from its limited size, but no records remain of how it was constructed. The shape is considered to be of a rectangular or apsidal form as noted by Vaughan (1914: 24) and no decisive conclusions have been made. The termination of the building is identified through the break in the blind façade found on the north wall. A conversation with Professor Biddle in 2013 provided no further insight into this and a geophysical survey was conducted to provide an answer as to the overall structural form of the building (5.9.1.1).

The columns of the arcade (Figure 159) at the west of the building are of Quarr stone and have possible Roman or Saxon origins, as based on comparisons to St Alban’s Abbey and St Botolph’s Church in Colchester, and Biddle’s (1972, 1987) recurring comments about previous features being robbed and reused. They act as the main entrance point to the building and were accessed via a small staircase from the cloister floor level, which was revealed in excavation (Crook, 2013). The excavation showed that the steps had been removed but the imprint was still visible within the central arch system.
The floor level found within the current building work is modern and is based on the wall benches found on the north and south walls. The area was covered with soil between 1580 and 1856 (Crook, 2013) and this acted as a preservation device for the remaining material. The current south wall is further north than the original, as is evident on the west wall internal scarring (Figure 160). The remains of the original wall are under the current Dean Garnier Garden (Crook, 2013) (right of Figure 159, behind the garden wall).
Kitchin’s (1943: 7) examination of the building led to a belief that evidence exists of a narrow slip of masonry that is one foot, ten inches (55 cm) wide, eastwards of this opening. This narrow slip could suggest that a thin wall once existed to act as an entrance point to the building leaving the front arcade as an external feature only. This was hypothetical and the possibility of its existence has been tested through the geophysical survey. It has also been suggested that the Chapter House once had stone vaults springing from a large central pillar (Kitchin, 1941: 6). This could refer to a single central pillar or could refer to two central demi-columns (one on the north and south walls) as seen at Bristol cathedral (Figure 161). The Bristol Chapter House, which dates to the mid-twelfth century, is similar in terms of size. Although Bristol is a later construction, and has a closed opening, the lower arcading is reminiscent of the remains found at Winchester. If Bristol is seen as being the closest resemblance to Winchester’s Chapter House then the two bays of vaulting found could have been used in similar fashion. The buttresses that now support the slype and cathedral library are of a later formation and it could be suggested that another system of arcading was used to support the roof structure. This increased height allows for the height of the arches at the front to be explained in relation to the other buildings.
The understanding of this building is therefore problematic. Following traditional practices, a reconstructed model can be created, as shown in Figure 162. This is based on some of the selective hypothesised ideas discussed above, some of which are unsubstantiated. It leads to an incorrect interpretation, such as that seen in the roofing style chosen, as it seems physically impossible to support the three roof types displayed, unless the postulated open layout is incorrect. To create a better model, a more systematic approach has to be used in testing these ideas. The limited information available does not help with this but structural analysis will at least show what is possible from the known information.
5.7.2 Survey

With the Chapter House being open, the building was captured via photogrammetry as it allowed the complicated geometry to be captured accurately and quickly. A total station survey was also carried out as part of the wider building survey of the precinct to allow for known measurements. The total station survey took a number of days to capture and the results are poor when compared to the photogrammetry model. The total station survey failed to replicate the columns and their capitals, making it problematical in converting the line data to solid material for use within structural tests as the curvature could not be accurately recorded.

The photogrammetry model was captured from two hundred and twenty five images within an hour and was processed over a day. These images were taken at varying angles as determined in B.2. A larger number of images were initially taken but were reduced to avoid unnecessary processing time. The images had one hundred and eighteen masks drawn to remove the redundant background information. This background data included people walking, signifying that
the background pixel data changed; as photogrammetry requires each pixel to be the same, the results would have been erroneous if processed. An example mask can be seen in Figure 163.

![Figure 163. Left. Original image used for photogrammetry processing. Right. Masked dataset removing background information](image)

The processed results seen in Figure 164 to Figure 166 show how realistic the model is. The data provided can be extracted and used, and rather than have to draw around the areas of interest, the solid mesh can be extracted directly from the model. There are some issues with the data as the focus within the data capture was the west and north walls. If there are not enough in-focus photographs captured the software is unable to produce a meshed model and instead interpolates the results to create an uneven surface. The south wall and grassed area are poor in quality due to this with the model containing unrepresentative height and surface depths. Photogrammetry relies on the photographs being correct to produce the model; using laser scanning would have removed these issues as the point cloud is created from a set position and all values, within a given distance, are accurate. This error is not problematical as the data required from the survey were captured correctly. Unlike the laser scan model, the photogrammetry dataset has an already meshed surface but relies on the texture to make the model look visually realistic. The mesh detail does contain the subtle features necessary for testing but it only has ten million faces, whereas a laser scan dataset would have several hundred million points from which to work, creating a greater sized mesh to work with.
Figure 164. Photogrammetry model of the Chapter House facing east showing the four main entrance columns

Figure 165. Photogrammetry model of the Chapter House showing the whole length of the north wall
Figure 166. Photogrammetry model of the Chapter House showing the side detail of north wall

The photogrammetry model was used as a basis from which hypothetical reconstructions of the building were created. It allowed for exact measurements to be known, having been scaled correctly through measurements taken on site; and it allowed for the removal of features, such as the flat buttress walls above the arcading (added to support the library above the slype), to create a model that shows the original features without having to rebuild it.

One element that is often left undiscussed is the height of the original building. It is unknown for certain, but from the photogrammetry results, a clear line can be seen on the left hand side of Figure 164, which cannot be clearly seen from the ground. This line matches with the top of the middle arch. On top of this, there are further masonry features that extend upwards and stop with a tapered edge indicative of a roof angle. From Figure 162 it can be seen that the cathedral authorities believe the roof shape would have been three separate pitched roofs; the photogrammetry model will be used to test how viable a single vault system was, and how high the building needed to be, without interfering with the appearance of the cathedral.
5.7.3 Research Questions Surrounding the Chapter House

The research questions surrounding the Chapter House are limited and are as follows

- What was the original shape of the building?
- What type of vault was used within the building?
- Was the building of an open or closed form to the cloisters?

5.8 The Refectory and Lavatorium

5.8.1 Assessment of the Refectory

The refectory (Figure 103 M) is known only through documentary evidence, with an account of its daily use published by Kitchin (1886) which was based on the fourteenth-century consuetudinary of the cathedral. The earliest reference of the refectory was made by Milner who commented that it was at the west of the south cloister walk, where a doorway with a pointed arch remained (Milner, 1798: 73). The location of this in reference to the cloisters, Number 10, and the refectory suggests that this was included in the construction of the thirteenth-century phase of building work. Vaughan (1914: 33) however suggested that the Prior’s hall was the refectory. Although Milner’s comments were made after demolition, following Benedictine form, Vaughan’s proposed location would not fit the Benedictine standard, and a position in the south range of the main cloisters seems the most logical. The geophysical survey that was conducted has identified a possible location.

Crook (2009: 32) believed that the Refectory had a length of 46 metres and a width of 9.75 metres. This is in similar proportion to Norwich’s 48.8 metres by 10.2 metres refectory. This is different to measurements suggested by Milner (1798: 136) who proposed that the refectory, based on ruined building work, was twelve metres in length. He further added that two long narrow windows existed on the west side in the Henry III style; that the north wall contained four round-headed windows in the Walkelin style and that the east end had two further windows. He further suggested that the hall had a width of 7 metres and a height of 12 metres and that it was once a single-storey construction that was later converted to two. If this representation of the building is true then the layout is very similar to Norwich cathedral’s refectory, in both size and style. Norwich will therefore be used as a basis for comparative studies.

Having inspected other buildings around the precinct and by comparing those refectories that still exist of the same period, it seems probable that the building did not contain a stone-vaulted ceiling but rather was similar to Norwich which had a scissor braced timber roof (Gilchrist, 2005: 124), as also seen in Pilgrims’ Hall of the same period (5.5.1.2). A conjectural reconstruction of the
inner of Norwich’s refectory is shown in Figure 167 but its form must be questioned. The inclusion of an internal plaster based ceiling seems inaccurate, as there appears to be no way to fix this in position. At Winchester, the inclusion of such a ceiling would seem unlikely, as both the cathedral and Pilgrims’ range were of an open form. Removing the conjectural ceiling Gilchrist’s model provides an example of the internal building work and this was used in the reconstruction of the refectory at Winchester.

Figure 167. A reconstruction of Norwich’s refectory by Margaret Mathews (Gilchrist, 2005: Plate 5). Reproduced by kind permission of Margaret Mathews.

5.8.2 Assessment of the Lavatorium

Little is known of the lavatorium at Winchester Cathedral except that it was located near to the Refectory; it would have been used by the monks to wash their hands before dining. The location of this building is unknown for sure, but with the large supply of water needed to drain the dirty water away, the layout of the Lockbourne system will assist in outlining potential building work found in the geophysics.

5.8.3 Research Questions Surrounding the Refectory and the Lavatorium

These research questions concentrate on the virtual reconstruction of the buildings.

- Where was the Lavatorium?
- What was the original form of the Refectory and Lavatorium?
- Was the Refectory able to support an internal vaulted ceiling as seen in Number 10?
5.9 The Geophysical Survey Results

A geophysical survey was completed of the Inner Close and surrounding precinct using both resistivity (B.4.1) and Ground Penetrating Radar (GPR) (B.4.3). Other types of survey methods were considered but with the number of cars and other metallic elements found on site, it was decided to concentrate on two techniques. Resistivity provided the ability to identify features close to the surface, whereas GPR allowed for the recording of depth variations, enabling the identification of subtle differences in the archaeological record.

5.9.1.1 Resistivity

Resistivity (B.4.1) was carried out using a Geoscan Research RM15 resistance metre (Geoscan Research, 2012b), with measurements taken at one-metre intervals along traverses spaced one metre apart. The survey grids used were twenty-by-twenty metres, enabling a maximum of four hundred readings per grid. The grids were set out using a Leica Viva GPS (Leica, 2016) and in places of dense tree cover, a Leica TC 307 total station was used. Creating a smaller grid of twenty-by-twenty metres enabled all open areas to be recorded as one, whilst limiting the number of partial grids. This created a record that is more genuine as the data needed less processing. The larger the number of partial grids, the more processing is needed to create a representation that follows a general pattern. With the larger grids and the majority of partial areas using the same remote sensors, the data provided enabled an understanding of what lay half a metre below the surface. Examining the data shows that a 0.5 metre spaced reading should have been used to show the features more clearly, but outlines of building work are nonetheless evident.

The resistivity survey data were imported into and processed using Geoplot 3.0 software (Geoscan Research, 2012a). The processing of the data was necessary to remove any effects produced by changes in the earth’s magnetic field during the course of survey, and to minimise any interference in the data from surface scatters of modern material. The data were despiked to remove any spikes from the data produced from the material on the ground surface. A mean traverse function was then applied to average out any changes in the data produced. Filters were then applied to flatten any high frequency points and small disturbances in the data. The data were then interpolated from the existing readings to improve the spatial resolution of the results across the traverse lines. The areas captured were the cloisters (Figure 103 M); the grassed area outside Number 9 (Figure 103 N); the grassed area near to the Pilgrims’ School (Figure 103 O); the Dean’s Garden (Figure 103 I); and the Chapter House ((Figure 103 C). The original intention of the
research was to include the Deanery within the overall evaluation but it was decided to remove this within the overall scope of the research. Nonetheless, the data includes more of the Lockbourne system and the results can be seen in Figure 168.

Figure 168. Resistivity results from the precinct of Winchester Cathedral. The red lines indicate seventeenth-century building work with the blue line showing the hypothesised Lockbourne system proposed by Crook
5.9.1.2 Ground Penetrating Radar (GPR)

GPR (8.4.3) was conducted in the area south of the cathedral in collaboration with Lizzie Richley. In previous years, GPR has also been completed on site with the focus being on the Outer Close, north of the cathedral. This previous work was completed by Kris Strutt, myself, Eleonora Gandolfi and Richard Milwain as part of our Masters research and it highlighted the potential of the technique at the cathedral. The GPR survey was completed as part of this research as it was thought that the method would provide a useful complementary technique to the resistivity survey. It would similarly ensure that as much of the remains of the masonry structures could be located as possible, adding to the fundamental aspects of the future virtual reconstructions of the building work. It was conducted using a Sensors and Software instrument with Smart Cart (Sensors & Software, 2016). A 500 MHz antenna was used, with traverses recorded at 0.25m intervals in one direction. The GPR data were processed in GPR slice (Geophysical Archaeometry Laboratory Inc, 2016) and all profiles were processed to remove background noise. A regain function was applied to strengthen the deeper responses to the radar signal. Once processed all of the data were sliced and resampled to produce a series of timeslices through the site. Each transverse position was recorded through the survey grid established for the resistivity survey and allowed for the variations in the topography to be included within the overall data.

With the data transformed into timeslices, the resultant depths could be calculated based on the local geological information and the excavation records. This allowed for the various results that were seen within the survey to be examined and compared. As context records exist of the varying archaeological material, each depth can be related to an archaeological period. The data from the survey were exported as a series of bitmaps, and were imported into and georeferenced in a GIS. An interpretation layer of archaeological and modern features was created which highlighted the nature of different anomalies in the survey data from their form, extent, size and other appropriate information. The results of some of these different timeslices can be seen in Figure 169.
Figure 169. GPR timeslices of the Inner Close. A) 50cm. B) 1 metre. C) 150cm. D) 2 metres
Chapter 5

The focus of the data capture has been the identification of the cloisters and the surrounding buildings. These data will be expanded on with the development of the structural analysis models in the following chapter. The survey data completed is important not only to the lost buildings but also in assisting the interpretations made within the other buildings. Research questions surrounding the lost buildings fall within the overall scope of the research, namely in testing whether hypothesised forms of the building work are representative of what is possible within their physical limits.

5.9.1.3 Research Questions Surrounding the use of Geophysics

The research queries attached to the use of geophysics are limited within the scope of the research.

- How useful is geophysics in outlining building work for use within structural modelling?

5.10 Conclusion

The chapter has provided a detailed review of the precinct buildings that are under investigation within the research completed at Winchester. It has touched upon the survey methods used and cross-referenced to Appendix A where more information, about the methodologies used, can be seen. The chapter has provided the research questions that are necessary within the archaeological use of structural analysis. Specific queries have been asked on both standing and ruined buildings that can be only be answered using engineering techniques. The benefit of providing detailed archaeological assessments of different buildings allows for a wider sphere of influence within the overall thesis aims, especially through the varied detail prevalent within the buildings under investigation.

Chapter Six will utilise all of the information provided from this chapter, as well as Chapter Four and provide an overview of the Finite Element Method investigation at Winchester. The survey data included within this chapter will be converted to CAD-based models and each of the research questions proposed could be answered through structural testing. Chapter Six will refer to the problems highlighted in Chapter Two in relation to virtual modelling and will utilise the methods discussed in Chapter Three. The work will be broken into sections related to the buildings under investigation. It will focus on the questions asked, whilst at the same time providing a review of the research aims of thesis. These overall aims will be discussed in Chapter Seven and will provide an overview of the archaeological research shown in this chapter as well as Chapter Four.
Chapter 6: Results: Structural Analysis at Winchester Cathedral

6.1 Introduction

Chapters Four and Five provided detailed reviews of the archaeological research that has been completed on Winchester Cathedral church and the Cathedral’s Precinct. The following chapter will use these data to analyse various interpretations of how these buildings were originally designed. The purpose of this chapter is to provide a working case study that identifies the process of how structural analysis results are examined and critiqued within archaeological research.

The chapter begins with an overview of the methodology used in creating the structural models and will explain the importance of correctly defining the material properties of the structural elements. The chapter will then go on to discuss the problems that were found in the modelling and testing phase of this case study. The chapter will then consider the results generated from the structural analysis test of the cathedral and will provide a short assessment of the Finite Element Modelling method used. The results of the structural tests of the precinct buildings are discussed in Appendix A.

6.2 Methodology

In this study, structural analysis was used to analyse the load-bearing structural system of the buildings at Winchester Cathedral and its surrounding precinct. These tests were used to calculate the responses of the structures under relevant loading through linear analysis. The purpose of these tests were to find the capability of the structural form from the viewpoint of stability.

Creating the Finite Element Models involved the production of a solid CAD model that was watertight and contained no overlapping or free parts. This solid model construction required a computer-aided design program such as AutoCAD or Rhino, both of which have varying user interfaces. The software used in the production of the models at Winchester was AutoCAD. The manufacture of these CAD models incorporated the use of boxes, cylinders, and extruded planar surfaces to create the required three-dimensional geometry. Boolean operations such as union and subtract were used throughout to create the allowed watertight models. A number of commands and processes were required to create these solid models; an understanding of working in three-dimensional space was essential within this process. When working in a two-
dimensional space, the ability to draw features is straightforward; with the addition of three dimensions, the ability to create a model becomes more challenging and requires a superior understanding of the computer-aided design program used. It is not however the purpose of this thesis to explain how best to produce these solid models, as the processes are dependent on the choices made by the operator, as well the subject modelled. If the solid model is created in an incorrect way, and gaps or overlapping features are present within the data, errors will exist. Any errors included will result in the Finite Element software being unable to process the produced model. In the case of the Winchester models, some errors were present and are discussed in 6.4.

Once suitable solid CAD models were generated, the data were imported into the Finite Element Model software Autodesk Simulation. These solid models were then processed to create the required Finite Element Models. This involved the examination of the solid CAD models in two stages. The first was through the production of a Finite Element mesh. This mesh was then processed to create a Finite Element solid model. If errors were present in the solid CAD model, the production of the Finite Element mesh failed. The software required all parts to be complete: if gaps or overlaps were present, the Finite Element software assumed that the model was incorrect and aborted the mesh production. This stage allowed for the validity of the solid CAD models, with the results used to alter and fix the original CAD designs. This process took several attempts to fix and was time consuming to complete, as very small gaps aborted the production of the mesh surface model. To ensure the highest quality mesh, bricks and tetrahedral finite elements were used (3.3.3.2). The solid mesh consisted of as many 8-node three-dimensional finite elements as possible with regard to the differing mesh sizes. These 8-node elements each have three degrees of freedom at each node (3.3.3.6) and allow for the complete movement of the building under investigation.

Once a suitable solid Finite Element model was produced, characteristics and boundary conditions were applied (3.3.3.6). Characteristics allow for the addition of the material properties of each element (6.3), with boundary conditions defining how the Finite Element Model will move under examination. If partial areas or specific parts are tested, boundary conditions are used to simulate the removed features. Boundary conditions are used throughout the examinations to remove the number of simultaneous equations required to be solved (per node), thus saving time and processing power. Once these boundary conditions were defined, the testing parameters were added, such as the gravitational force. Within the Winchester tests, a standard gravitational force of 9.80665 N/m² was used in the Z plane to simulate normal gravity conditions; if required this value could have been exaggerated. Attached to these parameters are specific examinations, such as force loading to specific parts. These could have been used in the analyses to test the functions of the buildings under investigation. Instead, the analyses performed focus on the potential of the
building under standard gravity conditions, allowing for the validity of the structures modelled; their functions and use have not be incorporated with the overall examination.

Created Finite Element Models are idealisation where “structural detail including geometry, material properties, loads and boundary conditions are simplified based on the analysis chosen and the features felt to be of importance” (Cooke et al., 2001: 3). Specific parts of the models could have been enhanced in the mesh detail to create a more focused analysis, but with updated software solutions, this process has become more automated, based on the imputed geometry. Once all of the parameters were set, and the CAD models were converted to a Finite Element Solid model, the mesh was processed through a system of algebraic equations (per node) that were used to solve the simultaneous equations required (3.3.3.2). The results that are shown incorporate all of the possible analyses discussed in 3.2; for the Winchester analyses, the main results used are the displacement; maximum principle stresses (tension); and minimum principle stresses (compression).

In continuum mechanics, stress is a measure of the average force per unit area of a surface within the body on which internal forces act. At every point in a stressed body there are at least three planes, where the corresponding stress vectors are perpendicular to the plane, and where there are no normal shear stresses. The three stresses normal to these principal planes are called principal stresses. The maximum principle stress provides the tension results of the model under analysis, with the minimum principle stress providing the compression results. The tension and compression results, as discussed in 3.3.3.8, are defined by the allowed amounts of the materials used; if the values generated exceed the allowed maximum, the created model is structural unstable. The following results are based on the resulting maximum stresses and strains.

The only criterion that has been used within the Finite Element analyses are the material strengths of the different building elements, tested under linear elastic behaviour. The results generated may differ under non-linear elastic behaviour, and when examining the geometric proportions chosen. The choice of linear elastic behaviour is controlled by the material definitions available, as well as by the complexity in understanding the results that would be included in the numerical analyses under non-linear behaviours. The generated results under linear elastic behaviour will still provide insights into the viability of the proposed reconstructions and will act as a guide for further more detailed analyses to be performed.

All of the models produced are based on the survey work and documentary research completed (Chapters Four and Five). These have been simplified for the Finite Element Models, due to the difficulties encountered in using the original modelled data. The material properties for each structural element are discussed below.
6.3 Material Properties

The material properties defined in Table 3 are the characteristics of the building work used in the simulation tests at Winchester. Regrettably, none of these properties are based on the structural examinations of the building work at Winchester, as the facilities and available materials were unable to be tested in laboratory conditions. Rather, the results are created from a number of different sources, and include the Modulus of Elasticity (Young’s Modulus); Mass density; Poisson Ration; allowed Compressive Strength; and the allowed Tensile Strength.

An explanation of each material property is provided below and all are based on linear elastic isotropic materials (3.3.3).

6.3.1 Oak and Pine

The material properties of Oak have been extracted from European Wood (2015a) with the poisson ration found in Green et al. (2011: 4-3) work. The values assigned to pine have also been taken from European Wood (2015b) and again the poisson ratio has been extracted from Green et al. (2011: 4-3).

6.3.2 Quarr Stone

The modelling approach used in the investigation at Winchester incorporates macro-modelling (3.3.3.8) and the materials assigned ignore the distinctions between the different individual units and joints. As a result, the material property for Quarr stone ignores the lime mortar strength and assumes that these are adequate to support the stone blocks.

6.3.2.1 Mass density

Quarr stone is a limestone and has an open and porous texture. According to Natural Stone (2002), high density limestone has a mass density greater than 2560 kg/m³, whereas a medium density limestone has between 2160 kg/m³ and 2560 kg/m³. When comparing known mass densities of similar limestone, such as Caen stone (2141 kg/m³) (Karanikoloudis, 2014: 63), there appears to be a difference between different geological formations. At the Monastery of Jerónimos, Lisbon the Pedra Lioz limestone used had a Mass density of 2345 kg/m³ (Lourenço et al., 2007a: 283). At Hyde Abbey in Winchester, evidence shows that the Quarr stone found are of a denser material than Caen, with the fossilised shells being smaller and more tightly packed (Hyde900, 2014). As the Hyde Abbey Quarr stone is dense, and as no Quarr stone was available
from Winchester Cathedral, a mass density of 2300 kg/m³ was chosen. The chosen mass density is also in line with the material properties put forward by Seward (2005: 20) (Figure 170).

<table>
<thead>
<tr>
<th>Properties</th>
<th>Clay brickwork</th>
<th>Calcium silicate brickwork</th>
<th>Dense concrete blockwork</th>
<th>Light-weight concrete blockwork</th>
<th>Aerated concrete blockwork</th>
<th>Natural limestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kN/m³)</td>
<td>16 – 22</td>
<td>20</td>
<td>15 – 21</td>
<td>7 – 16</td>
<td>4 – 9</td>
<td>22</td>
</tr>
<tr>
<td>Compressive strength (N/mm²)</td>
<td>5 – 104</td>
<td>14 – 48.5</td>
<td>7 – 40</td>
<td>3.5 – 10.5</td>
<td>2.8 – 10</td>
<td>10 – 50</td>
</tr>
<tr>
<td>Flexural strength (N/mm²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– plane of failure perpendicular to bed joints</td>
<td>1.5</td>
<td>0.9</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>– plane of failure parallel to bed joints</td>
<td>0.5</td>
<td>0.3</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Elastic modulus (N/mm²)</td>
<td>5 – 25 or 450-900 f*</td>
<td>14 – 18</td>
<td>10 – 25 or 300 f*</td>
<td>4 – 16</td>
<td>1.7 – 8</td>
<td>15</td>
</tr>
<tr>
<td>Creep factor – final creep strain to elastic strain at working stresses</td>
<td>1.2 – 4.0</td>
<td>–</td>
<td>2.0 – 7.0</td>
<td>2.0</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Reversible moisture movement (%)</td>
<td>0.02 (+)</td>
<td>0.01 – 0.05 (+)</td>
<td>0.02 – 0.06 (-)</td>
<td>0.03 – 0.06 (-)</td>
<td>0.02 – 0.03 (-)</td>
<td>0.01 (+)</td>
</tr>
<tr>
<td>Initial moisture expansion (+) or drying shrinkage (-) (%)</td>
<td>0.02 – 0.10 (+) (0.03 when on site)</td>
<td>0.01 – 0.05 (-)</td>
<td>0.02 – 0.06 (-)</td>
<td>0.05 – 0.06 (-)</td>
<td>0.05 – 0.09 (-)</td>
<td>0.01 (+)</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (x10⁻⁵/C)</td>
<td>5 – 8</td>
<td>8 – 14</td>
<td>6 – 14</td>
<td>7 – 12</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Long-term natural water absorption (%)</td>
<td>3.0 – 15.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity at 5% moisture content (W/m°C)</td>
<td>0.07 – 1.20</td>
<td>1.2</td>
<td>0.6 – 1.3</td>
<td>0.20 – 0.44</td>
<td>0.10 – 0.27</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Figure 170. The material properties of masonry (Seward, 2005: 20). ©The Institution of Structural Engineers 2005.

6.3.2.2 Modulus of Elasticity

Seward (2005: 20) postulated that the maximum Modulus of Elasticity for limestone was 15GPa; when examining the work completed by Al-Shayea (2004: 141), where a number of different types of limestone were tested, a range of between 18-103GPa were found. Oolitic limestone, being similar to Quarr, was 45GPa when at rest; Caen in comparison, as it is a fine grained limestone was found to have the elasticity of only 3GPa (Karanikoloudis, 2014: 63). As no tests have been performed on Quarr stone that can be found in the literature, and as Winchester cathedral was constructed from a mixture of Quarr and Oolitic limestone, a Modulus of Elasticity of 20GPa was chosen.
6.3.2.3 Compressive strength

The compressive strength of Quarr stone is again unknown. Taking data from Minerals Zone (2016), the average compressive strength of limestone is between 60MPa and 170MPa; Seward (2005: 20) stated that limestone has an average of 10MPa to 50MPa; whereas Kahraman (2001: 984) stated that the limestone tested had a compressive strength between 15MPa and 152MPa. When comparing the possible compressive strengths of Quarr stone, and when looking at the studies completed by Karanikoloudis (2014: 63) (Figure 171) on Caen stone, which has a much lower compressive strength at 5MPa, it makes the assessment of what value to assign difficult. Work completed by Sachpazis (1990: 80) does provide further insight into this, who tested the compressive strength of English Limestone from Northumberland; the results being 81MPa. With the various compressive strengths seen, and although the geological formation will differ slightly, the value of 81MPa was chosen from Sachpazis’ work, as this corresponds to the present-day results from Minerals Zone (2016).

![Figure 171. Caen Stone Material properties (Karanikoloudis, 2014: 63). © Georgios Karanikoloudis 2014, Open Access.](image)

6.3.2.4 Tensile Strength

The tensile strength of saccharoidal limestone (marble) can be seen in Price and Knill’s (1966: 442) work, with an average of tensile strength of between 5MPa and 21MPa. Marble, being stronger than Quarr limestone would have a lower tensile strength. Schmidt (1976: 165), who examined a number of different American based limestone, suggested that Indiana limestone had a tensile strength of 5.51MPa. This value was based on the limestone having a Modulus of Elasticity of 34.3GPa, which exceeds the value assigned to the Quarr stone. Instead, the value put forward by
Hoagland et al. (1973: 100) will be used within the material properties of Quarr stone, as the limestone tested had a Modulus of Elasticity of 19.3GPa giving a tensile strength of 3.58MPa.

6.3.2.5 Poisson Ratio

The Poisson ration of stone is a reasonably standard number throughout most of the literature, and usually has ratio of 0.2 to 0.3 (Blyth and De Freitas, 1984: 165). The value of 0.2 has been assigned to the Quarr Stone material.

6.3.3 Purbeck Marble

Stone Finder (2012) reported that Purbeck marble has the Mass Density of 2650 kg/m$^3$ and a compressive strength of between 98MPa and 280MPa. Stone Contact (2016) however stated that the mass density of Purbeck is 2497.9 kg/m$^3$, and the compressive strength is 98MPa. The Building Research Establishment (2000) added to this further by suggesting that the compressive strength of Green Purbeck is 145.7MPa. Through the examination of the available material, a compressive strength of 120MPa and a Mass Density of 2500 kg/m$^3$ have been assigned. When examining the possible tensile strength of Purbeck, the average tensile strengths of marble have been used (8MPa) (You, 2015: 436).

No academic references can be found for the elasticity of Purbeck and very little exists for marble. This is a constant setback within a large proportion of materials and is an issue that needs to be resolved if structural analysis testing becomes a popular tool within archaeology. Taking into account that Purbeck is a form of limestone material, which should contain a greater potential within the elasticity, and following the material properties of commercially available marble (Bath & Granite, 2016), where the average elasticity is between 10GPa and 34Gpa, a value of 28MPa has been assigned to the Purbeck material.

6.3.4 Wattle and Daub

Timber framed buildings would usually have a wattle lining, covered with a dried mud or daub (Johnson, 1999: 320). Through the literature research completed, no evidence of the structural properties of wattle of daub can be found. As no physical testing can be completed on the wattle and daub found at Winchester, the data used had to be extracted from other sources. Daub, being an organic material, has similarities to mud earth bricks, as seen in Watts and Yoldas’s (2004) work. In their research, they examined the material properties of dried mud bricks, as well as hand compressed and stabilised earth bricks, which included cement (Watts and Yoldas, 2004: 5); daub, also being compressed in nature, would have similar structural material properties to
compressed earth bricks but would be weaker overall due to the exclusion of cement. The structural properties for daub have therefore been extrapolated from Watts and Yoldas’s research to include the internal wattle (Watts and Yoldas, 2004: 9).

### 6.3.5 Strength Properties

Below are the material properties that have been used within the investigation at Winchester. It must be noted that these have been produced from the sources of information that were available. The results that have been generated must therefore be treated with some small reservation, with precise answers requiring material properties extracted from the building work under investigation. Using data from the site in question removes problems attached to geological formations; this approach however is commonly used within engineering, and is a method that should be encouraged within archaeology if no material details are available. As more data becomes available, through laboratory testing, greater material properties will be available.

Table 3. The material strength properties of the materials used in the analyses at Winchester Cathedral and the surrounding precinct buildings

<table>
<thead>
<tr>
<th>Materials used in Models</th>
<th>Modulus of Elasticity</th>
<th>Mass Density</th>
<th>Poisson Ratio</th>
<th>Compressive Strength</th>
<th>Tensile Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarr</td>
<td>20GPa</td>
<td>2300 kg/m³</td>
<td>0.2</td>
<td>81MPa</td>
<td>3.58MPa</td>
</tr>
<tr>
<td>Oak</td>
<td>13GPa</td>
<td>702 kg/m³</td>
<td>0.35</td>
<td>61MPa</td>
<td>90MPa</td>
</tr>
<tr>
<td>(at 12 % moisture content)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pine</td>
<td>11GPa</td>
<td>520 kg/m³</td>
<td>0.3</td>
<td>55MPa</td>
<td>104MPa</td>
</tr>
<tr>
<td>Purbeck</td>
<td>28GPa</td>
<td>2500 kg/m³</td>
<td>0.25</td>
<td>120MPa</td>
<td>8 pa</td>
</tr>
<tr>
<td>Wattle and Daub</td>
<td>2.5GPa</td>
<td>1700 kg/m³</td>
<td>0.15</td>
<td>2.55MPa</td>
<td>0.8MPa</td>
</tr>
</tbody>
</table>
6.4 Difficulties

As mentioned in 6.2, the creation of a Finite Element model requires a watertight CAD model, where each element created (such as stone) is designed as a singular form. Usually within engineering, the creation of CAD models focus on the building materials that are structurally important; the same process was used in the production of the models at Winchester, with elements such as window colonnettes, vault ribs and blind arcading all being included. The inclusion of these elements however added a number of errors within the model. Figure 172 provides an overview of the CAD model of the reconstructed Romanesque cathedral, based on the evidence collected in Chapter Four. In AutoCAD this model was created using object snapping, which is a tool that allows each new three-dimensional part to be ‘snapped’ together. This process removes possible gaps in the final dataset and allows for the creation of one solid model. However, as is the case when working with solid models in AutoCAD, errors may still be included. In AutoCAD, the model shown in Figure 172, appeared to be correct, but when imported into Rhino, the software displayed the results as an open polysurface, indicating that there were errors in the model, with gaps being present. The CAD modelling took several months to complete and great care was taken to avoid this error. In the original development of the Finite Element Model, this CAD model, which appeared to be correct, was directly imported into Autodesk Simulation. When processed, Autodesk Simulation consistently failed to produce a solid Finite Element Model. A consistent error was produced (Figure 173), and this took some time to realise why this occurred. On examining the model in Rhino, which has the ability to examine each edge of the solid geometry, a number of naked edges were found (Figure 174). Naked edges are edges that have only one adjacent face, and thus are treated as being open; creating a model that contains gaps and is not watertight.
Figure 172. Wireframe model of the completed cathedral model

Figure 173. Error in the meshing of the CAD model
On examining the results shown in Figure 174, the errors found were mainly contained within the extra detail included within the model, specifically those areas that contained cylindrical shapes, such as the colonnettes of the nave windows. Figure 175 provides an overview of how these window colonnettes appear as rendered objects, and from a first glance, the model appears to be passable. When examining the wireframe (Figure 176), the contained naked edges appear to relate to the connecting parts of the nave wall and the cylindrical colonnette. This error is confirmed in Figure 177, which highlights the top down view of the window colonnettes, with the error limited to the three-dimensional cylinder touching the surfaces of the three-dimensional wall. The same errors are seen in the nave piers in Figure 178, which include cylindrical shapes. To create a complete solid model, each element that was used to create the reconstructed model was unioned as one; this process made the errors problematical to fix. If each element were not unioned, the time associated with the meshing process in Autodesk Simulation would have been excessive and unwarranted, resulting in several hundred parts, and their connecting surfaces, needing to be examined individually. As the time spent producing the CAD models was already disproportionate to the final results necessary, and rather than restart the modelling process, these errors were fixed by removing the cylindrical shapes by adding three-dimensional rectangles and unioning them to create the necessary watertight model. As a result, the CAD model of the cathedral used in Autodesk Simulation is of a simplified form. The results shown will differ slightly to those that include these cylindrical shapes; these are negligible and do not affect the overall analyses performed. When modelling such details in the future, greater care must be made to avoid these surfaces touching one another; this is possible, but only during the initial modelling stages.
Figure 175. Nave window colonnettes

Figure 176. Wireframe model of the nave window colonnettes, highlighting the naked edges
Figure 177. Top down view of the wireframe nave window colonnettes showing the location of the naked edges

Figure 178. Internal wireframe of the nave piers and windows highlighting the naked edges

The cathedral was the first model that was tested and after several attempts, the errors were removed. On importing the other models under investigation into Autodesk Simulation, the same naked edge hindrance was found. Figure 179 provides the same open polysurface error in Rhino of the Chapter House, with Figure 180 highlighting the areas that contained the naked edges. These were again corrected and Figure 181 provides an overview of the closed polysurface notification, thus reporting that the model is suitable for Autodesk Simulation.
Figure 179. Screen capture of Rhino indicating that the Chapter House model is open and non-watertight

Figure 180. Screen capture of Rhino indicating where the naked edges (in red) are in the Chapter House model
The same errors are found in the reconstructed model of Number 10 (Figure 182), with the naked edges found predominantly on the vault ribs connecting to the central columns in the building’s undercroft. As a final error, the timber-framed roof of Pilgrim Range (Figure 183) also contained naked edges, predominately on the connecting parts of the trusses.
Once all of the naked errors in each model had been resolved, a further error was faced. Autodesk Simulation and AutoCAD are based around the same software parameters; Autodesk Simulation allows for the direct importation of an AutoCAD model, but unexpected errors in this importation were found when two or more solid parts were incorporated. This error is shown in Figure 184 with the stonework of the Chapter House and the Purbeck columns located in incorrect locations. The reason assigned for this error is unknown but this was fixed by importing the CAD model into Rhino. This imported model was then exported as a Rhino file format, and imported into Autodesk Simulation, where each element was positioned correctly.
On reviewing the errors found, the preferred software for creating these solid CAD models is still AutoCAD, due to three-dimensional processes available. Rhino could have been used, but the software interface is not as intuitive. Rhino however was a necessary tool to validate the created models, and should be used in future process to aid the production of the CAD models before importing them into Autodesk Simulation. As was found during this process, Autodesk also provide their own validation tool (Autodesk SimStudio), which attempts to correct any errors before importing them to Autodesk Simulation; this tool however was inadequate and was unable to fix the errors present.

Having repaired and simplified all of the CAD models, these were imported into Autodesk Simulation, where the structural analysis test were performed. The following provides a breakdown of the results gathered.
6.5 Cathedral Structural Tests

6.5.1 Research Questions

As specified in 4.4, a number of research question that could be answered using structural analysis were identified. It is not the purpose of this thesis to answer all of these questions; rather the thesis will be used to demonstrate how structural analysis could be used. Consequently, the research questions that will be answered are listed below and these will be answered through the following section:

- What led to the collapse of the Romanesque central tower?
- Could the original Romanesque cathedral have supported all of the towers proposed?
- Are the additions of the early twentieth-century flying buttresses on the south exterior nave wall supporting the cathedral? If so, could the second option of buttress have been chosen as an alternative?
- How have the changes in roofing style affected the building?
- Can structural analysis be used to correctly emulate known structural decay?

6.5.2 Creation of the Model

Following the difficulties outlined in 6.4, the cathedral model has been separated into key areas; these are the tower, retrochoir, transept, nave, west front, timber roof, and the crypt. The original created model of the cathedral can be seen in Figures 184 to 187. This model was created using the documentary research completed in Chapter Four, as well as the survey work completed on site. This survey work has been used directly within the CAD modelling process to enable a precise reproduction, based on the known surviving structural details (Figures 188 to 190). In total, the model took over three months to complete, with each element being carefully constructed. The production of unknown and controversial parts (e.g. the west front) have been created based on the known documentary research, as well through site visits to Bristol, Canterbury, Durham, Ely, Gloucester, Lincoln, Norwich, Peterborough, Rochester and Worcester cathedrals. The research questions outlined above will be answered in the following sections.
Figure 185. Overall CAD model of the Romanesque cathedral facing northeast

Figure 186. Overall CAD model of the Romanesque cathedral facing southwest
Figure 187. Top down view of the CAD model of the Romanesque cathedral

Figure 188. Underneath view of the CAD model of the Romanesque cathedral, highlighting the internal vaulting.
Figure 189. Overall CAD model of the Romanesque cathedral highlighting the laser scan model used in its construction (facing northeast)

Figure 190. Overall CAD model of the Romanesque cathedral highlighting the laser scan model used in its construction
6.5.3 The Original Tower

6.5.3.1 Creation of the Model

Sections 4.2.8 and 4.2.11 discussed the central tower modification following the collapse of the tower in 1107 AD. The tower piers that are found at Winchester cathedral suggest that a level of over engineering was incorporated into the design and unfortunately there exists very little to suggest how the original tower at Winchester was designed. On examining surviving Romanesque cathedrals, some evidence can be used and extrapolated to create an interpretation of how the original cathedral was designed. Through this process, and through structural testing, an idea of what led to the central tower collapse can be gained, as can an idea of the original height of the tower.

One of the comparable cathedrals can be found at Lincoln, with Figure 192 highlighting Lincoln’s modified central tower. This tower has a height of 82 metres and has been converted into the Gothic style. Lincoln’s tower is of a square form and is simplistic in design. Figure 193 provides an overview on Norwich cathedral’s central tower, and is similar in design to Lincoln’s, except that the converted tower includes a spire. The height of Norwich’s central tower, including the spire, is currently 96 metres (without the spire the tower’s height is 60 metres), with the tower’s fabric above the ridge dating to C. 1121-40 (Gilchrist, 2005: 70). The internal tower piers of Norwich cathedral are shown in Figure 194 which shows the uniformity of the fabric, unlike Winchester cathedral, which has enhanced tower piers.
Figure 192. Lincoln cathedral central tower
Figure 193. Norwich Cathedral central tower

Figure 194. Norwich cathedral tower piers
Similar to Norwich cathedral, the tower piers of Peterborough cathedral are also uniform in design, with the tower following the same arrangement as the piers. This simple form can be seen throughout England, where architecture survives and where specific to a square formed tower. As such, when creating the original tower at Winchester, this pier system has been used. The height of the tower at Winchester is however unknown (4.2.11); sources have remarked that the central tower was reduced in height when it was rebuilt, and are thus are able to state that the tower was taller than the current 45 metres. Taking into account the heights of Durham and Ely cathedral (66 metres), Canterbury cathedral (72 metres) and Lincoln cathedral (82 metres), various heights can be assigned to the tower at Winchester. These differing heights were tested, based on the evidence available at Winchester and the results are discussed below. The architectural style assigned to the tower is of a simple Romanesque form.

Figure 195. Peterborough cathedral tower piers
6.5.3.2  45-metre Tower

Figure 196 provides an overview of the original Romanesque tower at Winchester, set at a height of 45 metres, which is based on the current height of the central tower at Winchester. As the inclusion of a spire is debated, the model tested was based on the architectural form of the stonework. Figure 197 and Figure 198 provide a further overview of the reconstructed tower, with Figure 198 showing the size of the tower piers in relation to the surrounding nave and transept piers. The tested model has been sliced and boundary conditions have been applied to simulate the removed architecture. The material used throughout the cathedral study is Quarr stone (6.3.2).

Figure 196. The simplified CAD model of the 45-metre tower (facing northeast)
Figure 197. The simplified CAD model of the 45-metre tower (facing north)

Figure 198. The underneath of the simplified CAD model of the 45-metre tower, highlighting the size of the internal tower piers (facing southwest)
Chapter 6

With the model modified to allow the structural tests to be completed, the CAD model was converted into a Finite Element Model as shown in Figure 199. The Finite Element mesh contains a number of finite elements, with smaller elements added to the more complicated areas within the geometry.

![Figure 199. Meshed Finite Element model of the 45-metre tower](image1)

Figure 199 provides the maximum displacement of the tested model, with a maximum movement of 1.38 millimetres obtained.

![Figure 200. Displacement results of the 45-metre tower](image2)
The tensile stress of the tower at 45 metres was 3435705 N/m² (Figure 201), which is acceptable within the given material properties. The majority of tension found appears to be on the supporting nave and transept walls, as expected, due to the outwards force that the tower exerts on the building work.

Figure 201. Maximum principle stress results of the 45-metre tower

The compressive stress of the 45-metre tower was -3802238 N/m² (Figure 202) and is again acceptable within the maximum compressive stress of Quarr stone defined in the material properties. From Figure 202, the compression centres on the tower pier arches, with Figure 203 suggesting that the compression is being directed through the four tower piers; again, this is an expected result.

Figure 202. Minimum principle stress results of the 45-metre tower
Figure 203. Minimum principle stress results of the underneath of the 45-metre tower

The internal force, as shown in Figure 204 was 1584587 Newtons, with the majority of force being applied to the four central pier bases. These bases would have been supported by a foundation and it has been assumed in these tests that the foundation was adequate to support the tower. As noted in 4.2.11, the original tower did collapse, most likely due to an inadequate foundation or subsidence in the foundation; a structural test, which includes the foundation, has been included and will be discussed at the end of the section.

Figure 204. Internal force results of the 45-metre tower

Following the structural tests performed, as the maximum movement found is reasonable and as the tensile and compression stresses are within the allowed limits of the material properties, it can said that the 45 metre tower is of an acceptable form and is structurally valid.
6.5.3.3  66-metre Tower

The height of the tested 66-metre tower was based on the heights of Durham and Ely cathedrals. Figure 205 provides an overview of the reconstructed tower, with Figure 206 providing an overview of tower arches.

Figure 205. The simplified CAD model of the 66-metre tower (facing northeast)
The maximum displacement of the 66-metre tower was 2.99 millimetres (Figure 207). This value is slightly more than the previous 45-metre tower but again the movement found is permissible.

The tensile stress of the 66-metre tower was 3109916 N/m² (Figure 208). The value obtained is within the permitted results, and is less than the results found in the 45-metre tower. The tensile
value may be less, due to the increased weight of the tower directing the forces downwards, rather than sideways, thus producing less tension in the masonry.

Figure 208. Maximum principle stress results of the 66-metre tower

The compressive stress of the 66-metre tower was -5992098 N/m² (Figure 209) and again is within the permitted results. The results gained are greater than the previous, but as mentioned above, with an increased weight being applied to the tower piers, a larger compressive force is exerted.

Figure 209. Minimum principle stress results of the 66-metre tower

Figure 210 provides a further overview of the compression results found, with the highest compression values seen next to the arches of the tower. This is again highlighted in Figure 211, which provides a closer inspection of the interior arches.
Figure 210. Minimum principle stress results of the 66-metre tower, highlighting the compressive nature surrounding the central arch

Figure 211. Minimum principle stress results of the underneath of the 66-metre tower

The internal force of the 66-metre tower was 1788208 Newtons (Figure 212), again this in concentrated mainly on the four tower pier bases.
As with the 45-metre tower, the displacement value, as well as the compression and tensile stresses are acceptable: the 66-metre tower can be said to structurally valid. The height of the tower could therefore have been at 66 metres, and as Ely was designed after Winchester, this height is the most logical form.

### 6.5.3.4 72-metre Tower

The height of the tested 72-metre tower was based on the height of Canterbury cathedral before a fire destroyed the central tower, an overview of the created CAD model can be seen in Figure 213.
The maximum displacement of the 72-metre tower was 3.89 millimetres (Figure 214). As with the 45 and 66-metre tower, this movement is acceptable and is mainly found at the top of the tower.

The tensile stress of the 72-metre tower was 3885242 N/m² (Figure 215). This value exceeds the allowed total of Quarr stone and signifies that the 72-metre tower would fail due to tension, thus creating an invalid reconstruction.
Although the tensile stress of the 72-metre tower exceeds the allowed amount, the compressive stress was -7605620 N/m² (Figure 216). This value is acceptable but as shown in Figure 216, the compression is again concentrated around the tower arches, with the compression seen to be located higher than the 45 and 66-metre towers.

The internal force of the 72-metre tower was 2390205 Newtons, which is a significant increase in the internal force of the 66-metre tower. Again, the force is concentrated in four tower pier bases and may lead to an explanation of why the tension results are too high, with too much force being directed onto these bases (Figure 217).
With the tension results being over the permitted value, the structural tests indicate that a 72-metre tower was not possible, based on the evidence collected in Chapter Four.

### 82-metre Tower

Although the previous 72-metre tower failed under tension, it was important to test a further height, to see if a taller tower was possible. The tower height of 82 metres has been taken from Lincoln cathedral and Figure 218 provides an overview of the reconstructed model.
The maximum displacement of the 82-metre tower was 4.54 millimetres (Figure 219), again concentrated at the top of the tower.
The tensile stress of the 82-metre tower was 7741489 N/m² (Figure 220) which is over twice the allowed tensile stress of Quarr stone. As with the 72-metre tower, the 82 metre fails under tension.

The compressive stress of the 82-metre tower was -7869348 N/m² (Figure 221) which is a slight increase to the 72-metre tower. Again, this value is acceptable and under compression loading, the building is valid.

However, as the tower fails under tension, the building work is structurally unsound and the results show that a height of 82 metres would not have been possible based the reconstructed model.
6.5.3.6 82-metre Tower with Subsidence

Although the 82-metre tower failed under normal gravitational forces, it was important to test how such a tower would react with subsidence of the internal tower piers. Figure 222 provides the results of the maximum displacement of the 82 metre with subsidence present, with a value of 5.94 millimetres being generated. This value has increased under subsidence and is concentrated on south tower wall, where the subsidence was applied. This result is expected but a greater movement was anticipated.

With the subsidence included, the tensile stress of the 82-metre tower was 29362930 N/m² (Figure 223). This value is 8.2 times the maximum allowed and is a significant increase to the previous result. Using this data, it can be suggested that subsidence, or poor foundation work was the cause of the central tower collapse, as the increase in tensile stress is of such a magnitude that it necessarily follows that it would be of a similar increase with a lower tower height.

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Figure 222. Displacement results of the 82-metre tower with subsidence

Figure 223. Maximum principle stress results of the 82-metre tower with subsidence
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With the results generated from the structural tests of the original Romanesque tower, the original height of the tower was less than 72 metres, with the most likely height being 66 metres. The cause of the tower collapse, based on the height of 66 metres relates more to possible subsidence or poor foundation work, rather than through the support mechanism of the rest of the cathedral. Although the original tower has now been tested, the tower collapse could still relate to poor workmanship and faults in the stonework. This would seem questionable however due to the detail and craftsmanship shown throughout the cathedral.

6.5.4 The Current Tower

Although the first research question related to the cathedral has been answered, it was felt to be of importance to test how overengineered the rebuilt tower piers are. As a result, the current pier system was reconstructed and various increases in the tower height have been tested.

6.5.4.1 45-Metre Tower

The cathedral tower at Winchester currently stands at 45 metres. To prove that Finite Element Modelling is a suitable tool in predicating structural results, the height of the current central tower was tested. The created CAD model can be seen in Figure 224. Figure 225 highlights the change in the shape of the central tower arches following the modification, with Figure 226 providing an overview of the size of the central tower piers. These in comparison to Lincoln and Norwich are of a significant increase.
Figure 224. The simplified CAD model of the 45-metre tower with existing tower piers (facing northeast)

Figure 225. The simplified CAD model of the 45-metre tower with existing tower piers (facing north)
Figure 226. The underneath of the simplified CAD model of the 45-metre tower with existing tower piers, highlighting the size of the internal tower piers (facing southwest)

The maximum displacement of the 45-metre central tower at Winchester is 1.08 millimetres (Figure 227). This value is minimal in terms of movement and demonstrates that results are valid.

Figure 227. Displacement results of the 45-metre tower with existing tower piers

The tensile stress found within the 45-metre tower was 1630951 N/m² (Figure 228) and is within the allowed total of the tensile strength of the material. The greatest tension that exists within the model can be seen in the transept walls, which act as a support mechanism for the tower.
The compressive stress found was -3185188 N/m² (Figure 229) and again is permissible. The compression is mainly found next to the tower arches; as the tower piers are exaggerated in shape, the compression is minimal, with the piers supporting the forces applied, as shown in Figure 230.
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As with the tests performed on the original tower architecture, the internal force (Figure 231) of the current cathedral tower is concentrated within the bases of the tower piers, with the structural tests indicating an internal force of 2541799 Newtons. This is a significant increase to 1584587 Newtons found in the original form of the tower system, but is expected with the increase weight of the masonry.

Figure 231. Internal force results of the 45-metre tower with existing tower piers

As the current tower is still standing, and as the structural tests indicate that the model is structurally viable, the results suggest that Finite Element Modelling solutions are acceptable and reliable.

6.5.4.2 55-Metre Tower

In order to assess how over engineered the tower modification was, a 10 metre increase to the tower height has been applied, with the reconstructed 55 metre tower shown in Figure 232.
Figure 232. The simplified CAD model of the 55-metre tower with existing tower piers (facing northeast)

The maximum displacement of the 55-metre tower was 1.64 millimetres (Figure 233); again this value is minimal and is of a satisfactory movement.

Figure 233. Displacement results of the 55-metre tower with existing tower piers

The tensile stress of the 55-metre tower was 1898952 N/m² (Figure 234) and is within the possible allowed tensile strength of the material properties.
The compressive stress, as with the 45-metre tower, is within the permitted compressive strength of material properties, with a value of -3138662 N/m² being found, as shown in Figure 235.

With the height of the tower increased to 65 metres, the maximum displacement found is 2.35 millimetres, as shown in Figure 236.
The tensile stress of the 65-metre tower was 2883222 N/m² (Figure 237) and is acceptable within the tensile strength of the material properties.

The compressive stress of the 65-metre tower was -3702596 N/m² (Figure 238) and is within the permitted compressive strength of the material properties.
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6.5.4.4 75-metre Tower

With the tower increased to 75 metres (Figure 239) the maximum displacement found was 3.17 millimetres (Figure 240). As with the other results, this movement is acceptable and is concentrated around the top part of the tower.

Figure 239. The simplified CAD model of the 75-metre tower with existing tower piers (facing north)

Figure 240. Displacement results of the 75-metre tower with existing tower piers
The tensile stress of the 75 metre was 6569514 N/m² (Figure 241) and is almost twice the value of the tensile strength of the material property. The structural tests therefore show that the tower, as it stands today, would be unable to support a 75-metre tower, as it would fail under tension.

![Figure 241. Maximum principle stress results of the 75-metre tower with existing tower piers](image)

The compressive stress however is within the permitted value, with the results producing a value of -5112380 N/m².

![Figure 242. Minimum principle stress results of the 75-metre tower with existing tower piers](image)

With the structural results generated, it can be seen that the tower would fail if it were designed with a height of 75 metres. As the tower is currently 45 metres, it can be shown that the building work is over-engineered but fails at the same height as the original tower design. Although this is evident, the central tower arches do differ in terms of shape and size and this undoubtedly affects the structural feasibility. Perhaps with wider arch on the transept termination, the central tower would still be able to accommodate a taller tower.
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6.5.5 The Retrochoir

6.5.5.1 The Creation of the Model

The creation of the retrochoir model was based on the documentary research shown in sections 4.2.5, 4.2.7 and 4.2.13. With the retrochoir remodelled by Bishop Fox, very little remains of the original cathedral apse. The only evidence to support its shape and termination are found in the crypt (4.2.12). It was the intention of this thesis to include a remodelled form of the crypt within the investigation completed, but too many errors were generated during the CAD production of this section, as discussed in detail in 6.5.10. Instead, the crypt survey has been used to extract the possible shape and location of the apse within the Romanesque cathedral, as shown in Figure 243. This inclusion of the crypt survey is important within the reconstructed model, as it highlights a flaw in the reconstructed model created by Portsmouth University (Figure 4), in that their retrochoir is one bay too long. The reconstructed model created within these tests are therefore superior, in that survey data was used in its reconstruction.

![Figure 243. CAD model of the Romanesque cathedral showing the positioning of the crypt survey (facing north)](image)

As the only evidence of the apse appears in the crypt at Winchester, an examination of surviving Romanesque apses had to be completed. Figure 244 provides an outline of the apse at Norwich cathedral, highlighting the significant increase in pier shape around the semi-circular form. Figure 245 continues this overview with a focus on Norwich’s triforium bay, highlighting the difference between the straight section of the triforium and the semi-circular configuration.
On examining the architecture at Peterborough cathedral, the triforium bays in the apse are constructed in a different manner, with a clearer separation between the two semi-circular forms and the perpendicular walls (Figure 246). With the crypt survey of the apse form at Winchester,
the design is similar in style to Norwich, and the reconstructed model has been based on the form found there, as well as the evidence found within Winchester Cathedral’s transept.

6.5.5.2 The Original Retrochoir

Through the documentary research, as well as the survey work completed, a reconstruction of the original retrochoir has been generated, as seen in Figure 247 and Figure 248. This model
incorporates the original tower design mentioned by Crook (1993a) and Figure 249 highlights the internal view.

Figure 247. The simplified CAD model of the retrochoir (facing northwest)

Figure 248. The simplified CAD model of the retrochoir (facing southeast).
Figure 249. The simplified CAD model of the retrochoir (facing south)

The maximum displacement within the reconstructed model was 0.42 millimetres (Figure 250) and suggests that the inclusion of the retrochoir towers were possible.

Figure 250. Displacement results of the retrochoir

This statement is further supported by the tensile stress, which was 903745.5 N/m² and is within the permitted tensile strength of the material properties. The largest tensile stress found relates to the termination of the retrochoir and the connection with the tower, as shown in Figure 251. The location of this maximum stress value is surprising as it was thought that the greatest stress would be found near to the retrochoir towers.
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The structural validity of the retrochoir is confirmed through the compressive stress result, which was -1752207 N/m² (Figure 252), with the largest compressive stress found to be on the base of the semi-circular form of the apse (Figure 253).

As with the structural tests performed, a number of different examinations could take place. With the retrochoir, and with its semi-circular form, the applied force of the building work has been generated, as shown in Figure 254. The applied force results of 48945.77 Newtons provides an
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overview of how the retrochoir aisle piers supported the overall shape of this area, with a greater applied force seen in the aisle vault supports.

![Figure 254. Top down view of the applied force results of the retrochoir highlight the maximum value](image)

With the maximum displacement and the tensile and compressive stresses, the results of the reconstructed retrochoir are valid and the building could have supported the inclusion of two towers.

6.5.5.3 The Retrochoir with Applied Subsidence

When considering the cathedral, as pointed out in 4.2.17 and again by Lourenço (2001: 94), the foundations are what support the building. The force acting on these foundations are the surrounding soil and local geology. When the soil or supporting geology deforms through movement, as was the case at Winchester, the foundations are affected and this affects the overall building work. Small variations create a knock on effect and these are seen in the following results. The same model used in the previous examination has been used in this test, but included are subsidence variations of the southeast part of the retrochoir.

Within the applied subsidence, the maximum displacement was 3.84 millimetres (Figure 255). Although this value is small, the location of the apse is further west than the current subsidence found at the cathedral (4.2.17.3), and only part of this model has been exaggerated. The results follow the movement seen in the cathedral. If the current form of the cathedral were to be modelled and tested, the subsidence would be greater, as more of the building work would be affected.
With the subsidence applied, the tensile stress found within the cathedral was 3093761 N/m² (Figure 256). This value is within the limits of the tensile strength of the material property but is close to failing. Again, as the retrochoir was reconstructed in its original form, the subsidence area would have been further east. The results do however follow those found in the cathedral and it can be said that structural analysis is able to correctly emulate known structural decay.

As with the subsidence, a greater stress would be applied to the building in relation to its compression. The compressive stress found with the subsidence applied was -7226699 N/m² (Figure 257 and Figure 258) and is six times the previous result. This compression is seen in the connecting parts of the applied subsidence and the static building work (fixed in position by the foundation).
On examining the applied force of the subsidence, the maximum applied force of 42004373 Newtons can be seen next to the tower that is fixed in its position by the foundations (Figure 259). On comparing these results to the previous, the value given is greater and the location of the applied force differs, as the building has to react differently.
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Figure 259. Applied force results of the retrochoir with subsidence, highlighting the maximum value. The location of the maximum applied force has moved in comparison to the previous test without subsidence.

Using the results from the subsidence test as a guide, it can be said that structural analysis is able to emulate known structural decay, adding to the validity of the results generated within the overall structural tests performed at Winchester.

6.5.6 The Transept

6.5.6.1 The Creation of the Model

Winchester is fortunate to have surviving Romanesque features in the transept, and the majority of this evidence has been used in the recreated model. As discussed in 4.2.10, the transepts have been modified slightly and the recreated model focuses on the original construction. As with scarring found in the transepts, there is clear evidence to support the inclusion of two transept towers on both the north and south transepts. These towers were never included in the completed design of the cathedral, but the masonry found on site indicates that their inclusion were possible. On examining contemporary cathedral transepts, some indication of their intended design can be gained. Figure 260 provides an overview of the transept towers found at Canterbury cathedral and date to c. 1093-1109 AD, before the 1174 fire which burnt down the west front. The towers at Canterbury are substantial in design and are indicative of the potential design found at Winchester.
Figure 260. Canterbury cathedral transept tower, created c. 1093-1109

In comparison to Canterbury cathedral, Figure 261 provides an overview of the transept towers at Gloucester cathedral, which are smaller in design. The same can be said for the transept towers at Norwich (Figure 262), which include the original three bay Romanesque windows.
Both Canterbury cathedral and Gloucester cathedral do not have transept buttresses, but these are found at Norwich and at Peterborough cathedral (Figure 263). The inclusion of buttresses at...
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Winchester were incorporated into the design work of the cathedral transept, as shown in Figure 264, and have been included in the reconstructed model. It is not known whether these buttresses were necessary, and both variations have been tested. The creation of the model was based on the evidence found at Winchester, and includes the features at both Canterbury and Norwich cathedrals.

Figure 263. Peterborough cathedral exterior transept
6.5.6.2 The Transept with Buttresses Included

Figure 265 through to Figure 268 provide an overview of the reconstructed transept at Winchester cathedral. Due to the symmetry of the building, only one transept has been tested under gravitational loading, with the results expected to be the same for both designs. The layout of the transepts follow the evidence found at Winchester, with the laser scan model used throughout to recreate the known masonry. The included towers follow the geometry and scarring found on site, with their termination found on the transept aisles, as well as the outline of the external transept walls.
Figure 265. The simplified CAD model of the transept termination with buttresses (facing southwest)

Figure 266. The simplified CAD model of the transept termination with buttresses (facing south)
With the inclusion of the buttresses and towers, the maximum displacement of the transept was 0.49 millimetres (Figure 269). The maximum movement is be found at the top most part of the towers and is of a minimal value.
Figure 269. Displacement results of the transept termination with buttresses

The tensile stress of the transept was 1791659 N/m² (Figure 270) and is within the permitted results of the material property, with the largest stress seen in the supporting transept walls (Figure 271), as is expected.

Figure 270. Maximum principle stress results of the transept termination with buttresses

Figure 271. Maximum principle stress results of the transept termination with buttresses, highlighting the internal stresses
The compressive stress was -1712012 N/m² (Figure 272) and is again within the allowed compressive strength of the material. The compression is mostly in the exterior wall next to the buttresses, with further compression seen in the internal clerestory, again along the supporting transept walls (Figure 273).

![Figure 272. Minimum principle stress results of the transept termination with buttresses](image)

As shown in Figure 274 the internal force of 632966.6 Newtons was found to converge mainly on the bases of the buttresses, as is expected, considering that the buttresses relieve the overall forces found within the building work.

![Figure 273. Minimum principle stress results of the transept termination with buttresses, highlighting the internal stresses](image)
6.5.6.3 The Transept without Buttresses

As discussed in 6.5.6.1, structural tests have also been included to evaluate how the buttresses affect the overall strength of the building; these are shown in Figure 275 and Figure 276.
Figure 276. Top down view of the simplified CAD model of the transept termination without buttresses

Without the buttresses included, the maximum displacement found was 0.52 millimetres (Figure 277) and is a slight increase to the displacement results found with buttresses.

Figure 277. Displacement results of the transept termination without buttresses

The tensile stress was 2031649 N/m² (Figure 278). Without the buttresses, the tensile stresses generated are greater but are still acceptable and valid.
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Figure 278. Maximum principle stress results of the transept termination without buttresses

The compressive stress obtained was -1568593 N/m² (Figure 279) and is less than the previous result. Again, the compressive stresses are mainly found at the base of the transept wall, where the buttresses were previously included. The value is less, due to the removal of the weight that these buttresses would have exerted on the building work.

Figure 279. Minimum principle stress results of the transept termination without buttresses

As with the removal of the buttresses, the internal force of the building work was 920771.9 Newtons (Figure 280). The internal force is greater than the previous results, and again is an expected result. The internal force, rather than concentrated within the buttresses, are at fixed points, connected to the bases of the transept termination piers.
6.5.7 The Nave

6.5.7.1 The Creation of the Model

As discussed in 4.2.9, the nave of Winchester Cathedral has been modified from the original Romanesque form. The original nave piers are located within the converted Gothic piers, and their size are at a fixed dimension. On examining surviving Romanesque nave piers, a considerable division can be seen in the design work. Gloucester cathedral, as shown in Figure 281, includes substantial column supports, which now support the Gothic vaulting. These are disproportionate to the available dimensions found at Winchester.

Figure 280. Internal force results of the transept termination without buttresses
On observing the remains found at Ely cathedral (Figure 282), the nave piers alternative in shape, with the inclusions of a series of colonnettes, as well as large columns with scallop capitals. These colonnettes are also seen at Norwich (Figure 283) and at Peterborough cathedrals (Figure 284).
Figure 283. Norwich cathedral nave piers

Figure 284. Peterborough cathedral nave pier
As Ely was built shortly after the construction of Winchester, and as Norwich follows the form found at Winchester, the inclusion of the colonnette supports within the nave have been adopted in the reconstructed model of Winchester.

With the nave piers being modelled after Ely and Norwich, an examination of the triforium and clerestory bays was also necessary. At Winchester, these bays were removed due to the Gothic restyle; their sizes and the masonry work used are extracted from those found in the surviving transept bays. Their size however are unusual. At Ely, as shown in Figure 285, the triforium bays are supported by a thin central colonnette. At Winchester, this central column is also found, but is larger.

![Figure 285. Ely cathedral nave triforium bays.](image)

At Norwich (Figure 286), the triforium bays are of a single arch form, with the triforium support shafts substantial in size. These support shafts are similar in design to Rochester cathedral (Figure 287), with the exception that a double arch bay is included, with two supporting central colonnettes. Rochester cathedral is of a later design to Winchester, and the inclusion of these double colonnettes would unlikely be included at Winchester. Following the surviving remains at Winchester and on examining Ely and Norwich cathedral, the nave triforium follows a system of a large supporting shaft, with a large central support colonnette, separated into two arch responses.
Figure 286. Norwich cathedral nave triforium bays

Figure 287. Rochester cathedral triforium nave bays
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The Romanesque clerestory of the nave at Winchester survives, and is hidden behind the Gothic architecture. Originally included, and as seen in the transept, the clerestory would have contained a walkthrough, similar to that found at Norwich (Figure 288).

![Norwich cathedral nave clerestory walkthrough](image)

Figure 288. Norwich cathedral nave clerestory walkthrough

6.5.7.2 The Romanesque Nave with the Addition of Flat Buttresses

The cloisters found on the south side of the nave originally supported the Romanesque cathedral nave. The nave system has been modelled to include the original flat buttresses, which have been extended to the ground to simulate the inclusion of these cloister walls. The recreated model is shown in Figure 289 to Figure 291. With the difficulties discussed in 6.4, the nave piers have been simplified in order for Autodesk Simulation to run the necessary tests.
Figure 289. Exterior CAD model of the Cathedral South nave with flat buttresses (facing northeast)

Figure 290. Interior CAD model of the Cathedral south nave (facing southwest)
The maximum displacement of the nave was 0.14 millimetres, as shown in Figure 292.

The tensile stress was 264091.6 N/m² (Figure 293) and is within the permitted tensile strength of the material properties, with the largest tensile stresses seen in the aisle vaulting, as shown in Figure 294. The location of these tensions stresses are to be expected, as the central nave piers are redirecting the forces outwards.
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Figure 293. Maximum principle stress results of the south nave with flat buttresses

Figure 294. Maximum principle stress results of the south nave with flat buttresses, highlighting the internal stresses

The compressive stress was -311835 N/m² (Figure 295) and is again within the allowed compressive strength of the material property. As shown in Figure 296, the largest compression is seen in the relieving support columns of the nave aisle, and is foreseeable considering the tensions stresses found in the vaulting above.
Although the results indicated provide an assessment that the building work is structurally viable, there is some level of displacement found in the current building. As with the twentieth-century under pinning program (4.2.17) this displacement seems to be the results of subsidence or poor foundation support, as the building under gravitational loading, and with fixed foundation support is more than adequate to support the original construction.

6.5.7.3 The Romanesque Nave with the Addition Flying Buttresses

As discussed in 4.2.17.4, the cathedral introduced a series of flying buttresses to the south nave, to add a further support mechanism for the failing building. These have been modelled and tested; the CAD reconstruction are shown in Figure 297 and Figure 298. The testing has included
the original Romanesque reconstruction, as a way to highlight the differences between the support offered by the flat and flying buttresses.

Figure 297. Exterior CAD model of the Cathedral South nave with flying buttresses (facing northeast)

Figure 298. Interior CAD model of the Cathedral south nave (facing southeast)

The maximum displacement of the flying buttresses was 0.125 millimetres (Figure 299). This movement is less than the movement seen in the flat buttresses.
Figure 299. Displacement results of the south nave with flying buttresses

The tensile stress of the flying buttresses was 284098.3 N/m² (Figure 300). This value is within the allowed amount but is greater than the tensile stresses seen in the flat buttresses. As shown in Figure 301, the greatest tension is within the aisle vaulting. The inclusion of the flying buttresses were meant to relieve some of these stresses, but it would appear that the opposite has occurred.

Figure 300. Maximum principle stress results of the south nave with flying buttresses
With the inclusion of the flying buttresses and the added masonry, the compressive stress found was $-372472.3 \text{ N/m}^2$ (Figure 302). This compressive stress is within the allowed material properties but as with the tensile stress, is greater than the flat buttresses. This is to be expected, as a greater outward force is applied with the majority of stresses seen in the bases of these buttresses. The inclusion of the flying buttresses does relieve some of the stresses from the nave wall, but further compressive stresses can be seen at the connecting parts of the flying buttresses, and may over time create a secondary tension stress.
flying buttresses used only as an additional weight. The inclusion then of the flying buttresses was unnecessary, with the building work supported adequately by the original flat buttresses.

6.5.8 The West Front

6.5.8.1 The Creation of the Model

The west front is one of the most controversial and disputed features found at Winchester cathedral (4.2.9). The original west front was demolished and the only evidence that exists are the scarring found within the Outer Closer and the excavation work completed by Biddle in the 1970s (Biddle, 1970: 88). Documentary research has been completed to suggest the original layout of this elevation (4.2.9) and this has been used as basis for reconstruction. In order to create something realistic, comparable cathedrals had to be examined; this however is problematical in that most English Romanesque cathedral fronts have been converted into other styles. Figure 303 provides an overview of the extant remains of St Botolph’s Priory Church, Colchester in 1846. This image shows a substantial central doorway but little remains to suggest how the rest of the building work appeared. Instead, the majority of the reconstructed west front at Winchester has been based on the west front of the Abbey Aux Dames, Caen (Figure 304), which was built prior to Winchester. The Abbey Aux Dames shows a similar central doorway, with the inclusion of two flanking towers. When looking at one of the only English cathedrals that still incorporates Romanesque flanking towers, Rochester cathedral (Figure 305) cannot be used, as the excavation results by Biddle and the work completed by Crook (2010: 224) are in contrast to the building work shown.
Figure 303. West front of St Botolph’s Priory Church, Colchester 1846 (Rodwell, 1989: 24). After Dugdaler, 1846.

Image represents the West front of Abbey Aux Dames, Caen. Copyright permission was not gained. The image can be found in Plate 99 of W. Rodwell. 1989. Book of church archaeology. Published by Batsford Ltd, now Pavilion Books

An online image search of West front of Abbey Aux Dames, Caen will provide similar images

Figure 304. West front of Abbey Aux Dames, Caen (Fletcher, 1931: 169). © Pavilion Books
The central doorway shown in Figure 304 includes a central door column, used as a divide between the two wooden doors. The inclusion of this central column is unusual, as the Romanesque arch would normally have an outward relieving stress emanating downwards through the support columns attached. When examining the Romanesque doorways found at Lincoln (Figure 306), Rochester (Figure 307) and Bristol (Figure 308) this central column is absent. In order to understand how this central column would affect the building work at Winchester, both variations are tested.
Figure 306. Lincoln cathedral west front door

Figure 307. Rochester cathedral west front door
6.5.8.2 The West Front with a Central Door Column

Figure 309 through to Figure 311 provide an overview of the reconstructed west front, based on the documentary research completed. The design is similar to that found at the Abbey Aux Dames but removes the aisle doorways.
Figure 309. Exterior CAD model of the cathedral west front with a doorway arch column (facing northeast)

Figure 310. Exterior CAD model of the cathedral West front with a doorway arch column (facing east)
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The maximum displacement of the west front with a central doorway column was 0.79 millimetres, as shown in Figure 312.

The tensile stress was 1200141 N/m² and is within the allowed tensile strength of the material property, with the largest stresses seen in the supporting nave wall (Figure 313).
Figure 313. Maximum principle stress results of the cathedral west front with a doorway arch column

The compressive stress was -2707850 N/m² (Figure 314) with the largest compression seen at the central doorway column, which is alleviating the force exerted on the central doorway arch.

Figure 314. Minimum principle stress results of the cathedral west front with a doorway arch column

The internal force generated was 847875.3 Newtons (Figure 315), with the largest force seen at the bases of central doorway arch.
6.5.8.3 The West Front without a Central Door Column

Figure 316 and Figure 317 provide an overview of the west front reconstruction without the previous central door column included. The column shown in Figure 316 is the relieving column found within the cathedral, which supports the termination of the transept vaulting.

Figure 316. Exterior CAD model of the cathedral west front without a doorway arch column (facing east)
Figure 317. Interior CAD model of the cathedral west front without a doorway arch column (facing east)

The maximum displacement of the west front without a central doorway column was 0.79 millimetres (Figure 318), which is the same value as the previous result. This suggests that the movement seen within the building work has no connection to the supporting mechanism.

Figure 318. Displacement results of the cathedral west front without a doorway arch column

The tensile stress that was generated was 1181131 N/m² (Figure 319) and is less than previous tension results. This signifies that the archway is able to relieve the tension found and is more suited to the exclusion of the central doorway column.
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Figure 319. Maximum principle stress results of the cathedral west front without a doorway arch column

The compressive stress is again lower than the previous results with a value of -2554437 N/m², as shown in Figure 320 and Figure 321. The results generated show that a greater compressive force is seen within support columns of the doorway, and advocate that the inclusion of the central doorway column interferes with the relieving stress support system shown.

Figure 320. Minimum principle stress results of the cathedral west front without a doorway arch column
The internal force is however of a greater magnitude, with the generated forces being 1371838 Newtons (Figure 322). These forces are concentrated more in the connecting tower walls and show the outward relieving forces that the archway creates.

From the tests performed, it would be indicative to say that a central column system was not used within the design of the west front. Rather, as are seen elsewhere in England, the doorway was of a single arch support system.

6.5.9 The Timber Roof

6.5.9.1 The Creation of the Model

The timber roof of Winchester cathedral was briefly discussed in 4.2.14, with reference to four stages of timber designs. Figure 323 presents these four possible phases. The first two suggestions are noted as probable and have been tested to establish whether their form are realistic. It is unknown how the timber frame was erected, and variations in joints and connections have also been tested. The timber used in the original construction was oak, as found elsewhere at
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Winchester (Pilgrim Hall) but pine has also been included to test how suitable this choice in material could be.

Figure 323. Winchester Cathedral Nave roof (Munby and Fletcher, 1983: 102). © Taylor & Francis 1983. Reproduced with permission from Taylor & Francis, www.tandf.co.uk

6.5.9.2 Oak Timber Frame with a Longitudinal Support Beam

Figure 324 to Figure 326 provide an overview of the first interpretation by Munby and Fletcher (1983: 102) of Winchester Cathedral’s timber framed roof.
Figure 324. CAD model of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam (facing southeast)

Figure 325. Top down view of the CAD model of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam
Figure 326. Close-up view of the underneath of the CAD model of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam. The beams are positioned directly on top of the nave piers shafts.

The maximum displacement was 0.75 millimetres (Figure 327), with the highest movements seen in the connecting points of the timber with the west, south and north fronts, as well as the central tower.

Figure 327. Displacement results of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam

The tensile stress found within the stone was 3301880 N/m²; the tensile stress of the oak timber was 273949 N/m² (Figure 328). Both of the values generated are within the tensile strengths of both materials.
The compressive stress of the stone was -8114470 N/m²; the oak timber had a compressive stress of -603425 N/m² (Figure 329). Again, both of these values are within the allowed compressive strengths of each material.

6.5.9.3 **Oak Timber Frame with a Longitudinal Support Beam and a Ridge Beam**

Figure 330 to Figure 333 provide an overview of the first interpretation by Munby and Fletcher (1983: 102) of Winchester Cathedral’s timber framed roof with the addition of a ridge beam.
Figure 330. CAD model of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam and ridge beam (facing southeast)

Figure 331. CAD model of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam and ridge beam (facing south)
With the addition of the ridge beam, the maximum displacement found was 9.44 millimetres, as shown in Figure 334 and Figure 335. The movement shown is concentrated in the transept timbers and suggest that a modification in design is necessary within the model. The movement is acceptable but caution must be given in accepting these results.
The tensile stress of the stone was 1148400 N/m²; the oak timber was 1418620 N/m² (Figure 336). Even with the displacement seen, both tensile stresses generated are acceptable, and are less than the previous result.
357

Figure 336. Maximum principle stress results of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam and ridge beam

The compressive stress of the stone was -2206710 N/m²; the oak timber had a compressive stress of -2382370 N/m² (Figure 337). In comparison to the previous results, the compressive stress seen in the stone is higher, with the compressive stress of the timber being smaller. The compression difference in the two-timber frame designs are most likely due to the forces being exerted along the ridge beam, therefore creating an overall load that is supported by the pier shafts.

Figure 337. Minimum principle stress results of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam and ridge beam

6.5.9.4  **Oak Timber Frame with Munby and Fletcher’s (1983) Second Interpretation**

Figure 338 and Figure 339 provide an overview of the second interpretation by Munby and Fletcher (1983: 102) of Winchester Cathedral’s timber framed roof, where an additional support is added.
Figure 338. CAD model of Munby and Fletcher’s (1983) second interpretation of the cathedral timber roof, with a longitudinal support beam (facing southeast)

Figure 339. Close-up view of the CAD model of Munby and Fletcher’s (1983) second interpretation of the cathedral timber roof, with a longitudinal support beam

The maximum displacement of this second interpretation was 0.18 millimetres (Figure 340) and is less than the first interpretation.
Figure 340. Displacement results of Munby and Fletcher’s (1983) second interpretation of the cathedral timber roof, with a longitudinal support beam

The tensile stress of the stone was 628976 N/m²; with the oak timber having a tensile stress of 232642 N/m² (Figure 341). These values are again acceptable, with the stone having a much lower tensile stress than the first interpretation. This, as was the case with the ridge beam addition, is most likely due to the redirection of the forces applied, thanks to the addition of the new timber support.

Figure 341. Maximum principle stress results of Munby and Fletcher’s (1983) second interpretation of the cathedral timber roof, with a longitudinal support beam

The compressive stress of the stone was -1396750 N/m²; the oak timber had a compressive stress of -326675 N/m² (Figure 342). This compressive stress is much less than the first interpretation, with the stone being half the value.
With the three tests performed, it would appear that the interpretations created by Munby and Fletcher (1983) are correct. The addition of the ridge beam in the first interpretation was used as a test to see how the differing timber frame supports can aid structural integrity. With the additional longitudinal beams increasing the overall movement seen in the building work, a reasonable assessment can be made as to why the supports were added in the perpendicular, rather than in the horizontal, as seen in the second phase interpretation.

6.5.9.5 Pine Timber Frame with a Longitudinal Support Beam

With the same models used, but with pine added as a material property, the maximum displacement found in the first interpretation by Munby and Fletcher was 0.66 millimetres (Figure 343). This is lower than the oak model, but is to be expected when the material has a lower overall mass density and weight.
The tensile stress of the stone was 2678620 N/m²; the pine timber had a tensile stress of 202233 N/m² (Figure 344). Again, these values are lower than the oak equivalent and are within the allowable limits of the materials.

Figure 344. Maximum principle stress results of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam

The compressive stress of the stone was -6740250 N/m²; the pine timber had a compressive stress of -326675 N/m² (Figure 345). Predictably these results are lower than the previous calculations, but surprisingly the pine is almost half that of the oak counterpart.

Figure 345. Minimum principle stress results of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam

6.5.9.6 Pine Timber Frame with a Longitudinal Support Beam and a Ridge Beam

The maximum displacement of the second generated model with pine as a material property was 8.41 millimetres (Figure 346). This value is again lower than the oak counterpart is but is still high when considering the movement is associated with a perpendicular movement of the timber frame, as shown in Figure 347.
Figure 346. Displacement results of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam and ridge beam

Figure 347. Top down view of the displacement results of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam and ridge beam

The tensile stress of the stone was 945931 N/m²; the pine timber had a tensile stress of 1081380 N/m² (Figure 348). As expected, these values are less than the previous results.

Figure 348. Maximum principle stress results of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam and ridge beam
The compressive stress of the stone was -1734430 N/m², with the pine timber having a compressive stress of -1783400 N/m² (Figure 349). Both of these values are acceptable and lower than the oak model but unexpectedly, the pine timber is now more compressive in nature than the stone.

Figure 349. Minimum principle stress results of Munby and Fletcher’s (1983) first interpretation of the cathedral timber roof, with a longitudinal support beam and ridge beam

6.5.9.7 Pine Timber Frame with Munby and Fletcher’s (1983) Second Interpretation

The maximum displacement of the second interpretation of Munby and Fletcher timber framed structure, with pine as a material property was 0.18 millimetres (Figure 350). This movement is the same as the oak model.

Figure 350. Displacement results of Munby and Fletcher’s (1983) second interpretation of the cathedral timber roof, with a longitudinal support beam

The tensile stress of the stone was 542088 N/m²; the pine timber had a tensile stress of 180951 N/m². The compressive stress of the stone was -1231370 N/m²; the pine timber had a compressive stress of -268433 N/m². The values assigned to both the tensile and compressive stresses are lower.
With the tests completed, the results suggest that the oak used for the timber frame roof at Winchester was not the best material, with pine offering lower values within the structural tests. The timber used in the roofing will always be based on the available resources, and perhaps, with the large amount of wood needed, oak was the only available resource in the quantity needed. Since the redevelopment of the cathedral (4.2.17.3), different wood types have been used, including wood that is structurally weak such as softwood.

6.5.10 The Crypt

As stated in 6.5.5.1, the inclusion of a CAD model of the crypt was intended to be included within the structural tests performed. An example of the partial completed CAD model can be seen in Figure 351 to Figure 353.

Figure 351. Top down view of the partially completed CAD model of the crypt
The included CAD models were based on the survey work completed within the crypt (4.2.12) but the form found proved to be too difficult to accurately model in a three-dimensional space. The apse found in the crypt is of a wider form than that modelled in the retrochoir, due to the support that it would offer the cathedral. As the apse is of an unusual and disjointed shape, the construction of the CAD model required a greater separation into parts. Figure 354 provides an overview of the commencement of the apse within the crypt and it is these bays where the issues appeared.
When creating the groin-vaulted bays that are square or rectangular in form, three-dimensional boxes were used, with cylinders subtracted from these boxes to create the necessary geometry. This process created a uniform shape and was simplistic to generate. This method could not however be used within those vaults that contained tapered groins, as shown in Figure 355. Over a month of modelling was completed to create the necessary geometry shown, with various different attempts made in the modelling process to create a genuine and true reconstruction of the crypt. After many unsuccessful attempts, this process was stopped to concentrate on the rest of the modelling necessary. This is one criticism of using AutoCAD, in that the software is not intuitive within this type of modelling process; software, such as 3DS max would be more suitable as it would allow for the direct movement of each part of the generated model, rather than as a whole object.
6.5.11 Cathedral Conclusion

A number of research questions were included at the beginning of this section (6.5.1). The structural tests performed on the cathedral have been able to answer these. The collapse of the cathedral tower was most likely due to poor foundation or subsidence around the tower piers; a height of 66 metres was possible and the structural integrity of the surrounding walls of the tower (nave, transept and retrochoir) showed no overall weakness. The results have also shown that the intended towers of the original Romanesque cathedral were possible, and that the addition of the flying buttresses actually weaken the overall building due to increased tensions found in the nave aisle vaults. Structural analysis has also been able to emulate known structural decay, and the method has shown how the changes in roofing style affected the overall stability of the building; the addition of the support in the second phase of the timber frame of the cathedral greatly enhances the overall feasibility of the building. Thus the generated results provide a validation of the interpretations made; issues discussed in Chapter Two (e.g. realism (2.4.2), uncertainty (2.4.3), authenticity (2.4.4) and perception (2.4.6)) are less problematical and this data can now be used in the next stage of model production, through the addition of decorative features and the inclusion of environmental conditions to test the use and purpose of the building.
6.6 Precinct Results

The results generated from the precinct buildings can be found in Appendix A. These are included as an appendix due to the volume of results generated. For the purpose of the thesis, the main research aims are proved through the cathedral results shown above. An overview of the precinct buildings are shown in Table 4.

Table 4. The precinct structural analysis results

<table>
<thead>
<tr>
<th>Building</th>
<th>Structural results</th>
<th>Appendix Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number 10</td>
<td>• Both the 21° and 32° pitch are structurally valid.</td>
<td>A.1</td>
</tr>
<tr>
<td></td>
<td>• Structural analysis was able to simulate the subsidence of the central column</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• The subsidence was found to affect the 21° pitch roof more than the 32° pitch roof</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• The subsidence found requires a greater support from the surrounding central</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• The introduction of corbel supports, adds to the strength of the building</td>
<td></td>
</tr>
<tr>
<td>Pilgrim Range</td>
<td>• John Crook's interpretation is valid</td>
<td>A.2</td>
</tr>
<tr>
<td></td>
<td>• Creating a full hammer beam truss system would have been acceptable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Stress points in the model have identified a door location for the Pilgrims' Hall</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• With the removal of the scissor bracing in the timber-frame, the building fails,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Without the north buttresses included, the building almost fails</td>
<td></td>
</tr>
<tr>
<td>Cloisters</td>
<td>• Errors in the modelling process resulted in a limited research focus</td>
<td>A.3</td>
</tr>
</tbody>
</table>
• The outlines of the cloisters were identified
• The interpreted building work is valid
• Without using structural analysis, John Crook’s interpretation of the cloister roof support is incorrect

| Chapter House | • The Chapter House could have supported either a barrel vaulted or groin-vaulted ceiling
• A groin vault is plausible due to the evidence found in the cathedral
• The Chapter House would support a thin west wall, signifying that the building was closed | A.4 |

| Refectory | • Both variations in roof types were valid
• The king post design most probable due to the results of Number 10 | A.5 |

### 6.7 Assessment of Finite Element Modelling

The tests that have been performed throughout this chapter, with Appendix A, have provided an assessment of the potential of the buildings under investigation. For the large majority of results, the structural tests indicate that the interpretations made are valid, and are structural safe under gravitational loading. The use of this method provides a tool of assessment which removes the impartial and impractical issues discussed throughout Chapter Two; the method does provide a means to test authenticity and accuracy (2.4.4), limited to yes and no answers. The results generate further discussion points surrounding the created models, but these add to overall strength of the method, adding further points of discussion within the explanation and choices within the modelling process.

The models created were simplified in their design and this is one downfall in the modelling process used. Although Autodesk simulation could generate finite elements using geometry that is more detailed, the modelling process, and the time associated with the creation of the models, restricted the overall results gained. The difference between these generated results would be minimal in relation the structural properties of the buildings, but would be different nonetheless. If greater care was used in the modelling process to avoid the inclusion of naked edges, the original generated models, with the full structural detail, could have been used.

The generated structural models created were developed in AutoCAD, as a basis for the solid CAD models. On reviewing this process, and when dealing with more complicated geometry, such as
the groin vaults found in the crypt, other software packages should have been used. AutoCAD was used as the main modelling software as the software is commonly used within archaeology; Rhino and 3DS Max are more specialised modelling packages and require differing modelling approaches and thus requires an understanding of the more complicated software interfaces. As the tests performed should act as a basis for future development, the creation of the AutoCAD models was felt to be of more importance, as this will be the software that is used on a regular basis. The models could have been corrected in other software solutions, but this negated the purpose of using AutoCAD. Overall, the models generated are suitable but adaptations to the modelling process will be necessary if features that are more complicated are to be tested.

The generated results rely on the material properties used within the tests. As shown in 6.3, the material properties used are based on the evidence collected from a range of different sources; a greater solution would have been given had the materials from Winchester been tested to extract the material properties necessary. This, as mentioned before, is a common problem, and one that requires funding and time to invest in the laboratory based tests. Without these material properties, the generated results will still be questionable, and is again a downfall in the method used.

The process of creating and reading the Finite Element models are however basic, and unlike the structural analysis tests performed prior to the invention of the Finite Element method, the results can be generated by a click of a mouse in the predefined buttons found in the software used. The only manual work required is the assessment of the results against the material properties used, specifically their tensile and compressive strengths. If either of these values were greater than the allowed amount, the generated model would fail. The tests used at Winchester are based on linear analysis and this limits the number of potential results that can be generated. Under non-linear analysis, further evaluations of the model can be made, and include the analysis of temperature changes, flooding, traffic vibrations, earthquakes, etc. These are all-secondary in nature and allow specific questions to be asked that surround the use of the building, rather than its overall stability. For archaeological simulation, and to test the validity of the interpretations made, the gravitational effect is of more importance with the overview of stability and safety.

With these results and with them proving the validity of the interpretations made, these models can now be used in further modelling processes, such realistic three-dimensional modelling (addition of photorealistic colour), acoustic modelling, lighting analysis, or even within conservation practises. Using structural analysis as a hypothesised validity tool provides a greater basis on which discussions and arguments can be made, without such a tool, the interpretations made are just interpretations; with structural analysis, these models become scientific in nature.
and therefore have a firmer basis on which to argue the clarifications, which led to the interpreted model.

### 6.8 Conclusion

The chapter, as with Appendix A, has provided a case study of how structural analysis could be completed in archaeological research. The models tested have been evaluated based on the compressive and tensile stresses placed on the structures under gravitational loading. The results have shown that structural analysis can be used to validate the interpretations made, as well as providing a tool that allows specific research questions to be answered. These models in combination with the complexity of information used, allow for a movement away from the issues raised in Chapter Two, and provide a firmer basis on which archaeological simulation can be based.

The following chapter will use the results generated to discuss the main research aims of the thesis, as well as provide an overview of the work completed.
Chapter 7: The Potential of Structural Analysis in Archaeological Simulation

7.1 Research Questions

The aims of this thesis were four-fold (1.2) with the overall objective to present a new tool for the creation of graphical models in archaeology. The thesis has provided an archaeological examination of structural analysis and has shown how structural analysis can be used in the understanding of past buildings, creating a validation tool for interpretations. Individual research questions have been answered in Chapter Six that focus on the buildings at Winchester cathedral and an overall assessment of the main aims of the thesis are considered below.

7.1.1 The Benefits of Using Structural Analysis in an Archaeological Context

Structural analysis is a wide and encompassing technique that is used within engineering to create safe and reliable structures. This technique includes multiple possible testing scenarios (3.2.5) and an overview of structural analysis has been provided in Chapter Three. The focus of the investigations completed at Winchester were based on strain and stress relationships, specifically through the examination of compressive and tensile strengths of the modelled buildings under gravitational loading. The tests performed in Chapter Six highlight the differences that small variations in building design can create to the overall structural integrity of a building, such as the exclusion of the exterior buttresses of the cathedral transept (6.5.6). The questions raised in Chapter Six could only have been answered with structural analysis, signifying that the method is beneficial in an archaeological context. An example being the cathedral central tower (6.5.3), which could have been up to 66 metres high as its construction and supports were suitable; the collapse most likely occurred due to subsidence or a poor foundation, rather than through poor above ground workmanship in the construction of the cathedral. Previously this type of question would have been answered with some reservation, with archaeologists suggesting possible rationales as to the overall collapse. Structural analysis allows a more compelling answer and justification.

The generated results allow for a scientific and mathematical examination of the past; ‘scientific’ because a model with the same results using the same parameters can be recreated (Niccolucci and Hermon, 2010: 28). With the research completed in Chapters Four and Five, as with the models provided in Chapter Six, these results can be repeated to some degree. Changes to these models may be necessary due to new evidence, but the research will allow different users to
recreate these models and perform the same gravitational load tests. Interpretations of the surviving remains will always differ and a detailed review of the results generated are necessary; with sufficient research, recording, and careful CAD modelling, the interpretations can be justified, allowing for a model that is realistic based on the physical constraints of the building. Structural analysis is therefore a tool that allows hypothetical testing (2.5.4) to be corroborated and the results shown in Chapter Six define the limits of the interpretations possible. Structural analysis is not however just a tool for hypothetical testing but can be used for a number of functional analyses that examine the purpose and use of these past buildings, thus creating an analytical tool (2.5.2) that allows for further examinations in an archaeological context (see 7.2.2). Structural analysis therefore allows for further interpretations, providing a tool that surpasses simple validation.

Chapter Three provided an overview of structural analysis and the various fundamentals discussed were used throughout the tests completed at Winchester. Using these fundamentals as a basis will allow others to use structural analysis (within their own investigations) and to understand the concepts that create a valid model. The models must be created using thorough research and recording devices to be physically viable, but different interpretations are still possible. Within archaeological simulation, this process is customary and does not affect the overall creation; rather the method allows each building element to be considered in more detail, thus creating a stronger interpretation. As the loads and their application can vary between different hypothesised buildings, depending on many environmental factors, and different analysis types, no investigation is the same. Each analysis is unique, allowing each interpretation to be justified in a greater way than through the comparison of similar surviving features.

The construction of historic buildings was based on trial-and-error and experience (3.2.2) passed down to younger generations. The understanding that masons had of structural integrity would have been limited to those structures that survived and remained in position; adaptations are evident with masons trying new styles and approaches. The use of structural analysis in understanding these past buildings is based on the knowledge that has been gained in recent centuries. To compare the current engineering methods to the past is wrong, as the approaches in construction are evidently dissimilar; the results instead provide an idea of the methodologies used and this allows for an understanding as to why set construction decisions were made. If a model of a past building is recreated under structural analysis testing and this passes as being structurally reliable, the generated model may still be wrong in design, as an individual mason may have decided to adopt a new style. The testing performed will therefore never provide a complete understanding of the past; rather the tests will define whether our interpretations are structurally valid.
7.1.2 The Influence of Structural Analysis in Archaeological Graphical Simulations

An overview of the current processes in archaeological virtual modelling has been presented in detail in Chapter Two, completing the second research aim of this thesis.

The models created in Chapter Six may appear simplistic but contain a more focussed and scientific approach to the modelling process, one where the final data provide enough complexity of information for both experts and amateurs. The reconstructed models have dealt with the uncertainty engrained within virtual reconstructions (2.4.3) by including as much information as possible. Within the modelling, the reconstructions generated have highlighted the decisions that were incorporated in their production (Chapter Six), as well as the archaeological information that led to their basis (Chapter Four and Five). This moves away from the subjective nature that modelling can contain, as highlighted in 2.3 and instead incorporates both re-creation and reconstruction modelling techniques (2.4). This moves away from Box’s (1976) view (2.4) that all models are wrong. The models provide a description of the natural phenomena included; assumptions have been proved or refuted based on the tests performed and following Box’s Interative modelling approach (Figure 7); the generated models contain a greater degree of realism (2.4.2) that are represented in more than just a graphical interpretation.

Lowenthal (2015) believed that reconstructions act as a rectified past, whereby they are seen as true originals. With the generated results, these models can be used in such a way but are limited in their visual quality. Instead, they move away from a descriptive approach to the interpretations made (2.4.2) and remove the photorealistic nature of the modelling process, thus removing the photorealism that could distort how the model is understood. With the explanations of the structural results shown in connection to the CAD models, users are able to understand the processes and decisions made (2.4.2).

Visually the models are unappealing, and the perceptions gained are limited (2.4.6). Their creation resulted from an analytical tool (2.5.2), where set questions were asked as to the possible options available. Assessing these models, the available physical interactions of the material were used (2.5.3) through hypothesised testing (2.5.4). With the inclusion of as much evidence as possible, the accuracy of the presentation is greater and the authenticity attached (2.4.4) is more genuine.

Reilly and Beale (2015: 122) stated that the original intention of virtual reality in archaeology was to “describe a multi-dimensional approach to the modelling of the physical structures and process of field archaeology” (1.5). Using this multi-dimensional approach within this thesis has produced results that show how valuable structural analysis is as a validation tool. The method is one of many analytical tools that could be used; lighting analysis and acoustic testing also have their
place in archaeological simulation (2.5.4) but each of these allows for a limited understanding of
the results generated and in some ways can create a biased interpretation. Using structural
analysis within the creation of these methods as another tool in the modelling process, allows
each further test to have a firmer justification, as any test on a building requires the physical
characteristics to be correct before any further tests are performed. Structural analysis is not the
answer to creating perfect models; rather the method is of use in reconstructing the past based
on physical possibilities. Through the addition of mathematical calculations and the evaluation of
the forces contained, the model will have a firmer basis on which to act.

The models produced go beyond the translations of the data to images or worlds that mimic
reality, but instead create new spheres of reality that offer new experiences. Although the tests
completed are useful, the models produced are based on assumptions and the results will always
vary in accuracy. Producing a complete reconstruction from archaeological data is extremely
challenging, as every finite part of the building will be unknown. Assumptions, based on heavily
critiqued and evaluated data, have to be made and the results shown will never be better than
the production of a real life version. This however is unrealistic to complete, and so technology is
needed to provide the answers.

Investigations as to whether reconstructed buildings can withstand the gravitational loads form
the foundation of an additional layer of validation of the model. The technique is demanding and
difficult to implement but the benefits that can be gained will alter the way in which the past is
studied, creating a system that is more scientific, more systematic and more precise in the
validations made. Through structural analysis, the application of virtual reality will instead return
to the original purpose of what virtual reality was meant to be: a tool that helps to examine the
past, creating a system that validates or discredits the interpretations made, leading to a greater
inclusion of information that contains less uncertainty.

7.1.3 The Impact of Differing Surveying Methods in the Potential and Practice of Structural
Analysis

The survey methods throughout the investigation at Winchester are discussed in detail in
Appendix B and included the capture of laser scanning (B.1), photogrammetry (B.2), surveying
(B.3), and geophysics (B.4). The inclusion of these multiple recording methods enabled a more
detailed examination of the material found on site and allowed for clearer interpretations to be
made in the modelling process. Using just one method of recording would have limited the results
gained and each different recording method added to the overall interpretations possible. The
success that is attached to creating a model of the past is dependent on the quality and accuracy
of the survey data used (Premadasa, 2003: 424). At Winchester, through the different types of recording, the quality of the data differs but once combined offers a substantially accurate representation of the current building material.

The building survey of the precinct buildings and the interior of the crypt provide a useful overview of the building work, but incorporating this in a solid CAD model is extremely difficult due to the line representations that are shown in the drawings. The accuracy of the data collected is based on the operator and the available field of view that the total station has. Capturing successive points is a manual process and one that takes considerable time. There is no guarantee in this recording method that the collected results will be correct, unless the data are reviewed in real time (5.6.2). The results do provide an overview of the building work but no real analysis of the data can take place once away from the site; this is satisfactory if the operator processes the data into a CAD model, but if given to someone else, the understanding of what the model represents is only shown through this line data. This is not to say that total stations surveys should not be incorporated within structural models, as they should. Rather, greater care must be taken on site to record the features correctly and then used in conjunction with modern recording approaches, such as laser scanning, as the data can be integrated.

Although laser scanning was the most valuable recording method used, the time and computing power required to process the data were excessive. The storage requirements for the data were also considerable. On completing the structural analysis tests, it was found that Autodesk Simulation was able to test, via plane analysis (3.2.5.1); single slices of the laser scan data, adding to the suitability of the recording method. Rather than test a complete reconstructed model, specific sections of complete recorded structures could be examined, creating a further analytical tool. On producing the CAD models, laser scanning was useful in their construction but their production was only possible due to the understanding of how AutoCAD works in three dimensions. Without prior knowledge and understanding of the software, the creation of the models would have been challenging. For someone with no experience of the difficulties attached to working in three dimensions in AutoCAD, this would not be possible.

The laser scan models were converted to solid CAD models to avoid the issue shown in the case studies in 3.4, whereby only shells of the scan data were incorporated in the tests. This negated the purpose of the testing, and by creating exterior and interior scan models, exact dimensions of the building could be included. This same issue is prevalent in photogrammetry and great care was taken to capture the data correctly. Photogrammetry allows for a quicker data capture than laser scanning, but involves an unwarranted amount of time in processing the data for conversion to the structural models. Photogrammetry was able to help identify key features and this was
Chapter 7

easier to work with in AutoCAD due to the visual quality of the data, where exact outlines of the building material could be seen, as was the case with laser scanning. The two methods in conjunction provided a way to process the building work at Winchester in the quickest possible time, and with the least amount of processing. These were positioned into their place using the building survey captured, signifying the importance that each method had within the reconstructions at Winchester.

For those buildings that were known to exist, but where no extant remains survive, geophysics, through resistivity and GPR, was used to record below-ground remains. The results generated were incorporated into the overall model through the building survey and both were used in the reconstructions. The resistivity was only useful in the Chapter House reconstruction (5.7.2), as the data were unable to provide enough information as to the outlines and depths of the features. The GPR survey, through its radar technology, provided better results, as relevant depths were compared to the excavation work that has taken place at the precinct. The processing and capturing time of the GPR survey were lengthy but the results outweigh the negatives. GPR then is a more suitable method for providing the outlines of existing building work.

In order for structural analysis to develop into a tool that is suitable for archaeological simulation, there is a need for archaeological modelling to focus equally on the collection of volumetric and surface survey data. Volumetric data were available in places (Retrochoir) due to the work completed by the Parnassus Project (4.3.1.1), and this should be encouraged when completing similar work. This use of Electrical Resistance Tomography on standing walls is a new recording technique; the adoption of this volumetric data requires greater time to include within archaeological recording and is something to re-examine in the future, where this data is available, it should be used. The recording at Winchester was significant in that a large proportion of the building work was recorded; where parts could not be accessed, the documentary evidence and the recording work completed by John Crook was utilised. Without this structured format of documentary research and recording processes, the structural models would not have been possible. A varied recording methodology is therefore required in producing structural models, as this provides the highest opportunity to include all elements. Other recording methods, such as UAV drones, will add to this process, but with this comes a greater need to understand how each recording method should be captured and processed. Money and computer power will always control how a site is recorded but in a best-case scenario all of the methods used at Winchester should be employed in further investigations. This is not to say that all sites should be recorded in the same way; each building, site, or landscape requires a different recording methodology as each site is unique. The work completed in this thesis provides an overview of how to capture a large number of buildings, but this can easily be adapted to fit the purpose of structural testing.
7.2 Further Potential

7.2.1 Overview of the Work Completed

The creation of the Finite Element Models proved to be more complicated than was first anticipated. The results generated are trustworthy but the time involved in creating workable models was unduly long. The problems of the modelling process can be seen in 6.4 and emphasise the care needed in modelling complicated geometry. The naked edges proved problematical in the final testing. Through my previous structural work, these potential errors were known and great care was taken to avoid their inclusion in the Winchester data. That said, once the error locations were known, the models were fixed and simplified to create a workable solution. These simplified models would not be too dissimilar to the results generated through the original modelled solution, but naturally will differ. To avoid these errors, greater care should be given during the modelling process and these models should be evaluated in stages, rather than as one complete final solution. If this systematic verification had taken place, the models produced could have been completed sooner, a greater number of research questions outlined in Chapters Four and Five could have been tested. Instead, due to time limitation, a subset of these questions was answered. These still provide an overall assessment of how structural analysis can be used in an archaeological context, but it was hoped that further tests would be used to answer more specific points, as a way to identify the further potentials of the method.

As noted in 6.3, there lies a hindrance in the results generated; the material properties are based on assumptions. These material properties define the limits of the compressive and tensile strengths of the tests performed and their validation is based on the evidence found in the literature research. I am confident that these values can be trusted but without testing the materials at Winchester Cathedral, the results generated can never be confirmed. This is an inherent problem within the adoption of structural analysis and greater work must take place in testing the raw material. The results seen in the Parnassus Project (3.4) include these laboratory-tested materials. That project incorporated structural engineers who had the resources available to test the material. As archaeology adapts and becomes more scientific in its approach to studying the past, greater interdisciplinary collaborations are required to generate the necessary results. Archaeologists are able to create and perform the structural tests, as proved through this thesis, but help is required in defining the material properties.

The macro-model approach used in this thesis provides overviews of the whole structure and ignores the bonding agents that bind the buildings together. As the method develops, greater care is required in designing structural models that incorporate these bonding elements, as each
part will affect the overall structural integrity. This is dependent on the number of calculations required, as defined by the number of nodes present. The generated models include partial representations and boundary conditions added to simulate continuing architecture; the software was unable to process a complete model of the cathedral due to the time required to compute the solutions per node. The results are also limited in that they ignore the current cracks in the building work (unless modelled) and the results generated do not show how these cracks may form. Cracks are important in understanding the structural integrity of a building, as their presence will affect its integrity. These tests can be performed, as seen in Sukumar et al.’s (2015) work with the Extended Finite Element Method which assessed crack growth simulations. Within the models created at Winchester, this evaluation was not of importance as the focus of testing was to provide a tool for validating the reconstructed models produced and to ask archaeological questions. Once validated, the examination of cracks becomes a possible further test and is a further tool that can allow for a further insight into the potential of a building. The analysis of these cracks is one such method and others are discussed below.

7.2.2 Future Testing

Although the results shown in Chapter Six are promising and helpful in understanding the buildings at Winchester cathedral, there lies one major problem; all of the results are treated as whole objects whose internal features are solid. For the majority of building materials, and indeed for many other archaeological objects, there lie impurities within the internal features that cannot be seen unless the material is broken apart. The internal parts of the material that make up a building may contain small hollows that will ultimately affect the material’s structural strength. Understanding how these internal features affect the overall strength of a structure is key and is currently unstudied. In Finite Element Analysis, there exist software packages within computed tomography (B.5) that analyse internal parts of scanned elements, generally shown in medicine. Kopperdahl et al. (2014) highlighted this through the testing of Finite Element Analysis on spine and hip fractures, based on the analysis of differing bone material density, whereby each three-dimensional voxel is converted to a finite element, as seen in Figure 356. This provides an assessment of the bone material that allows a precise analysis to take place.
Chapter 7

Figure 356. Finite Element models of a vertebral body and a proximal femur showing the elastic modulus (Kopperdahl et al., 2014: 572). Reproduced with permission of Wiley & Sons, www.wiley.com.

Cabal et al. (2013) used Finite Element Analysis to estimate the peak force and biomechanical properties of the ultra-distal radius via computed tomography (B.5). Unlike the previous case study, the work focused on using the exterior data rather than the internal but at least provided an example of how computed tomography can be utilised, through the production of deformation curves in different bone types. Both of these examples have possible implications in osteological research as well as in building archaeology.

Computed tomography is a highly accurate and precise recording method, producing external shells of items recorded, as well as the overlooked internal aspects. Recording different building material types is a laborious and time-consuming process, but having individual elements recorded at such a high resolution will allow for a more precise analysis of an archaeological building, especially one that has collapsed, as computed tomography will allow for each stone, wall and timber to be reassembled virtually. Analysing these data will increase the processing times, and the calculations may not be possible unless enhanced computing power is used. If this type of analysis is possible, the results will provide answers that are more truthful and accurate. Taking this further, the application of seeing inside each element further adds to the possible investigations that can be completed, as each building element (a subset of building material) can be tested to see how the internal features affect the construction and use of a building. Applying this method within the study of the past will allow more in-depth questions to be asked. Although this was not undertaken for this thesis, the application is one that should be applied in the future.

The use of Finite Element Modelling however is not limited to building investigations. The method has been used with great success in palaeontology analysis; Ross (2005: 254) saw it as an addition to geometric morphometric to test morphological variances; Rayfield (2005) used the method to test the hypothetical forces acting on the skull of Allosaurus dinosaur (Figure 357); with Manning et al. (2009) using the method to examine the mechanical potential of velociraptor claws (Figure
The work produced by Mannning et al. (2009) (Figure 359) provides a further example of the use of computed tomography within this type of research, through the addition of Finite Element testing of both the internal and exterior parts of the claw. The results generated would not have been possible if using exterior surface analysis, with the calculations produced invalidating other previous concepts of how velociraptors were able to climb.

Finite Element Analysis has also been used in further biomechanical analyses; the examples seen below are taken from Alexander (2006: 1849-1853). These analyses include body mass and the analysis of centres of gravity, speed and manoeuvrability such as Carrier et al.’s work (2001) on the inertia of running dinosaurs. Further tests include posture; the hydrostatic pressures of blood flow (similar to the blood flow analysis in medical examinations seen in Taylor et al. (1998); forces of biting (Sakamoto, 2010); and acoustical variances in vocal tracts, tail whipping and other
defensive traits (Carpenter et al., 2005). Each type of analysis adds specific research questions to set archaeological questions, thus providing a tool that enables further archaeological discourse.

Further to palaeontology, and outside building analyses, Finite Element Modelling has a vast potential in osteological research. Figure 360 provides an overview of a both physical and three-dimensional analysis of a human femora failure under stance and fall loading configurations, and can be used to assess fracture marks on bone material that relate to falls or strikes.

Figure 360. An example of the experimental setup (top) and corresponding Finite Element model (bottom) in stance (left) and fall (right) loading configurations (Schileo et al., 2014: 3533). Reproduced with permission of Elsevier, www.elsevier.com.

The work completed by Jafari et al. (2003) is also of interest within osteological research. In Jararai et al.’s work a Finite Element Model of a human skull, generated through computed tomography, was used to analyse the stress distribution patterns within the craniofacial complex during rapid maxillary expansion. The results, as shown in Figure 361, are inadequate due to the lack of complexity of the developed mesh, but the research did indicate that the “transverse
orthopaedic forces not only produced an expansive force at the intermaxillary suture, but also high forces on various structures on the craniofacial complex” (Jafari et al., 2003: 19). A similar use of computed tomography in osteological research through Finite Element Modelling can be seen in Lengsfeld’s (1998) work, who focused on the evaluation of geometry-based and computed tomography voxel-based Finite Element Modelling of a human femur. The research found that the voxel-based hexahedron meshing approached provided more precise results due to the detail incorporated in the mesh; the results, in comparison to today’s technology are poor but highlights the importance in creating detailed meshes.

Figure 361. The pattern of computed Von-Mises stress distribution in the craniofacial complex with 5mm of expansion (Jafari et al., 2003: 16). Reproduced with permission of The Angle Orthodontist, www.angle.org.

Other potential uses of structural analysis within archaeology can be seen in Kilikoglou and Vekinis’s work (2002) who assessed the use of Finite Element Modelling on pottery (Figure 362). The results offer no visual data but rather an expression of the generated strain results. The work completed does provide a basis for this assessment through failure under static loading and impact. Rooster and Zieba (2012) added to this early research through the examination of a pottery kiln in Marea, Egypt where the kiln was assessed based on the soil loading applied to the structure (Figure 363). Structural analysis therefore has a place in assessing different types of ceramic material. With the large number of potsherds available in the archaeological record, a reconstructed model can assess how the pottery was damaged, either through its use (such as temperature variations in cooking) or through subsequent damage (e.g. dropping).
Further to ceramic-based studies, the use of structural analysis within maritime examinations can also be completed, by assessing the functionality and quality of ship hulls, specifically their permeability. Work has been completed on the Titanic shipwreck (Garzke et al., 2000), where the undamaged ship (stresses between the hull and water), the intermediate flooding (on impact), and prior to sinking (full flooding of the bows) were examined. The investigation focused on a forensic examination, specifically the shear stress of the material used. The results generated pointed to the “aft expansion joint of the Titanic, under the loading conditions just prior to sinking, being a strong candidate for structural failure based on the material strength and fracture...
mechanics investigations” (Garzke et al., 2000: 681). The results used a relatively poor mesh within the analysis but the method does show promise when analysing the buoyancy of historical shipwrecks; steel is relatively homogenous but the same method could be used on timber or other boat material.

Linked to the sinking analysis of ships, is the potential to understand their functional use, such as military gunships. Examinations seen in Sakamoto et al. (2007), Shen et al. (2010), and Hub et al. (2012) provide assessments of how Finite Element Modelling can be used to understand bullet impacts and how different velocities affect overall trajectory paths. The same methods used in these papers could be completed on historic ships to assess at what impact a ship would fail, or what effects would be applied to the ship if firing cannons. This same type of analysis is also of use in osteological research to give scientific answers to potential impact marks of bullets, stab wounds, or fracture marks in bone material.

There are a multitude of potential tests that could be completed using structural analysis; the case study at Winchester provides just small example of its overall potential. Other examinations such as vibration, critical buckling, temperature variations, electrical components, earthquake, hydrostatic, and movement (of people and objects) can all be tested, each providing a different assessment of the potential of a given building or object. Gravitational loading completed in this thesis provides the basis for these further tests, as without a functional building under its own weight, any further tests would be invalid.

7.3 Conclusion

The work completed at Winchester provided a useful and valuable case study in how to create and test structural models. Through the documentary research, recording and CAD modelling, each building element has been carefully considered and evaluated.

Chapters Two and Three of this thesis provide overviews of virtual modelling and structural analysis and should be used as a basis to develop this tool further. Chapters Four and Five highlight the documentary research completed, as well as the recording methods used; without such a detailed examination, the fundamentals of the created results would have no basis on which to substantiate the conclusions made. This process is key, as without a correct research methodology, the interpretations created are ineffectual. As the structural analysis adapts and grows, further research is required into its potential use to create an overall tool that will enable a more scientific approach to our graphical simulations, whilst at the same time providing an analytical tool that can substantiate our interpretations. This process was provided in Chapter Six, where all of the research completed within the thesis were combined to provide reconstructed
interpretations. These interpretations were tested under gravitational loads and specific research questions were answered throughout. Through the examination of the compressive and tensile strengths of the material used in the modelling, assessments were made to the validity of the interpretations. This procedure is straightforward and Chapter Six highlights the ease at which structural models can be evaluated under basic structural loads.

The final structural tests shown in Chapter Six have allowed for the validation of the interpretations made and these can now be used in future testing or future iterations of the models. The process requires considerable computing knowledge and time to invest in the creation of the models but as time progresses, and software solutions become more readily available, the process of validating archaeological simulations will become simpler. The current processes available require a number of different software solutions and need to be redefined to allow for a single workflow. Until this occurs, the adoption of structural analysis will be limited to those who are able to understand these different software packages and the results that they generate.

The nature of structural analysis is a complex process, involving many multi-faceted approaches and techniques. For the future of the tool within archaeological simulation and practice, there is a requirement for a multidisciplinary approach to be adopted. Through the inclusion of other disciplines, a greater in-depth structural analysis of complex masonry structures can be created, allowing more precise and complex processes to be incorporated, thus providing a greater tool on which the past can be examined. At the forefront of this multidisciplinary approach would be archaeologists, guiding the processes in which the models are designed, and the questions that could be asked; structural specialists would then be able to provide the solutions necessary, as well as providing an enhanced comprehension of the complex numerical results, creating the iterative feedback needed to advance our interpretations. As archaeologists, structural analysis can become an important tool, but unless we train as structural engineers, our understanding of the technological approaches used would be limited, when compared to those who are trained and qualified in the approaches used. Engineers already use the past as interesting case studies to work with but again are limited by the technical understanding of the archaeology and the way in which the extant remains provide evidence. Working together within a single multidisciplinary approach combines both expertise and it is only through this way that greater insights into the past can be created. This is not to deter from the results generated, as these are appropriate, rather, when further questions are asked, and more complex numerical solutions are required, we must look to external support and develop a single working methodology than be used by both archaeologists and engineers.
This thesis provides an overview of what structural analysis can provide to archaeology; great care has been taken to model the data within the limits of what the research has identified. There will always be a critical appraisal of the method and the results generated, as is expected when introducing a new method. The results have verified a number of theories of Winchester cathedral to be correct, whilst also disproving others. The thesis is meant to act a discussion point, and to generate a new approach to the modelling of the past. The generated models that have been validated allow for a greater accuracy and authority to be placed on the interpretations, whereby any uncertainties (2.4.3) have been evaluated based on their structural reliability. The potential of the method is therefore great but further work is required before it can be used more widely.

Nevertheless, it is hoped that this thesis has started the process and provided a possible solution to the points raised in the production of archaeological graphical simulations, whilst at the same time providing a tool that will enable specific research questions to be answered.
Appendices

Appendix A  Results: Structural Analysis at Winchester Cathedral Precinct

A.1  Number 10 Structural Tests

A.1.1  Research Questions

As with the cathedral, a number of research questions were created following the assessment of Number 10 and 10a (5.3) that could only be answered using structural analysis. These questions are listed below:

- How has the subsidence affected building 10?
- If the undercroft was designed with corbels, how would the vaulting have coped?
- Could external stairs have been a viable option based around the limited space available?
- What was the original form of the roof of Number 10?

A.1.2  The Creation of the Model

The creation of the model of Number 10 was based on the documentary research completed (5.4.1), as well as the survey worked captured on site, which included both a laser scan model of the undercroft and an overall building survey (5.4.3). Figure 364 provides an overview of the CAD model of Number 10, modelled directly within the survey results, with a top down view seen in Figure 365.
The capture of a laser scan model was beneficial in understanding the internal elements of Number 10, specifically the undercroft and the detailed rib vaulting seen (Figure 366).
Figure 366. View of the CAD model of Number 10, with the laser scan data of the current undercroft included

Although the undercroft found in Number 10 is rare, a similar design can be found in the crypt at Rochester cathedral as shown in Figure 367. This image highlights the difference in shape between the two undercrofts, with a steeper angle found at Rochester. The central columns are also smaller, but the overall design is similar, with the same rib vaulting used. As the crypt is used to support the main building work at Rochester, Figure 367 provides an overview of how structurally strong the undercroft system is, and has been used in the creation of the model of Number 10 as a guide where necessary.
Two variations in roof pitches are found in the scarring of the external south wall of Number 10. In 5.4.1.2.2, the first angle postulated was 22.5° (Crook, 2009: 35). On reconstructing the model, this angle suggested was incorrect, with the only possible angle between the east and west walls being 21°. The second scarring found had an angle of 32° and both of these variations have been tested.

**A.1.3 Number 10 with a 32° Pitch Roof**

**A.1.3.1 Reconstructed Interpretation**

The model follows the work in 5.4.1 with Figure 368 to Figure 371 providing an overview of the reconstructed CAD model of Number 10 with a 32° pitch roof.
Figure 368. CAD model of Number 10 with a 32° pitch roof (facing northwest)

Figure 369. CAD model of Number 10 with a 32° pitch roof (facing northeast)
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Figure 370. CAD model of Number 10 with a 32° pitch roof (facing west)

Figure 371. South elevation of the CAD model of Number 10 with a 32° pitch roof (facing north)

The created timber roof has been based on the location of the timber work that currently presides in the roof of Number 10 (5.4.1.2.2), and includes wall posts, arch braces, two queen-struts, and a central king-strut (Figure 372).
The internal CAD model of the undercroft, generated from the laser scan model can be seen in Figure 373, with a wireframe (Figure 374) providing a further overview of the vaulting geometry.
Figure 374. Underneath view of the wireframe model of CAD model of Number 10 with a 32° pitch roof (facing west).

The maximum displacement of the reconstructed Number 10 with a 32° pitch roof was 0.09 millimetres (Figure 375).

Figure 375. Displacement results of Number 10 with a 32° pitch roof

The tensile stress of the stone used in the building was 302199 N/m²; the oak timber had a tensile stress of 216792 N/m² (Figure 376). The tension stresses developed are within the allowed amounts of both materials, with the largest tensions seen in the crossing points of the undercroft vaulting (Figure 377).
The compressive stress of the stone was $-635673 \text{ N/m}^2$; the oak timber had a compressive stress of $-407084 \text{ N/m}^2$ (Figure 378), with both values being acceptable. The largest compressive forces can be seen in the central columns (Figure 379) and is to be expected considering that these act as the main support mechanism for the undercroft vaulting.
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Figure 379. Minimum principle stress results of Number 10 with a 32° pitch roof, with a focus on the central columns

The applied force generated is relatively low at 1933.49 Newtons, but as shown in Figure 380, these are seen at the bases of the supporting columns of the east and west walls, which are to be expected with the outward force applied in the vaulting.

Figure 380. Applied force results of Number 10 with a 32° pitch roof

The results therefore suggest that Number 10 was able to support a 32° pitch roof, and the included stairs add to the overall structural strength of the building work. The inclusion of the stairs were originally believed to be unsafe due to their location near to the main doorway of the building, but this has been proved an incorrect assumption.

A.1.3.2 Removal of The Timber Wall Plate

Part of the analysis of the timber roof, as discussed in 5.4.1.2.2, included the removal of the timber wall plates to see how this affected the overall structurally integrity of the building. The reconstructed CAD model of this removal can be seen in Figure 381.
With the wall plates removed, the maximum displacement found was of 0.17 millimetres (Figure 382). This value is slightly higher than with the wall plates included, with the greatest movement seen in the two queen struts.

The tensile stress of the stone was 225571 N/m²; the oak timber had a tensile stress of 232739 N/m² (Figure 383). The values generated are allowable, with the stone having less tensile stresses than previous results. The timber however contains a greater tensile stress and is to be expected with the removal of the wall plate support (Figure 384).
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Figure 383. Maximum principle stress results of Number 10 with a 32° pitch roof without a wall plate

Figure 384. Maximum principle stress results of the timber frame of Number 10 with a 32° pitch roof without a wall plate

The compressive stress of the stone was -635165 N/m²; the oak timber had a value of -389328 N/m² (Figure 385). Both of these results are lower than the previous analysis and it would seem that the removal of the wall plate adds to the overall integrity of the building.

Figure 385. Minimum principle stress results of Number 10 with a 32° pitch roof without a wall plate
A.1.3.3 **Number 10 with a 32° Pitch Roof and a Corbel Support**

The creation of the model, as seen in Figure 386 and Figure 387, answers a specific research question, with a focus seen on the removal the east and west support columns, replaced by a corbel support system.

![Figure 386. View of the CAD interior undercroft of Number 10 with a 32° pitch roof with corbel support (facing northwest)](image)

The maximum displacement found in this corbel only undercroft was 0.08 millimetres (Figure 388) and is less than the previous two results.

![Figure 387. View of the CAD interior undercroft of Number 10 with a 32° pitch roof with corbel support (facing west)](image)
The tensile stress of the stone was 281706 N/m²; the oak timber had a value of 124152 N/m² (Figure 389). Again, these values are satisfactory, with the stone containing less tensile stresses than the previous two models. The highest tension points in the corbel only model are found directly above the corbels and central columns in the second floor flooring (Figure 390 and Figure 391). The timber stress values seen in this model are almost half in comparison to the previous models and implies that the corbels act as a better support system.
The compressive stress of the stone was -612557 N/m²; the oak timber had a compressive stress of -701010 N/m² (Figure 392 and Figure 393). As with the tensile stresses, the stonework has a lower compressive force applied than in the results seen in the previous models. The timber frame however is almost doubled in value.
The applied force placed on the stonework was 1419.99 Newtons, which is less than 1933 Newtons applied to the first model. These forces can be seen as stress points (5.5.1) in the building work, as shown in Figure 394 to Figure 395, and are found mainly parallel to the corbels.
Figure 395. West elevation of the applied force results of Number 10 with a 32° pitch roof with corbel support

Figure 396. East elevation of the applied force results of Number 10 with a 32° pitch roof with corbel support

Although the compression seen in the timber roof is greater, the overall building contains less tensile and compressive forces and would suit the introduction of the vaults utilising just corbels as a support mechanism.

A.1.4 Number 10 with a 21° Pitch Roof

A.1.4.1 Reconstructed Interpretation

The CAD model seen in Figure 396 to Figure 398Figure 397 provides an overview of the reconstructed model of Number with a 21° pitch roof. Figure 399 highlights the difference in shape of the timber frame used.
Figure 397. CAD model of Number 10 with a 21° pitch roof (facing northwest)

Figure 398. South elevation of Number 10 CAD model with a 21° pitch roof (facing north)
Using the same analysis as the 32° pitch roof, the maximum displacement found was 0.1 millimetres (Figure 400) and is slightly more than the previous test.

The tensile stress of the stone was 286119 N/m², with the oak timber having a tensile stress of 97685.6 N/m² (Figure 401 and Figure 402). Again, these values are acceptable and are less than the previous 32° pitch roof.
Figure 401. Maximum principle stress results of Number 10 with a 21° pitch roof

Figure 402. Underneath view of the maximum principle stress results of Number 10 with a 21° pitch roof

The compressive stress of the stone was -638126 N/m² (Figure 403) and is greater than the 32° pitch equivalent, with the majority of compression seen in the central columns of the undercroft (Figure 404). The oak timber had a compressive stress of -255087 N/m²; almost less than double that of the 32° roof.

Figure 403. Minimum principle stress results of Number 10 with a 21° pitch roof
The overall structural integrity of the 21° pitch roof appears to be similar in validity to the 32° pitch roof. The change in pitch is therefore unrelated to the overall structural form, but was most likely adapted due to the subsidence found in the central columns in the current building work.

**A.1.4.2 Number 10 with a 21° Pitch Roof and a Corbel Support**

As with the 32° pitch roof, the 21° pitch roof has been examined without the supporting columns found on the east and west walls of the undercroft. The maximum displacement was 0.09 millimetres and is lower than the previous results (Figure 405).

The tensile stress of the stone was 230 761 N/m², with the oak timber having a tensile stress of 128074 N/m² (Figure 406). The stone has a lower tensile stress than the previous results, with the timber being greater in tension. This is similar to the results found within the 32° pitch roof.
Figure 406. Maximum principle stress results of Number 10 with a 21° pitch roof with supporting corbel

The compressive stress of the stone was -581087 N/m², with the oak timber having a value of -257081 N/m² (Figure 407). As with the tensile stress, the compressive nature of the corbel support is less in the stone. The timber roofing is greater, but compared to the 32° pitch roof, the compressive response is almost three times as less. As with the other results, the greatest compression stresses can be seen in the central support columns of the undercroft, as shown in Figure 408.

Figure 407. Minimum principle stress results of Number 10 with a 21° pitch roof with supporting corbel
A.1.5 Number 10 Subsidence of Central Column

Section 5.4.1.1 discussed how the subsidence has affected the overall form of Number 10, and the difference in heights of the central columns can be seen in Figure 409. As both the 32° and 21° pitch forms of roofing were proved structurally valid, both variations have been tested. In order to simulate the subsidence present, boundary conditions attached to the central column have been removed.
Appendices

A.1.5.1 32° Pitch Roof Subsidence

With the collapse of the central column support, the maximum movement can be found in and around the central column, as shown in Figure 410 and Figure 411.

Figure 410. Top down view of the displacement results of Number 10 with a 32° pitch roof with a central column collapse

Figure 411. Underneath view of the displacement results of Number 10 with a 32° pitch roof with a central column collapse

Figure 412 adds a further overview of this movement showing the height changes and central pulling of the column affected by the subsidence.
The tensile stress of the stone was 3477731 N/m² and within the limits of the allowed material strength. Figure 413 provides an overview of this result, with the maximum values seen in the rib vaulting, as well the central column, as indicated in the current undercroft.

The compressive stress of the stone was -2550986 N/m², with the maximum values located in the supporting columns that surround the central column, as shown in Figure 414 and Figure 415.
Figure 414. Minimum principle stress results of Number 10 with a 32° pitch roof with a central column collapse

Figure 415. Underneath view of the minimum principle stress results of Number 10 with a 32° pitch roof with a central column collapse. The image highlights the internal stress of the internal east wall

The structural tests performed emulate the responses seen in the current building work. The results do however contain less overall movement, but due to the reworking and modification found in the upper levels of Number 10, a greater overall force would now be exerted on the undercroft, thus increasing the potential of the subsidence found.

A.1.5.2  21° Pitch Roof Subsidence

As with the 32° pitch roof the generated subsidence results have a maximum movement within the central column under investigation, as shown in Figure 416 and Figure 417.
The tensile stress of the stone was 3563176 N/m² (Figure 418) and is greater in tension than the 32° pitch roof. This value is only 0.016MPa away from failing and is on the threshold of failing under tension. This tension, with the almost failure of the building, could be the reason why the building was adapted to incorporate the 32° pitch roof, as cracks would be evident in the vaulting.
Appendices

Figure 418. Sliced view of the maximum principle stress results of Number 10 with a 21° pitch roof with a central column collapse

The compressive stress of the stone, as shown in Figure 419, was $-3280212 \text{ N/m}^2$ and is again greater in compression than the 32° pitch roof. Figure 420 provides a further overview of this result, where the adjacent central support columns are under significant strain due to the increased force applied.

Figure 419. Top down view of the minimum principle stress results of Number 10 with a 21° pitch roof with a central column collapse
Figure 420. Sliced view of the minimum principle stress results of Number 10 with a 21° pitch roof with a central column collapse

The maximum reaction force found was 37832.39 Newtons with Figure 421 representing how the other central columns and bases support the building from total collapse. If further subsidence were to take place in these supporting columns, the building would fail.

Figure 421. Reaction force results of Number 10 with a 21° pitch roof with a central column collapse

A.1.6 Number 10 Conclusion

With the structural tests performed on Number 10, the research questions outlined in A.1.1 have been answered. The subsidence was found to affect the 21° pitch roof more than the 32° pitch roof and could be the reason assigned to the change in structural form. Overall, the subsidence requires greater support from the surrounding central columns, and if further subsidence were to take place in the other columns, the building would fail.
The removal of the supporting columns on the east and west walls have proved that a corbel support system would be possible, with both forms of building showing a stronger structural form. The inclusion of the external staircase has also been proved and as seen in Figure 422, the height of the staircase is lower than the overall cloister wall, providing an assessment that the staircase would be hidden from view.

Figure 422. The CAD model of Number 10 in its correct position next to the south cloister wall

The original form of the Number 10 is still unknown, but with the tests completed, both the 21° and 32° roofs were possible, with the change in form related to either subsidence issues or stylistic choices.

A.2 Pilgrim Range Structural Tests

A.2.1 Research Questions

As with the other buildings under investigation, a number of research questions were suggested in 5.5.3. These questions are listed below and will be answered through structural analysis testing:

- How accurate is John Crook’s conjectural plan of the Pilgrim Range in relation to its structural properties?
- How do the different truss systems affect the overall building?
• Would the use of one truss system throughout the range have been strong enough to support the building?
• Is a hip end roof plausible in the south range?
• Are the buttresses found in the north of the building necessary?

A.2.2 The Creation of the Models

The created models used in the structural analysis have been created based on the documentary research (5.5.1) and the survey work captured on site (5.5.2.). A large proportion of the known layout of Pilgrim Range can be found in Crook’s (Crook, 1991: 132) work and his interpreted reconstruction can be seen in Figure 423.

Figure 423. Reconstructed drawing of the Pilgrims’ Range (Crook, 1991: 130). Reproduced by kind permission of Cambridge University Press, www.cambridge.org.

The drawn elevations of the individual trusses of this building were extracted from Crook’s work and were placed in their correct position in AutoCAD using the overall floor plan of the building, as shown in Figure 424. These elevation drawings were scaled in relation to the laser scan model of Pilgrims’ Hall (Figure 425). Using these elevation drawings and the laser scan model, a completed CAD reconstruction was produced, as shown in Figure 426.
Appendices

Figure 424. John Crook’s truss interpretation drawings of Pilgrim Range arranged in their correct positions in AutoCAD

Figure 425. CAD model construction of Pilgrim Hall using the recorded laser scan data
A.2.3 **John Crook’s Interpretation**

As with the work completed in the cathedral timber roof investigation (6.5.9), both oak and pine have been tested at Pilgrim Range, to see if oak was a suitable material in the construction of the timber framed building.

A.2.3.1 **John Crook’s Interpretation with an Oak Timber Roof**

The reconstructed model of Pilgrim Range can be seen in Figure 427 to Figure 430; included within this building are three different material properties comprising of Quarr stone, wattle and daub, and oak.
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Figure 427. CAD model of Pilgrim Range facing southeast. Grey) Stone. Yellow) Wattle and Daub. Red) Timber

Figure 428. CAD model of Pilgrim Range facing northeast. Grey) Stone. Yellow) Wattle and Daub. Red) Timber
The images above provide an overview of the building complex, but the timber frame used has been separated to provide an overview of the separate truss systems, as shown in Figure 431 and Figure 432.
The max displacement of this first interpretation was 4.58 millimetres (Figure 433), and is concentrated in the Pilgrims’ Hall timber rafters. This movement is small overall and is acceptable.
The tensile stress of the stone was 649097 N/m²; the oak, 1309430 N/m²; and the wattle and daub, 115775 N/m² (Figure 434). All of these tensile stresses are within the allowable tensile strengths of the materials and suggest that John Crook’s interpretation is structurally viable under tension.

The Compressive stress of the stone was -926622 N/m²; the oak, -1675260 N/m²; and the wattle and daub, -192676 N/m² (Figure 435). Again, these compressive stresses are permissible, with the largest compression seen in Truss II (base-cruck).
A.2.3.2 **John Crook’s Interpretation with a Pine Timber Roof**

With pine used instead of oak, the structural tests performed founded a max displacement of 4.02 millimetres (Figure 436). This value is less than the oak equivalent but the same position of movement can be seen.

The tensile stress of the stone was 524064 N/m²; the pine, 1002360 N/m²; and the wattle and daub, 97729.4 N/m² (Figure 437). These values are acceptable and are less than those found in the oak model, suggesting that oak, and the weight included, adds to the overall stresses produced in the building.
The compressive stress of the stone was -680079 N/m²; the pine -1193290 N/m²; and the wattle and daub, -178932 N/m² (Figure 438). As with the tensile stress, these values are lower than the oak equivalent and supports the notion that oak was perhaps an incorrect wood type used in the timber frame of the building.

On examining the structural tests completed, John Crook’s interpretation of the Pilgrim Range seem to be valid. The weakest part of the building work can be seen in Truss II but generally, the inclusion of different truss types has no overall effect on the building.

A.2.4 Without North Buttresses

The buttresses shown in the tests above provide a relief system to the outward forces generated by the hammer beam trusses. To test the extent of how these buttresses add to overall strength of the building, they have removed, as shown in Figure 439 and Figure 440.
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Figure 439. CAD model of Pilgrim Range without stone buttresses facing southeast

Figure 440. Top down view of the CAD model of Pilgrim Range without stone buttresses facing northwest

With the buttresses included, the maximum displacement found was 4.61 millimetres (Figure 441). Although this movement is greater than with the buttresses included, the extra movement is minimal and suggest that the buttresses provided little support in terms of movement.
Without the buttresses, the tensile stress of the stone was 1236330 N/m²; the oak timber, 2584690 N/m²; and the wattle and daub, 130537 N/m² (Figure 442). Without the buttresses, the tensile stresses of the stone and oak are almost double the previous value. These values are still within the limits of the material properties but the results do suggest that the buttresses are a necessity to support the forces applied.

The compressive stress of the stone was -791621 N/m²; the oak, -4139960 N/m²; and the wattle and daub, -259898 N/m² (Figure 443). As the buttresses add to the weight of the building, the compression shown in the stone is less than the previous result; the oak however provides a compressive stress that is almost four times the value, with the wattle and daub stress also being greater. This shows that the removal of the buttresses have redirected the forces in the building from the stonework, and are now supported by the oak and attached wattle and daub.
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Figure 443. Minimum principle stress results of Pilgrim Range without stone buttresses

A.2.5 Door Location

As discussed in 5.5.1.3, the doorway included in John Crook’s interpretation is unknown and four different positions have been used to identify the possible location. The results shown highlight how structural stress points can provide indications of these forms of openings, with small variations in door locations generating different results.

A.2.5.1 Door Location One

The first door location can be seen in Figure 444 and Figure 445, with the doorway included within the main supporting wall.

Figure 444. CAD model of Pilgrim Range with the first door location facing southeast
The max displacement of this door location provides a movement of 2.14 millimetres (Figure 446). The tensile stress of the stone was 2302540 N/m²; the oak, 1372320 N/m²; and the wattle and daub, 55779.5 N/m² (Figure 447). The tensile stresses generated are allowable, and the inclusion of the doorway within the support wall, although unlikely, provide no overall tensile concerns.
The compressive stress of the stone was -2982030 N/m²; the oak, -836619 N/m²; and the wattle and daub, -119324 N/m² (Figure 448).

The compressive stresses seen above are allowable, but when examining the applied force (572 Newtons), a number of stress points are generated and indicate an uneven distribution of forces within the building (Figure 449).
Figure 449. Applied force results of Pilgrim Range with the first door location

A.2.5.2 Door Location Two

The second door location can be seen in Figure 450 and Figure 451, with the doorway separated from the supporting wall.

Figure 450. CAD model of Pilgrim Range with the second door location facing southeast
The max displacement of this door location provides a movement of 2.25 millimetres (Figure 452) and is greater than the first door location.

The tensile stress of the stone was 1917480 N/m²; the oak, 650109 N/m²; and the wattle and daub, 57332.3 N/m² (Figure 453). With the doorway moved into a more open area, with supporting walls either side, the overall tensile stresses are lower, with the timber being almost twice as less.
The compressive stress of the stone was -3829250 N/m²; the oak, -707303 N/m²; and the wattle and daub, -115285 N/m² (Figure 454). The compressive stress seen in the stone is greater, with the compressive forces in the timber and wattle and daub being lower.

The applied force of the second door location is great at 739 Newtons (Figure 455), but the stresses points seen are more evenly spread, with a redirection of the forces shown in the supporting buttresses, unlike the previous results.
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Figure 455. Applied force results of Pilgrim Range with the second door location

A.2.5.3 Door Location Three

The third door location can be seen in Figure 456 and Figure 457, with the doorway moved further north from the previous location.

Figure 456. CAD model of Pilgrim Range with the third door location facing northeast
The max displacement of this door location provides a movement of 2.25 millimetres and is the same as second door location (Figure 458).

The tensile stress of the stone was 1629100 N/m²; the oak 650100 N/m²; and the wattle and daub 57370.3 N/m² (Figure 459Figure 458). The results shown contain lower tensile stresses in the stone compared to the previous two results; the timber frame contains the same stress values as the second door location; and the wattle and daub has a greater stress value.
The compressive stress of the stone was -7819880 N/m²; the oak, -708893 N/m²; and the wattle and daub, -114140 N/m² (Figure 460). The compressive stress seen in the stone are almost double the previous results; the timber is again higher and the wattle and daub stresses are slightly less.

The applied force created is 739.83 Newtons (Figure 461) and is the same value as the second door location. A higher stress point can be seen in above the doorway, and with the other results generated, it would appear the second door location is more favourable.
A.2.5.4  Door Location Four

The fourth door location can be seen in Figure 462 and Figure 463, with the doorway added to a supporting buttress. This door location is the opposite of the first door location.

Figure 462. CAD model of Pilgrim Range with the fourth door location facing northeast
The max displacement of this door location provides a movement of 2.24 millimetres (Figure 464) and is slightly less than second and third models.

The tensile stress of the stone was 2773570 N/m²; the oak, 954162 N/m²; and the wattle and daub, 55951.75 N/m² (Figure 465). The tensile stress found in the stone is the highest of the four door locations; the timber stresses are less than the first door location, but are higher than the two central doorways.
Figure 465. Maximum principle stress results of Pilgrim Range with the fourth door location

The compressive stress of the stone was -8135130 N/m²; the oak, -696942 N/m²; and the wattle and daub, -116995 N/m² (Figure 466). As with the tensile stresses, the compressive stress in the stone is the highest of the four door locations; the timber surprisingly has the lowest value overall; with the wattle and daub being greater than the first door location.

Figure 466. Minimum principle stress results of Pilgrim Range with the fourth door location

The applied force generated (736 Newtons) (Figure 467) is the second lowest of the four door locations, but highlights the redirection of the forces that should be generated within the buttresses connected to the doorway. With these results, and the results from the other door locations, the second position seems the most logical.
A.2.6   Removal of Scissor Bracing

The results discussed so far have concentrated on the stonework found at Pilgrim Range, with little discussed on the timber roof. The timber roof is supported by a scissor brace and in order to test the structural form of this support mechanism, the bracing has been removed and tested, as shown in Figure 468 and Figure 469.
The maximum displacement found in the building without a scissor bracing support was 2.39 millimetres, and is concentrated in the south part of the building (Figure 470 and Figure 471).

Figure 469. CAD model of the Pilgrim Range timber roof without scissor bracing (angled north)

Figure 470. Displacement results of Pilgrim Range roof without scissor bracing (facing southeast)
Figure 471. Displacement results of Pilgrim Range roof without scissor bracing (facing northwest)

The tensile stress of the stone was 10756900 N/m²; the oak, 18869300 N/m²; and the wattle and daub, 7181750 N/m² (Figure 472). With the scissor bracing removed, the stone and wattle and daub fails under tension, with the stone being three times the allowed amount of the material property.

Figure 472. Maximum principle stress results of Pilgrim Range roof without scissor bracing

The compressive stress of the stone was -15930000 N/m²; the oak, -33485400 N/m²; and the wattle and daub, -5281910 N/m² (Figure 473). With the scissor bracing removed, the stone and oak values are allowable, but the wattle and daub fails under compression, with almost double the allowed value produced.
Figure 473. Minimum principle stress results of Pilgrim Range roof without scissor bracing

The internal force produced was 460 Newtons, which is over double the amount found with scissor bracing included (Figure 474).

Figure 474. Internal force of Pilgrim Range. Top) Without Scissor bracing. Bottom) With Scissor bracing

The applied force produced was 460 Newtons, and is again over double the amount found with scissor bracing included (Figure 475).
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Figure 475. Applied force of Pilgrim Range. Top) Without Scissor bracing. Bottom) With Scissor bracing

As the structural tests indicate a failure in both the tension and compressive nature of the building, the inclusion of the scissor bracing within the timber-framed roof is of great importance and is a necessary feature in the stability of the building.

A.2.7 Hamme r Beam

The inclusion of different truss systems within the building is an unusual approach in design. In order to test the feasibility of a single truss type, the Pilgrim Range has been modelled with only hammer beam trusses, as shown in Figure 476 to Figure 478, with the overall design of the hammer beam roof seen in Figure 479. As the addition of wattle and daub within the building are based on limited excavation results, and as the hammer beam system relies on the cantilevered wall supports that terminate on the wall, the building has been developed to include only stone walls.
Figure 476. CAD model of the Pilgrim Range with hammer beam trusses (facing southeast)

Figure 477. CAD model of the Pilgrim Range with hammer beam trusses (facing east)
Figure 478. CAD model of the Pilgrim Range with hammer beam trusses (facing northeast)

Figure 479. CAD model of the Pilgrim Range with hammer beam trusses

The maximum displacement was 0.06 millimetres (Figure 480) and is the best result overall.
The tensile stress of the stone was 142315 N/m²; the oak was 161731 N/m² (Figure 481). These are again the lowest values produced, but is explained with the additional support seen in the stone walls.

The compressive stress of the stone was -160108 N/m²; the oak was -178338 N/m² (Figure 482). Again, these values are the lowest produced. Figure 483 and Figure 484 provide a further overview of this truss system, and highlight how the hammer beam trusses are able to alleviate the forces applied to the timber roof.
The inclusion of a single truss support system within Pilgrim Range is therefore possible.
A.3 The Cloisters

A.3.1 Research Questions

As noted in 5.3.2, a number of research questions have been proposed within the examination of the cloisters. These questions are listed below but unfortunately, these could not be answered using structural analysis:

- What was the original form of the cloisters?
- What roofing types were possible?
- Were different heights possible?

A.3.2 The Creation of the Models

Very little evidence exists at Winchester of the original cloister garth. The research completed in 5.3.1 provided an overview of the available data, and in order to create a model that is realistic, a number of other cloister garths had to be examined; the majority of these have been converted to a later architectural style and are used simply as a guide to the possible form at Winchester. At Canterbury (Figure 485), the cloisters found are of the Gothic style, and show a systematic form within the bays. This form is also seen in the Gothic designs at Gloucester (Figure 486), Norwich (Figure 487), and Worcester (Figure 488). Originally, these cloisters would have been designed in the Romanesque style, and an overview of their overall shape can be used in the reconstruction at Winchester.
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Figure 485. Canterbury cathedral cloisters

Figure 486. Gloucester cathedral cloisters
The large majority of the converted cloister garths now include some form of vaulting, as shown at Gloucester cathedral (Figure 489) and Lincoln cathedral (Figure 490). The internal view found indicates that the cloister walls were constructed at the same elevation, offering a support
mechanism for the vaulting. It is unknown if the Romanesque cloister walls would have been at the same height.

Figure 489. Gloucester cathedral internal view of the cloisters

Figure 490. Internal view of Lincoln cathedral cloisters
In those cloister garths that do not contain an internal stone vault, such as Durham cathedral (Figure 491 and Figure 492), the timber framed used is of a simple form, and is in contradiction to the arrangement suggested by John Crook (5.3.1).
Crook suggested that the internal wall of the cloister at Winchester was of a lower height, and the roof was sloped. As with the work completed on Pilgrim Range, Crook’s interpretation has been tested. The problematical obstacle that challenges his interpretation surrounds the different heights found in the external cloister walls (Chapter House). On examining the extant remains of Rochester cathedral (Figure 493), variations in the height of the cloister walls can be seen, and adds some justification to the form suggested by Crook.
Figure 493. Rochester cathedral cloister remains. On the left are the remains of the Chapter House, with the right side showing the remains of the internal wall of the cloisters. These have different heights.

In Crook’s original interpretation, the exact dimensions of the cloister walls and their location were unknown. Following the GPR survey completed on site (5.9.1.2), an outline of the cloisters were discovered. This outline (Figure 494) has proved valuable in the creation of the cloister model, and identifies that geophysics is an essential process necessary in the creation of unknown features (5.9.1.3). Figure 495 to Figure 497 provide an overview of the created model using the GPR results.
Figure 494. Top down view of the GPR survey results

Figure 495. Top down view of the GPR survey results with the reconstructed model
A.3.3 Building Work

With the generated base model created (Figure 498), which included the known positions and dimensions of the inner walls, variations in roofing style could be created. In order to test these variations, the form suggested by Crook was examined first to test the feasibility of the building work shown. The base model includes the Chapter House west front, as well as the discovered refectory and lavatorium (5.8).
The maximum displacement found of the interpreted model was 0.04 millimetres (Figure 499) and suggests that building work shown is viable.

The tensile stress of the stone was 111556 N/m², with the Purbeck marble of the Chapter House having a tensile stress of 46820.4 N/m² (Figure 500 and Figure 501). These values are allowable within the material properties and shown to be highest on the outer walls when connected to other building work (e.g. the cathedral south nave).
The compressive stress of the stone was -357025 N/m²; the Purbeck marble of the Chapter House was -43752.4 N/m² (Figure 502). Again, these values are allowable and are mainly concentrated at the bases of the refectory building.
The applied force seen in the cloister design was 135.95 Newtons (Figure 503), with stress points seen in the arches (Figure 504). These stress points are expected within the form created and highlight the relieving nature that the arch columns provide.

With the structural tests performed, the basic layout of the cloisters can be given, but variations in this style and form are still possible, and require further examination.

**A.3.4 Assessment of the Possible Timber Frame Assemblies**

A number of different timber roof designs were intended to be tested through structural analysis; however, on importing the CAD models into Autodesk Simulation, the software was unable to create the necessary Finite Element Model, due to errors in the connection of the timber posts and the attached walls. Various attempts were made to correct this error (Figure 505 and Figure 506) but the software was unable to produce the necessary mesh, and no further structural tests
could be performed. Instead of relying on the structural tests, as was the case for the other buildings, the arrangement of the timber supports can be completed through a general overview of the created models. In the original created models, four variations were generated, with only two discussed in these results.

A.3.5 John Crook’s Interpretation

The first interpretation modelled, was the interpretation made by John Crook, as shown in Figure 507. When Crook suggested this possible form, the interpreted inner wall of the cloisters were
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nearer to the external wall. As a result, the angle of the timber support is incorrect and as shown in Figure 508 and Figure 509, are included at the height of the walkthrough. This would seem illogical considering that the cloister walkway would have been open; at the current angle suggested, the monks who would have used this walkway would have had to duck to avoid hitting the supports.

Figure 507. John Crook's cloister interpretation (facing northeast). Grey) Stone. Red) Timber supports. Green) Purbeck marble

Figure 508. South elevation of John Crook's cloister interpretation, with timber clearly seen through the walkway. Grey) Stone. Red) Timber supports
A.3.6 Alternative Interpretation

As an alternative interpretation, rather than the timbers supports abutting the exterior wall in an inverted position, the second interpretation has the timber supports in an elevated position as shown in Figure 510. On examining the walkway in Figure 511, this interpretation seems more valid, as the walkway is open, and is able to support the differing heights found in the cloister garth.

Figure 509. North elevation of John Crook’s cloister interpretation, with timber clearly seen through the walkway. Grey) Stone. Red) Timber supports

Figure 510. Alternative cloister interpretation (facing northeast). Grey) Stone. Red) Timber supports. Green) Purbeck marble
In order to support the claim that this interpretation is valid, structural tests are needed. The CAD model therefore requires carefully editing to allow these tests to be generated. This is important, as leaving the interpretation open, establishes the issues discussed in Chapter Two. As a result, it must be noted that this interpretation is has been generated through the documentary and survey work completed, and should only be used as a guide.

A.4 Chapter House

A.4.1 Research Questions

The research questions proposed in 5.7.3 are listed below and will be answered through the structural analysis tests performed:

- What was the original shape of the building?
- What type of vault was used within the building?
- Was the building of an open form or was it closed?

A.4.2 The Creation of the Models

The models generated are based on the documentary research completed in 5.7, as well as the survey work collected on site at Winchester (s 5.7.2 and 5.9.1.1). The resistivity results have proved that the Chapter House was designed in a rectangular form, and this has been used as a basis within the examination of similar Chapter Houses. Bristol, as mentioned in 5.7.2, is the only comparable Chapter House with the same design and shape that still survives. On examining
converted Gothic style Chapter Houses, all of the entrances to the building, although included within the cloisters, are of a closed form. This can be seen at Gloucester (Figure 512), Rochester (Figure 513), and at Bristol (Figure 514). It makes little sense to have the Chapter House at Winchester as an open formed building, as no other examples exists. As such, a closed from has been generated and these have been tested with varying styles of vaulting.

Figure 512. Gloucester cathedral Chapter House entrance
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Figure 513. Rochester cathedral Chapter House remains

Figure 514. Bristol cathedral Chapter House entrance

The basis of the models created are on the photogrammetry survey work (Figure 515) and the laser scan model captured (Figure 516 and Figure 517). These provide the dimensions of the building, and provide solutions to the overall height of the building.
Figure 515. Chapter House reconstruction based on the captured photogrammetry model

Figure 516. Chapter House reconstruction based on the captured laser scan model
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Figure 517. The height of the Chapter House reconstruction. This is based on the captured laser scan model and the height of the current library

A.4.2.1 **Barrel vaulted**

The first reconstructed model can be seen in Figure 518 to Figure 520, and is of a barrel-vaulted design. The barrel vault shown in these figures is of an open form, and allow for the inclusion of a timber-framed roof directly above. The inclusion of the timber roofing has not been completed within the tests performed, as a focus has instead been given to the vaulting found within the Chapter House. The materials used within the investigations are Quarr stone and Purbeck marble.
Figure 518. CAD model of the open barrel vaulted roof of Chapter House (facing northeast). Grey) Stone. Green) Purbeck marble

Figure 519. CAD model of the open barrel vaulted roof of Chapter House (facing east). Grey) Stone. Green) Purbeck marble
The maximum displacement of this open barrel vault was 0.21 millimetres (Figure 521), concentrated in the middle part of the vaulting.

The tensile stress of the stone was 119839 N/m²; the Purbeck marble was 17957.6 N/m² (Figure 522). The tension found within the building are mainly in the vault, as to be expected, and the above the central arch. The results generated are within the permitted tensile strengths of both materials, and the inclusion of a closed opening is structurally viable under tension.
Figure 522. Maximum principle stress results of the open barrel vaulted roof of Chapter House

The compressive stress of the stone was -379809 N/m²; the Purbeck marble was -534498 N/m² (Figure 523), both of which are within the permitted values. The compressive stresses seen are concentrated at the bases of the north and south walls (Figure 524), relieving the outward stresses generated by the vault, as shown in Figure 525.

Figure 523. Minimum principle stress results of the open barrel vaulted roof of Chapter House
Figure 524. Sliced internal view of the minimum principle stress results of the open barrel vaulted roof of Chapter House

Figure 525. Sliced internal view of the minimum principle stress results of the open barrel vaulted roof of Chapter House, showing the direction force of the stresses

With the structural results, the model created of the Chapter House is of a viable form.

A.4.2.2 Barrel Vaulted Roof With Infill

The second model created (Figure 526 and Figure 527) shows the same barrel vault as the previous test, but includes an infilled portion that creates a flat surface on which a timber roof can be positioned.
Figure 526. Underneath view of the CAD model of the infilled barrel vaulted roof of Chapter House (facing northeast). Grey) Stone. Green) Purbeck marble

Figure 527. CAD model of the infilled barrel vaulted roof of Chapter House (facing northeast). Grey) Stone. Green) Purbeck marble
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The maximum displacement of this second model 0.36 millimetres (Figure 528) and is slightly more than the previous results, due to mainly to the increased weight of the vaulting.

![Figure 528. Displacement results of the infilled barrel vaulted roof of the Chapter House](image)

The tensile stress of the stone was 310559 N/m²; the Purbeck marble had a value of 42502.3 N/m² (Figure 529). These results are a substantial increase to the open style barrel vault, but are still acceptable values. The largest stress is again seen in the centre of the vaulting.

![Figure 529. Maximum principle stress results of the infilled barrel vaulted roof of the Chapter House](image)

The compressive stress of the stone was -913407 N/m²; the Purbeck marble -758630 N/m² (Figure 530). Again, these results are greater than the previous model, but are to be expected with the further weight added. Figure 531 provides a further overview of the compression found at the Chapter House, with the largest compression of the west elevation found in the Purbeck support columns. The overall building however has a greater outward force applied (Figure 532) and could lead to a possible collapse if the building were affected by subsidence. The open form barrel vault is therefore more feasible in the stability of the overall building.
Figure 530. Minimum principle stress results of the infilled barrel vaulted roof of the Chapter House.

Figure 531. West elevation of the minimum principle stress results of the infilled barrel vaulted roof of the Chapter House.

Figure 532. Sliced internal view of the minimum principle stress results of the infilled barrel vaulted roof of the Chapter House, showing the direction force of the stresses.
A.4.2.3  **Groin vaulted**

The third model created is similar to the design found in the undercroft of Number 10, with the generated CAD of the groin vaulted Chapter House seen in Figure 533 and Figure 534, with wireframe models showing the internal detail seen in Figure 535 and Figure 536.

*Figure 533. CAD model of the groin vaulted roof of the Chapter House (facing northeast). Grey) Stone. Green) Purbeck marble*
Figure 534. CAD model of the groin vaulted roof of the Chapter House (facing east). Grey) Stone.
Green) Purbeck marble
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Figure 535. Wireframe model of the groin vaulted roof of the Chapter House (facing northeast)

Figure 536. Top down view of the wireframe model of the groin vaulted roof of the Chapter House (facing northeast)
The maximum displacement of this groin vault was 0.65 millimetres (Figure 537). The value is greater than the barrel-vaulted roof but is minimal.

![Figure 537. Displacement results of the groin vaulted roof of the Chapter House](image)

The tensile stress of the stone was 786276 N/m², with the Purbeck marble having a value of 30559 N/m² (Figure 538). The tensile stress developed in the stone has almost increased by seven times the value than that found in the open form barrel vault. The Purbeck marble is also greater in tension. The overall tension found is still permissible, and is concentrated in the top part of the groin vault (Figure 539). The position of the tension within the building is smaller and is more realistic when examining the building work found elsewhere at Winchester cathedral.

![Figure 538. Underneath view of the maximum principle stress results of the groin vaulted roof of the Chapter House](image)
Figure 539. Top down view of the maximum principle stress results of the groin-vaulted roof of the Chapter House

The compressive stress of the stone was -1271980 N/m²; the Purbeck was -689240 N/m² (Figure 540 and Figure 541). The results generated show that the stone has the highest compressive results from the three variations but is concentrated in the base of the central vault column, as well as the relieving vault ribbing (Figure 542).

Figure 540. Minimum principle stress results of the groin vaulted roof of the Chapter House (facing southeast)
A.4.3 Chapter House Conclusion

The structural tests performed suggest that all three variations of the Chapter House are possible. With the vaulting seen in the undercroft of Number 10, as well as the groin vaulting seen in the cathedral, the last tested model seems the most logical. The tension and compression results found are within the overall strengths of the materials used. The generated results also suggest that the inclusion of a timber roof would be suitable, as the tension values generated are only one fifth of the tensile strength of the material. This in association with the closed opening provides further support to the model generated being realistic.
A.5 Refectory

A.5.1 Research Questions

Section 5.8.3 provided overall research questions for the Lavatorium and the Refectory and are listed below. Within the analysis performed, only the Refectory has been examined.

- Where was the Lavatorium? This has been answered in A.3.2 and can be found north of the refectory, attached the inner cloister wall, as seen at Gloucester cathedral.
- What was the original form of the Refectory?

A.5.2 The Creation of the Refectory Model

The model has been created based on the documentary research completed (5.8) and the GPR results (5.9.1.2). This data has been used in connection with the surviving extant remains at Norwich (Figure 543) and the work completed by Gilchrist (2005). Norwich’s refectory was of a longer length than Winchester’s and has been used as a guide only. Two variations of timber roofing have been included, and unlike Norwich, the inner ceiling has been left open, as was the case within the original Winchester cathedral design.

Figure 543. Norwich cathedral refectory windows
A.5.2.1  King Post Timber Frame Roof

The generated model of the Refectory can be seen in Figure 544, with the timber frame used in the investigation seen in Figure 545. This design is similar in style to the timber roof examined in Number 10 (A.1.3). The building is of a smaller length than postulated by Crook (5.9.1.2), as the geophysics results show a clear outline of the building work.

Figure 544. CAD model of the refectory with a king post timber frame (facing southeast). Grey) Stone. Red) Timber

Figure 545. CAD model of the refectory king post timber frame
The maximum displacement found was 0.15 millimetres (Figure 546), concentrated mainly in the timber frame.

The tensile stress of the stone was 81364.4 N/m²; the oak timber was 191122 N/m² (Figure 547). Both of these values are within the allowed material tensile strengths, and show that the model has little tension and is structurally viable.

The compressive stress of the stone was -409568 N/m²; the oak was -195342 N/m² (Figure 548). Again, these values are lower than compressive strengths of the materials and can be used to suggest the form of the refectory.
A.5.2.2 Scissor Bracing Timber Frame Roof

The second generated model (Figure 549) included the addition of a scissor bracing timber roof (Figure 550), similar in style to the timber-framed roof of Pilgrims Range.
The maximum displacement of this second model was 0.32 millimetres (Figure 551) and again is found within the timber roof.

The tensile stress of the stone was 126458 N/m²; the oak was 304682 N/m² (Figure 552). Both tensile stresses are greater than the previous model but are still within the allowed tensile strengths of the materials.
Figure 552. Maximum principle stress results of the refectory with a scissor bracing timber frame

The compressive stress of the stone was -430376 N/m²; the oak was -278037 N/m² (Figure 553). Again, both materials are greater in compression than the previous king post timber roof design, and is most likely due to the outward force generated by the scissor bracing.

Figure 553. Minimum principle stress results of the refectory with a scissor bracing timber frame

A.5.3 Refectory Conclusion

With the tests completed on this unknown building design, the results suggest that the king post timber roof is the safest design option. The results provide an overview of the original form, and both options are valid in terms of stability. The original form remains unknown, and to state that one design was used over the other would lead to the problems discussed in Chapter Two. Instead, on looking at the dates of the original constructions of Number 10 and Pilgrim Range, as well as the size variations, it would be analytical to suggest that the king post timber frame was used in the original building work.
Appendix B  Introduction to Survey Methods

The aim of this appendix is to highlight and explain the available tools currently used in archaeology to record historic buildings. The focus will be on two types of recording methods, but comments will be given on others. This appendix will assess how useful the technologies are and will show the possibilities of what each method can provide. The technologies that are outlined are all useful within structural analysis, with some offering more than others. The potential of their use depends on the results that can be gained with each. The purpose of this appendix is to outline the positives and negatives and discuss what methods should be utilised for future recording.

B.1  Laser Scanning

In 2003 it was noted that “archaeology was becoming one of the main areas of applications for Range imaging” (Godin et al., 2003: 11); the statement remains true. The use of range and terrestrial laser scanning has developed in archaeology but the technique is still developing. Laser scanning has been utilised in a number of disciplines and is prominent within archaeological recording. The hindrance to the method becoming a conventional tool is its cost, computing power and the necessary skill to use the equipment correctly.

Laser scanning or three-dimensional scanning has been used increasingly for cultural heritage recording (Boehler and Marbs, 2004: 291), and allows for the collection of surface data to provide accurate measurements of visible objects. There are three main types of laser scanning methods: triangulation or range scanning; time of flight laser scanning; and phase laser scanning. Each of these offers different recording abilities, with some being suited to certain objects or areas. Each method provides a different range of resolutions and accuracies and as the technology becomes more advanced, more options are available for recording archaeological remains. These techniques have developed at different rates and this is evident in the papers that have been published since laser scanning’s first introduction within the discipline at the end of the twentieth Century (Xiao et al., 2007: 5792).

Terrestrial scan data through three-dimensional visualisation allow for detailed documentation of architecture which can be used to create three-dimensional vectors from which reconstructions can be made (Lambers et al., 2007: 1710). The method provides a high speed operation that offers an approach for three-dimensional spatial data acquisition where three-dimensional data of any large scale, complex, irregular, standard or nonstandard object or scene can be captured.
The captured data are visualised through the production of point clouds with final results seen through line drawings, CAD models, three-dimensional surface models and video animations (Boehler and Marbs, 2004: 292). The method provides the most effective way to quickly obtain the data of the observed object (Chen et al., 2005: 1) and enables measurements of areas that were unable to be collected previously.

The way in which laser scanning records allows for coverage of an object through a regular grid pattern, whereas recording methods such as photogrammetry concentrate on an object’s discontinuities and representative structures (Grussenmeyer et al., 2008: 215). When considering section drawings or plan drawings of an excavation, the data represented follow a specific pattern of recording and may often miss key information that was thought to be irrelevant. Laser scanning counteracts this by the assimilation of multiple scan positions creating overlapping datasets, removing any ambiguity associated with previous recording methods. There are many issues however that need to be considered when completing a recording process and lie mainly within target obstruction and field of view. Laser scanning will record anything that is within a given field of view; if for example, a tree branch blocked the line of sight to the object recorded, the scanner would only record the entities in the foreground, ignoring anything that it cannot see. The acquisition of multiple scans removes this problem but it is important to understand how the laser scanner will interact with the surrounding area, as incomplete datasets provide the same problems as graphical representations drawn by hand.

There exist three different types of laser scanning techniques. Each provides a different way to capture and process the recorded objects, requiring different skills and abilities. Each laser scan model follows the same methodology, through pre-processing the dataset by programming the scanners and thinking about how to record the object in question; recording the objects; stitching the multiple datasets together; and by processing the results. Although a basic methodology exists, differences in recording strategies can be seen in each of the three techniques. Each technique requires a set understanding of the technology used to formulate a capture scenario. How will the end result appear? What is the resolution of the device? What problems will there be in recording certain sections? How will the data tie together? Each of these questions must be answered with each technique providing different answers.

### B.1.1 Triangulation Laser Scanning

Triangulation or range laser scanning is suited more to the recording of small objects but can be used on larger surfaces. The technique has existed for many years and the development of this technology within archaeology rapidly grew into a key resource of recording artefacts. One of the
first examples of this can be seen in the work of Boehler et al. (2002) who recorded a number of case examples to identify the technology’s potential within cultural heritage; these included a statue, a sculptural arrangement, an excavated Roman boat and an architectural façade. The façade in this study is of interest as the level of detail gathered was extremely high but was limited to a very small section, signifying that the technique has potential in recording small areas of interest for structural analysis purposes.

Triangulation or range laser scanning is a technique that is more suited to the recording of small objects. The technique works by projecting a light spot or line onto the surface of an object. The position of the spot or line is recorded through a CCD (charge-coupled device) camera whilst the angle of the light beam is recorded by the internal mechanisms of the scanner (Figure 554); a calculation is made between these two elements and the relative distances are determined. The accuracy of the final scan data is reliant on the accuracy of the light angle recorded. Errors occur within any type of laser scanning method, though they are more prominent in the triangulation dataset when recording edges. The errors seen within edge detection are a flat triangulation of data that are unrepresentative of the original and occur when part of a laser point or line is partially visible on a surface edge; the CCD camera records this partial visibility as being whole and the scanner responds by perfectly matching each together. This is evident in all types of triangulation based laser scanners but can be corrected through editing.

Triangulation based scanners require a greater number of multiple scan positions that are close to one another to avoid general issues within the field of view. The process involved includes a range map capture; conversion to point data; meshing; and removal of unwanted errors. Multiple scans provide a jigsaw affect where each of the scans are unified; the majority of data that is collected is redundant due to overlap. Most triangulation based scanners work within a limited range of light; if the ambient light is too dark or bright, no data will be recorded. They will also not record black or shiny surfaces unless blue light technology is incorporated within the scanner system. Blue light technology projects a pattern across a surface where two cameras capture the displacement of changing pattern; this depth variation in the displacement of the pattern provides a calculation of the measurements. Unlike the CCD camera system, where single measurements are taken, based on where the light contacts the part of the surface recorded, the blue light allows for a completed surface capture. Blue light technology follows more of a structured light processing variation but it enables micron resolution and has the ability to record dark and shiny surfaces.
Appendices

Figure 554. Triangulation laser scanner calculation. The CCD camera and laser line are recorded from two positions and are combined to create distances (Fu et al., 2011: 779). © 2011 IEEE

Triangulation based scanners are the preferred method for recording small objects and normally have the capabilities to record from micron to millimetre resolution. The majority of scanners follow the same workflow that includes a range map capture, which is then converted to point data. The point data is then meshed directly within the capturing process and the mesh is edited to remove erroneous and unnecessary data.

B.1.2 Time of Flight Laser Scanning

Time of flight is a scanning technique that is based on the understanding of the speed of light. The method works by projecting a laser beam onto a surface that is returned along the same path. As the speed of light is known, the scanner calculates the time that it takes for the laser to return, creating a distance based on time. A time of flight scanner is usually set up to record these lengths at intervals of a picosecond through a rotating mirror, allowing several hundred thousand points to be captured in a second. The method can be used on a wide range of areas and is more suited to the recording of large distances, through a 360° horizontal view from the ground, and in a fixed position for LiDAR capture. The majority of scanners have the ability to record a distance of up to three hundred metres, with some newer versions produced by Leica having the ability to record up to six hundred metres. Most time of flight scanners allow for the resolution and the distance of the point data to be set manually within the capturing software. Photographs are also captured during this process and are projected onto the point clouds to provide RGB values per point.

Time of flight laser scanners can be seen as an advanced total station. One main drawback to the technique is the time associated with recording one scan; this is dependent on the distance and
resolution chosen, as well as the equipment used but can take several hours to complete. Smaller distances do not equate to shorter scan times as a greater point density could be recorded. When collecting data a consideration has to be made in terms of the level of detail required and the time available to record these scans. The majority of operators will place the scanner in a central position, record an overall scan, and then focus on specific areas at differing point spacings. Further considerations have to be made in terms of the areas that are recorded, especially when recording in large public spaces. To capture longer distances, a stronger light source is required; most time of flight scanners utilise a class 2 or 3 laser, requiring the operator and public to be set distances away for health and safety reasons. Creating scans in public spaces also becomes problematic when movement interrupts the laser. This creates unwanted data through the capture of the movement, and can lead to errors in the returning signal.

The collection of time of flight laser scanning follows the same overall workflow seen in Figure 555. The methodology can be altered to fit the needs of the environment that the scanner is used in and each operator will have different working alternatives that suit specific areas of interest.

Figure 555. The workflow of a time of flight laser scanner from site visit through to point cloud production (Shih et al., 2007: 504). Reproduced with permission of Elsevier, www.elsevier.com.
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B.1.3 Phase Laser Scanning

Phase laser scanning is a method that is similar to time of flight, except that comparisons are made between outgoing and returning signals rather than calculating the time taken for the light to return (Figure 556).

Figure 556. Comparison of time of flight and Phase shift laser signal (Faro, 2011). © Faro 2011.

Phase laser scanning provides an electronic distance measurement of coaxial intensity that are modulated optically that reflects off a target. The difference between the transmitted light and the reflected light provide a phase difference that equates to a distance. As the phase laser provides a continuous light beam, the offsets of the phases are measured and unique integers are created based on the multiple modulated wavelengths, thus creating a point cloud (Figure 557). The laser emitted is a continuous beam and the laser signal on which a modulated signal is superimposed is maintained and received at a constant value. The reflection of the laser beam is similar to time of flight but is continuous rather than pulse based; a small part of the laser signal is returned back to the instrument along the same path with the weakened signal amplified and separated in a process known as demodulation. These two separate signals are compared and a series of phase angles are solved by simultaneous equations to give a slant range or distance (Petrie and Toth, 2008: 18-19)
Figure 557. a) Amplitude modulation with the measuring wave is being used to vary the amplitude of the carrier wave, and (b) amplitude modulation of the emitted beam is performed by passing it through a KDP or KTP crystal to which a voltage has been applied (Petrie and Toth, 2008: 19). Image redrawn and edited from Price and Uren (1989)

The technique provides a greater accuracy of data due to the phase shift of the laser beam calculated; it provides a much faster data acquisition and offers a reduced amount of erroneous data. The one disadvantage to this technique is that it works on a limited range of about one hundred metres and cannot be used on areas that require a greater recorded distance. The method, as is the case with time of flight, allows for the collection of data in all ambient light conditions, from very dark to extremely bright environments. The majority of existing phase scanners work with a limited amount of manual settings regarding distance and point spacing. Unlike the time of flight technique, the scanners cannot specify areas of interest and are controlled instead by stated field of views within the scanner.

B.1.4 Case Studies and Discussions

The laser scanning conducted on the medieval church of Leopoli-Cencelle in Italy by Alvaro et al. (2009) had the main aim of creating a model using the secure and precise data which laser scanning offered. The use of laser scanner was required to solve all problems related to precision measurements and represents objects whose graphic documentation was previously difficult to understand (Alvaro et al., 2009: 3). Two separate scanners were used, the Leica Scanstation 2 for the upper part of the church and the Leica HDS 6000 for the crypt. The Scanstation 2 provided a point density of 50,000 points per second with the HDS 6000 offering 500,000 points per second (Alvaro et al., 2009: 6). In total twenty scans were recorded, seven within the crypt and thirteen in
the church. The results from these different scanners were merged together to create a complete model with the high-resolution dataset of the crypt being reduced to a quarter of its original resolution. This occurred due to the difficulties associated with processing the two varying resolutions and is difficult to understand why this was the case. With the data reduced, the record provided has had key sections removed of the recorded detail and this methodology goes against the aim of the initial research. The removal of data limits the ability to analyse a given model and although the results published in the paper are accurate, reservations remain about why one type of scanner was not used throughout with the same point spacings. Any recording that takes place should focus on the full documentation of the given area; rather than use separate types of recording, a full data capture should be completed using the decided technique.

Another example of laser scanning can be seen in the research carried out on the Roman theatre of Clunia by Finat et al. (2005). The research provides an assessment regarding the possibilities of laser scanning within conservation and restoration. Overall, the dataset gathered are adequate but there is nothing remarkable with the model produced. The overview given of the scan data is useful but the technology has since moved forward in terms of resolution and point density. This is key in understanding the changes that have occurred within laser scanning since its first use within archaeology. The technology has advanced greatly, higher resolution datasets are now available and the results from these early examples are at a quality that offer very little due to the point density that was once available. Technology changes, and with changing technology, newer models are superior. Early point clouds, although not worthless, offer very little quality controlled data. With newer technologies available, the data are superseded by a newer methods and this will continue happen. Great care has to be taken in producing a record that is future proof, whereby focus is given to acquisition rather than the technology used. An evaluation of methodological approaches is the most important factor within this comparison; through the majority of the papers that have been published, the same methodological approach is used. Instead of following standardised workflows, an updated methodological approach is required. One that focuses on using three-dimensional recording to answer set research question rather than because the technology is available.

Having outlined the need to compare methodological approaches it is important to examine research that focuses more on the archaeological implications. Amongst the foremost is the work completed by Balzani et al. (2004) whose research project aimed at studying the architectural scale of the monuments in the Forum of Pompeii. The use of laser scanning allowed for a complete documentation of the different types of restoration from the last centuries and provided evidence for the evolution in problems concerning the conservation on site as it allowed for dimensional, morphological, structural, stratigraphical and colourimetric data (Balzani et al.,
The scanner used on site was a three-dimensional Cyrax 2500 laser scanner and it provided a 6mm accuracy; the settings used varied depending on the area captured, with 50mm point spacing used on the urban surroundings and 10mm point spacing on the architecture (Balzani et al., 2004: 173). In total 43 scan positions were used to capture 468 scans of the entire area. The number of scans captured is significant and is due to the scanner used, which had the ability to alter the range of the laser beam through its time of flight system. This allowed for specific areas of interest to be selected. Although this was useful at Pompeii, it would be counterintuitive at some archaeological sites, as it requires too much time to capture. Instead some projects, like the one at Portus (2014), follow a systematic procedure on site where the resolution is fixed and the scanner is moved on a regular basis, allowing for the resolution to be consistent throughout the scanning. This changing methodology allows for a larger number of scan positions to be recorded, allowing a greater area to be covered. It saves time in recording, which is often an issue when using terrestrial laser scanning, and removes the problems associated with uneven point representation.

A three-dimensional model contains more information than a line drawing, yielding better results and conveying the three-dimensional shapes in a more accurate way (Boehler and Marbs, 2004: 293). As the method records everything within a given field of view, the results are not limited to what is perceived to be the most important features. The use of the method therefore opens up possibilities of geometric analysis or evaluations of a monument’s state of conservation and static conditions (Salonia et al., 2007: 1). It offers interpretation without subjective interpretation and allows for the measurement and monitoring of physical change. It creates a permanent record from which comparisons can be made over time as evident in the work completed at Portus (2014) through the documentation of the excavation process. It allows for the ability to survey inaccessible and high areas of interest as well as being able to record features that were previously unknown. The methodological approach to recording is the fundamental aspect in how this is achieved and requires logical reasoning as to how the scanner functions and records.

### B.1.5 Issues Surrounding the use of Laser Scanning

#### B.1.5.1 Field of View

There are many issues that require consideration when discussing laser scanning. The most important aspects relate to registration, field of view, density of data capture and requirements to add additional information (Barber et al., 2003: 620). Field of view and registration go hand in hand, if the targets used are out of the line of field of view of the scanner then registration becomes an issue. In order to create a complete model there is a need to create one that does
not contain any missing information and great consideration must be given in understanding what the laser scanner will record in a given area. Through mentally visualising what the dataset will look like, a systematic recording strategy can be created. This allows for a continual assessment of the scanning, with each field of view of the scan requiring slight changes to the number scans recorded.

B.1.5.2 Density

Density is an issue often left undiscussed. Capturing a higher density of points will result in an enhanced model both visually and geometrically; if the density of points is too high, then the model will be unusable unless used on a high specification computer. Capturing a higher number of points will result in the files being larger, to visualise these and manipulate the data, increased RAM is required. Increasing the point number captured is beneficial as it provides a greater resource to work from but considerations have to be made as to the purpose of the scanning. If a scan is able to capture 43 million points and 200 scans are captured, the data will need to be reduced to make it functional. Rather than remove these features using automated software, it would be better to take this consideration during the scanning. Changing the point density of the different scans will result in resolution changes, but if a large number of scan positions are captured, the changing resolution will be negligible. If capturing small areas of interest, a constant point density is preferred, as it allows for an enhanced scan.

B.1.5.3 Environmental Conditions

There are further errors that could affect the overall resolution of the data produced and relate to the uncontrollable environment of the working areas. Although these following examples taken from Godin et al. (2003) are not always relevant they must always be considered when examining the final results. Inadequate mounting of the device, if incorrectly positioned due to the topography of the area, will affect the field of view and areas of interest may not be included in the final scan. Vibration from cars, planes and large groups of people will result in the scanner moving, creating errors in the returning signal of the light. Varying temperatures will also affect the results of the scan data; going from cool environments to extremely hot areas, will greatly change the operating functionality of the scanner and limit the power of light source, thus affecting the overall distance available in the capture.

B.1.5.4 Resolution

The term ‘resolution’ is used in different contexts when discussing the performance of laser scanners (Boehler et al., 2003: 699). Resolution is meant to describe the ability of the scanner in
recording a given object and usually is expressed in lengths. However, this is not generally the case when multiple laser scan positions are used; a manufacturer will provide the maximum potential from measured readings that equate to points collected per second or metre. These are expressed as measurements between any two given points from a single scan. As an example, a scanner could have the potential to produce 500,000 points per second with each point having a distance of ±2mm. The term resolution relates to this point space: from a single scan, following the guide given by the manufacturer, we are able to say that the resolution of the scan data is ±2mm. When multiple scan positions are used, this value is incorrect. A scanner can never reproduce an even spread of points at the same geographical position as other scans; although the scanner may be set up in the same way, there will always be discrepancies in the overlapping data.

**B.1.5.5 Error**

Error is a common within scan data and it is unavoidable, due to the way in which the distance of the laser beams are calculated. If for example a glass window were recorded, a number of erroneous points would be given because the reflectivity and the opaqueness of the glass as returning signal would be at differing angles, or none at all. In many cases, the laser would penetrate the window and give readings associated with the interior section. The same can be said for uneven surfaces such as historical buildings. Over time, the recorded building would decay and an uneven surface would be present; the laser beam once introduced would then have difficulties in returning the signal at these uneven edges. Errors also occur due to the environmental conditions of the surrounding area where the scanner is used, most frequently through temperature, atmospheric pressure and interfering radiation (Boehler et al., 2003: 700). Developers have many ways in counteracting these through the introduction of range limits, laser class types, increased field of view and better stitching software to remove erroneous data.

This understanding of error associated within laser scanning is important in trying to understand the resolution of a complete laser scan model. The erroneous data when compared to the millions of points produced by a single scan will not affect the overall model in terms of its representation, but it will affect it in terms of the point density. With multiple scan positions, the point density of a laser scan model will increase. Changing the field of view of the scanner we are able to record the occlusions that were previously present (through field of view) and as the point positioning will likely differ to the other scans, the gaps that were present in the ±2mm spacing of the first scan are no longer valid. With the increase in the number of scans, the error associated with the model will be greater and the points may not be representative of the object in question. This increase in the number of points creates a model that is hard to understand in terms of
resolution. The model will still contain the ±2mm resolution that the manufacture provided through the individual scans but the overall resolution provided will differ greatly.

In order to create a model that follows a specific resolution, the laser scan data has to be decimated to create an even spread of points at set distances and could be from as little as a tenth of a millimetre to many metres. This can be seen in too many case studies and should never be completed, as there is fundamental flaw associated with creating a set spacing; the removal of data based on a statistical representation. Standard deviation is used to calculate resolution within scan data and it is used to estimate the level of detail present. The estimation of standard deviation is only a statistical value (Boehler et al., 2002: 434) and there will always be points outside of the level of probability. Through multiple scans the point density increases with the number of scans taken, meaning that the ±2mm gap will be partially filled by overlapping scans. This ±2mm gap within one scan is of great importance as it may result in the loss of data associated with an edge, corner or unique feature of the building in question.

Through overlapping scans, the model slowly builds up and any data that may be missing is captured. The data captured will be an uneven array of points spread across a virtual space, with no control of where those points will be in its raw format. Certain features may not have the greatest point density due to erroneous data or limited field of view and the spacing associated with them may be greater than the applied point spacing required. This leads to a system where areas of importance can be removed through automated scan processing options. It should be noted that any archaeological scanning should follow the pattern that every point recorded is kept unless multiple points are present in the same exact position. The reason for this is that every detail of the recorded work is important and it should not be neglected from the analysis that has taken place as it allows for a greater resolution of data in terms of point density.

B.1.5.6 Collimation

Pulse laser beams send out a constant light and the changes in distance are calculated based on frequency changes. The further the light travels, the greater the variance in light angle. As a scan rotates on an 180° vertical axis and a 360° horizontal axis, the mirror and lenses within the systems have an optimal distance before diffraction causes errors. If recording a building from a fixed position, the distance of the laser beam will change. If the distance is greater than the optimal allowed, light may vary from its "straight" line, causing errors in the reading. Resolution is limited by the diffraction of the laser beam as collimation is not maintained with the change in distances (Beraldin et al., 2005: 145). Collimated light is where a light ray is parallel and spreads light minimally. As distances change, the diffraction of the light causes the light ray to change direction, which results in errors in the path of the light. Through the act of collimation, light rays
can be adjusted based on an optimal axis (Figure 558). With laser scanning systems, collimation can be fixed through a series of mirrors and lenses to direct the projection of the rays if the object is the same distance; with landscape and building based surveys, the distances of the recorded features from a single position change during the scan rotation, causing collimation variations. No central point of collimation is possible unless specific areas are chosen, based on the optimal axis. Recording features from one position then results in collimation errors and multiple stations are required to accurately record features of interest. A single recording of an elevation cannot be deemed correct if the angle of recording is too narrow. Capturing data within narrow areas requires the addition of multiple scan positions or, alternatively, a different recording method should be used.

Figure 558. The act of collimation. The light is directed through two mirrors, focussing the light ray on a specific area of interest based on the optical axis for investigation (Japan Science Engineering Co, 2016). © 2016 Japan Science Engineering Co. Ltd.

B.1.6 Disadvantages

As is the case with many technologies and survey recording equipment, there are a number of disadvantages associated with their use. The first and most important is that laser scanning, through the collection and processing of the data takes a significant amount of time and skill. The time associated with producing a finished model varies with the technique used but experience shows that for every day spent capturing, a week of processing will be needed. This can be reduced depending on the object or site that is recorded, along with the necessary preparation
and forward thinking in the collection of the raw data and how each scan will be registered.

Another important disadvantage is the size of the files produced. These vary depending on the equipment used and the point density available but in general, one complete file will be several gigabytes in size. Associated with this is the need to keep the raw, stitched, processed and merged data separate to allow for a complete workflow that enables a backup of each step.

Other disadvantages of laser scanning are associated with capturing. The technique is not suited to recording every type of material or surface. It struggles with shiny reflective surfaces due to the reflection of the laser. Black areas absorb the laser and affect the return rate and areas that contain transparent features, such as glass, will not record the exterior surface detail. The method is equally poor at capturing linear features due to the number of scans required. With a limited field of view available, the results are affected greatly by objects that are in the line of site of the laser. In open areas, objects such as vegetation and ditches will affect the quality of scan data, with partial data being inherent in objects behind them. The method is not the best tool for everything and should not be used instead of traditional means, but rather, it should be used in conjunction with them. An example of this can be seen in Lee et al. (2009) work who focused on the comparison of terrestrial laser scanning and aerial photogrammetry in identifying ridges of rice paddies. Although it was found that a combination of both techniques offered insights into the field boundaries, it was best to use a traditional total station survey to identify them as vegetation, as they acted as obstructions that affected the overall results.

B.1.7 Data Representation

Although laser scanning enables an area to be digitally recorded, the data are represented through point clouds. From this, the data can be manipulated to view the results from aerial positions and elevation plans and cross sections can be created automatically. Fly through animations can be generated instead of static images and with the ability to measure and position the scan data in any way that is needed, the system creates a product that delivers more than traditional methods (Lerma et al., 2011: 414). A point cloud is still just a model of a single measurements meaning that it could limit the understanding of the area captured because of the data, when zoomed in, could become see-through and hard to understand (Zimmermann and Eßer, 2008: 61). Meshing and increasing the point size can counteract this. Working with these point clouds can however be problematic in terms of referencing different point cloud densities and a consideration in respect to the loss of information that may take place must be noted (Finat et al., 2005: 2). This is due to the problems of matching key features within the raw data, as there will be a varying number of points, meaning that features may be misrepresented. This can be seen when producing repeated scans of the same building over a given time and comparing the
results. Although the scan data represents the real life object, the precise point data will never be exactly the same (Boehler et al., 2003: 696) and direct comparisons cannot be given; instead the point density of a given model is compared and subtle changes can be viewed through the observation of the object’s features.

B.1.8 Conclusion

To fully understand the use of three-dimensional recording there was a need to establish a set background into the discipline. Laser scanning from its earliest development in archaeology can now be seen as a standard tool that should be used in documenting cultural heritage sites and historic buildings (Al-Kheder et al., 2009: 537). In many ways, such as in recording excavation section plans, laser scanning has revolutionised the way in which archaeology can be recorded. Although a greater skill set may be required to capture the dataset and to process the relevant data, the results speak for themselves. The importance of laser scanning can be seen in the way that it is used by professionals. It acts as a protection of the site through a digital format; it can be used for restoration and conservations needs; it provides a way to monitor and interpret a given site or building through multiple scan periods. Furthermore it can be used as a way to manage the workflow of a site, allowing for the identification of areas that have not been recorded through missing spatial data present within the results (Lerma et al., 2011: 417).

The method allows the ability to move around and visualise a given site or a given building as a virtual model, creating a greater analysis to take place. Normal surveying tools still have their benefits and in some cases are still required in processing the laser scan data, but in many cases, the comparable results are inadequate and unrepresentative of the original. The movement towards laser scanning and in many ways photogrammetry creates a new sphere of understanding within archaeological investigation. To create a model that is accurate and usable considerations have to be made within the point density of the scan as well as the scan positions in relation to the field views of available. The methodology that is used within the thesis is one that combines these features, to create a dataset that is usable for structural analysis testing, through continuously changing the scanning procedure based on what is necessary on site. A constant point spacing is used at set distances and the scanner will be moved, rather than increasing the scanning range. This will allow for a quicker capture rate, whilst at the same time, providing a high-resolution model to work.
Appendices

B.2 Photogrammetry

Aerial photography of archaeological remains has existed since 1906 when an aerial photograph of Stonehenge was taken from a hot air balloon (Bewley, 2003: 274). The method was developed greatly by Crawford (1923) until it became a natural occurrence with the documentation of a site. There are many issues surrounding aerial photography, such as lens distortion, field of view, angle of capture and environmental conditions that affect the interpretations that can be made. One way to remove this problem can be seen in the adaptation of photogrammetry. The earliest use of photogrammetry was in landscape-based studies, and was useful within cartography as it limits lens distortion and subsequently removes errors within the data, allowing for a more accurate documentation tool. This initial production of photogrammetry modelling was based on the invention of stereophotogrammetry which was created around Carl Pulfrich’s initial research into Stereoscopy (Christianson and Hofstetter, 1972) in 1911. This was based on the principle that different angles, such as through a human’s left and right eye, provide different perceptions of a site. Through the collection of two images slightly offset against each other, the images have the ability to remove the inconsistencies and provide an image that is not restricted to single view and provides the illusion of depth, as is the case when the world is visualised through both eyes. The use of this technique was of great importance within World War II and was developed further with the introduction of computers and digital photographs.

The adaptation of photogrammetric modelling within archaeology, except for simple landscape based analysis, only really came about with the introduction of other three-dimensional recording techniques. Photogrammetry took a number of years to develop fully within archaeology but provided the ability to capture a landscape or a given object with a simple digital camera. The main method that is currently used within archaeology is analytical stereo photogrammetry (structure from motion) and works by capturing overlapping features that are then stitched and processed to produce a virtual representation (Boehler and Marbs, 2004: 291). As the dataset is produced from digital photographs there is a need to always capture this data correctly using the same settings, making sure that the area or object is always in focus. This is often forgotten when discussing photogrammetry but in order to create accurate reconstructions there is a need to have more than just a basic understanding of photography.
B.2.1 Potential and Difficulties

B.2.1.1 Environmental Conditions

Photogrammetry has great potential within the archaeological understanding of the site but in order for its potential to be reached a number of considerations must take place during the capturing stage of the data. These considerations lie mainly in the problems associated with the collection of data and relate to general issues that occur in photography. Within landscape based studies the main issues associated with aerial oblique photography are the environmental conditions and the local geology (van Leusen et al., 2011: 35). If a site when recorded is sunny, the results gathered could be restricted due to the over exposure of sunlight in the images or through potential shadowing of low reliefs in the landscapes.

B.2.1.2 Lighting

Capturing the data using the same methodology in oblique aerial photographs must be followed and an understanding of how different lighting environments affect the final dataset must be followed. Lighting is a key issue and when working on an archaeological site it is something that cannot truly be controlled. The sun and subsequent shadows will produce a series of errors in the mesh of the final model because the overlapping RGB values will be different. This can be fixed if the data gathered is correct. In order for this to happen, the data produced must follow a specific workflow when dealing with capturing onsite photographs, specifically aimed at producing photogrammetry models. The ideal conditions would be to light the object of interest from multiple positions (to remove shadow) and capture a series of photographs from different angles. When dealing with large areas, this becomes somewhat impossible to do. Instead, the captured data should be completed when the sun is either fully lighting the area or providing enough shadow relief from the surrounding features that the results will not be affected.

B.2.1.3 Exposure

Related to lighting is the issue of over exposure. When capturing photographs, shutter speed, aperture, ISO (image sensitivity) and white balance must be corrected to produce a successful image. The combination of these different elements within digital photography is often hard to understand fully and most users on an archaeological site rely too much on the automatic settings that cameras have. These settings provide adequate results for an amateur but to fully understand an archaeological site; the images collected have to contain as little error as possible as it could affect the interpretations made. Similarly, this must be followed within photogrammetry. The only way to avoid having a series of errors in the collected photographs is
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to capture the data manually. To do this, these four main settings mentioned must be altered each time a dataset is captured, as the settings will untimely decide how the final model will appear. As the sun is always moving, providing different lighting angles and shadows, the settings used will never be the same. Slight differences in the settings allow for different amounts of light to be captured within the photograph and it avoids the problems of over exposure that will affect the production of the model.

B.2.1.4 Lens Distortion and Camera Resolution

Other issues related to the data capture of photogrammetry models are those of lens distortion and resolution. Lens distortion is something that can be corrected using modern day software such as Adobe Lightroom but it is often something that is not corrected before the data is processed. Lens distortion will differ greatly depending on the size and quality of the lens used. The photographs may appear to be normal but all unprocessed images will contain a slight distortion that stretch parts of the images. When considering the overlapping photographs needed to produce a photogrammetry model, this stretching may prove costly, as the data will not match exactly. Most photogrammetry software will fix these issues when the data is processed; to do this beforehand will sometimes results in erroneous data, as the software expects this error to be present. This processing option is an additional tool and is sometimes never done; if using the data for metric analysis, this tool must be performed. Using suitable and high specification lenses will remove the errors contained during this processing.

The resolution of the camera plays an equally important role within the production of a photogrammetry model. Most would assume that a higher resolution image would provide a high-resolution model but this is not the case. Increased resolution will ultimately provide a better model but the production of a suitable model lies mainly in the number of images captured. Capturing enough images that allow for the multiple angles needed will provide a suitable model. This can be produced using relatively low-resolution datasets when compared to the high specification cameras now produced, as it just requires a greater number of images to be captured. Using higher resolution cameras does not necessarily mean that a reduced amount of data should be captured but rather a consideration of what is being captured must be made instead. Using a 36mpx camera instead of an 18mpx camera means that the pixels recorded provide more information. As this data contains more information, the captured images could be collected from a distance further away, requiring fewer images to be captured. If this same data capture were applied with a low-resolution dataset, then the results would be poor because it would not contain all of the necessary data. If the higher resolution dataset was captured, using a low-resolution setup, then it would contain too much information and it would take longer to
process and requires greater computing power. As a result, creating a photogrammetry model is not an easy task; a detailed understanding of photography is needed to produce a model that is correct. It is not just a case of visiting a site and capturing a series of images; a strict methodological approach is needed and an understanding of how the software will process the data is required. Amateurs in the technique can capture results but the majority of models produced will rely too much on the texture and the mesh will contain too many errors if the methodology is not followed. This proves problematic when considering the overall accuracy of the model as small details will be missed in the algorithmic production of the model.

### B.2.2 Case Studies

One of the earliest versions of digital photogrammetry within archaeology can be seen through the work carried out by Bewley (2003) who, as a part of English Heritage, captured a number of aerial photographs in 2000 of Cawthorn Camps in North Yorkshire. Although the results are better than single images, the model produced relied too much on the texture and would be deemed inadequate when compared with the equivalent available today. The work carried out highlighted the potential of the technique and offered not just a graphical representation, but also a simulation of the real that allowed for endless investigations and non-invasive documentation (2003: 457). Bewley’s work identified the importance that photography has within understanding an archaeological site and although there are countless examples of digital recording of buildings, excavations and landscapes, there had been very little work completed on the development of using these images to produce three-dimensional representations until this point. Photography is a tool that is used daily within the process of recording but the development of photogrammetry using these digital images only really occurred after Bewley’s work was completed. It has since developed to the point where the results are very much comparable to laser scanning and the following discusses its benefit within the process of archaeological interpretation.

The work completed by Bitelli et al. (2002) focused on the comparison of laser scan data and photogrammetry. It was found that the laser scanner provided a short data acquisition time, gave immediate results and produced very accurate three-dimensional models that could be used to detect and model vertical walls (Bitelli et al., 2002: 119). Photogrammetry on the other hand provided a photographic richness that is unparalleled and although the results were similar it should have instead been used to complement a laser survey to correct erroneous or missing parts of the overall dataset (Bitelli et al., 2002: 119). Although the production of the photogrammetry models was based on the earliest versions of known modelling software, the suggestion of a combination of the data follows others, in that very little faith is given to the result that photogrammetry produces as the details rely too much on the photographic representation.
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rather than the surface detail. Although this has been the case in the last decade, the software associated and therefore the algorithms have greatly increased, meaning that the advice given by Bitelli et al. (2002) should be disregarded, as the development of any technique will always overlook the past decisions that others have made. The inclusion mentioned focuses more on the combination of laser scan data with the digital images captured for photogrammetry and Guarnieri et al. (2006) argue that the previous work carried out by others is not a true integration and that their work moves away from this by having a true integration of the two different three-dimensional datasets. Their work does include this fusion of data but the integration itself is poor as the models produced from the photogrammetry are limited in terms of mesh size. The overall model is based on a photogrammetry survey of the Villa Giovanelli in northern Italy and integrates high-resolution laser scan models of the statues on the front façade of the building. In terms of representing the building, the final virtual renders produced do provide an accurate representation of the building, but as is the case with most photogrammetry surveys, the model relies too much on the texture.

Another example can be seen in the work carried out by Bologna University and the Soprintendenza Archeologica di Pompei (Bitelli et al., 2002) who completed a detailed photogrammetry survey of the Nymphaea of Pompeii to highlight the different architectural and decorative styles used. The results allowed for a documentation of the architecture quickly and the results could be used as a comparison. Although the surface detail was not the greatest, photogrammetry was the best recording method to use on the areas recorded simply because of the time associated with the capturing. Yet another example can be seen in work by Al Rawashdeh (2013) on the Roman amphitheatre in Anman, Jordan which was built in the reign of Marcus Aurelius. The methods used within this work consisted of two aerial photographs, ground control points recorded through a total station and close range photographs (Al Rawashdeh, 2013: 244). The aerial photographs were used to create a digital elevation model that could be placed in GIS that included the surrounding area, with the photographs used to create a three-dimensional model, which was again placed in GIS. The model produced provides an example of how GIS can play a part in the modelling procedure but the results are too low in resolution for it to be useful in terms of any practical analysis. The wrong software was used to stitch the data and although the methodology provided is useful there are other methods, such as LiDAR, that are better suited to this type of data capture.

B.2.3 When to use Photogrammetry

To develop the different types of recording techniques, there is always a need to choose the correct method for the right object or area. As was the case with the examples shown above, the
data produced are often limited because it was the wrong recording method. The ability to choose the right technique comes down to the understanding of what the results are going to show. To the unexperienced, this is extremely hard to do. Within photogrammetry there needs to be a full understanding of how the photographs are going to be processed. When recording a vertical wall there are issues such as angle of capture that will affect the results produced. Photographs may be taken from the ground level of a 20-metre wall; when processed the results will be accurate until the point where the continuation of focus of the images from the bottom of the wall to the top of wall becomes an issue. As the majority of the bottom section will have the same focal range, the results will be acceptable but with the change in angle, the point where the bottom and top part of the images are at different focal lengths, errors are introduced, as the pixels in the different images will not relate to one another. Texture has been stressed in this section but the majority of users will work around this error by adding the texture that negates the purpose of photogrammetric recording. The aim of any photogrammetric model is to replicate the object recorded in a three-dimensional environment and to do this the mesh has to be accurate. The only way to do this is to correctly capture the area of interest within the limitations of what is available.

A lot has been said about how photogrammetry should be captured and why it is useful within archaeological interpretation. To those who use the technique it is obvious as to why but for those who do not use it, the following points out key reasons why photogrammetry is an important part within the digital documentation in archaeology and are taken from Grussenmeyer et al. (2008: 213). The photogrammetric record provides a superior level of detail contained within the texture than any other digital recording technique. Although it has been pointed out that the mesh plays a more significant part within the understanding of the model, the texture does play a significant role in adding realism to it and to have the texture draped over the model is something that is hard to do to the same extent within laser scanning or other recording techniques. Several economic aspects are advantageous within collecting and processing the data. The only equipment needed is a basic DLSR camera and suitable lenses and as these are often used for archaeological recording; this expense is minimal when compared to the several hundred thousands of pounds needed to buy a laser scanner. The software is also relatively inexpensive and free software can be used to visualise the models; more so than with laser scanning. As the equipment is only a camera, the advantage of using this technique is that it is easy to transport, not only to site but on site as well. Many laser scanners weigh over 25 kilograms and have to be placed on specialised tripods that become difficult to move repeatedly. Similarly, because the photogrammetry equipment weighs very little and is a case of capturing enough photographs, the
collection time is far quicker than any other technique when compared to the results that it produces.

These four main features make photogrammetry an ideal recording method. The one downside to the technique is the unknown factor that surrounds what the results show and cannot be known until the data is processed, as the obtained accuracy and image resolution may not meet the requirement needed (Xiao et al., 2007: 5791). This proves problematic if a site is visited and the data is captured and processed at a later point. If there are errors or gaps in the dataset then these cannot be corrected unless the site is visited again. This proves even more problematic if the site is in a foreign country or has changed or been destroyed since the first capture.

**B.2.4 Conclusion**

Photogrammetry provides these results and with recent updates to the software used shown in Miles (2014), the data provided can now be seen to be comparable to the laser scan results in terms of point data and surface detail. The use of these techniques provides users with the ability to manipulate the data to the specific requirements of the archaeologists who wish to study them (Lambers et al., 2007: 1710). As the two different types of recording techniques are very similar in the results that they produce, a combination of photogrammetry and terrestrial laser scanning will enable higher data acquisition rates at a higher accuracy which in turn enables high spatial data density of a given area (Al-Kheder et al., 2009: 537). It is through the combination of these techniques that a full coverage of data can be collected. Both of these techniques have limitations in terms of the final dataset but capturing separate sections and combining both allows for a dataset that is further enriched and fuller in terms of spatial data. There is no doubt that the combination of laser scanning and photogrammetry can supplement each other to produce high resolution three-dimensional recordings (Kadobayashi et al., 2004: 401). Both techniques should be utilised fully which can then be used to visualise a site, whilst still having the ability to focus on individual areas of interest. The methodology that should be used for any archaeological investigation should be one that follows one simple rule; the correct method should be used rather than trying to capture as many areas or objects as possible with the same technique simply because it is already on site.

Within the thesis, photogrammetry is used to analyse how useful the technique is within structural analysis testing. The methodology used for these captures follows a single focal point of focus; an ISO of 200 to remove image grain; a suitable aperture to capture the depth of field required; and a suitable shutter speed to allow enough light in the image without creating
movement. The images were captured using a tripod to remove any issues of image stabilisation and were captured using a Nikon D7000 and a high specification prime lens.

B.3 Surveying

Surveying may be defined as the art of making measurements of the relative positions of natural and man-made features on the earth’s surface (Bannister et al., 1998: 1). Within archaeology, building and landscape surveying are the two general types of recording methods that are used. In simple terms, it is the practice of measuring angles, heights and distances. The act of surveying has existed for several thousands of years, with the Ancient Egyptians utilising this greatly in the creation of their pyramids. The Romans continued this development, although relying on measuring rods and ropes, created a system of straightness within the majority of their roads and buildings. This general practice continued up into the medieval period with the establishment of field boundaries. It was not until AD 1551 when Abel Foullon created his Holometre (Taylor, 1929: 207) as seen in Figure 559 that modern surveying techniques really developed. The method that was created was based around the triangulation of key features through the device as seen in Figure 560. The triangulation method, which is still used today, provides the necessary measurements from which angles, distances and heights can be determined.

Figure 559. Foullon’s Holometre (Taylor, 1929: 207). Reproduced with permission of Taylor & Francis, www.tandf.co.uk.
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Figure 560. Triangulation by the Holometre (Taylor, 1929: 209). Reproduced with permission of Taylor & Francis, www.tandf.co.uk.

This triangulation method has been developed greatly over the years and in 1787, Jesse Ramsden created the first precision theodolite (McConnell, 2007) which was a precision instrument meant specifically for the measurement of angles in the horizontal and vertical planes. Over the rest of the eighteenth and nineteenth centuries, the development of these theodolites became more precise, using more up to date machinery to produce them. By the mid part of the twentieth century, the technology was developed further to allow greater distances to be recorded. Thanks in part to the technological advances made during World War Two, the introduction of the Electronic Distance Measurement (EDM) via the transmission of multi-frequency phase shift of light waves allowed for distances up to kilometres away to be recorded. Following the boom of the computer age, the large EDM devices were miniaturised and via computer programming of the measurements recorded, total stations became a common tool within surveying. The early introduction of the total station came about in 1970 and since then the speed, accuracy and precision have been improved. The maths behind the total station is the same as the first theodolite, with the only difference being the electronic capabilities that it offers, as the basis of the measurements made are still centred on triangulation and Pythagorean Theorem.

The method took its rise within engineering and has since been employed within archaeological investigation to accurately and precisely record large open landscapes and buildings. Overall, the method provides a ways to visualise the data in a three-dimensional output but the representation of this is through basic points and lines connecting them together. The recorded sections of both of these are controlled by the person operating the machinery and as such, the
total station could have a sub millimetre accuracy but if recorded incorrectly, the data provided would be useless. Errors will always be inherent within a total station survey, from the incorrectly measured height values of the total station, to an uneven detail pole for the prism, through to subtle movements or the tripod support. All of these errors will affect the angles and measurements produced therefore creating an output that has incorrectly measured points. Experienced operators can reduce these errors, but errors could still be contained within the data. As the person controlling the total station chooses the areas to record, what may be considered unimportant could be the opposite.

The selection process by surveyors differs greatly depending on the person. For some, some parts of a building could be ignored due to uncertainties, time constraints or lack of understanding with the period associated with the building. Therefore, the analysis made will be based on data that is not complete and surveying in its current form needs to be changed. The introduction of GPS (Global Positioning System) and RTK units (Real Time Kinematic) have made the surveys more accurate due georeferenced point data, but when compared to laser scan models, the results speak for themselves. Work completed by Romano and Schoenbrun (1993), Summers et al. (1996) and Biggins et al. (1999) show how useful surveying was and at the time how accurate the results were. Surveying itself is still a useful tool. It is extremely good at gaining a rough outline of a building, it is needed to record tie-in points with photogrammetric data and laser scan models and it can be used to mark out grids for geophysical surveys. The technology has however been superseded by something better (Biggins et al., 1999: 8) and the continuation of the tool is limited within archaeology. The overall representations, unless used for something specific are poor, and the data contained is inadequate. Building surveying, if the money and computing power is there, is generally better suited to more advance three-dimensional recording techniques. When dealing with landscapes, much more can be gained from aerial photogrammetric data and LiDAR datasets. A combination of the two will always aid the investigation but for future research the new developments that have been made, mean that total station surveying is now limited.

**B.4 Geophysics**

There are a multitude of different geophysical techniques that can be used to record the remains of buildings. Rarely have these techniques been used on standing buildings but rather are used to locate features below the ground that help identify the outline and shape of past buildings. In practice geophysics enables the existence of types of particular materials to be assessed on strict physical criteria, and is an essential tool within the locating and mapping out of materials not visible to the human eye. The techniques that are most commonly used include Resistivity, Magnetometry, Ground Penetrating Radar, Seismic, Electromagnetic prospection, Thermal
prospection and Chemical prospection. All of these different techniques provide different ways to analyse the same data and in theory, a combination of them should be used in any archaeological investigation so that the varying results can be compared and confirmed.

**B.4.1 Resistivity**

A resistivity survey is based on the resistance to an electrical current passed through the ground with different material soil having different resistivity values. The electrical resistance of the ground is dependent upon the amount and distribution of moisture within it. If the area is too moist or too dry, the results provided will be poor and could be hard to distinguish the features present. These features are generally shown via a disruption of the resistance passed through the soil (Clark, 2003). If the area is too moist then the electrical charge passed through will be dispersed along the surface, whereas if it is too dry, the charge provided will not be able to pass through the soil. Within this, there are a number of different arrays that can be used, such as Wenner, Square, Double dipole, Palmer and Schlumberger arrays. The most common however is that of the Twin Probe array. The Twin Probe array works by having two fixed probes that pass the electrical current through the ground and two mobile probes that close the circuit. As the mobile probes move, the resistance provided will alter if features are present, as seen in Figure 561. It is through this way that the readings are generated and converted to graphical representations through the comparison of the ohm readings provided per survey grid. Importantly the final readings that are given depend on the resistivity of the ground, the distance between probes, and the strength of the current used. All of these factors affect how the data are interpreted.
Resistivity surveying is one of the most used methods within archaeology but the method itself is limited. The collection of the data over a large area can take a long time to complete and the depth produced within the data is only half of the space between the two mobile probes. If the spacing between the probes were only one metre, than the maximum depth captured would be that of half a metre. For building work near to the top of the surface, this is sufficient, but for deeper remains, other methods have to be used. To increase the depth, the twin probe array could have extended spacing between the mobile probes or alternatively a multiplexer resistivity array could be used. The quality of the data provided would be limited unless the current used was greatly increased.

B.4.2 Magnetometry

Magnetometry, like resistivity, is also one of the most commonly used types of geophysical survey techniques in archaeology. The method works via the careful measurement of the magnitude or differences in magnitudes of the earth’s magnetic field. As the magnetic field of the earth is a constant via the movement of the material in the Earth’s core, the method is able to identify any magnetic changes over a surface. These changes relate to some form of geological or
archaeological features. The changing magnetic field of archaeological data can happen in one of two ways. The first is via the soil properties. The introduction, mainly through human interaction, of Magnetite, Maghemite and Haematite allow for the differences in the magnetic properties of the soil’s iron content to be extracted when compared the earth’s overall properties. With archaeological materials, the process of heating material will affect their magnetic properties. If a material is heated above its Curie temperature then it becomes demagnetised as the ions present lose any magnetic properties. As the material is cooled, the ions become remagnetised by the earth’s magnetic field. The polarity of the material aligns to that of the Earth’s magnetic field providing it with a much stronger magnetic property as seen in Figure 562. Magnetometry then is best suited to the recording of archaeological features that have been fired, such as bricks, or contain a high level of metal, such as Roman roads.

Figure 562. Magnetic field of an archaeological feature (Clark, 2003). Reproduced with permission from Taylor & Francis, www.tandf.co.uk

The most commonly used type of magnetometer within archaeology is that of a Fluxgate Gradiometer. This type of magnetometer has a permeable nickel alloy core that is magnetised by the earth’s core. When an alternating current is applied, a voltage is produced. This voltage affects the magnetic property of the core and as a result, it is the change in its permeability that is measured, based on the area covered. The method allows for a fast data capture of a large area with results gathered outlining those sections that contain highly magnetised material. Although useful in large open areas, the method is affected greatly by manmade features that are now present, such as metal fences, bins, cars and drain pipe covers. The method is a viable option but
for unknown areas of interest, those that contain stone features, and those in built up environments the method provides little.

**B.4.3 Ground Penetrating Radar**

Ground Penetrating Radar (GPR) works by the transmission of high frequency electromagnetic radio pulses into the Earth’s surface. The signals that are sent into the ground are reflected by changes in material and are measured by the time taken between the transmission and reception of these radio pulses. The systems used, vary in terms of depth penetration due to the varying level of frequencies used in the electromagnetic signals sent. The different antennas that are used within GPR at the surface emit these different rates of frequencies with very shallow items needing a higher rate of frequency compared to those at significant depths that require a far lower rate. More on the range of antenna strengths and relative depths can be seen in Figure 563 but these do not take into account the electrical conductivity and magnetic permeability of the soil, which affects the signal strength.

![Figure 563. Comparing different antenna frequencies with maximum probable depths of penetration (Smith and Jol, 1995: 99). Reproduced with permission of Elsevier, www.elsevier.com.](image-url)
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The depths produced are represented through nanoseconds with 20 nanoseconds roughly equalling one metre. The data are collected in a series of traverses to give sliced views of the surface below and these are stitched together to create a continuous profile of data that can be manipulated in three-dimensional space. Unlike the other techniques, this method can provide three-dimensional voxel data as it provides actual depths rather than two-dimensional profiles. The data provided are similar to the survey techniques mentioned above. Although these will never be as clear as the laser scan models, the data can be extracted digitally to provide virtual replicas of the building work and foundations that are hidden below the surface. The method is best suited to recording archaeological data but the time taken to record areas of interest can be long; the data processing associated with GPR is excessive, and large storage capacities are required to hold a simple survey. Another downside to the method is through the way in which the radio pulses are sent. As it reflects off changing material, areas of high-density geology mixed in with archaeology provide results that are hard to distinguish.

Overall geophysics has its place in building surveying as a nonintrusive tool but considerations have to be made to data storage, length of capture time, local geological conditions, weather variations and local archaeological finds. These changing factors affect the choice of tool used, and it is recommend that a combination of the different techniques should be used to provide the most accurate data possible.

B.5 Other Methods

Although the main methods of surveying within archaeology have been discussed there are, and will always be, a number of other techniques that could be used. A full explanation falls outside the scope of this research. However two such example of this are Structured Light scanning and Computed Tomography recording. Structured light scanning as seen in the work by Gühring (2000), Stumpfel et al. (2003) and more recently Papadaki et al. (2015) is a system that measures the three-dimensional shape of an object using a number of projected light patterns onto an object’s surface and a camera system to record them. The patterns are converted within relevant software and depths are extracted. Some of the systems such as the Brueckmann structured light scanner offer resolutions up to several microns. The system however is an updated version of the triangulation laser scanning technique and is not suited to the recording of large areas of buildings due to the file sizes that would be inherent within the data. This method is not suited to surveying buildings and will not be used within this research. Rather, like triangulation, the focus of recording should be that of small objects or key areas of interest.
Computed Tomography is an imaging technique that generates reconstructions of three-dimensional images via the inverse Radon Transform (Kak et al., 1988). Within this method a series of x-rays are taken from a 360° rotation of the object recorded and are processed to create a complete virtual model of both the interior and exterior parts of the recorded section. More on the process along with an example dataset can be seen in the author’s paper on *The use of computed tomography for the study of archaeological coins* (Miles et al., 2016) as the finer details of its use requires more explanation than that provided. Although Computed Tomography is limited as to what it can record in terms of size, the potential of the method in understanding the internal details of building material may be useful in fully understanding a building and its structural reliability. The method is very expensive to complete and not every project can utilise it. The processing of the data is demanding but the results that gained outweigh this. Although this method has not been used in this research, the concluding chapter does advocate its use within future research as the method allows for internal structural analysis test to be performed.
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