The Digital Reconstruction of the Sutton Hoo Ship

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This article describes the digital reconstruction of the ship remains from Mound 1, at the early 7th-century Anglo-Saxon burial ground at Sutton Hoo, East Anglia, UK. This research provides a critical component of the wider project to build a full-scale reconstruction of the Sutton Hoo ship. The nature of the archaeological record relating to the Sutton Hoo ship is outlined, and the subsequent assumptions underpinning the digital reconstruction explained, followed by a step-by-step account of that work. Hydrostatic testing of the resulting digitally reconstructed hull is then presented, allowing new insight into the capacity and capability of the vessel.

Keywords: Sutton Hoo, Anglo-Saxon, ship-burial, reconstruction, digital, experimental archaeology.

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Introduction

The early 7th-century-AD Anglo-Saxon ship-burial site found under Mound 1 at Sutton Hoo in Suffolk, England, is one of the earliest, richest, and most important ship burials from early medieval northwest Europe. Indeed, it is one of the most famous archaeological sites in the world, a status stemming mainly from the stunning wealth of grave-goods excavated from the site and now displayed in the British Museum. The imprint of the ship, *c.*27 m in length, left behind in the soil, attests to a large vessel fit to contain a royal burial. The vessel itself is the largest pre-Viking clinker-built vessel found so far, giving a further indication of its overall significance, and to nautical archaeology in particular. The general arrangement of the ship, its burial, and place within the wider context of the site has been understood through initial excavation in 1939, and further re-excavation in mid and late 20th century (see Carver, 1998; 2005; 2017 for overviews of the work). More widely, the maritime aspects of Anglo-Saxon England, including the conceptual position of Sutton Hoo, have been increasingly explored and disseminated (Carver, 1990; 2014; Carver and Lovelock, 2013; Klein *et al*., 2014). More specific to Experimental Boat and Ship Archaeology (EBSA) research, a half-scale reconstruction of the ship was built in the 1990s and subjected to trial voyages (Gifford and Gifford, 1996). However, the detail of the vessel has not been reconstructed or investigated from an experimental archaeological perspective using the digital techniques now available. These have considerable potential to offer a new perspective on the construction and use of the ship, while also offering the opportunity to explore the application of such techniques to maritime archaeological material.

After a long period of gestation, an integrated project to undertake the design, construction, and trialling of a full-scale reconstruction of the Mound 1 ship was initiated in 2014 at Woodbridge, close to the Sutton Hoo burial ground, under the auspices of a group of local and international stake-holders united as the Sutton Hoo Ship's Company[1]. The overall objectives of the project are to create an interpretation of the Anglo-Saxon ship from Mound 1 that provides the best possible means of testing and understanding how the ship could have been used under a range of different conditions. This will be achieved by: using modern technologies and a range of professional skills to interpret data from records of the 1939 and 1967 excavations including information about the impact of the burial process and passage of time to develop a design brief for a ship resembling the ship that was built and subsequently buried in Mound 1; using the design brief to build a ship based on the current understanding of the materials and building methods that would have been used by Anglo-Saxon shipbuilders; carrying out estuary, river and sea-trials to test hypotheses regarding how the ship was propelled and manoeuvred (by oars and/or sail), what it could have been used for, what it may have carried, under what conditions was it safe and therefore where it might have been sailed; carrying out experiments on portage to inform the likely methods of moving the ship over

[1] https://saxonship.org/

land, as was eventually achieved in the journey to its place of burial; providing a comprehensible, informative and entertaining means of engaging the public and so increasing understanding and appreciation of Anglo-Saxon life and culture; and achieving these objectives in a way that enables local people of Woodbridge to engage in all stages of the project either through active participation in the build process or ancillary activities, such as recording, interpretation, and guiding.

With the above in mind, the work of delivering the elements of the project directly concerned with the ship reconstruction was split into four phases (originally set out in Carver, 2015):

1) design the ship, propose the hypotheses for testing and publish the design;
2) construct the ship, and assess and publish the experience;
3) test the ship in different conditions, making different journeys and publish the results; and
4) complete publication and dispose of the ship to a good home.

Those familiar with a wider discussion of EBSA will appreciate that these phases relate, in a general sense, to the project stages outlined by Coates *et al.* (1995: 294, fig. 1), while also taking into account the concerns and thoughts expressed by Crumlin-Pedersen (1995). In addition, it will be noted that several of the overall objectives relate to motivating factors outside the purely academic ones, and these are no less important in the context of the overall project because of the value that they bring to the community of Woodbridge and the general public more widely (see also Goodburn, 1993: 200–202). Phase One itself was termed 'The Design Phase', and was originally conceived in February 2016 as comprising a single aim (formally set out in Whitewright, 2017), namely: To establish the design for the proposed reconstruction of the Mound 1 ship, that can be taken forward to Phase Two. This should take into account relevant archaeological, historical and experimental material, and expert opinion.

Achieving this aim was itself founded on the completion of four objectives set out in the Phase One project design (Whitewright, 2017):

1) Assimilation of existing material relating to reconstructing the Mound 1 ship into 3D modelling systems in advance of testing;
2) Establishment and testing of a basic hypothetical reconstruction through computational methods to ensure basic criteria of stability, flotation, and so on are met;
3) Modelling the hypothetical reconstruction into a full construction model through computational methods to ensure its feasibility, functionality and to inform the physical building in Phase Two;
4) Consultation with selected experts in the field of EBSA to seek their opinion regarding the subsequent building process, construction details, and so on.

Of these, Objective 1 has remained ongoing for duration of the work on the project and, given the difficult nature of the dataset resulting from the excavation of Sutton Hoo, is likely to remain an ongoing part of the wider project throughout all its phases. Objective 2 was completed in 2016 with the publication (Handley, 2016) of a naval architecture assessment, using a faired version of the 1939 lines plan to represent the underlying hull shape. That work reached the conclusion that the ship, as envisaged by a lines plan alone, met fundamental criteria of stability, flotation, and so on. Work then began on Objective 3, the process of which is formally described below, to undertake a more detailed reconstruction of the vessel using digital techniques to allow the modelling of individual components, based on the original archaeological record. Although expressed as a 'reconstruction model' to distinguish it from the 'lines plan' model underpinning Objective 2, the output aimed to remain as far as possible within the realm of the 'minimum reconstruction' as outlined by Crumlin-Pedersen and McGrail (2006: 56–57).[1] Finally, consultation to achieve Objective 4 was undertaken across Phase One, with particular efforts focused on a dedicated international symposium held in Woodbridge (October 2018), and at the 15th International Symposium for Boat and Ship Archaeology (ISBSA 15) held in Marseilles (October 2018). The former of these dealt with targeted questions and discussion around the reconstruction project, while the latter entailed the presentation of a poster, two interim reports, and a 3D printed model of the reconstruction to the ISBSA delegates.

With the above in mind, this paper sets out the process by which Phase One of the project has been undertaken, with the aim of producing and presenting a digital reconstruction of the Sutton Hoo ship in advance of full-scale reconstruction (Fig. 1). The findings of Phase One in relation to the digital reconstruction of the Sutton Hoo ship are presented, and in doing so the process of consultation and dissemination, via peer-reviewed publication, is completed. It begins with an overview of the available dataset appertaining to the Sutton Hoo ship, representing the 'preservation by record' of the now-destroyed ship remains. A number of assumptions arising from this are then set out, alongside three guiding principles that were adopted to aid the digital reconstruction process. That process is described on a step-by-step basis, prior to coverage of the hydrostatic testing conducted on the resulting model. As well as its place within the overall Sutton Hoo project, the work sheds new light on the potential cargo-carrying capacity of the Sutton Hoo ship, as well as highlighting the power of digital EBSA processes, and some of the challenges faced when using them.

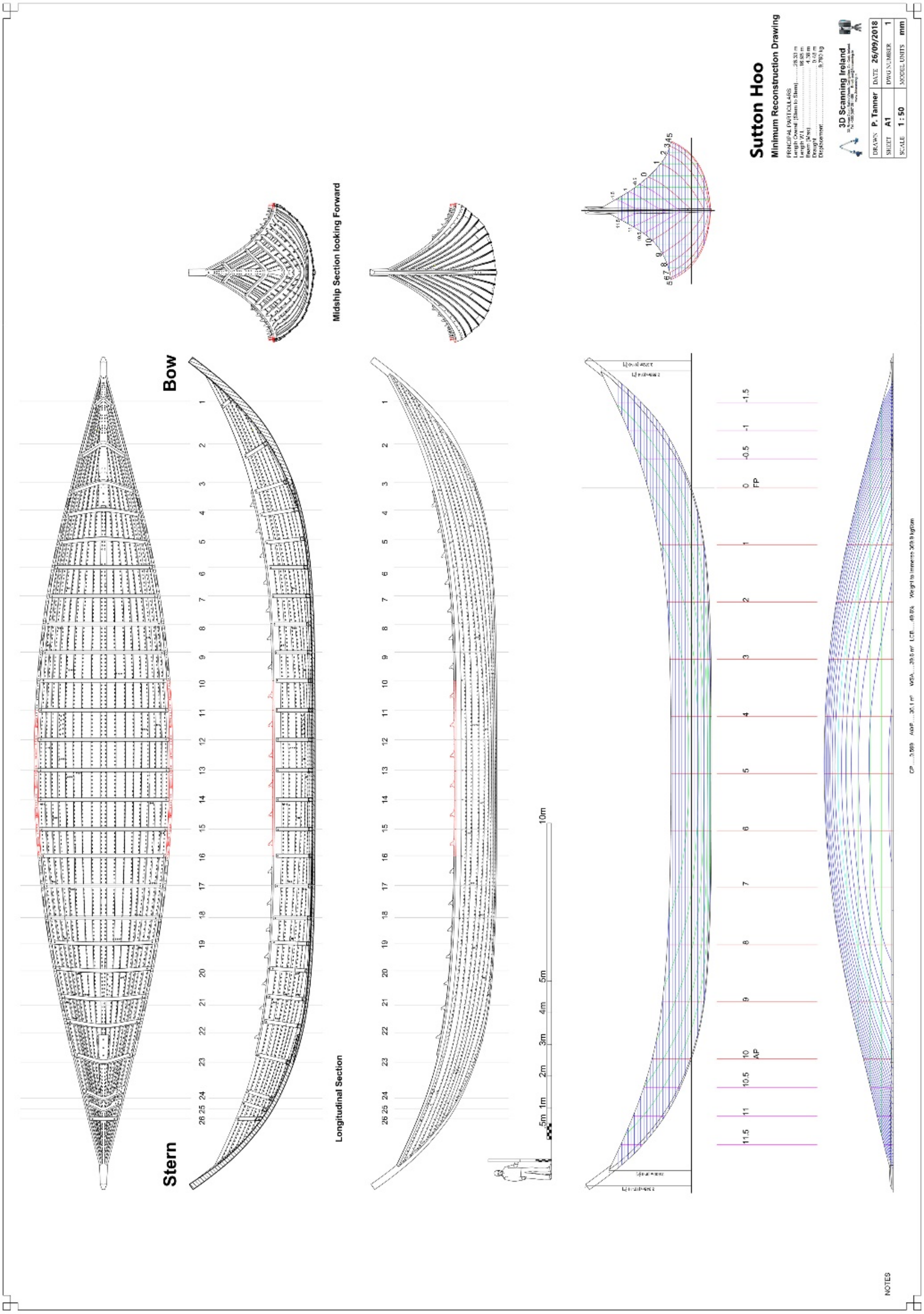

Figure 1. *Minimum reconstruction drawing of the Sutton Hoo ship: plan, profile, cross-section and hull lines (Sutton Hoo Ship's Company).*

The archaeological record of the ship

Chronology of investigation

Sutton Hoo is on the eastern side of the river Deben, across from Woodbridge, Suffolk, England. The burial ground is in a dominating position, 30 m in elevation, on acid, sandy soil. There are 17 mounds of various sizes, and three of them were excavated in 1938. These had been robbed but showed clear evidence of high-status Anglo-Saxons and in one case of a ship-burial. 'Mound 1', the most prominent, showed signs of some disturbance at its western end, and it was not excavated until 8 May 1939, by Basil Brown and two assistants (for an extended account, see Carver, 1998: 2–24; 2005: chapter 6). A rivet from the bow of the ship was discovered within three days. Charles Phillips took over the project while the ship was being unearthed, and the burial chamber was opened on 20 July. The treasure was removed by 31 July. Soon afterwards it was donated by the landowner, Edith Pretty, to the nation, and it is now in the British Museum. Recovered gold coins have been dated as AD 610–630, and most experts are content to attribute the grave to Rædwald, King of East Anglia, who died AD 624–625.

Due to the acidic soil, no wood from the ship's hull survived, but careful excavation meant the surface of the wood was still defined by a delicate crust. The interior surface of the clinkered planking had been pushed to the exterior, to form a thin carbon layer, with the shanks of the rivets standing proud and *in situ*. The shape of the ribs largely survived, rectangular in section, and filled with sand. The overall length was roughly 27 m, and the beam 4 m. A team of three from the Science Museum, led by Commander J.K.D. Hutchison, began to survey the ship on 9 August. They worked until 22 August. Phillips pursued several investigations with Hutchison, in particular looking for evidence concerning the keel, stem, and stern. Two capable amateur photographers, Mercie Lack and Barbara Wagstaff, made an invaluable record of the proceedings, the archive of which is held in the British Museum.

The process of surveying and recording the impression of the ship in the ground is described by Crosley (1942). Datum lines were established, and through a three-person operation, the horizontal and vertical position of a rivet at a point 'adjacent to the clench nail near a rib' could be measured (Crosley, 1942: 110). This process was repeated for rivets on each of the eight rows up the frame (Crosley, 1942: 110). As a result of this approach, Crosley notes (1942: 110) that 'a few hundred dimensions were taken on the port and starboard sides between the 26 ribs of the ship'. It was evident to Crosley that the ship was canted by at least 5 degrees, and there was at least one place where the keel was not straight. The line of the keel was recorded by uncovering the iron nails between the frames and stem/keel/stern along the centreline, and then recording their horizontal and vertical locations, the latter with a dumpy level (Crosley, 1942: 110).

This work resulted in the primary dimensional record of the 1939 excavation in the form of two plans, which survive as a microfiche in the archives of the Science Museum (Fig. 2). One (Science Museum, 1939a), shows a lines plan (Fig. 2a), and is described here as the 1939 lines plan (Table 1). Crosley had also produced a 'provisional drawing' (Science Museum, 1939b), in September 1939, and Hutchison, who had gone on active service almost immediately after the war started, signed off a tracing of it on 30 November 1939. This second drawing (Fig. 2b) consists of a plan, profile, and cross-sections to show the constructional details of the vessel, along with details of elements such as rivets, gunwale spikes, and so on. It is described here as the 1939 reconstruction drawing (Table 1). Unfortunately, Hutchinson died from natural causes in 1944, and his widow burned all his papers. In a further twist of fate, the room at the Science Museum where all the notes from the survey were archived was later destroyed by a bomb. This left the two drawings and the archive of photos from Lack and Wagstaff as the primary record of the excavation.

Table 1*: Existing lines and reconstruction drawings derived from the archaeological excavation of the Sutton Hoo ship, as described and included in this paper.*

Description in this paper	Made by	Reference for original source	Shown in this paper as:
The 1939 lines plan	A.S. Crosley	Science Museum reconstruction drawings of the Sutton Hoo Ship, 1939. 2012/A, lines plan. (Image copyright: Science Museum/Science & Society Picture Library). Also reproduced in (Phillips, 1940a) and (Phillips, 1940b)	Fig. 2 A)
The 1939 reconstruction drawing	A.S. Crosley	Science Museum reconstruction drawings of the Sutton Hoo Ship, 1939. 2012/B, construction plan and profile, details of fastenings (Image copyright: Science Museum/Science & Society Picture Library). Also available as: Science Museum 1939. Drawing No 2012/B, Provisional Drawing, 2 Sheets, Sheet 2. Colchester and Ipswich Museum.	Fig. 2 B)
The 1973 lines plan	Colin Mudie	Evans, A. C. and Bruce-Mitford, B., 1975, The Ship. In R. Bruce-Mitford (ed.) *The Sutton Hoo Ship Burial*, 345-435. London. As figure 324.	Not reproduced
The 1975 reconstruction drawing	British Museum	Evans, A. C. and Bruce-Mitford, B., 1975, The Ship. In R. Bruce-Mitford (ed.) *The Sutton Hoo Ship Burial*, 345-435. London. As figure 325.	Fig. 5

The site was revisited by the British Museum from 1965 to 1970 (see Carver, 1998: 25–51). The ship had simply been covered by bracken when it was left in 1939, and the stern suffered some damage when the site was used by the army in 1942. The much-degraded remains, together with the 1939 photographs, were investigated exhaustively as part of the wider publication of the site (Bruce-Mitford, 1975). A lines plan (submitted by the naval architect Colin Mudie in 1973) and a reconstruction drawing were published (Bruce-Mitford, 1975: figs 324 and 325) and are described here as the 1973 lines plan and 1975 reconstruction drawing respectively (Table 1). However, Bruce-Mitford does not comment on them or even reference them in the text of the 1975 volume. This situation arose because two key members of Bruce-Mitford's team had been seconded to the National Maritime Museum when the Anglo-Saxon Graveney boat was discovered in September 1970 (Evans and Fenwick, 1971). At the termination of that period of work, Mound 1 was assumed to contain nothing more of archaeological interest. As a result, the Sutton Hoo Research Project, 1983–1992 (Carver, 1998: 52–92) focused on the wider site and did not undertake further investigation of Mound 1, although the previous findings were reassessed in its definitive report (Carver, 2005: 177–199).

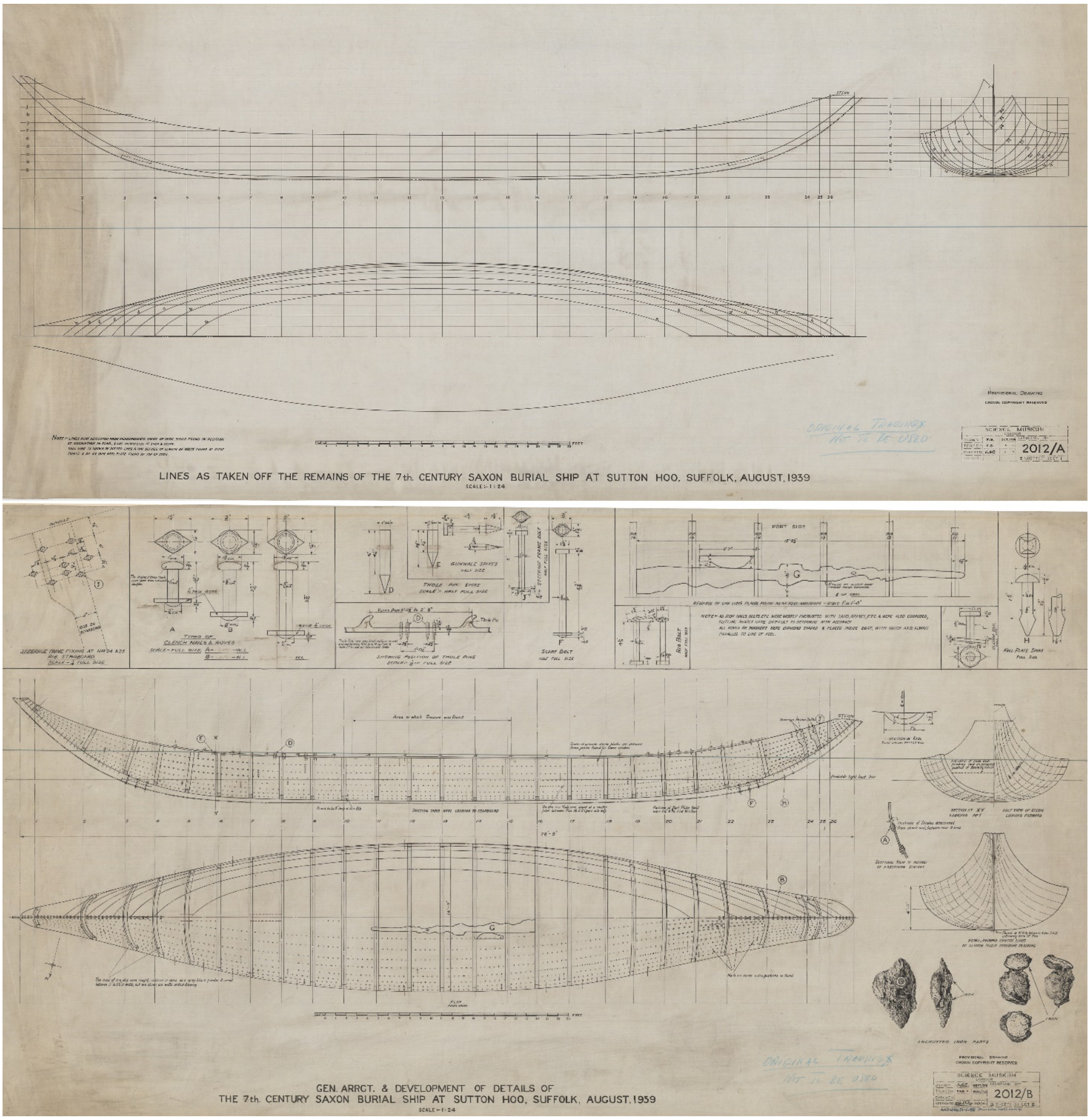

Figure 2. *Science Museum reconstruction drawings of the Sutton Hoo Ship, 1939: A) Top: 2012/A, lines plan; B) Bottom: 2012/B, construction plan and profile, details of fastenings (Image copyright: Science Museum/Science & Society Picture Library).*

Commentary on the 1939 data

The photographic archive provides an impressive view of the 'ghost' ship (Fig. 3) and also illustrates the coherence of the surviving remains, both in terms of the overall shape, and rivet alignment (Fig. 4). However, as highlighted above, the documentation regarding the shape of the hull is sparse. Bruce-Mitford (1975: 234–235) identifies limitations (in his view) of the 'provisional' 1939 reconstruction drawing (Fig 2b). Among these, rivets shown as a starboard elevation were actually a mirror-image of rivets on the port side. Only 18 tholes (the hooked wooden cleats used as a fulcrum for the oar) were drawn, in an improbable relation to the thwarts. This threw doubt on the rib-spacings themselves, although later these were found to be correct. To Bruce-Mitford, the positions of the scarfs of the stem and sternpost to the keel looked implausible, and so the 1975 volume and accompanying 1975 reconstruction drawings propose (Evans and Bruce-Mitford, 1975: 392–398) different positions for them to those claimed by Phillips (1940a: 348).

The 1939 lines plan (Fig. 2a), and reconstruction drawing (Fig. 2b), show a plausible representation of the hull shape 'as found', although work must have been done on the original measurements to rectify the tilt and twist of the hull which Crosley reports (1942: 110) as having been observed during the survey. By contrast, Crosley made no attempt to reinstate the spreading of the planks away from the posts at the stem and particularly the stern of the vessel (discussed below). The body plan on the 1939 reconstruction drawing includes 'centre lines of the clench nails used to secure the planking', but on examination, they are illustrative only. Crosley states that the measurements were taken to a point 'adjacent' to a rivet. This is somewhat ambiguous, but a case can be made that the likeliest place is the tip of the rivet. It reduces the risk of disturbing the rivet, it does not depend on the cleaning around the rivet and gives the best chance of consistency during a delicate and repetitive three-man operation.

By working on rivets close to a rib, the surveyors were presumably hoping for more stable positions along the line of the rib, and so better results when 'un-tilting' the measurements. It must be assumed that the rivets between ribs, and therefore each measurement station were extrapolated, presumably based on average distances between them. The overall curvature of the inside of the hull in profile can be assumed to have been well recorded through the process of measuring the relative heights of the fastenings between frames and stem/keel/stern with a dumpy level. Finally, naval historian R.C. Anderson (1942) provided subsequent comment on how to rectify the collapsed planking at stem and stern. These forms had been termed 're-entrant curves' by Phillips (1940b: 190), who saw them as a feature of the vessel, rather than something to be rectified during reconstruction. All subsequent analysis has agreed with Anderson's view that the planking in bow and stern was collapsed.

Figure 3*. General view of the excavation of the ship in 1939, looking towards the bow (Image copyright: The Trustees of the British Museum).*

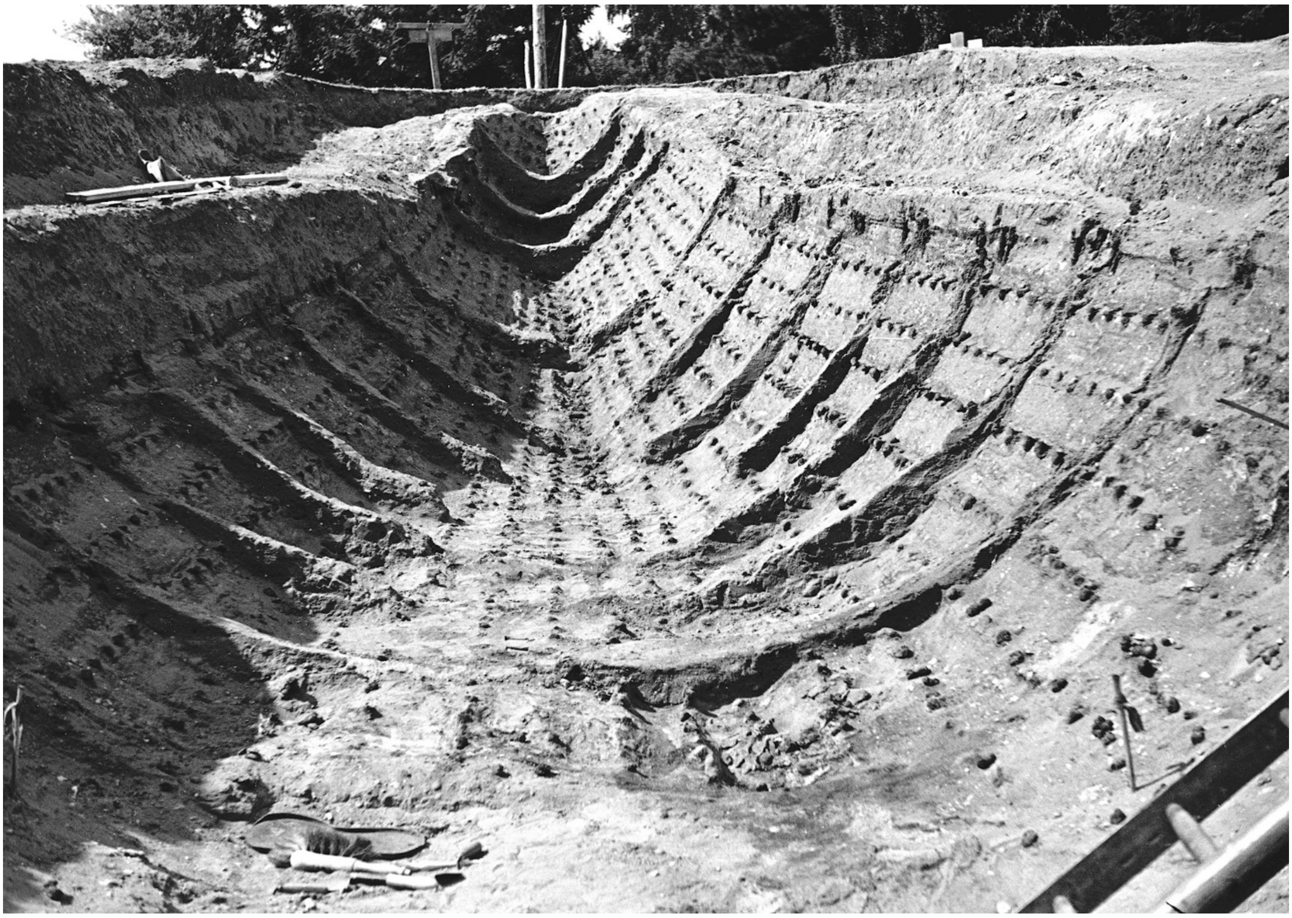

Figure 4*. Detailed internal view of the ship in 1939, looking towards the stern (Image copyright: The Trustees of the British Museum).*

Commentary on data published in 1975

Strake-width data

Strake-width measurements taken from the imprint in 1967 are tabulated in Bruce-Mitford (1975: 354, table 19) and captioned 'Showing (in inches) the width of the strakes measured on the line of the ribs'. Bruce-Mitford notes further (1975: 356) that 'The measurements were taken from the centre point of a series of roves along the line of each rib.' So they are from mid-land to mid-land and exclude the plank overlap. The variation in this data reflects the state of the ship as found by the 1965–70 excavation, including the large areas where no archaeological material survived; there is no information at all for ribs 1–4 and 26. The central burial chamber area is totally denuded, and the port side better endowed than the starboard side.

Rivet-plan data

The 1975 volume (Bruce-Mitford, 1975), includes eight cards, which are plans showing the horizontal positions of all the rivets found *in situ* in the 1965–70 excavation. The lines of the strake rivets are distinctly wavy. It is difficult to imagine that useful information regarding hull shape can be drawn from this data. For the bottom of the ship, where it is comparatively flat, the rivet-plan cards reflect the data shown in the strake-width table (1975: table 19). Reference to the cards show how difficult these measurements must have been. The variation in the data across the table is explained. Table 19 is therefore useful, but mainly as a way of showing average widths, and general trends. Finally, there are some rivet locations for the burial chamber offered (Bruce-Mitford, 1975: 177, fig. 112), derived from various unpublished field plans made by archaeologist Stuart Piggott and Phillips in 1939 (Bruce-Mitford, 1975: 140–144). One of these plans (Bruce-Mitford, 1975: 236, plate H (i)), shows the lines of rivets were not straight, and the widths shown there are similar to those in table 19 of the 1975 volume.

Reconstruction drawings

These drawings are next to each other as fold-out diagrams (Bruce-Mitford, 1975).

- 'The Lines Plan of the Sutton Hoo ship, drawn in 1973 by Colin Mudie' (Bruce-Mitford, 1975: 434, fig. 324). This drawing corrects for plank-spreading at the bow and stern, showing gunwales more as suggested by Anderson (1942).
- 'Archaeological reconstruction of the Sutton Hoo ship, based on the 1939 photographic record and information gained in the 1966–7 re-excavation… ' Bruce-Mitford, 1975: 435, fig. 325) (Fig. 5). The plan shows rivets for both port and starboard sides and the elevation rivets for the starboard side. It reflects Bruce-Mitford's views on the number and positions of tholes, and where the keel was scarfed to stem and stern.

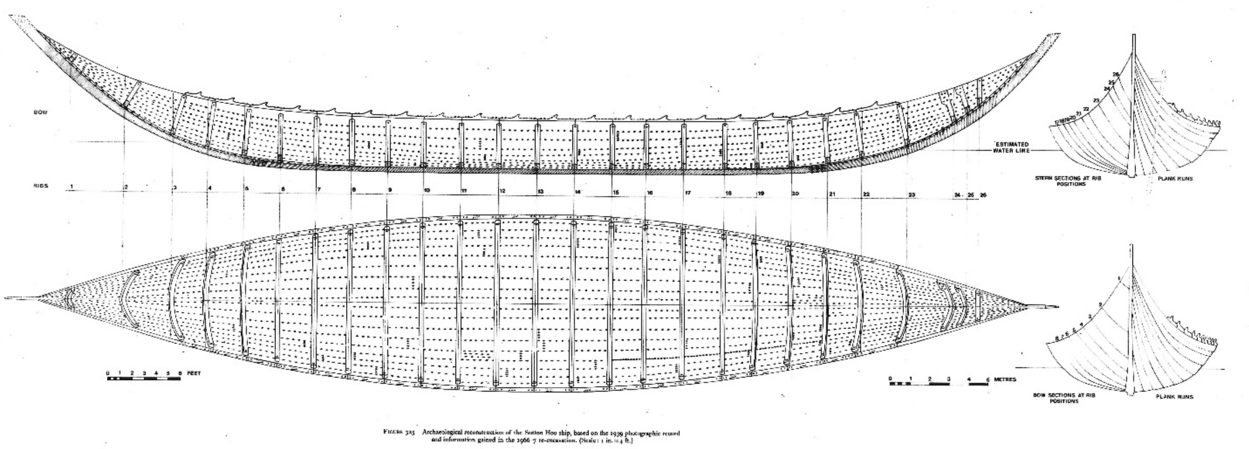

Figure 5*. Construction plan, profile and cross-sections as published by Bruce-Mitford (1975: fig. 325) (Image copyright: The Trustees of the British Museum).*

When considering these two drawings, the 1973 lines plan is to a slightly larger scale than the 1975 reconstruction. It shows 25 evenly spaced sections at intervals of just over 300 mm (3 feet). By contrast, the archaeological reconstruction marks off the mid-points of the bottoms of the 26 ribs, and the variations in rib spacing are quite clear. The body plan of the reconstruction also shows both plank runs and section lines. The midships section corresponds to the *inside* of the planking. Meanwhile, the elevation included in the reconstruction shows the expected eight rows of strake rivets. Forward of frame 8, and aft of frame 19, the reconstruction drawing also shows rivets for the join of the garboard strake to the stem, keel, and stern. This must show where the internal ‘wings’ of the stem, the keel and the stern project upwards sufficiently for the rivets to be distinguishable away from the bottom centreline groove in these parts. The 1973 lines plan appears to have assumed the keel was flat in the middle portion, with keel rocker introduced somewhere in the region of frames 9 and 18, and increasing towards the ends of the vessel.

Similar rocker is seen on the 1975 reconstruction drawing if the line above the keel rivets is used. The rivets are shown there as diamonds, indicating roves. The consistency with the lines plan confirms that the lines are drawn to the internal shape and that the intention of the reconstruction drawing is to indicate actual rove positions. The caveats to the interpretation of these drawings are that the rivet positions are marked on the hull shape as dimensioned and faired by Mudie in 1973, but that Mudie’s assumptions about distortions in the hull and plank-spreading, and how he rectified them are not known. Additionally, Mudie is known to have been dissatisfied with the 1973 lines, submitted to meet a British Museum deadline. He continued working on the drawing, and slightly different lines from 1974 (marked as ‘internal’) do exist. Finally, evidence for the distances between lines of strake rivets shows short-term variation. The trends have to come from photographs, or from the 1939 lines plan.

Summary

The overview of the excavation and recording of the Sutton Hoo ship in the two British Museum campaigns indicates that the archaeological record of the ship is a variable one. The 1939 work recorded the remains in their most complete state, but the records of this work are limited. By contrast, the 1965–70 project produced a highly detailed, orderly, and coherently published account, but of a much-reduced set of archaeological remains. Considering all of this in modern UK archaeological parlance, the total archaeological record of the Sutton Hoo vessel might be classified as ‘Level 2’ (CiFA, 2014: 14):

> *Basic overall dimensions with a record of hull form, scantling, fittings, and fastenings, accompanied by an extensive photographic record with scale drawings of significant features, fittings and/or ancillary components. This record will allow correct interpretation of the vessel or parts thereof and may allow a simple reconstruction of the vessel or part thereof.*

The very nature of the archaeological remains of the Sutton Hoo ship, lacking significant structural remains, steerage, etc, dictates that the highest level of record (Level 3: CiFA, 2014: 15) could not be achieved even if the site was excavated today. Set against this, the documented extent of the ship's hull, as a proportion of the overall original vessel is clearly high and includes elements such as the gunwale and sheer-line, that are uncommon in the archaeological record (CiFA, 2014: 18). As such, reconstruction of the overall form should be grounded on far greater certainty than that afforded by many reconstruction projects. With the above in mind, attention can turn to describing the process of digitally reconstructing the Sutton Hoo ship on the basis of the surviving archaeological record. The first step of this is to outline the assumptions and guiding principles underpinning that process.

Assumptions and guiding principles

Throughout the digital modelling of the ship, a series of assumptions were made to provide the foundation for an understanding of the archaeological record, and to resolve problems faced with the interpretation of that record. These assumptions were based on a review of the existing available datasets, augmented by an ongoing appreciation of their nature, manner of creation, and challenges to use, as the project progressed. The assumptions can be stated as follows:

1. The 1939 excavation represented the most complete access to the archaeological remains of the ship within its burial trench, because of its previously unexcavated status. Therefore, the 1939 data should be considered of primary importance as a record of the vessel.
2. Phillips' team, standing in the excavated trench in 1939, had the best view of the archaeological remains that anyone has ever had, and will ever have. Therefore, Phillips' published papers (1940a; 1940b) represent a key way to resolve discrepancies, by returning to his published observations of what he had observed in 1939.
3. The archaeological site excavated 1965–70 had been subject to additional site formation processes as a result of the damage to the site between 1939 and the 1960s. But, later records still have the potential to confirm the existence of features originally recorded in 1939, or to provide observations on the 1939 excavation through discussion with those present at the earlier date.
4. Both phases of excavation recorded the preserved remains to the degree of precision allowable at the time, in both cases with a focus on recording the rivet locations in three-dimensions, as a means to arrive at the shape of the hull. Therefore, an error of at least +/-10 mm is probably to be expected in the original datasets to account for the recording method and subsequent scaling of results.
5. Both the 1939 and 1975 reconstruction drawings (Figs 2b and 5) 'faired' the recorded rivet positions in order to provide a realistic reconstructed hull shape, rather than a distorted one representing the 'as found' remains. The exception to this is the collapsed hood-end planking which was left un-

rectified in the 1939 drawings, but which was later rectified in the 1973 and 1975 drawings. As such, the twist and tilt, evident to the 1939 recording team, was rectified in the production of their drawings.

6. The extreme ends of the ship, as reconstructed in 1939 and 1975 are largely conjectural. Phillips observed (1940a: 348) that the layout was difficult to determine, and that understanding the planking at the ends should be left for experts to address. By 1967 the ends of the vessel were absent with 2.2 m lost from the bow and 1.76 m lost from the stern (Bruce-Mitford, 1975: 256).

In addition, a set of guiding principles were established, to provide a means to inform decision making and help resolve areas of the ship with discrepancies in the data, apparent errors in the data, or where there was missing data. These were created with reference to previous work on EBSA (Goodburn, 1993; Coates *et* al. 1995; Crumlin-Pedersen, 1995; Crumlin-Pedersen and McGrail, 2006), but were intended to be practical and useful for this project, rather than for establishing further theoretical discourse within the discipline. Our guidelines were that:

1. The original archaeological record, as far as it could be accessed and accepting its challenges to use, should take primacy at all times, including over subsequent reconstructions.
2. In the absence of a particular archaeological record from Sutton Hoo, comparable archaeological material should inform the choices made in reconstruction, wherever possible.
3. That in the absence of any archaeological evidence, either original or comparative, decision making should be informed by generally accepted traditional clinker shipbuilding practice, including from more recent periods.

Finally, throughout Phase One of the project, the view has been taken that the (digital) reconstruction presented here is simply one part of the overall progression towards a full-scale build. Within this, each stage builds on the previous one, adding detail and making practical choices based on the discovery and understanding of such detail. This inevitably results in refinements, adjustments, alterations, and changes as the work progresses. It is expected that the realities of full-scale shipbuilding, with real materials, are likely to result in some divergence from the reconstruction published here. This should be accepted, and recorded during the full-scale build, in order to understand the rationale of a builder in making such choices and to identify areas of the reconstruction process, in this case a digital one, that can be improved in the future.

Reconstructing the Sutton Hoo ship

As noted, the underlying principle behind the digital reconstruction of the Sutton Hoo ship was that it should be based on the available archaeological evidence, which comprised primarily the fastenings of the original vessel. The shape and individual components that formed the vessel's hull should be created through reference to that archaeological data. Such an approach has been noted (Crumlin-Pedersen and McGrail, 2006: 54) as practical and applicable for the reconstruction of the Ladby Ship (Bischoff, 2003), the archaeological remains of which were also comprised primarily of iron rivets. For Sutton Hoo, the approach relied on the application of an established method of building the digital ship, component by component, in the computer programme Rhino3D (Tanner, 2013a; 2013b; 2018; 2019). A generalized workflow for this, as applied to the Sutton Hoo ship is listed here, and then described in more detail:

1. Plotting and initial orientation of fastening (rivets, bolts and spikes) locations using actual or interpolated existing data.
2. Building the ship using temporary digital strakes. Provisionally lofting and attaching the strakes also locates the keel, and stem/sternposts, based on the fastenings.
3. Identification and correction of observable anomalies, discrepancies, and distortions in fastening positions.
4. Finalization of plank runs, keel and stem/sternposts.
5. Insertion of known internal structure.

For the avoidance of doubt, it can be emphasized here that such a reconstruction process does not entail the creation of a lines plan from the 3D rivet data, into which structural components are added retrospectively. Rather, the lines plan shown in Figure 1 is derived from the construction plan, which itself is created through the process just summarized. The status of the vessel's fastenings as the primary archaeological data dictate that its hull form must be reconstructed on the basis of the planking, rather than other elements, such as the frames. As such, the process of reconstructing the planks and strake runs is the first element described below, before moving on to the framing of the ship.

Planking

The available 1939 rivet data (Fig. 2b) provided an overall set of positions for the roves, keel bolts, and gunwale spikes. Of these, the clinker rivets represented the most important aspect of the recorded data, because of their ability to describe the run of the planks in the original ship, and by extension its overall hull form. Additionally, rivet shank dimensions indicated the likely original plank thickness, while their vertical separation alluded to the original plank widths. The rivets were plotted in Rhino 3D (Fig. 6) based on their internal rove (for the rivets) or head (for bolts and spikes), because their original recording (above) was assumed to refer to that part of the fastening. The rivets were then given an initial orientation to suit their location in the hull; perpendicular to the assumed run of planks, and with orientation varying depending on its general position in the hull. A set of temporary strakes was then lofted and attached, using the initial rivet locations as a reference;[2] every individual rivet was then re-orientated perpendicular to its adjacent plank surface while maintaining the known location of the rove on the inboard face. This was repeated for all 3,598 plank rivets. In some cases, it resulted in moving the outboard ends of the rivet heads by as much as 50 mm (2 inches) from their initial orientation but resulted in a set of rivets that accorded with the overall temporary strake runs.

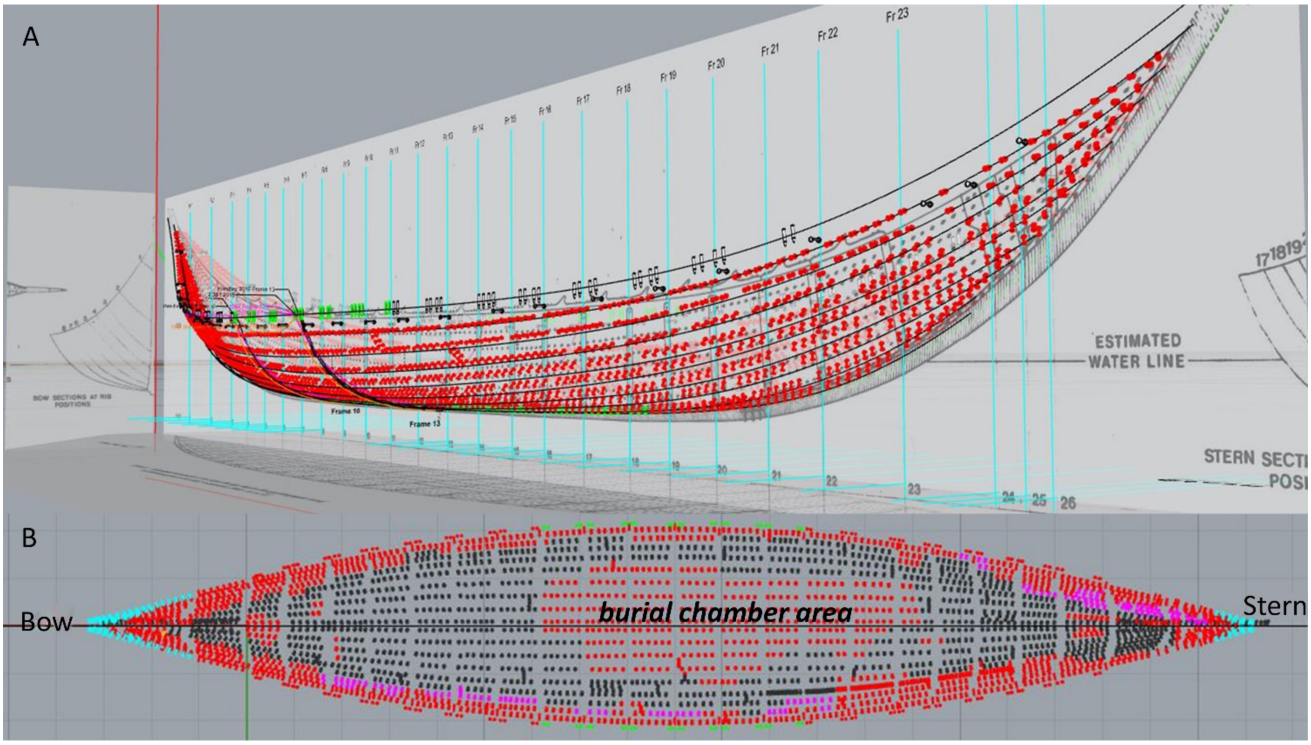

Figure 6. *A) Top: Initial plotting of rivets in Rhino3D, in this case against the British Museum reconstruction shown in Figure 5. B) Bottom: Plan of final overall plotted rivet positions. Black = Correspondence between 1939 and 1975 published location. Pink = Recorded in 1939, not recorded in 1975. Cyan = Position moved between 1939 and 1975. Red = Data absent from 1975 rivet plan, or 1939 and 1975 (central burial area). Green = Thole spikes in the central area (Sutton Hoo Ship's Company).*

Once the rivets had been positioned and orientated, the temporary strake was replaced with a revised provisional digital strake. This was lofted through the rivet positions following a smooth curve that aimed to pass through as many rivet locations as possible. The runs of the provisional strakes agreed with the majority of the rivet locations, although a number of anomalies and discrepancies in rivet locations were identified and corrected (Table 2). These ranged from individual rivets that appeared to have simply been plotted in the wrong place in the published plans (Fig. 7a), to longer rows of rivets that could represent errors in recording, draughting, or indeed genuine distortions in the hull (Fig. 7b). The latter in turn could have come about during building, use, deposition, or subsequent site formation. Given the nature of the site, the survival of the archaeological remains, and the level of error inherent in the recording methods obligatory at the time, such issues were considered to be inevitable. In all cases, it was assumed that the original vessel would have been built with a set of strakes that followed relatively smooth curves (in accordance with principle 2 and 3 above), and so the rivets in question were corrected to match the majority of other rivets.

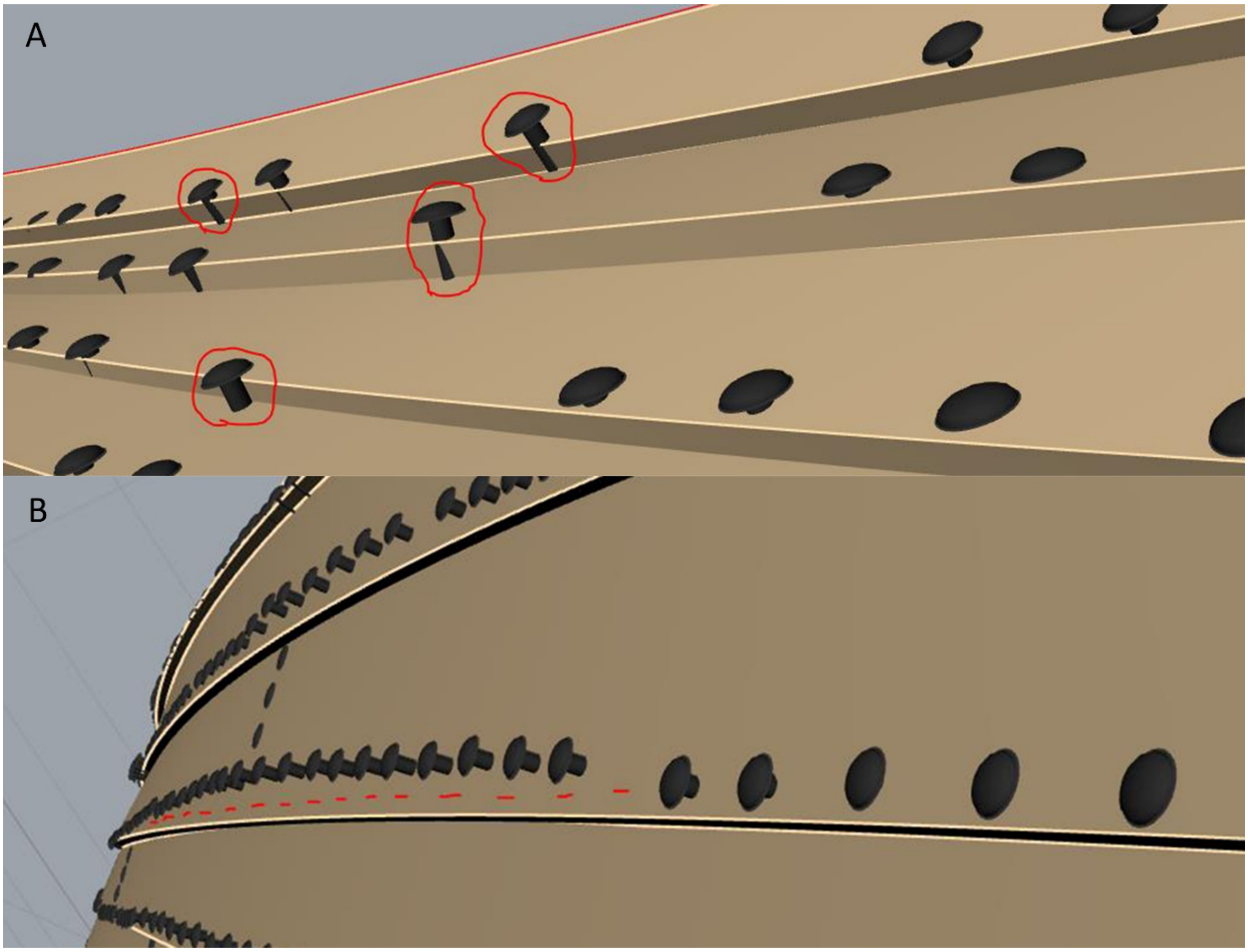

Figure 7*. Corrections to identified errors in published rivet data. A) Top: Individual location error, circled in red, relative to provisional strake run. B) Bottom: Group location error, relative to provisional strake run. The probable line is indicated by the red dotted line (Sutton Hoo Ship's Company).*

Table 2. *Anomalies and discrepancies in rivet locations, alongside possible causes, identified during digital reconstruction*

Discrepancy/Anomaly	Suggested Cause
Individual location error	Error in the original recording and/or plotting.
Localized un-fair region of plank width	Error in recording of a set of rivets. Error in plotting a set of rivets during drafting. Original localized anomaly in plank width when built due to material limitation or build error, resulting in an unfair strake run.
Localized distortion in hull shape	Error in recording of a set of rivets. Error in plotting a set of rivets during drafting. Over-fairing of original locations during production of published drawings. Localized distortion created during construction. Localized distortion created during use. Localized distortion created by deposition and/or site-formation processes.

Plank widths

During the provisional digital lofting of the strakes, and prior to their finalization, attention was given to the plank widths that the plotted rivet positions indicated as present in the original ship. It was clear from the existing data that strake widths tapered towards the fore and aft ends of the vessel, but particular efforts were made to compare widths at any given cross-sections. Was the ship built with strakes comprised of planks of differing widths, or of uniform widths, when considered transversally? This question was posed because uniform widths were used to check the girth of the lines plan only modelling, initially conducted earlier in Phase One of the project (Handley, 2016: 7.2).

Checking of the provisionally lofted strakes, and their corresponding rivets in cross-section revealed the likely answer to the original plank-width arrangement. Analysis of the midships cross-section (frame 13) during digital reconstruction (Fig. 8) illustrated the presence of differing plank widths, when viewed in cross-section, in the originally drafted rivet data. It also focused attention on a difference between the rivet locations in the 1975 plan, and the present reconstruction, in three areas of the bottom, bilges, and sides, as follows:

- *Bottom:* It was noted that the 1975 garboard and second plank were narrower than the present reconstruction, following the lofting of the provisional strakes. This difference is indicated by the red (1975) and blue (Present) rivets shown in (Fig. 8). This element of the vessel had limited rivet data from the 1939 or 1975 excavations because of the burial chamber (see Fig. 6). Close inspection of the 1975 data revealed that the garboard and second strake rivets had been straightened to run parallel to the keel through the burial chamber area, rather than being allowed to assume a smooth curve. The effect of this was to move the published rivet positions inboard, thereby narrowing the garboard and second strake amidships. This was resolved by retaining the smooth curve of the provisional digital strakes, which was felt appropriate in line with Principle Two and Three (above), which in turn imposed a wider (340 mm) garboard and second strake than in the 1975 publication.

- *Bilge*: There was a very close correlation between the projected plank widths and the plotted rivet positions derived from the 1939 and 1975 plans.
- *Sides*: the provisionally lofted top-strakes were found to be slightly narrower than the strakes recorded in 1939 (the physical remains of these were absent in the later re-excavation), and so the provisional strakes were widened accordingly to match the recorded archaeological data, prior to finalization.

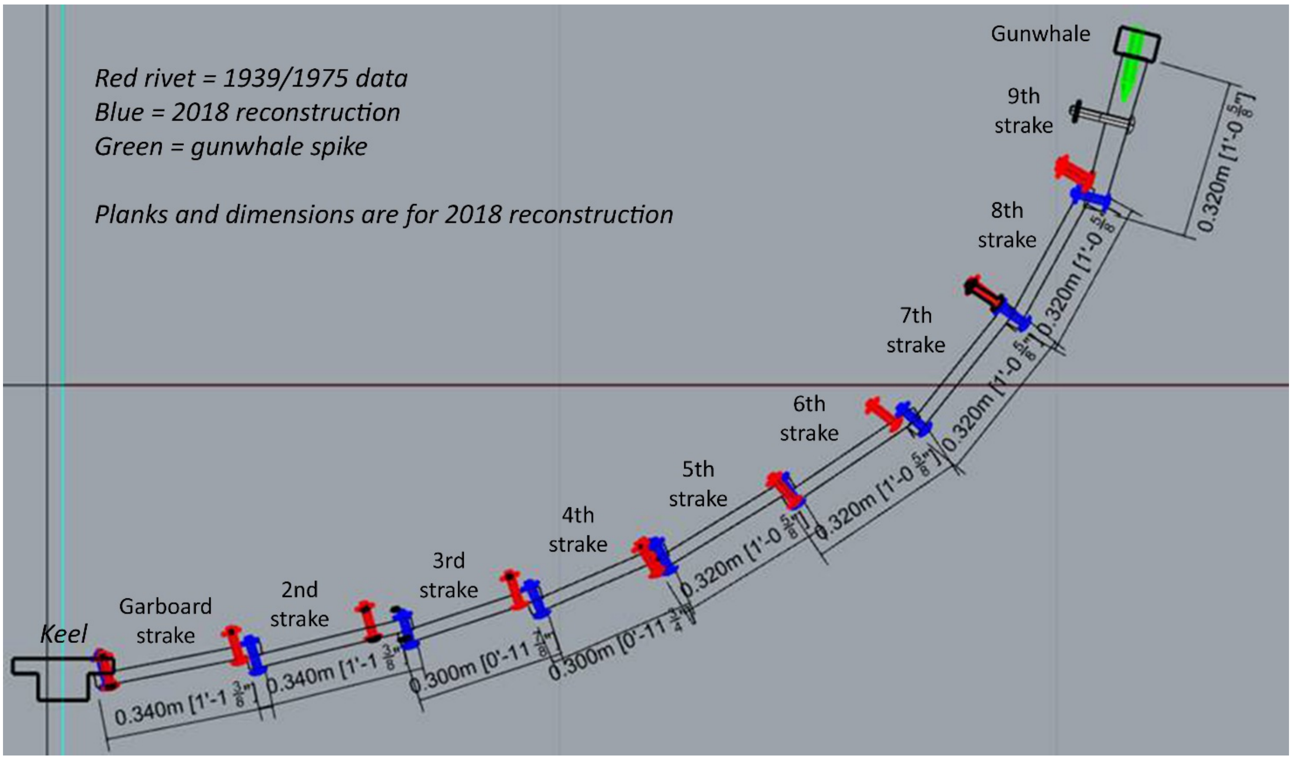

***Figure 8**. Cross-section of interpreted plank widths and rivet locations amidships (frame 13), plotted in conjunction with 1975 published data (Sutton Hoo Ship's Company).*

Overall, midships at frame 13, the reconciliation of the archaeological record with the digital lofting indicates the presence of strakes of different, rather than uniform, widths in the vessel. The results in this area also tallied with the overall plank-width data provided in the 1975 publication (Evans and Bruce-Mitford, 1975: table 19) which indicates that each frame station shows a variation in plank width. Reference to the wider comparative archaeological evidence from NW Europe, both pre-dating (for example Nydam: Gøthche,

2000) and post-dating Sutton Hoo (for example Kvalsund 2 (*c.*AD 700), Oseberg (AD 820), Gokstad (AD 895): Bruce-Mitford, 1975: fig. 291; and Ladby (c.AD 900): Bischoff and Jensen, 2001: 207–208) indicate clinker-built ships with planks of different widths at the same transverse position in the hull. Finally, plank-scarfs were located in accordance with the analysis set out in 1975 (Care-Evans and Bruce-Mitford, 1975: 361–365), although it should be noted that this is an element that might be expected to be subject to alteration in a full-scale build as a result of timber availability.

Hood-ends

Having established a feasible distribution of plank widths in the midships area of the vessel, focus then switched to the stem and stern. Rather than simply lofting finalized digital planks from the midships area to the ends of the vessel following the published rivet positions, careful consideration was also given to the hood-ends of the vessel, for two reasons. Firstly, because of the difficulty in interpreting them experienced by Phillips in 1939 (see Assumption Six) and, secondly, because their absence in 1965–70 must, out of necessity, have led to their rectification through fairing during the production of the 1975 plan. These issues and a suggested resolution are discussed here because they are critical in resolving the form and appearance of the bow and stern of the reconstructed vessel.

Having directly considered the ends of the vessel during excavation and survey in 1939, Phillips (1940a: 348) comments that the complex positions of rivets in both ends of the ship where planking met both stem and sternposts made it difficult to determine the exact layout of the hood-ends. He offers a further observation (1940a: 348) that: ‘The management of the planking fore and aft in its relations to the stem and the sternposts must be left to experts.’ This difficulty in unpicking the hood-end remains is perhaps reflected in Phillips’ recourse to the complex reversed or ‘re-entrant’ curve for the gunwale of the ship forward and aft that characterizes the 1939 reconstruction drawing (Fig. 2b). In effect, that drawing publishes the hood-end rivets in their ‘as found’ position in the ground, a position that Phillips did not see as being the result of the hood-ends spreading from the stem/sternpost following deposition. Rather, his opinion (1940a: 348–349) was that it was a deliberate feature of the design of the ship, attested in the preserved archaeological remains.

However, Phillips’ interpretation has been questioned, and largely overturned, in favour of a shape that is more conventional for a clinker-built vessel. In particular, Anderson (1942: 83–85) writing shortly after the 1939 excavation discusses the ‘unexplained blunt-nosed finish at either end’ and suggests these are in fact the result of spreading, as it would be both difficult and pointless to construct such a shape. Anderson is of the opinion that the Sutton Hoo ship was built with ‘normal pointed ends’ based on the ease with which it is possible to correct the lines by continuing the stem and sternposts (Anderson, 1942: 84), which also raised the sheer-line. Anderson states (1942: 85) that such a liberty would be far less serious than introducing some sort of blunt-nosed finish for which there is no evidence, and which would involve some almost impossible juggling with the plank ends. On review, Anderson's rationale and general interpretation seem entirely plausible; that the position of the hood-end planks in 1939 was caused by their detachment and spreading from the bow, following deposition. As noted in Assumption Six above, by the time of re-excavation of the ship significant parts of the extreme ends of the vessel had been lost. In addition, it is noted that the strake lines, as delineated by the rivets, were almost impossible to distinguish at the bow and the stern (Evans and Bruce-Mitford, 1975: 378). As such, it is reasonable to assume that the 1973 lines plan by Mudie took Anderson's general theory of what the bow and stern looked like in producing a faired interpretation of the strake runs, which attempted to return the rivets and planks to their original position prior to spreading.

The process described above of locating, aligning, and finalizing the rivets and planks provided acceptable results when lofting the majority of the strakes, along the majority of the length of the vessel. Initial lofting at the ends of the ship used the 1975 rivet locations because they represented a pre-existing academically published solution to the problem of restitution of the spread hood-ends. However, the rivets and hood-end positions, when plotted, did not readily lend themselves to feasible full-scale construction. For example, the plank widths became so narrow and crowded, relatively high up the stem and sternpost (Fig. 9), as to prevent them being secured to the posts with more than one rivet per plank. Because of this, the hood-ends, the reconstructed 1975 rivet positions in the bow and stern, and the related strake runs, were felt to require further investigation because of the practical concerns of narrow, crowded planking that the digital modelling had highlighted.

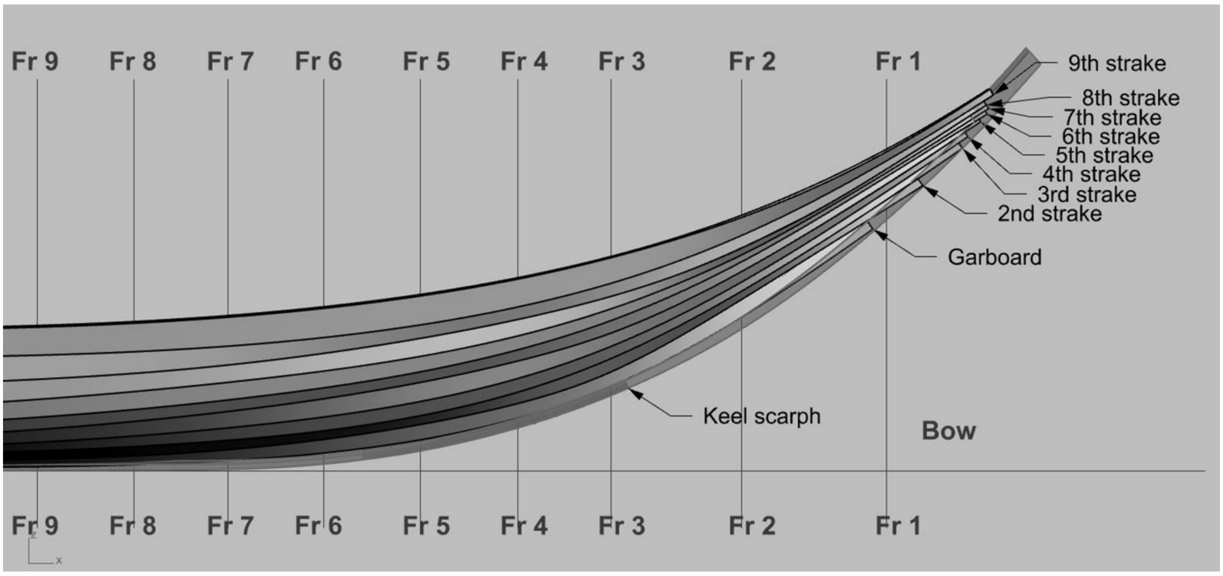

***Figure 9**. Forward hood-ends, using rivet locations and plank runs from 1975 (see Fig. 5), to illustrate the clustering of hood-ends towards the top of the stem (Sutton Hoo Ship's Company).*

This work started by considering the nature of the hood-ends themselves on the basis of comparative evidence. Later 11th-century ship finds built in a Nordic clinker tradition, employed 'stepped', or mixed stepped/rabbeted hood-ends (for example Skuldelev 1, 2, 3, and 5 in Crumlin-Pedersen and Olsen, 2002). The arrangement is also present in the 10th-century Ladby Ship, a ship-burial preserved only through the surviving rivets and nails, where it was possible to detect stepped lower hood-ends through the distribution of the surviving fastenings (Bischoff, 2003: 73–74). In contrast to Ladby, the 9th-century ships from Oseberg and Gokstad, and the 3rd/4th century AD Nydam ship carried a rabbeted stem (Bischoff, 2003: 73). At Sutton Hoo, neither the recorded/published rivet locations nor the associated photographic archive, show any evidence for stepped hood-ends (cf Evans & Bruce-Mitford 1975: 384–386). Therefore, a rabbeted stem and sternpost was considered most likely, which accorded with the closest comparative evidence from the Nydam ship (cf Evans & Bruce-Mitford, 1975: 388, 390). The garboard hood-ends on the Nydam vessel were also noted as lying much lower down the stem/sternpost than on the 1975 reconstruction drawing of Sutton Hoo, which terminated at frame 2. With this in mind, a cluster of rivets, just forward of frame 3 (Fig. 9), but surviving in 1965–70, provide a likely alternative position for the garboard hood-end fastenings, much lower than those proposed in 1939 and 1975 but comparable to the garboard hood-end locations at Nydam. A further cluster at frame 2 (Fig. 9) provided a potential location for the hood-ends of strake two, again, much lower down the stem than previously reconstructed. The re-location of the garboard and strake 2 hood-ends to a lower position freed up more space along the rest of the stem/sternposts for the hood-ends of the remaining planks, allowing the plank widths there to be better proportioned relative to the widths amidships. The hood-ends were less crowded, and each could be fastened by at least two nails. A final consequence of this process was that the sheer-line of the vessel was raised slightly at the ends, in comparison to the 1975 reconstruction drawing, in order to maintain the fair run of the strakes, with a consistent taper, into the stem and sternposts. To an extent, this completes the raising of the sheer-line first undertaken by Anderson (1942: 84) in his initial rectification of the spreading of the vessel ends.

Keel and posts

The cross-sectional form of the ship's keel and stem/sternposts is relatively uncontroversial. Phillips was able to provide (1940a: 348) an estimate of the keel's cross-section and suggested dimensions following the 1939 excavation. This was largely corroborated during the 1965–70 re-excavation (Evans and Bruce-Mitford, 1975: 375–382, fig 290; Bruce-Mitford, 1975: 268), which included a box section taken through the keel area of the vessel. The detailed analysis undertaken post re-excavation provided cross-sections of the keel and stem amidships, towards frame 8 and at the stem frame 1, a noted caveat is that the depth of the midship cross-section is a minimum reconstruction, with the actual depth unknown (Evans and Bruce-Mitford, 1975: fig.

290). The 1975 keel cross-sections have therefore been applied here as representing the most detailed understanding available.

The form of the stem and sternposts relies on the interpretation of the rivet locations at either end of the ship. These were recorded in three-dimensions in 1939 and where possible in 1965–70. The latter investigation (Evans and Bruce-Mitford 1975: 382–391) also undertook a detailed analysis of the photographic archive and related data from 1939. The cross-section and internal profile of the stem and sternposts are therefore as well understood as is possible, and the 1975 form was adopted on this basis, along with the estimate for the outboard projection based on comparative analysis.

A significant discrepancy exists between the length of the vessel's keel as published in 1939 and 1975. Phillips (1940a: 348) notes that the minimum length of the keel between the keel-to-post scarf joints is 'not less than 60 feet'. On this basis, the 1939 drawings show a keel length of 18.29 m (60 feet) between the keel-to-post scarfs. By contrast, the 1975 reconstruction drawing shows a much shorter keel length of 14.24 m (46 feet 8 inches) between both keel-to-post scarfs. This reflects Evans and Bruce-Mitford's analysis and subsequent interpretation (1975: 392–398) of the three possible keel-to-post scarph arrangements:

1. As per Phillips' 1940 interpretation: a *c.*17.5–18 m (60 feet) keel, with substantial rocker and a single scarf at either end.
2. As published in 1975: a 14 m (46 feet) keel, flat in profile and with a single scarf at either end.
3. Alternative proposal (Evans and Bruce-Mitford, 1975: 398): a double scarf, allowing an upper and lower stem/sternpost, in accordance with evidence from Gokstad and Oseberg.

One rationale behind the shorter keel of the 1975 publication was to allow for a flat keel with limited or no rocker (Evans and Bruce-Mitford, 1975: 398). The imposition of a flat keel on an early medieval vessel, without conclusive evidence, should itself be undertaken with caution (see discussion by Crumlin-Pedersen and McGrail, 2006: 54); such an approach during reconstruction for display was partially to blame for the incorrectly reconstructed shape of the Oseberg ship—with disastrous consequences for the subsequent full-scale reconstruction, *Dronningen*, launched in 1987 (Bischoff, 2012). Further information on the presence of keel rocker was derived during the digital modelling of the rivet locations. This highlighted a discrepancy between the vertical positions of the garboard/keel rivets as published in 1939 and 1975 and the vertical position of the keel itself, as shown in the respective reconstruction drawings. In both cases, the top of the keel has been drawn well below the rivets that indicate where its upper surface should have been, forward of frame 9 (Fig. 10a). As a result, the original drawings show a keel profile that is perfectly flat between frames 8 and 17 for 1939 (Fig. 2b), and between frames 9 and 18 for 1975 (Fig. 5), before curving upwards to meet the stem and sternposts. The process of digital modelling, by placing the top of the keel where the recorded rivets indicate it should lie (Fig. 10b), indicates that the keel had more rocker or curvature than originally published. Consequently, the revised keel profile does not have a completely flat section anywhere along its length, although it can be noted that the section between frames 10 and 16 has the smallest degree of curvature. This represents a revision of the overall rocker of the keel as a result of the correction of the published discrepancy. With this in mind, and taking Bruce-Mitford's own analysis of the relationship between keel rocker and length, Phillip's original interpretation of the keel length has been retained here. A caveat to this is that the archaeological evidence for the keel-scarfs is limited. Any future full-scale physical reconstruction could adopt the double scarf highlighted above, or even an additional midships keel-scarf. Both of these could help mitigate practical considerations relating to timber availability while retaining the overall form of the vessel's keel and posts.

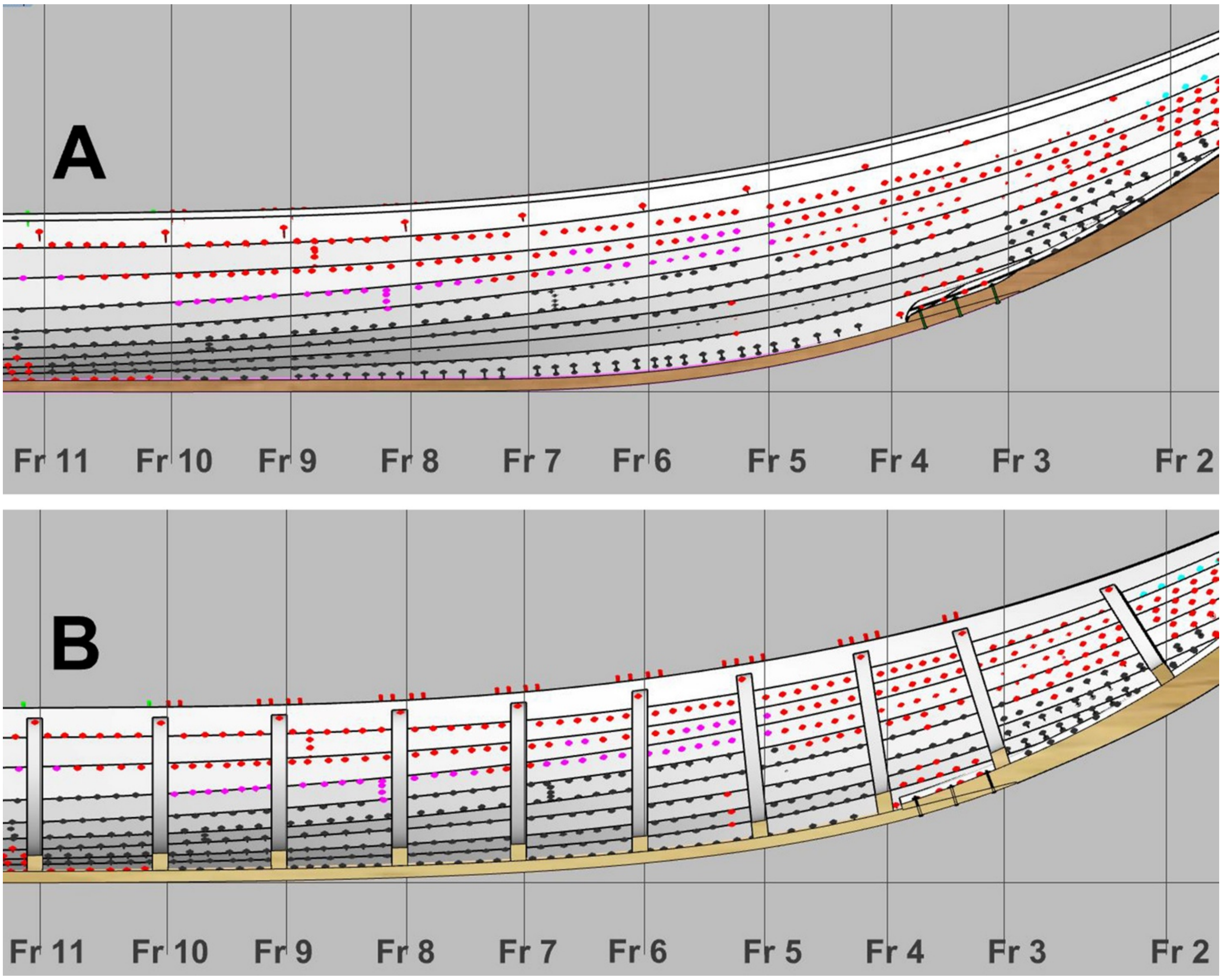

Figure 10. *Rectification of keel rocker, based on published rivet locations: A) Top: Original keel profile which does not conform to recorded rivet locations, and can be seen to drop below their vertical position; B) Bottom: Revised keel profile with rocker to match recorded rivet locations (Sutton Hoo Ship's Company).*

Internal structure

Much of the focus of the digital reconstruction of the Sutton Hoo vessel has been on the most accurate possible interpretation of the plank runs, partly because that is where the archaeological evidence was focused, and partly because the shell-based nature of the vessel's construction sequence dictates that the frames take their shape from the planking that they are placed within. However, some account must be taken of the internal structure of the ship to allow those elements to be modelled and included in analysis. Because of the overall lack of evidence for internal structure, an approach of 'minimal reconstruction' has been applied to the interior of the vessel.

Frame spacing and dimensions have been derived from the information recorded in 1939 (Phillips, 1940a: 349–350, fig. 1) when the frames were present only through the darkened impressions left behind in the soil (Phillips, 1940a: 349). Evans and Bruce-Mitford (1975: 365–373) provide a detailed account of the efforts made during their re-excavation, without much success, to increase the archaeological dataset relating to the ribs. A set of 26 frames were therefore modelled, rectangular in cross-section, 76 mm (3 inch) moulded and 101 mm (4 inch) sided. Phillips' diagram (1940a: fig. 1) illustrating the frames and gunwales, shows the former with a narrowed, chamfered 'neck', just below the square frame head. The evidence for this is unclear, and so the frames in the digital reconstruction were modelled with a plain, squared top. As per the surviving archaeological evidence, all the frames have been secured at their head with an iron rivet 108 mm (4¼ inches) long (Phillips, 1940a: 350). The frame-to-plank fastening down the remainder of each frame is unclear. Phillip's original interpretation allowed for the frames to be lashed to cleats on the internal face of the planks, although he acknowledged this was based on negative evidence, rather than any archaeological certainty (Phillips, 1940a: 350). Subsequent analysis by Anderson (1950) questioned this theory and provided a strong alternative argument in which the frames were treenailed to the planks. This view was corroborated by Evans and Bruce-Mitford who concluded (1975: 373) that the frames were joggled to fit the planks and probably fastened with treenails. No evidence survives to indicate the composition of individual frame stations; that is grown floor-timber, half-frame, and futtock, and so on, and consideration of this will be an important element in the final planning of a full-scale build.

The most in-depth and reasoned analysis of the form of the oar tholes and their arrangement along the gunwale comes from the 1975 publication (Evans and Bruce-Mitford, 1975: 403–406), which forms the basis of the current reconstruction. This allows for a minimum of 14 pairs of oar tholes; seven pairs located between frames 3 and 10, and seven pairs between frames 16 and 23. This would allow for a rowing crew of 28. Additionally, oar tholes could potentially have been present in the midships area between frames 10 and 16 but removed to facilitate the construction of the burial chamber (Evans and Bruce-Mitford 1975: 405–

406). This area could accommodate an additional six pairs of oar tholes, allowing for an extra 12 rowers and taking the maximum potential rowing crew to 40. Regardless of whether tholes were present or absent in the central area of the ship, it would be unlikely to have been constructed with a gap or step in the sheer-line. As such, it seems reasonable to assume that the raised thole rail was continued throughout the central burial chamber area; however, these sections could equally have been fitted without the 'claw-like' tholes used for rowing.

Finally, there is no reliable evidence for other internal fittings and structures (Evans and Bruce-Mitford, 1975: 410) such as thwarts, thwart risers, stringers, floorboards, and so on. It can be readily postulated that they must have existed on a vessel of this size and length to provide it with adequate structural integrity and to facilitate activities such as rowing. With the latter in mind, and to allow more accurate hydrostatic testing, simple thwarts were included in the digital model. These were placed athwartships, resting on each frame at a level corresponding with the foot of the gunwale strake.

Overall characteristics

The characteristics of the reconstruction presented here (Figs 1 and 11) are summarized in Table 3. Based on the available archaeological evidence this suggests a vessel with an overall length of *c.*26.33 m (86 feet 4½ inches) depending on the extended lengths of the stem and sternposts above the termination of the hood-ends. The ship has an overall beam of 4.39 m (14 feet 5 inches) and a depth midships of 1.34 m (4 feet 4¾ inches), increasing to a height of 3.46 m (11feet 4 inches) at either end. The hull consists of nine overlapping (clinker) strakes per-side, fastened with iron nails and roves. The overall makeup of each strake is unclear; however, based on extant rivet position data strake four is constructed of six individual planks, ranging in length from 2.8 m to 5.2 m. Each side of the vessel uses 218.5 m of planking giving a total of 437 linear metres of (presumably) oak planking. Some 3600 iron nail and roves were used to fasten the hull planking, with a further 297 nail and roves used for scarf fastenings. And 160 pointed iron spike nails, 25 mm (1 inch) diameter by 150 mm (6 inches) long, were used to fasten the thole rails to the gunwales. Plus 58 longer nail and rove fastenings, averaging between 115 mm (4½ inches) to 127 mm (5 inches) long were used to secure the 26 frame heads to the 9th strake. The combined weight of all iron fastenings is 868 kg.

Certain anomalies, clear within the documented rivet locations, such as the cluster of ten scarf rivets on the port side fifth strake between frames 11 and 12, as well as the cluster of nine scarf rivets on the garboard strake starboard side between frames 20 and 21, suggest some form of maintenance or repair during the vessels use life. This, in turn, reinforces the existing interpretation of the vessel as having been a functioning ship (see Phillips, 1940a: 354; Evans and Bruce-Mitford, 1975: 412–413) rather than a purpose-built ceremonial burial vessel. The doubling up of clench nails and roves on the 5th/6th strake connection, between frames 15 and 21, also suggest the possibility of refastening to cure a leaking plank seam. One single nail and rove, labelled rivet 2000 during the re-excavation, positioned 342 mm forward of frame 2, and probably associated with either the hood-end of strake 3 or the connection between strakes three and four, was unique in that its orientation was the reverse of all other nails, having its head on the inboard side and the rove to the exterior.

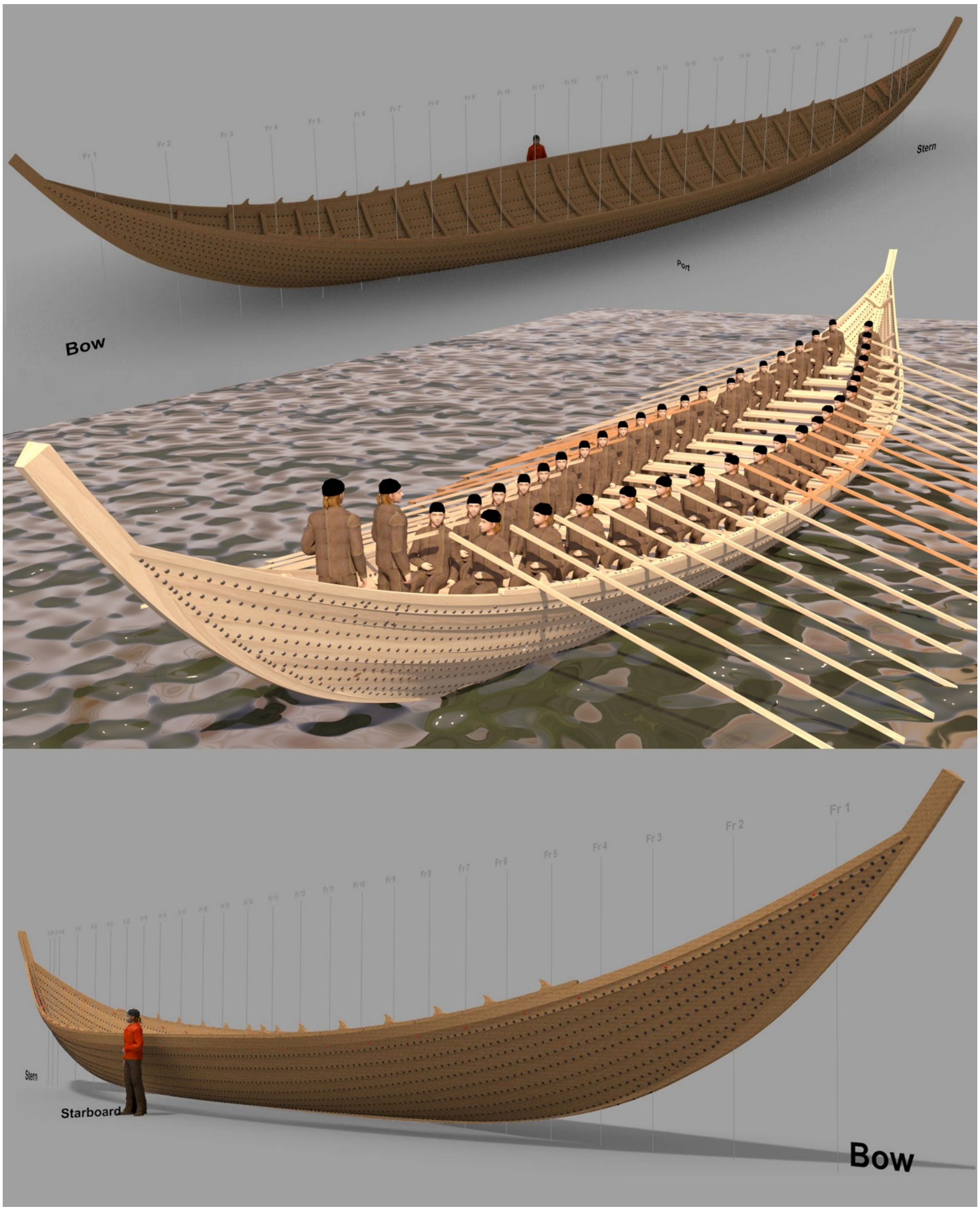

Figure 11*. Overview visualization of the digital reconstruction. Top: looking from above, from port. Centre: Afloat, from the starboard quarter in the ballasted flotation condition (see Fig. 12c), with an indicative crew. Bottom: from the starboard bow (Sutton Hoo Ship's Company).*

Table 3. *General characteristics, displacement is based on the flotation conditions described in the hydrostatic analysis (see Table 4)*

Length overall 26.33 m (86'–4")	Length at sheer 25.10 m (82'–4¼")	Length of Keel 18.48 m (60'–7 ½")
Beam 4.39 m (14'–5")	Midship Depth 1.34 m (4'–4 ¾")	Height at Stem 3.46 m (11'–4")
Lightship displ. 4885 kg	Draught 0.33 m	Freeboard 0.95 m
Fully crewed displ. 11,493 kg	Draught 0.52 m	Freeboard 0.76 m
Ballasted displ. 16,116 kg	Draught 0.63 m	Freeboard 0.65 m
Fully laden displ. 21,124 kg	Draught 0.74 m	Freeboard 0.54 m

Hydrostatic analysis

The successful operation of a full-scale reconstruction can be greatly enhanced if factors such as vessel stability, flotation condition, and capacity are understood in the most complete manner possible, prior to building and launching. Potential speed is obviously interesting too because it can be compared to subsequent 'real-world' trial speeds to enhance our understanding of the effectiveness of the computationally modelled tests and results. Naval design software, such as Orca 3D, offers a route here. It requires the individual modelling of each component part of the vessel described above, and the ability to assign a material (generally iron and oak) to each part. The veracity of this approach in accurately predicting hydrostatic characteristics has been demonstrated through the reverse modelling of a full-size vessel; *Hanorah*, a West Cork Heir Island lobster yawl (Tanner, 2018). This work has illustrated the high levels of accuracy achievable between predicted and real-world results for critical aspects, elements such as weight and displacement, while using average material densities. It has also been applied to existing maritime archaeological datasets for the purpose of digitally reconstructing vessels ranging from logboats to large sailing ships (see Tanner, 2013a; 2013b; 2018; 2019). In the case of the Sutton Hoo vessel, the digital reconstruction described above allows for hydrostatic testing of the modelled vessel to establish flotation conditions, stability, capacity, and potential speed.

Flotation, stability, and capacity

The digital reconstruction of the vessel (Figs 1 and 11), comprising all the individual components listed above (Overall Characteristics), were analysed using the weight reporting feature in Orca 3D. This gave a total weight for the vessel as of 4885 kg, with the centre of gravity located 0.06 m forward of amidships, and 0.93 m above the bottom of the keel (baseline). This condition has been termed here as 'lightship', and the vessel will float with a very slight 0.25 degree bow down trim (Fig. 12a). Further comparative details are given in Table 4 and the corresponding stability curve is shown in Fig. 12a.

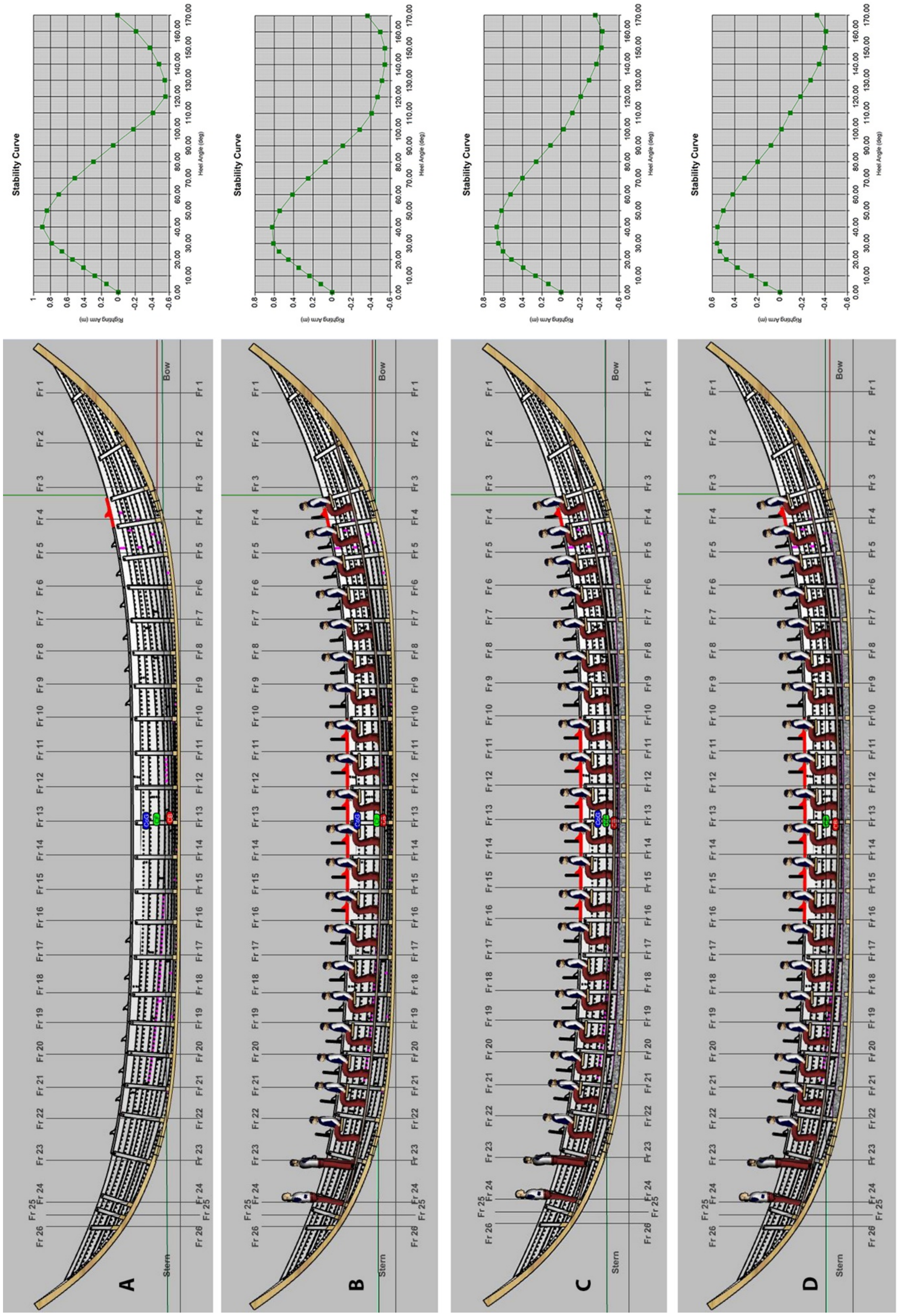

Figure 12*. Flotation conditions and corresponding stability curves of the reconstructed Sutton Hoo ship: A) 'lightship'; B) minimal loading'; C) 'ballasted'; D) fully laden (Sutton Hoo Ship's Company).*

Table 4. *Flotation conditions: comparative details*

Vessel Condition	A) Lightship	B) Minimal loading	C) Ballasted	D) Fully laden
Displacement	4,885 kg	11,493 kg	16,116 kg	21,124 kg
Waterline length	15.660 m	17.309 m	18.020 m	18.632 m
Navigational draft	0.330 m	0.524 m	0.630 m	0.738 m
Freeboard (midships)	0.952 m	0.759 m	0.647 m	0.539 m
Prismatic coefficient (Cp)	0.598	0.599	0.600	0.600
Block coefficient (Cb)	0.353	0.382	0.396	0.404
Wetted surface area	29. 95 m^2	42.27 m^2	48.56 m^2	54.42 m^2
Maximum heeling angle	30°	21°	18°	15°

In order for the vessel to be assessed in a useable state—that is in a condition where it could be rowed—generic thwarts, oars have been added to match the tholes, including the six sets that might have existed in the central area of the ship. In addition, a generic floor was inserted at a suitable height for the rowers to brace their feet. This added a combined weight of 3248 kg for the thwarts, oars and flooring. A crew to fit this thole configuration was modelled as 40 rowers, a helm and captain (Fig. 12b). Using an average of 80 kg per person, this added a further 3360 kg of weight. In this configuration, here termed 'minimal loading', the combined total weight for the vessel is 11,493 kg and the centre of gravity is raised to 1.05 m above the baseline (bottom of keel). Further comparative details are given in Table 4 and the corresponding stability curve is shown in Fig. 12b.

It should be noted that the vessel in its lightship (Fig 12a) and minimal loaded (Fig 12b) configuration has a relatively high centre of gravity, resulting in transverse metacentric heights of 1.611 m and 1.376 m respectively. This has the effect of making the vessel appear tender or unstable, and a one-tonne weight (or 12 people) placed at the widest point would heel the vessel to 7.5° and 13.5° respectively. Consequently, it was decided that 125 mm (5 inches) of internal stone ballast would likely be placed between frames 5 and 22, adding 4623 kg of weight and greatly increasing the initial stability of the vessel. Informal discussion at the international symposium in Woodbridge (October 2018) with crewmembers from the reconstructed Nydam ship revealed that similar ballasting had been needed in that vessel (O.B. Søndergaard, pers. comm.). With the addition of the 125 mm (5 inches) of internal stone ballast the combined deadweight for the vessel increases to 16,116 kg, but the centre of gravity moves aft to 0.05 m aft of amidships, and is lowered to just 0.849 m above the bottom of the keel, resulting in a more stable vessel which will only heel by 4° when one tonne is added at the widest point. This aft movement of the COG changes the bow down trim from 0.25 degrees to 0.1 degrees, or a level fore and aft trim. In this configuration, the vessel is referred to as 'ballasted' and further comparative details are given in Table 4 with the corresponding stability curve shown in Fig 12c.

Consideration of the vessel's potential freeboard provides an avenue for understanding its maximum capacity—either as an oared cargo vessel or as a means to convey military equipment (horses, people, etc). Ethnographic evidence suggests that for inland waters, small boats were loaded to very little freeboard (McGrail, 1978: 91). Seagoing data is not readily available, but a medieval Icelandic Law from *c.*1280 (the Grågås Codex) states that the minimum freeboard (F) of a cargo ship should be F=2D/5, where D = depth of the hull amidships (Morken, 1980: 178). For the Sutton Hoo ship, this would be F=2 x 1.34 m/5, which equates to a midships freeboard of 0.536 m and is considerably less than either figure given for the empty bare ship, or minimally loaded vessel (Table 4). Loading the ship to such a minimum freeboard allows a total displacement of 21,124 kg.

Taking into account the total displacement of the minimally loaded vessel (11,493 kg), and the inclusion of ballast (4,623 kg) to improve stability, this gives a remaining capacity of 5008 kg for additional people or cargo that can be added to the vessel in order to achieve the minimum freeboard flotation condition. Achieving this purely through additional people (assuming an 80 kg average) would require 63 extra people, which is unfeasible within the confines of the ship. As an alternative, provisions for five days, personal equipment, and so on, as summarized in Table 5 was added, to allow the ship to reach its minimum freeboard condition.

Table 5. *Additional loading required to attain a 'fully laden' condition.*

Item	Weight	Notes
Vessel Deadweight	4885 kg	Weights of all individual elements of the minimum reconstruction of the vessel
Additional elements	3248 kg	Additional tholes in the central area, thwarts, oars, and flooring
42 Crew	3360 kg	42 people x 80kg average
Internal ballast	4623 kg	125 mm (5") stone ballast between frames 5 and 22
Additional capacity	5008 kg	Available as cargo, provisions, or a combination of both
Total	21,124 kg	–

The vessel in this condition can be considered as 'fully laden' (Fig. 12d) and, as noted above, has a total weight of 21,124 kg. Further comparative details are given in Table 4 and the corresponding stability curve is shown in Fig. 12d. This potential capability of the ship as an oared cargo-carrier, or at the very least as a royal vessel with considerable capacity to move cargo if needed, has not been widely explored thus far. As such it opens up a fresh avenue for understanding the roles and tasks that the vessel might have played in the early 7th century, aside from acting as a high-status people carrier.

Speed potential

A displacement hull like the Sutton Hoo ship generates a bow and a stern wave as it moves forward, with the boat sitting in the trough between the two waves. As the boat accelerates to higher speeds a greater amount of power is required to overcome this wave resistance until a stage is reached where the power required to accelerate further becomes exponential. This point is referred to as the displacement trap. The displacement trap results in a theoretical maximum hull speed, which is calculated as 1.34 knots multiplied by the square root of the waterline length (LWL) in feet (Marchaj, 1964: 297). Boats which do achieve speeds where velocity (V)/(√LWL) > 1.40 may appear to be planing. At speeds (V)/(√LWL) > 1.70 dynamic lift begins and boats will be said to be semi-planing, and at speeds (V)/(√LWL) > 3.20 boats are truly planing or skimming (Marchaj, 1964: fig 158). Displacement boats like the Sutton Hoo ship can only exceed (V)/(√LWL) = 1.40 in ideal conditions or with excessive use of mechanical power. From 1.34√LWL, and taking the waterline length of the minimally loaded vessel, the Sutton Hoo ship, therefore, has a theoretical max hull speed of 1.34 x √55.7 = 10 knots.

Assessment of the speed potential of the vessel is based on propulsion being provided by oar. This is founded on the presence of tholes along both sides of the ship, and the wider use of oars, rather than paddles, on large vessels across the wider North Sea region at this time (McGrail, 2001: 211; Crumlin-Pedersen, 2010: 69–70). Available figures (Coates *et al*., 1990; McGrail, 1997: 216; Nayling and McGrail, 2004: 189) indicate the maximum output of a rower, pulling from a fixed seat, is about 750 watts (1 horsepower (hp)) sustainable for a very short time. Over a period of 10–20 minutes *c.*250 watts (0.3 hp) should be sustainable, while 60–70 watts output is considered comfortable over much longer periods. Taking the latter figure, in combination with a 40-rower arrangement (used for both the minimally loaded and fully laden vessels) and an assumption that the rowers are operating in an effective and efficient manner, gives a potential power output of *c.*2.6 kW (65 W x 40) for long sustainable periods, and 10 kW (250 W x 40) for a 10–20 minute period. A higher number might be achievable for very short periods of time. These outputs, in conjunction with the crewed flotation conditions outlined above (minimally loaded, ballasted, and fully laden) allowed a Holtrop powering analysis (Holtrop, 1984) to be conducted using the Orca3D marine plug-in for Rhino3D. This provides a set of required power outputs to allow various theoretical speeds to be achieved (Table 6).

Table 6. *Power required, based on Holtrop analysis, for the ship in its Minimally Loaded and Fully Laden configurations*

Power Required	**Minimally Loaded**	**Ballasted**	**Fully Laden**
Power required to achieve 0.5 knots	0.002 kW (0.002hp)	0.002 kW (0.002hp)	0.003 kW (0.002hp)
Power required to achieve 1 knot	0.014 kW (0.02hp)	0.016 kW (0.02hp)	0.018 kW (0.02hp)
Power required to achieve 1.5 knots	0.045 kW (0.06hp)	0.052 kW (0.07hp)	0.058 kW (0.08hp)
Power required to achieve 2 knots	0.103 kW (0.14hp)	0.118 kW (0.16hp)	0.132 kW (0.18hp)
Power required to achieve 2.5 knots	0.195 kW (0.26hp)	0.224 kW (0.30hp)	0.251 kW (0.34hp)
Power required to achieve 3 knots	0.329 kW (0.44hp)	0.378 kW (0.51hp)	0.423 kW (0.57hp)
Power required to achieve 3.5 knots	0.513 kW (0.69hp)	0.589 kW (0.79hp)	0.660 kW (0.89hp)
Power required to achieve 4 knots	0.759 kW (1.09hp)	0.870 kW (1.17hp)	0.974 kW (1.31hp)
Power required to achieve 4.5 knots	1.081 kW (1.45hp)	1.236 kW (1.66hp)	1.380 kW (1.85hp)
Power required to achieve 5 knots	1.499 kW (2.01hp)	1.710 kW (2.29hp)	1.907 kW (2.56hp)
Power required to achieve 6 knots	2.735 kW (3.67hp)	3.120 kW (4.18hp)	3.476 kW (4.66hp)
Power required to achieve 7 knots	4.828 kW (6.47hp)	5.536 kW (7.42hp)	6.180 kW (8.29hp)
Power required to achieve 8 knots	7.663 kW (10.27hp)	9.082 kW (12.18hp)	10.435 kW (13.99hp)
Power required to achieve 9 knots	11.697 kW (15.69hp)	13.799 kW (18.51hp)	15.889 kW (21.31hp)
Power required to achieve 10 knots	19.451 kW (26.08hp)	22.935 kW (30.76hp)	26.322 kW (35.30hp)
40 rowers cruising all-day	5.9 knots	5.6 knots	5.5 knots
40 rowers 20-minute sprint	8.8 knots	8.2 knots	8.0 knots
28 rowers cruising all-day	5.2 knots	5.1 knots	4.9 knots
28 rowers 20-minute sprint	7.7 knots	7.4 knots	7.2 knots

Reference to these results indicates that even in its fully laden configuration, the vessel could be rowed comfortably at *c.*5.5 knots for long periods of time and 8 knots for a short intense effort. Meanwhile, in its minimally loaded state the ship could be comfortably rowed at just under 6 knots for long periods, and potentially reach speeds of almost 9 knots for shorter intervals. It is interesting to note from Table 6 that the potential speed generated by 28 rowers, keeping the central area as a cargo or high-status passenger space, is typically just 0.5 knots below the fully crewed 40-rower output when cruising. A clear caveat to this analysis is that the introduction of less effective or efficient rowers (either through power or technique), or operation in less than optimal conditions (such as rougher waters) will naturally reduce the power output and the corresponding speed. Comparing these modelled results with the experience of rowing a full-scale vessel, including observation on how increased experience over time in rowing a ship as large as Sutton Hoo translates to increases in performance will be a key part of any future trial-phase of the full-size reconstruction.

Discussion and conclusion

This article has set out to present a digital reconstruction of the Sutton Hoo ship as part of the first phase of work within a wider project to undertake a full-scale build and subsequent sea-trials. The aims and objectives of this phase of the project have been met, and a minimum reconstruction has been tested to demonstrate the hydrostatic validity of the proposed reconstruction in advance of the full-scale build. The methods used represent the realization of a fully digital process by which the ship is rebuilt, component by component, based on the available archaeological record. The expert consultation undertaken with this work made clear the need to fully set out any assumptions made on the part of the reconstructors, what the London Charter (Denard, 2009: 1–13) describes as the 'paradata' (the reasoning and decision-making process) and these have been included here, alongside the methodology. We would recommend this as a key element for other projects to help explain the process of transposing the archaeological record into a digital model.

It is important to recall the nature of the dataset surviving from Sutton Hoo. The data on the ship obtained from the 1939 excavation is demonstrably incomplete. However, the application of digital processes described above allows the reconciliation of multiple datasets in a manner that was not available to previous reconstruction efforts. This has allowed the rectification of drafting errors, resolution of areas of disagreement, and refinement of the overall hull shape to better reflect the archaeological record and its implications, rather than the limitations of 2D paper drawing. Despite this, it can be reasonably expected that the demands of full-scale construction will lead to further refinements, revisions, and alterations to the reconstruction proposed here. This is to be expected and should not be resisted by slavishly following the digital blueprints. Instead, such changes must be carefully documented and the rationale for them recorded to allow the overall process of moving from design to full-scale build to be more properly understood and for subsequent changes to the vessel to be fully accounted for. Proceeding from the digital model to a full-scale version of such a large vessel will require careful monitoring at each stage. Since this is an experimental project from which it is hoped much will be learnt about Anglo-Saxon water transport and seafaring, elements of the design will be put to the test during the build and subsequent trials. This will require detailed on site recording of the materials, shapes, and assembly for comparative purposes during all phases

The detailed modelling of the vessel outlined here has demonstrated that the underlying flotation and stability characteristics of the Sutton Hoo ship are within practical bounds. Moreover, the hydrostatic analysis is consistent with the Sutton Hoo ship serving multiple functions. It was undoubtedly a very large and impressive vessel, but its manner of use could be changed and adapted as required by circumstance. The vessel could operate as a very fast troop-carrying ship with the potential to deliver a large, heavily equipped, fighting force. At the opposite end of the functional spectrum, it had the capacity to carry a considerable quantity of cargo, supplies or other material up and down the rivers of East Anglia and along the coasts of the southern North Sea. Finally, it could also provide the means for conveying a royal party in comfort in the centre of the vessel. This is illustrated diagrammatically in Figure 13, showing just one of the many possible crewing configurations for the ship. Testing and validating or dismissing these different configurations at full-scale represents a critical area for future work in the project. This is important not just for illuminating the Sutton Hoo ship itself, but for helping to understand and refine the strengths and weaknesses of the digital processes described here.

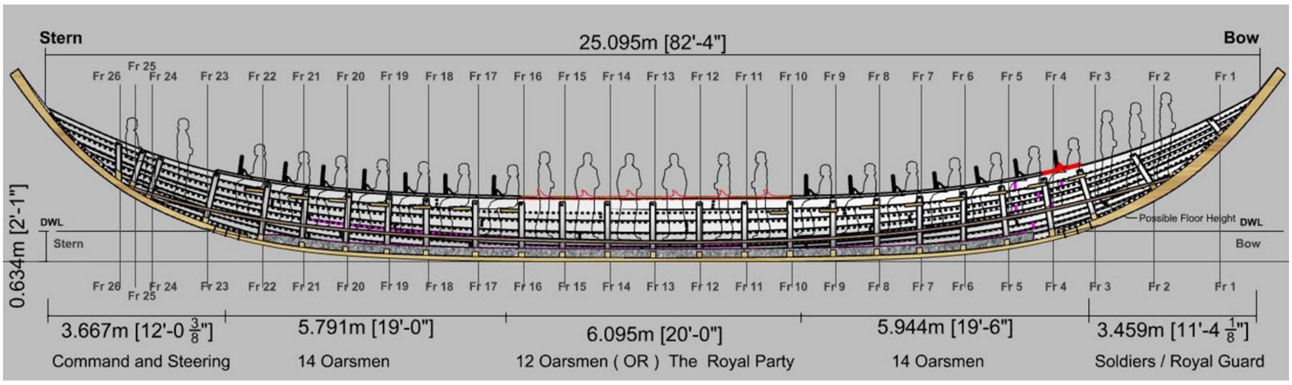

Figure 13*. Potential arrangement of internal space, crew, and passengers for the Sutton Hoo ship when conveying a high-status group in the central area of the vessel (Sutton Hoo Ship's Company).*

One final critical area of future work within the project relates to developing an understanding of how a vessel with significant sheer across its length, could be rowed in an effective and efficient manner, in a variety of sea and river conditions. Further digital modelling is likely to go some way to achieving this, but the creation of a full-scale section of the vessel is likely to allow a much better real-world understanding of the range of parameters, and possible solutions, involved. Doing this will allow the vessel to realize its full potential as a research tool, and ensure that it is used in the most effective way, with minimal potential for mishap, when eventually launched.

Finally, it is perhaps telling, that in passing comment on the process of archaeological excavation, analysis, and interpretation of Sutton Hoo, Carver has observed (1998: 92) that:

> *It must be emphasized that a definitive version of the Sutton Hoo story can never be given. The model offered in Chapters 4–6 [of Carver, 1998] is a construction, a work of interpretation drawing on the evidence, of imagination supported by science. If parts of the edifice seem at times too brightly coloured, they rest nevertheless on fairly solid foundations.*

Such sentiment could easily be applied to the ship at the heart of the Mound 1 burial. The nature of the data dictates that there is no single objective record, from which a single 'true' iteration of the early 7th century vessel can be reconstructed. There is instead a range of interpretations, varying in accordance with the perspective and personal experience of those involved; a statement that is itself perhaps true of any maritime archaeological reconstruction. The work presented here has sought to understand the available dataset in the fullest way possible, and to interpret such data using the best archaeological tools currently available. In doing this, a reconstruction is presented that we believe best represents the surviving evidence of the excavated vessel. Moreover, the nature of this work, resting in the application of digital reconstructive methods has allowed new light to be shone on the potential function of the vessel beyond that of a funerary artefact. At the same time, the future full-scale reconstruction of the ship can be undertaken from a position of greater knowledge and understanding of what the resulting vessel may be capable of, and critically, of what research questions will be best asked of it.

Endnotes

1) Crumlin-Pedersen and McGrail (2006: 57–57) set out a 'minimum reconstruction' as being: 'reconstructions based on the excavated evidence… using valid comparative evidence to "fill in" the missing parts, but without recourse to naval architectural conjectures, alien elements, or anachronistic intrusions.'

2) The lofting process itself, used to create the digital strakes on the Sutton Hoo ship can be summarized from a technical standpoint as follows. A three-dimensional curve is created passing initially through every rivet along a documented strake edge. Once a curve has been created for the upper and lower edge of a particular strake, a series of plank cross-sections are created, typically, one at the beginning and end of both 3D curves, and maybe with more in between depending on the strake. The digital strake is then "lofted" or created by using the "sweep two rails" command in Rhino, which extrudes the shape starting with the first plank cross-section shape, morphing through the intermediate cross-section shapes, and terminating at the last plank cross-section shape, while all the time following the path of the two strake edge guide curves. This has the effect of creating a digital strake which passes through every

documented rivet position (see Fig. 7a). The end result, however, is a very wavy or distorted strake which is unlikely to represent what was originally built. The second phase is the balancing act between relocating individual mal-positioned rivets or smoothing localized distortion (see Fig. 7b) to arrive at a fair or sweet strake run as subsequently discussed.

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