UNIVERSITY OF SOUTHAMPTON
FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS
Fluid-Structure Interaction Research Group

Concurrent Engineering in the Context of the Composite Leisure Boatbuilding Industry

by

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ABSTRACT

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Leisure boatbuilding is an industry that has tight profit margins and growing competition due to the global nature of the industry. It is a growth market with the number of high-earning potential customers increasing worldwide. For British boatbuilding to retain and increase its high standing within these global markets investment is required to develop larger profits and market share. Concurrent engineering is a method of design that has given large benefits to a multitude of industries but is ill-defined within leisure boatbuilding.

This thesis investigates the nature of British boatbuilding and develops concurrent engineering within this context. To develop faster design while increasing quality this thesis concentrates on automated communication. A number of tools are developed focusing on structures and production. These include a mass and cost multi-objective optimisation tool further developing first principles rules using a Genetic Algorithm, a reliability tool to increase the speed of iterative design and a design history tool focusing on data mining using neural networks within a grid computing structure. Furthermore, a concurrent engineering methodology specific to leisure boatbuilding has been developed leading to a design environment for use within this sector. The resulting work develops techniques that increase the knowledge available to engineers in an intuitive, quantitative, manner.

Contents

Acknowledgements

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Nomenclature

a,b = Stiffener spacing

a_s= Crown width

a_{mn} = Coefficient for grillage analysis

$A_{i,j}$= Laminate stiffness terms

$A_{sx,sy}$ = Axial rigidities of longitudinal and transverse stiffeners

b_s= Crown thickness

b,g= Numbers of beams and girders

C = Cost

c_s= Web width

$D_{sx,sy,Tx,Ty}$= Stiffener rigidities

d_{na}=Distance of the cross sectional area of stiffeners to the neutral axis

d_s= Web height

E = Young's modulus

E_{f1} = Young's modulus of fibre

$e_{x,y}$=Distance from the mid-plan of the plating to the centroid of the stiffeners

f_{ci}=Fibre content by weight

G = Shear modulus

I = Second moment of area

I_{cx} = Moment of inertia

K_n=Square stiffness matrix

L,B = Length and breadth of plate

M= Reliability index

M= Mass

M_s= Moments of stiffeners

m,n = Wave numbers

$m_{\sigma f}$= Mean stress magnification factor

$n_{b,g}$=Number of beams or girders

P =Pressure

P_f= Probability of failure

p_n= Importance of the variable for genetic algorithm weighting function

Q= Demand

Q_{ij}= Elasticity tensors

Q_s= Shear force of stiffeners

q(x,y)=Pressure at a given point on plate

R= Capacity

R_n=Forces and moments acting on beam

S_{12}= Shear strength in the 1-2 plane of a ply

T_{Plate}= Plate thickness

t = Ply thickness

U_{mn},V_{mn},W_{mn},X_{mn},Y_{mn}= Coefficients for initial conditions of TSDT

u_0,v_0,w_0,ϕ_0,ϕ_0= Initial conditions of TSDT

$\bar{Q}$=Reduced stiffness terms

V_f=Volume Fraction

w = Deflection

$\bar{w}$= Non-dimensionalised deflection

w_n= Weighting of the variable for genetic algorithm weighting function

X_C,X_T= Tensile and compressive strength parallel to fibres

X_n=Variable output for genetic algorithm weighting function

Y_C,Y_T= Tensile and compressive strength transverse to fibres z= Height of laminate

α= Sensitivity factor

β=Safety index

δ_{Bn}=Unknown beam displacements and rotations

ϵ, γ = Stiffness

ϵ_{1T} = Tensile failure strain

ϵ_{1C} = Compressive failure strain

μ = Mean

$\rho_{\perp\parallel}$= Slope of the longitudinal fracture envelope

$\rho_{\perp\perp}$= Slope of the transverse fracture envelope

σ = Variance

σ= Stress

σ_{cri}= Critical Stress

σ_{1D}= Stress value for linear degradation

τ= Shear stress

υ = Poisson's ratio

Φ = Cumulative function of the standard normal distribution

$H(\mathbf{X}_i)$= Sample performance

$\widehat{\nabla^{(k)}}\ell$= Gradient of the response

$\mathcal{S}^{(k)}(\mathbf{u}; \mathbf{X}_i)$ = Score function

1 Introduction

1.1 Background

Engineering systems are designed and produced to balance as effectively as possible a large number of objectives under specific constraints. The effectiveness of the system is dependent upon all the inputs. In the context of boat design and production, the inputs are grouped into subsystems such as hull topology, engine installation and so forth. These subsystems have mutual dependencies or inputs, for example, hull weight influences seakeeping performance which influences the type of installed engine plant which in turn affects hull weight and subsequently seakeeping. Design therefore is a compromise and the engineers responsible for each subsystem need to communicate effectively their objectives and constraints for the benefit of the final system: the boat.

Due to the tight profit margins associated with boatbuilding and the growing competition from overseas companies it is important that vessels are designed and produced at a lower cost while still being suited to the current market trends. Boat design, like all design, involves interdependencies between different subsystems of a vessel, i.e. structures and production. It is the relationship between these subsystems that determines the difference between a design that meets customer requirements and makes a profit or one that fails to meet these criteria. For example a structural engineer may make a decision to create the scantlings in a certain manner, this choice may mean that the production costs go up a large amount as this topology is difficult to produce however a similar arrangement, which is not optimum for the structures, may have only slightly impacted the structural subsystem but substantially decrease the cost of the boat. “Concurrent engineering” uses parallel design processes, as opposed to linear design, with interdependent project teams to ensure that all the expertise of the design engineers are utilised during the entire span of the design aiding the transfer of knowledge between these subsystems. Typical linear design can allow subsystems to concentrate overly on the individual task and lose sight of the overall objectives as seen in Figure 1 taken from Sarafin [1].

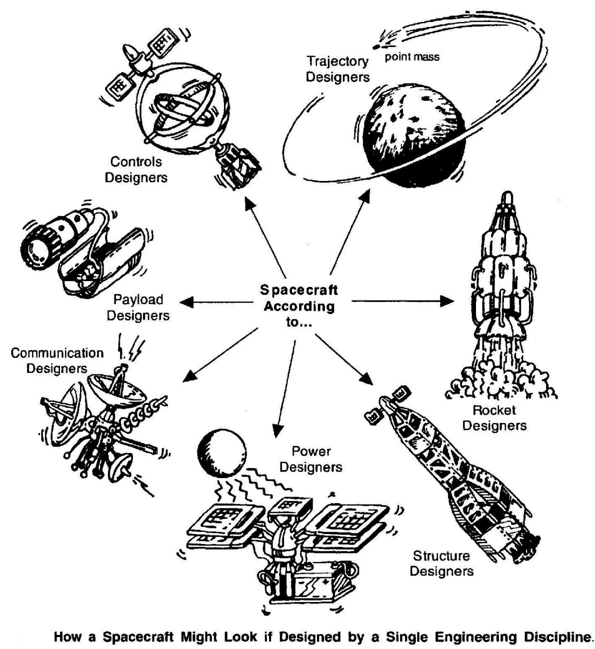

Figure 1: Individual task orientated design

As a result of employing a concurrent engineering philosophy, the relationships between the different subsystems of the boat can be identified, impacts of change readily assessed and ultimately a boat targeting customer requirements can be produced. As part of concurrent engineering, subsystems are developed by separate members of the design team and it is the way that these design engineers work together that determines the success of the project. This process allows designers the ability to best comprehend the aims and difficulties faced by other subsystems. An example of subsystem concurrency is "design for production" which creates links between designing a boat for function while also producing at reduced cost, this leads to a cost effective and efficient final product. The ability to amalgamate different subsystems of design, through concurrent tools, allows designers to focus, with greater ease, on the general design aims rather than those of the subsystem.

Finding the optimum solution between effective design and low cost makes design complex due to numerous inputs and the interactions between each variable. It has been said that 5-7% of a product's cost comes from the design and this can have an effect of 70-80% on the final cost, as shown by Swift [2], meaning that the production costs can be greatly reduced at the design stage. This makes the design stage important and requires that it is completed quickly while fulfilling customer requirements, reducing cost and increasing sales. Being first to market or releasing at a defined market peak are also factors governing overall sales. This, combined with rapid design, allows for either increased quality or reduced cost and adds emphasis to a fast design process while increasing sales. Computational methods are increasingly being used to decrease the time taken to optimise these designs while still accurately finding the optimum result. The ability to work in parallel means the time to complete a design will, depending upon the effectiveness of the communication, be shorter from start to finish.

1.2 Research Objectives and Purpose

1.2.1 Research Novelty

Concurrent engineering has been a useful tool in increasing the profitability of companies in many industries including aerospace, automotive and shipbuilding but is ill-defined in boatbuilding. These tools have already been produced to increase the effectiveness of communication within the design period. The next step in the evolution of these designs is the development of better communication and the utilisation of automated communication, through the medium of design tools, to disseminate information about subsystems between designers. The use of automated communication will allow designers the ability to more effectively understand the other subsystem they interact with on their own and through this process they can use the more expensive direct communication for the development of more imaginative solutions to problems. The tools developed have been centralised around the communication between structural designers and production engineers as this is an area with close links. The novelty in the approach is the development of a leisure boatbuilding specific concurrent engineering environment and the further development of automated communication methods to help spread knowledge throughout the design subsystems.

1.2.2 Research Aim

The aim of the work presented in this thesis can be stated in broad terms as: "To develop a concurrent engineering system, consisting of a number of design tools and a design environment, for use in the field of leisure boat design". This thesis investigates the manner in which automation can be more effectively realised through the collaborative modelling of sections of design and production with the aim of creating practical solutions. This aim can then be more formally stated as the research question, research purpose and research objectives:

1. **Research Question:** Can concurrent engineering be adapted for use within the boatbuilding industry?

2. **Research Purpose:** The purpose of the research is to investigate, adopt and develop methods that will allow effective communication between different subsections

of a vessel during the design phase specifically for boatbuilding.

3. **Research Objective:** The desired result of this study is an environment for concurrent engineering with tools developed to aid this approach. Sub-objectives of the research are:

    - To assess the requirements of the boatbuilding industry.
    - To create models aimed specifically at design and production.
    - Verification of models developed.
    - To extend current structural optimisation to allow for a more design centric method.
    - To investigate the use of reliability analyses as a means of intuitively understanding other design subsystems.
    - To propose a concurrent engineering environment specific to boatbuilding that these models can be incorporated into.

1.2.3 Scope of the Research

Modelling has been undertaken in the areas of both structures and production. These models have been created as accurately as possible with information freely available from public sources. The research has limited itself to the investigation of monocoque composite grillage panels. Furthermore investigation into optimisation has been carried out using genetic algorithms and reliability analysis using Monte Carlo methods as these methods will allow an easy expansion for use in larger optimisation and reliability situations. Structural analysis has been limited to that of first principles to allow for fast computational time due to the stochastic methods in use. Development of the concurrent engineering environment has remained limited to that of a theoretical study using previous work as a basis for its construction, testing did not occur on the concurrent engineering environment specifically due to the inability to find a suitable method. Further to these constraints experiments have not been considered as all models used have been verified against previous work. The work on optimisation has been developed further as a basis of work from Manepaan [3]. The reliability work has been validated against work carried out by Blake et al. [4]. The concurrent engineering environment has been a further development of work by Sobey et al. [5]. Concepts used herein have been formed using inputs and feedback from the British boatbuilding community.

1.3 Outline of the Study

Chapter 2 outlines the current state of the art in terms of structural modelling, optimisation, reliability and concurrent engineering. Chapter 3 relays the overall methodology for the design system developed. It shows the concurrent engineering environment and the manner in which different stages of the design and the different design subsystems interact. Chapter 4 shows the methods used for the structural design outlining the first principles method that has been chosen for further development in the next chapters. Chapter 5 discusses the genetic algorithm and direct methods used for the optimisation developing Quality Function Deployment as a tool to create objective weightings. Chapter 6 develops the technique of reliability analysis to understand the manner in which design changes will affect other subsystems. Chapter 7 shows the concurrent engineering environment created and the manner in which it will interact with both the tools, current and created, developing ideas for collaborative work within the industry. A tool to use design histories within the design environment to increase communication using neural networks is also outlined. Chapters 8 to 11 report on the analysis of the different tools showing comparisons between the tools and an application incorporating their use. Finally Chapter 12 summarises the work that has been performed, proposing areas that may be developed in the future to create a better understanding of both design for production and concurrent engineering.

1.4 Publications

Articles:

Sobey, A.J., Blake, J.I.R., Shenoi, R.A. and Waddams, A. Concurrent Engineering in the context of FRP boats, Ship and Boat International, July 2007

Sobey, A.J., Blake, J.I.R., Shenoi, R.A. and Waddams, A. Concurrent Engineering in the context of FRP boats, Ship and Boat International, 2009

Sobey, A.J., Blake, J.I.R. and Shenoi, R.A. Concurrent Engineering in the context of FRP boats, Via Mare, 2009

Conferences:

Sobey, A.J., Blake, J.I.R. and Shenoi, R.A., Optimization of Composite Boat Hull Structures, Compit 08, Liege

Sobey, A.J., Blake, J.I.R. and Shenoi, R.A., Optimisation of Composite Boat Hull Structures as Part of a Concurrent Engineering Environment, HIPER 08, Naples

Sobey, A.J., Blake, J.I.R. and Shenoi, R.A., Design histories for enhanced concurrent structural design, ICCSE 2009, Malaysia

Sobey, A.J., Blake, J.I.R. and Shenoi, R.A., Concurrent design and optimisation of FRP boat structures, DCOSMY 2009, Genoa

Sobey, A.J., Blake, J.I.R. and Shenoi, R.A., Optimisation of FRP structures for Marine Vessel Design and Production, OMAE 09, Hawaii

Sobey, A.J., Blake, J.I.R. and Shenoi, R.A., Design for Production in FRP Boats, ICCM 2009, Edinburgh

Sobey, A.J., Blake, J.I.R. and Shenoi, R.A., Stochastic methods used in design optimisation of composite boat hull topologies, Light Weight Marine Structures 2009, Glasgow

Sobey, A.J., Blake, J.I.R. and Shenoi, R.A., Concurrent engineering principles applied to marine composite structures for reduction in production costs through robust design, Marien & Offshore Composites 2010, London, UK

Journals:

Sobey, A.J., Blake, J.I.R. and Shenoi, R.A., Optimisation approaches to design synthesis of marine composite structures, *Schiffstechnik Bd.54 - Ship Technology Research*, 56/1, pp.24-30, 2007

Sobey, A.J., Blake, J.I.R. and Shenoi, R.A., Design histories for enhanced concurrent structural design, *Proceedings of World Academy of Science, Engineering and Technology*, Vol.38, 2009

Blake, J.I.R., N. Yang, P. K. Das, Sobey, A.J., and Shenoi, R.A. The Application of Reliability Methods in the Design of Tophat Stiffened Composite Panels under In-plane Loading, Reliability Engineering and System Safety (Submitted)

Sobey, A.J., Blake, J.I.R. and Shenoi, R.A., Concurrent Engineering environment for boatbuilding design, *Design Studies*(Submitted)

2 Literature Review

Boatbuilding is an industry with tight profit margins and low volumes of boats produced each year. While this industry is a growth market there is increasing competition from traditional boatbuilding nations and more recently nations without a tradition of boat construction. Due to the nature of design controlling a large amount of the cost of a product, as well as determining its marketability, it would be beneficial to evaluate and produce a concurrent engineering methodology specific to the composite boatbuilding industry itself. Concurrent engineering is a popular tool in many industries and therefore there are many methods currently available. As such, it is important to determine the areas of work that have already been completed.

This chapter starts with structural composites modelling and predictive behaviour. Further to this, different methods of modelling composite structures have been compared to ensure that the best method to suit the application has been chosen.

Reliability methods have been investigated to determine the different methods available for reliability analyses and to further determine the areas that have been previously approached in this subject area.

Different methods for multiobjective optimisation have been considered to determine a method of optimisation suitable for design purposes. Previous work within structural optimisation has been listed and a review of the fundamentals behind genetic algorithms has been explained.

Finally a review of concurrent engineering has been covered including a look at engineering design methods outlining current methods for engineering design, a review of the current state of design within the leisure boatbuilding industry and a review of concurrent engineering in all industries.

The aim of this chapter is to demonstrate the development of the different subject matters to show the current state of the art in each area, show the selection process of techniques and the interaction betweens the different subject areas. The appropriate methods have then been outlined in Chapter 3 with their implementation being covered in Chapters 4 to 7.

2.1 Structural Modelling

2.1.1 Composite Mechanics

Composite materials are used in a wide and varied number of applications and utilised within a number of different tasks as they have a high strength to weight ratio, excellent corrosion resistance, fatigue life to name but a few. These properties are due to the nature of composite materials being able to be formed in different ways both in terms of the material layup itself and the topology but also the processing techniques that are used to produce the material. This can lead to a complex problem in determining the manner in which the material will behave once in its role. Composite mechanics have been developed to understand the materials and how they will behave given a certain layup. First the stress components σ_{ij} shown on perpendicular planes have been presented in Figure 2. These stresses can be determined using Hooke's law shown in eq. 1

$$\sigma_{ij} = Q_{ijkl}\epsilon_{kl} \tag{1}$$

where σ_{ij}= second-order stress tensor, ϵ_{kl}= second-order strain tensor and Q_{ijkl}= fourth-order elasticity tensors with i,j,k,l= 1,2,3,4. Using the symmetric properties of the material

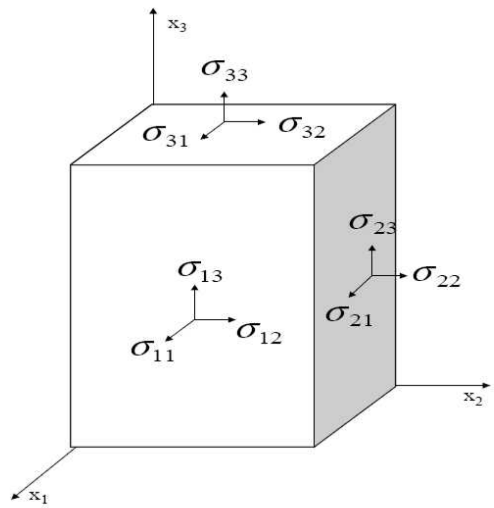

Figure 2: Stress Components

eq. 1 can be written in the form of eq. 2.

$$\begin{vmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{vmatrix} = \begin{vmatrix} Q_{11} & Q_{12} & Q_{13} & Q_{14} & Q_{15} & Q_{15} \\ & Q_{22} & Q_{23} & Q_{24} & Q_{25} & Q_{26} \\ & & Q_{33} & Q_{34} & Q_{35} & Q_{36} \\ & & & Q_{44} & Q_{45} & Q_{46} \\ & & & & Q_{55} & Q_{56} \\ & & & & & Q_{66} \end{vmatrix} \begin{vmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \epsilon_4 \\ \epsilon_5 \\ \epsilon_6 \end{vmatrix} \tag{2}$$

When assuming a thin plate this can be reduced to a two-dimensional space, the stress-strain relationship can be simplified as can be seen in eq.3.

$$\begin{vmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{vmatrix} = \begin{vmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & 2Q_{66} \end{vmatrix} \begin{vmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_6 \end{vmatrix} \tag{3}$$

For this two-dimensional consideration the constitutive relation becomes,

$$\begin{vmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_6 \end{vmatrix} = \begin{vmatrix} \frac{1}{E_{11}} & -\frac{\nu_{12}}{E_{11}} & 0 \\ -\frac{\nu_{12}}{E_{11}} & \frac{1}{E_{22}} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{vmatrix} \begin{vmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{vmatrix} \tag{4}$$

where E_{ij}= Young's modulus and υ_{ij}= Poisson's ratio. By substituting eq. 4 into eq. 3 it is then possible to determine the compliance tensors shown in eq. 5

$$Q_{11} = \frac{E_{11}}{1 - \upsilon_{12}E_{22}/E_{11}}, \;\; Q_{22} = \frac{E_{12}}{1 - \upsilon_{12}E_{22}/E_{11}}, \;\; Q_{12} = \frac{\upsilon_{21}E_{22}}{1 - \upsilon_{12}E_{22}/E_{11}}, \;\; Q_{66} = G_{12} \tag{5}$$

It is then possible to transform these stresses from the global axes (x-y plane) to the local axes (L-T plane) as can be seen in Figure 3. The stress can then be defined in the local axes as given in eqs.6 to 8.

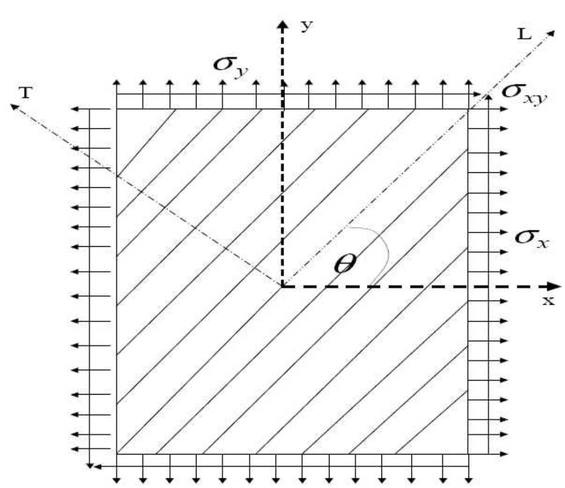

Figure 3: An orthotropic lamina with material axes orientated with respect to reference co-ordinate axes

$$\sigma_L = \sigma_x cos^2\theta + \sigma_y sin^2\theta + \sigma_{xy}(2sin\theta cos\theta) \tag{6}$$

$$\sigma_T = \sigma_x sin^2\theta + \sigma_y cos^2\theta - \sigma_{xy}(2sin\theta cos\theta) \tag{7}$$

$$\sigma_{LT} = -\sigma_x(sin\theta cos\theta) + \sigma_y(sin\theta cos\theta) + \sigma_{xy}(cos^2\theta - sin^2\theta) \tag{8}$$

The stress in matrix form as given in eq. 9.

$$\begin{vmatrix} \sigma_L \\ \sigma_T \\ \sigma_{LT} \end{vmatrix} = [T] \begin{vmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{vmatrix} \tag{9}$$

where [T] is defined in eq.10

$$[\mathrm{T}] = \begin{vmatrix} cos^2\theta & sin^2\theta & 2sin\theta cos\theta \\ sin^2\theta & cos^2\theta & 2sin\theta cos\theta \\ sin\theta cos\theta & sin\theta cos\theta & cos^2\theta - sin^2\theta \end{vmatrix} \tag{10}$$

The strain relation can be written in a similar manner to that of the stresses as seen in eq.11.

$$\begin{vmatrix} \epsilon_L \\ \epsilon_T \\ \frac{1}{2}\epsilon_{LT} \end{vmatrix} = [T] \begin{vmatrix} \epsilon_x \\ \epsilon_y \\ \frac{1}{2}\epsilon_{xy} \end{vmatrix} \tag{11}$$

Basing this upon the x-y plane it can be seen that eq.3 can be modified to the following eq.12

$$\begin{vmatrix} \sigma_L \\ \sigma_T \\ \sigma_{LT} \end{vmatrix} = [T]^{-1} \begin{vmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & 2Q_{66} \end{vmatrix} [T] \begin{vmatrix} \epsilon_x \\ \epsilon_y \\ \frac{1}{2}\epsilon_{xy} \end{vmatrix} = [\bar{Q}] \begin{vmatrix} \epsilon_x \\ \epsilon_y \\ \frac{1}{2}\epsilon_{xy} \end{vmatrix} \tag{12}$$

The matrix $[\bar{Q}]$ can then be defined as the transformed stiffness matrix. This representation of basic composite theory, found in many text books, has been included to aid readers with basic composite thoeyr. An understanding of these equations is key to understanding some of the structural modelling that is introduced later in the text.

2.1.2 Analytical and Numerical Structural Modelling

Boat structures are designed in one of three main ways:

1. Classification Society Rules - Phenomenological and Safety Factors
2. Classification Society Rules - Partial Safety Factors
3. Deterministic

One of the most popular methods for design in the marine industry are classification society rules. These rules are dependent upon the country of origin and the country to which the vessel will be sold. Classification society rules are designed to a set of rules based on first principles methods and experiments, including safety factors based upon the vast experience of the classification society. These safety factors, while ensuring a safe boat and fast design cycle, often mean that the topologies developed are heavier and thicker than can be calculated from first principle methods.

The second methods that can be used are reliability methods for structural design. These methods have become popular in the civil engineering industry including CIRIA [6] and DNV [7] and are used within these society rules. These methods are based upon finding a target probability of failure. Reliability methods are often analyised using either first or second order reliability methods (FORM or SORM) or can also be found using simulation methods (e.g. Monte Carlo).

Finally the last method for structural design in boats are deterministic methods which use first principles for the design. There are many different first principle methods that approximate the exact stresses and strains that will affect the vessel and are constrained using failure criteria. These methods will ensure a low mass but require careful validation to ensure safety of the structure. The problem with the development of these methods within FRP has been that the failure criteria used are not fully developed leading to either over conservative or unsafe vessels. This has led to these techniques being rarely used for direct design and more often used as a validation technique. Each different first principle method has its own advantages and disadvantages and are used in different scenarios. A comparison of these methods can be seen in Table 1.

Table 1: Comparison of Structural Analysis Methods

Techniques	Based on	Unidirectional stiffened plate	Cross stiffened plate	Accuracy	Comments
Composite beam method	Beam theory	Yes	Indirect	High	Slow
Equivalent orthotropic method	Plate theory	Yes	Yes	High	No stress for stiffeners
Folded plate method	Beam theory and plate theory	Yes	Indirect	V. High	Reduces with increased stiffeners
Grillage analysis	Minimum potential energy and beam theory	Yes	Yes	Hight	Fast resolution to solve
Finite element analysis	Finite element method	Yes	Yes	V. High (With good mesh)	Very slow

Equivalent orthotropic method uses the flexural and torsional rigidity of the plate and stiffeners to represent the panel. This method is derived from classical plate theory for unstiffened plates as shown in eq. 13

$$q = D_x \frac{\partial^4 w}{\partial x^4} + 2H \frac{\partial^4 w}{\partial x^2 \partial y^2} + Dy \frac{\partial^4 w}{\partial y^4} \tag{13}$$

where $D_x = E_x h^3/12(1 - \upsilon_x \upsilon_y)$, $H = \upsilon_x D_y + 2G_{xy} h^3/12$ and $D_y = E_y h^3/12(1 - \upsilon_x \upsilon_y)$.

These formulae have been developed further, as given by eq. 14 to cope with laminates under lateral loads, q, by Smith [8]

$$D_{11}\frac{\partial^4 w}{\partial x^4} + 2(D_{12} + 2D_{66})\frac{\partial^4 w}{\partial x^2 \partial y^2} + D_{22}\frac{\partial^4 w}{\partial y^4} = q \tag{14}$$

where $D_{11} = D_x + (D_{sx} + A_{sx}\epsilon_x^2)/b,\ D_{12} = \upsilon_y D_x,\ D_{66} = \frac{G_{xy}h^3}{12} + \frac{1}{2}\left(\frac{D_{Tx}}{b}\frac{D_{Ty}}{a}\right)$ and $D_{22} = D_y + (D_{sy} + A_{sy}\epsilon_y^2)/a$

where A_{sx} and A_{sy} are axial rigidities of longitudinal and transverse stiffeners, D_{sx} and D_{sy} are flexural rigidities of stiffeners about their centroids, D_{Tx} and D_{Ty} are stiffener torsional rigidities, a and b are the spacing of transverse (y-direction) and longitudinal (x-direction) stiffeners respectively, and ϵ_x and ϵ_y are the distances from the mid-plane of the plating to centroids of the stiffeners.

Folded plate method is created from a combination of plate and beam theory. The idea is presented in Smith [9] as a method to describe a generalized plate theory. This was to allow the method to be used for further applications than was previously possible. The plate that was used was unidirectionally stiffened while being simply supported on two opposite sides. From this, simple beam theory can be solved to find the forces and moments with the entire panel being represented as an isotropic Fourier series. Continuity conditions are then defined along the interconnecting boundaries between plates and beams, followed by applying an equilibrium condition on each beam element. From this, the matrix equation, shown in eq. 15, can be established and solved to provide the displacement solution.

$$K_n \delta_{Bn} = -R_n \tag{15}$$

Where K_n is a square stiffness matrix of order $4n_B$, n_B is number of beams, δ_{Bn} is a column matrix of unknown beam displacements and rotations and R_n is a column matrix of forces and moments acting on the beams due to lateral loads and initial deformations.

There are a number of grillage analyses based on different rules each with different accuracies. The main methods are displacement method, force method and energy method. The displacement method is the most commonly used version of grillage theory as reported in Clarkson [10]. The method that has been followed in this thesis is Navier energy method which is covered in more detail in Chapter 4. This is due to the accuracy level being sufficient for the requirements of the grillage model but also having the computational efficiency to be able to work with a genetic algorithm allowing a solution in a reasonable period of time. The grillage theory has been used to represent a part of a boat hull, as shown in figure 4, a number of these grillages could then be modelled to represent an entire boat hull.

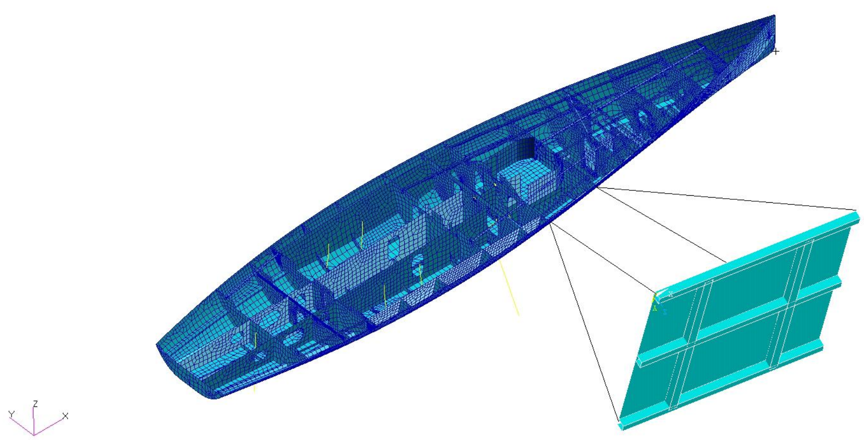

Figure 4: A grillage used to represent part of a hull structure

Finite element analysis is a method of structural analysis which uses approximations to partial differential equations using the finite element method. Structures are investigated in similar ways to other methods in that it breaks down a model of the object into equations where the problems become solvable. The method works by selecting nodes and meshes over the object to be analysed. The nodes will determine where the unknowns will be approximated and the mesh will be used to determine the properties of the material. This method has the added advantage that parts drawn up in the finite element analysis software can then be transported into computer aided design software saving time in the design process.

2.2 Reliability Analysis

2.2.1 Reliability Methods

Reliability techniques have been in development for a number of years. These methods first appeared in a mathematical form in the 1920's by Mayer [11] and further developed by Streletzki [12] and Wierzbieki [13]. Practical usage of these methods was not developed until the late 1960's with the development of a second-moment reliability index by Cornell [14]. This was further increased by the format-invariant reliability index from Hasofer [15]. Furthermore a reliability index was developed by Rackwitz and Fiessler [16]. This were useful in less complex problems however simulation has been introduced to deal with cases that are difficult or impossible to solve. Sun and Yamada [17] assumed an ultimate strength criteria as a basic design criteria and a Weibull distribution was assigned to interpret their statistical characteristics. This was replicated by Wetherhold [18] using a closed form expansion method and good agreement was reached. Cassenti [19] furthered deterministic methods by developing the probabilistic static failure analysis procedure of unidirectional laminated composite structures. Yang [20] presented a reliability analysis of laminated plates based on the last-ply-failure analysis concept. Cederbaum [21] presented work related to in-plane loads using first ply-failure on symmetric angle-ply laminates. Thomas [22],[23] developed an analysis result for single continuous lamina and laminated plate based on weakest link theory and furthered this work by presenting a more precise reliability estimation subjected to multi-axial loads. Kam [24] predicted the reliability of simply supported angle-ply and cantilever symmetric laminated plates subject to large deflections within the context of first-ply-failure. Gurvich [25],[26] developed a probabilistic failure model for the reliability of laminated composites subjected to combined lateral pressure and in-plane loads based on a ply group concept and this was further developed to include both a ply group and a laminated plate subjected to uni-axial tensile loads. Kam [27] developed an analysis procedure of clamped symmetric laminated plates subjected to central point loads based on the first-ply-failure analysis. Mahadevan [28] developed progressive probabilistic progressive failure analysis of laminated plates based on last-ply-failure analysis. Finally Shenoi et al. [29] has furthered this work in terms of the development of reliability for small marine craft using in-plane stresses and deterministic methods. This work has been used in terms of analysis but the use of the reliability as a design for production tool is missing from the literature. Furthermore the work of Blake et al. has not been reproduced using simulation methods. Finally work needs to continue looking at reliability with more stringent failure criteria which will constrain the behaviour of the structure more realistically.

The development of reliability has been dependent upon two main solutions which are deterministic and simulation methods. The most popular three methods for solving for the reliability index are:

1. **FORM:** First-order reliability methods are created using a first-order Taylor series expansion. The initial step is to create an equation approximating the limit state of the equation using parameters relative to capacity, R, and demand, Q as can be seen from eq.16:

$$M = R - Q \tag{16}$$

It can the be seen that if these values are statistically independent design variables then the mean and variance of the reliability index, M, will be dependent upon the mean and variance of the input values given by

$$\mu_M = \mu_R - \mu_Q \tag{17}$$

$$\sigma_M = \sigma_R + \sigma_Q \tag{18}$$

It can then be stated that if the demand is larger than the capacity then failure will occur and that this is dependent upon the statistical inputs as shown in eq.19

$$P_f = P[M < 0] = \Phi\left(\frac{\mu_M}{\sigma_M}\right) = 1 - \Phi\left(\frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 - \sigma_Q^2}}\right) \tag{19}$$

where Φ= cumulative function of the standard normal basic design variable. For these results it can be seen that the probability of failure is dependent upon the ratio of the mean to its standard deviation. It is then possible to define a safety index as given in eq. 20.

$$P_f = \Phi(-\beta) \tag{20}$$

For the situation where there are multiple input variables it can be seen that equation 16 can be expanded using a Taylor series and in this case only the first order terms are kept as shown in eq. 21

$$M = f(\bar{X}_1, \bar{X}_2, \ldots, \bar{X}_n) + \sum_{i=1}^{n} \frac{\partial f}{\partial X_i}(X_i - \bar{X}_i)) \tag{21}$$

From here it is possible to obtain an approximation for the mean and the variance as shown in eqs. 22 and 23.

$$\mu_M = f(\bar{X}_1, \bar{X}_2, \ldots, \bar{X}_n) + \sum_{i=1}^{n} \frac{\partial f}{\partial X_i}(X_i - \bar{X}_i)) \tag{22}$$

$$\sigma_M^2 = \sum_{i=1}^{n}\sum_{j=1}^{n}\left(\frac{\partial f}{\partial X_i}\right)\left(\frac{\partial f}{\partial X_j}\right)Cov(X_i, X_j) \tag{23}$$

It is then possible to show for design variables that are statistically independent that the variance can be expressed

$$\sigma_M^2 = \sum_{i=1}^{n}\left(\frac{\partial f}{\partial X_i}\right)^2 Var(X_i) \tag{24}$$

The solution to this problem is fast although there is an inability to solve problems in which the inputs are statistically dependent. Furthermore there are problems that are difficult to solve.

2. **SORM:** Second-order reliability methods are based upon a second order Taylor series expansion. They are very similar to those found in first-order reliability methods having the same advantages and disadvantages. These solutions give more accurate results however they have the disadvantage that they are more complex to solve than the first-order solutions.

3. **Simulation:** Simulation methods can be used to reproduce the manner in which a system might react in the real world. Reliability analyses can therefore be determined by running a simulation that captures the manner in which that system would react in the real world. For the case of reliability simulation it is usually carried out using Monte Carlo simulations. This method has the advantages that it can be used to solve very complex problems easily and deal with inputs that are statistically dependent. Furthermore, the solution of different problems is less time consuming as the code is easy to manipulate. The main disadvantage is that to determine a given probability accurately takes runs orders of magnitude larger than the reciprocal of the magnitude of the expected probability, resulting in long runtimes.

2.2.2 Structural Safety Analysis

Reliability methods are used to predict the performance of structures in areas where there is a high level of variability. There are many different methods for the determination of the reliability of a product which fall into two main categories: analytical and simulation. Analytical methods have the advantage that they are computationally inexpensive compared to those carried out with simulation. The main problem can be that these methods can be complicated to solve. There are three levels in reliability analysis: level-1, level-2 and level-3. Level-3 is the full probabilistic method where the model determines the link between the basic design variables affecting the response of the structure and the true nature of the failure domain. Level-2 is a semi-probabilistic method where the failure domain is idealised and is often connected with simplified probability functions of the basic design variables. An example of a Level-2 method is the First Order Reliability Method(FORM) where a first-order Taylor series is used as approximation to the limit sate. This technique can also be undertaken using a second-order Taylor expansion series and this is a Second Order Reliability Method(SORM). Finally the level-1 approach is a deterministic approach using either central or partial safety factors. Level-3 methods are rarely used due to the difficulty of modelling fully the entire structural and failure models and are generally used in research whereas most of the design codes available are using level-1 reliability with some codes moving towards level-2. These include the American Institute of Steel Construction(AISC) Load and Resistance Factor Design(LRFD) code for steel building [30], the Ontario Highway Bridge Design Code for bridges [31] and European codes such as CEC. Further to civil design the marine industry is starting to develop codes utilising reliability techniques with DNV [7] and IMO [32] developing reliability based sections to their codes.

For the development of different codes it is important to have a target reliability.

This target reliability will be dependent upon the application and the object for which the reliability is required. Table 2 [33] lists a number of different probabilities of failure compiled by the ISSC implicit in the design of different structures.

Table 2: Annual P_f in existing structures

Type of Structure	Relevant Code	Remarks	Annual P_f
Production Ship	"current codes"	In North Sea	10^{-4}
		In the tropics	$< 10^{-4}$
Merchant Ship	"current codes"	In North Sea	10^{-3}
Cylindrical Shells	NPD/DNV, API RP2T	Normal Distribution for wave load effects	$10^{-6} - 10^{-4}$
		Lognormal distribution for wave load effects	$10^{-5} - 5 \times 10^{-4}$
Stiff. flat plates	NPD/DNV API RP2T		$10^{-5} - 5 \times 10^{-4}$
Stiff. panels	API RP2T, RCC/API Bul-2U		10^{-4}
Stiff. plates	API RP2T, RCC/API Bul-2U		10^{-3}
Stiff. shell bays	API RP2T, RCC/API Bul-2U		3×10^{-4}
Fixed offshore structures	API RP2A LRFD CSAS471		4×10^{-4}
	CSAS471		$10^{-5} - 10^{-4}$

Further to this the ISSC further released a list of recommended reliabilities for floating structures based upon expert opinions Table 3 [34].

Table 3: Recommended floating production systems target reliability

Unit	Failure Probability
Monohulls	$10^{-5} - 10^{-3}$
Hulls	$10^{-4} - 10^{-3}$
Moorings	$2 \times 10^{-3} - 10^{-2}$
Hull	$10^{-4} - 10^{-3}$
Tethers	$10^{-5} - 10^{-4}$

Finally from Table 4 [35] it is possible to see a number of values for reliability associated with different qualitative circumstances and the reaction that society would have to them. Values in these tables represent the sorts of probabilities of failure associated with different

Table 4: Society's general reaction to hazards

Probability	Society Reaction
10^{-3}	This level is unacceptable to everyone. When probability approaches this level, immediate action should be taken to reduce the hazard
10^{-4}	People are willing to spend public money to control hazards at this level. Safety slogans popularized for accidents in this category show an element of fear (e.g., the life you save may be your own)
10^{-5}	Though rare, people still recognize these hazards, warn children (e.g., drowning, poisoning). Some accept inconvenience to avoid such hazards (e.g., avoid air travel)
10^{-6}	Not of great concern to the average person. People are aware of these hazards, but feel "it can never happen to me" - a sense of resignation if they do (e.g., an "act of God")

events and applications. It is therefore important before reliability analysis is carried out to understand these values and to determine a suitable target probabilities of failure for the structure being investigated.

2.3 Multiobjective Optimisation

2.3.1 Optimisation Methods

Optimisation is already a well used tool for structural design with many different techniques being used. The aims of optimisation will be to reach a compromise between all of the different subsystems of a product. These compromises should be directed towards fulfilling a number of customer requirements creating an imbalance in the importance of certain subsystems and output variables. The output variable(s) will need to be either maximised or minimised depending on the input variables and will be changed based upon the topology of design as well as the materials and production techniques used. These input variables could be either non-numeric inputs such as the choice of a type of design (these methods have not been covered here) or numerical inputs such as dimensions, materials choices, layups, etc.. The type of optimisation that will be chosen will depend upon the input type and also the search space required for investigation.

There are many different sorts of optimisation algorithms. The first early optimisation techniques, as stated by Keane [36] were direct methods such as classical gradient based methods and hill climbers developed in the 1960's. This group of optimisation methods can be used to find the exact answer to a problem as long as enough iterations occur. The disadvantage of such methods is that they often get stuck at a local optimum which may be a long distance from the global optimum.

There are a number of different hill climb methods that are used regularly including Hooke and Jeeves [37] and sequential quadratic programming. The Hooke and Jeeves method uses two steps to explore the search space. The first of these is to determine the pattern of the fitness function in the area surrounding the search. The second of these is a pattern search which will determine the direction in which the algorithm will move so as to not always search along the coordinate axes.

Further to these methods, simplex method is another linear method created by Dantzig in 1947 as reported by the same in [38]. Simplex method is based upon simplexes or an n-dimensional analogue of a triangle where each feasible vertex of the feasible set is tested and the fitness function can be seen to either increase or decrease. If the fitness function increases then the algorithm will select this as the next optimum point. If no adjacent points can be found to increase the size of the fitness function then the optimum solution has been found. These methods of searching are very quick in the manner in which they search and also find close to optimal answers. The disadvantage with these search methods is that they have a tendency to get stuck at local optima depending on the starting point of the search. These sorts of searches have therefore become less common on complex problems with stochastic methods becoming more popular.

Stochastic methods make use of random searches to investigate the potential search space. These methods were first developed in the late 1960's and first used in the late 1970's and early 1980's as reported in [36]. Stochastic methods can investigate large search spaces but are characterised by large computational times and often only find a value which is close to a global optimum rather than the exact value. The disadvantages to these problems can be reduced by some extent through the addition of classical gradient based methods and hill climbers.

Genetic algorithms are an optimisation method based upon Darwin's theory of evolution. First developed in the 1950's by Fraser [39] these methods were not considered in the field of artificial systems. This work was further developed in the 1960's by Holland [40], [41] and [42]. This work was then built upon and by the late 1980's genetic algorithms were being used to solve many optimisation problems as shown in Goldberg [43]. These methods use survival of the fittest combined with mutation and crossover of genetic material to develop optimal solutions that gradually evolve towards the global optimum. Due to the mutation and crossover of strings between parents and children the solution will find a point near to global optimum given enough generations. The disadvantage of this method can be high computational expense and a solution that is close to the global optimum without reaching it.

Particle swarm optimisation was first developed in 1995 and reported in Kennedy [44]. This method of optimisation is similar to genetic algorithms in that it maps behaviour of humans to reach a global optimum. In the case of particle swarm optimisation it copies the way in which humans interact with each other in that people with similar interests will be close to each other in socio-cognitive space. A number of initial solutions are created artificially in the search space. These particles will then "move" about the search space. As the particles move around the space they can determine whether they have increased a fitness function defined by whether they improve the design or not. The particles can remember where they have been and also can interact with their neighbours. Through multiple steps it is possible to determine where an optimum value may lie and these particles will swarm to these areas further investigating the potential global optimum value.

Simulated annealing, developed by Kirkpatrick [45], is based around the process of annealing in metallurgy. The process works by having a global parameter that simulates the heat in annealing. As the temperature drops the particles in the solution have less energy and therefore move around the space less thereby constraining their movements.

Further to these methods of optimisation are design of experiments and response surface methods which are used to try and reduce the computational time required for the optimisation process. These methods were first developed by Box and Wilson in 1951 [46]. These methods have gained popularity since the mid-1980's due to the use of computationally expensive methods to develop models in certain areas of design, especially structural and fluids modelling. It is infeasible to run these programmes multiple times, as required, for optimisation using methods such as genetic algorithms. In these cases it is important to try and develop methods that allow fewer runs to be carried out but to still allow optimisation over a wide search space. Design of experiments, as shown in Montgomery [47], splits the search space up into equally spaced points. Outputs can then be assessed from these points to determine what is the most optimum point. Further optimisation can be carried out from these points to try and gain the global optimum point. This method can have difficulties if the global optimum is a narrow peak and the curve to this optimum is missed by the design of experiments search, meaning a non-optimum point will be reached. Response surface methods take this technique further by trying to generate the curve between these points with many different methods of doing this which include: Polynomial Response [46], Spatial correlation models, "Kriging", [48] and more recently neural networks [49].

Optimisation specific to ship structures has been carried out over a number of years. One of the first instances of this was by Hughes [50], who developed a program to look at large complex ship structures. During the early 1980's work started on multiobjective optimisation trying to include design for production into the optimisation problem as reported in Souther [51], Kuo [52], and this work has continued into this century by Rigo [53], Klanac [54] and Maneepan [3]. Different techniques have been used for this optimisation following an evolution through more complex methods of structural modelling and optimisation improvements. The next steps in structural optimisation will be the development of optimisation codes which cope with more variables while retaining accuracy and confidence of the designers. For these optimisation methods to be fully accepted it will be important to increase the speed at which optimisation occurs, from an order of magnitude of days or months for large and complex problems, and also the complexity of the inputs into the optimisation such as through the use of more complicated computational fluid dynamics and finite element analysis.

A comparison of these methods can be seen in Table 5

2.3.2 Structural Optimisation

Many of the problems created in engineering involve a compromise between different areas of the product. These problems are being solved increasingly through the use of

Table 5: Comparison of Optimisation Techniques

Techniques	Based on	Computational efficiency	Global optimum	Accuracy	Multiobjective
Genetic Algorithms	Darwinian Evolution	Slow	Yes	High	Finds solution slow
Particle Swarm method	Swarms of animals	Slow	Yes	High	Find solutions slow
Simulated annealing method	Annealing	Yes	Fixed	High dependent on time	Normally used for discrete solutions
Hill climb	Linear	High	May fail on complex problems	Exact	Likely to fail
Simplex	Linear	Very High	May fail on complex problems	Exact	Likely to fail

optimisation. Optimisation algorithms first started to be used in the 1960's. These algorithms were then applied to grillages presented in papers by Kavlie [55] and Moses and Onoda [56]. These early optimisation routines were summarised at the International Ship and Offshore Structures Conference [57]. Much of the work that has been carried out in ship structures has been carried out solely on the structures and the problem of objective functions and multiobjective optimisation was not approached until the 1980's. Some of these early papers include Souther [51], Kuo et al. [52] and Winkle and Baird [58] and more recently the problem has been approached by Rigo [53]. Further to this it has been shown that genetic algorithms can be used as an effective tool to optimise ship structures, including the contributions in the papers by Okada et al. [59], Nobukawa et al. [60], Sekulski et al. [61], [62], [63] and Maneepan et al. [3]. These early works concentrate mainly upon metallic structures. Within the work on composite structures multiobjective optimisation has not been explicitly tried for structural scantling design purposes. Composite optimisation also requires further constraints on the model to allow for wider search spaces to be investigated with realistic results.

2.3.3 Genetic Algorithms

Genetic algorithms are a multiobjective optimisation method that will allow accurate resolution of results while searching a large search space. Genetic algorithms work by copying the process of DNA transfer in living organisms. They then use the process of evolution to find the optimum solution for a given search space.

Initial population: The first step in generating a solution for the genetic algorithm is to develop the initial population of strings. This is achieved through a random number generator, which for the work presented here, can be found in Numerical "Numerical Recipes" [64]. The strings are made up of binary numbers each section of which represents part of the topology of the stiffener.

Exploiting operator: The exploiting operator is the selection process which chooses the strings to be used and those which will no longer be used. This is undertaken using the criteria of a fitness function which will normally be based on a function of the inputs $f(x)$ for maximisation or $1/f(x)$ for minimisation problems. The main exploiting operators are outlined below.

- Roulette Wheel - Roulette wheel selection is based upon a roulette wheel with the different sizes of the slots being based on the level of fitness that the string receives. The higher the fitness value in proportion to the rest of the fitness values, as shown in eq. 25, the better the chance of the string being selected for the next generation. Strings will be picked for the next generation until enough are picked to fill the population size.

$$p_k = \frac{f(x_k)}{\sum_{k=1}^{n} f(x_k)} \tag{25}$$

  where n is the population size and k = 1,2,...,n

- Tournament - Tournament selection is carried out using only the values with the best fitness. This is undertaken by picking a tournament size and from this selection choosing the fittest selections to go through to the next round.

- Ranking Selection - Ranking selection is carried out in much the same way as tournament selection. It is slightly different in that all of the strings have a better chance of being selected for the next round. In this method all of the strings are ranked and then selected based on that order. Eq. 26 defines the probability of selecting a given string.

$$p_k = \frac{2k}{m^2 + m} \tag{26}$$

  where k is the k^{th} chromosome in order of ascending fitness and m is the fittest chromosome.

- Elitism Selection - This is a process of selection that can be used in conjunction with the other forms of selection. This selection route ensures that the string with the highest fitness is passed on to the next round of the genetic algorithm without being changed.

Exploring operators: As the genetic algorithm gradually evolves towards the optimum solution, exploring operators are used to make sure that the entire search space is being investigated by broadening the search. This is performed in two main ways through either mutation or crossover as shown in Figure 5.

Crossover: Crossover is the process by which the algorithm will make changes between different strings. Crossover recycles the current genetic material and will make sure that all areas are searched.

- Single point crossover is when two strings are selected and a point is randomly generated at which to split them. One part of each string is then attached to the

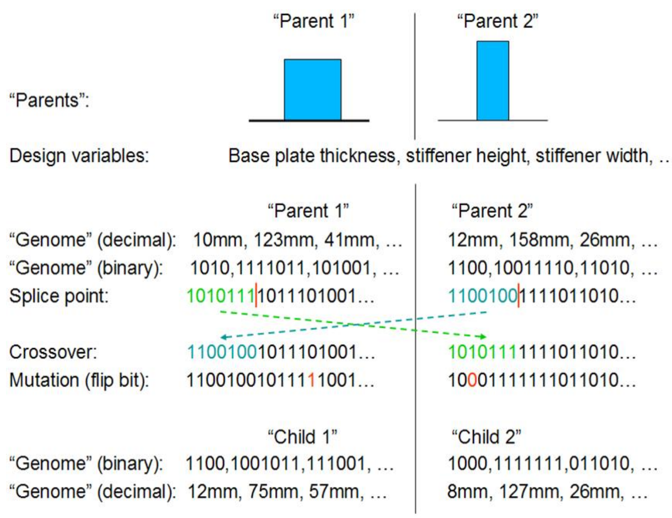

Figure 5: The process of mutation and crossover in genetic algorithms

other part of the string leaving both with a different defined topology. This process is shown in Figure 5.

- Double point crossover is similar to single point crossover but the string is split in two places and the new sections are then inserted into the strings.

- Uniform crossover directly compares the two strings at a point and will make a change between the two based on a probability factor.

- Direction based crossover, also known as heuristic crossover, uses an objective function to generate new results as shown in eq. 27 from Michalewicz [65].

$$x_o = r(x_2 - x_1) + x_2 \tag{27}$$

where x_2 is not worse than x_1 therefore fitness(x_2) $\leq$ fitness(x_1) for minimisation and fitness(x_2) $\geq$ fitness(x_1) for maximisation problems, r is a random number x_o

is the offspring and x_1 and x_2 are the parent strings.

- Arithmetical crossover is when an arithmetic method is performed to produce the new offspring, an example of which can be found in Bazaraa [66] and shown in eq. 28

$$\gamma_1 x_1 + \gamma_2 x_2 \tag{28}$$

where the multiplier $\gamma_1 + \gamma_2 = 1$ and $\gamma_1 > 0$ and $\gamma_2 > 0$

Mutation: Mutation is the process of changing the strings independent of the other strings in the algorithm. Mutation makes sure that the results do not converge on local optima and that the search space is fully investigated.

- Static mutation is where the mutation has a probability to change in any part of the string. The algorithm will work down the string and determine against a random number generator whether the mutation will occur or not.

- Gaussian mutation is based on a Gaussian distribution of numbers that are used to mutate the value of the string if a certain probability is reached. If the Gaussian adapted string is above a lower or upper boundary the value will be put at that boundary. An example of a Gaussian selection method is shown in eq. 29

$$x'_k = x_k + \beta_G \eta \tag{29}$$

where β_g is the scaling parameter and η is generated independently for each gene and standard deviation of a Gaussian distribution function

- Dynamic mutation uses small random changes around a point to make sure that the whole spread of the search is not changed. This is used later on in the search process to make sure that the final answer is correct.

2.4 Concurrent Engineering Environment

2.4.1 Engineering Design Methods

As has been previously discussed in Chapter 1 the process of design is a small part of the cost of the product but effects most of the final cost. It is therefore very important that this process is carried out efficiently while producing the best product possible. Pahl [67] describes problem solving, such as in the case of design, as involving "step-by-step analysis and synthesis. In it we proceed from the qualitative to the quantitative, each new step more concrete than the last.". This definition shows the manner in which a design idea must become a fully formed design before being produced. The process is defined in a number of steps by Pahl [67]:

- Planning and Task Clarification
- Conceptual Design
- Embodiment Design
- Detailed Design

The first step is to gather the information that is required for the task. Then the constraints of the product must be determined and the task that the final product will undertake decided, this process will hereby by referred to as customer requirements. The next step is the conceptual design during which a principal solution is reached by abstracting the essential problems, establishing function structures, searching for suitable working principles and combining those principles into a working structure. The embodiement design constructs the overall layout of the design. Finally the detailed design stage is the process where the arrangement, forms, dimensions and surface properties of all the individual parts are finally laid down. This process is carried out using a number of different methodologies.

The most well known methodology for the design of ship and other marine structures is the "Design Spiral" created by Evans [68]. Within the design spiral, shown in Figure 6,

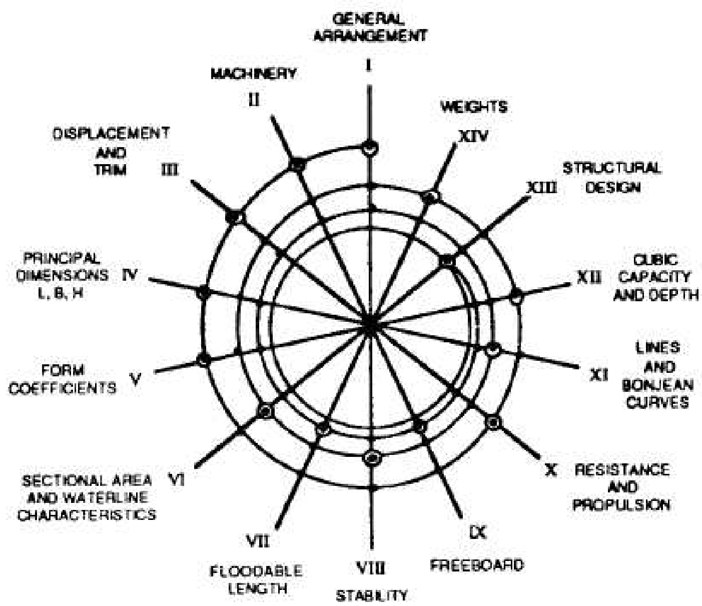

Figure 6: General Design Spiral

the design is started at the general arrangement where this subsystem designer carries out initial calculations. As the design continues it is passed onto the machinery subsystem designer and through until the weights subsystem designer has completed their work and made design changes. At the end of this first spiral the final design can be evaluated and from here a second spiral can be started where refinements can be made to the original design based upon the changes made by other subsystem designers. A problem that can often occur with this type of design method is that a design decision made by one subsystem designer may have found that changes have been taken out of the design by the time that one iteration of the process has occurred. This may mean that there is a requirement to replace the current design with the old design, due to its importance to the specified subsystem, therefore slowing down the process and making it harder to reach a compromise between designs. Furthermore from the design spiral given by Evans [68], and shown in Figure 6, it can be seen that production is not specifically taken into account.

2.4.2 Current Leisure Boat Design

For the boatbuilding industry there is a lack of publicly available information defining the process of design, specific to the industry, and little information defining the industry itself. A survey has therefore been carried out within this research to determine the characteristics of leisure boatbuilding. This survey consisted of 20 companies from which replies were received from 8. Within these 8 companies there is a variation between the companies that produce boats, those that design them and some which carry out both tasks.

The leisure boatbuilding industry is one where there is a large variability within the products that are made. The size of the boats within the industry ranges from a low of 16ft to the largest vessels at 135ft reported in "A sector competitiveness analysis of the UK leisure boatbuilding industry"[69], a value that is ever increasing. Most of these boats are made using E-glass based polymer matrix composites with a large majority using hand layup for the production either solely using this as the production method or in combination with other methods. Within all of the companies it was felt that the product development was an evolutionary process with incremental product development rather than large product break-throughs. This is performed by taking an existing hull form and making changes to this to suit the size of the vessel planned.

The structural design process for the leisure boatbuilding industry is similar to that outlined in the previous section 2.4.1. This process consists of a concept design and detailed design stages after which point production will begin. Looking more specifically at the structural design a major part of this subsystem will be that of the hull design. For the design of structures a general sequence of actions is defined by Claughton [70]:

1. Define initial dimensions of structural element

2. Establish load case

3. Select the strength analysis method

4. Define the allowable deflections, stresses and/or strains

5. Analyse and adjust scantlings for optimum design

In this process an initial determination of the dimensions will be determined from the customer requirements, a load case will be established based upon the type of environment that the vessel is expected to encounter, the strength that is required from this load can then be calculated using constraints based on deflections and stresses. Finally the topology can then be adapted to suit the specific case the boat will be expecting to operate under. It is this process that must be recreated with automated tools to define an optimised first iteration of scantling determinations.

2.4.3 Concurrent Engineering

Concurrent engineering is a process that uses parallel design processes as opposed to the sequential that are found within design in many industries. Concurrent engineering is defined by Syan [71] as “a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the onset, to consider all elements of the product life cycle from concept through disposal, including quality, cost, schedule and user requirements”. This definition shows the manner in which different areas of the design process must be integrated together taking into account a holistic view of the design. Concurrent engineering has been defined in many ways further to this definition, however a set of common key points is:

- Parallel design
- Multidisciplinary team
- Facility
- Software infrastructure
- Support and understanding for the environment

There is little current literature specific to the process of concurrent engineering. It is possible to see from previous literature the prevalence of concurrent engineering in other industries. Many companies within the aerospace industry also made the transition and found success from Airbus through Airbus Concurrent Engineering (ACE) [72] and Boeing military aircraft company in 1999 reported in Shishko [73]. Astronautics is another industry where concurrent engineering has been used with NASA and ESA developing the

Project Design Centre (PDC) at the Jet Propulsion Laboratory in 1994 seen in Finkel [74] and Concurrent Design Facility (CDF) at ESTEC in 1998 and reported in Bandecchi [75] respectively. More specifically to the marine industry it can be seen from Bennet [76] that in 1996 many companies within shipbuilding had started to use concurrent engineering. Research is now being concentrated upon tools which often fall under the umbrella of concurrent engineering, as presented by Eaglesham [77], including:

- Integrated Project Teams (IPT)
- Digital Product Definition (DPD)
- Digital Pre-assembly/Mock-up (DPA)
- Computer Integrated Manufacturing (CIM)
- Lean Manufacturing (LM)
- Design for X-ability (DFX)
- Total Quality Management (TQM)
- Quality Function Deployment (QFD)
- Supplier Involvement on Product Team (SI)
- Customer Involvement on Product Team (CI)

It is therefore important when developing concurrent engineering to understand the interaction between the different techniques. The combination of these different processes leads to the holistic view integral to concurrent engineering.

Concurrent engineering has had a beneficial effect upon the industries within which it has been used. Due to the prevalence of concurrent engineering in many different

Table 6: Comparison of Industry Characteristics

Characteristic	Shipbuilding	Aerospace	Automotive	Boatbuilding
Production Facilities	Few simultaneous	Few simultaneous	1000's simultaneous	Few simultaneous
Development Process	Concurrent design Production	Design Prototype Custom manufacture	Design prototype Bulk manufacture	Straight to production Custom Manufacture
Design Collaboration	Real time	Pre-production	Pre-production	Pre-production

fields it is important to understand the similarities and differences between the industries to be able to take the techniques that are most useful in each of the different areas. Table 6, taken from Gwyther [78], illustrates these similarities and differences and has been expanded to include boatbuilding characteristics. From the entries to this table it is possible to see that aerospace and shipbuilding applications have many similarities with those of boatbuilding. This is because the volumes of boats produced are small in comparison to the products of the automotive industry. An advantage the aerospace and shipbuilding industries have over boatbuilding are the level of resources that they have available within the companies.

Concurrent engineering has had a large effect on multiple characteristics as can be seen from Bennet [76] and presented in Table 7 which shows the percentage change in given company characteristics when concurrent engineering is implemented. It is important to note the large improvements that have been made within the industry particularly in productivity and quality while gaining a reduction in development time and engineering changes. Not only has concurrent engineering been greatly beneficial in the shipbuilding community but aerospace has seen great benefits to and Table 8 gives those identified by Eaglesham [77]. The results from the aerospace industry are similar to shipbuilding

Table 7: Concurrent Engineering in Shipbuilding

Characteristic	Change
Development time	30-70% reduction
Engineering changes	65-90% reduction
Time to market	20-90% reduction
Overall quality	200-600% improvement
Productivity	20-110% improvement
Dollar sales	5-50% improvement
Return on assets	20-120% improvement

Table 8: Concurrent Engineering in Aerospace

Characteristic	Change
Development time	50% reduction
Engineering changes	50% reduction
Cost Savings	$68M reduction

showing an ability to transfer the technique. Figure 7 from, Sharples [79] shows how the concurrent engineering environment improved time to complete production in the aerospace industry, a saving of approximately ten months. This highlights the difference, in time, between both approaches, sequential and concurrent.

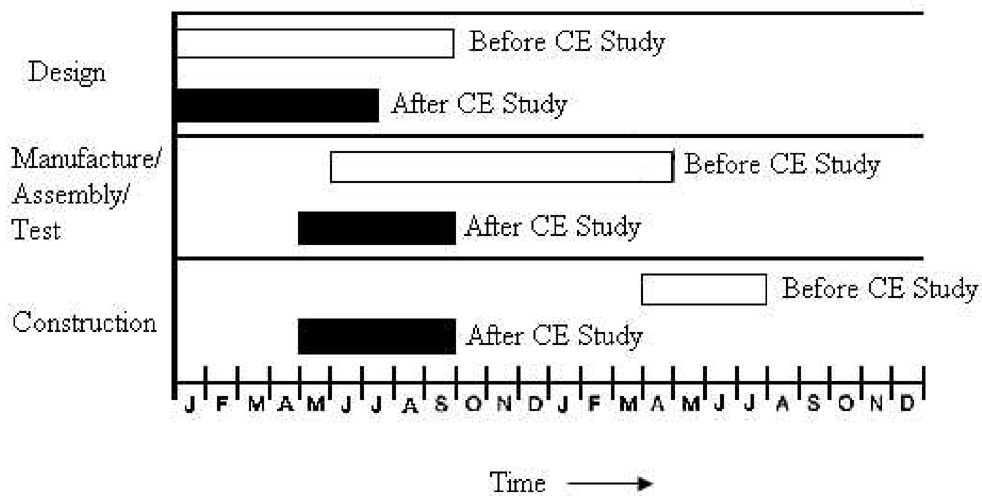

Figure 7: Improvements gained during concurrent engineering

2.5 Summary

A large amount of work has already been researched within concurrent engineering. There has been no reported work within the leisure boatbuilding community on the topic of concurrent engineering. Within the field of concurrent engineering there are a number of subtopics within which work is being investigated. These topics include Design for X, Integrated Project Teams, Quality Function Deployment, Supplier and Customer Involvement on Product teams, all of which have been chosen for further investigation in the research presented here due to their importance in developing a concurrent engineering environment focusing on design for production. The field of structural modelling has been a well covered topic and from within the work it can be seen that Navier grillage method will provide a fast solution for the stresses within the grillage and Third Order Shear Deformation theory will determine the stresses within the panels between the stiffeners and is employed due to its ability to accurately assess complex layups. Within the subject of optimisation multiobjective optimisation is becoming more prevalent and the work has concentrated mainly upon metallic structures. Within the topic of optimisation composite materials have been covered in far less detail than metallic ones. Furthermore the use of multi-objective design with genetic algorithms for composite materials has not been covered. Finally reliability methods are being developed in the marine sector in E-glass but this work has not yet been approached using stochastic reliability methods. Work on production reliability within the marine sector has not been developed and the use of both of these methods within a design framework has not been considered. Chapter 3 covers the development of the methodology behind the concurrent engineering environment showing the method of design that will be used and the manner in which the tools that have been developed sit inside this framework.

3 Methodology for Design

3.1 Introduction

To utilise concurrent engineering within the leisure boatbuilding industry it will be important to develop a methodology for design that will incorporate the important factors of the design processes, both boatbuilding and concurrent, and combine them. For each subsystem of the boat the design engineers will use different tools to aid them through the process. Concurrency within the design team can be aided if the tools themselves are built around a concurrent approach. The method outlined is based around structural design for production but could equally be incorporated within the design of other subsystems and could be expanded with multiple subsystems becoming involved. The methodology of the design has been developed previously, as found in the paper by Pahl [80] and shown in overview in Figure 8. The different steps in the figure are developed in Sections 3.2.1 to 3.2.3.

The design process starts with the concept design of the boat. It is at this stage that the design goals will be set and possible solutions to these goals are created, this is outlined in section 3.2.1.

3.2 Design Methodology

3.2.1 Concept Design

At the start of the design process it is important to fully define the concept that the design engineers will be working to and is the first step of Figure 8 and expanded in Figure 10. This is an important stage as parallel design processes, e.g. concurrent engineering, involve more engineers working on a problem at any one time than would be the case for

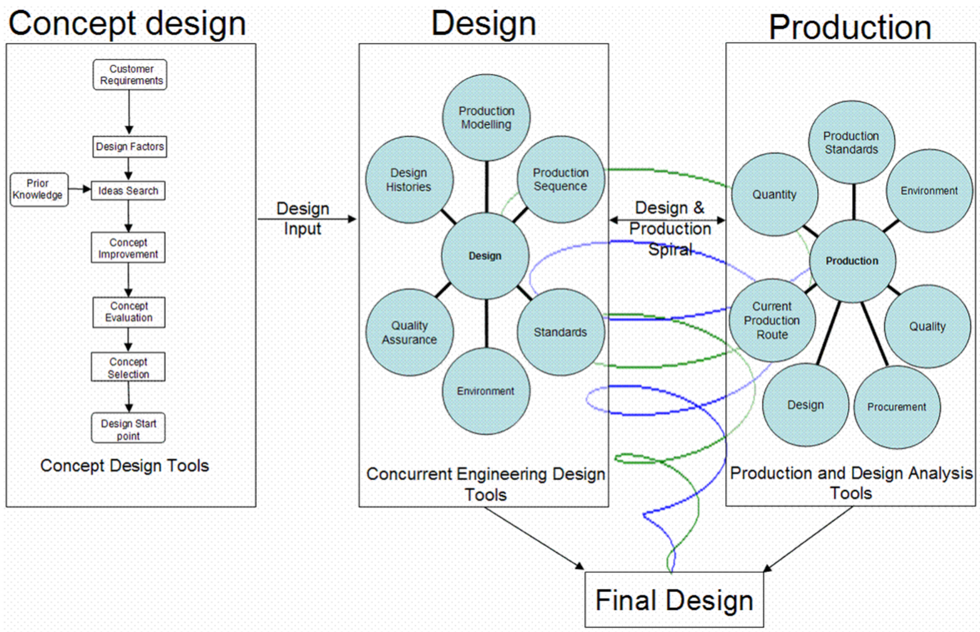

Figure 8: Stages of project design

sequential design. If at any point during the design the entire concept changes or is ended more man hours would have been invested, leading to higher expense. This is shown in Aitshalia et al. [81] where it is possible to see that for a series process the cost of failure is:

$$E(\text{cost})_s = \frac{c_i}{p_i} \tag{30}$$

where $E(\text{cost})_s$ is series cost, c_i is cost of stage i, and p_i is probability of success for stage i. In the case of the concurrent, parallel, process this cost will be:

$$E(cost)_p = \sum_{i=1}^{m} c_i + \frac{1-p_i}{p_i} \sum_{k=i}^{m} c_k \tag{31}$$

where $E(\text{cost})_p$ is parallel cost and c_k is cost of stage k. If a comparison is made between these costs, up to a given point in the design, costs will be higher for parallel design than sequential design. This is because more members of the team have been involved. This factor indicates that if a redesign is to be undertaken or the project is scrapped then more money will have been wasted. Concept design is important as the ability to influence the product cost is now at its highest, as is the ability to make changes to the design. The influence is illustrated in Lombardo [82] and included in Figure 9. Mistakes made in the concept design will have the furthest reaching consequences allowing production of a boat that does not reach the correct market or a product that is expensive to produce. It is therefore crucial for concurrent engineering that concept design is completed with a high quality and the results of this stage of the design are adhered to for the remaining stages of the design. One benefit of concurrency is that due to the nature of the process all the members of the company who could add input at this stage will be involved indicating a more focused process. The concept design stage is shown in Figure 10.

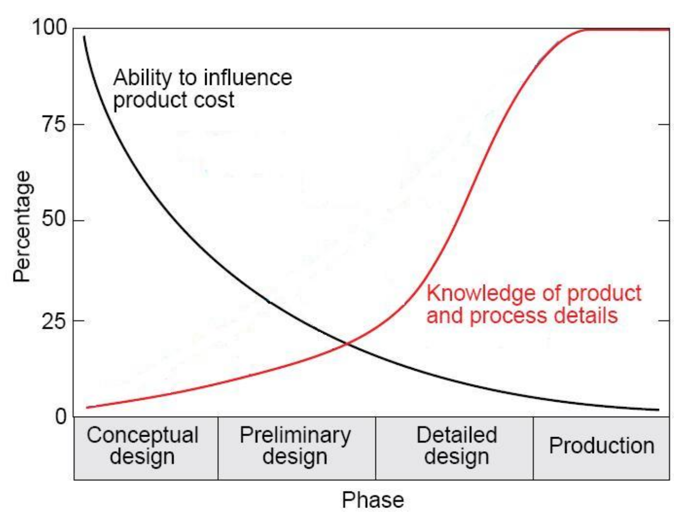

Figure 9: Importance of Concept Design

The concept design stage can be achieved using different methods but Quality Function Deployment (QFD), a method to transform user demands into design quality, and Concept Design Analysis (CODA), a method that aids the conceptual design and selection phase within new product development, have been chosen due their quantifiable nature and ability to combine with a genetic algorithm. These methods take the customer requirements and, with the input of previous boats and the knowledge of the design engineers, produces initial values for the design process as well as the overview of the boat that should be produced during the design phase. The concept design therefore follows a number of steps as follows:

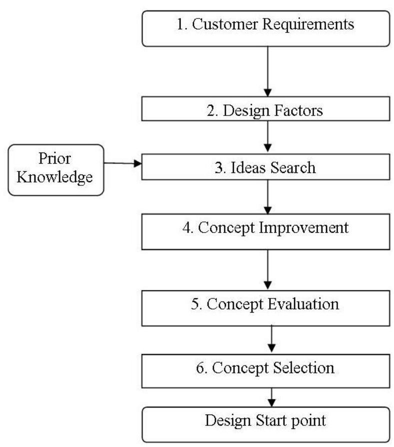

Figure 10: Concept Design Processes

1. The design must start with the goals of the project. These will come from discussion with customers about what they would like to purchase and knowledge of products of rival companies, the companys own designs and from an exploitable gap in the market.

2. Once the goals of the design have been decided the next stage is to determine the measurable quantities that are most important to the concept and to judge how

much these different quantities will affect the customer requirements that have been chosen.

3. The third step is a combination of looking at old designs, due to the evolutionary nature of boat design, and trying to include new concepts to develop ideas solving the customer goals.

4. The next stage is to improve these conceptual ideas by solving any problems associated with them or negating disadvantages that may be related to that concept. This will allow the generation of a list of potential solutions.

5. The concepts must be compared to each other to determine which of the ideas best suits the customer requirements and create the largest profit.

6. Finally a design concept must be chosen that will then be developed further.

From this point the design iteration part of the design can be started adding detail to the ideas from the concept design and quantifiable weightings can be introduced to the optimisation. The optimisation of the structure can then be used to generate an initial point for the structural design taking into account the production process.

3.2.2 Detailed Design

The stage following concept design involves a more detailed development of each subsystem. Detailed design involves an iterative process to produce the final design for the vessel. For the current method being developed the focus for the design tools has been that of the boat structures. Figure 11 covers the areas affecting the design of the hull scantlings of the boat. The detailed design section is the most time consuming in the the development of a boat. Concept design and initial design tools will help to start this design phase at a point further down the design spiral, shown in Figure 8. This will reduce the number of iterations required and hence the overall time for the design. From Figure 11 it is possible to see the different areas affecting the structural subsection, each of which are explained below:

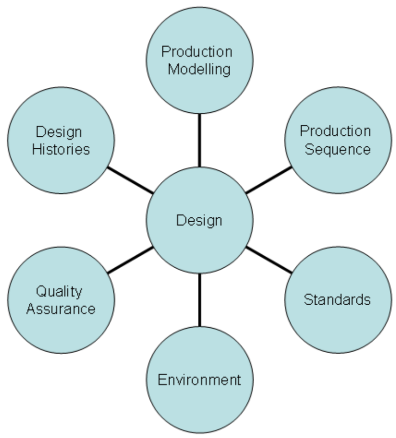

Figure 11: Design Inputs

- Production modelling - The ability to determine the potential cost benefits that could be gained from the yard if the designer changed the topology of the boat. This will require a compromise between cost efficiency, performance and aesthetics.

- Production process - The cost to change the production yard and the manner in which the boats are produced may affect the choice of volume of boats, dimensions, etc.. The production process will also play a factor in determining the maximum quality, production rate and the materials available for a given production technique.

- Standards - Standards will determine the structural topology for the boat, though standards can be substituted for first principles methods and/or reliability analysis.

- Environment - This will be the effect of the vessel, during operations, upon the environment. The pressure to become ‘green’, from legislation and customers, is growing and therefore emphasis on more environmentally friendly vessels will become important.

- Quality assurance - The quality of the design must be determined assuring the boat has a high quality design which is visually pleasing and exhibits the characteristics set by the customer requirements.

- Design histories - The previous designs developed by the company will affect the way in which new designs are created and therefore experience of advantages and disadvantages from previous designs will be important. The ability to feed this knowledge into the design phase will allow for a higher standard of design and save time.

Different subsystems must work together to form a design that fits the requirements for the vessel. Each designer will need to work with a different compliment of other boat subsystems. It is determining which subsystems will have the most impact on a designer and which other areas of the vessel the designer will have the most impact upon that will allow an optimum design. For each of the subsystems of the boat all of these important relationships will need to be determined. Once these relationships have been determined it is then possible to produce concurrent tools that focus on one section of the design but which also take into account other key sections. This approach could be followed for other subsystems but the current tools focus on structures for boat hulls, the development of which is given in more detail in Chapters 4 and 5.

3.2.3 Production Design

As has been demonstrated it is important to make sure that the production team has an input into the design stage. Most of the cost is spent at the production stage which becomes difficult to change once the design stage is completed. Designers often do not know in detail how the decisions they make will affect the costs during production or the effect they may have on the quality of the build. This is due to the relationship between the two teams where locations are often separated and communication can be minimal. Tools that predict the reaction of the production process and production engineers are key to low cost, high quality designs.

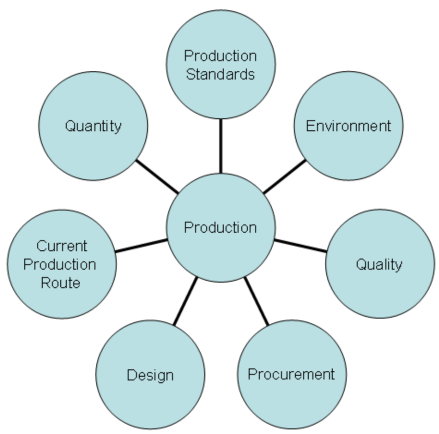

Figure 12: Production Inputs

Each of the sections in the production stage, shown in Figure 12, represent an input into the decision process and affects the choices made about the best route to take to produce a certain vessel or how expensive this route will prove to be.

- Production standards - Standards do not just apply to design. Production yards must conform to health and safety standards as well as other legislation.

- Environment - Being “environmentally friendly” during the production process is an increasingly important factor. The need to reduce emissions for better worker health and safety is another issue to be considered.

- Quality - The quality of the boat will be a key part of the production process and a compromise will need to be found between producing a large volume of cheap boats and the quality of the hulls.

- Procurement - The expense of the materials used and new materials that become available will determine the final cost of the vessel.

- Design - The design process will play a large part in the production process as the topology, layup, etc., of the boat will affect the difficulty of constructing the boat. A well thought out design will reduce the cost of production.

- Current Production route - The production route can be changed depending on the volume of boats being produced and the expense of moving equipment around the shop floor. This will also take into account previous production routes that have been used at the yard and other series of boats being produced.

- Quantity - The amount of boats that will be built affects the likelihood of using a certain production process as the equipment and the expertise may be expensive to hire but a large volume of product may make this change worth while. This value may include other boats the company is considering producing.

3.3 Design Tools

3.3.1 Introduction

To develop automated communication between the different subsystems of the design, different techniques are used to transfer this information, as can be seen in Figure 13. Further to the tools that have been developed, interactions between the main groups of people who will have input into the design have been mapped to show the inter relation between the tools and the people using them.

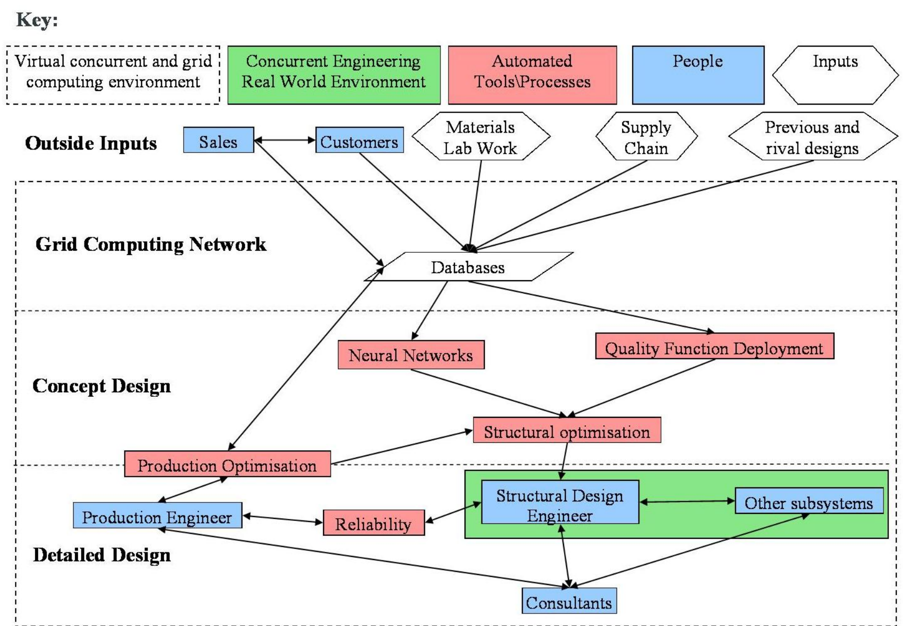

Figure 13: Design Relationships

This process starts with a number of different inputs, sales, customers, materials, supply chain and previous designs all of which can be entered into databases so that the information and data is stored for future use. From the database the concept design can start involving Quality Function Deployment as this allows opinions relating to the success of the design to be quantified. This process can be aided by the use of neural networks that can adapt the outputs based on similar successful/unsuccessful designs that have been created previously. This process can then produce weightings of importance for the design that can then be fed into an optimisation. This optimisation will model the relevant subsystems of the design and produce a viable design that adheres to the customer requirements. This optimisation will produce a starting point for the design which can then be carried out using an iterative design process between different subsystems of design to be created within the concurrent engineering environment. The iterative design process is aided by the system architecture which aims to develop a method for rapid transfer of data and information between the different subsystems. Furthermore this process is aided through the use of reliability which is used to ensure that designs are created in such a manner that there is the most room for error within the production process. A summary of the tools created for the concurrent engineering environment is given next:

- Quality Function Deployment - This technique is used within industry to gain a quantitative insight into the requirements of a customer. It therefore allows future numerical methods to utilise the requirements of the customer.

- Neural Networks - These are used to recognise and search previous designs and new parts to ensure that the iterative design stage is carried out to the best of the designers abilities.

- Structural modelling - Boat hulls that are produced must have the structural integrity to withstand operating loads. This requirement can be fulfilled using first principles methods combined with failure criteria, reliability methods, safety factors or classification societies.

- Production Modelling - It is of key importance for the design and the success of businesses that any design produced is able to be built with the lowest cost possible. Production models allow each design to be costed accurately determining the effect different design decisions make.

- System Architecture - The ability to communicate between subsystems is of key importance and it is down to the system architecture of the design systems to ensure that this process is as rapid and efficient as possible.

- Optimisation - The use of genetic optimisation combined with Classification Society rules or first principles methods has been used to develop a compromise between different designs.

- Reliability - Using composite materials it is of key importance that modelling is carried out to reflect the variability inherent within the materials themselves. Reliability ensures an understanding of the variability in the materials.

3.3.2 Structural Modelling Tool

The structural modelling tool has been developed to work with both the optimisation and the reliability tools. It is this modelling that will try and replicate the knowledge of a designer during the design process. This tool has been developed using a first principles approach including Navier Grillage theory, elastic equivalent properties, Third Order Shear Deformation Theory and a number of different failure criteria to constrain the problem. Grillage theory works upon the basis that all of the stresses within the plate are transferred to the stiffeners therefore Third Order Shear Deformation theory is required to ensure that the panel thickness between the stiffeners is large enough to support these pressures. The failure criteria to which these stresses are compared have been selected from the recommendations of the World Wide Failure Exercise [83]. The materials compared were a selection of different composite fibres and resins that could have layups at different angles and with different numbers of plys.

3.3.3 Multiobjective Optimisation Tool

The multiobjective optimisation tool is developed as a link between the concept design and the detailed design sections of the process. The tool will allow the ability to use the concept design weightings and some of the values that have been developed to create an optimised topology for the stiffened plate. The multiobjective optimisation has been performed using a genetic algorithm between the cost and the mass of the plate. A further addition to this algorithm has been Quality Function Deployment that has been used to provide the objective weightings for the genetic algorithm and hence provide a design orientated algorithm that will provide a link between customer requirements through to the initial stages of detailed design. The results from this optimisation can then be developed further through compromise with other subsystems.

3.3.4 Reliability Analysis Tool

The reliability analysis tool has been developed for two reasons. The first is to allow an understanding between the effects that changes in the design will make to either production or the structure. The second is to try and develop a reliability based approach for structural design. The reliability analysis has been carried out using a Monte Carlo simulation. This method simulates creating many plates and evaluating them against a set criteria using modelling techniques. This process has been carried out for both structural and production models in an attempt to determine the factors that most affect these outputs and furthermore allow designs that create reliable structures.

3.3.5 Concurrent Engineering Environment

The concurrent engineering environment has been written by the author to allow all designers to interact with each other and the design tools. The aim of this environment is to allow the maximum communication to occur between members of the design team. The development of the concurrent engineering tool has included collaborative engineering between different companies in an effort to develop the most up-to-date technologies with low cost. This environment consists of two main areas: one for transporting the data, defined here as quantitative knowledge associated with the design, and the second for information, knowledge about the design in a qualitative state. Further to these areas neural networks have been capitalised to ensure that previous designs are taken into account during the design process. Finally, grid computing has been utilised to allow fast computations to create shared databases on materials and products so that the entire industry can have up-to-date and accurate knowledge of the associated technologies and supply chain.

3.4 Summary

A method for boat design has been developed for use within concurrent boatbuilding design. The section of this design process related to structural design and production has been expanded upon and tool frameworks developed to show the possibilities available within the concurrent engineering framework. Areas of input into these stages have been developed for both structural and production engineers. The design method has then been inter-related to people and companies outside of these two subsystems. The environment aids the communication throughout the design process. Chapter 4 goes on to discuss the methods for modelling structures for composite boat hulls.

4 Structural Modelling Tool

4.1 Introduction

Structures are an important part of the design process as it is the determination of the topology of a boat which will ensure that the conditions encountered can be withstood yet also determine the mass, hence the emissions, and performance of a boat when in service. Classification society rules are the main method of boat design within yards and therefore both ISO 12215-5 and Lloyd's Register Rules for Special Service Craft have been modelled. Further to this first principles modelling has been extended from Maneepan [3], through the addition of more stringent failure criteria and reliability investigations to continue the development of a model that will allow for investigation into lighter, more efficient craft.

For the development of the first principles rules, Navier grillage theory will be used in association with elastic equivalent properties to model the stiffeners within the boat hull. The plates between these stiffeners have been modelled using third order shear deformation theory to allow complex layups to be modelled accurately. Finally the model has been constrained using failure criteria from the World Wide Failure Exercise, a maximum deformation criteria and a buckling criteria for the stiffeners.

4.2 Grillage Method

4.2.1 Navier Grillage Theory

The grillage analysis uses the Navier summations of points within the grillage to develop the deflection of the stiffeners, and hence the stresses, the topology of which is shown in Figure 14.

In the verification at the end of this chapter, the results reported in Chapters 8 to 11,

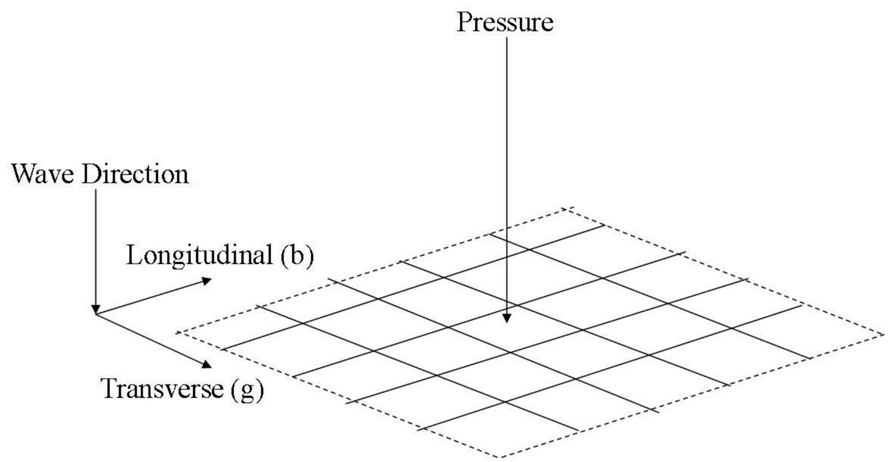

Figure 14: Grillage topology

and the optimisation, presented in Chapter 5, the values of the wave numbers, m and n, have been kept at 11 as this gave fast computational times while being very close to the point of convergence. The equation giving deflection of the stiffened plate can be seen in Eq.32 and is a double summation dependent on the wave numbers

$$w(x, y) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} a_{mn} \sin \frac{m\pi x}{L} \sin \frac{n\pi y}{B} \tag{32}$$

where the value of a_{mn} is a coefficient found from Eq.33. The coefficient a_{mn} is dependent on the flexural rigidities in each beam or girder (D_s) found from Eq.46 as part of the elastic equivalent properties.

$$a_{mn} = \frac{16PLB}{\pi^6 mn \left\{ m^4(g+1)\frac{D_g}{L^3} + n^4(b+1)\frac{D_b}{B^3} \right\}} \tag{33}$$

Each coefficient a_{mn} is found based on the assumption that the change in potential energy from the deflection will be a minimum. From the deflection curve of the q^{th} beam and p^{th} girder, where $x_q = qL/(b+1)$ and $y_p = pB/(g+1)$ are constants to investigate the deflections along the specified beam, it is possible to show the strain energy, V:

$$V = \int_0^L \frac{D_g}{2}\left(\frac{\partial^2 w}{\partial x^2}\right)^2_{y=y_p} dx + \int_0^B \frac{D_b}{2}\left(\frac{\partial^2 w}{\partial y^2}\right)^2_{x=x_q} dy \tag{34}$$

The work done on the grillage can be shown to be:

$$\int_0^L \int_0^B P \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} a_{mn} \sin\frac{m\pi x}{L} \sin\frac{n\pi y}{B} dxdy \tag{35}$$

Minimising the potential energy ($\partial V/\partial a_{mn}$) and equating it to the work done it is then possible to find a_{mn} in Eq.33. The moments can be found in the beams or girders (M_s) from Eq.36:

$$M_s = -D_s\frac{\partial^2 w}{\partial x^2} \tag{36}$$

The shear force can also be found for the beams and girders Q_s from Eq.37

$$Q_s = \frac{\partial M_s}{\partial x} \tag{37}$$

Finally, using the maximum moments and shear force in the grillage the maximum stress σ_{max} and shear stress τ_s can be determined as shown in eqs. 38 and 39, where $E_{s(i)}$ is the longitudinal modulus of elasticity of the element of a stiffener, M_s is the moment created in the stiffener, d_{na} is the vertical distance of the centroid of an element to the neutral axis, D_s is the structural rigidity of a stiffener and Q_s is the shear force in the stiffener:

$$\sigma_{max} = \frac{E_{s(i)} M_s d_n a}{D_s} \tag{38}$$

$$\tau_s = \frac{E_{s(i)} Q_s}{D_s}\int_0^s d_{na} ds \tag{39}$$

4.2.2 Elastic Equivalent Properties

It is possible to determine the reduced stiffness terms (Q_{ij}) from the elastic properties in each ply of each element, shown in Figure 15 where E_1,E_2,υ_{12},υ_{21} and G_{12} are the properties of the material in each element, i,

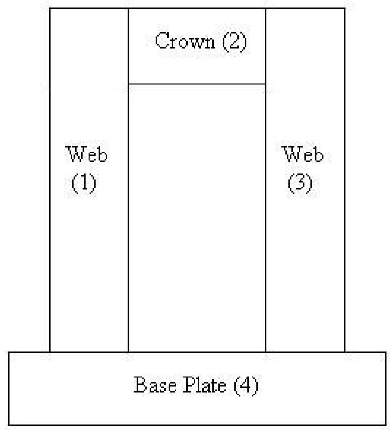

Figure 15: Stiffener element names and numbers

$$Q_{11} = \frac{E_1}{1-\upsilon_{12}\upsilon_{21}}, \quad Q_{22} = \frac{E_2}{1-\upsilon_{12}\upsilon_{21}}, \quad Q_{12} = \frac{\upsilon_{21}E_1}{1-\upsilon_{12}\upsilon_{21}}, \quad Q_{66} = G_{12} \tag{40}$$

From these values it is then possible to calculate the transformed reduced stiffness terms ($\bar{Q}_{ij}$) for each ply, depending on the angle of the ply specified, where θ is the angle of each ply of each element:

$$\bar{Q}_{11} = cos^4\theta Q_{11} + sin^4\theta Q_{22} + 2cos^2\theta sin^2\theta Q_{12} + 4cos^4\theta sin^2\theta Q_{66} \tag{41}$$

$$\bar{Q}_{12} = cos^2\theta sin^2\theta Q_{11} + cos^2\theta sin^2\theta Q_{22} + (cos^4\theta + sin^4\theta)Q_{12} - 4cos^2\theta sin^2\theta Q_{66} \tag{42}$$

$$\bar{Q}_{22} = sin^4\theta Q_{11} + cos^4\theta Q_{22} + 2cos^2\theta sin^2\theta Q_{12} + 4cos^4\theta sin^2\theta Q_{66} \tag{43}$$

The laminate stiffness terms for each element can then be found by summing the transformed reduced stiffness terms for each of the plies where t_k is the thickness of each ply of each element:

$$A_{ij} = \sum_{k=1}^{N} t_k(\bar{Q}_{ij})_k \tag{44}$$

The Young's modulus for the material can then be found for each element of the stiffener:

$$E_i = \frac{(A_{11}A_{22} - A_{12}^2)}{A_{22}t} \tag{45}$$

It is then possible to find the flexural rigidity of the stiffener (D_g,D_b), in either the longitudinal or transverse directions, from the following equation:

$$D_g = \sum_{i=1}^{N_g} E_{g(i)} I_{g(i)} \quad D_b = \sum_{i=1}^{N_b} E_{b(i)} I_{b(i)} \tag{46}$$

Finally it is also possible to find the second moment of area for each element of the stiffener using Eq.47. Where $I_{cx(i)}$is the moment of inertia of each element about its own neutral axis, $a_{(i)}$ is the area of each element and $d_{na(i)}$ is the distance of the elements cross section to the beam or girders neutral axis:

$$I_{(i)} = I_{cx(i)} + a_{(i)}d_{na(i)}^2 \tag{47}$$

The flexural rigidity found using stress analysis can then be used to determine the stresses in the stiffeners using the Navier grillage method.

4.3 Third Order Shear Deformation Theory

Grillage methods find the maximum stresses in the stiffeners by assuming that the entire load is passed through to the stiffening members. It is also important to make sure that the plates of the hull are thick enough to withstand the expected loads. This can be performed computationally inexpensively using classical laminate plate theory and first order shear deformation theory for single plies. As more layers are required it is necessary to use higher order shear deformation theories but these are computationally more expensive. Plate analysis has been calculated using third order shear deformation theory [84] to determine the stresses and strains required for the failure criteria as this will allow the full benefits of using different layups in the material to be used.

First the boundary conditions for a plate can be defined from Eqs.48 to 52:

$$u_0(x,y) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} U_{mn} \cos \alpha x \sin \beta y \tag{48}$$

$$v_0(x,y) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} V_{mn} \sin \alpha x \cos \beta y \tag{49}$$

$$w_0(x,y) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} W_{mn} \sin \alpha x \sin \beta y \tag{50}$$

$$\phi_x(x,y) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} X_{mn} \cos \alpha x \sin \beta y \tag{51}$$

$$\phi_y(x,y) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} Y_{mn} \sin \alpha x \cos \beta y \tag{52}$$

where each value (U_{mn}, V_{mn}, W_{mn}, X_{mn} and Y_{mn}) is a coefficient that must be determined from Eq.55, $\alpha = \pi m/L$ and $\beta = \pi n/B$. The vertical forces at each point on the plate, q(x,y), are determined from Eq.53:

$$q(x,y)=\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}Q_{mn}\sin\alpha x\sin\beta y \tag{53}$$

where Q_{mn} is the lateral loading on the plate and is given by:

$$Q_{mn}(z)=\frac{4}{LB}\int_0^L\int_0^B q(x,y)\sin\frac{m\pi x}{L}\sin\frac{n\pi y}{B}dxdy \tag{54}$$

It is then possible to find the coefficients of the boundary conditions using the stiffness matrix [C] by substituting Eqs.48 to 54 into the equations of motion.

$$[C][\Delta]=\begin{vmatrix}0\\0\\Q_{mn}\\0\\0\end{vmatrix} \qquad [\Delta]=\begin{vmatrix}U_{mn}\\V_{mn}\\W_{mn}\\X_{mn}\\Y_{mn}\end{vmatrix} \tag{55}$$

Where $Q_{mn}=-\frac{16q_0}{\pi^2 mn}$ for uniform loading and q_0 is the load on the plate. The stiffness matrix [C], found from Eq.58, can be used to show the relation between the stress resultants and the strains:

$$\begin{vmatrix}\{N\}\\\{M\}\\\{P\}\end{vmatrix}=\begin{vmatrix}[A]&[B]&[E]\\ [B]&[D]&[F]\\ [E]&[F]&[H]\end{vmatrix}\begin{vmatrix}\{\epsilon^{(0)}\}\\\{\epsilon^{(1)}\}\\\{\epsilon^{(2)}\}\end{vmatrix} \tag{56}$$

$$\begin{vmatrix}\{Q\}\\\{R\}\end{vmatrix}=\begin{vmatrix}[A]&[D]\\ [D]&[F]\end{vmatrix}\begin{vmatrix}\{\gamma^{(0)}\}\\\{\gamma^{(2)}\}\end{vmatrix} \tag{57}$$

The values relating to this matrix [C] can be found from the use of Eq.58

$$(A_{mn},B_{ij},D_{mn},E_{ij},F_{mn},H_{ij})=(\bar{Q}_{ij},\bar{Q}_{mn})(1,z,z^2,z^3,z^4,z^6)dz$$

$$(i,j=1,2,6),\ \ (m,n=1,2,4,6) \tag{58}$$

It is then possible to determine the values of the strains from the displacement relations.

$$\left|\begin{matrix}\{\epsilon_{xx}\}\\ \{\epsilon_{yy}\}\\ \{\gamma_{xy}\}\end{matrix}\right| = \left|\begin{matrix}\frac{\partial u_0}{\partial x}+\frac{1}{2}\left(\dfrac{\partial w_0}{\partial x}\right)^2\\ \frac{\partial v_0}{\partial y}+\frac{1}{2}\left(\dfrac{\partial w_0}{\partial y}\right)^2\\ \frac{\partial u_0}{\partial y}+\frac{\partial v_0}{\partial x}+\frac{\partial w_0}{\partial x}\frac{\partial w_0}{\partial y}\end{matrix}\right| + z\left|\begin{matrix}\frac{\partial \phi_x}{\partial x}\\ \frac{\partial \phi_y}{\partial y}\\ \frac{\partial \phi_x}{\partial y}+\frac{\partial \phi_y}{\partial x}\end{matrix}\right| + z^3\left|\begin{matrix}-c_1\left(\dfrac{\partial \phi_x}{\partial x}+\dfrac{\partial^2 w_0}{\partial x^2}\right)\\ -c_1\left(\dfrac{\partial \phi_y}{\partial y}+\dfrac{\partial^2 w_0}{\partial y^2}\right)\\ -c_1\left(\dfrac{\partial \phi_x}{\partial y}+\dfrac{\partial y}{\partial x}+2\dfrac{\partial^2 w_0}{\partial x\partial y}\right)\end{matrix}\right| \tag{59}$$

$$\left|\begin{matrix}\{\gamma_{yz}\}\\ \{\gamma_{xz}\}\end{matrix}\right| = \left|\begin{matrix}\phi_y+\frac{\partial w_0}{\partial y}\\ \phi_x+\frac{\partial w_0}{\partial x}\end{matrix}\right| + z^2\left|\begin{matrix}-c_2\left(\phi_y+\dfrac{\partial w_0}{\partial y}\right)\\ -c_2\left(\phi_x+\dfrac{\partial w_0}{\partial x}\right)\end{matrix}\right| \tag{60}$$

= The stresses and strains then allow the use of failure mechanisms to determine whether a given thickness of plate will fail.

4.4 Failure Criteria

Further to previous work reported by Sobey [85] failure criteria have been added to the model to more accurately model the behaviour of the composite materials. The failure criteria used came from the 'World Wide Failure Exercise' (WWFE) [86], [87] and [88]. The choice made for each failure type can be seen from Table 9 and was based upon the findings of the World Wide Failiure Exercise. In the cases where a choice could be made between a conservative and unconservative estimate it has been decided to use a conservative estimate. This will lead to thicker hull designs but will ensure the safety of the vessel and therefore allows a fair comparison with classification society rules. Different methods have been compared by Soden [83]. The use of the three methods ensures that at least one of the proposed failure criteria for each type of failure has been used and these have been outlined in the World Wide Failure Exercise [83] and included in Table 9.

Table 9: Failure Criteria

Failure Type	Criteria
Predicting the response of lamina	Puck [89], [90] and Tsai [91], [92]
Predicting final strength of multidirectional laminates	Puck
Predicting the deformation of laminates	Zinoviev [93], [94] and Puck

The exercise concluded that in the case of buckling criteria that they 'did not address the prediction of buckling modes of failure' [83]. Buckling is a key part of failure in hull stiffeners and therefore an Euler based rule, seen in equation 61, where the crown and web are assumed to be taken as clamped at both ends has been used to constrain the model for both the crown and the webs and is taken from [95].

$$\sigma_{cri,web} = \frac{6.97\pi^2 E_s}{12(1-\upsilon_{12}^2(d_s/c_s)^2)}, \quad \sigma_{cri,crown} = \frac{6.97\pi^2 E_s}{12(1-\upsilon_{12}^2(a_s/b_s)^2)} \tag{61}$$

Furthermore an arbitrary deflection criteria of 10% of the length has been included to ensure that materials with a low stiffness and cost can not be selected without creating a thicker topology.

4.4.1 Puck Failure Criteria

The Puck failure criteria is based upon 3-D phenomenological models, which are based on real life occurances. The method is a composite laminate theory method which is nonlinear to solve. The Puck method is recommended by the World Wide Failure Exericse to be used for predicting strength of unidirectional laminae and this method has been used as it gives a more conservative view for the failure of the laminates. Puck's formulation is also used for predicting the initial strength of multidirectional laminates as other methods did not predict the failure very well. Puck is further recommended to be used to predict final strength of multidirectional laminates.

Table 10: Puck failure criteria

Fibre failure in tension	$\frac{1}{\epsilon_{1T}}\left(\epsilon_1 + \frac{v_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right) = 1$
Fibre failure in compression	$\frac{1}{\epsilon_{1C}}\left\|\left(\epsilon_1 + \frac{v_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right)\right\| = 1 - (10\gamma_{21})^2$
Inter-fibre failure mode A (for transverse tension)	$\sqrt{\left(\frac{\tau_{12}}{S_{12}}\right)^2 + \left(\rho_{\perp\parallel}^{(+)}\frac{Y_T}{S_{21}}\right)^2 + \left(\frac{\sigma_2}{Y_T}\right)^2} + \rho_{\perp\parallel}^{(+)}\frac{\sigma_2}{S_{12}} = 1 - \frac{\sigma_1}{\sigma_{1D}}$
Inter-fibre failure mode B (for moderate transverse compression)	$\frac{1}{S_{21}}\left(\sqrt{\tau_{21}^2 + \left(\rho_{\perp\parallel}^{(-)}\sigma_2\right)^2}\right) + \rho_{\perp\parallel}^{(-)}\sigma_2 = 1 - \frac{\sigma_1}{\sigma_{1D}}$
Inter-fibre failure mode C (for large transverse tension)	$\left[\left(\frac{\tau_{21}}{2\left(1+\rho_{\perp\perp}^{(-)}\right)S_{21}}\right)^2 + \left(\frac{\sigma_2}{Y_C}\right)^2\right]\frac{Y_C}{(-\sigma_2)} = 1 - \frac{\sigma_1}{\sigma_{1D}}$

4.4.2 Zinoviev Failure Criteria

The Zinoviev failure criteria is based on the development of maximum stress theory. This method is based on composite laminate theory and has a linear solution. Zinoviev is recommended by the World Wide Failure Exercise to predict the deformation of laminates along with a non-linear method such as Puck.

Table 11: Zinoviev failure criteria

Longitudinal tension failure	$\sigma_1 = X_T$
Longitudinal compressive failure	$\sigma_1 = X_C$
Transverse tensile failure	$\sigma_2 = Y_T$
Transverse compressive failure	$\sigma_2 = X_C$
In-plane shear failure	$\tau_{12} = S_{12}$

4.4.3 Tsai Failure Criteria

The Tsai failure criteria is developed through an interactive progressive quadratic failure criterion. This method is also based on composite laminate theory and is linear in its solution. The Tsai failure criteria are used in conjunction with Puck to determine the response of lamina. The Tsai failure criteria is the best fit to the test data reported in Soden [83] for the behaviour of the laminates. This criterion underestimates the failure stress at given points and so the Puck failure criterion can be used to check that failure does not occur.

$$\left(\frac{\sigma_1}{X_T X_C}\right)^2+\left(\frac{\sigma_2}{Y_T Y_C}\right)^2+\left(\frac{1}{X_T}-\frac{1}{X_C}\right)\sigma_1+\left(\frac{1}{Y_T}-\frac{1}{Y_C}\right)\sigma_2+\left(\frac{2F_1 2\sigma_1\sigma_2}{\sqrt{X_T X_C Y_T Y_C}}\right)+\left(\frac{\tau_{12}}{S_{12}}\right)^2=1 \tag{62}$$

4.5 Classification Society Rules

Classification society rules are the main rules for structural design of hulls used within the boatbuilding community. These rules are based upon first principles and have been developed from years of experience. They use safety factors reduce the likelihood to an acceptable level. It is premised that these rules are overly conservative and create hull forms that are more massive than is required for the environmental actions faced during their service lives.

4.5.1 Lloyd's Register

Lloyd's Register Rules for Special Service Craft is a classification society rule developed for craft over 24m in length. The rules have a specific set for development of composite structures. The rules allow for new materials to be used once the required mechanical properties that have been found from experiment.

Determination of the structures are based on defining the boat characteristics and the environment that it is expected that it will be operating in. This can be used to produce a pressure value dependent upon the position of the panel within the hull form. The panel thickness is then defined using this pressure and the distance seperating the stiffeners. The stiffener geometry itself is determined from minimum thickness failure critera and determination of the stress encountered. These can be compared to stress limits and deflection limits dependent upon the position of the panel and the pressure.

4.5.2 ISO 12215-5

ISO 11215-5 is a new standard for scantling determination developed for recreational craft under 24m. These rules also have a specific section for composite materials. ISO 12215-5 also allows determination of materials through testing and as such the same properties have been used as for the first principles models.

The determination of the structures using ISO 12215-5 is similar to that for Lloyd's Register Rules. The pressure is determined from the conditions and the characteristics of the boat. The panel thickness is determined from the pressure, the stiffener spacing and the expected stress which allows for a less conservative estimate of the hull thickness. The stiffeners are determined through assessing the stresses found to ensure that they are of a size that will withstand these loads and the web area and section modulus but are further constrained by ratio limits between sections of the stiffeners.

4.6 Structural Verification

4.6.1 Grillage Verification

Verification of the first principles structural analysis method was carried out to ensure that elastic stress theory would create reasonable correlation with experimental results. The results from the grillage method have been compared to those found in Clarkson [10], using folded plate method, for a panel with a length and width of 3180 mm. The panel consisted of 4 transverse beams and longitdinal girders with dimensions 254 mm deep 127 mm wide with 18.288 mm thick flanges and 9.144 mm thick webs and a pressure of 137.9 kPa was applied to each panel. The results are presented in Table 12 with a comparison with the work of Maneepan, Navier Grillage, to allow verification that the values gained from the code were correct.

Table 12: Verification of Navier method grillage analysis - Stress

Property	Clarkson [10]	Maneepan [3]	Sobey
Deflection	9.63 mm	9.93 mm	9.87 mm
Stress	165.52 MPa	171.19 MPa	170.13 MPa

These results were obtained with a wave number of 11. This is not the lowest value of wave number for solution convergence, but is high enough to allow more complicated grillages time to converge as can be seen in Figure 16.

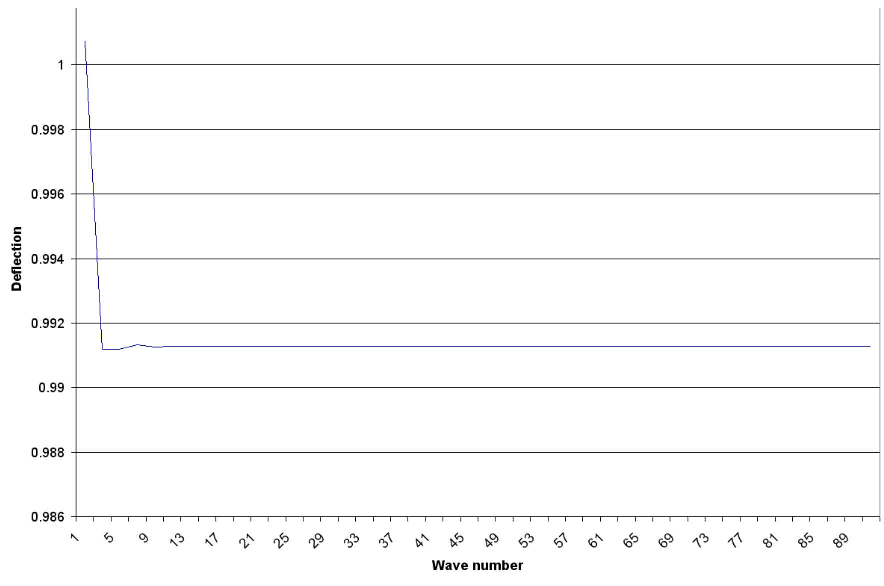

Figure 16: Determination of the convergence point for Navier Grillage theory

These values were found to be close to results calculated by Maneepan in and are similar to Clarkson's, grillage, which was also compared to experiment but remains slightly conservative. The Navier grillage method was used for the stiffener modelling.

A verification of the shear stress has been made by performing calculations to create a comparison with a rectangular box beam found in Datoo [96]. The web height is 50 mm and the flange widths are 200 mm. The Young's modulus of the flanges are 54.1 kN/mm^2. The Young's modulus of the web is 17.7 kN/mm^2. A shear force of Q= 10 kN is found in the stiffeners. The thickness of the flanges are 1.0 mm and the thickness of the web is 0.5 mm. τ_1 is the shear stress at the corner of the crown element, τ_2 is the shear stress at the N.A. of the cross section.

These values had no deviation from the results found in Maneepan and there is only a small deviation found compared to the results found in Datoo. It is therefore considered

Table 13: Verification of Navier method grillage analysis - Shear Stress

Property	Datoo [96] (MPa)	Maneepan [3] (MPa)	Sobey (MPa)
τ_1	99	98.72	98.72
τ_2	101	102.76	102.76

that the grillage theory is capable of calculating the shear stress.

Finally the elastic equivalent properties were compared to Datoo [96] using lamina properties E_1= 140 kN/mm^2, E_2= 10 kN/mm^2, G_{12}= 5 kN/mm^2, υ_{12}= 0.3 and a ply thickness= 0.125 mm for each of the 8 plies all having a 0° ply angle where the result was identical to Datoo's value of 140 GPa.

4.6.2 Third order Shear Deformation Theory Verification

For the verification of Third order Shear Deformation Theory a layup of [0/90] has been used with simply supported boundary conditions. The length to width ratio (L/B) of the plate is equal to 1.0 and the length to thickness ratio (L/t) is varied. The material properties are E_1= 175 GPa, E_2= 7 GPa, G_{12}= G_{13}= 3.5 GPa, G_{23}= 1.4 GPa, and υ_{12}= υ_{13}= 0.25. The load acting on the plate is q_0= 50 kPa for Eqn 53 and Q_{mn}. This produces the nondimensionalised values for the deflection, $\bar{w}$, given in Table 14 where the nondimensionalising factor is $w_0 \frac{E_2 h^3}{B^4 q_0}$.

These values can be expanded upon in Figure 17 to show the effect of the change in thickness on the value of the deflection.

A wave number of nine has been selected for use within the verification and the optimisations. Table 18 shows the convergence of the third order shear deformation theory with varying wave number and it is possible to see that a wave number of nine

Table 14: Verification of Third Order Shear Stress Deformation theory (TSDT)

L/t	Reddy($\bar{w} \times 10^2$)	TSDT($\bar{w} \times 10^2$)
10	1.0219	1.0102
20	0.7572	0.7546
100	0.6697	0.6696

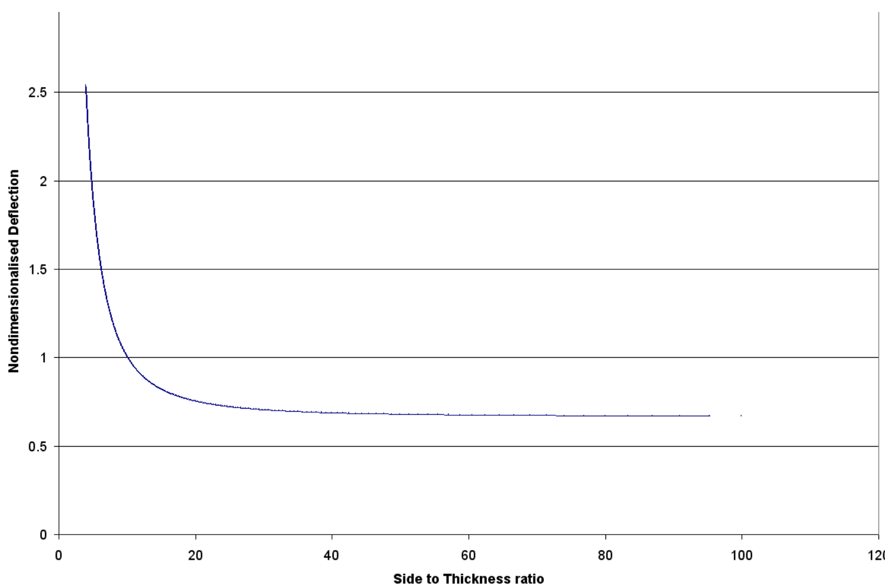

Figure 17: Verification of Third order Shear Deformation Theory

produces convergent results.

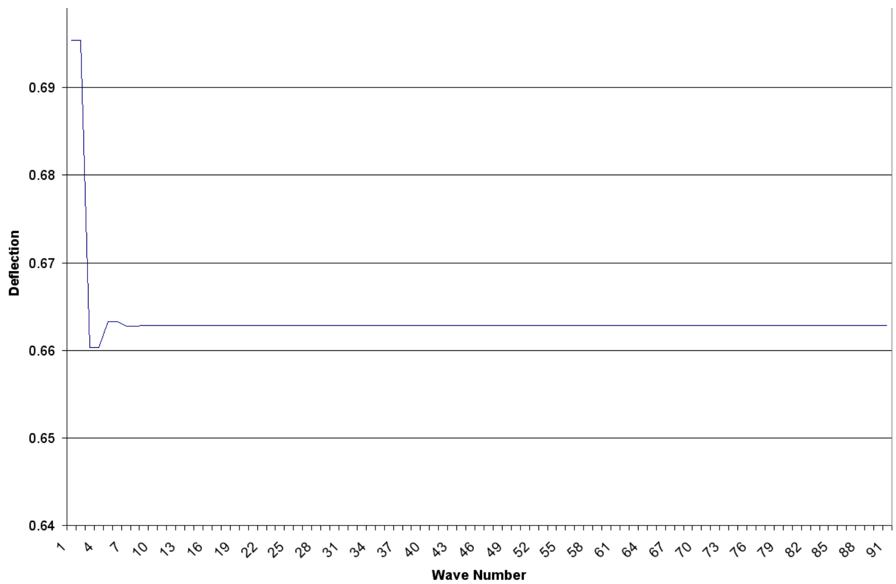

Figure 18: Third order Shear Deformation Theory point of convergence

From the verification of the third order shear deformation theory it is possible to see that the results have at most a 1% deviation from those given in Reddy at a value for the wave numbers of nine showing Third order Shear Deformation Theory has been modelled accurately.

4.6.3 Failure Criteria Verification

The failure criteria code have been validated against the original criterion to ensure that they are working correctly. The Puck failure criteria has been compared to that of Puck [90] and the results can be seen in Figure 19. The Zinoviev failure envelope can be seen in Figure 20 and can be compared to that seen in Zinoviev [94]. The envelope for the Tsai failure envelope can be seen in Figure 21 and can be compared with that seen in

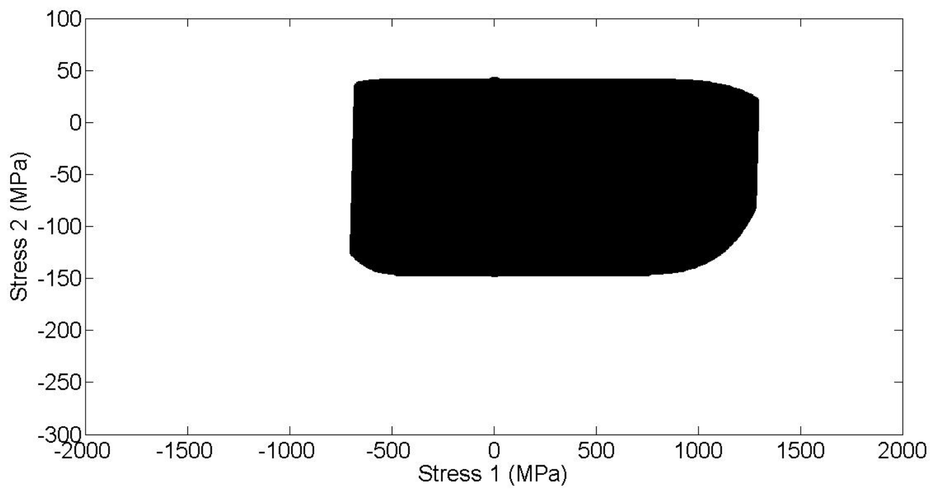

Figure 19: Failure envelope for Puck failure criteria

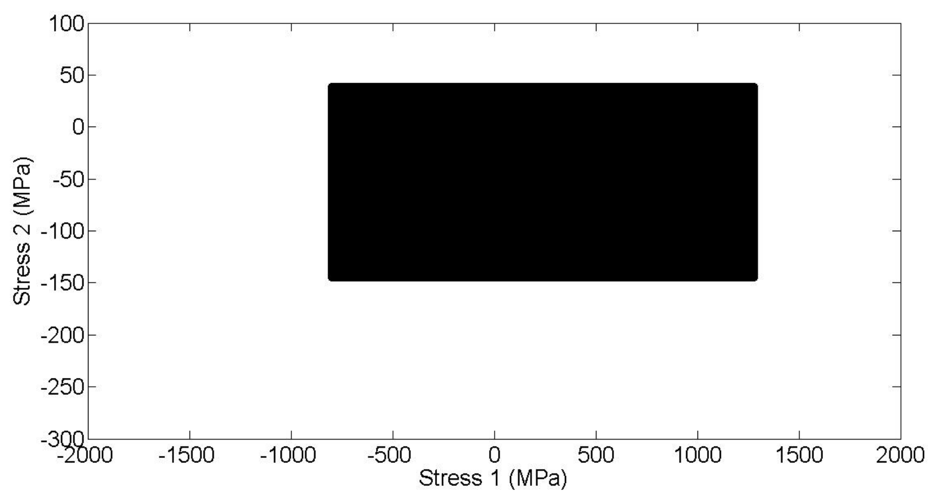

Figure 20: Failure envelope for Zinoviev failure criteria

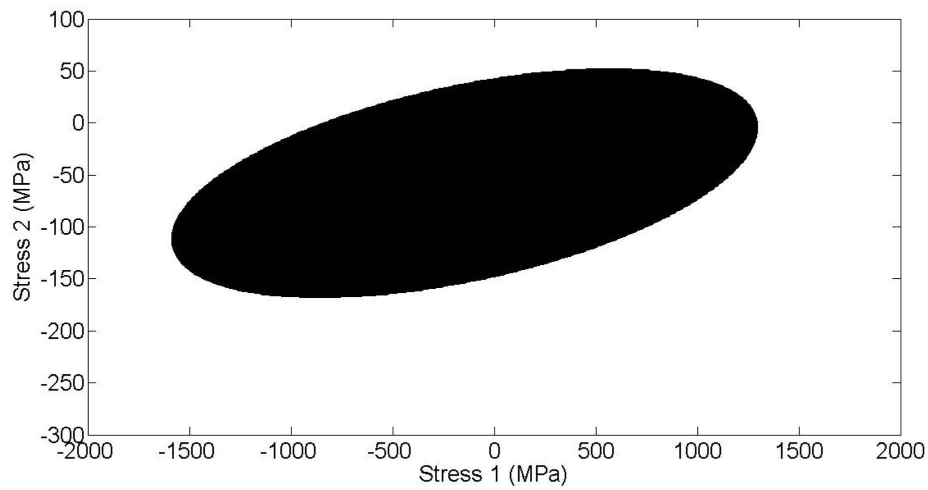

Figure 21: Failure envelope for Tsai failure criteria

Tsai [92]. From all of these plots it can be seen that the criteria give a good correlation with the original results. Finally an amalgamation of the chosen failure criteria can be seen in Figure 22. The failure criteria shown match those given in the original papers. The combined total gives a criteria that covers all of the stress values given by experiments but remains a conservative estimate. All the failure criteria have therefore been used to constrain the results using the first principles method.

4.7 Summary

This chapter has outlined a structural model to determine the stress and deflection within a flat composite panel subject to out of plane loading. This model includes a computationally inexpensive grillage analysis and third order shear deformation for the plate analysis. These techniques have been used within optimisation processes, outlined in Chapter 5, to allow for the determination of panels that have the lowest cost and mass for their applications. Verification of these models has been included in Chapter 8. The next chapter

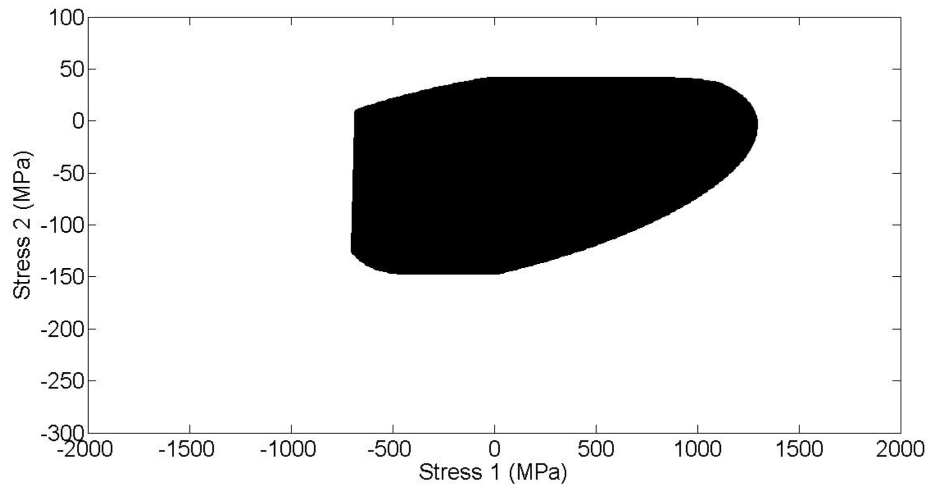

Figure 22: Failure envelope for combined total failure criteria

shows the development of the techniques that have been applied for optimisation.

5 Multiobjective Optimisation Tool

5.1 Introduction

The process of design is a compromise between the different characteristics that are required for the successful operation of the product. The optimum design is one in which the input variables create characteristics that best map those required. In the interest of the research presented herein multiobjective optimisation has been investigated within structural design for production using genetic algorithms for use within the boatbuilding industry.

5.2 Genetic Algorithm

A genetic algorithm has been developed to find the optimum compromise between mass and cost in hull topology of composite boats. The cost has been found from a production model developed using parametric cost modelling. The mass was found from the topology of the stiffeners and the properties of the materials being used. The final factor was that of meeting the criteria of structural integrity which has been developed using both classification society rules and first principles, including the failure criteria outlined in Chapter 4.

Genetic algorithms perform the process of optimisation using Darwin's theory of evolution. Using this method an objective function is developed. This function determines the fitness with which a solution fits the "customer objectives", for example, as an analogy in nature, the ability to avoid predators. The function will be determined from outputs from a model, for example the ability to run and climb trees to escape predators. These outputs will be reliant upon inputs given into the models, for instance the height and weight of an animal. The inputs can be controlled by strings of code, equivalent to DNA, which will determine the object's properties, in this example the height and weight. The overall fitness is therefore dependent upon a number of outputs which are all dependent upon a number of inputs. In this example the ability to avoid predators may be dependent upon the ability to run and climb trees which are themselves dependent upon the abilities of the animal, to climb, such as height and weight. These dimensions are determined from the strings of code. In each generation a number of strings are generated, representing a number of different parents. Each generation is determined from the previous one, based on survival of the fittest. This is performed by crossing over the strings and creating mutations as can be seen in Figure 5. Crossover means that the strings are split and a section of the string is transferred to a corresponding section of a different string analogous to "conception". In return the same section of the second string is transferred to the first leaving two new strings. Mutation is when one piece of the string can be randomly transformed changing the values of the string. The fittest offspring are used to generate the next generation and this makes sure that the search is clustered around the optimum areas. These techniques ensure that the entire search space is investigated and not just current areas of interest. As the algorithm runs the best overall dimensions can be determined as the combinations are compared and the fittest dimensions for the function are finally found.

The weighting for the genetic algorithm consists of all of the outputs to be optimised. These values must be summed to develop a function value representing how fit an output is for the inputs chosen. The highest values will then be selected as the elite input for that generation. All values being minimised will be the reciprocal of the function value. Function values to be minimised will usually be much smaller than the values to be maximised. To allow these function values to have an equal share in the optimisation it is important to ensure all of the function values have a similar order of magnitude. Some design objectives will also be more important to the design than others. The importance of the variables are normally decided in the concept design element of the design, based on customer requirements and design objectives. As the structural optimisation examples used in Chapters 8 to 10 have not been part of a design process it has been decided to make mass and cost equally important for verification purposes. The equation for the final weighted function is Eq.63 where p_n is importance of the variable, w_n is weighting of the variable, and X_n is a variable output. It is

$$W = \sum_{n=1}^{n} p_n w_n X_n \tag{63}$$

The genetic algorithm was organised into an embedded algorithm, shown in Figure 23 with the first optimising the stiffener spacings, material type, number of plies and ply angles. The second algorithm produces the stiffener topology which is the base and crown widths, plate thickness, crown height, web thickness and web height. For each stiffener spacing, material and ply angle the best stiffener topology can be found and these optimum plates can be compared.

The genetic algorithm chracteristics were developed as shown in Table 15.

Table 15: Genetic Algorithm Characteristics

Generations	200
Strings	100
Mutation Rate	0.002
Crossover Rate	0.65
Selection Method	Tournament
Crossover Method	Uniform

The different properties can vary between different constraints, as listed in Table 16,

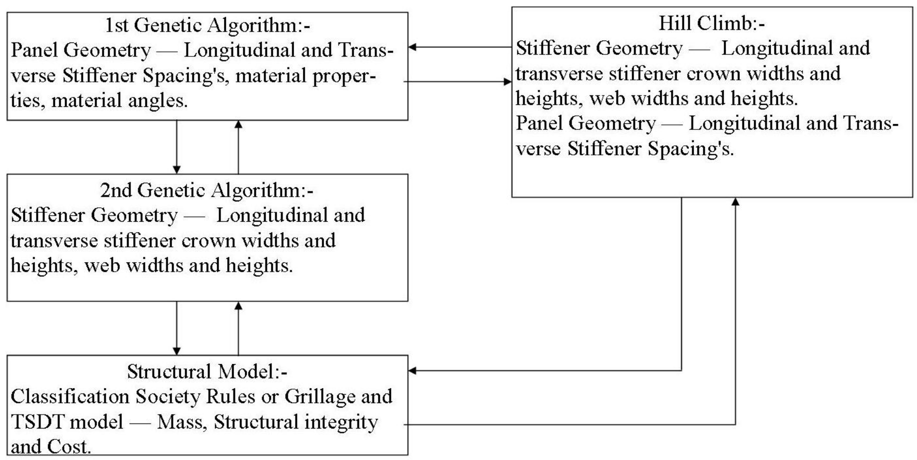

Figure 23: Embedded Algorithm

and these values have been chosen to effectively unconstrain the problem.

5.3 Direct Method

Due to the nature of how genetic algorithms work the optimisation may not always reach its global optimum value, it will give a result close to this point. To speed the process of optimisation and succeed in reaching the global optimum, direct methods can be used after the genetic algorithm. The author employs hill climbs as this is a simple method for the computations to reach the optimum result. The hill climb is carried out by varying each of the model inputs first positively then negatively. If the output of these values leads to a higher fitness function this new value for the input is used. If a lower result is found then the value is reset and the next input variable is changed.

Table 16: Genetic Algorithm Constraints

Longitudinal Stiffener Spacing	0-10230mm
Transverse Stiffener Spacing	0-2046mm
Ply Angles	0,90
Ply Materials	E-glass, Aramid, Carbon, HM Carbon
Number of Plies	0-32
Long. Crown Width	0-102.3mm
Long. Crown Height	0-20.46mm
Long. Web Width	0-20.46mm
Long. Web Height	0-102.3mm
Trans. Crown Width	0-102.3mm
Trans. Crown Height	0-20.46mm
Trans. Web Width	0-20.46mm
Trans. Web Height	0-102.3mm
Plate Thickness	0-102.3mm
Stiffener Base Width	0-102.3mm
Stiffener Base Width	0-102.3mm

5.4 Quality Function Deployment for Weighting Determination

Genetic algorithms require weightings, as seen in eq.63, for the multiobjective optimisation to produce results that are useful and relevant to the design. The normal method for selecting these weightings is for the designer to select the value. This is a subjective choice and as outlined previously, in Section 3 concept design is of key importance to the design process. As it is so important to produce these results around a customer-centric ethos the use of an objective method to determine the weightings is utilised: Quality Function Deployment (QFD).

QFD is a tool that will encourage designs to exact the wishes of the customer. It is used within industry to help the concept design. This process is therefore implemented within concept design and additionally the process can be used to output the weightings for the genetic algorithm. According to Lin [97] there are five main steps in the traditional approach to QFD and they are:

1. Customer Requirements

2. Planning Matrix

3. Technical Requirements

4. Inter-relationships

5. Roof

Added to this is a binary matrix which will allow a connection with Concept Design Analysis (CoDA). Each stage of these processes try to quantify the data which will be required for the design. A description of each stage and a small artificial example using a stiffened panel for the side of a hull is used to show how this technique can be used to connect with a genetic algorithm.

1. **Customer Requirements:**

   This is the stage at which the customer requirements are drawn up. Customer requirements could be a direct demand from a customer, a task to meet a strategic objective of the company or a redesign of a current model based on the advice of sales staff, but would ideally have elements of all of these. At this stage it will be important to decide what the aims of developing a new model will be. This information can be gathered in a number of ways such as by questionnaires, discussions with current or future clients and also by allowing feedback from sales personnel. It is important for the designers to consider previous designs and to make sure these customer requirements fit with the goals of the company and do not contradict what has happened with previous designs. A short list of possible customer requirements for a stiffened panel is shown in Table 17.

   Table 17: Customer requirements

Light
Cheap
Withstand environment
Watertight

   In this example it is determined that for the plate it will need to be cheap and light as these will allow increased vessel performance while increasing the profit margin. Furthermore the ability to withstand the environment and being watertight will be vital to the success of the product.

2. **Planning Matrix:** The next stage of the QFD is to develop the importance of each of the customer requirements. The example for this step is shown in Table 18.

Table 18: Planning matrix

Customer requirements	Importance
Light	6
Cheap	7
Withstand environment	9
Watertight	9

These values reflect the importance, 9 being high and 0 being low, as viewed by the customer. In this example it can be seen that it is most important to withstand the environment and to have a watertight hull. The next most important factor will be for the hull to be cheap and finally for it to be light.

3. **Technical requirements:** The next stage of the design is to try and develop the design criterion which will be quantitative in nature as opposed to the qualitative customer requirements. These will be drawn up by the design team and should be measurable values that will be related to the customer requirements. The design team will also try to determine which of these criteria should be increased or decreased to improve the design as is shown in Table 19

Table 19: Technical Requirements

	$\downarrow$	$\downarrow$	$\leftrightarrow$
Customer requirements	Mass	Cost	Meets Standards
Light			
Cheap			
Withstand environment			
Watertight			

In this design it has been decided that mass, cost and meeting standards are the design criteria that will best meet these customer requirements. It can also be seen that in this example it will be important to try and reduce the mass and the cost of the design.

4. **Interrelationships:** The next stage of the design will determine how the design criteria will affect the customer requirements and hence how changes in dimensions will allow for an increase in design quality. This process can be time consuming as it is difficult to rate the relationships, from 0- no dependency on each other to 9 - very dependent on each other, between every customer requirement and each of the design criteria as can be seen from Table 20. This can be undertaken in terms of qualitative values which can be quantified using fuzzy logic.

Table 20: Interrelationships - Quantitative

	$\downarrow$	$\downarrow$	$\leftrightarrow$
Customer requirements	Mass	Cost	Meets Standards
Light	8	2	6
Cheap	6	8	6
Withstand environment	6	6	8
Watertight	6	6	8
Technical Priorities	198	176	222
Percentage	33.2	29.5	37.2

A definition of fuzzy logic by Klir [98] is that it can "be thought of as the application side of fuzzy set theory dealing with well thought out real world expert values for a complex problem". A fuzzy set is defined by Zadeh [99] as "a class of objects with a continuum of grades of membership". This form of problem solving was developed for problems that are vague. This means that it is possible to mass together numbers under one term. The form of fuzzy logic that the author has used is called triangular fuzzy logic as numbers are grouped together in threes under one banner. The reason for using this form of fuzzy logic is "This type of fuzzy number is used because it is easily specified by an expert" Pedrycz [100]. The advantage of using fuzzy logic in this research work is that it will increase the speed at which decisions are made. There are two main problems when carrying out the process of QFD quantitatively. First, it is difficult to rate these different qualities on a numerical scale as the numbers are not definitively defined and reported by [101]. People have different ideas over which number to give a relationship but may agree on a descriptive answer. The use of fuzzy logic should reduce this problem and allow a faster process using the QFD.

The second problem is that people get confused when they are requested to rate alternatives quantitatively and forget the criteria by which they are marking. For example when rating how much of a relationship one property has to another some assessors will be found to use a rating of 0-9 on the strength of that relationship i.e. they affect each other significantly so a 9. If this relationship is a negative relationship this may result in members of the assessing group rating the relationship as a 0 which would actually refer to there being no relationship. As can be seen from this example the use of words was much easier to use and this change can be performed using fuzzy logic.

Using this fuzzy logic it is then possible to repopulate the table qualitatively shown in Table 21.

Through this formulation a number of technical priorities will become available and these can be standardised so that they can be used as weightings within the genetic

Table 21: Interrelationships - Qualitative

	↓	↓	
Customer requirements	Mass	Cost	Meets Standards
Light	High	Low	Medium
Cheap	Medium	High	Medium
Withstand environment	Medium	Medium	High
Watertight	Medium	Medium	High

algorithm. The technical priorities are created by multiplying the design criteria rating against the importance rating and summing these values. From this example it will be possible to develop weightings of approximately 0.332 Mass, 0.295 Cost and 0.372 Meet Standards.

5. **Roof** The roof of the QFD is the place where the relationships between the design criteria can be rated. Differing goals will affect a design quantity in different ways. It is therefore important to know how much these different design loads affect each other but at the same time in which direction these parts should be increased so as to create the optimum design. The first stage is to rate whether the relationship is positive or negative. It will then be important to rate whether this is a strong or weak relationship as can be seen from Figure 24.

5.5 Optimisation Verification

Genetic algorithms can be tested to determine if the optimisation that has been carried out reaches the optimum value. This is investigated by starting the algorithm at different points and determining if, at the finish, all the algorithms reach approximately the same

Customer Requirements	Design Criteria Weightings	Mass	Cost	Meet standards
Light	6	8	2	6
Cheap	7	6	8	6
Withstand impact	9	6	6	8
Water tight	9	6	6	8
Technical Priorities		198	176	222
Percentage of total		33.2	29.5	37.2

Figure 24: Stiffener element names and numbers

fitness function of between 0.00064-0.0007. The method of genetic alogrithms requires that the best fitness value, after each generation, will gradually increase. This leads to a distinctive handgun shaped graph when fitness function is plotted against generation. If the same algorithm is started from different points, represented by the different lines in the plot, this will lead to the optimisation reaching similar fitness functions as shown in Figure 25.

As can be seen from the examples in Figure 25 the graph follows the distinctive genetic algorithm shape where each of the individual strands reaches a similar final result. This shows that the algorithm is working correctly therefore validating the optimisation.

5.6 Summary

An optimisation algorithm has been reported that will produce an optimised panel for given boat models. The optimisation process uses a combination of genetic algorithms and direct methods to create optimum results and this process has been programmed and

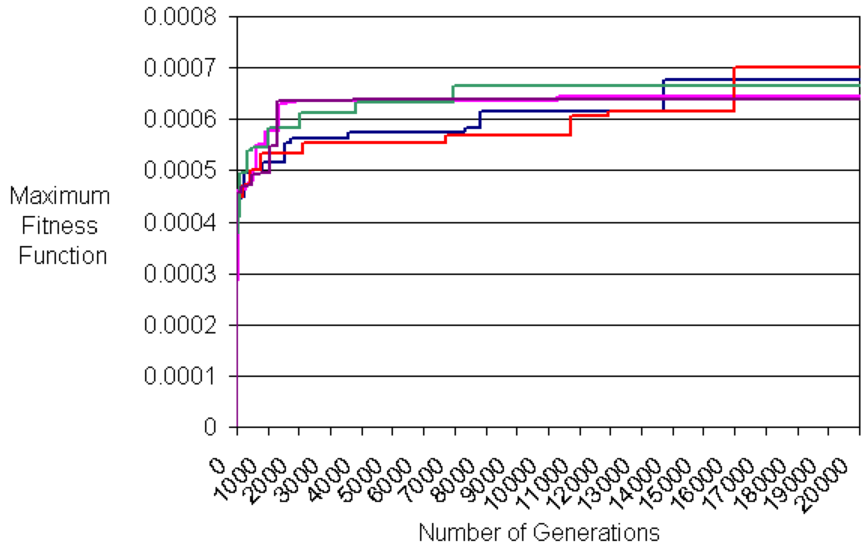

Figure 25: Verification of genetic algorithm using different starting points

validated. The addition of Quality Function Deployment has allowed this algorithm to become specific to the task of design by quatifying the weightings. The addition of the structural and production modelling from Chapters 4 and 7 has allowed this optimisation procedure to be used to optimise boat hulls and the results will be reported in Chapter 8 to 11. Further development in the modelling of other subsystems will allow the optimisation to more comprehensively optimise the boat hull. Chapter 6, presents the development of a reliability analysis tool to allow an understanding of the relations between structural and production problems allowing designers greater knowledge of the behaviour of the subsystem.

6 Reliability Analysis Tool

6.1 Introduction

During the construction and use of an engineered object there are many uncertainties that are faced that could compromise the effectiveness of this object in fulfilling its function. For an accurate determination of the performance an object will exhibit it is important to be able to model these factors. Reliability methods determine the probability of an event occurring allowing an indication of the likelihood of an undesirable result. This has in turn allowed for the design of boats to be constrained not by the stresses that it is predicted it will encounter but by the likelihood over the service life of failure. This theory can also be applied to production ensuring that a design is easily produced with a low mean cost.

Computational modelling has been carried out in two main areas: that of structures and production, which are covered in Chapters 4 and 7, with reliability analysis carried out in both areas. The structural reliability analysis has been performed for two reasons. The first is to determine safety factors which can be used within the optimisation process to allow extension of the structural model and further constrain it. The second is to allow a reliability analysis to be performed to compare different panels and to allow designers a more comprehensive understanding of how changes will affect a design. Further to this analysis, production has been analysed to better understand how changes through production from the as designed panel may increase the target cost but reduce the average cost for the panel.

6.2 Monte Carlo Simulation

A Monte Carlo simulation method has been chosen for the prediction of the reliability as this technique will allow an ability to easily make changes to the models and to allow systems' reliability and covariance to be added in future models. The Monte Carlo method has three main steps:

1. Generate a randomly distributed set of input variables.
2. Perform calculations based on the set of input variables.
3. Determine probability from a large number of repetitions.

A number of simulations were run for each set of statistical distributions resulting in a given reliability for that product and the production technique used. For each of these simulations the values of the input variables must be determined. The first step is to generate a uniform distribution that can then be mapped using the quantile function to the distribution function. The uniform distribution was chosen using "Numerical Recipes" [64]. This function will then generate a number of values for each variable and these are mapped to different distributions which represent the manner in which the variable behaves. The number of simulation runs (N) can be calculated using the works of Nowak and Collins [102] and their expression:

$$N = \frac{1 - P_{true}}{V_{\bar{P}}^2(P_{true})} \tag{64}$$

where P_{true} is the theoretically correct probability, and $V_{\bar{P}}^2$ is the coefficient of variation of the estimate.

For a high accuracy, orders of magnitude more simulations than the reciprocal of the magnitude of the probability being determined must be used. For this situation it is possible to estimate the correct probability of failure from that of Blake et al. [4], determined using Second-Order Reliability Methods, and, using an arbitrary accuracy of 10% for the probability of failure, indicating that approximately 10^8 generations will be required.

Having determined the statistical input variables for each simulation it is then possible to determine the outputs. In this case outputs are deflection, failure criteria, mean cost or maximum stress from the model of Chapter 4. These outputs can be compared to the limit state. The general limit state function is given by:

$$g(R,Q) = R - Q \tag{65}$$

where R is capacity and Q is demand. For the determination of a specific reliability it is important to determine the limit states that bound the characteristics of interest i.e. maximum stress. The performance function for the limit state is given as:

$$P_f = P(R - Q < 0) = P(g < 0) \tag{66}$$

where P_f is probability of failure. The probability of failure is the probability of the demand being larger than the capacity and for the problems asociated herein it is the probability that the rectangular simply supported panel of FRP construction will fail because of a pressure load on one of its faces. The probability of failure often has a low order of magnitude and is a difficult number to practically interpret. This value is often converted to a reliability index which can be related to the coefficient of variation of this limit state function. The reliability index from Nowak and Collins [102] is given by

$$\beta = -\Phi^{-1}(P_f) \tag{67}$$

where Φ is cumulative distribution function of the Normal function. Values for the reliability index are given in Table 22 for decreasing probability of failure.

Table 22: Reliability index in comparison to probability of failure

Probability of Failure	Reliability Index
10^{-1}	1.28
10^{-2}	2.33
10^{-3}	3.09
10^{-4}	3.71
10^{-5}	4.26
10^{-6}	4.75
10^{-7}	5.19
10^{-8}	5.62
10^{-9}	5.99

Reliability is dependant upon the statistical distributions of the inputs. Different inputs are generally grouped together with statistical distributions as found in structural codes e.g. CIRIA [6], DNV [7] or EUROCOMP [103]. Typical distributions for pressure and material definitions are Weibull distributions and Normal distributions respectively, as can be seen from Table 23 given by the DNV design rules. Both of these distributions are shown in Figure 26 with the Weibull shape factor being changed to demonstrate different shapes that are possible with this distribution. By increasing the coefficient of variation for the pressure it is possible to see a higher likelihood of failure for the panel an increase in the shape function had the opposite effect.

Table 23: Typical Distributions for Input Variables

Variable	Distribution Type
Wind - Short Term	Normal
Wind - Long Term	Weibull
Waves - Short Term heights	Rayleigh
Waves - Wave Period	Longuet-Higgins
Current - Long Term Speed	Weibull
Current - Extreme Yearly	Gumbel
Forces	Lognormal
Fatigue - Scale parameter on S-N Curve	Lognormal
Fatigue - Fatigue Threshold	Lognormal
Fracture Mechanics - Scale Parameter on da/dN Curve	Lognormal
Fracture Mechanics - Initial Crack Size	Exponential
Properties - Yield Strength (Steel)	Normal
Properties - Young's Modulus	Normal
Properties - Initial Deformation of Panels	Normal
Ship Data - Still Water Bending Moment	Normal

The Weibull distribution probability density function as given in Shenoi et al. [29] is:

$$f(P) = \frac{\alpha}{\beta}\left(\frac{P}{\beta}\right)^{\alpha-1} e^{-\left(\frac{P}{\beta}\right)^{\alpha}} \tag{68}$$

where α = shape factor, β = scale factor and P = input.

For the Weibull distribution a shape and scale factor are required. These values can be found using the equations for the mean and the standard deviation as given in Shenoi

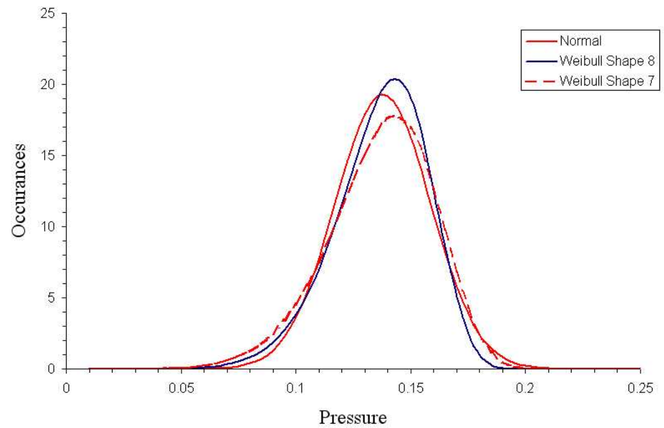

Figure 26: Pressure Distributions

et al. [29]. They are

$$\text{mean} = \beta\Gamma\left(\frac{1}{\alpha}+1\right) \tag{69}$$

and

$$SD = \beta\sqrt{\Gamma\left(\frac{2}{\alpha}+1\right)-\Gamma\left(\frac{1}{\alpha}+1\right)^2} \tag{70}$$

where Γ is the gamma function. IT is defined in Sehnoi et al. [29] to be

$$\Gamma(\alpha) = \int_0^\infty e^{-x}x^{\alpha-1}dx, \alpha > 0. \tag{71}$$

Since $\Gamma(\alpha)$ is an approximation it can lead to further inaccuracies within the modelling of the input distributions.

The probability density function for the Normal distribution is (Shenoi et al. [29]):

$$f(P) = \frac{1}{\sigma\sqrt{2\pi}}e\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \tag{72}$$

Having generated a random number for the input variable these values can then be inputted into the structural or production model. After this processing it will be possible to determine the reliability of the panel and the sensitivity of the structure to each input variable.

As part of the understanding of different subsystems it is useful to know the manner in which different variables relate to each other and which have no real influence on the probability of failure. This can be undertaken using a sensitivity index, which allows an understanding of how changes made to a variable will effect the reliability, defined in Rubinstein [104],

$$\widehat{\nabla^{(k)}}\ell(\mathbf{u}) = \frac{1}{N}\sum_{i=1}^{N} H(\mathbf{X}_i)\mathcal{S}^{(k)}(\mathbf{u};\mathbf{X}_i) \tag{73}$$

where $\widehat{\nabla^{(k)}}\ell(\mathbf{u})$ is the gradient of the response, $H(\mathbf{X}_i)$ is sample performance and $\mathcal{S}^{(k)}(\mathbf{u};\mathbf{X}_i)$ is score function. The gradient can be found from the score functions of each distribution defined in Rubinstein [104] and shown in eq. 74, for the Normal distribution, and eq. 75, for the Weibull distribution.

$$\mathcal{S}(\mathbf{u};x) = (\sigma^{-2}(x-\mu), -\sigma^{-1} + \sigma^{-3}(x-\mu)^2) \tag{74}$$

$$\mathcal{S}(\mathbf{u};x) = (\alpha - 1 + \ln(\beta x)[1-(\beta x)^{\alpha}], \frac{\alpha}{\beta}[1-(\beta x)^{\alpha}]) \tag{75}$$

These sensitivity numbers relate the effect that the input characteristics have upon the output. These values are the gradient and therefore the larger the value the higher the effect the input has on the output reliability index.

For use within the design process it is possible to create partial safety factors to be used with the structural models to ensure that the required probability of failure is produced from the input object. Partial safety factors can be used with first principle analysis to form the topology of the plate, developing solutions with no probability of failure. The partial safety factors are formed using (Shenoi et al. [29]),

$$\gamma = \frac{1 + \alpha\beta\upsilon_\chi}{1 + k\upsilon_\chi} \tag{76}$$

where γ is the partial safety factor, α is the sensitivity factor, β is the reliability index, υ_χ is the coefficient of variation of the random variable and k is the fractile used to determine the characteristic value.

6.3 Structural Reliability

For the determination of a specific reliability it is important to ascertain the limit states that are specific to that characteristic. In the case of the structural reliability these are the limit states for failure of the panel. In terms of a boat hull the most important factors are that the material does not break (the ultimate strength limit state) and that the hull does not deflect too much and impact upon the operability (service limit state). The limit states for the panels are given by

$$\begin{aligned} \sigma_{stress} &= X_t(E_f, E_r, V_f, \epsilon_f^*) \\ &\quad -\sigma_{max}(L, B, P, E_f, E_r, G_F, G_r, V_f) \end{aligned} \tag{77}$$

$$\begin{aligned} \sigma_{def} &= k \times w_{max} \\ &\quad -w(L, B, P, E_f, E_r, G_F, G_r, V_f) \end{aligned} \tag{78}$$

$$\begin{aligned} \sigma_{failure} &= Crit_{Fail}(E_f, E_r, V_f, \epsilon_f^*, \epsilon_r^*) \\ &\quad -(\sigma_{max}(L, B, P, E_f, E_r, G_F, G_r, V_f) + \tau(L, B, P, E_f, E_r, G_F, G_r, V_f) \\ &\quad +w(L, B, P, E_f, E_r, G_F, G_r, V_f) + \sigma_{buck}(E_s, \upsilon_{12}, a_s, b_s, d_s, c_s)) \end{aligned} \tag{79}$$

where σ_{stress} is the stress limit state, σ_{def} is the delfection limit state and $\sigma_{failure}$ is the failure state for the failure criteria summarised in

6.4 Failurecriteriaoverview

. In the case of the stress and failure limit states the capacity is the strength of the material and this is dependent upon a number of factors within the panel. The demand is created by the pressure of the water impacting on the side of the hull. In the case of the maximum stress this is given by eq. 80 and in the case of the failure criteria these are listed in Chapter 4.

$$X_t = (E_f V_f + E_m V_m)\epsilon_{1T} \quad (80)$$

For the deflection, the capacity is given by an arbitrary value of twice the mean deflection of the panel. This means that comparison between plates made from different materials can be difficult to make as the criteria for failure is a comparison with that individual plate's mean deflection. However this arbitrary value has been used to ensure verification of the work with that carried out by Blake et al. [4]. The variables affecting the deflection of the panel are the same as those for the stress of the plate.

6.5 Production Reliability

When constructing hulls it is important that the cost is as low as possible to increase the profit margins. An understanding of the way in which panels can be built with a more predictable cost can help reduce the overall costs. The most effective production process can be found by reducing the potential for the cost to go above that of the mean plate. Further to the possibility of a plate costing more than the mean, the same failure criteria as for the structures are added. If a plate fails its structural assessment the cost of the panel is assumed to be £1m. This is taken to be the potential cost a failed boat may have in terms of loss of lives or use. The variables within the cost of the stiffened panel are the dimensions of the plate and the volume fraction of fibres. The dimensions are configured as it is the size of these different sections that take time to build and money for raw materials. The volume fraction of fibre is an important factor as the cost of resin and fibres are often quite different from each other. This therefore leads to the production limit state eq. 81,

$$\begin{aligned} \sigma_{cost} &= C_{Average} \\ &\quad - C_{max}(L, B, P, V_f, a_s, b_s, c_s, d_s, T_{plate}) \end{aligned} \tag{81}$$

From these values it is then possible to determine the reliability of the panel in terms of cost and give a larger understanding to the structural engineer about the manner with which changes made within the panel will affect the cost.

6.6 Verification of Reliability Code

6.6.1 Monte Carlo Simulation Convergence

A Monte Carlo simulation technique is used to approximate the probability of failure and to determine the number of generations that are required for an accurate comparison with other reliability methods. N= 4.44×10^8 is obtained from Eq. 64 for the recommended number of simulations for the estimate. From Table 24 it is possible to see the results gathered for different numbers of simulations showing convergance with larger numbers of runs.

Table 24: Verification of Monte Carlo Simulation

Runs	Failures	Probability of Failure
10^1	0	0
10^2	0	0
10^3	0	0
10^4	0	0
10^5	0	0
10^6	1	1×10^{-6}
10^7	18	1.8×10^{-6}
10^8	146	1.46×10^{-6}
4.44×10^8	675	1.53×10^{-6}
10^9	1490	1.49×10^{-6}

6.6.2 Structural Reliability Verification

Verification of the Monte Carlo simulation being used for the reliability studies was determined by comparison with work previously carried out on a composite grillage plate. To determine the reliability of the plate it is assumed to have characteristics as shown in Table 25 taken from Shenoi et al's [29].

It is then possible to compare these results with those produced in a previous study, Table 26.

From these results it is possible to see that a good degree of accuracy to Shenoi et al's [29] results can be determined. For the deflection limit state the Monte Carlo simulation ran to 5.5% of the probability of failure and 1.43% of the reliability index for the FORM results. Compared to the SORM results the Monte Carlo simulation produced

Table 25: Panel Properties - Structural Verification Study

Material	Mean	Coefficient of Variance(%)	Distribution
Length	3810mm	3	Normal
Breadth	3810mm	3	Normal
Pressure	137kPa	15	Weibull
E_f	826GPa	5	Normal
E_m	3GPa	3	Normal
G_f	413GPa	3	Normal
G_m	1.09GPa	3	Normal
V_f	0.6	3	Normal
ϵ_f	0.3	3	Normal

Table 26: Comparison of FORM/SORM and Monte Carlo Simulation

		Probability of Failure P_f (10^{-6})	
Method	Reliability Index,β	Deflection Limit State	Stress Limit State
FORM [29]	4.6927	1.384	0
SORM [29]	4.7446	1.045	0
Monte Carlo	4.97	1.49	0

results 39.7% of the probability of failure giving 1.48% of the reliability index. The value of the 39.7% can be partly explained from the possible variability found within input distributions and data as can be seen in Sobey et al. [105] and also due to the nature of the difference between a stochastic and deterministic solution to the same problem. This shows the method could be used for the analysis of the structurally optimised plate.

6.6.3 Sensitivity Verification

Having validated the Monte Carlo methods it is then possible to determine the sensitivity of the output to each of the inputs. In terms of the structural model, stress and deflection limit states, these results are shown in Figure 27 for the case of the Carbon/Epoxy panel and Figure 28 for the E-glass/Vinylester test case.

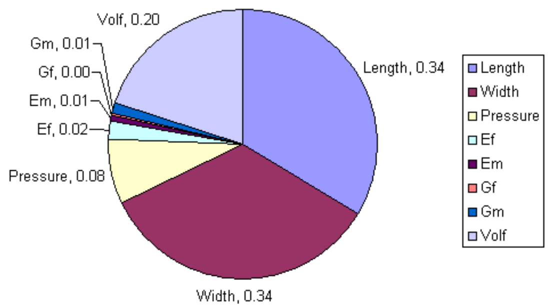

Figure 27: Sensitivity of structural model to inputs - Carbon/Epoxy

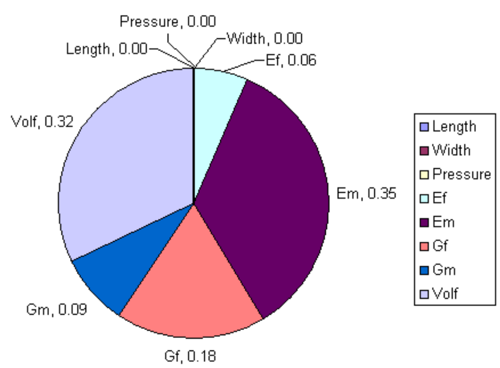

Figure 28: Sensitivity of structural model to inputs - E-glass/Vinylester

The results show that the stress limit state is not broken, the stress never goes beyond the maximum stress value, using the material variability chosen. This is because the stresses are in the region of 170MPa for the average panel which is an order lower than the failure stress of 1470MPa in the case of the Carbon/Epoxy and 887.5MPa E-glass/Vinylester. The results for the stress have therefore been discounted.

For the results shown in Table 27 and 28 each of the gradients has been normalised using the average value for the characteristic seen in Table 25. Using these normalised values it is possible to compare these values to each other in terms of effect on the deflection. These quantities were then compared to those represneted by Shenoi et al. [29] and show a good correlation between the importance of each. The main difference between the two sets of results was that the current results were less sensitive to the pressure. The difference between the two sets of sensitivity values could have been produced, in part, by the difference between input distributions.

The sensitivity and reliability of the panel to different inputs can be predicted. The modelling has been carried out using Normal distributions assuming that production engineers are as likely to make a mistake in one direction as another. It was assumed that the thickness of the stiffeners, being dependent on the number of plies, had a small variation. The properties for these results are shown in Table 27 where it has been assumed that the Carbon/Epoxy is made using pre-preg where as the E-glass/Vinylester was made using hand layup.

The results for the Carbon/Epoxy sensitivities are shown in Figure 29 and the E-glass/Vinylester case is shown in Figure 30.

From these figures it is possible to see that the pressure and volume fraction played the largest part on the cost. This is because these values have a significant impact on the failure of the panel due to deflection and the significant penalties imposed in this state. As the cost of the materials was different between the resin and the fibre a change in volume fraction led to a significant change in the cost. The use of analogous production models

Table 27: Panel Material Properties - Cost

	Carbon/Epoxy		E-glass/Vinylester		
Material	Mean	CoV(%)	Mean	CoV(%)	Distribution
Length	3810mm	3	3810mm	3	Normal
Breadth	3810mm	3	3810mm	3	Normal
V_f	0.6	1	0.5	10	Normal
Crown Height	18.288mm	10	18.288mm	10	Normal
Crown Width	127mm	10	127mm	10	Normal
Web Height	254mm	1	254mm	1	Normal
Web width	9.144mm	1	9.144mm	1	Normal
Plate Thickness	18.288mm	1	18.288mm	1	Normal

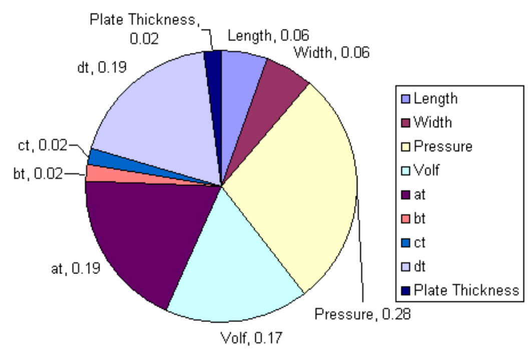

Figure 29: Carbon/Epoxy sensitivity of cost to inputs - Carbon/Epoxy

will also affect the sensitivity of each input to the reliability. The sensitivity results can therefore be more accurately representative of the real life scenario by using production models that better represent the actual processes in a yard.

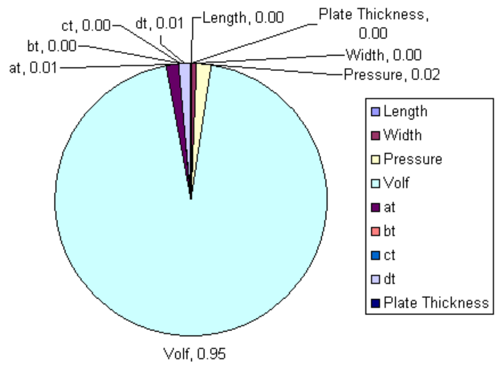

Figure 30: E-glass/Vinylester sensitivity of cost to inputs - E-glass/Vinylester

6.7 Summary

Reliability methods have been investigated to determine the effect of variability within the composite materials and to create a tool which creates an understanding between different subsystems of design and production. The tool used Monte Carlo simulations to determine the reliability due to the method's ability to deal with large systems and covariance which will be required for future development. This tool is dependent upon structural and production models and different limit states have been developed for each model. The tool, including analysis of sensitivity of different parts, has been shown to work when comparing previous results using other computational strategies. Chapter 7 outlines the concurrent engineering environment used to combine all of the techniques to allow effective autonomous communication.

7 Concurrent Engineering Environment

7.1 Introduction

Concurrent engineering, as has already been outlined in Section 3, can bring about beneficial changes to the output of a company. Concurrent engineering is dependent upon the transfer of information and data between members of the design team. This process means that every member of the design team knows or has access to everything that is available to the other members. "Data" and "information" require different methods of transfer. Information will ideally be transferred through direct conversation between design team members. It is not always possible for direct communication to take place and therefore it is important that methods are put in place to allow effective indirect communication. Furthermore, automated methods of communication between design members will allow faster knowledge transfer. Low level information can be transferred through these systems while higher level decisions can be developed using more expensive direct communication. Data will be transferred between subsystem designers using computational exchange.

7.2 Design Environment

One of the most important parts of the concurrent engineering method is the concurrent engineering environment itself. This environment is used to ensure that communication of all types can be effective between members of the design team. This includes the design team within the same company, consultants and production engineers. The design environment can therefore be split into the four following sections:

- Information transfer
- Data transfer

- Data storage
- Computer hardware

The information transfer can be further split into distributed transfer between members of the design team in different locations and transfer between members of the design team in closer proximity. Data transfer occurs in an automated manner between subsystems of the design. Computer hardware consists of a shared grid computing network for the entire boatbuilding community to increase computational power while reducing maintenance and purchase costs. This system will need to be outsourced to allow for the opportunity to have shared floating licenses. Data storage consists of a number of databases that must be easily accessible and produce information and data that is relevant to the design situation.

Relations between the different sections of the concurrent engineering environment are shown in Figure 31. The diagram shows the connections to exchange the data between companies and designers. If designer 1 is a structural engineer with company 1, green box, he/she will be able to communicate with the hydrodynamics designer, labelled designer 2 in blue box, through the use of either an information or data transfer. The data transfer will work in terms of quantitative data and once set up will transfer all changes automatically or alternatively could be through the use of the same piece of software i.e. CAD where changes here will permeate the entire design. The information transfer will be via spoken word, forums and the transfer of pictures, graphs and so forth. It will be possible for the structural designer to communicate with the databases either directly or through the use of neural networks automatically selecting the required information or data. Each method of exchange will be reliant upon computers in a consortium grid computing network that will handle computational calculations for the companies. Company 2 will have exactly the same setup sharing the same computational resources though some

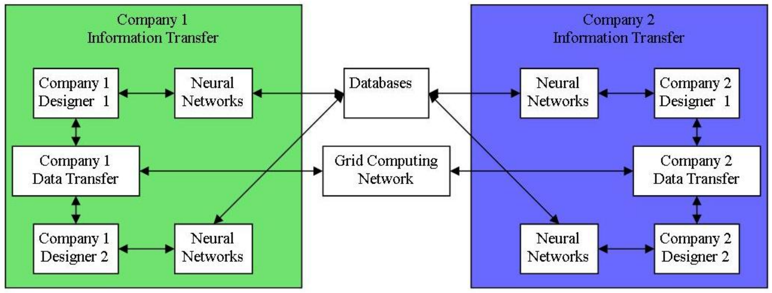

Figure 31: Relational diagram

of the more confidential databases will be entirely independent. The system will be set up to ensure that the private resources of each company cannot be shared but the cost of upkeep will be vastly reduced for both companies.

7.2.1 Data Transfer

There is a requirement for data to be transferred between all sections or subsystems of the design for effective concurrent engineering, allowing updates to any subsystem to permeate through the rest of the design. For use within British boatbuilding it is important that development costs are kept low, as determined from the questionnaire seen in appendix B, and therefore spreadsheets have been linked to allow effective transfer between subsystems as shown in Figure 32.

During data exchange, data is transferred between subsystem spreadsheets during breaks within the design sessions.

1. During the design sessions themselves subsystem designers make requests for data they require from other subsystems, as an example the production engineer may request the number of beams in the structure from the structural engineer.

2. The request passes through the data exchange and if the data has already been

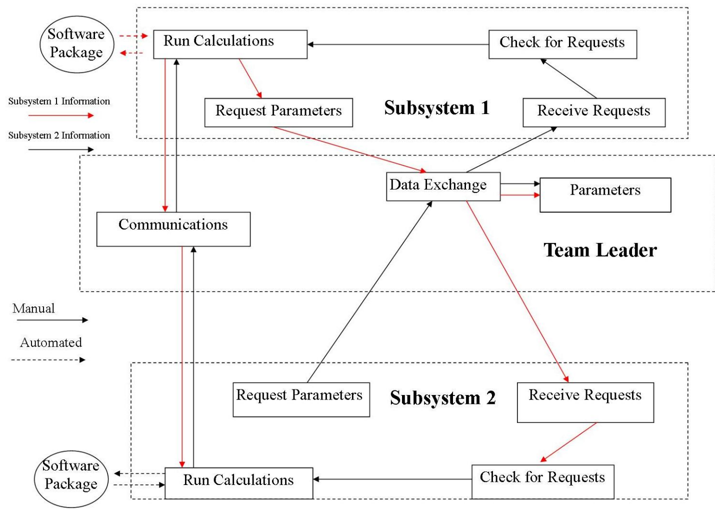

Figure 32: Data transfer between two subsystems

requested from another subsystem is passed directly back. If not, the request is then passed on to the subsystem from which the data was required. Following the example if the structural engineer has already given the information to another subsystem (the number of beams has already been given to the layout subsystem) this information can automatically be passed back. If not, the next step occurs.

3. After the session break the subsystem to which the data has been requested will receive the request: the structural engineer will now receive a request for the number of beams.

4. During the next session the data can then be passed into the "requested information" spreadsheet. The structural engineer can now reply to the request.

5. At the next design break this data is then passed back to the original subsystem. Any changes to this data will automatically be passed through the system and as such changes to subsystems permeate through the entire design. A link has now

been formed: any changes made by the structural engineer will automatically update the production engineer's calculations.

It is important that design software can be attached to the correct design subsystem easily and effectively. There are two main methods of connecting software. The first method is shown in Figure 33 where all of the different subsystems are connected to a centralised hub. This system will allow new subsystems to be attached to the hub and as

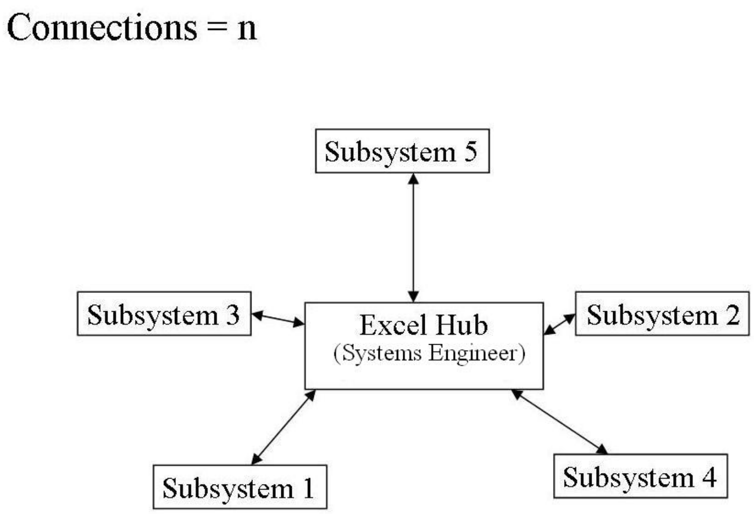

Figure 33: Hub software connection method

such will be easier to connect and maintain. The use of a centralised data exchange will allow the system engineer to keep track of the data being transferred and the locations they are being accessed from. This will allow system engineers to keep track of the interactions that occur the most, furthering their understanding of the status of the design and a greater knowledge of the interactions that occur within the design process. This greater understanding will allow changes to the design process to benefit future results. A problem with this method is if the link breaks then this subsystem is totally isolated. The second method is shown in Figure 34 where all of the subsystems are attached directly to each other. This system has advantages in terms of speed and also means that the breaking of one link can not isolate a subsystem and will only inhibit communication.

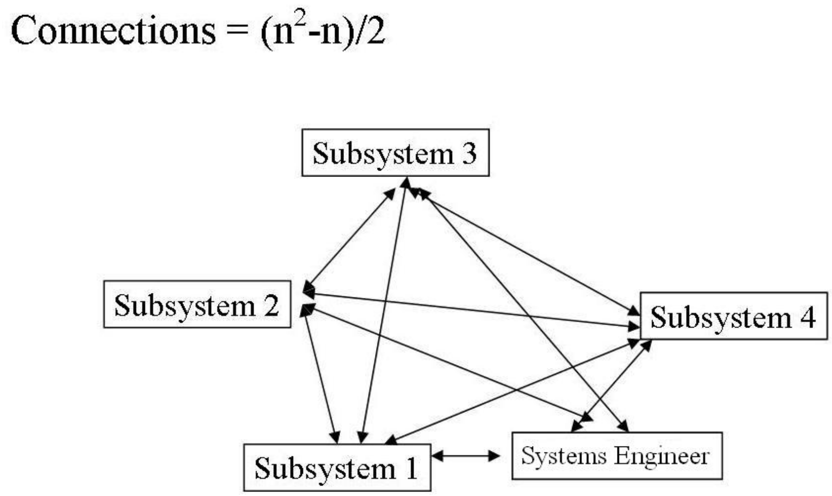

Figure 34: Peer to Peer software connection method

7.2.2 Information Transfer

The information transfer is carried out using three methods:

- Direct Transfer
- Networked information transfer environment
- Design tools

Direct transfer is conversation between members of the design team. This is the most important type of information transfer as this will allow the greatest understanding between the members of the team. The main disadvantage with this sort of communication is the expense in terms of time for the process. This can be further exacerbated through travel time as design team members work in different locations from each other.

Networked information transfer environment is the environment created to transfer the information in the event that direct communication is not available. With the capabilities included within Web 2.0 it is now possible to use this technology to create virtual meeting rooms and forums to allow discussion of issues within the design. Furthermore, new technology, such as Google Wave, will allow tools that link anywhere in the world and will allow full customisation and adaption. These technologies allow questions to be asked and answered from anywhere in the world. A further advantage to this system is that diagrams and data can be easily accessed and that both members of the team do not need to be available at the same times. The disadvantage of this manner of working is that it is slow if multiple queries and replies are required.

Design tools will pass the information either indirectly, directly or both. These tools will allow for information to be added to the design codes allowing indirect communication through modelling. This method allows designers to have a full understanding of different areas of the design, e.g. multiobjective optimisation using production modelling to allow structural designers to understand production problems. The other method is directed though the use of data mining, e.g. finding comments attached to previous design versions allowing designers to understand why decisions were made, for example, structures being constructed using a given topology for cost saving reasons.

7.2.3 Databases

To receive the full benefits from the system databases, information will need to be constantly updated and feedback will need to be developed about previous designs. The databases will be in three main parts:

- Materials database - Consisting of fibre, resin types, independent materials properties and supplier ratings.
- Parts database - Consisting of different boat parts, e.g. engines, rudders and propeller blades, that will be rated on mechanical properties, dimensions, supplier ratings and so forth.
- Design history database - Previous design versions will be saved and new designs will be compared on an overall and a subsystem by subsystem basis to try and create matches. The designs will be rated on similarity to previous vessels and success of those vessels.

There are a small number of boatbuilders and whilst companies may work in a similar area they often do not directly compete with each other on like for like vessels. This means that these companies can start to share resources. Through the use of grid computing it is possible to collate information between the different companies within the industry without the insecurities of directly transferring this data. Databases can also have a benefit with supply chain and past experiences. Though companies may be small, as an industry, they may have more control by rating suppliers and switching from companies that regularly give poor service. Databases of previous designs mean that a company developing a new boat may find a competitor already failed or had success in that area steering them to follow other objectives.

Each of the different databases will have to work in a slightly different manner depending on the inputs that are given to them. The materials database can have data entered into it in any manner that is required as this data will come from independent research companies compiling the database. The parts' database will be input using a web service that will allow outside companies to enter the required data for their component. This information can then be fed via XML into a relational database to allow for easy searches. Finally the design history database will be created using spreadsheets as this is the method used by the designers to transfer data throughout the system. It will require companies to create a standard name type and header. A further problem could be the reuse of old information which could cause problems with semantic differences as the process evolves.

Each of these different databases will be affected by different subsystems. The search time for each of the tools can be cut down upon by removing the requirement to investigate certain databases during this period. This means that if dimensions have been picked for an engine then the propulsion subsystem will be the database which is compared against. This will help to reduce computational expense and to reduce the busy computational period between design sessions.

7.2.4 Collaborative Data Sharing Environment

Collaborative engineering between different companies can increase the productivity of a sector allowing the selected companies increased sales against the rest of the competition reported by Browning [106]. It will be important for any information and data to be compartmentalised between companies, especially those in direct competition. A data sharing network will therefore allow sharing of certain resources between the industry members to strengthen a given sector. The ability of the databases for new and current parts will be dependent on the amount of feedback for old parts and the percentage of currently available parts catalogued. The more members of the industry that work on this feedback, the greater effect it will have. As an example, a company may use a certain engine for a given design. If the supplier is late with the product it can be recorded in the database. Furthermore if this engine fails after 15 years of service when it is designed for 20 then a further comment can be made. When other boatbuilders go to use this company then they are made aware of the problem with that supplier. By commenting on all companies available this puts pressure on suppliers to create a good working environment giving the industry more potential to affect changes in the supply chain.

7.3 Design Histories

Santayana [107] states “Those who cannot remember the past are condemned to repeat it.”. This reflects the importance in understanding and using that understanding of past experiences to increase the quality of what is currently being worked on.

The neural networks within the environment will be used to search through the different databases that are available in order to disseminate information to the designers on possible other techniques, parts and materials that are available within the current markets and previous designs that are used. This ability to search through these designs will help engineers to explore new possible design routes and will also help the production engineers to give feedback on the suppliers that are most reliable. As the design is carried out the neural networks will catagorise new parts and lines that are being drawn. As the new parts are quantified it will be possible to determine what similarities this data has with parts or previous designs already in the database. The weightings from the neural networks will be “taught” by all members of the design team. This will be enabled by gaining feedback from the presented parts against the parts that are accepted by the designer. The parts will be listed in order from best to worst taking into account all of the engineers associated with the project. Connected to this data will also be information from other subsystems further allowing the designer to take a holistic view of the design implications of a certain part. A simple example of this process is the selection of an engine by size alone. In this example the layout engineer has left a 2.1m by 2.6m gap for the engine. There are three current engines currently used within this company 2m by 2m, 3m by 3m and 4m by 4m. The neural network will then list these three parts as the 2m by 2m followed by the 3m by 3m and finally the 4m by 4m. Further to these designs there is also a 2m by 2.5m engine developed by a company that the boat designer has never used before also listed but this has a poor reputation for quality and reliability from the other boatbuilders within the consortium. This engine therefore is listed second in the list after the 2m by 2m engine. The engineer looks at these options and selects the 3m by 3m engine as he knows from experience that the engine gap often gets larger as the design continues. If this process continues then the neural network will learn that this is the correct option and list will evolve to read 3m by 3m, 2m by 2m, 2m by 2.5m and finally 4m by 4m.

Neural networks are based upon the theory of neurons in the brain to develop "adaptive learning". Neurons in the brain work by being stimulated by an electrical pulse. Further pulses can then be sent forwards to more neurons and, depending on the neurons stimulated, memories can either be remembered or created. The basic formula for the stimulation of each neuron is therefore shown in eq. 82,

$$\begin{aligned} f_j(\textstyle\sum w_j x_j) &\geq i \;\; x_{[j+1]} \rightarrow 1 \\ f_j(\textstyle\sum w_j x_j) &< i \;\; x_{[j+1]} \rightarrow 0 \end{aligned} \tag{82}$$

where f_j= non-linear function w_j = weighting function x_j= input from node and i= node threshold. From these equations it is possible to see that the neurons take impulses from neurons connected to them and give certain outputs based on the stimulus. Eventually an output will be chosen which most closely emulates the inputs that have been given.

There are different sorts of networks that react in different ways so that the characteristics of learning that are required can be given. The recognition of different parts can be a relatively easy task as the pre-grouping of different types of part can easily be carried out, such as engines or propellers. This gives a relatively simple problem with few parameters outlining a different engine. The recognition of different line plans within a CAD drawing is a more difficult task due to the multitude of different parameters that make up a picture and will therefore involve the use of multi-layer neural networks. To make sure that all parts can be determined using the same system a multi-layer neural network system has therefore been employed.

The basis behind a multilayer neural network is that there are input and output layers which in between have a number of hidden layers. If the activation function for the hidden units is $g(u) = 1/(1 + e^{-u})$, where $u = at$ and for the output units $g(u) = u$, and the network has been set up to determine the functions $y_i = F_i x_k$ from the input variable x_k to the output variable y_i the number of layers can be determined using eq.83

$$y_i = \sum_j w_j x_j - i \tag{83}$$

for no hidden layers and for one hidden layer eq.84 can be used

$$y_i = \sum_k W_k g\left(\sum_j w_j x_j - i\right) - \theta_j \tag{84}$$

According to Cybenko [108] for an arbitrary accuracy, no more than two hidden layers are required (assuming that there are enough given units per layer), but that only one layer is required for continuous, as opposed to discrete, functions shown by Cybenko [108] and Hornik [109]. Since the variables that will be entered into the neural network will be continuous the networks have been produced with one hidden layer as can be seen from Figure 35.

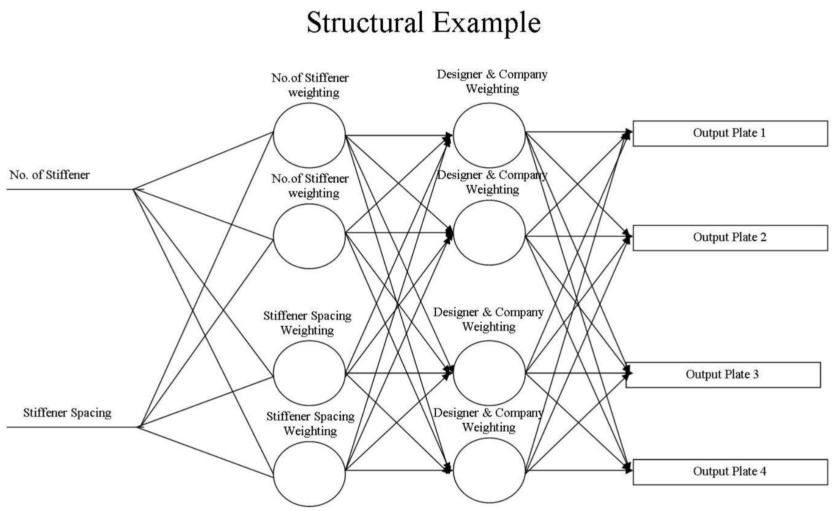

Figure 35: Neural networks for catagorising a plate

The final step in the determination of the neural networks will be to find the method of learning for the network. The network will need to be continuously learning so that all of the feedback gathered over time will aid its output performance. For the system to be immediately useful there is a requirement that the networks have already learnt to recognise parts of the system. The system will need an initial training period followed by a continuous period of learning while the software is working. The designers themselves have an opportunity to give feedback to the system but this may not always be forthcoming. This therefore determines that the system should have a capability to deal with both supervised and unsupervised learning.

As an example, when creating a design a structural engineer will have a given pressure, length and breadth of a plate. A decision may be made about the number of stiffeners that they want to use. The neural network will then automatically select similar designs from previous version histories. It will be looking for boats of a similar size and type. From within these choices it will also select designs that have a similar number of stiffeners. The structural designer will now be able to look at this design and see, if this is not the final design, how the design evolved from this point. For example a choice of four stiffeners may have been made. From the design histories it can be seen that the choice in an old design reduced this value to three but during service this was found to be insufficient in the conditions within which the boat was used. It is now possible for the structural designer to make a decision improving the design from past experience. As designs are selected by the neural network any that are not felt to be similar can be rejected and the network will learn to select in the manner of that designer.

The ability of the neural networks to learn means that increased numbers of designs educate the neural network tool, providing increasingly helpful solutions. The design will be able to take learning from individual designers using the tool, companies they work for, vessels similar in type and also the entire industry as a whole if database information is shared. This should allow an increase in innovative new designs and the increased capability to learn from past successes and mistakes.

7.4 Production Modelling

Production has an effect upon the process of optimisation as it will change the significance of different input values. A strong and light structure that is expensive to produce will have no use within a boatyard. An attempt to produce a low cost hull will have an intrinsic effect upon the topology of the hull. There are many factors that affect the cost of the hull, each of which will permeate through to other subsystems of the boat. It is therefore important to understand how the changes that are made in regards to production techniques, materials and topology affect the overall cost. The cost of the final product can be split into materials and production costs

$$C_{\text{Total}} = C_{\text{Production}} + C_{\text{Materials}} \tag{85}$$

The materials cost can then be subdivided as

$$C_{Materials} = C_{Plate} + C_{Stiffeners} \tag{86}$$

The cost of the plate can be found from eq.87

$$\begin{aligned} C_{Plate} &= (M_{Plate} \times C_{Resin} \times (1 - f_{ci})) + \\ &\quad (M_{Plate} \times C_{Fibre} \times f_{ci}) \end{aligned} \tag{87}$$

Finally the stiffener cost can be found from eq.88

$$\begin{aligned} C_{Stiffeners} &= (M_{girder} \times C_{Resin} \times (1 - f_{ci})) + (M_{girder} \times C_{Fibre} \times f_{ci}) \times n_g + \\ &\quad (M_{beam} \times C_{Resin} \times (1 - f_{ci}) + (M_{beam} \times C_{Fibre} \times f_{ci}) \times n_b \end{aligned} \tag{88}$$

where C_x= cost of element, M_x= mass of element, and f_{ci}= fibre content by weight, $n_{b,g}$= number of beams or girders. Having found the cost of the materials it is important to determine the cost for the production of the hulls. This was performed initially using the time model from Shenoi [110] which has been reproduced in Appendix A. An addition has been made to this model as it was prepared for a sandwich panel. As can be seen from the original model there is no penalty to cost for building multiple stiffeners. Therefore a model to be integrated with the original was developed and can be seen in Table 28. The production cost is based on a parametric model, using probabilistic relationships between different parts of the vessel and the cost, which does not consider all of the potential factors that will affect the cost.

For the above equations an estimate of the costs for each material is listed in Table 29.

Table 28: Stiffener cost model

Action	Cost(mins)
Cutting cloth	10 minutes/sqm/ply
Laying cloth	5 minutes/sqm/cloth
Cutting and laying core	60 minutes/sqm/core
Apply resin with brush or roll	10 minutes/sqm

Table 29: Constant costs throughout production

Quantity	Cost £/kg
E-glass Fibre	2
High Strength Carbon Fibre	15
High Modulus Carbon Fibre	30
Aramid	10
Epoxy	20
Vinylester	5
Wages	20

7.5 Concurrent Engineering Environment Verification

The production models required testing to determine the extent to which different factors affected the topology of the plate. Optimisation results were performed with the method outlined in chapter 5 using the original production model shown in Tables 30 and 31 and the new production model shown in Tables 32 and 33.

From the tables shown it can be seen that the results created using the new production model, Tables 32 and 33, have a much larger stiffener spacing than those produced with

Table 30: Stiffener Topology for Original Production Model

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness
Longitudinal	3mm	0.5mm	3.31mm	0.5mm
Transverse	9.65mm	0.5mm	6.63mm	0.5mm

Table 31: Plate Topology for Original Production Model

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness
Plate Topology	5380mm	9mm	2mm

Table 32: Stiffener Topology for New Production Model

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness
Longitudinal	65.4mm	0.42mm	16.6mm	17.08mm
Transverse	36.1mm	0.26mm	67.9mm	11.46mm

Table 33: Plate Topology for New Production Model

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness
Plate Topology	260mm	2200mm	3.1mm

the original model, Tables 30 and 31. From these models it can be seen that the new production model found an optimised stiffener topology more similar to those found within current boat hulls. The original production model having no penalty for extra stiffeners produced a model that reduced the area and the mass of the hull. The final shape being similar to those of a sandwich panel. During the production process however each stiffener needs the production of a new core and the placement of that core: a time intensive process. The new production model reflects this time intensiveness.

It can also be seen that the production model has a large effect upon the topology of the panel. To reduce the cost within the model it is important to increase the number of stiffeners but reduce their size. For the production process a large number of stiffeners is expensive. Therefore the topology of the plate is highly dependent upon this number of stiffeners. The new production model has been used as a more realistic interpretation of the production process. However due to the importance of the cost model seen within these results further work will be required to ensure that the production model is as accurate to the process in each production yard as possible.

7.6 Summary

A concurrent engineering environment has been proposed specific to the boatbuilding industry using a combination between up-to-date technologies with those that are cost effective. This environment will encapsulate the other tools developed allowing swift transfer of data and information between different members of the design team. This environment will allow the investigation of work performed previously at a company through the use of the design history tool. Finally a production model has been developed to allow costing of the products that have been created. It was found that the production models had a large effect on the topology of the plates and therefore careful examination of these models will be required in the future. Verification of the models and determination of results for the optimisation follows in Chapter 8 to determine that the automated tools were capable of an optimisation of a boat hull and the effect that the different failure constraints had upon the model.

8 Structural Modelling: Failure Criteria Analysis

For each of the failure criteria reported in section 4.4 a comparison has been made between the optimised structures that can be created using a genetic algorithm within the constraints of the failure criteria. The choice of structural models have been introduced in Chapter 4 in more detail but comprises of Navier Grillage Theory for assessing the stiffeners and Third order Shear Deformation Theory for assessing the plates between the stiffeners. The genetic algorithm used has been introduced in Chapter 5 with the specific values for this algorithm being summarised in Table 15 and comprises of a mass versus cost fitness function, each with a weighting of 0.5 for the results shown in this Chapter. Each failure model has been used as the assesment for failure or success separately and finally a combined model, using all of the failure criteria together, has been created and optimised to determine the manner in which these different constraints affect the optimisation.

For each of the different failure criterion a simple study has been performed on a horizontal section of hull at the bottom of the boat. This has been carried out using a grillage panel length of 24m and width 2m. The length is determined as being the length of the boat so as to fit both Lloyd's Register Rules and ISO 12215-5. The width is taken as an arbitrary value to represent a slice through this hull length. This stiffened panel has a simply supported boundary condition and is developed with the constraints of the genetic algorithm outlined in Table 16. The first principles rules have been implemented using the pressure, 131.47kPa, from Lloyd's Register for Special Service Craft as this gives the most conservative estimate ensuring that the masses and costs used within the comparison are likely to be for the worst case scenario.

8.1 Puck

The first optimisation was run using the Puck failure criterion of sub-section 4.4.1. The topology of the stiffened panel that was produced using the Puck failure criteria with the first principles method can be seen in Table 34. The optimised thickness of the stiffened plate and the spacing of the transverse and longitudinal stiffeners from the Puck criteria analysis are reported in Table 35.

Table 34: Stiffener Topology for Puck Failure Criteria

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness
Longitudinal	100.7mm	0.86mm	5.6mm	1.78mm
Transverse	36.1mm	4.16mm	5.6mm	2.78mm

Table 35: Plate Topology for Puck failure criteria

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness
Plate Topology	2200mm	570mm	1.2mm

The web thickness of 0.86mm is small in comparison to those that would be expected in a real life application. Due to the Puck failure criteria being stress based the optimisation of the plate is attempting to reduce the stress within the plate and as such the web thickness does not play an important role. The plate topology is similar to that in the final total failure envelope with a wide stiffener spacing and a small panel thickness. This topology is produced as the Puck failure criteria is dependent upon the maximum stress found within the plate. This therefore means that for a low stress in the stiffener a high neutral axis is required. The thickness of the web therefore does not affect this value as much as the thickness of the crown and its distance from the panel. Furthermore out of plane pressure on the panel develops a stress that is not as complex as a real life situation leading to a thinner panel and a large stiffener spacing which is able to withstand these stresses.

8.2 Tsai

The second optimisation was run using the Tsai failure criterion of sub-section 4.4.3. The optimised topology produced using only the Tsai failure criteria can be seen in Table 36. The optimised plate topology is reported in Table 37.

Table 36: Stiffener Topology for Tsai failure criteria

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness
Longitudinal	38.3mm	0.02mm	1.1mm	6.28mm
Transverse	71.3mm	0.14mm	12.5mm	4.9mm

Table 37: Plate Topology for Tsai failure criteria

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness
Plate Topology	430mm	40mm	0.5mm

This failure criteria again produced a topology with a thin web thickness due to the nature of the optimisation attempting to reduce stress but web thickness having little effect on this value. The stiffeners themselves are small in comparison to those from the Puck criterion. Furthermore the stiffener spacings are narrow and the panel thickness is thinner. The criteria of the World Wide Failure Exercise are similar, being reliant on the maximum stress and having been produced to fit the same experimental data, it would be expected that the plate produced would be similar to that of the Puck criterion. The mass produced using the Tsai failure criteria is small and the cost quite large compared to the other plates, as seen in Figures 36 and 37, and therefore it is likely that the different shape of the failure envelope led the evolution of the genetic algorithm down a different route. This is shown from the small stiffener spacing. The extra stiffeners therefore allowed a reduction in the stiffener size but created extra cost. This shows that for a large number of stiffeners a high cost is incured but a low mass is possible. Due to the weightings being equal between the mass and the cost it was possible to gain a similar fitness function by either having equal mass and cost or reducing one value with a penalty to the other. This is supported by Figure 25 which shows that after the number of generations chosen it is possible that the optimisation had reached a close to optimum value as opposed to the the fully optimised value.

8.3 Zinoviev

The third optimisation was run using the Zinoviev failure criterion of sub-section 4.4.2. The topology of the optimum stiffener plate using only the Zinoviev failure criterion can be seen in Table 38.

Table 38: Stiffener Topology for Zinoviev failure criteria

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness
Longitudinal	91.9mm	0.06mm	0.2mm	17.22mm
Transverse	95.3mm	0.02mm	22.4mm	2.02mm

Furthermore the optimised plate topology can be seen in 39.

Table 39: Plate Topology for Zinoviev failure criteria

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness
Plate Topology	1130mm	2200mm	1.5mm

The Zinoviev criterion produced a similar panel to the other failure criteria selected from the World Wide Failure Criteria producing a high stiffener with a thin web and a thick crown. Zinoviev did show a large difference between the transverse and longitudinal stiffeners. The longitudinal stiffener shape did not appear to make much of a difference to the plate strength with the transverse stiffeners providing most of the strength. This is why the longitudinal crown is small. Furthermore the stiffener spacings are a large distance apart with a thin panel. The stiffener topology was most similar to that produced using the Puck failure criteria. This result is to be expected as the Zinoviev and Puck failure envelopes are similar, as can be seen in Chapter 4.

8.4 Deflection

The fourth optimisation was run using the arbitrary failure criteria of 10% of the length of the grillage was run. This failure criterion meant that the maximum deflection of the plate could be no more than 10% of its length. The resulting optimised stiffener topology can be seen from Table 40.

Table 40: Stiffener Topology for Deflection

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness
Longitudinal	45.8mm	0.84mm	6.6mm	13.86mm
Transverse	83.5mm	0.52mm	23.5mm	1mm

The optimised plate topology for the deflection failure criteria can be seen in Table 41.

Table 41: Plate Topology for Deflection

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness
Plate Topology	430mm	170mm	0.7mm

This optimised plate topology is similar to those found using the World Wide Failure Exercise criteria and this is due to the stress in the panel being based upon the deflection. This requirement means that to minimise one output, stress, a similar topology will be required to minimise the other, deflection. This therefore meant for a low deflection it was also important to have a high neutral axis. Further to this criteria the material property would have been more important as the materials stiffness would have made a difference to the deflection. Since the material selected was E-glass, due to its low cost, the stiffening elements were required to be much larger due to the poor stiffness chracteristics of the material or a larger number of stiffeners are required. This showed that in terms of the grillage plate, the failure criteria chosen and the predicted pressure that the constraints for deflection were more important than those of stress. The deflection criteria requires that the stiffener spacing is small as more stiffeners created a less flexible panel. Furthermore the thickness of the panel is small as this part of the topology did not affect the deflection of the plate.

8.5 Buckling

Finally a buckling failure criteria has been applied to the stiffeners on the grillage. The buckling criteria was, as outlined in section 4.4, applied to the stiffeners. The resulting optimised topology for the buckling criteria was given in Table 42.

Table 42: Stiffener Topology for Buckling

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness
Longitudinal	37.2mm	2.34mm	33.9mm	6.76mm
Transverse	45.9mm	2.94mm	82.7mm	2.1mm

The optimised plate topology for the buckling failure criteria is shown in Table 43.

Table 43: Plate Topology for Buckling

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness
Plate Topology	2130mm	2200mm	0.1mm

The buckling criteria developed a stiffener topology different to those found using the other failure criteria. The main difference with this criteria was it developed a stiffener web thickness and crown height that was thicker than the corresponding dimensions found using the other criteria. This is due to buckling being dependant on the equivalent thickness of the stiffening elements in comparison the length of those elements. For buckling not to occur there is still a requirement that the stress was low and therefore it can be seen that the stiffening elements produced during the optimisation were tall to increase the neutral axis. The plate topology developed a wide stiffener spacing and a thin panel thickness as these criteria did not affect the buckling of the stiffener. It is premised that the 10% arbitrary value that is used for the failure criteria is not a small enough value. Within the example that is used here, even though it is a small boat, the criteria allows a deflection of 2.4m. This value would have a considerable impact on the inside layout of the boat. Further work is required to determine the value for which this criteria may give a more accurate interpretation.

8.6 Amalgamated

Finally all of the failure criteria were combined to develop an optimised panel to ensure that the plate did not break. Through amalgamating all of the failure criteria it is possible to ensure that the plate will not fail in any of these different modes of failure for the static loading conditions. The three World Wide Failure Exercise criteria ensured that the stress within the plate was not too high, the deflection criteria ensured that the plate did not impinge on the inside layout of the boat and finally the buckling failure criteria ensured that buckling did not occur through having low thickness in comparison to height for the stiffeners. These failure criteria combined to produce an optimised stiffener topology shown in Table 44.

Table 44: Stiffener Topology for combined total failure envelope

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness
Longitudinal	84.1mm	3.5mm	101.1mm	5.32mm
Transverse	46.1mm	1.26mm	101.1mm	9.16mm

The optimised plate topology for the combined failure criteria can be seen in Table 45.

Table 45: Plate Topology for combined total failure envelope

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness
Plate Topology	2200mm	720mm	3.3mm

This combined failure stiffener has similar traits to all of the previous criteria and developed a plate topoloigy that was similar in shape to those of the World Wide Failure Exercise and deflection criteria but with a thicker web thickness and crown height. This result was expected as the combined envelope, seen in Chapter 4, was smaller than the other World Wide Failure Exercise results while adding the extra web and crown thickness required to avoid buckling.

8.7 Summary

A method for first principles structural modelling has been developed, this model has been verified previously in Chapter 4. The model has been attached to an optimisation algorithm and different failure models have been tested to determine the manner in which they affect the optimum structure. A review of these results for the mass and cost of this section are shown in Figures 36 and 37.

From these results it is possible to see that the amalgamated result has the highest combined mass and cost of the models. This result is unsurprising as this model will be the mostly tightly constrained however in current design methodlogies a worst case, using the worst individual case, design approach is taken. From these results it can be seen that an amalgamation of all of the limit states is required to capture the worst case

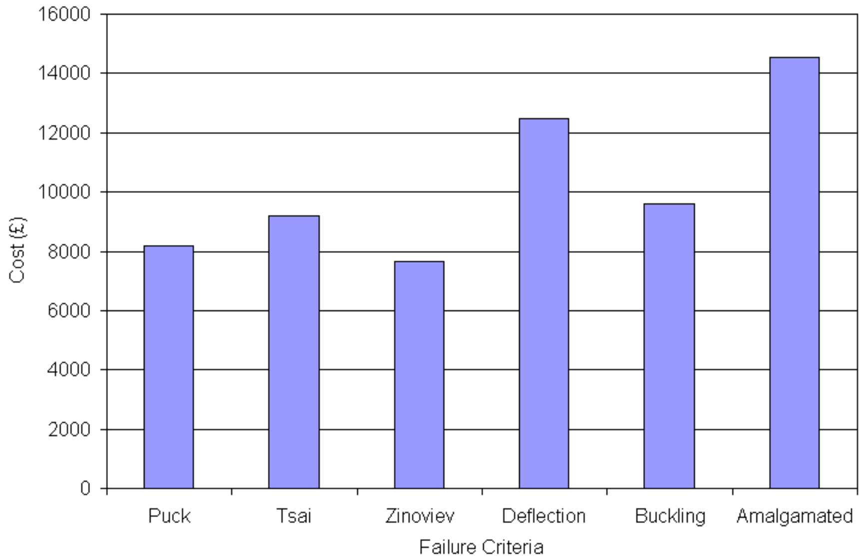

Figure 36: Comparison of cost for failure criteria

scenario. The models of the World Wide Failure Exercise, Puck, Tsai and Zinoviev, and maximum deflection criteria developed a similar topology with small web thickness and crown height. These results show a similarity between them except for the Tsai failure criteria where it is possible that the genetic algorithm followed a different evolutionary route. This route was because of the use of a 50/50 weighting between mass and cost. It was therefore possible to gain a similar fitness function result between those that used a small stiffener spacing and therefore generated a lower mass and higher cost and those that used a larger stiffener spacing therefore generating a lower cost and a higher mass. The buckling failure criteria ensured that the stiffener web and crown thicknesses were larger than for the other cases. This result could be improved through the introduction of more generations within the optimisation. This can be seen from the manner in which it varies from the other topologies with a higher cost but a lower mass than the other World Wide Failure Exercise. As was discussed previously in Chapter 5 a fault of the genetic algorithm

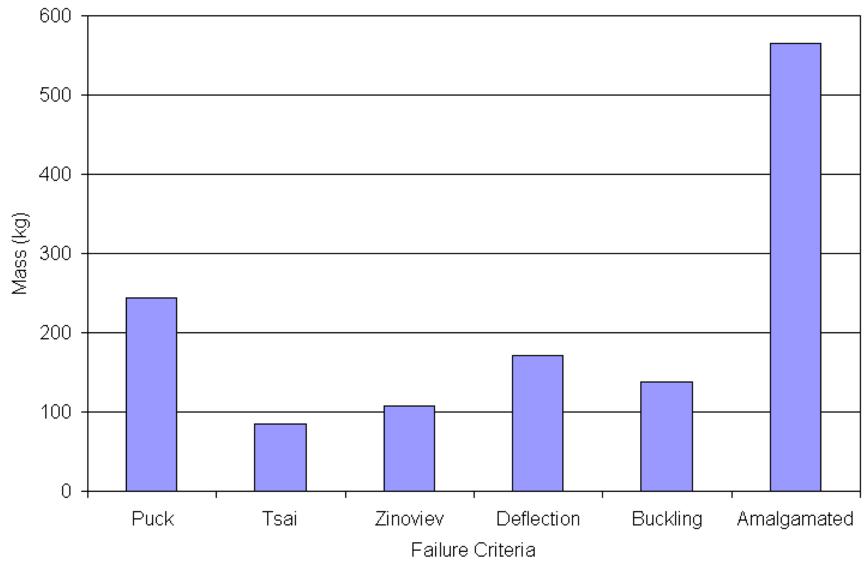

Figure 37: Comparison of mass for failure criteria

is that it may find a close to optimum solution. A comparison of the fitness functions show that the Tsai failure criteria was slightly below that of the Puck failure criteria supporting this argument as does Figure 25 which shows that the final fitness function was slightly different for optimisations that were run from different starting points. This factor can be reduced through an increase in generations.

These criteria show that the amalgamation of these criteria forms a conservative estimate for the maximum stress as the dimensions for the amalgamated shape have a larger mass and cost than for any of the individual criteria. Chapter 9 compares the first principles structural modelling with those of Lloyds Register Rules for Special Service Craft and ISO 12215-5 using an optimisation technique.

9 Multiobjective Optimisation: Plate Analysis

An optimisation of the different structural models has been carried out to make a comparison between the first principles models and those of the classification society rules. The choice of failure criteria and the structural models for the first principles approach have been introduced in Chapter 4 in more detail. Further to this classification society rules, ISO 12215-5 and Lloyd's Register Rules for Special Service Craft, have been chosen for comparison. The genetic algorithm used has been introduced in Chapter 5 and comprises of a mass versus cost fitness function, each with a weighting of 0.5, described within that Chapter. For each of the different structural models a simple study has been performed on a section of hull. The optimisation was on a grillage panel with a length of 24m and a width of 2m. The length is determined as being the length of the boat so as to fit both Lloyd's Register Rules and ISO 12215-5. For the case of the classification society rules the pressure has been determined for the bottom of the hull. In the case of the Lloyd's register rules this pressure was 131.47kPa and for the case of the ISO 12215-5 this was 97.31kPa. The first principles rules have been run using the pressure from Lloyd's Register Rules for Special Service Craft as this gives the most conservative estimate allowing worst case scenario for the comparison with the structural models.

9.1 First Principles

The first principles method has been developed as shown in Chapter 4 using an amalgamation of all of the failure criteria to constrain the results. The stiffener topology that resulted from the genetic algorithm is shown in Table 46 as a reproduction of the results shown in Table 44. The plate topology that has been developed is shown in Table 47 as a reproduction of the results shown in Table 45.

Table 46: Stiffener Topology for First Principles Panel

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness	Base Width
Longitudinal	84.1mm	3.5mm	101.1mm	5.32mm	97.4mm
Transverse	46.1mm	1.26mm	101.1mm	9.16mm	102.6mm

Table 47: Plate Topology for First Principles Panel

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness	Composite Layup
Plate Topology	2200mm	720mm	3.3mm	0/0/0/90/90/90

The topology for this optimisation is the same as for that found with the amalgamated failure criteria. The topology has rectangular stiffeners which are widely spaced. This grillage is positioned on a panel that has a small thickness with a material made of E-glass. The use of E-glass was as expected as this is the predominant material used in the leisure boatbuilding industry due to its low cost. This therefore means that for the applications within the industry even though the material requires extra mass to be added to the grillage to reduce the deformation of the plate this is less of a penalty to the mass than the choice of carbon fibre would be to the cost. In comparison to the panels that are developed using classification society rules the thicknesses of the parts are smaller and the stiffener spacing is much wider. This larger stiffener spacing results from a lack of constraints on this criteria which are developed in the classification society rules.

9.2 Lloyd's Register

A Lloyd's Register Rules for Special Service Craft structural model has been developed for use with the genetic algorithm. This model was developed using Part 5 - Design and Loading Criteria for specification of the pressure and Part 8 - Hull Construction in Composite to determine the topology of the plate. This model has used the code developed to produce a structural topology as shown in Table 48. The topology for the plate assessed using this structural model can be seen in Table 49.

Table 48: Stiffener Topology for Lloyd's Register Rules

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness	Base Width
Longitudinal	19.45mm	2.6mm	42.5mm	2.6mm	42.18mm
Transverse	82mm	6mm	44.5mm	6mm	100mm

Table 49: Plate Topology for Lloyd's Register Rules

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness	Composite Layup
Plate Topology	212mm	222mm	5.4mm	90/0/0

The topology that has been produced using the Lloyds Register Rules is much thicker than that produced using the first principles methodology. The stiffener spacing is much smaller than that found using the first principles method as can be seen in Tables 47 and 49. Furthermore even with the smaller stiffener size the thickness of the panel is of a much larger size than can be seen with the first principles model, 2.1mm. This was to be expected as the development of the Lloyd's Register Rules adds safety factors to the values found from first principles to ensure that failure does not occur. As discussed for the first principles model this material selection was the same as found within industry. The stiffener spacing is developed as the Lloyds Register Rules require a stiffener spacing dependant upon the maximum pressure expected. Furthermore the minimum thickness required under any pressure is 5mm and therefore a small increment in thickness above this value for a high pressure is reasonable. The number of plys was 3 as this is the number of plys for a material of up to 9mm thick. Finally the stiffener thickness is to be expected due to the large safety factors, 3 times, involved in using Lloyds Register Rules.

9.3 ISO 12215-5

The final method of structural modelling to be optimised with the genetic algorithm was developed using ISO 12215-5. The resulting stiffener topology for this optimisation can be seen in Table 50. The plate topology for the optimisation can be seen in Table 51.

Table 50: Stiffener Topology for ISO-12215

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness	Base Width
Longitudinal	10mm	1.17mm	1mm	4.39mm	212.35mm
Transverse	161mm	5.66mm	4mm	4.03mm	212.35mm

Table 51: Plate Topology for ISO-12215

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness	Layup
Plate Topology	386mm	232mm	10.6mm	90/0/0/0/90

This topology was smaller in terms of mass than that found with the Lloyds register rules optimisation. ISO 12215 is developed for smaller craft, 24m and under, than for

Lloyd's Register for Special Service Craft, 24m and over and therefore the rules are for smaller craft resulting in smaller structures. It is therefore expected that the loads on these craft will be smaller. Furthermore ISO 12215-5 has taken into account partial safety factors, as opposed to the phenomological safety factors found in Lloyd's Register Rules, therefore reducing the topology calculated when using these rules. The topology creates a larger mass than for the first principles rules due to the partial safety factors that have been used. These partial safety factors have been made in addition to the first principles in an attempt to reduce the probability of failure to an acceptable level for use in leisure boatbuilding. The optimised result for the stiffened shape is triangular unlike the stiffener topology developed for the first principle rules and for Lloyds Register Rules. The resulting plate had thin stiffeners and a thick panel. The ply layup consisted of 5 plys with 90° on the outside and 0° on the inside. It is a surprising result to have a triangular stiffener as it would have increased the stress due to the low neutral axis. It is premised that this triangular stiffener shape is developed due to the minimum height in comparison to the thickness of the web criteria that is used within ISO 12215-5. A triangular shape is not optimal in terms of height of neutral axis in comparison to the mass required to gain that value. This is no longer true when the height is pre determined and therefore the triangular shape will reduce the mass as much as possible while still gaining the neutral axis height required. This neutral axis height requirment is further reduced due to the small stiffener spacing produced within the rules.

9.4 Summary

Having previously developed and verified a first principles structural model and a genetic algorithm for optimisation, this model has been compared against topologies produced through classification society rules. The results for these model can be seen in Figures 38 and 39 which make a comparison between the models based on cost and mass.

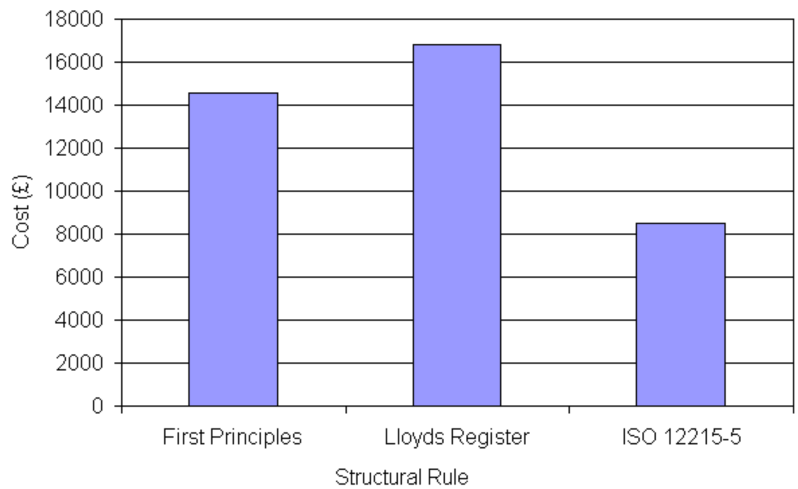

Figure 38: Comparison of cost for structural optimisations

From the results it is possible to see that the first principles method produced the lowest mass and cost and the Lloyd's Register Rules for Special Service Craft produced the heaviest grillages. These results are not surprising as the Lloyds Register Rules have been developed with safety factors with the first principles method having a minimal safety factor and ISO 1225-5 using partial safety factors.

The material selection was that of E-glass and this is because the stiffener application does not require a high strength. The stiffness required to ensure that the plate does not have a high deflection can be produced using extra material due to the low cost of the material. This penalty to the mass is less than the potential penalty to the cost of using carbon fibres. It can be seen that the ply angles are not as expected in a real world situation and as such a further improvement could be to optimise the ply angles for the stiffener and the plate in a seperate genetic algorithm. This would allow a more relistic ply angle and number while also ensuring that the results were closer to an optimum

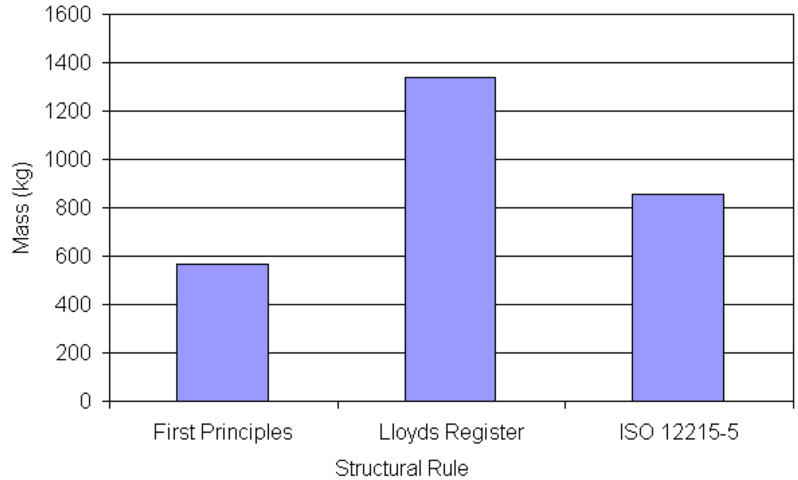

Figure 39: Comparison of mass for structural optimisations

value.

Stiffener spacing within the different models varies largely due to the constraints created within the classification society rules. A methodology of stiffener spacing, based upon the pressure on the hull with a high pressure producing stiffeners that are close together, varies differently between each set of rules. This is a constraint not created within the first principles rules. Furthermore there is a minimum thickness requirement: the first principles rules have no minimum thickness requirement and since the resulting stress the structure is under is low a small thickness develops.

The first principles model shows that there is potential for a reduction in the thickness required by classification society rules. The first principles method is reliant upon the pressures that have been developed from these classification society rules which may not be an accurate portrayal of pressure encountered during service. Further to this the material properties which have been compared against have been for those at the beginning of life. Since many craft have a service life of 15-20 years or more this may have a further effect on the model. The stresses have been for out-of-plane loading and do not take into account residual stresses in the boat or for internal stresses developed within the application. Finally these designs have been for a minimum thickness for the predicted stresses and deflections and these results do not take into account problems in manufacturing to these specifications or the problems encountered in predicting the pressure. Chapter 10 analyses these results in terms of the reliability of the panel for both structures and production allowing the determination of partial factors to reduce the potential variability developed from having many unknowns for first principles modelling.

10 Optimised Plate Reliability Analysis

For the optimised plates given in Chapter 9 probabilities of failure have been investigated to determine the reliability of the structures that have been designed. This has been performed using the methodlogy that has been outlined in Chapter 6. Furthermore, sensitivity analysis has been carried out to determine the manner in which the different properties affect the structural and production design. The stiffened plates have geometric variation as outlined in Table 52 and for comparison used the same coefficients of variation as that of the earlier study by Shenoi et al. [29].

Table 52: Panel Properties

Design Variable	Mean	Coefficient of Variance(%)	Distribution
Panel Length, L	24000mm	3	Normal
Panel Breadth, B	2000mm	3	Normal
Pressure	131kPa	15	Weibull
E_f	71GPa	5	Normal
E_m	3GPa	3	Normal
G_f	35.5GPa	3	Normal
G_m	1.09GPa	3	Normal
V_f	0.55	3	Normal
ϵ_f	0.03	3	Normal
Crown Width	Rule Specific	3	Normal
Crown Height	Rule Specific	1	Normal
Web Width	Rule Specific	1	Normal
Wed Height	Rule Specific	3	Normal

10.1 First Principles

The reliability for the first principles model has therefore been carried out using the stiffener topology given in Table 53 and reproduced from that given in 44.

Table 53: Stiffener Topology for reliability comparison - First Principles

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness
Longitudinal	84.1mm	3.5mm	101.1mm	5.32mm
Transverse	46.1mm	1.26mm	101.1mm	9.16mm

The plate topology is given in Table 54 and reproduced from 45.

Table 54: Plate Topology for reliability comparison - First Principles

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness
Plate Topology	2200mm	720mm	3.3mm

The topology for an optimised plate designed from first principles is given in the above tables. This topology has been used to determine structural reliability, in terms of how often a plate that might break the limit state is produced, and production reliability, in terms of how often a plate with a cost higher than the cost limit state is produced. The reliability analysis has been used to investigate the sensitivity of the outputs, the stress, strength, deflection and cost, to the input characteristics. The sensitivity values have been normalised by multiplying the mean of the characteristic, as represented in Table 52, and have been represented as a percentile to give an easy understanding of the effect these characteristics have on the reliability.

10.1.1 First Principles Structural Reliability

The structural reliability for the first principles model resulted in a probability of failure of 6 $\times 10^6$. According to society reactions in Table 4 is a level that would not concern the average person and is below that required by the DNV rules. The sensitivity analysis has been shown in figure 40 with the four largest values shown in contrast to the other values. The values for this sensitivity analysis has been repeated in Table 55. This analysis has

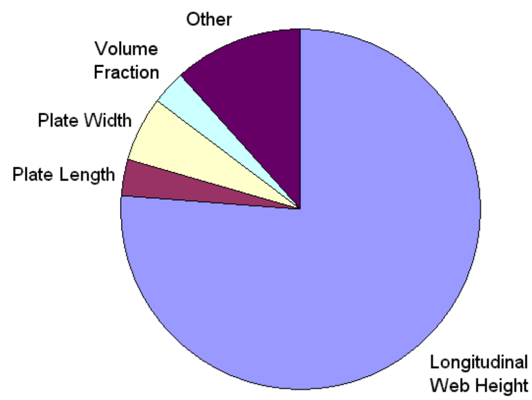

Figure 40: First principles structural sensitivity

been performed to inform production engineers how the decisions they make may affect the structural engineers' subsystem. The sensitivity analysis will return a high value for characteristics that have a large effect on the probability of failure and a lower value for those that have a lower effect. The results of the sensitivity analysis show where changes in cost can be made so as to ensure that the structural reliability stays at an acceptable level to the designer. These results show that longitudinal web height is by far the most important design variable to the structural engineer and must therefore be manufactured with a high quality by the production engineers. The other parts of the plate are less important and therefore could be produced with a lower quality to save time and cost

Table 55: First Principles Structural Sensitivity Results

Design Variable	Sensitivity	Design Variable	Sensitivity
Length	0.0343	Transverse Crown Width	0.0199
Breadth	0.0572	Transverse Crown Height	0.0026
Pressure	0.0136	Transverse Web Width	0.0062
E_f	0.0101	Transverse Web Height	0.0014
E_m	0.0002	Longitudinal Crown Width	0.0243
G_f	0.0026	Longitudinal Crown Height	0.0249
G_m	0.0024	Longitudinal Web Width	0.0005
V_f	0.0321	Longitudinal Web Height	0.7609
ϵ_f	0.0069		

without large repercussions in the structural integrity.

10.1.2 First Principles Production Reliability

Further to the structural reliability, production has also been analysed to determine the sensitivity of the cost to the different characteristic properties of the material. This analysis has been performed to allow the structural engineers an understanding of the manner in which the decisions they make will affect the cost of the product. It is important to ensure that negative changes, those that reduce the relaibility, that must be made are performed on characteristics with a low sensitivity and vice versa. The results for this analysis have been shown in Figure 41 and have been listed in Table 56 with the four largest values shown in contrast to the other values. It can be seen from these results that for the first principles structure the production is reliant upon the length and the width of

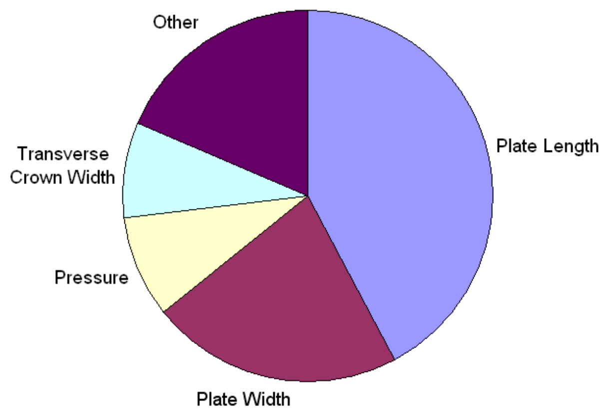

Figure 41: First principles production sensitivity

the panel. This is because the length and breadth are the largest composite dimension and therefore a percentage change on these values increases the cost of the panel the most. This indicates that the structural engineer will not want to extend the distance at which this stiffener spacing is used and if it is longer then a different topology will be required: for longer hull lengths a smaller stiffener spacing will be required. Furthermore the longitudinal stiffeners effect the cost to a higher extent than the transverse stiffeners. Within these values the web height and crown width have a large affect. Even though the transverse crown width is the most sensitive stiffener element. This is due to the coefficients of variation being higher whilst having a larger dimension size than the other stiffener dimensions.

10.2 Lloyds Register

The reliability for the Lloyds Register Rules optimised plate has also been determined. The stiffener topology is shown in Table 57. The plate topology is shown in Table 58. The reliability analysis has been performed with results as follows.

Table 56: First Principles Production Sensitivity Results

Material	Sensitivity
Length	0.4224
Breadth	0.2196
Pressure	0.0893
V_f	0.0263
Transverse Crown Width	0.0835
Transverse Crown Height	0.0001
Transverse Web Width	0.0004
Transverse Web Height	0.0314
Longitudinal Crown Width	0.0415
Longitudinal Crown Height	0.0668
Longitudinal Web Width	0.0078
Longitudinal Web Height	0.0109

Table 57: Stiffener Topology for reliability comparison - Lloyd's Register

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness	Base Wdith
Longitudinal	19.45mm	2.6mm	42.5mm	2.6mm	42.18mm
Transverse	82mm	6mm	44.5mm	6mm	100mm

10.2.1 Lloyds Register Structural Reliability

The Lloyds Register Rules optimised plate had a probability of failure of 2.33 $\times 10^{-5}$. Further to this the sensitivity analysis from this calculation results in the percentage

Table 58: Plate Topology for reliability comparison - Lloyd's Register

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness	Composite Layup
Plate Topology	212mm	222mm	5.4mm	90/0/0

sensitivities shown in Figure 42 with the four largest values shown in contrast to the other values. These values can be seen quantitatively in Table 59.

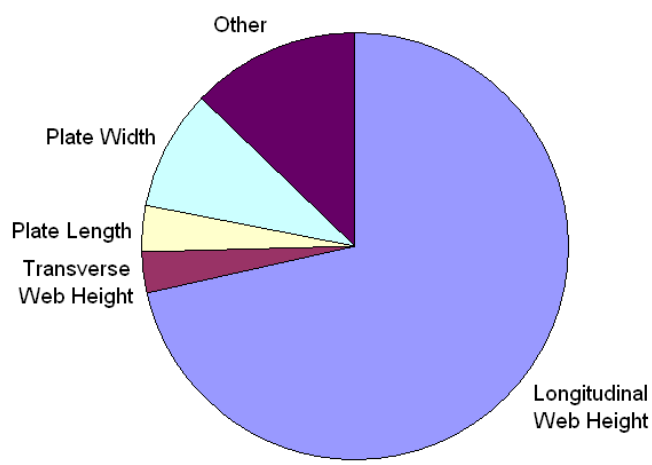

Figure 42: Lloyds register structural sensitivity

The structural reliability of the Lloyds plate can be seen to be most affected by the longitudinal web height which is the same as that for the first principles stiffened panel. This is because the stiffened panels were similar to each other in terms of proportions of the stiffeners. While the first principles stiffeners were smaller than those of the Lloyd's stiffened panel the entire topology of the stiffeners is similar. This therefore means that the web height will affect the deflection in the plate to a similar extent and this result is as expected. Again this means that production engineers would want to produce this

Table 59: Lloyds Register Structural Sensitivity Results

Material	Sensitivity	Material	Sensitivity
Length	0.0337	Transverse Crown Width	0.023
Breadth	0.0885	Transverse Crown Height	0.0054
Pressure	0.0197	Transverse Web Width	0.0116
E_f	0.012	Transverse Web Height	0.0296
E_m	0.0036	Longitudinal Crown Width	0.0069
G_f	0.0011	Longitudinal Crown Height	0.0034
G_m	0.0003	Longitudinal Web Width	0.0132
V_f	0.0296	Longitudinal Web Height	0.6935
ϵ_f	0.0249		

part with the highest quality, increasing the cost, in order to ensure a high reliability.

10.2.2 Lloyds Register Production Reliability

The Lloyds Register Rules structurally optimised plate has been analysed to determine the production sensitivity. The results for this sensitivity analysis have been shown in Figure 43 with the four largest values shown in contrast to the other values. These values have been recorded quantitatively in Table 60. For the production of the Lloyds Register Rules plate the cost is most sensitive to the transverse web height and the length of the plate. It is therefore important for the structural engineer to ensure that the stiffener spacing used here is not used past this length, in this case 24m. Therefore if the plate were to become longer, i.e. an extension of the boat length or distance over which the stiffener spacing was used, then a small stiffener spacing would be required. This also

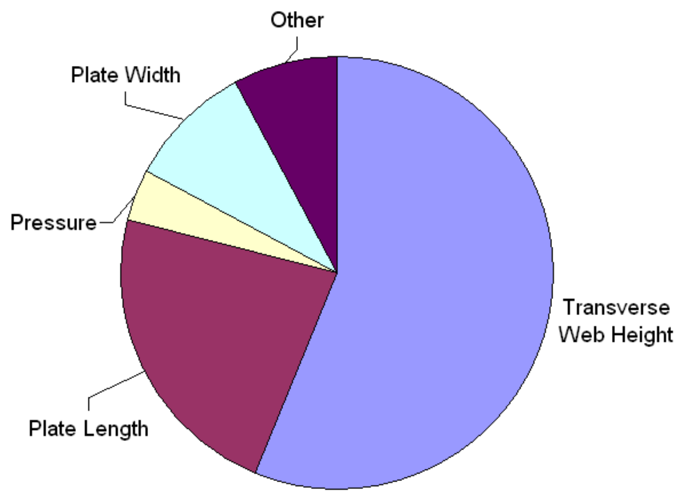

Figure 43: Lloyds register production sensitivity

means that if further strength is required that the web height is not increased. Vice versa if a small strength can be tolerated then these dimensions will be the first to be reduced to ensure a low cost.

10.3 ISO 12215-5

The reliability of the ISO 12215-5 plate has been determined for both structures and production. The ISO 12215-5 optimised structural plate has a topology developed as shown in Table 61. The plate has a topology as shown in Table 62. The optimised structures have been analysed for reliability as shown in the next sections.

10.3.1 ISO 12215-5 Structural Reliability

The structural reliability for the ISO 12215-5 plate has a probability of failure of 2.61 $\times 10^{-6}$. The plate has a structural sensitivity as shown in Figure 44 with the four largest

Table 60: Lloyds Register Production Sensitivity Results

Material	Sensitivity
Length	0.2297
Breadth	0.0939
Pressure	0.0376
V_f	0.0072
Transverse Crown Width	0.0223
Transverse Crown Height	0.0003
Transverse Web Width	0.0010
Transverse Web Height	0.5600
Longitudinal Crown Width	0.0241
Longitudinal Crown Height	0.0179
Longitudinal Web Width	0.0038
Longitudinal Web Height	0.0022

Table 61: Stiffener Topology for reliability comparison - ISO 12215-5

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness	Base Width
Longitudinal	10mm	1.17mm	1mm	4.39mm	212.35mm
Transverse	161mm	5.66mm	4mm	4.03mm	212.35mm

values shown in contrast to the other values.

The values from this figure have been listed in Table 63.

The ISO 12215-5 plate is most structurally sensitive to the volume of fibres in the

Table 62: Plate Topology for reliability comparison - ISO 12215-5

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness	Layup
Plate Topology	386mm	232mm	10.6mm	90/0/0/0/90

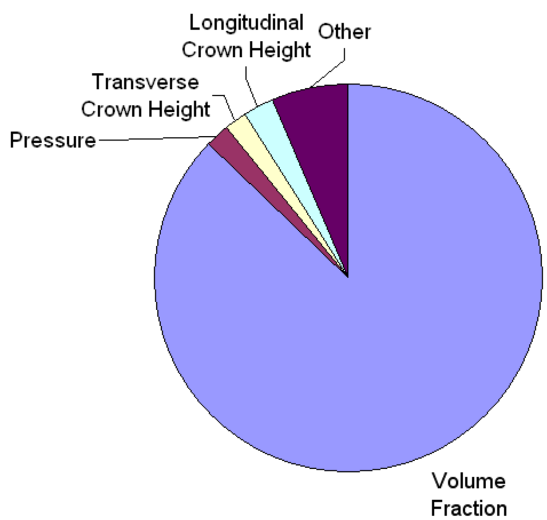

Figure 44: ISO 12215-5 structural sensitivity

plate and therefore production engineers will need to ensure that the volume fraction is accurately produced. The other values are less sensitive and therefore to reduce the cost these values should be the ones to concentrate on as the a reduction in the volume fraction of fibre could lead to structural failure.

10.3.2 ISO 12215-5 Production Reliability

The ISO 12215-5 plate has been analysed to determine the sensitivity of the cost to the different characteristics of the plate. These values have been shown in Figure 45 with the four largest values shown in contrast to the other values. These values have been listed

Table 63: ISO 12215-5 Structural Sensitivity Results

Material	Sensitivity	Material	Sensitivity
Length	0.002	Transverse Crown Width	0.0066
Breadth	0.0069	Transverse Crown Height	0.0195
Pressure	0.0194	Transverse Web Width	0.0004
E_f	0.0015	Transverse Web Height	0.0046
E_m	0.0019	Longitudinal Crown Width	0.0038
G_f	0.0002	Longitudinal Crown Height	0.0240
G_m	0.0034	Longitudinal Web Width	0.0192
V_f	0.8730	Longitudinal Web Height	0.0059
ϵ_f	0.0076		

in Table 64.

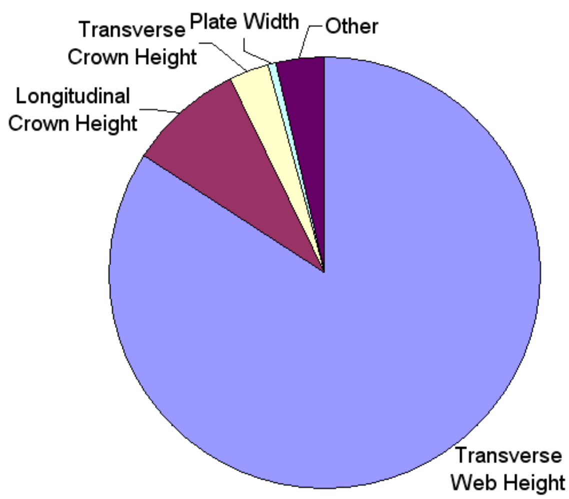

Figure 45: ISO 12215-5 production sensitivity

Table 64: ISO 12215-5 Register Production Sensitivity Results

Material	Sensitivity
Length	0.00758
Breadth	0.00769
Pressure	0.00029
V_f	0.00759
Transverse Crown Width	0.00761
Transverse Crown Height	0.03085
Transverse Web Width	0.00356
Transverse Web Height	0.84132
Longitudinal Crown Width	0.00045
Longitudinal Crown Height	0.08535
Longitudinal Web Width	0.00006
Longitudinal Web Height	0.00764

For the ISO 12215-5 plate it can be seen that the transverse web height will have the largest effect on the plate and therefore increases in this value would be inadvisable, hence, concentrating on reducing this value would be beneficial to the cost of the design. The longitudinal stiffeners have a much lower effect on the cost. Therefore if changes are to be made to decrease the cost it would be better to concentrate on the transverse stiffeners. Furthermore the volume fraction makes only a small difference so there is no requirement to change this value as it will take a large adjustment to affect a significant shift in the cost.

10.4 Summary

A methodology for structural reliability has been developed and verified against previous work as shown in Chapter 6. This reliability method has been used to make assessments of optimisations each with different structural models. The different results for the models have been listed in Table 65.

Table 65: Comparison of Lloyds Register Rules for Special Service Craft and First Principles Probabilities of Failure

Method	Safety Factor	Reliability Index,β	Probability of Failure, P_f
Lloyds Register Rules for Special Service Craft	3	4.07	2.33×10^{-5}
First Principles Method	Minimal	4.38	6×10^{-6}
ISO 12215-5	Partial	4.56	2.61×10^{-6}

The reliabilities shown have similar values to each other a very surprising result due to the difference in safety factors for each set of strcutural modelling. It can be seen that the Lloyds Register Rules solution is the least reliable of the stiffened plates. This result is unexpected as this plate would be expected to be the most reliable due to the large safety factors used within the creation of these rules. The ISO standard would be expected to be the next most reliable plate as it uses partial safety factors to reduce the risk to a useable level while still gaining a reduction in mass.

Finally the first principles approach, which uses failure criteria, would be expected to be the least reliable. All of the failures were due to deflection and this failure criteria is for an arbitrary value of twice the mean deflection. For each of the methods the plate failed when they reached twice the mean value of deflection for this method. This therefore means that the Lloyds plate, with its smaller mean deflection, would fail at a lower deflection value than the other methods. This is not realistic within a boat design where the deflection criteria is in place to ensure that the hull walls do not encroach on the interior of the boat. A new deflection criteria needs to be put into place to ensure that the different methods can be fairly compared against each other as the current criteria of twice the mean value is arbitrary and is unfair when different materials are compared.

The designs do not produce a stress failure. This therefore indicates that further work must concentrate on other modes of failure and also to increase the stress analysis to include residual stresses and in plane loading for the vessel to corroberate the fact that the stress failures do not occur during service. Analysis of the pressures created on the hull will require investigation to ensure that the values that have been used are conservative compared to the pressure resulting from service. This structural analysis has concentrated on the strength of the hull at beginning of life and not considering residual or internal stresses and investigations into these areas will provide a more comprehensive study into structural modelling. It is unrealistic to expect a boat to fail due to maximum stress at the beginning of life if the conditions it meets are not larger than have been anticipated during design.

It is possible to see from the reliability results that the sensitivity of the parts are dependant upon the dimensions of the plate. This knowledge shows that general statements cannot be made about which part should be changed for any given design and that it is of key importance that this analysis must be carried out for each individual design. Furthermore as shown by Sobey et al. [105] the input distributions can have a large impact upon the final output probability of failure of the model. For the modelling of the input distributions this does not just indicate finding a good match to the results but also that the distributions themselves have a high relaibility in terms of accurately determining mean and variance. It is therefore of key importance that for use of these reliability techniques that the input distributions are modelled accurately from experimental data found from real applications.

The use of reliability analysis as a tool for design for production and automated communication has been shown. This methodology has shown the manner in which it can be useful for analysing designs so that subsystem designers more intuitively understand the other subsystems of the boat. Furthermore it has been shown that to gain a realistic idea of the probability of failure of the composite grillages that further development is required for the models and the failure criteria.

11 Application of the Concurrent Engineering Environment

The automated tools of the concurrent engineering methodology has been applied to the creation of a grillage. This case study starts with Quality Function Deployment which is used to generate the weightings for the optimisation process. The optimisation is then run using the first principles grillage method. Finally a reliability analysis of the panel is carried out and partial safety factors are formulated to ensure that the panel does not fail during service. This results in a topology that should be safe during service but optimum for both the mass and the cost.

11.1 Quality Function Deployment

The Quality Function Deployment process has been used to create a customer requirements for a fictitious customer. The results of this Quality Function Deployment can be seen in Table 66.

In Table 66 the requirements of a fictitious customer have been represented quantitatively. In this example the customer requires lots of gadgets on board the boat which in turn effects the mass of the hull to a high extent as each item will have a mass but will not require a change in the cost of the hull structure significantly. The customer also requires a fast boat which will also affect the hull in much the same way as having lots of gadgets on board will. The customer does not require a cheap boat which will not affect the mass of the boat but has a high relation to the cost of the boat. Finally the customer would also like the hull to withstand impacts and be watertight both of which will have impacts on the mass and the cost of the hull. The results have led to the requirements of a hull in which a low mass is important in the final design. From

Table 66: Quality Function Deployment - Case Study

		↓	↓
Customer requirements	Design Criteria Weighting	Mass	Cost
Lots of Gadgets	9	9	4
Fast	9	9	3
Cheap	2	2	9
Withstand Impact	6	8	8
Watertight	6	8	8
Technical Priorities		262	177
Technical Priorities as a Percentage		59.7	40.3

Table 66 it is possible to see that the weighting for the cost is approximately 0.4 and for the mass it is about 0.6. This process is heavily biased towards the mass of the hull assuming that the hull was produced in a situation where boat mass was more important than the cost of the hull. It is also possible to see from the arrows on the quality function deployment that these values must be reduced and it is therefore possible to determine that the values must all be reciprocals within the weighting equation, eq. 63. For a real design, the process of Quality Function Deployment would be much larger with 20 to 30 different customer requirements and design criteria. This process would then generate a more even weighting distribution as the end design is normally a compromise between all of the different characteristics with most of these areas being important to the success of the final product.

11.2 Optimisation Study

Having developed the weightings for the optimisation process a genetic algorithm has been run using the first principles structural model. The optimisation has been performed in the same manner as in each Chapter 8 to 10 including the pressure of 131.47kPa the same 24m length and 2m width to allow a fair comparison between the results. The stiffener topology for the case study, using the weighting from the Quality Function Deployment, is therefore shown in Table 67.

Table 67: Stiffener Topology for Case Study

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness*Width	Base
Longitudinal	79.3mm	2mm	11.1mm	10.94mm	101.4
Transverse	64mm	1.98mm	92.7mm	3.84mm	62.7

The topology for the plate can then be seen in Table 68.

Table 68: Plate Topology for Case Study

	Longitudinal Stiffener Spacing	Transverse Stiffener Spacing	Plate Thickness	Layup
Plate Topology	390mm	2200mm	3.3mm	90/0/0/0/90/90

This plate has similarities with the plate from the first principles optimisation. However the stiffener spacing is smaller and hence the size of the stiffeners have been reduced. This is as expected from the previous results as an effective decrease in mass involves the increase in stiffeners however this comes at a penalty in cost. Hence for a low mass, high cost scenario, like the case study, a small stiffener spacing can be expected. Having developed an optimised plate a reliability analysis can then be performed to determine the manner in which design changes can be made and to also produce partial safety factors for the grillage.

11.3 Reliability Study

A reliability analysis has been carried out upon the developed plate resulting in a probability of failure of 7.76 $\times 10^{-5}$. Checking this reliability factor against DNV rules [7] this is a "safe" reliability and falls in the region of "rare" to "not of great concern to the average person". Having determined this reliability it is then possible to determine the sensitivity of the stucture to different input variables, Figure 46 shows the sensitivity to the structural solutions, having the four largest variables shown in contrast with the rest lumped together.

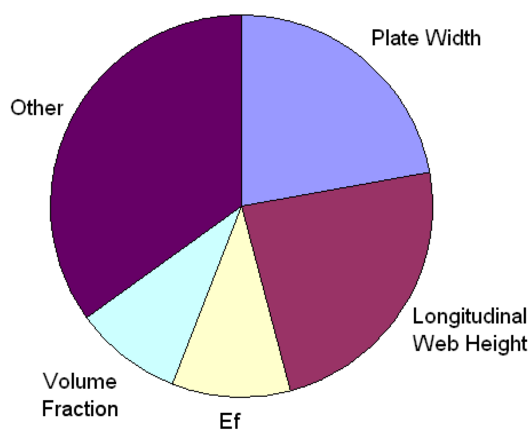

Figure 46: Case study structural sensitivity

These results have been reproduced quantitatively in Table 69.

From these results it is possible to determine the most sensitive parts of the structure to increasing or decreasing the probability of failure. It can be seen from these results that

Table 69: Case Study Structural Sensitivity Results

Material	Sensitivity	Material	Sensitivity
Length	0.099	Transverse Crown Width	0.06
Breadth	0.267	Transverse Crown Height	0.002
Pressure	0.06	Transverse Web Width	0.034
E_f	0.121	Transverse Web Height	0.004
E_m	0.006	Longitudinal Crown Width	0.044
G_f	0.002	Longitudinal Crown Height	0.065
G_m	0.003	Longitudinal Web Width	0.034
V_f	0.108	Longitudinal Web Height	0.087

the breadth of the plate, Young's modulus of the E-glass fibres and the volume fraction are the most important. This requirement means that an increase in breadth or a decrease in the other values should not be made by the production engineer. From these results it is possible to see that the transverse web and crown heights can be created faster and with a lower accuracy, to reduce cost, as these parts are less structurally integral and that the longitudinal stiffeners are more important than the corresponding transverse ones.

Having determined the results for the structural sensitivity it was then important to determine the cost sensitivity of the plates as shown in Figure 47 with the four largest values shown in contrast to the other values. The results for these sensitivities have been shown quantitatively in Table 70. The results show that the length and breadth of the stiffened panel have the most effect on the cost. After this result it is the longitudinal crown width that has the next largest effect. These results show that the volume fraction had little effect on the cost and as this had a large effect on the structure, structural

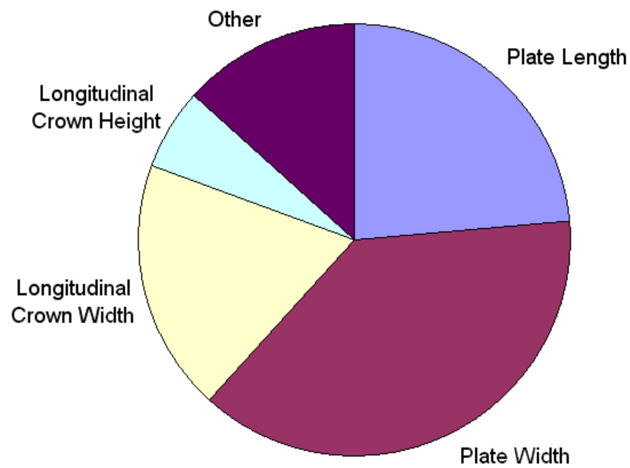

Figure 47: Case study production sensitivity

engineers may wish to change this number to increase strength with a small increase in the cost.

From these sensitivity analyses it is then possible to develop a set of partial factors, through the method outlined in Chapter 6, for structural integrity giving the resulting topology and corresponding partial factors for the plate as can be seen in Table 71. This analysis has been performed to gain a more effective analysis in comparison to the classification society rules taking into account that deterministic methods can not be used for real life designs and safety factors will need to be taken into account. The resulting topology is only a slight increment above that already seen within the plate dimensions. This is because the probability of failure of the case study was low and therefore was a stable panel to begin with. Partial factors to reduce this probability of failure are therefore going to be small. A larger difference between the relaibility obtained and that required would have produced a much larger set of safety factors.

Table 70: Case Study Production Sensitivity Results

Material	Sensitivity
Length	0.2353
Breadth	0.3825
Pressure	0.0253
V_f	0.0256
Transverse Crown Width	0.0066
Transverse Crown Height	0.0001
Transverse Web Width	0.0018
Transverse Web Height	0.0563
Longitudinal Crown Width	0.1874
Longitudinal Crown Height	0.0621
Longitudinal Web Width	0.0040
Longitudinal Web Height	0.0130

11.4 Summary

These models have then been combined together and test studies have been carried out upon the models to ensure that they are working correctly. Finally these techniques have been combined together on a small case study to show that the methods can work in combination. The case study showed the manner in which a Quality Function Deployment can be used within the genetic algorithm to develop results more closely related to customer requirements. In the example given it was deemed that a low mass was more important than the cost. A comparison with the mass and cost developed from the other optimisations can be seen in Figures 48 and 49.

Table 71: Stiffener Topology for Case Study with Partial Safety Factors

Stiffener Type	Web Height	Web Thickness	Crown Width	Crown Thickness
Longitudinal				
Safety Factor	1	1.05	1.03	1
Topology	79.39mm	2.1mm	11.48mm	10.96mm
Transverse				
Safety Factor	1.11	1.11	1.03	1.21
Topology	71.35mm	2.2mm	95.14mm	4.66mm

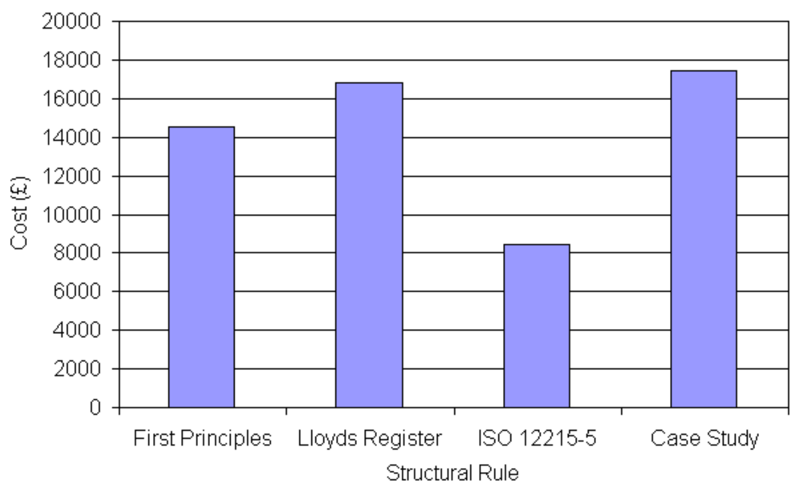

Figure 48: Comparison of cost for structural optimisations

These results show that the model developed a hull that had a lower mass but as cost was less important this hull became more costly. This result was to be expected and validates the use of Quality Function Deployment with genetic algorithms. While the results show a difference occurs when the weighting ratio changes this value will need to be

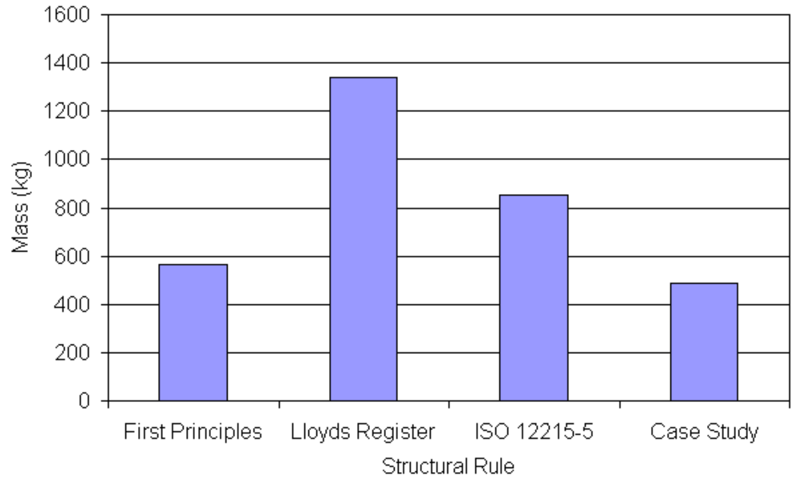

Figure 49: Comparison of mass for structural optimisations

assessed for each yard to determine how the sensitivity of these values effects the overall weighting as a level of subjectiveness is required in the Quality Function Deployment creation.

A reliability analysis has been carried out on these results and it can be seen the hull became less reliable as mass is reduced. The arbitrary nature of the deflection criterion should be noted when making comparisons between different models. Further to this, partial factors gave a small increase in mass and cost but due to the high reliability of the plate only a small change was necessary. In the case where this plate was less reliable the partial safety factor plate would have been larger. It is difficult to make a comparison between the partial factors developed in this methodology with those of the ISO 12215-5 plate without further modelling using fatigue criteria and a holistic model of the boat loading.

A method for aiding the process between concept and detailed design has been determined. This methodology has been validated and the effects of the different sections investigated. It has been determined that further constraints for the structural model should be investigated. Furthermore it has been shown that the models are highly dependent upon production modelling which will require further investigation. The tools developed have been created to fit in with a larger concurrent engineering methodology specific to the boatbuilding community. Chapter 12 summarises the findings of the concurrent engineering approach and details of work that will further validate the findings and ensure that a more detailed design is created early in a project.

12 Conclusions and Recommendations

12.1 Conclusions

The leisure boatbuilding industry has low profit margins and volumes of product. It is therefore key that engineers can carry out design work quickly and effectively while ensuring the final designs are both high quality and low cost. Concurrent engineering is a process for design that has had a great effect within other industries around the world. The current work looks into the manner in which concurrent engineering can be developed within the boatbuilding industry while developing techniques that will allow a smooth transition of the process into design offices.

A method for concurrent design within the boatbuilding industry has been developed. This method has been created specifically for the industry using a combination of affordable current methods with a new methodology and tool base. The methodology has been based around the manner in which boatbuilding is currently approached, building upon a strong input from the supply chain and the customer. Optimisation has been developed to aid the concept design stage and to transfer through to the initial stages of the detailed design. Detailed design and production have been aided using reliability as a method of generating a better understanding between the design team. The introduction of a design environment and a tool to search design histories has been used to aid the communication during the detailed design stage.

Included within the structural analysis of the composite grillage panel are up to date failure criteria further constraining the model from that of the previous work. These new criteria have been investigated to determine the effects that these values have upon the structure and compared with those of classification society rules.

Optimisation has been developed to allow the dimensions of the stiffeners to become part of the input variables and the input constraints have been expanded to allow the problem to be become less constrained allowing the optimised result to take any realistic form. The optimisation process has been expanded so that it has become a more design orientated tool using Quality Function Deployment as a customer centric initialisation point. Production modelling has been further expanded and the importance that this modelling has over the final design has been investigated.

Reliability analyses has been investigated to understand the manner in which stiffened panels react to different input variables. Production reliability has been invesitgated to understand the manner in which panels could be produced in a cost reliable fashion. Finally, partial factors were developed to allow a comparison with the first principles and classification society results.

A concurrent engineering environment has been adapted for use within the boatbuilding industry. Methods have been developed for the effective transfer of both data and information between the design team. A method of extracting information from previous designs has also been determined. The transfer methods have been incorporated within an environment that will allow a fast and cheap solution to the computing challenges associated with the concurrent engineering environment. The environment has been developed conceptually and the next stage in development will be to determine the benefits that it creates in industry.

A list of main contributions of this research work are summarised as follows:

- Review of the boatbuilding industry and determination of the requirements therein.
- Continued development of models associated with areas of the design for production.
- Verification of the models created
- Further development of Genetic Algorithm optimisation as a robust design tool.

- An analysis of structural and production reliability within composite construction.
- Proposed an effective method for concurrent engineering within the leisure boatbuilding community.

12.2 Recommendations for Future Work

Testing of the concurrent engineering environment will be required through determining the difference in design time and quality before and after the integration of the environment into industry. Further development of concurrent engineering within the leisure boatbuilding industry could be achieved through investigation of a number of different areas:

- Development of hydroelasticity models for first principles modelling to determine the pressure loads during service.
- Development of fatigue failure criteria for first principles modelling to determine the effect that fatigue will have both upon the reliability and the optimisation of the model.
- Create a detailed production model further developing the current model to allow for a production reliability analysis to be carried out and coefficients of variation to be accurately determined.
- Development of optimisation to include models of a full ship hull including stresses from internal sources.
- Develop full FEA models to ensure that the maximum stresses calculated within the grillage are accurate for the full model.

- Experimental validation of the finally optimised designs.
- Improvements to the Genetic Algorithm to allow more generations to be run.

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A SSA Production Model

Table 72: SSA Hand layup Production Model

Action	Time(mins)
Fairing Compound	10 minutes/sqm
Smoothing Fairing Compound	60 minutes/sqm
Apply Release Compound	10 minutes/sqm/ply
Cutting cloth	10 minutes/sqm/ply
Laying cloth	5 minutes/sqm/cloth
Cutting and laying core	60 minutes/sqm/core
Apply resin with brush or roll	10 minutes/sqm
Remove the components from the mould	30 minutes/sqm
Quality Inspection	3 minutes/sqm
Trim	15 minutes/m/edge

B Questionnaires