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The Reconstruction and Analysis of Archaeological Boats and Ships

by

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Thesis for the degree of Doctor of Philosophy

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ABSTRACT

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The Reconstruction and Analysis of Archaeological Boats and Ships

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Old ships and shipwrecks have long held an almost mythical fascination in the human mind. Ever since the Renaissance, Greek and Roman ships have been a subject for antiquarian interest, often with speculation rife due to the paucity of evidence, limited mainly to literary sources and representations on monuments, mosaics, and art works. People have always had a fascination with, and a desire to imagine, visualise or reconstruct the ships that have come from the antiquarian and archaeological records. Ship reconstruction from archaeological remains is almost as old as ship archaeology.

This thesis presents the techniques and methodologies developed and used for accurate and efficient data capture, in the form of three-dimensional digital documentation, allowing innovative approaches to organising, analysing, comparing, and disseminating data pertaining to the archaeological find. Subsequent advanced digital three-dimensional modelling, combining all the documented data enables detailed accurate reassembly of the surviving elements, as well as the ability to digitally model missing elements to aid in hypothetical reconstructions. These digital reconstructions can have future uses in terms of physical reassembly replica building, and ongoing conservation/analysis of ongoing changes in reconstructed physical remains in a museum.

The final phase involves the use of naval architecture software to accurately calculate factors such as centre of gravity and total weight, allowing the establishment of actual floatation conditions, as well as examining external factors such as crew, cargo, wind and wave loading in order to examine hydrostatic and stability performance, as well as potential speed and power analysis, thereby resulting in a more definitive hypothetical reconstruction of archaeological ship and boat finds.

"Those who fall in love with practice without science are like a sailor who steers a ship without a helm or compass, and who never can be certain whither he is going" – Leonardo da Vinci

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Academic Thesis: Declaration of Authorship

I, Pat Thomas Tanner declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

The Reconstruction and Analysis of Archaeological Boats and Ships

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:

Jones, Toby, Nigel Nayling, and Pat Tanner

2013 Digitally Reconstructing the Newport Medieval Ship: 3D Designs and Dynamic Visualisations for Recreating the Original Hull Form, Loading Factors, Displacement and Sailing Characteristics. , editors Colin Breen and Wes Forsythe. *ACUA Underwater Archaeology Proceedings 2013, SHA Leicester*:123–130.

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Signed: Pat Tanner

Date: 19/09/2020

Definitions and Abbreviations

ISBSA	International Symposium on Boat and Ship Archaeology
IJNA	International Journal of Nautical Archaeology
MDF	Medium Density Fibreboard
DWL	Design (or Datum) Water Line
AP	Aft Perpendicular, the point where the design water line (DWL) intersects with the stern
FP	Forward Perpendicular, the point where the design water line (DWL) intersects with the stem
LCG	Longitudinal centre of gravity
TCG	Transverse Centre of Gravity
VCG	Vertical Centre of Gravity

Overall Dimensions:

LOA	Length Overall, the length of the vessel, from forward end of stem to aft end of sternpost. Length Extreme is the length of the vessel, including fixtures and fittings such as bowsprit and rudder
BOA	Beam Overall, the maximum beam of the vessel
D	Depth Overall, the maximum depth of the vessel, from the deepest point in the water to the highest point above the water excluding rigging.
Loa/Boa	The ratio of the Length Overall to the Beam Overall
Boa/D	The ratio of the Beam Overall to the Depth Overall

Waterline Dimensions:

Lwl	Waterline length of the vessel
Bwl	Waterline beam of the vessel
T	Navigational Draft, the distance, perpendicular to the flotation plane, from the flotation plane down to the deepest point on the vessel
Lwl/Bwl	The ratio of the Waterline Length to the Waterline Beam.
Bwl/T	The ratio of the Waterline Beam to the Navigational Draft.
D/T	The ratio of the Depth Overall to the Navigational Draft

Volumetric Values:

Displacement	The overall weight of the vessel, as defined in the input or calculated from the defined flotation condition.
Volume	The integrated underwater volume of the vessel
LCB	The longitudinal centre of buoyancy of the resultant vessel orientation
TCB	The transverse centre of buoyancy of the resultant vessel orientation
VCB	The vertical centre of buoyancy of the resultant vessel orientation
Wet Area	The area of the underwater surfaces
Moment to Trim	The longitudinal moment required to trim the vessel between the fore and aft ends of the waterline.
D/L Ratio	The displacement length ratio, which is always expressed in imperial units of long tons/ft^3. It is defined as (Displacement in long tons / (Length in feet/100)^3)
FB/Lwl	The ratio of LCB to LWL, measured from the forward end of LWL; a value less than 0.5 means that the LCB is forward of the midpoint of LWL.
TCB/Bwl	The ratio of the transverse centre of buoyancy to the waterline beam.

Waterplane Values:

Awp:	The area of the waterplane of the resultant vessel orientation
LCF	The longitudinal centre of flotation of the resultant vessel orientation
TCF	The transverse centre of flotation of the resultant vessel orientation
Weight to Immerse:	the weight required to sink the vessel one unit in the direction perpendicular to the equilibrium flotation plane.
FF/Lwl	The ratio of LCF to LWL, measured from the forward end of LWL; a value less than 0.5 means that the LCF is forward of the midpoint of LWL.
TCF/Bwl	The ratio of the transverse centre of flotation to the waterline beam.

Sectional Parameters:

Ax	The maximum underwater sectional area calculated using sections. The maximum value is interpolated from the sections, by fitting a parabola to the station of maximum sectional area and the two stations on either side of it.
Ax Location	The longitudinal location of the station of maximum area (see note on interpolation above)
Ax Location / Lwl:	The ratio of Ax Location to LWL, measured from the forward end of LWL; a value less than 0.5 means that the Ax is forward of the midpoint of LWL.

Hull Form Coefficients:

Cb	The block coefficient of the resultant vessel orientation due to the defined flotation condition, defined as (displaced volume / (LWL x BWL x T)), where T is the maximum navigational
Cp	The prismatic coefficient of the resultant vessel orientation, defined as (displaced volume / (LWL x Ax)), where Ax is the maximum sectional area
Cvp	The vertical prismatic coefficient of the resultant vessel orientation, defined as (displaced volume / (AWP x T)), where T is the maximum navigational draft
Cx	The maximum section coefficient of the resultant model orientation, defined as (Ax / (BWL x T)), where T is the maximum navigational draft
Cwp	The waterplane coefficient of the resultant vessel orientation, defined as (AWP / (LWL x BWL)).
Cws	The wetted surface coefficient of the resultant vessel orientation, defined as (wetted surface / SQRT(displaced volume * LWL)).

Static Stability Parameters:

I (transverse)	The transverse moment of inertia of the waterplane
I (longitudinal)	The longitudinal moment of inertia of the waterplane
BMt	The transverse metacentric radius (distance from the vertical centre of buoyancy to the transverse metacenter) of the resultant flotation condition
BMl	The longitudinal metacentric radius (distance from the vertical centre of buoyancy to the longitudinal metacenter) of the resultant flotation condition
GMt	The transverse metacentric height (distance from the vertical centre of gravity to the transverse metacenter) of the resultant flotation condition
GMl	The longitudinal metacentric height (distance from the vertical centre of gravity to the longitudinal metacenter) of the resultant flotation condition
Mt	The height of the transverse metacenter in the resultant flotation condition, measured from the equilibrium flotation plane
Ml	The height of the longitudinal metacenter in the resultant flotation condition, measured from the equilibrium flotation plane.

Appendix A Literary Descriptions of Ships

As noted by Casson (1971:171–83), the capacity of seagoing freighters has been consistently under-estimated. Based on fragments of the port regulations from Thasos, and dating to the second half of the 3rd century BC, Casson states that that craft of 70 – 80 tons burden were reckoned as the smallest suitable for overseas shipping, and from the 5th century BC onwards, vessels of 100 -150 tons burden were in common use, while those of 350 to 500 tons, while considered large, were by no means rare. Casson (ibid:172) notes that the imperial Roman government preferred vessels of 340 tons for its grain fleet, and when it came to passengers, vessels could take up to 600 passengers on longer voyages.

In addition to these large (340 ton) merchant ships, Casson (1971:172–3) notes reference also exists, of what might be called 'super-freighter'. Shortly after the middle of the 3rd century BC a three-masted, three-decked grain carrier of some 1,700 – 1,900 tons burden came off the ways under the eye of Archimedes himself. And in subsequent centuries these 1,300-ton freighters plied the grain route between Alexandria and Rome. At least three such, operated out of Alexandria. The first was *Syracusia* (A.1 below), the second was the Isis (A.2 below), and the third was the vessel used by Caligula to transport the obelisk, now standing in front of St. Peter's, which was transported from Alexandria to Rome. The obelisk itself weighs 322 tonnes, with another 174 tonnes of pedestal stones in four pieces, which were probably transported in the hold. The obelisk itself had to be transported on deck, resulting in the ship requiring considerable additional ballasting, probably 800-900 tonnes of lentils, giving a combined total of 1,300 tonnes (Casson 1971:189).

A.1 The Syracusia

Although Athenaeus does not provide any dimensions for the ship designed by Archimedes, the itemised cargo on her maiden voyage: 60,000 measures of grain, 10,000 jars of pickled fish, 20,000 talents of wool, 20,000 talents of miscellaneous items have led to estimates of its cargo weight ranging from 3,650 to 4,200 tons (Casson 1995:185). However, Casson queries the measurement units used and suggests a refined cargo weight of 1,940 tons (ibid: 186). In addition, the ship also carried several ships boats, the largest of which was 78 tons (Turfa and Steinmayer 1999). Turfa and Steinmayer (1999:105–125) using estimates of timber quantity used, estimated deck sizes, and calculating weights for the itemised cargo, ship equipment and personnel arrive at a combined total weight of 4,229 tons. Regarding the shape of the vessel, Turfa and Steinmayer suggest overall dimensions for the Syracusia of 36 ft deep (based on two decks of 9 ft, and 18 ft for the lower bilge deck), a beam of 50.4 ft (1.4 times the depth) and a length of 201.6 ft (4 times the beam), rounded off to 200 x 50 x 36 feet or 61.5 x 15.4 x 10.8 m (Figure 1 2).

While a shoebox shape would have a displacement at half depth of 5,114.3 m^3, a block coefficient of 0.8 (typical of a cargo vessel) would result in an underwater volume of 4,091.5 m^3 giving a saltwater displacement of 4,192 tons.

The Syracusia's lowest deck, reached by numerous companionways, was for working cargo. The second deck giving access to cabins, 30 in all, along both sides of the ship, as well as the owners cabin complete with three internal cubicles, a kitchen aft of these and all having multi coloured mosaic covered floors with trim, overheads and doors all carefully worked. The third deck had a gymnasium, flourishing plant beds watered through covered lead tiles as well as promenades lined for shade with arbors of white ivy and grapes rooted in large earth filled jars. Alongside these a chapel to Aphrodite. The bulkheads and overhead were of cypress and the doors were of ivory and cedar. Other features on the upper deck included a reading room, library, a bath including three copper tubs and a 50-gallon coloured stone basin, accommodation for passengers, stables for ten horses, a sealed 20,000-gallon water tank as well as a lead lined seawater fish tank. Beams protruding outboard supported wood bins, ovens, stoves, millstones and other services. In addition to eight towers, two aft, two forward and the rest amidships, each as tall as the superstructure and housing four marines as well as two archer, a battlemented parapet surrounding a raised fighting deck resting on pillars ran across the ship, on which was set a catapult designed by Archimedes, and capable of hurling an 180-pound stone or 18 foot dart over 200 yards. Each of the three masts was fitted with two booms for dropping missiles down on an enemy vessel (Casson 1971).

A.2 The Isis

The Isis was a large grain freighter on the Alexandria – Rome run, which was blown off course on one voyage, and put into Athens in the second century AD, where it was visited by Lucian, who reported some of her details (ibid:186). Described by Lucian as having a length of 120 cubits (55 m), with a beam more than quarter of that (13.72 m +), and 29 cubits (13.25 m) from deck to deepest point in the bilge. Lucian did not provide a capacity, and various estimates have suggested 1,500 to 3,500 tons. Casson calculates the capacity, based on estimating the keel length to have been 63.5% the overall length, similar proportions to that of a 16th century Venetian Man-of-War. And using a tonnage formula of (length of keel x beam x ½ beam / 94) applies this to Lucian's dimensions to achieve 1,228 tons burden.

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Appendix B Articles on Reconstructions and Replicas

B.1 Mariner's Mirror articles with reconstruction in the title

1926 Sailing Model of the Old Impregnable: A 1925 Reconstruction of a 'Naval Pinnace' at Plymouth to Create a Sailing Model of HMS Impregnable (1810).: Vaughan, Herbert. *The Mariner's Mirror* 12(2):223–224.

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B.5 List of full-scale replicas built

‘Viking’ 1892, Norway – a replica of the Norwegian grave ship at Gokstad

‘Saga Siglar’ 1983, Roskilde – a replica of Skuldelev 1, lost off Catalonia in 1992 after a world circumnavigation

‘Roar Ege’ 1984, Roskilde – a replica of Skuldelev 3

‘Dronningen’ 1987, Norway - a replica of the Oseberg ship, lost during first sailing trials

‘Helge Ask’ 1991, Roskilde – a replica of Skuldelev 5

‘Hansekogge’ 1991, Kiel – a replica of the Bremen Cog

‘Ubena’ 1991, Bremerhaven – a replica of the Bremen Cog

‘Kraka Fyr’ 1998, Roskilde – a replica of Skuldelev 6

‘Tilia Alsie’ 1994-99, Island of Als – a replica of the Hjortspring find (Crumlin-Pedersen and Trakadas 2003)

‘Roland Von Bremen’ 2000, place – a replica of Bremen Cog

‘Ottar’ 2000, Roskilde – a ‘new and improved’ replica of Skuldelev 1 based on the experiences of ‘Saga Siglar’

‘Sea Stallion form Glendalough’ 2004, Roskilde – a replica of Skuldelev 2

‘Skjoldungen’ 2010-2, Roskilde – a revised replica of Skuldelev 6 based on alternate lower stem profile

‘Jewel of Muscat’ 2010, Qantab, Oman – a replica Arab Dhow from the Belitung ship find (Vosmer 2010)

‘Gyptis’ 2013, France – a replica of Jules-Verne 9 find

‘Morgawr’ 2013, Falmouth – a replica based on the Ferriby boat finds (Van de Noort et al. 2014)

‘Ma’agan Mikhael II’ 2016, Israel – a replica of the Ma’agan Mikhael find

Min of the Desert?

Bedan Seyad – a replica of the Omani 19th century sewn fishing vessel (Ghidoni 2019)

B.6 Bibliography of Replicas

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Appendix C Reconstructions based on archaeological evidence

The case studies discussed below are presented in chronological order (by date of excavation), and are by no means an exhaustive listing, rather, select examples are chosen as representative of significant developments or revolutions in documentation and reconstruction methodology.

Where possible, details about how the archaeological information was recorded, subsequently reconstructed and published are included. However, the focus of many project reports is on results and not the process or methodology. The lack of such details in many reports makes it difficult to understand how and, critically, why certain methods were chosen and others rejected.

However, an attempt has been made to select significant ship hull excavations from the last two centuries, focussing especially on those projects where the approach or methodology has developed or evolved. In geographic terms, the examples are primarily from North-western Europe and the Mediterranean.

C.1 The Woolwich Ship 1912 (1,130 words)

A large ship discovered at Woolwich in 1912 (Laughton 1914; Anderson 1959; Salisbury 1961; Glasgow 1971; Anderson 1972), originally reported to be a mid-eighteenth-century merchant vessel, lay neglected for over a year, during which time much of the timber had been sawn up and sold. It was subsequently reported in a daily newspaper as being none other than Henry VIII's largest ship the *Henry Grace á Dieu* known (or believed) to have been destroyed by fire at Woolwich in 1553. Further suggestions at an identity included the *Pelican*, although that vessel was almost certainly known to have dropped to pieces at Deptford. In March 1914 the Admiralty appointed a committee, the Deputy Director of Naval Construction together with three members of the Society for Nautical Research to decide if possible, on the date and origin of the remains (Anderson 1959:94–96).

The goals set out by the committee were: 1 The site where the wreck lay; 2 The Hull subdivided as, 2A the form and size of the wreck, 2B Historical note on tonnage measurement, 2C Historical note on naval architecture, 2D Historical note on Shipwrightry, and 2E The wreck compared to known practice; 3 The artefacts found in the wreck; 4 The question of identification; and Appendix 1 a glossary, and Appendix 2 a bibliography. The only parts completed during the 4 months preceding the outbreak of the First World War were sections 2A, 2B, and 2C together with Appendix 1 and 2 (ibid: 96).

Sections 2A, B, and C of the original report was by L.G. Carr Laughton, one of the original committee members, and he continued to study and add notes to his original report, one dated as added Sept. 1927 over 13 years since the draft version was created. By this point Laughton, based on the 52 inch diameter of the mast, and his revised estimates adding 14ft of keel length and nearly as much to the beam gave a keel length of 135 ft and 55 ft beam which were pencilled into his original report, was of the opinion that the Woolwich wreck was in fact the *Henry Grace á Dieu.* A conclusion to which Anderson also subscribed (ibid: 98).

Salisbury (1961:81–90) notes the discovery of the Woolwich wreck was dogged by bad luck from the very beginning, and by the time the Admiralty Committee was appointed in March 1914 the dismembered timbers still lay on the wharf, but had not been examined in detail by the time war broke out in August, and by 1918 all physical evidence of the wreck apart from a few scraps of timber had disappeared. Fortunately however, the discovery of the wreck had come soon after the finding of a Roman wreck on the County Hall site, and during excavations at Woolwich the L.C.C. (London County Council) took a series of photographs of the wreck in-situ, and their surveyors made notes and later prepared drawings. Salisbury proposed to give a résumé of the information made available by L.C.C. From this information Salisbury noted from the observer's comments that several stone shot were found, ranging from 3¼ to 12 inch in diameter, several commented on the use of treenails and the absence of metal fastenings, and many stated that there was no trace of burnt timber. In view of the efforts to connect the wreck with the *Henry Grace á Dieu,* Salisbury states that there can be no doubt that this latter point was thoroughly investigated.

Salisbury states that the L.C.C. drawings furnish: *'by far the most valuable record of the wreck and gain in value from the fact that they were not made by naval architects and are therefore relatively free from anachronisms.'* he also notes that some point which may have struck a naval architect as unusual have been left unexplained and indefinite. The main drawings created were sections (Figure 1) and a site plan (Figure 2) which Salisbury notes contain details unlike any ship built in England from the seventh century onwards, and the nearest parallels are to be found in the wreck of the *Henry Grace á Dieu* as described by Anderson in the 1934 Mariner's Mirror. The most obvious feature he notes is the remains of the mast which consists of a central core of pine encapsulated in an octagonal oak outer sheathing with a diameter of 52 inches which is much larger than a seventeenth century mast, probably indicating a relatively earlier date (ibid:85).

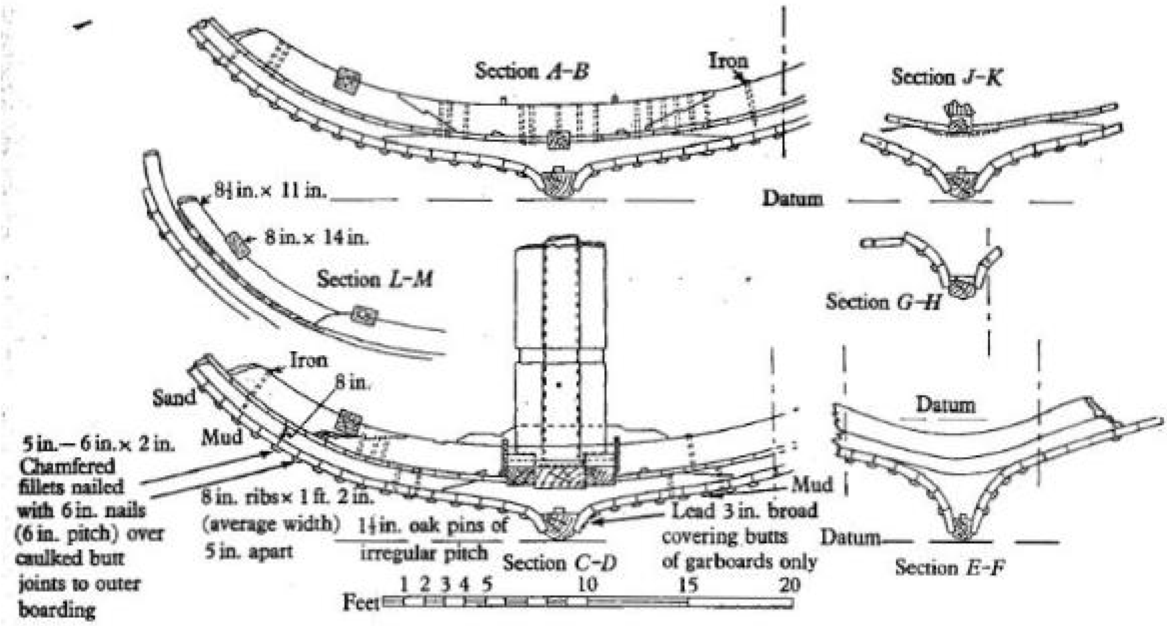

Figure 1 Sections through the Woolwich Ship (after Salisbury 1961:85)

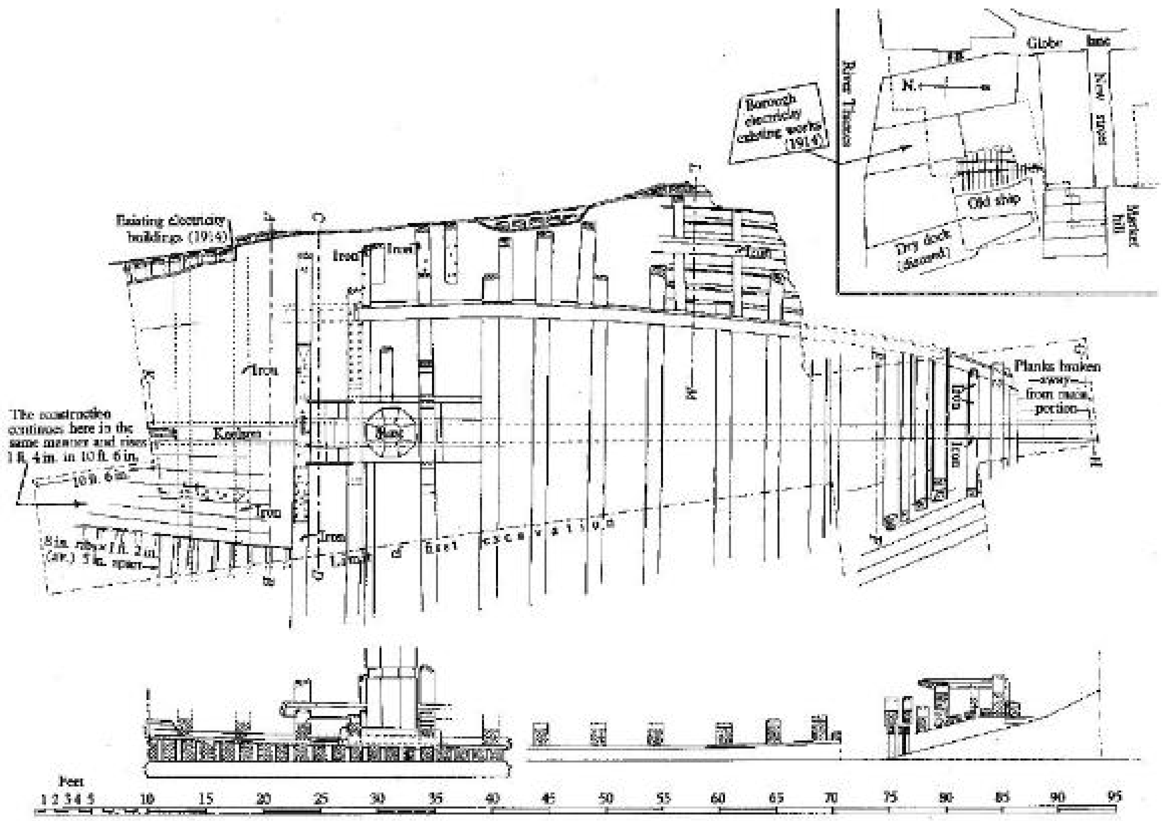

Figure 2 Site plan of the Woolwich ship (after Salisbury 1961:88)

On the matter of the dimensions of the wreck, Salisbury notes the breadth of the surviving material to be 43 ft and as there appears to be little overall distortion the maximum beam must have been at least 45 ft. The length is noted as being more uncertain, but the forward end of the keel is assumed from evidence within the drawings and estimated to be 48 ft forward of the mast base. Using Baker's Fragments of Ancient Shipwrightry of 1586, Salisbury estimated the keel to have been 115 – 120 ft in length. The draught of the vessel is then estimated based on the excavated keel lying between 6 and 8 ft below high-water mark, which Salisbury states resulted in the vessel having a draught of 9 ft at most and probably 2 ft less when floated into her last berth.

Salisbury concludes his résumé with a list of potential candidates for the wreck which include: the *Henry Grace á Dieu* burnt at Woolwich in 1553; the *Great Galley* built in 1515, rebuilt in 1523, and again in 1536-37 which disappears from the records between 1562-65; and the *Sovereign* built in 1488 and rebuilt in 1509-10 which was reported as lying in a dock at Woolwich in 1521, and was in such a state that '*she must be new made from the keel upwards*', and notes that unless new facts or knowledge of individual ships comes to light the Woolwich wreck can be identified with the *Sovereign* more satisfactorily than with any other ship (ibid:90).

The identity of the Woolwich wreck was further augmented by Glasgow (1971:302) when he provided details on the faith of the *Great Galley* which was subsequently rebuilt and renamed as the *White Bear* which according to Anderson (1972:103) ended her days at Deptford, and as such precludes her from consideration as a candidate for the Woolwich wreck, leaving the *Henry Grace á Dieu* and the *Sovereign* as possibilities.

This report or 'proposed résumé' of the wreck published by Salisbury in 1961, some 49 years after the initial discovery gives a description of the site, general estimated overall dimensions of the vessel, as well as detailed measurements of significant elements. It explains some of the reasoning for decisions made, as well as describing how certain findings were interpreted and utilised in the conclusions. The main focus of the committee was all aimed at the ultimate goal of identifying the wreck in order to finalise the dating.

C.2 Ferriby prehistoric, sewn plank boats 1937

The Wright brothers began to record the first of the Ferriby prehistoric, sewn plank boats that they had found on the northern foreshore of the Humber estuary in 1937. The initial find consisted of three planks projecting between the high and low tide marks. The planks were over 40ft (12.2m) in length and clearly represented a boat. The planks were photographed and carefully measured, before being recovered. Excavated again in 1939, and examined in more detail, the boat was described as being made of oak planks set edge to edge and the seams caulked with moss, covered with thin battens of oak (Figure 2-12), with yew withes sewing the planks and batten together (Wright and Wright 1939; 1947).

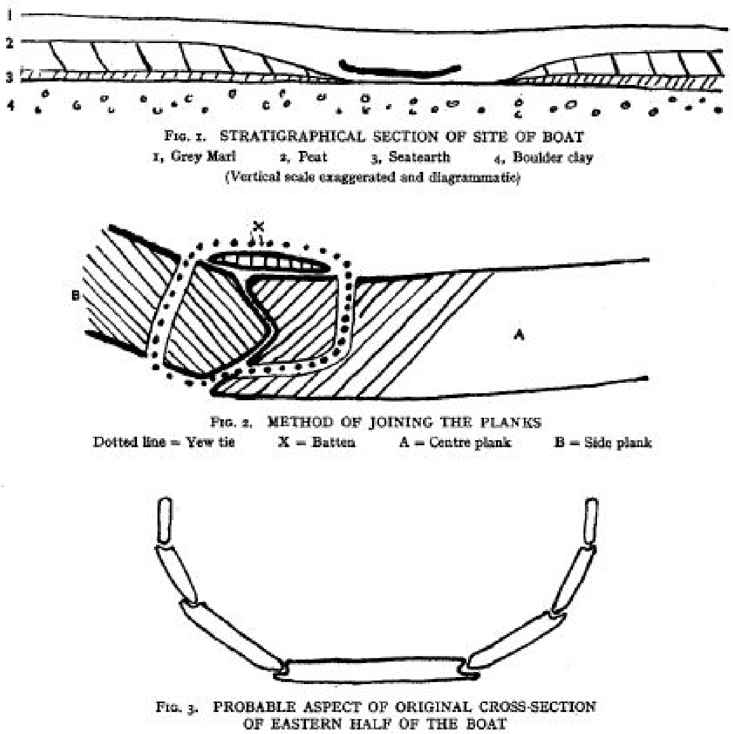

Figure 2-3 Ferriby 1 sewn boat (after Wright 1939)

Further excavations in 1946 revealed more details of the original vessel and uncovered the keel portion of a second boat labelled Ferriby 2. It was now confirmed the bottom of Ferriby 1 consisted of three planks, the keel and one side of which were made of composite pieces. All were shaped from solid oak trunks. Most had long cracks which had been repaired, and scarf joints were very short (75mm) which were not fastened together, except for the individual stitching through adjacent planks. Wright (1947:239–241) states they were unable to determine the form of the ends of the vessel.. A drawing of (presumably) the surviving excavated material is included in the 1947 report (Figure 2-13)

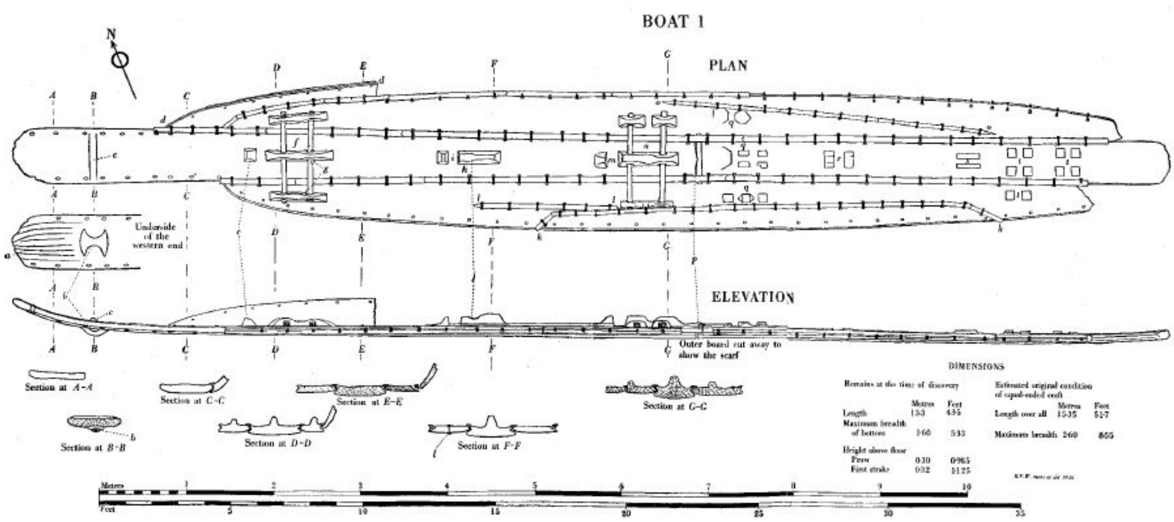

Figure 2-4 Ferriby 1 Excavated remains (after Wright 1947)

For the reconstruction Wright states that Ferriby 2 adds little information and focusses mainly on Ferriby 1. The extent western end of the keel is assumed to be almost complete and based on stitching hole spacings it is deduced that there was a total of three strakes per side, apart from the outer bottom planks (ibid: 244). A cleat underneath the exterior is interpreted as being for a longitudinal binding and a schematic view of the reconstructed western end is shown in Figure 2-14.

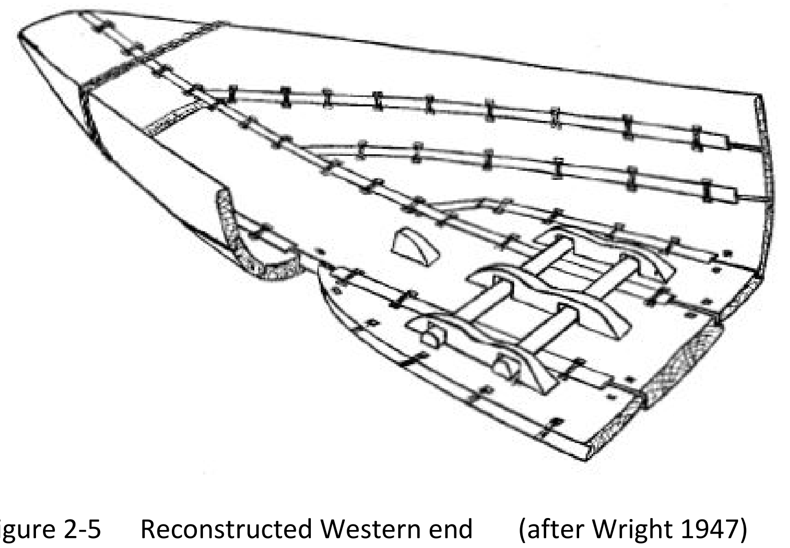

Figure 2-5 Reconstructed Western end (after Wright 1947)

The series of slots carved into the central keel plank are interpreted as being braces for heavy transverse ribs, as Wright reasons that a boat of this size would need some form of internal bracing, either by thwarts or ribs if it were to be capable of riding any sort of seas. As a result, Wright suggests a series of ribs wedged between the floor cleats, and stout thwarts lashed across the gunwales (Figure 2-15). A pair of parallel ridges aligned fore and aft were noted towards the eastern end of the keel plank, which was suggested as possibly being part of a mast step. The final result is described by Wright as a large open boat with punt-like extremities, over 50ft (15.24m) in length, and a beam of about 8ft 6 inches (2.6m) amidships. The excellent workmanship in the seams made it a sound vessel, and to move such a boat with the type of paddle found nearby would require a fairly large crew, but this is not considered a problem as the breadth would afford much greater capacity than a dugout of similar length. The addition of a mast and sail would open the possibilities of long voyages both in the estuary and perhaps up and down the coast (ibid: 246-247).

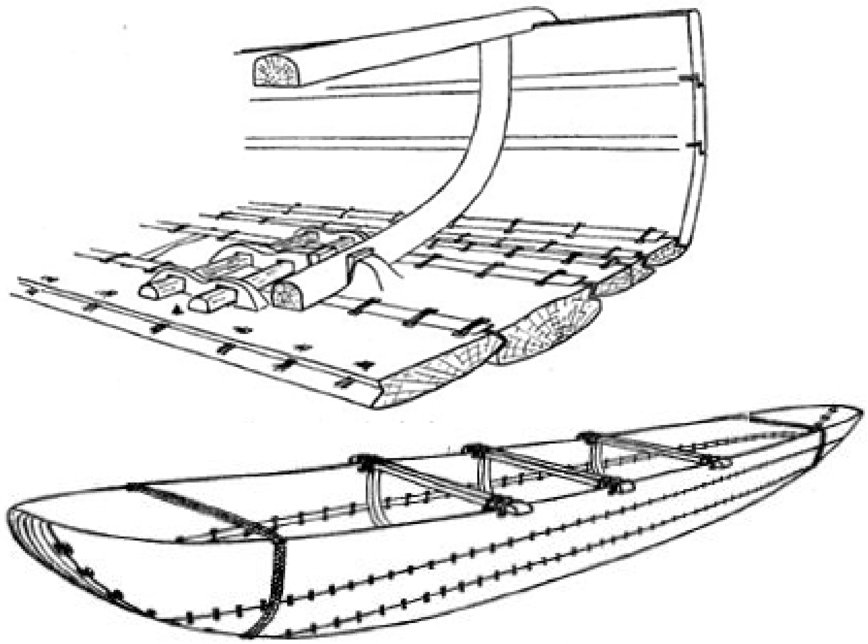

Figure 2-6 Reconstructed Ferriby 1 (after Wright 1947)

Wright made the first step towards reconstruction by assembling a 1/8 scale model of the excavated remains according to his records and the surviving remains. In this model the bottom planks were flat for most of their length as they lay in pieces on the concrete floor, apart from one end where the keel plank curved upwards over a length of about 2 m. During intermittent studies over many years, certain details of the original records were either forgotten, neglected or set aside. Between 1946 and 1988 at least five attempts were made on paper and by small scale models to reconstruct Ferriby 1 (Figure 2-16), but all had difficulties with closing the ends of the hull, and none had sufficient depth to be useful in anything but calm water.

Shortly prior to the opening of an exhibition on the Ferriby boats at the National Maritime Museum, Wright realised he had ‘neglected’ the rocker originally recorded in the bottom of the vessel (Wright 1990:18). Three models were originally planned for the exhibition:
a minimum reconstruction model, adding as little as possible to the excavated remains;
another as the first, but also including a hide wash-strake to increase hull depth; and
an Egyptian-style version with a hogging truss but (unlike most Egyptian boats) without rocker.
Wright insisted on adding a fourth model of a reconstruction with a rockered bottom to the exhibition.

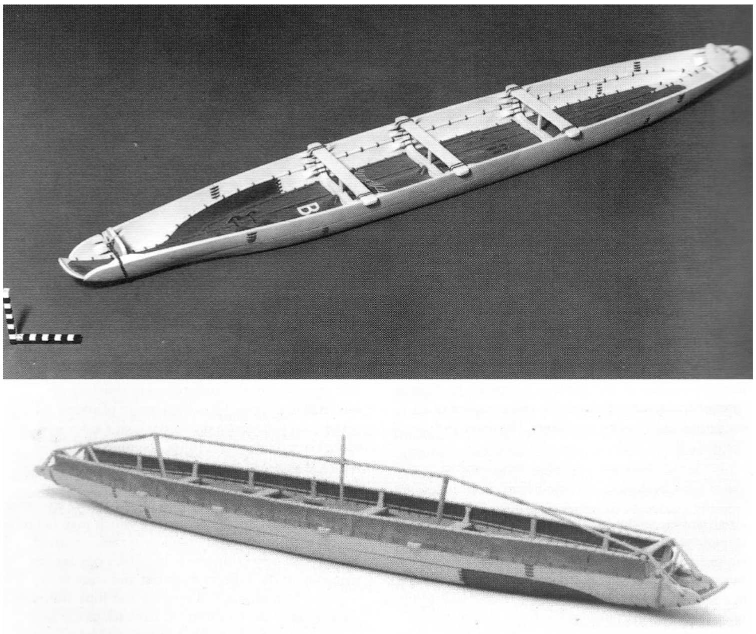

Figure 2-7 Two of the Ferriby 1 hypothetical reconstruction models

After consideration of alternatives together with John Coates (Wright 1990:85–116), Wright’s preferred hypothesis for a reconstructed boat (Figure 2-17) consisted of: an equal-ended rockered bottom-structure composed of a keel strake and outer bottom-strake on each side; sides consisting of 3 strakes each of 2 or 3 planks; up to 6 frames, each of a long and a short grown crook: lodged in slots or against stops on the keel strake; secured to the side-strakes by lashing to cleats and to the sheer strakes by slotting rib-ends through vertical holes in rails moulded on their inner top edges (feature derived from Ferriby 4[1]); each end of the hull secured by a girth-lashing passing through the cleat on the underside of the keel-strake; and up to nine thwarts located at the level of the top edge of the second side-strakes, notched over the plank-edges and protruding to the outside of the hull with the lower edges of the sheer strakes cut away to accommodate ends of thwarts (feature derived from Ferriby 4).

[1] Ferriby 4 was dated to circa 535-355 BC, at least 1,500 years later than Ferriby 1

Coates (in Wright 1990) estimated the empty weight of the vessel to be 3.8 tonnes, increasing to 4 tonnes when loaded with equipment, and an unladen draft of 0.35m, giving a freeboard amidships of 0.60m. With a freeboard of 0.4 m and draft of 0.58 m, the boat could carry a combined load of 6.7 tonnes. A crew of 20 (18 paddlers) weighing circa 1.5 tonnes leaves over 5.0 tonnes for cargo and/or passengers. There would be room in the reconstruction for 30 passengers weighing say 2.3 tonnes, with baggage or cargo capacity limited by volume rather than weight. With such loads the vessel as reconstructed would be very stable (Wright 1994:29–31).

For the performance Coates estimated that with 18 paddlers a speed of 6 knots could be maintained for about half an hour and would drop to circa 5.2 knots with 12 paddlers. This, Wright states, would be satisfactory for crossing the Humber estuary but only at slack high water if using 12 paddlers (ibid: 30).

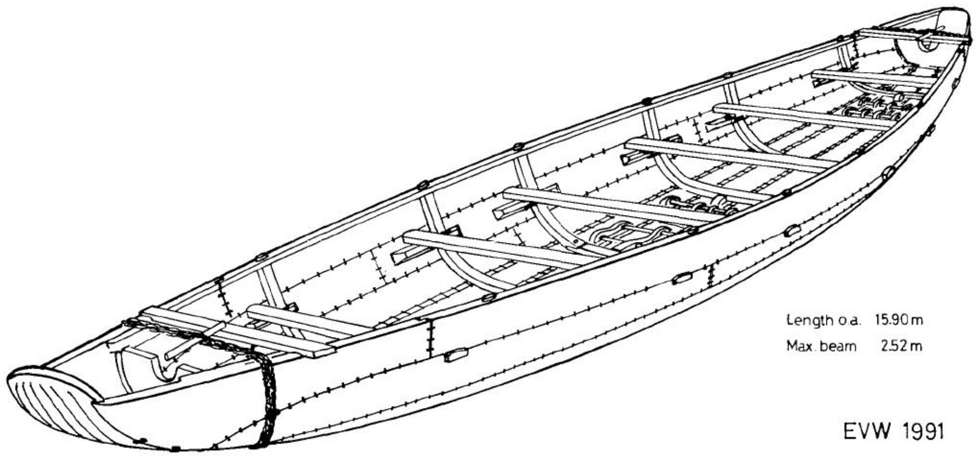

Figure 2-8 Hypothetical reconstruction of Ferriby 1 (after Wright 1994)

In 2001 the Ferriby 1 boat was once again subjected to dating attempts as the earlier efforts had proved unsuccessful due to the timbers being ‘contaminated’ by the conservation materials previously used. The results moved the dating from the originally believed 1,500 BC, to the earlier 2nd millennium BC (Wright *et al*. 2001:733). Wright further states this dating puts the Ferriby boat in the same category as those found at Kilnsea and Caldicot to form a convincing group of plank-built, early Bronze Age boats that were used for seafaring (ibid:733).

Crumlin- Pedersen noted that in the case of both the Ferriby and Dover boats there is considerable uncertainty about the shaping and height of the sides, the sheer of the hull, and the boat’s rocker. He states that while Wright and Coates estimate the vessel to have been quite seaworthy, employed for navigation in the estuary as well as coastal cargo carrying and short open sea crossings, McGrail on the other hand favours Wright’s initial flat-bottomed minimum reconstruction, which would make it a vessel suitable for a ferry used for river crossing in the Humber River where it was found (Crumlin-Pedersen and Trakadas 2003:213–14).

Crumlin-Pedersen states (2003:217) that McGrail also appears reluctant to accept bending or 'stretching' of the building materials in the process of construction, even though Wright has found evidence for this on some of the planks in Ferriby 1 (Wright 1994:31–32). If the minimum solution alone differs from the original vessel, then calculation of the performance of a vessel and its potential areas of operation, may provide severely misleading results.

For these Bronze Age sewn plank boats, ship technical calculations have been involved in the analyses from the point of view that, only by quantifying these conditions, can a basis be formed for a scientific analysis of the original qualities of the vessel found, and hence its sphere of operation. By following this route, it is indeed possible to determine various coefficients that can describe the form and the hydrostatic qualities for each individual vessel whose shape, size, weight and centre of gravity are known. The relevance of these calculations, however, is impaired by the fundamental uncertainty that is attached to the reconstruction solution selected by the archaeologist as a starting point (Crumlin-Pedersen and Trakadas 2003:217–8).

When studying the hydrodynamic conditions, the problems are even greater. While it is possible to carry out advanced technical calculations, the results of these are dependent on a number of factors which are not known in advance for ancient ships. In the case of modern ships, a combination of experiments with scale models, tank tests and full-scale sea trials has made it possible to develop correlation factors that permit reasonably reliable predictions of performance for new vessels of known types. Such work on ancient ships has not been fully undertaken in order to corroborate the results (Crumlin-Pedersen and Trakadas 2003:218).

Robert Van de Noort investigated the remains of a sewn plank boat discovered on the beach at Kilnsea, near Hull in 1996. While stating there was insufficient material surviving to attempt a reconstruction of the vessel, the remains were noted as closely resembling that of its nearest neighbour the Ferriby 1 boat from 40km upstream. Van de Noort suggested that coastal or seafaring functions should be contemplated based on its location in the outer estuary, where its use as a ferry would be considered impractical.

Van de Noort states that while the debate has always centred around the assessment of seaworthiness of reconstructed vessels (see Coates in Wright 1990; McGrail 1981; McGrail 1998a), the distribution of all known sewn plank boats of Bronze Age date such as at Kilnsea, Brigg, Caldicot and, most significantly, Dover are all in tidal rivers near estuaries or the coast (Figure 2-18). As such, Van de Noort states the assessment of seaworthiness may well be considered of limited value in terms of the late Neolithic Bronze Age exchange, and concludes that sewn plank boats were sea-going vessels, capable of carrying small cargoes, and reaching

Continental Europe (Van De Noort *et al*. 1999:134–35). However, is it just a case that this is where the survival of remains is most likely – in the intertidal mud?

Figure 2-9 Distribution of known Bronze Age sewn plank boats in the U.K. (Pat Tanner)

For this reconstruction it would appear to be based primarily on scale models constructed from the scale drawings and survey notes. The 'excavated remains' drawing is clearly an interpretation, devoid of the rocker which Wright states was present. Traditionally calculated basic hydrostatic coefficients and performance analysis were employed; however, uncertainty remains regarding the actual reconstructed hull form and the vessels proposed sphere of operations.

C.3 Yassi Ada 7th century AD Shipwreck 1961

The underwater documentation techniques developed during the Yassi Ada excavations were a revolutionary development. The underwater excavations from 1961-64 which were led by George Bass from the University of Pennsylvania decided that photography was probably the best way to document the site in order to make use of the limited bottom time and speed up the recording process. A stepped grid framework of angle iron was constructed and positioned over the cargo and vessel remains resulting in a 2 x 2 m grid further subdivided by lines. A raised photography tower was used to take photographs of each square during various stages of the excavation. The artefacts and hull structure were then traced over and correctly scaled to repair issues such as parallax and refraction. The resulting site plans were compared to direct measurements taken from the site and found to be accurate (Bass 1975:96–106). Steffy states the remains of the Yassi Ada ship were so sparsely preserved (Figure 2-15) that the exact construction sequence remains in doubt, and initial examination of the surviving material such as

> 'Iron planking nails penetrating only halfway through frames, half-log wales above deck level, strange framing patterns, and poorly fitting mortice-and-tenon joints were but a few aspects of the hull remains that would have perplexed anyone steeped in the traditions of good shipbuilding.'(Steffy 1982a:65).

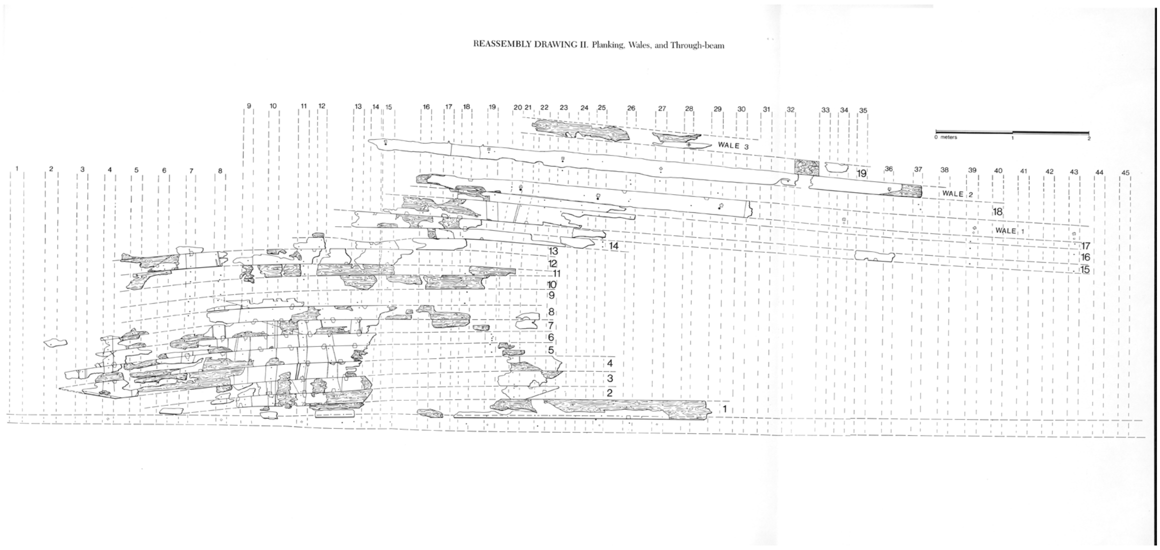

Figure 2-10 Yassi Ada Planking, wales and through hull beams (after Steffy 1982)

However, experimentation with several models and years of research, while admittedly a slow and tedious process, allowed the application of the excavated material to a three-dimensional study which generally produced valuable disclosures and allowed the development of a set of lines (Steffy 1982a:65). The reconstruction of the seventh-century merchantman is described by Steffy as largely hypothetical based on 10% of hull survival (Steffy 1994:80–81). 1:10 scale replicas of all the wood that had been recorded were made, with nail and bolt holes indicated. The strips were then bent to various shapes until the pieces of model planking were aligned with respect to the fastening holes. External and internal planking assemblies were next aligned to each other using known bolt holes and angles, these were then shimmed apart at the estimated 14 cm frame thickness and adjusted until the maximum amount of evidence was satisfied. Steffy states this was a tedious method, but the most accurate one which could be devised to satisfy such a small amount of excavated evidence (Steffy 1982a:65). Hull section drawings were then created from the assembled partial model[2] (Figure 2-16 left), allowing the creation of what Steffy labels a 'mould and batten' model (Figure 2-16 right).

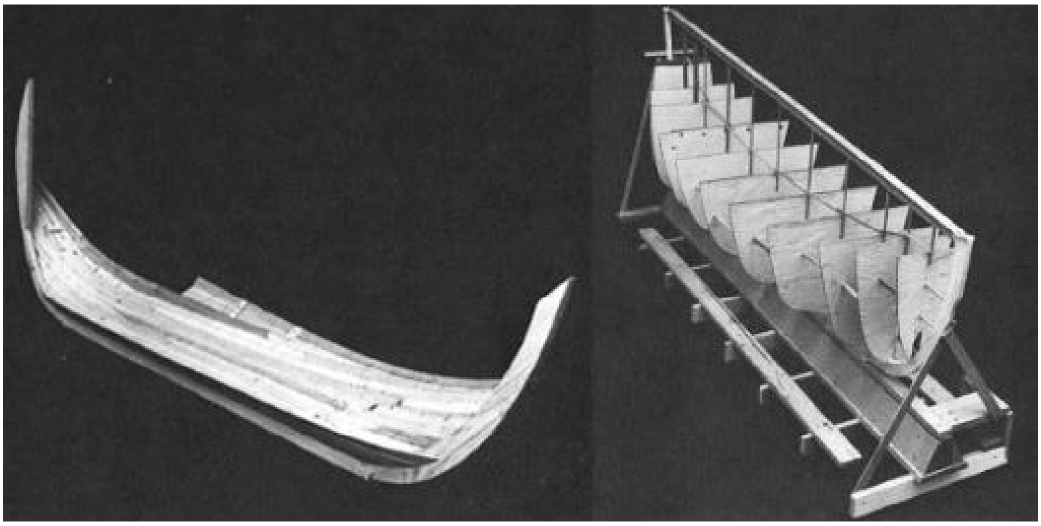

Figure 2-11 Yassi Ada Research model and 'Mould and Batten' model (after Steffy 1982)

Once the battens produced a satisfactory form in agreement with as much of the evidence as possible their positions were fixed, and a series of hull sections were measured in order to produce a set of drawings of the ship's lines. Steffy notes that these published lines drawings were largely correct for the area of the ship below the waterline, but they were not satisfactory in the bow and stern area above the water (ibid: 66). Further highly detailed 1:10 scale models were produced using additional information learned during the excavation of the *Pantano Longari* ship remains and the *Kyrenia* ship. Steffy states that new lines (Figure 2-18) and construction plans evolved based on this new information[3] as well as many countless hours of additional research and model building, and while the bow area remains conjectural, there is at least a basis of fact for it (ibid: 66).

[2] This involves the creation of moulds of the hull section shape, generated from the hull section drawings, which are placed at their assigned locations along the keel. Battens (thin strips of wood longer than anticipated length of the hull) are then laid along the edges of the moulds. All moulds are then trimmed or shimmed to produce a fair batten curve, extended to meet the stem and stern.
[3] The Pantano Longari is dated to the 7th century AD (Throckmorton and Throckmorton 1973:262), while Kyrenia is dated to the 4th century BC (Steffy 1985), with a span of 1,000 years, how valid is the additional information learned?

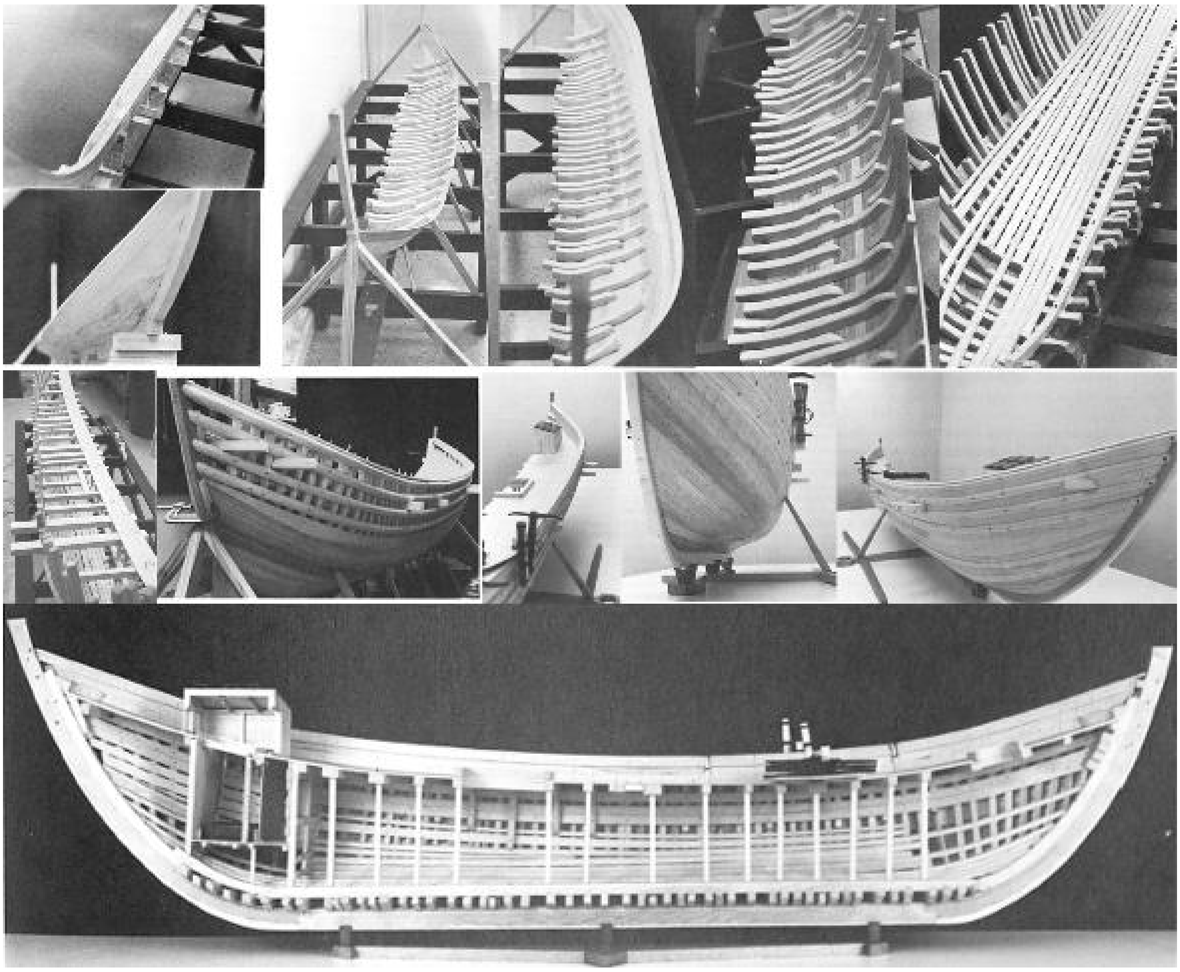

Figure 2-12 Yassi Ada additional research models (after Steffy 1982)

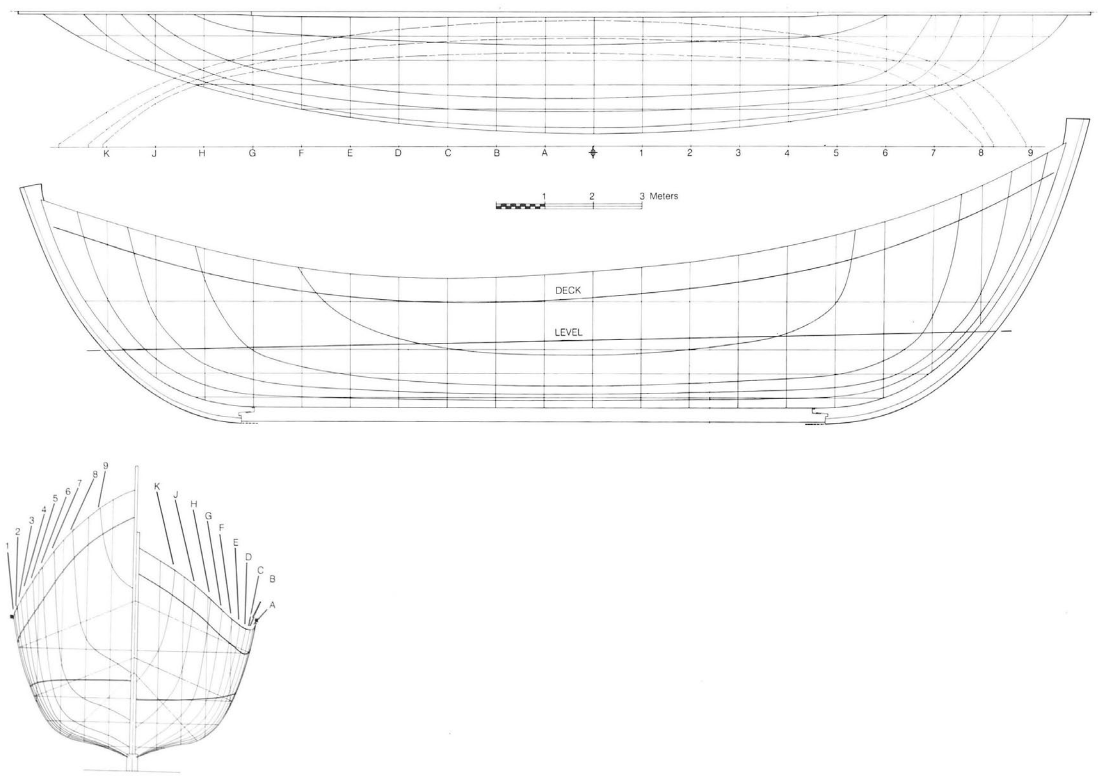

Figure 2-13 Yassi Ada lines plan (after Steffy 1982: Fig. 4.4)

For the analysis of the ship Steffy states that the ship models played a very helpful role in the reconstruction of the ship, while they failed in some cases to resolve problems, and also left a multitude of unanswered questions, their three-dimensional scope very often served to suggest solutions which were not immediately evident without the benefit of three-dimensional construction (Steffy 1982a:84). The lines of the vessel, with its extremely fine entry, slightly hollow garboard sections, widest beam located well into the after half, and the overall 'spoon' or crescent-shaped hull might seem surprising to students of the architecture of latter-day sailing ships, however the exceptionally well preserved *Kyrenia* ship had a similar heavy afterbody and fine bow. Steffy notes that while the models and tank test used were crude, experiments were conducted to study effects such as steering oars on hull performance and while the technology was extremely limited, the hull was found to sail best under a fore-and-aft (lateen) rig for the given location of the mainmast and steering oars. The tests also proved beyond doubt that if the vessel had been square-rigged it must have had a foresail such as an artemon.

In dealing with the waterline of the vessel, which directly dictates the cargo capacity, Steffy states that it was unknown how the vessel was trimmed, level or down by the stern, and his decision was to float the ship in a stern down condition with her load waterline located near strake 16[4] as this was where the shipwright transitioned form the edge fastened mortice and tenon construction to simple nailed fastenings. The initial tonnage for the vessel had been estimated on the old customhouse formula of tonnage = (length of keel x beam x depth of hold) ÷ 94 giving an estimated 40 tons. The same calculations applied to the revised overall dimensions gave a tonnage of 51.5 tons. However Steffy states these formulas actually calculate the volume tonnage and were fairly accurate when applied to the full-proportioned hulls of the seventeenth and eighteenth centuries for which they were intended, but do not necessarily determine the payload that could be carried by the spoon or crescent-shape ancient hulls or those ships where the keel had no relationship to the length of their holds (ibid: 86). Steffy's listed tonnage for the ship is based on the calculated total displacement of the vessel based on the assumed load waterline and subtracting the weight of the ship and its equipment. For this Steffy calculated a total displacement of 72.86 tons at the load waterline and estimated the effective weight of the ship at 20 tons, giving a tonnage capacity of 53 tons at the load waterline (Table 2-1).

The ship was carrying approximately 900 amphorae at the time of sinking, which if filled would weigh just over 37 tons, and based on the reconstructed models the vessel is estimated to have been capable of stowing as many as 1,200 such amphorae below decks, which would weigh just over 50 tons, so the estimated tonnage proved reasonable (Steffy 1982a:86).

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[4] Steffy selected this location for the waterline based on the change in hull construction at strake 16

Length on deck	20.52 m	Displacement (indicated waterline)	72.86 tons
Length (indicated waterline)	18.22 m	Beam-to-length ratio	1:4
Length of keel	12.00 m	Keel and posts	cypress
Beam (maximum)	5.22 m	Frames	elm
Beam (molded)	5.02 m	Planking	pine
Depth in hold	2.25 m	Fastenings	iron
Tons burden	60 tons		

Table 2-1 Yassi Ada Characteristics (after Steffy 1982)

A subsequent publication by Van Doorninck (2015) re-examined the ship focussing more on the cargo and artefacts recovered during the excavation. Van Doorninck notes that since the initial publication of Yassi Ada 1 (Bass *et al*. 1982), the vessel has undergone a slow but radical change. An inscription and the overall design and outfitting of the vessel suggest that the ship in some way or other served the church. With her low slender lines, designed for speed at the expense of cargo capacity, being remarkedly well equipped, with a well-appointed galley and a covered deckhouse complete with tiled roof, which although impractical at sea lent an aura of elegance and relative importance to the vessel (van Doorninck 2015:206). Further analysis of the amphorae suggests that many contained wine and olive oil, as well as sweet oil (for religious use):

> 'Our ship set sail on what was to be her final voyage fully laden with wine and olive oil, destined, I have argued, for Heraclius's army in the East. She also carried some jars containing sweet oil for liturgical purposes, particularly essential for a Byzantine army engaged in a holy war. I think it likely that she would have been part of a convoy and may have been stationed on the convoy's shoreward flank because of her relatively high mobility and light load. In any case, she came too close to the small coastal island of Yassi Ada, struck its treacherous reef, and sank to the south of the reef while attempting to reach the island'.(van Doorninck 2015:212)

For this reconstruction, the scaled site survey drawings were created from photography. Together with timber drawings (it is unclear whether these were scaled or full-size drawings), these were then used to create an initial scaled research model to determine the shapes of the surviving planks. Subsequent models were created to develop the hull shape. With further detailed models employed to develop additional features. The reconstruction process would appear to be based primarily on scale models constructed, adjusted or modified until a satisfactory result is achieved, somewhat akin to a trial and error process. The resulting methodology makes it difficult to document alterations made during the reconstruction process. Tonnage formulas and calculated displacement were used as a means to validate the resulting reconstruction, however as noted by Steffy, Yassi Ada and Kyrenia had a similar heavy afterbody and fine bow. A critical observer might be forgiven for asking if there was really no change in 1,000 years of hull form development, or is this a result of two reconstructions by the same individual?

C.4 Yassi Ada reappraisal 2015

A subsequent publication by Van Doorninck (2015) re-examined the ship focussing more on the cargo and artefacts recovered during the excavation. Van Doorninck notes that since the initial publication of Yassi Ada 1 (Bass et al. 1982), has undergone a slow but radical change. An inscription on the captain's steelyard (a balance or scales) and the overall design and outfitting of the vessel combine to suggest that the ship in some way or other served the church. The inscription (belonging to) Georgios Elder Sea-Captain, initially interpreted as Georgios being an elder (senior) sea captain, is interpreted by Van Doorninck as Georgios being an Elder (priest) in the church and a sea captain (ibid: 205).

Van Doorninck also states the ship with her low slender lines was designed for speed at the expense of cargo capacity as the hold through much of its length was unable to carry more than three or four layers of the globular amphorae. In addition, the ship was remarkedly well equipped, carrying 11 anchors, the carpenter's chest contained some 40 tools as well as several bags of nails and sheet lead ready for repairs while at sea. The well-appointed galley contained equipment lockers, a large tiled firebox, with a movable iron grill, a mortar and pestle as well as 21 ceramic cooking pots in a variety of sizes, two cauldrons and a baking pan of copper, serving utensils including several copper or bronze pitchers, glass bottles, 18 ceramic pitchers and jugs, and at least four or five settings of fine table ware, and was covered by a deckhouse complete with tiled roof, which although impractical at sea lent an aura of elegance and relative importance to the vessel (ibid: 206). Further analysis of the amphorae suggests that many contained wine and olive oil, as well as sweet oil (for religious use). For the final voyage of the ship Van Doorninck states:

'Our ship set sail on what was to be her final voyage fully laden with wine and olive oil, destined, I have argued, for Heraclius's army in the East. She also carried some jars containing sweet oil for liturgical purposes, particularly essential for a Byzantine army engaged in a holy war. I think it likely that she would have been part of a convoy and may have been stationed on the convoy's shoreward flank because of her relatively high mobility and light load. In any case, she came too close to the small coastal island of Yassi Ada, struck its treacherous reef, and sank to the south of the reef while attempting to reach the island'.(van Doorninck 2015:212)

C.5 Skuldelev Vessels 1962

Discovered in 1958, the remains of five[5] eleventh-century Viking ships were located, recorded and excavated from a site in Roskilde fjord, Denmark (see Johnstone 1969; Crumlin-Pedersen and Olsen 2002). Following the construction of a coffer dam and the pumping out of the water, the visible remains were documented and removed. The delicate and fragmentary nature of the wrecks (Figure 2-19), as well as the sheer volume of material meant a detailed survey using traditional methods with grid lines and drawings would have been exceedingly difficult and time consuming. The waterlogged hull timbers were documented in-situ using stereo photogrammetry, which was later used to create 2D in-situ site plans of the excavated vessels (Crumlin-Pedersen 2002a:51).

The work of creating the site plans took place sometime after the excavations, and as no independent control points were taken in the field, the accuracy of the recordings could not be verified. However, controlling the site plans against the actual ship timbers showed the accuracy of the photogrammetrical survey equalled that of traditional methods. Crumlin-Pedersen also noted that the many cracks and splits in the timbers were often more clearly visible than the actual plank edges, and other structural features, and these dominated many of the drawings produced by the surveyors. Consequently, these drawings needed to be interpreted by archaeologists in order to determine the lines relevant to the features and structure of the ship compared to the countless features to be observed in the stereo photos (ibid: 52-3)

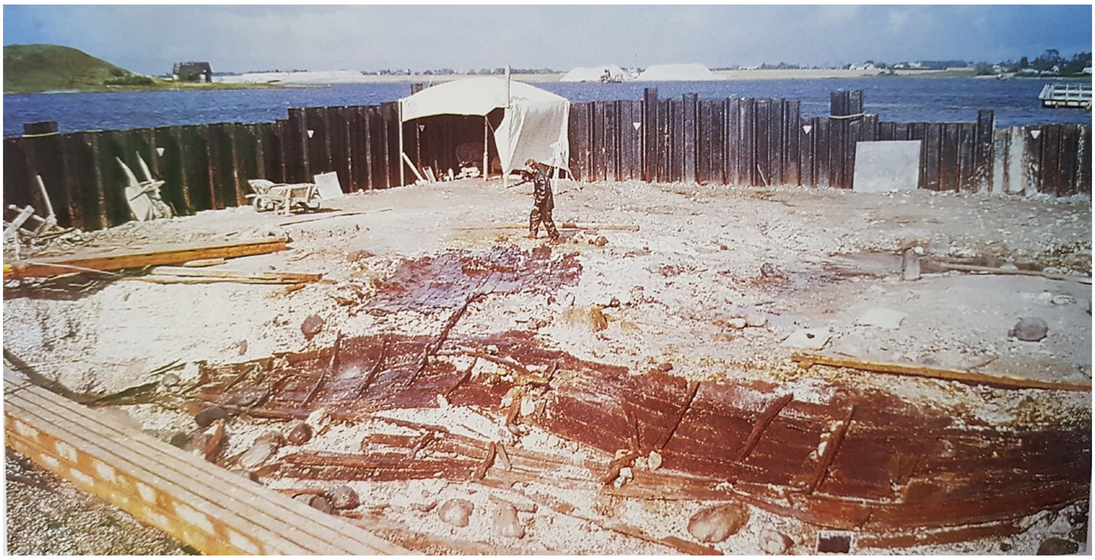

Figure 2-14 Skuldelev 5 wreck uncovered (after Olsen and Crumlin-Pedersen 2002)

[5] Initially thought to be 6 wrecks, wreck 4 turned out to be a few coherent strakes about 20 m away from wreck 3, but actually belonged to wreck 2. For simplicity the numbering system wreck 1 – 6 was retained, with wreck 4 becoming amalgamated into wreck 2.

The delay in processing the plans also meant it was not possible to check if all parts of the site had been photographed, or whether the photographs matched the strict requirements of the photogrammetrical method. It was subsequently discovered that damage to the camera equipment meant the photographs taken of the midship portion of *Skuldelev 3* were not suitable for use, and the excavation plan had to be reconstructed with the aid of ordinary photographs and measurements taken from the excavated timbers (Crumlin-Pedersen 2002a:51–2).

During the post-excavation documentation stage, the individual waterlogged timbers were subjected to a second phase of more detailed recording. Crumlin-Pedersen, with his naval engineering background believed that it was possible to collect enough data from the original ship timbers to recreate the original hull form and was seen as critical to understanding the design and shape of the original hull form as well as probable construction sequence. The individual ship timbers were cleaned and documented using ‘elevated plane tracing’ (Figure 2-20)

The process, one of the earliest examples of documenting ship timbers using full-scale drawing, was initially aimed at providing a method to document the many fragmented planks, providing a means for fitting the fragments together, while also providing a record of the waterlogged wood which could be compared to the conserved wood to gauge the effects of conservation such as shrinkage. Crumlin-Pedersen (2002a:54) states that during subsequent work on the Skuldelev ships and other ship finds of a similar nature, this principle of full-scale documentation proved to be an indispensable element in the detailed analysis and reconstruction of the ships .

The process involved a transparent sheet of drafting film supported on a glass plate suspended above the individual ship timber. The features to be recorded were then projected onto the drafting film, and with some training, the reflecting surface of the folio could be used to indicate when the feature being recorded, the tip of the pen and the mirrored reflection of the draftsman's eye were merging, showing that the projection was perpendicular to the glass plate. Colour codes were used to differentiate between original edges and intentional features recorded in black, and fractures and other damage recorded in red. The precision of this method is normally within a few millimetres, giving a precise documentation of the original waterlogged timbers, especially for the strakes, as the individual planks were normally flattened but retained their edge curvature and cross section (ibid:54-5).

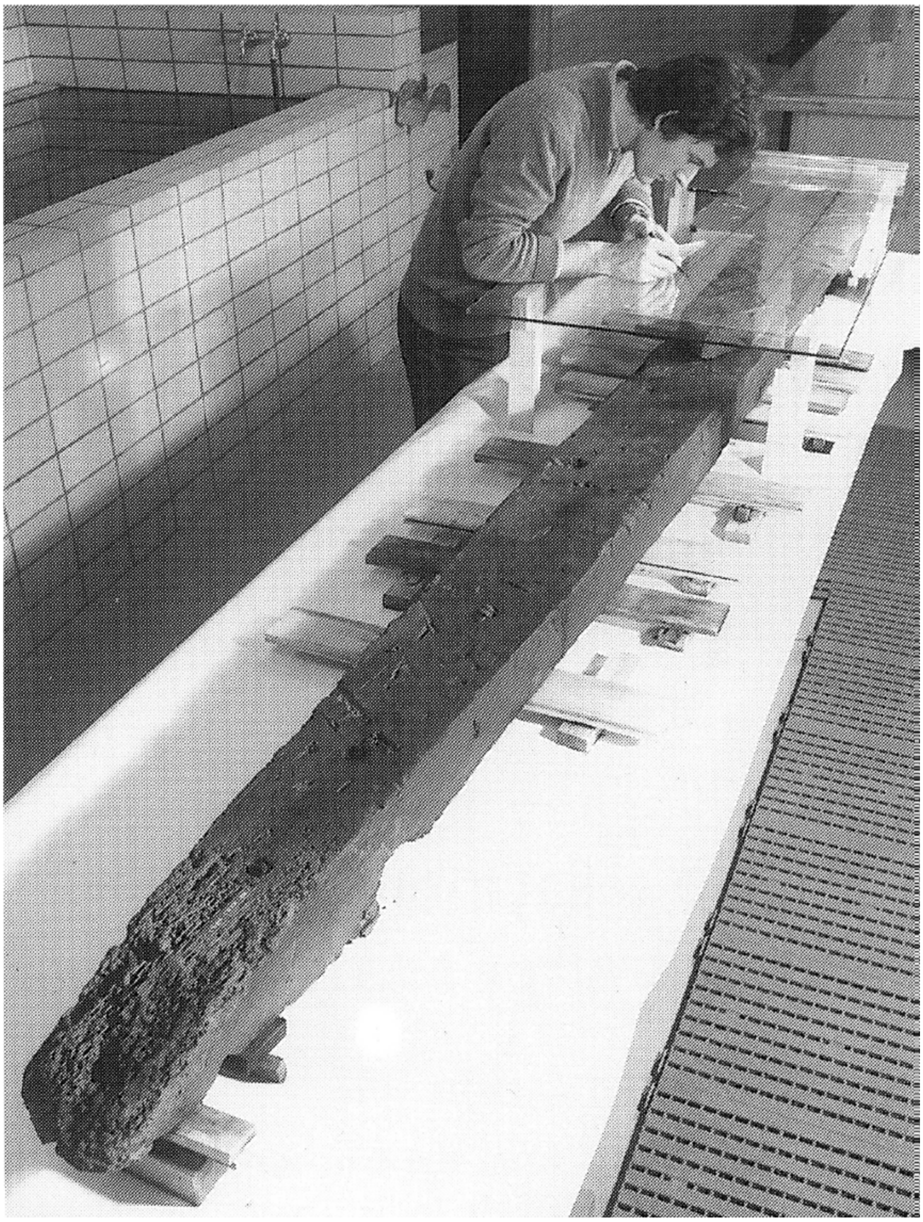

Figure 2-15 Elevated plane tracing (after Crumlin-Pedersen 1997:74)

However, Crumlin-Pedersen notes that for curved timbers the accuracy was not as high and other methods had to be used, but experience from using this documentation technique, first developed in the 1960's is very good[6] (Crumlin-Pedersen 1977:168–173). Since the technique was developed, several kilometres of drawings have been used as patterns for the reassembly of ships as well as controls for conservation (Crumlin-Pedersen 2002a:54). These full-scale drawings (Figure 2-21) are subsequently reduced to 1:10 scale drawings using photography or computer scanning for use in the ship's timbers catalogue.

[6] Crumlin-Pedersen states that recording in full scale is usually considerably more accurate than with scaled drawings. The full-size tracing of edges, holes and other features leaves no room for false readings and imprecise plotting. The traditional method of manual recording and scaled drawing, based on measured coordinates of a limited number of points, and completing the outline between those points by eye, does not eliminate errors to the same degree (Crumlin-Pedersen *et al*. 2002:53–54)

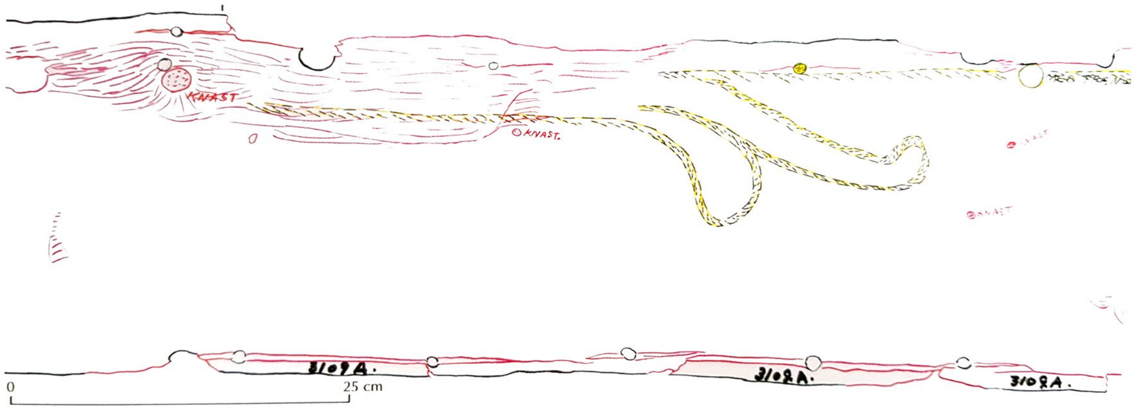

Figure 2-16 Example of full-scale drawing of a section of Skuldelev 5 plank (after Crumlin-Pedersen 2002)

The ships were restored as museum exhibits between 1968 and 1993. As discussed by Crumlin Pedersen, there are several choices for the method of display, the remains can be displayed 'as found in situ' such as the Ladby Ship (Sorensen 2001), or as a mock-up of the excavation situation as was done for the North Ferriby, Graveney and Sutton Hoo vessels at the Archaeology of the Boat exhibition in the National Maritime Museum Greenwich, or as a restored vessel in a museum display. In the case of the Skuldelev ships the decision was to display fully restored vessels, with the minimum of steel supporting structure, similar to the method used by Harald Åkerlund in the display of the Falsterbo ship restored in 1947-49 at the Falsterbo museum in Scania, slender steel bands used in the plank lands to support the planking and mark the likely continuation of the missing strakes (Crumlin-Pedersen 2002b:87–89).

The exact shape and form of each hull was not known when the restoration commenced as the 1:10 scale drawings and models were still under construction at the model workshop, and moulds based on the full-scale drawings were used in a trial-and-error basis by the restoration team of Victor Jeppesen a shipwright from Frederikssund and three assistants. During the excavation no attempt had been made to preserve the curvature of individual planks as this was considered irrelevant to the restoration of the ships which was to be based on the full-scale drawings of each individual element recorded in their flattened-out condition (ibid:91).

During the restoration process each plank had to be restored to its original shape as fitted to the hull, which normally entailed bending longitudinally as well as twisting along its longitudinal axis. At the same time broken or damaged fragments had to be replaced and reattached. Crumlin-Pedersen describes the conserved wood as hard and dry at normal temperatures (below 30°C) which broke like glass if dropped to the floor, but when heated to 60°C the 'wood' became soft and pliable allowing the planks to be reshaped. Various methods such as toothpicks and coated thin copper wire were used to secure fragments in place (ibid: 91).

Skuldelev 1 was the first ship to be restored as a museum exhibit in 1968-9. Decisions had to made at an early stage during the reconstructions, the orientation of the original keel was not known, whether the keel sat level or was deeper aft, whether the keel was straight or had some degree of rocker. Severe issues with distortion of the surviving moulded stem pieces during conservation meant all the stems had to be replaced with modern replicas. Some of the floor timbers were evidently not symmetrical about the centre plane, as well as distortions to the timbers during conservation, or the release of tension within the original wood. One example was the keel of Skuldelev 5 which twisted through 90° during conservation (ibid: 94). Some of the assumptions made during the early stages turned out to be incorrect and led in some cases to somewhat dubious appearances of the ships in the museum.

The keel of Skuldelev 5 which was initially laid flat, should have been deeper aft, and while restoring the ship with a horizontal sheerline amidships, meant this could only be achieved by including a wedge shaped part to one of the strakes, no evidence for which was documented. This left the strake with a long split opening up towards the forward end. Another error with the planking for Skuldelev 1 being left to fall outboard too much meant the internal knees did not fit. By the time the error was realised it was not possible to repair or alter the hull shape, meaning the bow area of this ship is not a genuine reflection of its original appearance (ibid: 95).

As noted by Crumlin Pedersen, the original timbers are subject to distortion, shrinkage and other factors due to the conservation process (Jensen *et al*. 2002) and consequently the ships as exhibited in the museum, are not completely identical in all their features to the original ships (Crumlin-Pedersen 2002a:55). Therefore, it is necessary to use the condition of the wood as it was prior to conservation, as the starting point for studying the ships as they were prior to scuttling, and for this, the full-scale drawings and their reduced 1:10 scale versions were the ideal solution as a basis for the modelling and full-scale reconstruction of the ships (ibid: 55).

For the three-dimensional representation of each ship at 1:10 scale, the plank and frame elements were traced onto cardboard or wood and cut out. The holes for rivets and treenails were used as a key in positioning each element in relation to the next leading to the construction of working models in cardboard or wood. These models had a dual purpose: the primary pattern for preparing a ‘torso drawing’; and providing a guideline in accordance with the shape of the preserved parts of the ship when trying to extrapolate the missing parts of the hull. This process began at Brede during the 1960’s and continued until after 1990 with several interruptions in the 1970’s and 1980’s (ibid: 56).

For Skuldelev 1 the first 3D working model was constructed in 1976-77 and based on this model a preliminary reconstruction drawing and set of lines were completed in 1977. These drawings were used for the construction of the replica *Saga Siglar* built in 1983, as well as scale models at 1:20 and 1:10 for museum exhibits (Figure 2-22).

Figure 2-17 Skuldelev 1 museum exhibit model (after Crumlin-Pedersen 2002)

Some problems with fitting together the scaled down parts had not been solved with these first attempts and therefore a new working model was created in 1996-97 to resolve these issues (Crumlin-Pedersen 2002c:121). This revealed some unexpected details such as the lateral curvature of the keel possibly explained by the repair work being carried out during the use life of the vessel. Once a satisfactory model had been achieved the lines were recorded and drawn as an 'inner-edge lines-plan' (Figure 2-23), tracing all of the inboard upper edges of each strake as well as the external outline of the keel. According to Crumlin-Pedersen this 'inner-edge lines-plan' provided a very reliable representation of the original shape of the ship before it was scuttled, as the well-preserved port planking and internal timbers leaves practically no room for variation in its shape or size.

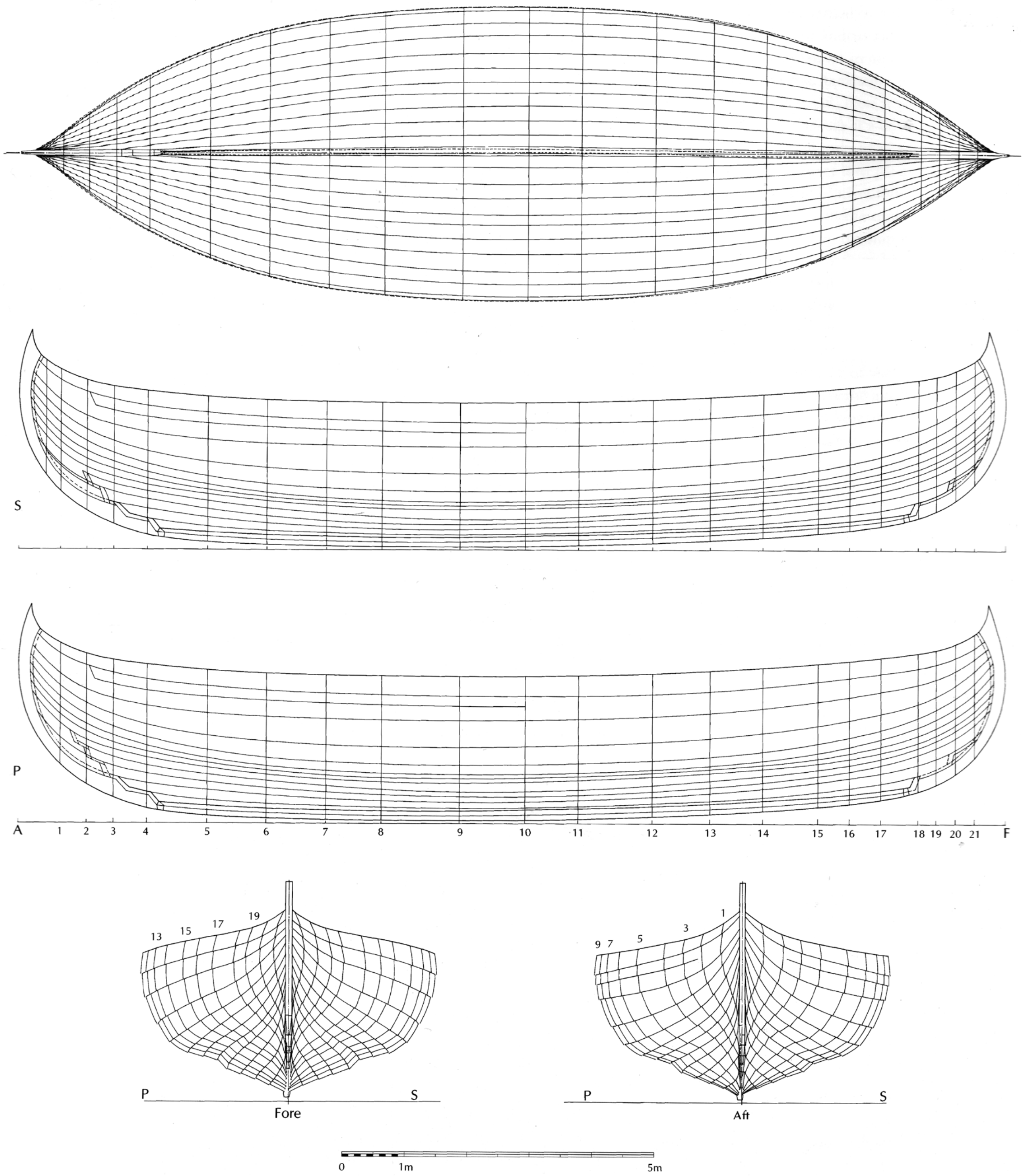

Figure 2-18 ‘Inner-Edge Lines-Plan’ of Skuldelev 1 (after Crumlin-Pedersen 2002)

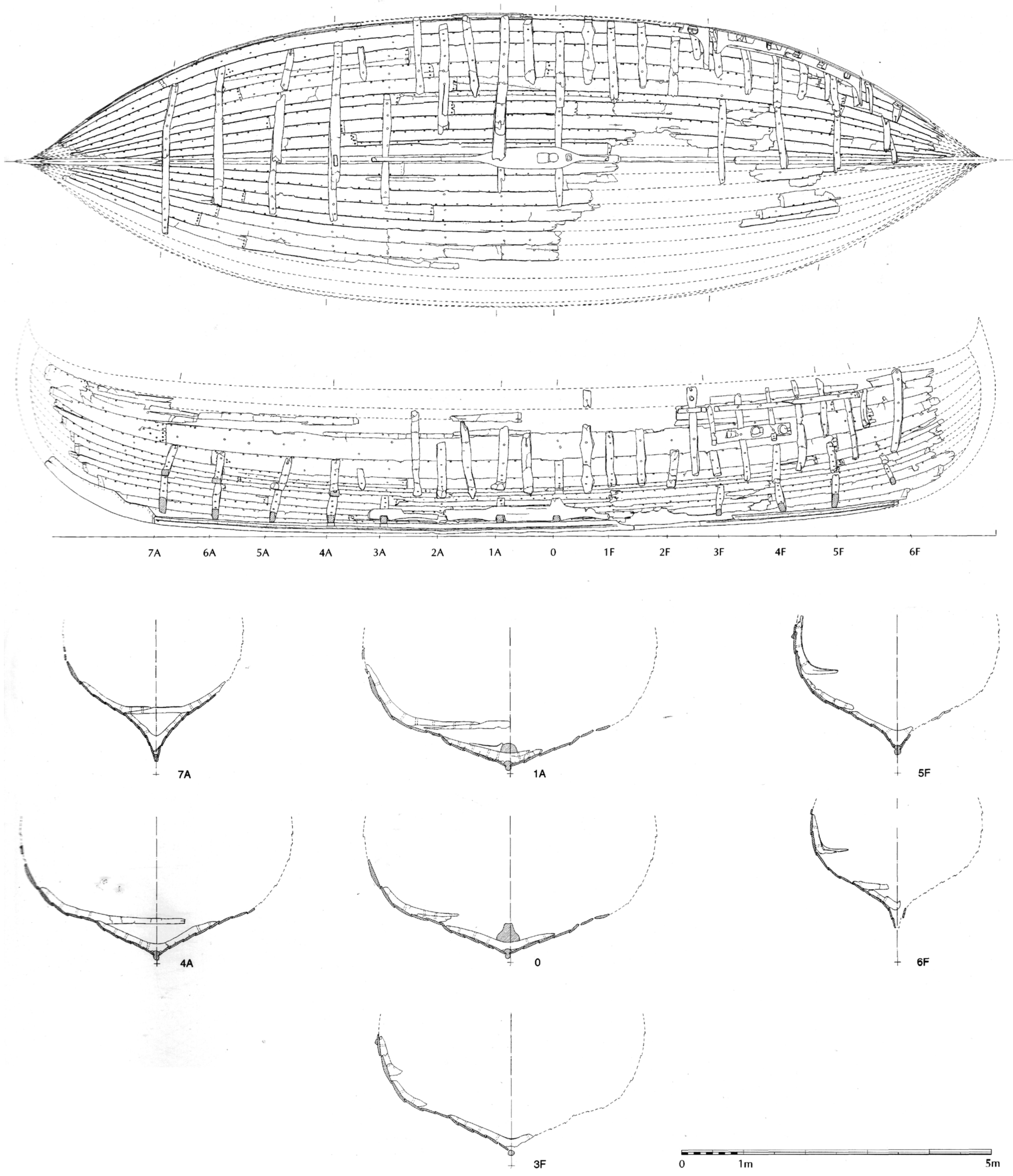

Figure 2-19 Skuldelev 1 'torso' drawing (after Crumlin-Pedersen 2002)

This ‘inner-edge lines-plan’ is then used as the basis for the creation of a ‘torso drawing’ (Figure 2-24) which is described as a drawing of all the recovered parts for which the original position in the ship could be identified (ibid: 125). Further analysis work allowed the creation of additional drawings such as the distribution of wood species (Figure 2-25), repairs and or alterations to the original hull. A subsequent replica *Ottar* was built in 2000.

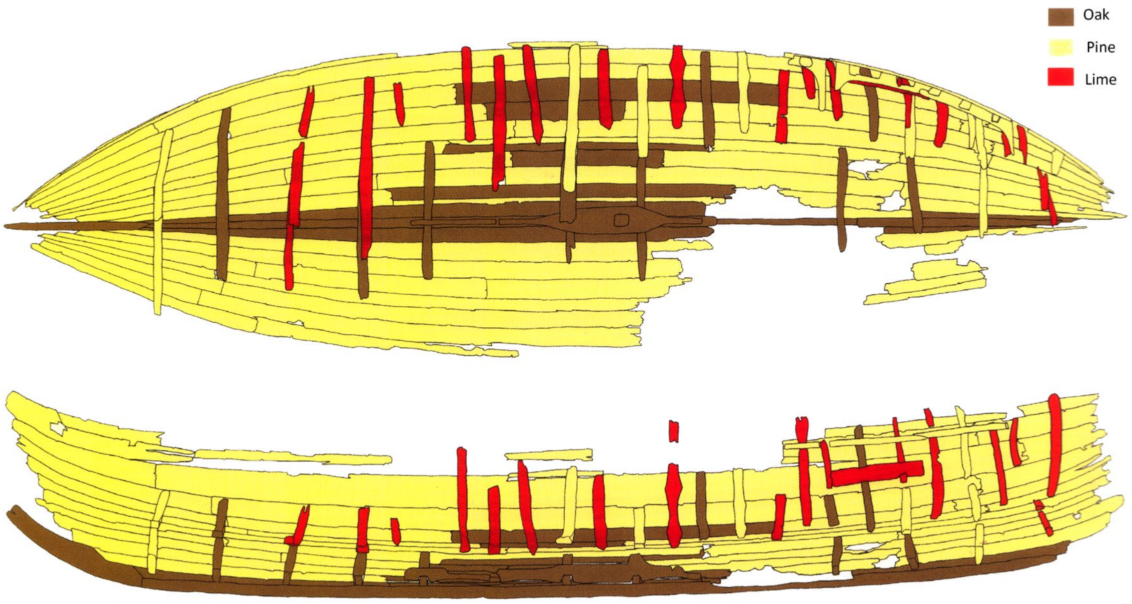

Figure 2-20 Skuldelev 1 wood species distribution (after Crumlin-Pedersen 2002)

Skuldelev 2 was reassembled in the museum from 1977 to 1982 and again from 1986 to 1993. A cardboard research model at 1:10 scale was constructed in 1994-5, and a replica, ***Sea Stallion from Glendalough* was built in 2000-04**. Skuldelev 3 was reassembled in the museum in 1969 and the first working model was built in 1977. A replica *Roar Ege* was built in 1985. Skuldelev 5 was reassembled as a museum exhibit in 1969, the first 3D working model was constructed in 1985, and a full-scale replica ***Helge Ask* was built in 1990-91**. Skuldelev 6 is 11.2 m long and 2.5 m wide. The vessels purpose was not entirely clear, probably built for fishing, later modified by the addition of an additional strake possibly for use as a cargo vessel. Skuldelev 6 has been replicated as ***Kraka Fyr* in 1998** by the Roskilde Viking Ship Museum. As no fore-stem or aft-stem was preserved for Skuldelev 6, the builders initially imitated the stepped stems from Skuldelev 3, however subsequent archaeological evidence suggested the ship may have had stems of a different (Norwegian) design and the museum replicated the original ship again as ***Skjoldungen* in 2010-12**. While also staying true to the original remains, Skjoldungen has a different interpretation of the bow and stern design (vikingeskibsmuseet.dk 2018).

Throughout the publication The Skuldelev ships I: topography, archaeology, history, conservation and display, the authors mention references to ‘The Skuldelev Ships Volume II’ which discusses the models and replica constructions in further detail, however, this second volume remains unpublished. Mc Grail was never certain how Crumlin-Pedersen and his Roskilde associates transformed their Skuldelev reconstruction drawings into full scale vessels, since his boatbuilders used traditional Viking Age boat-building methods such as 'by eye and using rules of thumb'. A year before Crumlin-Pedersen died, he told Mc Grail he would deal with that matter in his next Skuldelev volume, but he never completed it (S. McGrail 2015, pers. comm., 29 Jan.).

The Skuldelev process created scaled site plan drawings from photogrammetry, while the ship timbers were documented using full-scale elevated plane tracing. All the Skuldelev ships were reassembled for public display prior to detailed hull reconstruction or analysis. The full-scale drawings were reduced to 1:10 scale and cut-out from cardboard stock as flat two-dimensional planks, where damaged or distorted planks were repaired prior to being re-shaped to create the perceived hull form. The subsequent 1:10 scale reconstructed model was then documented and drawn as the scaled 'inner-edge lines plan'. From this a 'torso drawing' was created representing the original timbers with displaced elements repaired or repositioned. Static hydrostatic calculations were completed using proprietary software to determine hull form coefficients and displacements. Scaled display models for the museum are then constructed followed by a full-scale replica, at times requiring alterations (full-scale trial and error) due to the differences between model cardboard and real timber.

C.6 Kyrenia Ship 1968-69

Excavated in 1968-69 under the direction of Michael Katzev, the 4th century BC *Kyrenia* ship included a cargo of approximately 400 amphorae belonging to more than 8 different types. The well-preserved wooden hull, which had been sheathed in lead, consisted of nearly 6,000 wooden fragments in an area of circa 6 x 12 m. Steffy estimated that nearly 60% of the hull survived (Figure 2-26) including rigging artefacts, a steering oar blade and scattered fragments of fastenings providing additional information about the portion of the ship which had disappeared (Steffy 1985:72–74).

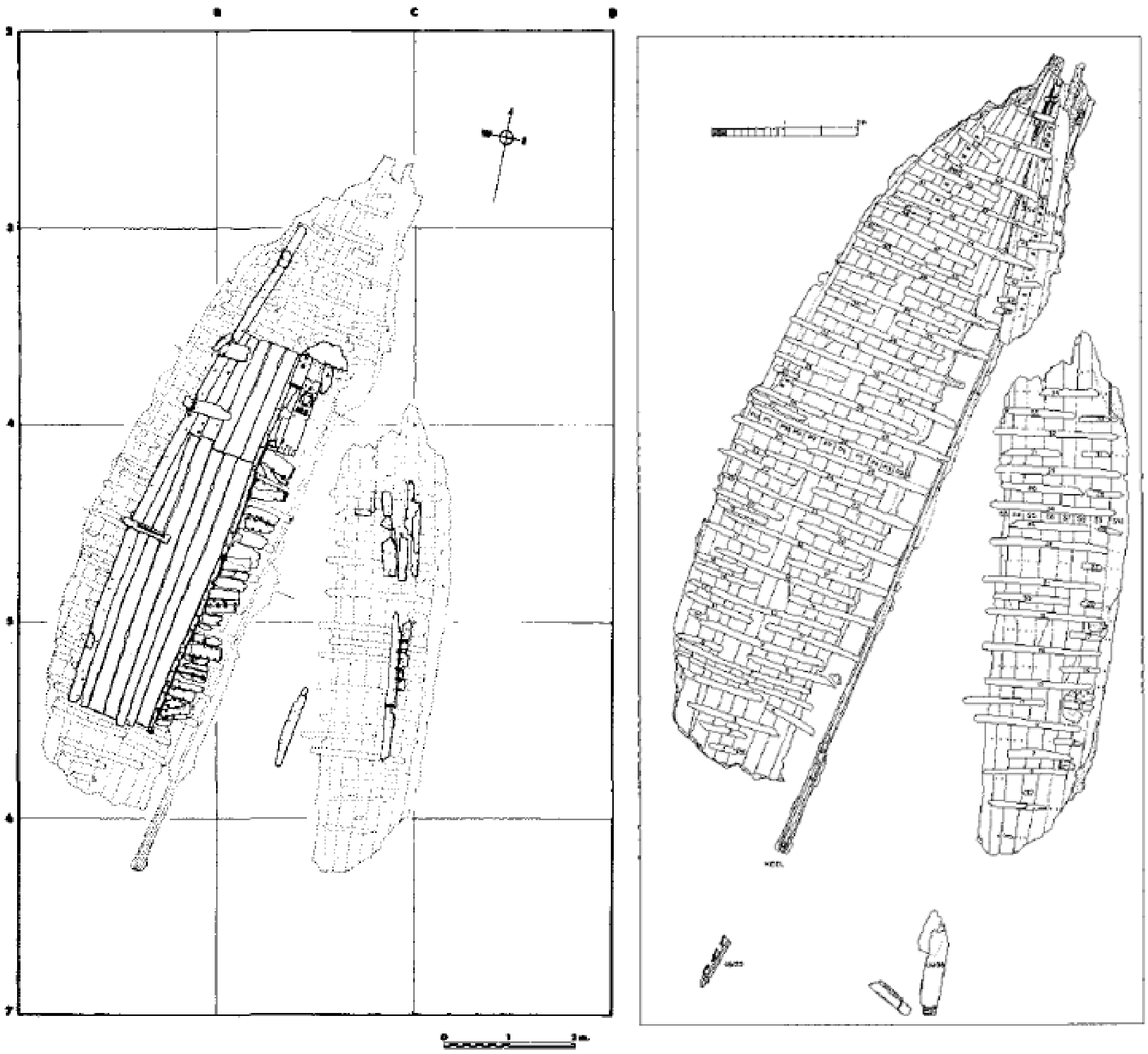

Figure 2-21 Kyrenia site plan (after Steffy 1985)

Steffy (1989:249) states that nautical archaeology through the medium of well-preserved shipwrecks often clarifies what could only be summarised before, but archaeology alone cannot supply all the answers. Some materials are so fragile that they are destroyed even by the most careful removal of overburden, some do not survive recording and conservation, and the greatest obstacle is that no shipwreck is completely preserved, there are gaps where nothing survives, topsides usually disappear, and distortion belies the original hull shape.

Another dimension which can add to the study of ship construction and handling which overrides some of these shortcomings is what Steffy calls three-dimensional research, a form of experimental archaeology utilising models, mock-ups, replicas of individual components, fragment assemblies, and other physical devices designed to solve problems. During the reconstruction of the *Kyrenia* ship a total of 18 such research models were employed, ranging from a working model of the mast step to a full scale two-meter long replica of the hull's midship section. Some were as simple as a single plank scarph, while others duplicated every joint, nail and curvature in the original hull. The full-scale replica being the latest and most elaborate of these three-dimensional research models, all of which have the potential for probing subject areas which graphic and archival research cannot satisfy. The nature of their construction is such that one is forced to duplicate the original builder's movements, thereby revealing techniques and processes. Their shape permits volume interpretations where only areas could be interpreted graphically. Their comparative strength sets limits for error, and their resistance to unnatural curves refutes blatantly false assumptions. Most importantly, these models are subject to the laws of physics and geometry, and thereby their conclusions can be proven (ibid: 249-50).

Just like all other forms of investigation, the resultant value of research models is directly related to the faithfulness of reproduction and the extent of applied information. It cannot be expected to obtain reliable information from a replica if it is built from different materials or by different techniques than that of its prototype. It is not possible to replicate an ancient ship, or even draw its hull lines, by directly reproducing what is seen on a shipwreck. That vessel has been distorted and flattened into the seabed, some of the timbers being bent or cracked to shapes and sizes which contradict their original true characteristics. Firstly it is necessary to understand what to build, how to build it and what information can be obtained from it, a long and involved process which Steffy was in the process of preparing for his future publication (ibid: 250) 'Wooden Ship Building And The Interpretation Of Shipwrecks' (Steffy 1994).

The interpretation of the *Kyrenia* ship began with the start of excavations, cargo distribution and seabed hull dispersal are important in the study of hull construction. After a site plan was produced, hull parameters could be determined, and as soon as timbers were excavated, they were photographed, and full-size drawings made. At this stage all reconstruction work could be handled by graphical methods, but already details were appearing which could not be fully understood. At this early stage of the project three-dimensional models were first employed as aids in the study of the hull. Some of the models were simple or crude which nevertheless provided answers needed to proceed. Others involved a full-size replica of the port bow section consisting of a suspected replacement strake with the so-called ‘patch-tenons’ which served to illustrate and understand the method in which ancient carpenters replaced rotten strakes.

One of the real benefits of three-dimensional research is that duplicating the work of the ancient shipwright automatically reveals unexpected problems and techniques which ancient boatbuilders experienced. Engineers call this phenomenon ‘spin-off’, the accidental acquisition of knowledge beyond that intended for the project through the familiarity and confidence gained by frequent and concentrated experimentation. Steffy states that some interesting ‘spin-offs’ of the *Kyrenia* project included important understanding of ancient construction techniques and a better understanding of the nature and sequence of repair work carried out on the hull.

Another of the more basic models used was the ‘mould and batten’ model as an early method of determining the hull shape. Steffy states:

> ‘it would be unwise to attempt to reassemble the wreck remains without first learning something about the vessel’s design and construction.’[7]

The original function of these ‘mould and batten’ models was to supply such information, but even after the hull fragments were reassembled there were still questions about its design and construction. By 1974 the reassembly of the *Kyrenia* wreck in Kyrenia castle (Figure 2-27) provided most of the information for the full-scale replica *Kyrenia II* but some of the details had to be acquired from the models used to determine the hull design and construction (Steffy 1989:252). The final lines drawings (Figure 2-28) were the result of a combination of information sources, most of which was confirmed by the three-dimensional models. Dimensions were checked between waterlogged wood and original survey measurements, as well as between impressions (compression marks) made by the contact of one member against another.

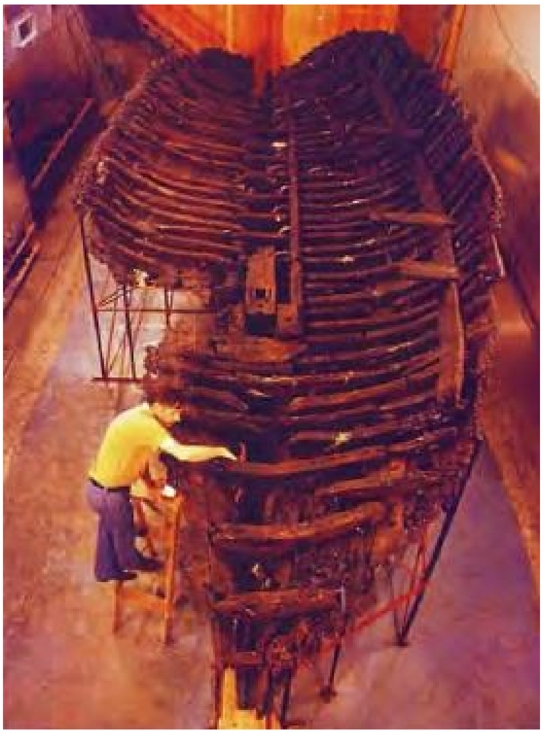

Figure 2-22 J. Richard Steffy reassembling the Kyrenia Ship (after Katzev 2008)

[7] In 1969 Skuldelev 1 had already been reassembled as a museum exhibit, prior to any research model or reconstruction work being completed, it is unclear if Steffy’ s comments are related to the issues the Danes were having with reassembly, or whether it is his own common sense approach.

Total distances along curved elements were checked against the sum of individual fragments or elements. In addition to recording existing curvature of frames and planks, curvature between cracks and breaks were also recorded and plotted as the geometric sum of a series of arcs. This plotted curvature was then checked against those of contacting members such as frames, nail and joint spacings and other supporting data. All of this information was compiled directly onto hardboard sheets which visually described the hull shape. The hardboard 'moulds' were marked with all kind of additional supporting information such as plank seams, nail locations and important tool marks. Once enough of these 'moulds' had evolved, it was possible to project hull lines by connecting them with thin battens along the levels of plank seams.

In all a total of five 'mould and batten' models were used to develop the final *Kyrenia* lines (Figure 2-28), and it took several years to arrive at what Steffy considered to be the most accurate set of lines possible. Steffy states that these 'mould and batten' models had been replaced by 1989 with computer generated graphics, and more complex details analysed with what he calls fragmentary models (Steffy 1989:253).

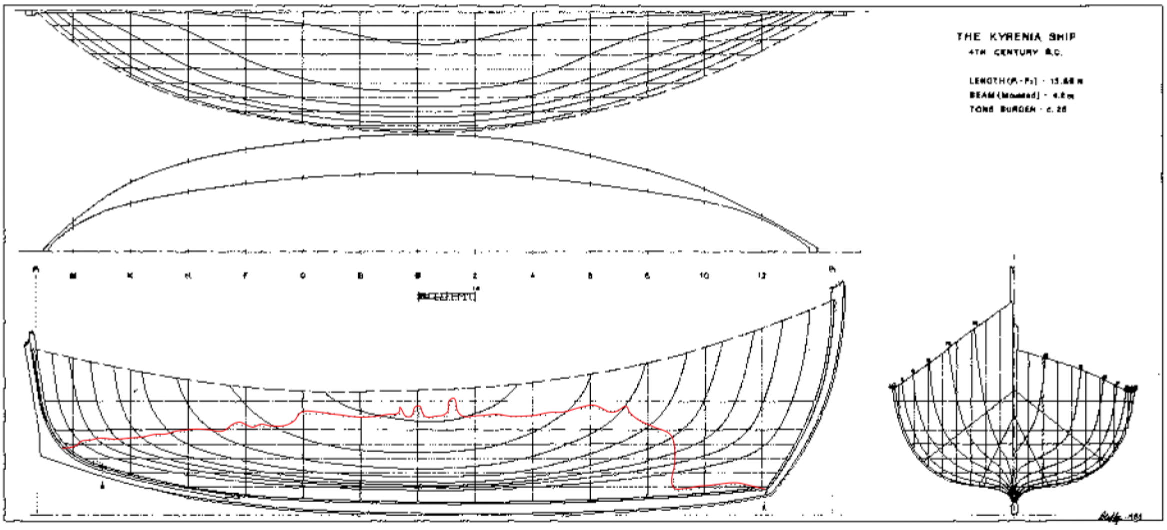

Figure 2-23 Kyrenia lines plan[8] (after Steffy 1985)

Steffy estimates the Kyrenia ship to have been 13.6 m long, 4.6 m wide and circa 25 tons burden. He concludes that three-dimensional models have weaknesses, they are time consuming and consequently expensive to produce. A certain level of manual dexterity is required to design and produce such models, and for those reasons Steffy was experimenting with graphical computer alternatives. While models should not replace two-dimensional graphic or archival studies, they

[8] The extant remains were indicated as a dashed line by Steffy and have been highlighted in red for clarity by this author.

were seen by Steffy as making significant contributions where results cannot be obtained by other means and having an important niche in the study of shipwrecks.

As part of the ongoing research into the *Kyrenia* ship Suzan Katzev and Laina Swiny were investigating the cargo within the ship. In 2004 all 384 of the original amphorae in their various shape and size were replicated and used in experiments loading them onto a full-scale replica of the ship (
Figure 2-29). The majority of amphorae were loaded empty onto the ship, with the weight difference compensated for by the addition of beach pebbles around the three rows of replicated millstones centred over the keel.

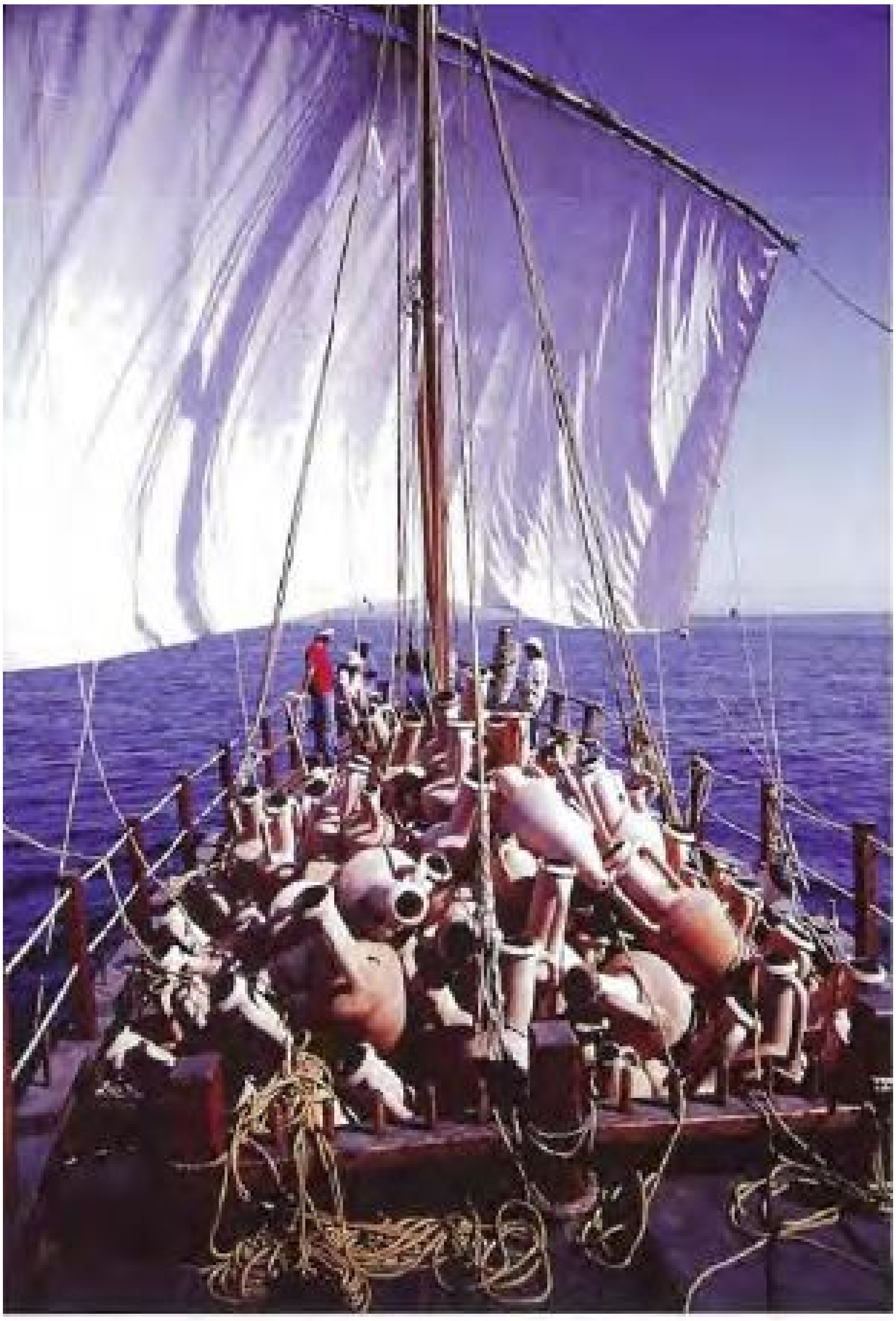

Figure 2-24 The Kyrenia replica loaded with Amphora (after Katzev 2008)

Three layers of amphorae were loaded with the smaller ones nestled on top at random angles. When the ship sailed from the old port of Limassol, she carried 12 metric tonnes[9]. All of the upper level of amphorae were empty, and these were piled noticeably high. The sheer volume of jars excavated from the wreck were not fitting comfortably within the conjectured hull. Furthermore, had the upper level been filled with liquid the vessel would have been dangerously unstable in heavy winds.

Steffy had already added two extra strakes to what had been physically preserved of the hull's height. Both sailing replicas *Kyrenia II* and *Kyrenia Liberty* had proven extremely seaworthy while carrying circa 10 tons, but neither had sailed with the full 17 tons of cargo[10]. Had some evidence been overlooked? Perhaps the ancient hull had been higher still? (Katzev 2008:77–79).

The Kyrenia project initially used cargo distribution and seabed hull dispersal as well as a graphical two-dimensional site plan and the excavated timbers were drawn full-size. Then the project switched to three-dimensional research in the form of models. As timbers were excavated, they were photographed, and full-size drawings made. Simple models were used to study the hull form, crude models to provide answers needed to proceed, a full-size replica of the port bow section consisting of a suspected replacement strake with the so-called 'patch-tenons', 'mould and batten' models used to develop the final hull lines, and even the reassembly of the vessel for display to answer some outstanding issues. A total of 18 different models were employed, in what appear as a trial-and-error approach. The final lines drawings were the result of a combination of information sources, most of which was confirmed by the three-dimensional models. Tonnage formulas and calculated displacement were used as a means to validate the resulting reconstruction.

[9] 29 volcanic millstones found during the excavation weighed on average 57 kg each. The main cargo of 220 Rhodian amphora weigh 49 kg each. This equates to a total of 1,653 kg for the millstones and 10,780 kg for the 220 Rhodian amphorae giving a cargo weight of 12,433 kg (12.5 metric tonnes).

[10] The total cargo was estimated at 17 tons based on material found in the ship during excavation.

C.7 Graveney Boat 1970

In 1970 this tenth-century clinker-built boat, excavated under ‘rescue’ conditions from a north Kent tidal channel that flowed into the River Thames, was taken to Greenwich for study and conservation. In due course this led to the establishment of an Archaeological Research Centre at the National Maritime Museum, in essence from 1972, and formally from 1976. The first publication of the Graveney boat was a note in The Mariner’s Mirror by Basil Greenhill (1971:142).

In 1972 more information was published by Valerie Fenwick in a National Maritime Museum publication, and in the first issue of the International Journal of Nautical Archaeology (Valerie Fenwick 1972). A definitive volume was published in the National Maritime Museum Archaeological Series in 1978 (Fenwick 1978). Described as a merchantman of circa 14 m long with a beam of 3.9 m. The vessel was originally radiocarbon dated to A.D 944 $\pm$30 later revised in 1983 to AD 885 $\pm$10 (Ali 2016:17). Much of the methodology used in documentation and reconstruction had its roots in the Skuldelev project, largely due to the influence of Crumlin-Pedersen who came over to help with the excavation.

With only ten days to record and excavate the vessel, an enormous effort was made to record the ship in every detail. Closely measured (Figure 2-30) and, photographed, a plaster cast of the surviving hull shape was subsequently constructed before, the timbers were lifted, washed and re-photographed before packing and transport to the National Maritime Museum. The underlying principle (as in the Skuldelev project) being that even if the timbers could not be preserved, the recorded detail alone would be sufficient to enable a reconstruction.

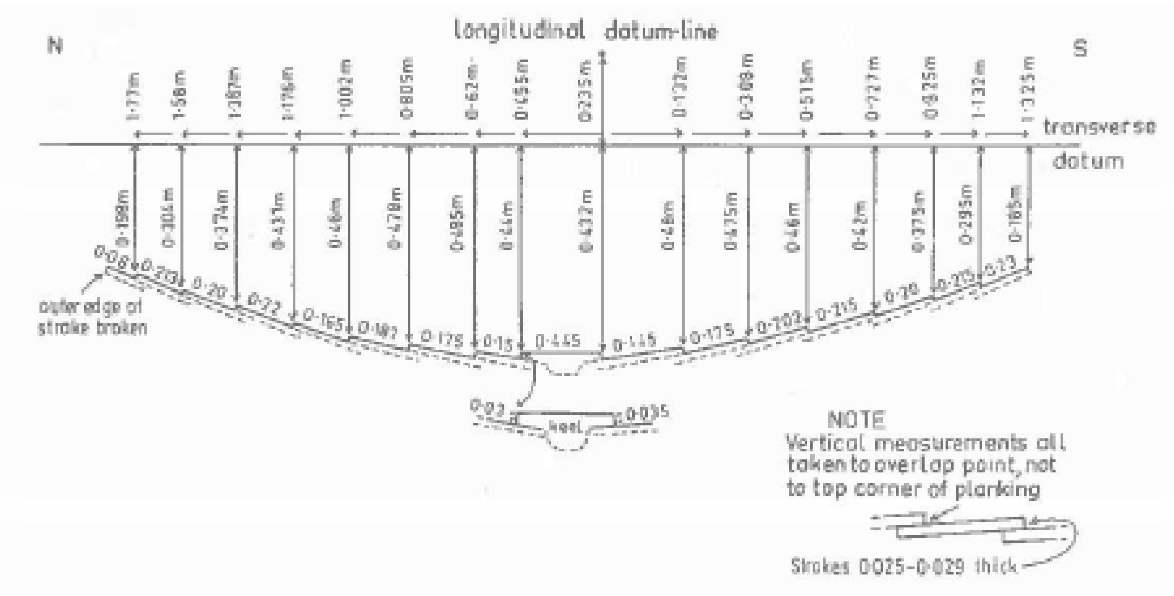

Figure 2-25 Graveney boat site cross-section (after Fenwick 1978)

McKee (1978a:35) noted that in addition to giving a description of what was found, records of the boat were needed for two other purposes, firstly to reassemble the remains and secondly to collect the evidence on which to base a reconstruction. McKee was aware of the difference between both projected and developed surfaces, as he noted

> 'A tracing is a development of a part's surface; direct work on the grid table gives a projection of it.'

There is an issue when attempting to represent curved or non-planar elements using two-dimensional drafting techniques. Traditional two-dimensional drafting uses a series of orthographic projections, of the visible shape onto reference planes. Typically consisting of top; front; both side views; and in some cases, cross sections or slices through the recorded object. When this technique is employed on object parallel to the reference plane, a true representation of the dimensions is achieved. Take a straight 1 m long, 100 cm wide by 2.5 cm example 'plank', once correctly orientated relative to the drawing, the traditional two-dimensional drafting approach generates the exact surfaces shape and dimensions of each face of the plank, as all faces are planar and parallel to the reference planes (Figure 2-31). Each 'view' in the two-dimensional drawing generates the expected dimensions for those planar faces represented. In effect a developed surface of each planar face.

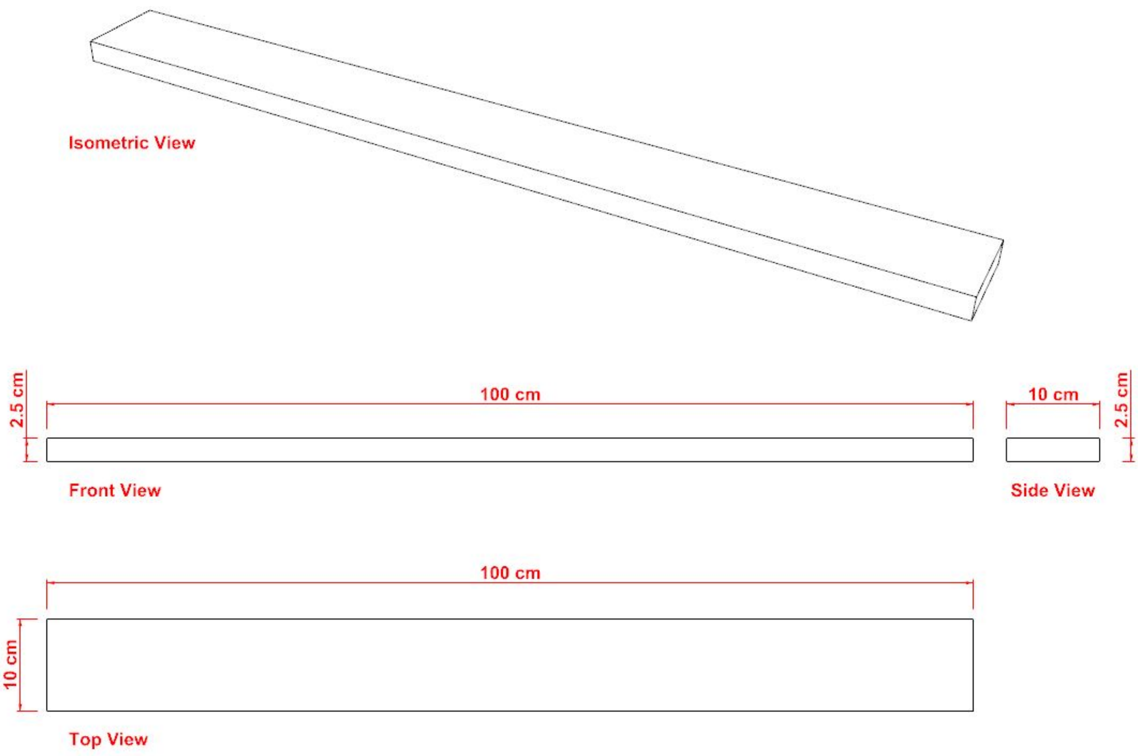

Figure 2-26 Projection drawing of a straight plank(Pat Tanner)

However, on curved or angled objects, if traditional two-dimensional drafting techniques are employed, it is a projection of the visible surface which is recorded rather than the actual physical shape and size of that surface. Taking the same 1 m long plank, and twist one end through 45° (say a garboard strake transitioning from flat amidships towards vertical as it nears the hood ends). If the traditional two-dimensional drafting techniques are employed as in Figure 2-32, it is the visible projected surfaces which are recorded, and in this case the plank appears to narrow towards the right hand extremity when viewed in the top view by as much as 29% as a result of the 45° twist. Consequently, it is only by the geometric generation of a developed surface drawing that this representation could be converted into a true representation of the recorded object.

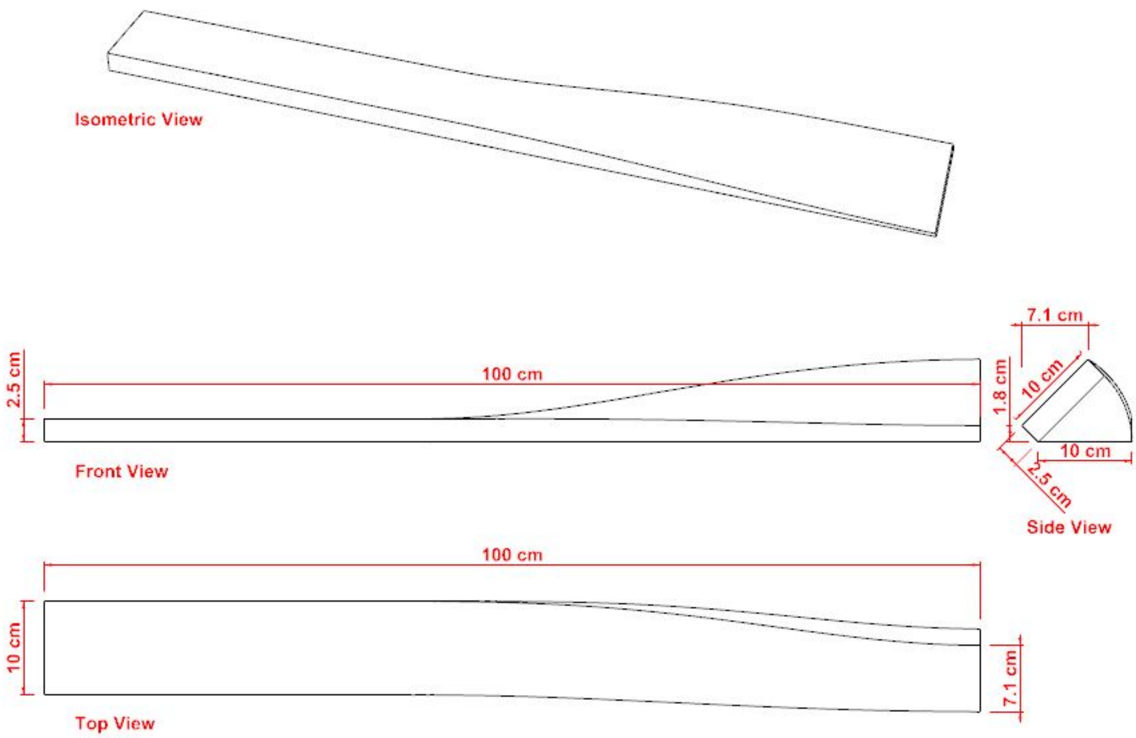

Figure 2-27 Projection drawing of a twisted plank(Pat Tanner)

Each of the timbers was examined and measured using two approaches. In the first approach, the timbers were measured using a direct measurement system, by placing the timber on a 10 cm square gridded worksurface and taking measurements from the reference grid to the timbers features[11] and the results recorded as sketches and measurements in a 'direct measurement book' (Figure 2-33 left).

In the second approach, rather than the *Skuldelev* elevated plane tracing method, which also generated projected surface drawings of each timber, a method of contact tracing was developed. The surface of the timber was flooded with water and covered with a film of 0.5 mm polythene, the surface tension drawing the two together. Felt pens were then used to record the timber

[11] Effectively, the timbers were recorded as a series of offsets from a baseline grid, an incredibly inefficient method even by 1970 standards, however it was more accurate than the available alternatives.

reference number, recording date, and to trace the features such as original edges, fastening holes and builders tool marks, with additional colours used to record damaged edges or wear marks or other material adhering to the timber surface (Figure 2-33 right). As the full-scale tracings were not convenient for study, these were manually reduced to 1:10 scale by redrawing using proportional dividers.

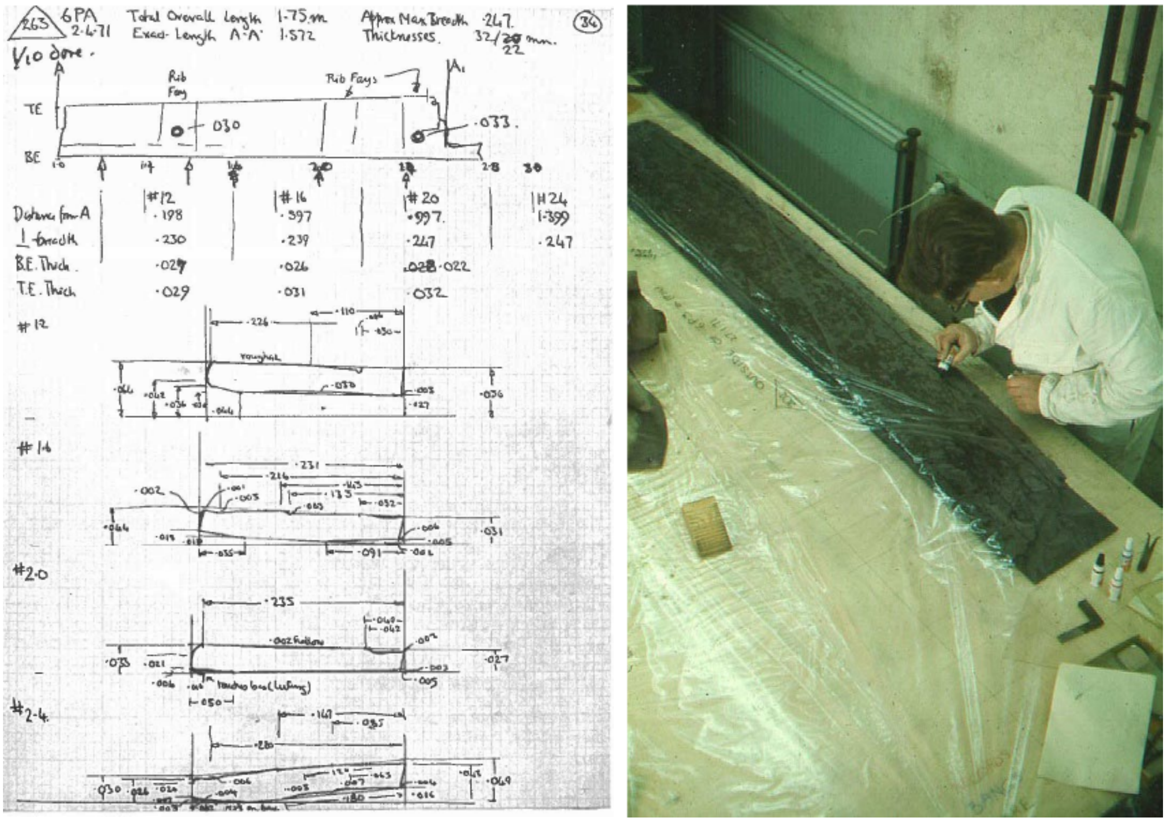

Figure 2-28 Page from McKee's 'Direct measurement book' left, and contact tracing method right.

An initial paper based (two-dimensional) attempt at reconstruction used the site plans, photographs and 1:10 scale drawings of the boat timbers. Using pattern matching of the nail holes and other fastening provided an exclusive solution for the location of strakes and planks relative to each other as well as to the frames. With the positions of the components more or less certain two attempts were made to generate a conventional lines drawing, but neither could be demonstrated to be correct and these attempts were abandoned. Reconstructing a three-dimensional shape on paper meant that all corrections involved simultaneous changes in all three planes. The task of keeping track of these on the sheer, body and half breadth plans together was considered too forbidding and liable to all sorts of errors (McKee 1978b:265–6), and even more so when considering the shape of a boat. The shell of a boat may adopt a number of different but related shapes (Figure 2-34) until one or more dimensions are fixed as is the case with partial shipwrecks. The sides will come together if the ends are forced apart, such as altering the rake of the stem or stern post, and if the rocker is increased the midship section will flatten[12]. Three-dimensional model building was seen by McKee as the obvious solution:

> A model certainly met the requirements of flexibility, deferred decisions, and ease of correction. Even when it was well advanced, it worked like a three-dimensional pencil drawing, which could be easily modified when necessary. (Should a set of conventional drawings be required, the lines could be taken off in the usual way.) (ibid: 267).

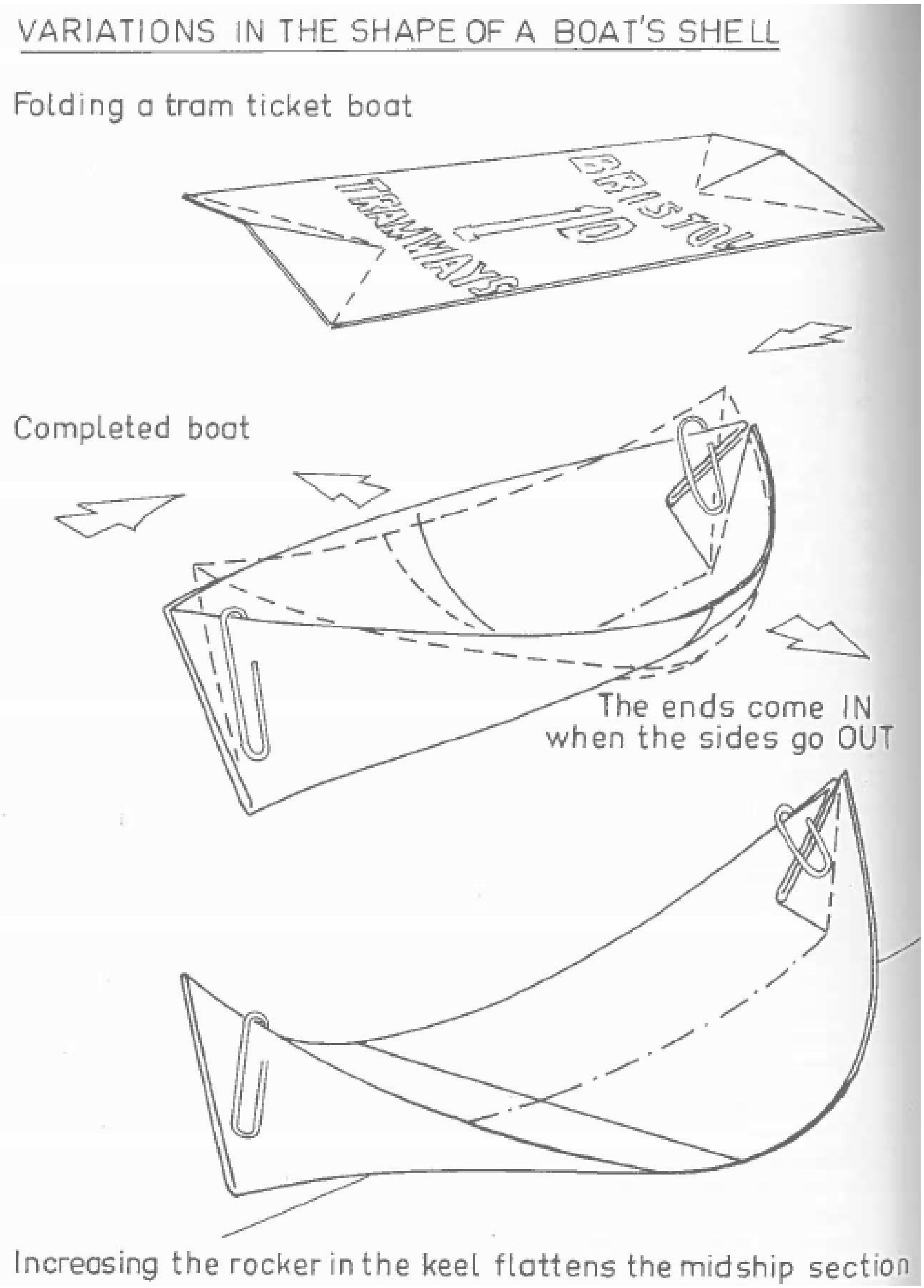

Figure 2-29 Variations in Shape of a boat's shell (after McKee in Fenwick 1978)

[12] These are some of the issues with the original *Dronningen* replica of the Oseberg ship as identified by Oseberg project 2006 (Bischoff 2012:340)

The first model was built as an unconstrained (free-floating) model, constructed following the perceived building sequence of the original vessel. The keel was first modelled, then posts added and finally planking from the garboard to the sheer. However once three or more strakes were added the emerging shape appeared so ungainly that the attempt was abandoned (McKee 1978b:269). During the construction of this model certain assumptions were made. The sternpost was assumed to be a straight extension of the surviving portion, and the missing forward half of the vessel was assumed to be a mirror of the extant after half. This included assuming the position for the forward post.

On the model, in order to distinguish what was real from what had been assumed, a colour code was used[13]. A black line was drawn at the limit of the parts as found-thus two thirds along the model keel was a jagged black line taken from the 1 :10 scale drawing. A brown line was drawn where an obvious missing fragment had been replaced; corners of damaged scarfs were the most common examples of this. Green was used when the fragment of a recovered part could be completed with some certainty and corroborative evidence for doing so could be produced. Components which could be deduced from surrounding evidence, even though no part of them had been recovered, were coloured blue (all the upper planking and the rising). Completely conjectural items like thwarts, mast-step and rudder were coloured red (ibid: 271).

As the keel was springy and the scarphed connection to the sternpost fragile, a second model was attempted using a strongback (Figure 2-35), (stout heavy timbers often used to support the keel and post in the early stages of construction). This secured the keel into a predetermined longitudinal curve (rocker) which was tweaked and adjusted until the garboard strake fit snugly. As additional strakes were added an incremental error began developing along the sternpost due to an incorrect assumption of the sternpost angle and this model too was abandoned and dissembled (ibid: 271).

Another model was started and in addition to the external strongback to control the initial curvature or rocker of the keel, an internal strongback (Figure 2-36) with moulds was employed to control the evolving planking and hull shape. The shape of these moulds was developed from the site sections recorded by Peter Marsden, the projected shape of the frames from the grid table recording, photographs and the initial shape developing from the first four strakes as fitted to the rockered keel. '*It was decided that this new shape was as good as could be obtained within the limitations of the techniques employed'* (ibid: 275).

[13] Unfortunately, on all the published lines plan and construction plan drawings none of these colour coded identifiers were included, nor was the outline of the surviving remains indicated, making it difficult to discern factual from conjectural.

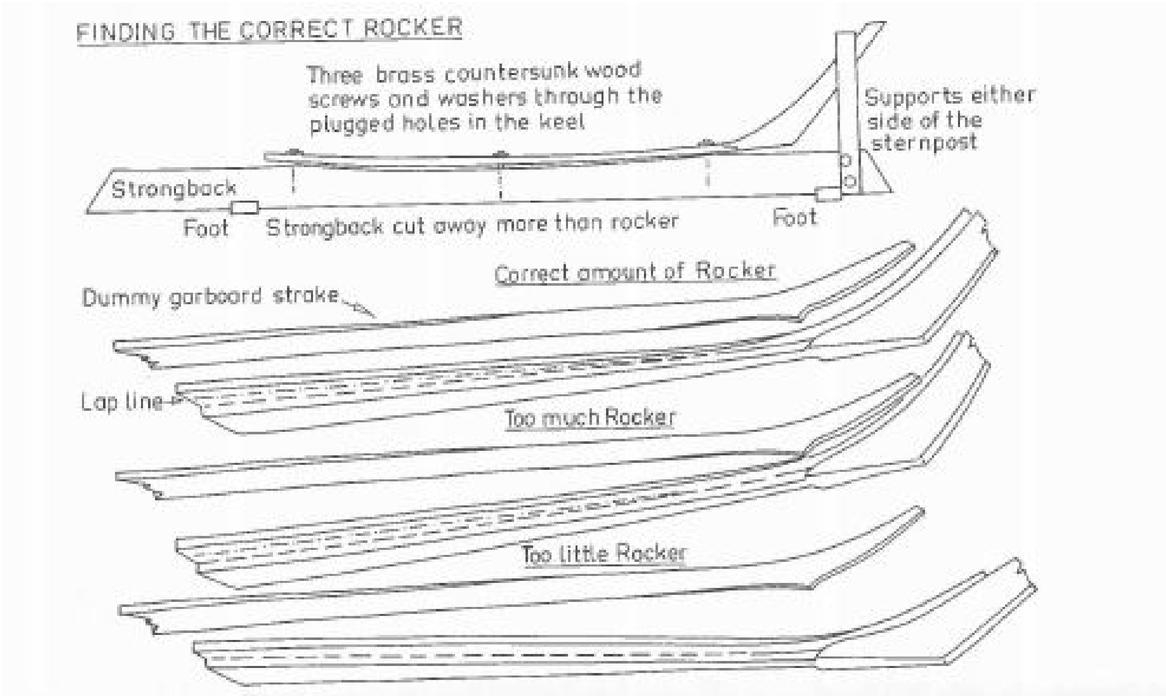

Figure 2-30 Graveney - strongback used to find the correct rocker (after McKee in Fenwick 1978)

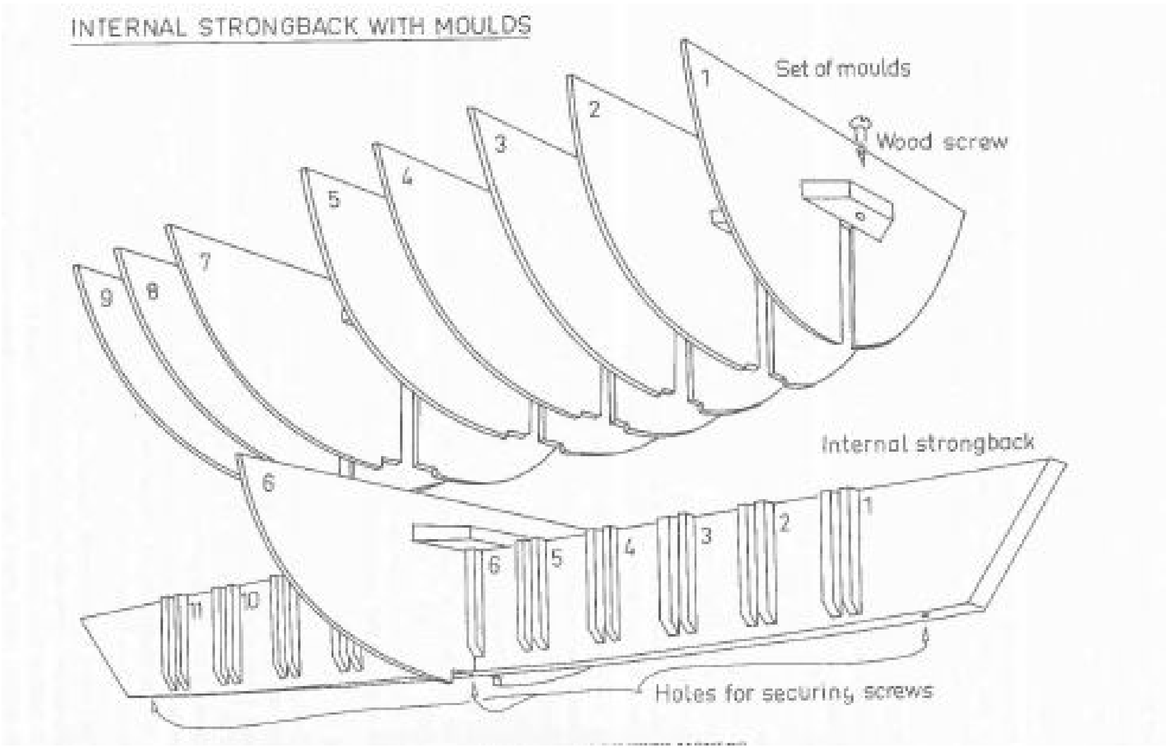

Figure 2-31 Graveney - internal strongback with moulds (after McKee in Fenwick 1978)

Evidence from the surviving material indicated a minimum of at least 8 strakes per side, boats with from eight to twelve strakes were drawn and their weight plotted on a displacement curve based on the underwater shape of the find. Eleven strakes were selected as the most likely number, as more than this would have given an excessive overall length in relation to the keel [14], even though McKee commented that the vessel looked like it could take more freeboard (ibid: 275-7). An alternative plum stem arrangement which would not contradict any of the archaeological evidence is illustrated by McKee (Figure 2-37). If the plum stem or some version of it were used, additional strakes could be added to increase the seemingly low freeboard without and excessive increase to the overall length. Instead a compromise between the minimum and maximum reconstructions was selected as the hypothetical reconstruction with eleven strakes per side (ibid: 285) despite the apparently low freeboard (Figure 2-38).

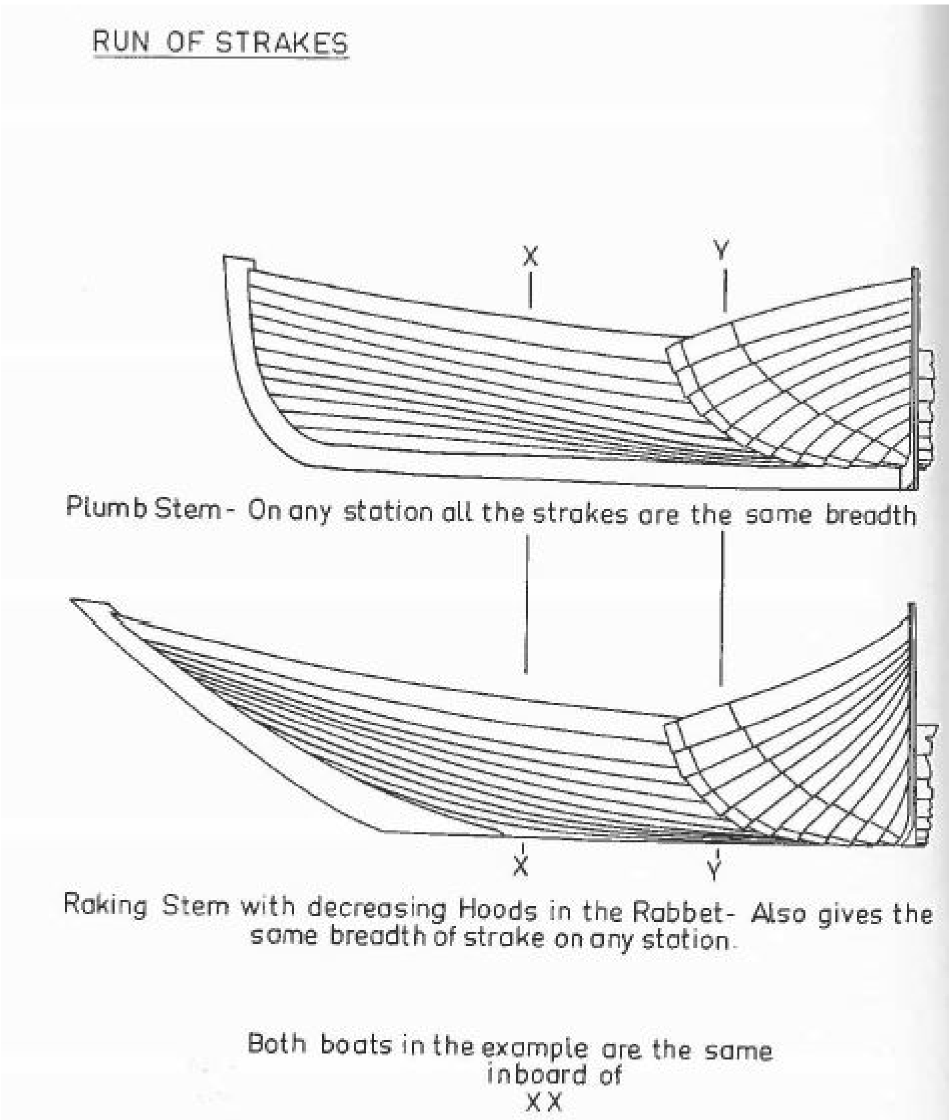

Figure 2-32 Alternative stem arrangements (after McKee in Fenwick 1978)

[14] The relationship between the overall length of the vessel and the number of strakes is not a normal consideration and is only caused in this situation with the assumption by McKee, that both posts extended as straight continuations of the angled 2.2 m length of surviving sternpost.

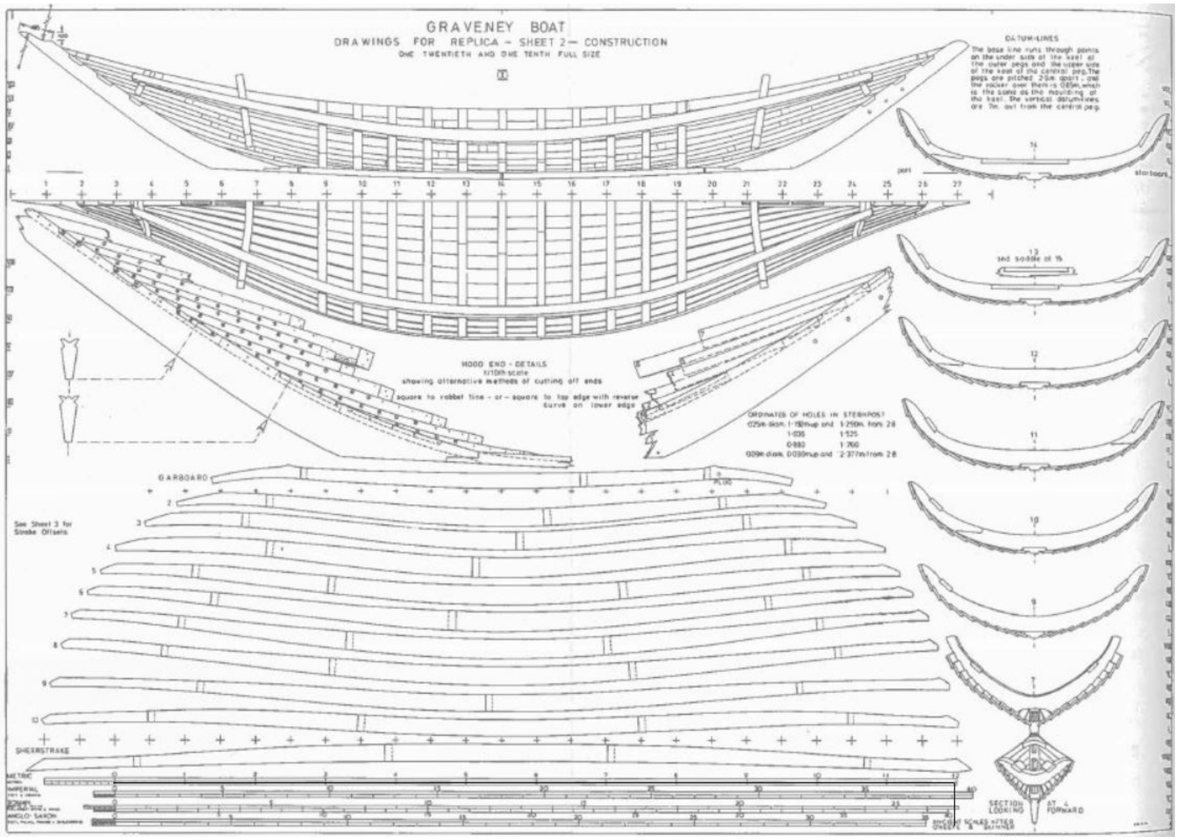

Figure 2-33 Construction drawings for Graveney replica (after McKee in Fenwick 1978)

Graveney site plan was documented using traditional measurements and offsets. Initial recording of timbers used offset measurements and scale drawings. This was supplemented with full-scale contact-tracing of the timbers. Full-scale drawings were subsequently redrawn to scale and cut-out to create two-dimensional cardboard models of each plank, which was reassembled into a scale three-dimensional model of the perceived hull form. Basic static stability and hydrostatic coefficients were calculated. Additionally, a half-scale replica was constructed by Gifford (1996) to analyse seakeeping qualities.

C.8 Serçe Limani 1977-79

First discovered in the early 1970's, the 11th century site was not excavated until 1977 due to the outbreak of hostilities in 1974. The underwater excavation techniques developed for other Mediterranean sites such as at *Yassi Ada* were employed**.** The fragmentary hull remains were documented using 1:1 elevated plane tracing, recording each side of every fragment, using colour coded pens to document tool marks, nail holes, and other features. The individual timbers were also documented using photography with banks of lighting to illuminate features such as wood grain. These tracings and photographs were sent to Steffy, who used them initially to create a 1:10 scale diorama of the wreck site as it lay flattened on the seabed. Steffy then created physical 1:10 scale models of each timber fragment and used the nail holes to align the pieces to create a 1:10 scale model of the fragmentary hull remains, including additional elements such as anchor concretions and the rock outcropping which had added to the hull distortion. This was a new form of model devised for the *Serçe Limani* project, given the dubious name 'fragment model' and is essentially a three-dimensional expression of the revised wreck plan. The resulting three-dimensional site plan, Steffy claimed was infinitely better to work with than 2D drawings (Steffy 2004a:125).

Subsequently a revised wreck plan was produced with dislodged or disarticulated pieces replaced in close proximity to their original neighbours, Steffy notes that even with the aid of the original site diorama there were still elements which could not be positioned until the final hull remains were assembled in the museum. Next various mould and batten models were created, the first to confirm hull dimensions and form, while subsequent versions were developed as the frame drawings were reduced to scale and studied. Eventually strips were added to generate planked models allowing the diagonal projections and plank seams to be developed on a single model. Steffy states the mould and batten models were the single most important vehicle in the development of hull shapes (Figure 2-39) for *Serçe Limani* (ibid:125).

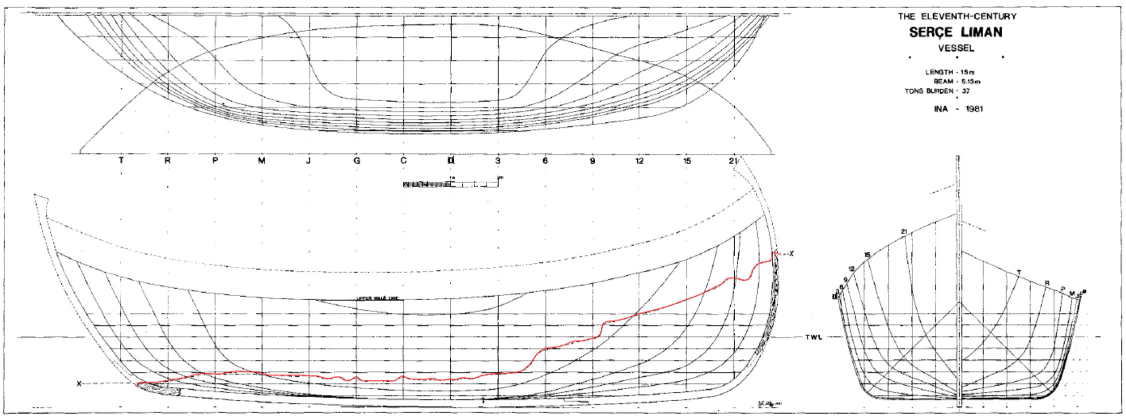

Figure 2-34 Serçe Limani lines plan the red line indicates extent of surviving remains (after Steffy 1982)

For the reconstruction Steffy suggests a vessel of 15 m length overall, with a beam of 5.13 m and a tonnage rating of approximately 37 metric tonnes, and notes that by comparison to *Kyrenia* a ship of near identical length and width, *Serçe Limani* could accommodate an additional 10 volume tons of cargo (Steffy 1982b:32). The final 2004 publication provides slightly differing values for the displacement and cargo capacity of the ship, with the vessel and its gear gaining an additional 6 tonnes of weight (Steffy 2004b:269), both sets of data are set-out in Table 2-2 and Table 2-3.

Length on deck	15 m	Displacement (indicated waterline)	43.2 tonnes
Length (indicated waterline)	14.5 m	Estimated weight of Hull and gear	15 tonnes
Length of keel		Beam-to-length ratio	1:2.94
Beam (maximum)	5.13 m		
Beam (molded)			
Depth in hold			
Tonnage	37 tonnes[15]		

Table 2-2 Serçe Limani Characteristics – 1982 (after Steffy 1982)

Length on deck	15 m	Displacement (load waterline)	56.27 tonnes
Length (indicated waterline)	14.5 m	Estimated weight of Hull and gear	21 tonnes
Length of keel		Beam-to-length ratio	1:2.94
Beam (maximum)	5.13 m	Freeboard at load waterline	c. 1 m
Beam (molded)		Prismatic coefficient	0.72
Depth in hold		Block coefficient	0.65
Tonnage	34.73 tons[16]	Midship coefficient	0.89

Table 2-3 Serçe Limani Characteristics – 2004 (after Steffy 2004)

For *Serçe Limani,* the scaled site survey drawings were created from photography as with *Yassi Ada*, and timbers were documented full-scale using elevated-plane tracing. Steffy again immediately switched to three-dimensional research, creating a site diorama model of the as found wreck. Various models were then used to develop the hull form and create reconstruction drawings. Tonnage formulas and calculated displacement were used as a means to validate the resulting reconstruction.

[15] The tonnage in 1982 is listed as 37 tonnes, which together with the vessels weight would cause the ship to float at the 8th waterline rather than the indicated 6th waterline. If the 6th waterline was used for flotation the tonnage would be reduced to 28.2 tonnes.
[16] The tonnage in 2004 is listed as 34.73 long tons which equates to 35.29 metric tonnes.

C.9 Grace Dieu 1980-85 -2005

An 1874 survey reported in The Graphic, dated 27th November 1875, described a wreck (Figure 2-36) measuring over 130 ft (39.6 m) long and more than 10 ft (3 m) deep, as well as a figurehead which was reportedly removed from the wreck, 'a lion with its paws erect', which stood outside a nearby cottage, and was ultimately cut-up for firewood.

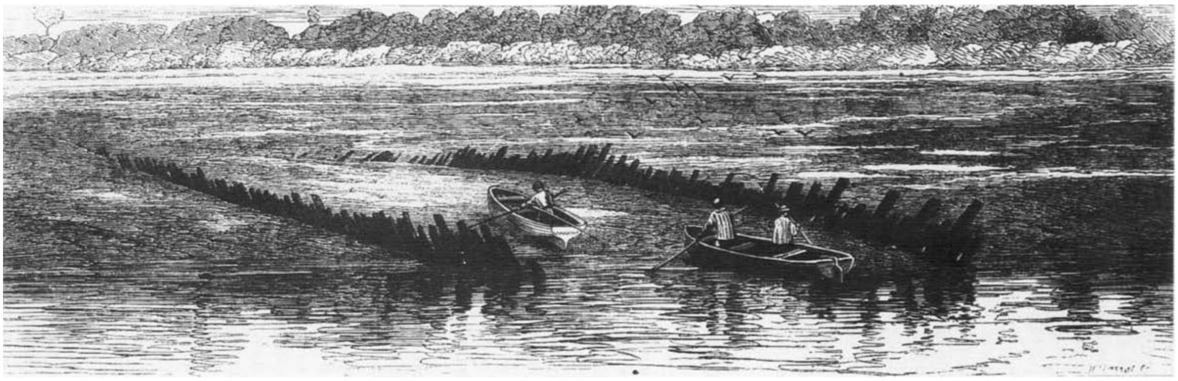

Figure 2-35 A drawing of the R. Hamble wreck published in The Graphic 1875 (after Friel 1993)

Other mentions of the wreck include: a query about an old ship half buried in the mud (L. R. 1911:319); another query regarding a 130 ft (39.6 m) long "Viking" ship (Brindley 1926:350); subsequent fieldwork in 1933 confirmed the remains as still being 135 ft (41.1 m) by 37½ ft (11.4 m) and identified the vessel as potentially that of Henry V's flagship the *Grace Dieu* (Anderson 1938:112–3). Prynne estimated the ship based on the shape at the widest portion had a greatest beam in the order of 50 ft (15.24 m) wide, suggesting a ship of 1,400 to 1,500 'tons', and an estimated 2,750 'tons at 21 ft (6.4 m) draught (see Prynne 1968:115–28; Prynne 1976).

Prynne states that the Grace Dieu:

> "is worth salving, because she is worth seeing in herself due to the massive size, and the inevitable 'bits and pieces' sure to be found, together with a model and pictures would present a view of medieval nautical history unrivalled in the world." (Prynne 1968).

Further excavations on *Grace Dieu* were carried out from 1980-1985 by the National Maritime Museum, Greenwich's ARC undertook annual fieldwork on this designated site, and three articles on this work and on related documentary studies were subsequently published in the IJNA. Sampling of the small number of available timbers[17] from the wreck has confirmed oak planking, which '*…even at this late date were not sawn into planks but rather were radially split according to traditional clinker shipbuilding practice*'.

[17] Of the 14 available timbers, 11 were parts of planking, 3 were framing fragments and 1 piece of internal structure. All pieces are small fragments of circa 1.6 m or less.

Radiocarbon dating confirmed a felling date of late 13th to late 15th century at 95% probability, dates which bracket the known building date of AD 1418 for *Grace Dieu* (Clarke *et al*. 1993:25).

Existence of the unusual triple thickness clinker planking was confirmed, with thick layers of moss caulking material, and a combination iron nails and wedged treenails for fastenings (Figure 2-37). Smaller nails were used to tack the planks together prior to the main clenching. The available partial framing elements, all of which were less than 1.2 m in length show evidence of joggles cut in the outboard faces to accommodate the clinker planking, with rebates notched within the joggles to accommodate the nail roves, indicating the framing was most likely fitted after planking (ibid:26-33).

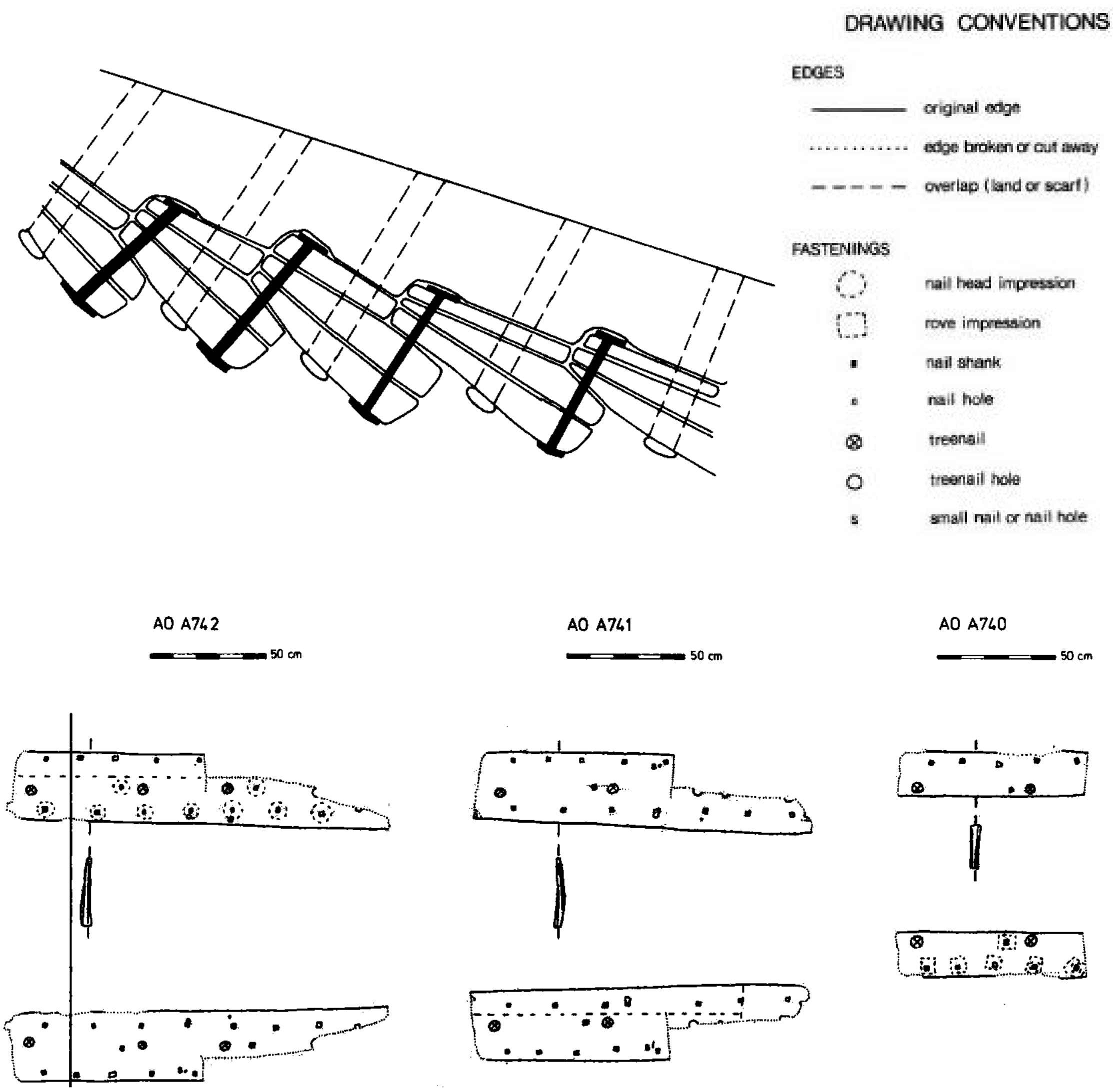

Figure 7. Greenwich triple planking fragment. Left to right, outer plank (AOA742); middle plank (AOA741); inner plank (AOA740). (Drawing: NMM, Greenwich.)

Figure 2-36 Triple clinker planking and plank fragments from Grace Dieu (After Clarke *et al*. 1993)

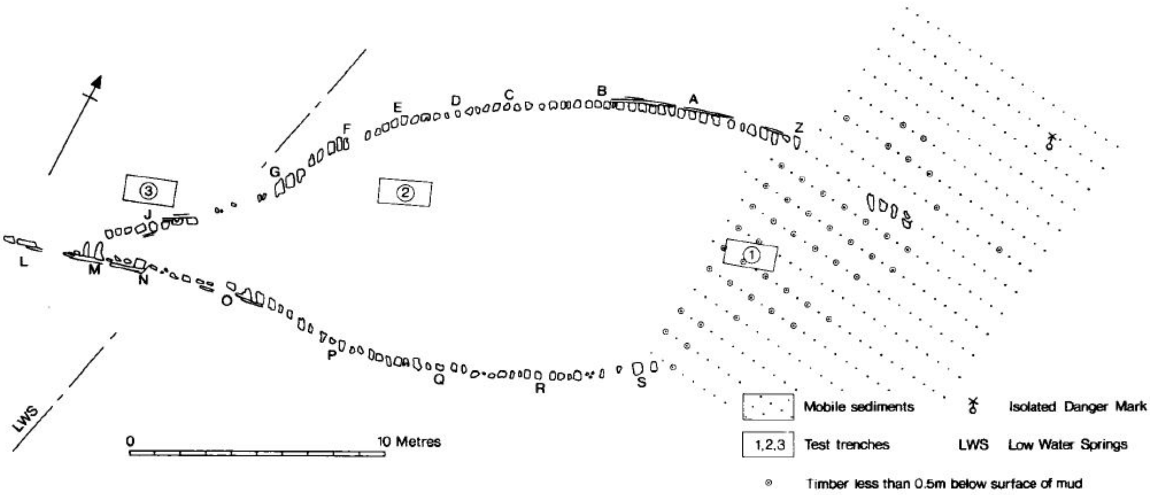

Figure 2-37 Grace Dieu site plan 1983-84 (after Clarke *et al*. 1993)

A site survey of the visible wreck structure was carried out in 1983-84 (Figure 2-38) and also identified a second nearby contemporaneous wreck, which has been tentatively identified as the *Holigost,* the second of the four great ships[18] all built for Henry V between November 1413 and the autumn of 1416 but remains un-investigated to this date (Clarke *et al*. 1993).

Friel (1993) researched the literary evidence for the *Grace Dieu* and noted its build date as commencing in July AD 1416, and a blessing of the ship by the Bishop of Bangor in July AD 1418 suggests *'…the vessel had reached some stage of completion'* . Friel notes the difficulty in determining the exact workforce and cost of the ship, partially due to other vessels being constructed at the same time but suggests the workforce in mid-1417 could have included up to 50 shipwrights. Inventories of timber for the ships include a total of 2,735 Oaks, 14 Ashes, 1,145 Beeches and 12 Elms, or 3,906 trees. Other receipts for the period include a total of 23 tuns, 7 cwt of iron nails and roves, the sale in AD 1421 of 3,360 lbs of broken clench, indicating a wastage rate of under 6.5%, 4,012 treenails received in December AD 1416, as well as 15 lasts of pitch and 15 lasts, 5 barrels of tar between AD 1416 – 1420 (ibid:5-7). Friel also notes from the records, mention of the rigging which included: 1 great mast; 2 other masts; 1 bowsprit; 1 mesan sail; 2 sail yards; and 2 sails with 3 bonnets. He estimates the great mast to have been in the region of 190-200 ft (58 – 61 m) in height, and notes records of 6 'great anchors' of approximately 1 ton each for the ship(ibid:8-9).

Despite these documentary resources, there are little or no records of the actual dimensions of the ship. Friel (ibid:17) notes the only contemporary written records are those in the diary of

[18] The Four Great Ships were: The *Trinite Royal* (500-540 tuns burden); *Holigost* (740-760 tuns burden); *Jesus* (1,000 tuns burden); and Grace Dieu (1,400 tuns burden).

Albizzi, the captain of a Florentine galley which visited Southampton in AD 1430. Albizzi gives dimensions in Tuscan bracchia (equivalent to 1.9 ft or 0.58 m). Prynne (1977) suggests Albizzi probably used a bracchia of 2 ft and covered his approximation with '*or thereabouts*'. Albizzi's dimensions for the *Grace Dieu* are the height of the mast as 102 bracchia (193–204 ft, 58.9–62.2 m), and the length of the ship at 92 bracchia (174.8–184 ft, 53–56 m), with a breadth of 50 bracchia (95–100 ft, 28.9–30 m). A forecastle height above the water of 26 bracchia (49.4–52 ft, 14.9–15.8 m) and a circumference of the mast at the main deck of 11 brachia (20.9-22 ft). Prynne gives two alternatives for the ship, suggesting the length is measured on the main deck, giving a total length of 218 ft (67 m) and the breadth is simply a translation error and should be 50 ft (15.4 m) rather than Albizzi's 100 ft (31 m) breadth, which would result in a length to beam ratio of 2:1.

McGrail notes the importance of the *Grace Dieu* wreck as being one of the very few, from a period of great change, in both shipbuilding and rigging techniques used in Atlantic Europe. During this time period, as well as a change from single-masted square-rigged, to three masted rigs and lateen sails, there was also a change in construction techniques. From the 'shell-first' sequence of construction to the 'frame-first' sequence of construction. As these technological changes are not well documented, any wreck from this period is of great importance (McGrail 1993). According to McGrail the River Hamble wreck, whether correctly identified as the *Grace Dieu* or not, is built of radially-split, clinker-laid strakes, edge-fastened by clench nails, with a caulking of moss and tar, features which are characteristic of the Viking/Nordic tradition. Her estimated dimensions of 40 m length and 15 m breadth[19] are both much greater than the largest of those earlier vessels in this tradition.

It was as a result of these investigations, that much of the items listed in documentary sources, and the way in which they were used, became clear from the excavated work of archaeology (Rose 2011:65). Even armed with plentiful literary resources, and supplemented with rigorous scientific archaeological investigations, there is still considerable uncertainty regarding the overall dimensions of the vessel as well as the design and construction of the upper works and castles of this ship. There exists a single dimension in the literary sources, a height of 26 bracchia (circa 15m) for the height of the forecastle given by Albizzi the Florentine commander. Likewise, there is evidence for three masts, spars and sails as listed in her inventory, but the arrangement of masts and rigging is only conjectural (ibid:68).

On the matter of planking construction, McGrail questions the evidence for short lengths, some of which were fastened together forming the triple clinker hull. He wrongly states:

[19] McGrail does not cite sources for these dimensions.

> "In a shell-built, clinker-planked boat it is generally the practice nowadays to scarf individual planks together before fitting an entire strake as one unit to the keel or to the strakes already in place."(McGrail 1993:47).

I have never constructed a clinker vessel in this manner, nor have I ever seen it so done, except in the case of small "kit-style" clinker punts where the planking is supplied as a developed shape drawing to be cut from sheet plywood and pre-assembled into strakes prior to fitting. "Normal" practice is to shape and fit the plank to the vessel with the ½ scarph already pre-formed, then create the subsequent plank and cut a matching ½ scarph to suit the one already fitted to the hull.

A more recent investigation in 2005 (Plets *et al*. 2009) used a 3D Chirp sub bottom profiler, a form of acoustic underwater system used to detect shallowly buried objects in very shallow waters. The stated resolution of said system was between 7.6 to 11 cm vertically and 40 to 70 cm horizontally with positional accuracy controlled by a terrestrial RTK system to an accuracy of 2 cm. Plets *et al*. note that while the 3D reconstruction with decametric levels of accuracy will never obtain the same accuracy as can be recorded manually from exposed wrecks, the acoustic data can be used to portray a faired 3D version of the original hull of the vessel (Figure 2-39).

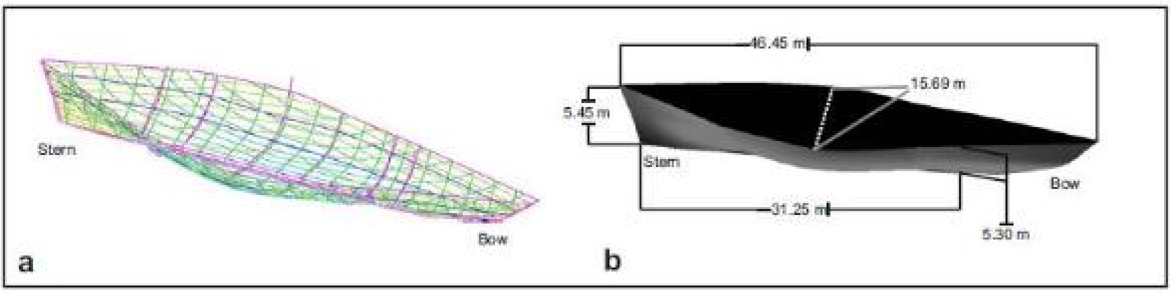

Figure 2-38 Hypothetical faired 3D reconstruction of the Grace Dieu wreck (after Plets *et al*. 2009)

The recording methods used on the *Grace Dieu* timbers, recording original edges, damaged edges, details of plank lands, nail and rove impressions, as well as nail holes and treenail locations are the same techniques still in use to this day. However, there has still not been any attempt at a reconstruction of what both Prynne and McGrail have noted is a very significant shipwreck.

C.10 Ma’agan Mikhael Ship 1985

In 1985 off the shoreline of Kibbutz Ma'agan Mikhael, the remains of a circa 14.4 m small sailing merchantman of approx. 23 tons displacement, dating to the fifth-century BC and believed to have been in good to new condition at the time of sinking was discovered. The preserved remains were 11.5 m long by 3.11 m wide and 1.5 m deep and was excavated over three seasons under the direction of Jay Rosloff, a former assistant to Dick Steffy, who had assisted Steffy with the *Serçe Limani* ship reconstruction. Underwater recording consisted of direct manual measurements from fixed datum points using measuring tapes (DSM method), and depths recorded with plumb lines. The wreck was abundantly photographed using colour and B&W film as well as videography. Hull timbers were cleaned, and all sides recorded for their main features such as contours, main dimensions, nail remains and sewing holes. Post conservation the timbers were again recorded in minute detail to the level of wood grain, knots, tapered pegs and nails. Wood species identification was also carried out post conservation. This approach of drawing the main features prior to conservation and detailed hand drawings after conservation was considered a good compromise by Yaacov Kahanov, due to the condition of the timbers and the documentation tools available at the time (Kahanov 2011:162–164).

Kahanov states the hull was reassembled using two main guiding principles: archaeological accuracy and research accessibility. The ship was reassembled 'shell first', with the keel and posts placed on temporary adjustable scaffolding, followed by the garboard and subsequent strakes, supported by MDF transverse supports which were cut following the original shape of the frames but 15 cm outside the hull (Figure 2-40). The battens and transverse MDF supports provided adequate support to the planking, which was adjusted to conform with other features, in particular the frames which provided accurate information regarding the original hull form[20]. The hull was thus assembled and dismantled three times, and the final fourth assembly achieved, according to Kahanov, a match to the original archaeological find as recorded in-situ[21]. The gaps that remained matching the accuracy of the carpentry of the original ship (ibid: 166-7)

Kahanov (2011) notes the main objective for recording the excavated ship was to provide a basis for reconstructing the ship as far as is feasible from the archaeological findings. Based on the reassembled remains, two reconstructions of the hull lines were suggested (Winters and Kahanov 2004). Later with evidence from contemporary shipwrecks, iconography and the creation of both

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[20] It would appear that Kahanov is assuming the frames (as documented), have retained the shape of the original hull form and not altered in any way or form.

[21] Therefore, the form of the ship as displayed in the museum is the ‘as-found’ shape and not the original hull shape.

computer based and physical scale models, a third and more comprehensive reconstruction, including planking patterns was proposed (Ben Zeev *et al*. 2009). Adina Ben Zeev studied under Patrice Pomey at the University of Provence, where she learned that centre's working methods, and applied these techniques to the *Ma'agan Mikhael* evidence.

Figure 2-39 Reassembly of Ma'agan Mikhael ship (photo: Hect museum)

With circa 25% of the original hull surviving (Figure 2-41 and Figure 2-42), the shape of the stem and stern posts, the midships section shape and the depth of the hull were identified as necessary missing elements, in order to determine the overall length, shape and form of the vessel. The Haifa team had to rely heavily on iconographic evidence as well as evidence from two near-contemporary Mediterranean reconstructions, *Jules Verne 7* and *Kyrenia*, the upper part of *Ma'agan Mikhael's* cross section for example, is extrapolated from *Kyrenia* (Ben Zeev *et al*. 2009:62) so the question must be asked, how valid is the reconstruction? McGrail (2010:446) states that on projects where the surviving timbers include the keel, an undisturbed, near complete bow and stern, and at least part of the top edge of the sides, a valid reconstruction may well prove possible[22]. The Haifa team's approach to the *Ma'agan Mikhael* reconstruction was to build three scale models, but unlike the methods employed by Pomey it does not appear that they built a specific as-found scale model.

[22] This appears to be an extreme criterion, which few if any shipwrecks could realistically satisfy, and perhaps reflects McGrail's 'minimal hypothetical solution' philosophy.

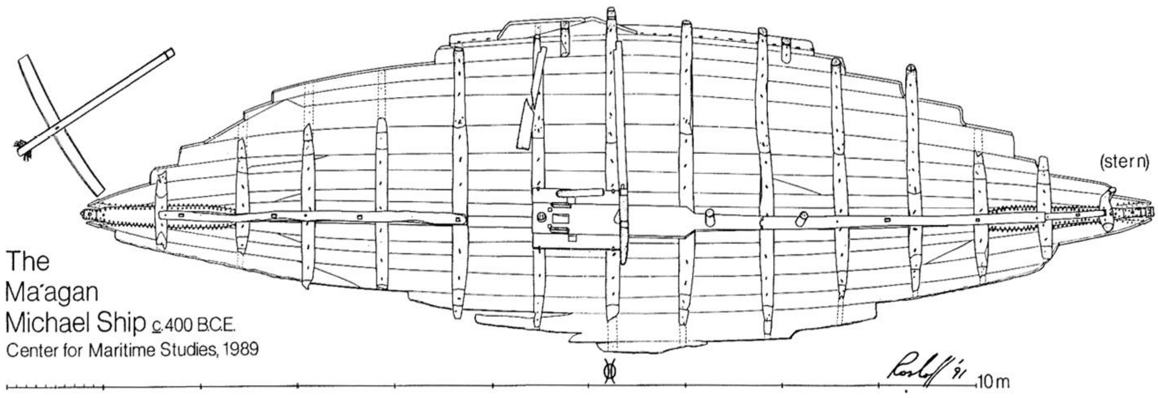

Figure 2-40 Ma'agan Mikhael Ship site plan (after Kahanov 1998)

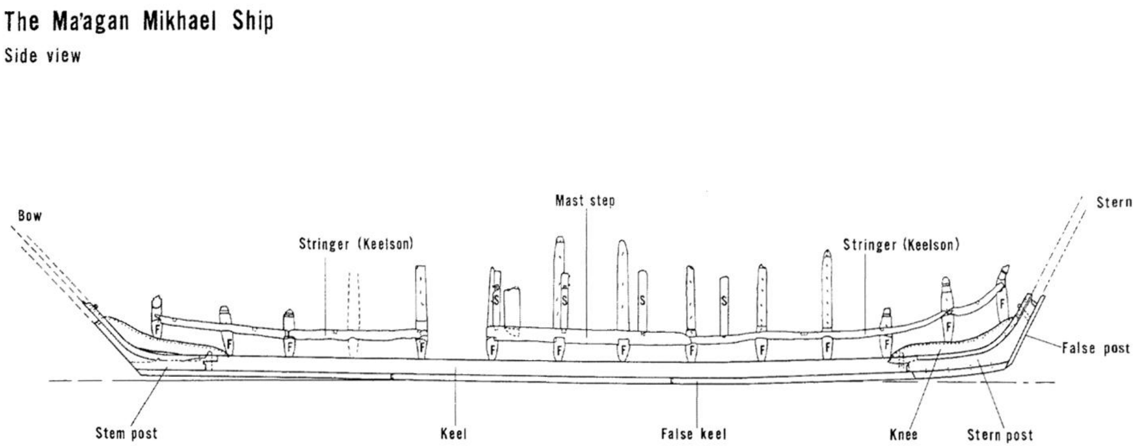

Figure 2-41 Ma'agan Mikhael Ship side view (after Kahanov 1998)

For the reconstruction Kahanov (Winters and Kahanov 2004:130) states that the archaeological remains defined the bottom part of the ship, including the turn of the bilge, meaning the range of possible reconstruction options was considerably narrow. It was decided that the *Ma'agan Mikhael* ship had been similar in hull shape to the *Kyrenia* ship and the resulting reconstructed lines (Figure 2-43) were tested for displacement and static stability. With the wale located at the waterline, as in *Kyrenia*, *Ma'agan Mikhael* would have a draft of 1.1 m resulting in a displacement of 15 tons and freeboard amidships of 76 cm. Further examination of the archaeological data revealed a cargo of 12.5 tons, and conservative estimates for the weight of ship and crew were 5.5 tons giving a combined weight of 18 tons. Such a weight would result in a draft of 1.2 m and leave just 65 cm of freeboard amidships. Such results led Kahanov to the conclusion that the ship as drawn was not seaworthy as the gunwale would be awash as just 24° angle of heel (ibid: 131). As a result, the shape of the vessel was modified above the extant remains to create a revised hull form of 23 tons displacement (a massive 27.7% increase) with a positive stability up to 60° angle of heel (ibid: 131-32). The original vessel did sink, why create such an oversized reconstruction?

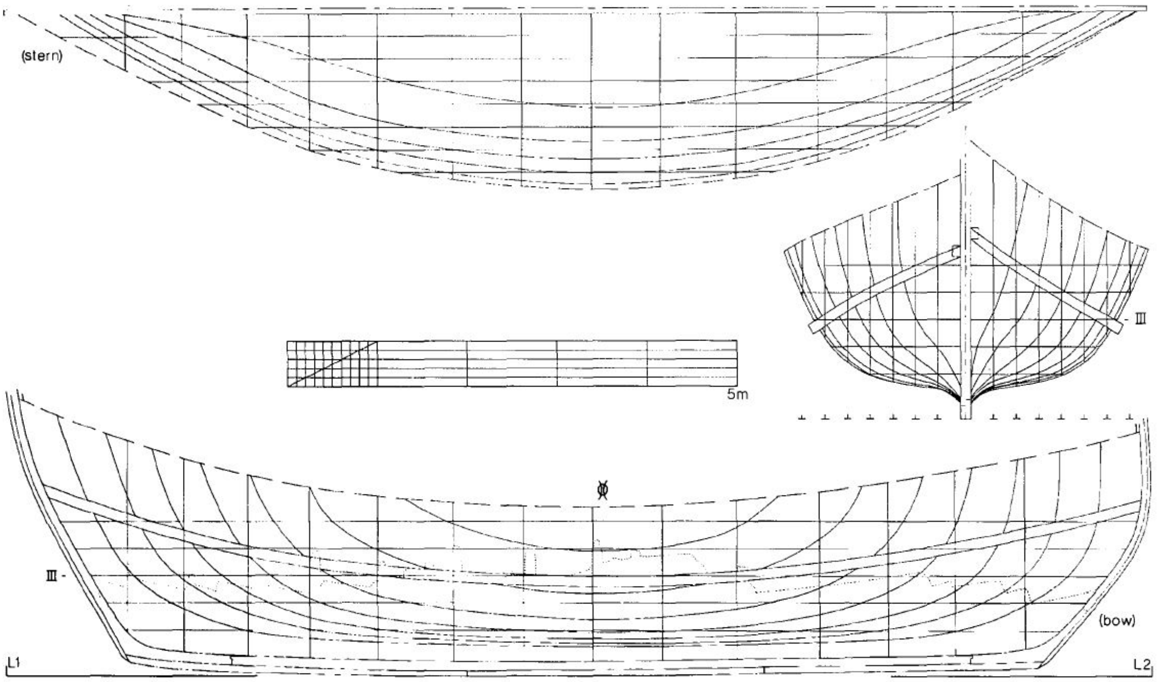

Figure 2-42 Ma'agan Mikhael initial lines plan drawings (after Winters and Kahanov 2004)

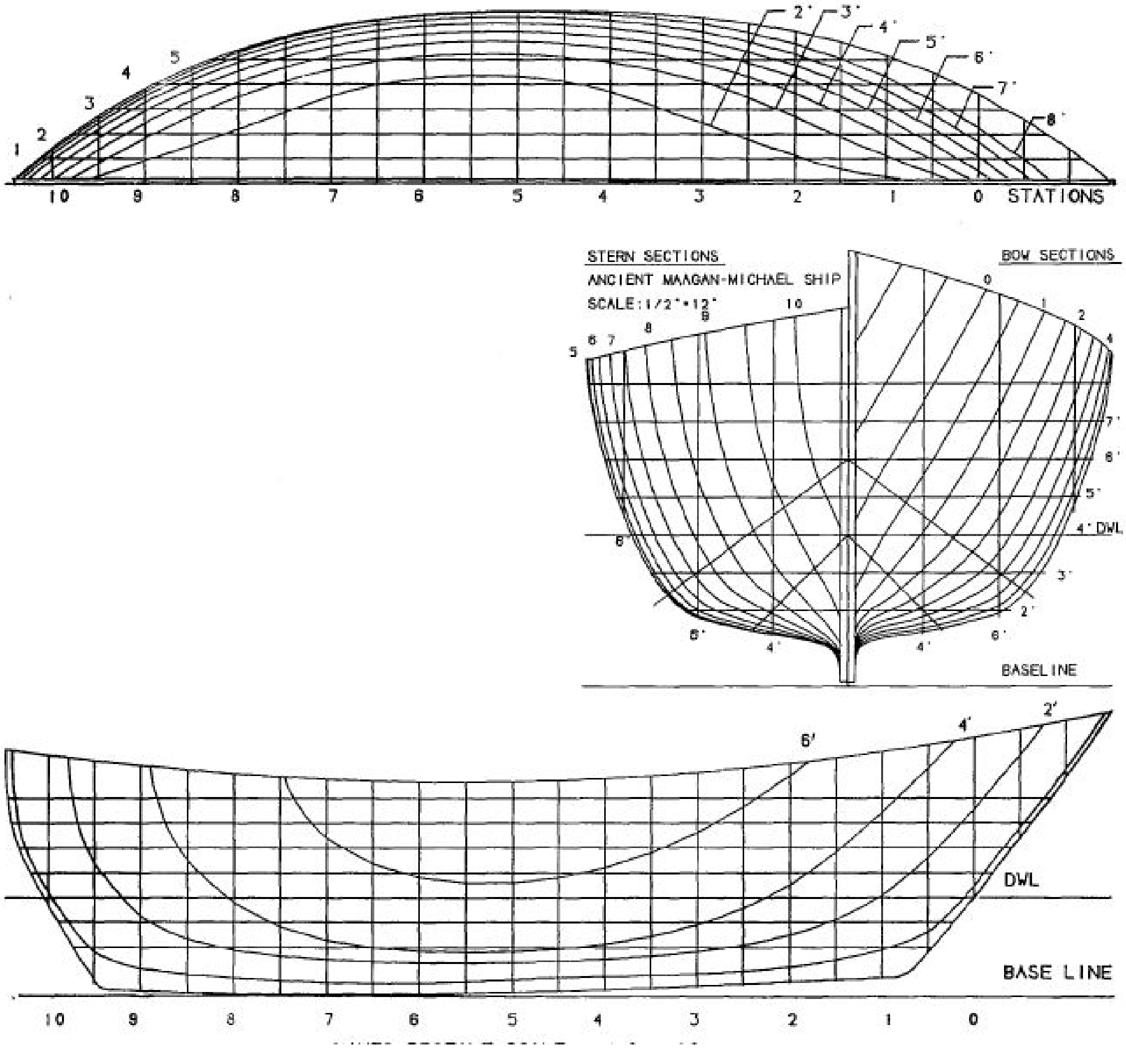

Figure 2-43 Ma'agan Mikhael revised lines plan drawings (after Winters and Kahanov 2004)

McGrail (2010:447) notes that scale model building is, in his experience, the best place to start, as lines are best drawn after the hull reconstruction has been achieved, proceeding from the known (an 'as-found' model) to the unknown, leading, if successful, to a reconstruction model or scale drawing.

McGrail quotes: Van Doorninck (Yassi Ada I (1982), 47–53); Steffy discussing the Kyrenia ship (Tropis I (1989), 249–62); and McKee's three models of the Graveney boat (in Fenwick 1978:265–302) as authorities for such model building. And he further suggests that prior to building any replica, the Haifa team should firstly re-examine all published evaluations and subsequently either publish a detailed and well-argued case for the validity of this reconstruction, make further attempts to evolve a valid reconstruction, or decide that insufficient evidence was excavated to justify any reconstruction (McGrail 2010:447).

For Ma'agan Mikhael, the reassembly of the hull remains was initially the primary focus in reconstruction. The remains were reassembled up to four times (trial-and-error) and subsequently used as the basis for two suggested reconstructions of the hull lines. Heavy reliance on iconographic evidence as well as near-contemporary Mediterranean reconstructions, was used to extrapolate the overall reconstructed hull form. The approach was to build three scale models, but a specific as-found scale model was not built. Hydrostatic analysis was carried out on the reconstructed vessel but was deemed to be unseaworthy, and the shape was modified above the extant remains to create a revised hull form with a 27.7% increase in displacement.

C.11 Barland's Farm 1993

In 1993 at Barland's Farm, Magor, Gwent, Wales, the remains measuring circa 9.7 x 2.6 x 0.7 m of a planked boat were discovered. The timbers were dated by dendrochronology to the late third century AD, and many features, identified by McGrail (1995) as characteristic of the Romano-Celtic tradition, led to labelling the vessel as Romano-Celtic (see McGrail 1995; McGrail and Roberts 1999; Nayling and McGrail 2004). Five main groups of timbers, all oak, were excavated: a complete plank-keel consisting of two strakes side-by-side; lower part of the stem-post; a large portion of the framing timbers, consisting of floor timbers, pairs of half frames, and inter-frame side timbers; planking consisting of complete second or outer bottom strakes, parts of 5 port strakes, and parts of three starboard strakes; and a short mast-step timber.

Documentation of the remains included: photography; traditional survey using baselines and offsets to produce two-dimensional site sections all related to Ordnance Datum (OD – the reference level for land mapping in the United Kingdom); and photogrammetric survey (Figure 2-45) once the ship was fully exposed. Individual timbers were recorded using 1:5 scale drawings[23], which were subsequently reduced to 1:10 scale and used by a model builder (not an archaeologist) to create a 1:10 scale 'as found' model[24].

The model was then measured to produce 'original measured drawings' of the remains. It should be noted that these 'original measured drawings' were created at half the size of the research model, 1:20 scale as the resulting drawing measured 0.65 x 0.5 m and was considered, by the authors, to be a more manageable size than if a 1:10 scale drawing had been used (Nayling and McGrail 2004:165).

If the scale of a drawing is reduced, it becomes necessary to omit details for reasons of clarity and to avoid a cluttered drawing:

> …we note that the tool-marks have been omitted, no doubt because recording was done on a 1/5 scale and not with a transparency on a 1/1 scale, a frequently used method (p.112). Details tend to be dropped when smaller scales are used for recording finds (Arnold 2005:349).

[23] The institute for archaeologists recommends that survey drawings produced at a scale less that 1:1 should be annotated with or accompanied by a table of 1:1 measurements (Institute for Archaeologists 2008a:7).

[24] McGrail's definition of 'as-found' is – 'the boat as found, but with distortions and compressions removed, displaced elements replaced, fragmented timbers made whole, and the hull rotated to its deduced attitude when afloat' (Crumlin-Pedersen and McGrail 2006; McGrail 2007). This involves interpretation and differs from Steffy and Pomey who both construct the initial model 'exactly' as-found devoid of interpretation.

Additionally, the lines used in scaled drawings are a significant factor, a 0.5mm pen (commonly used in inking drawings) would create a 0.5mm thick line, which at 1:10 scale represents 5 mm of full-scale thickness. The same pen if used at 1:20 scale would represent or obscure 1 cm of full-scale size. The drawings are further reduced, due to the publication process, resulting in an impracticable 1:34.4 scale for the publication (Nayling and McGrail 2004:166 foldout).

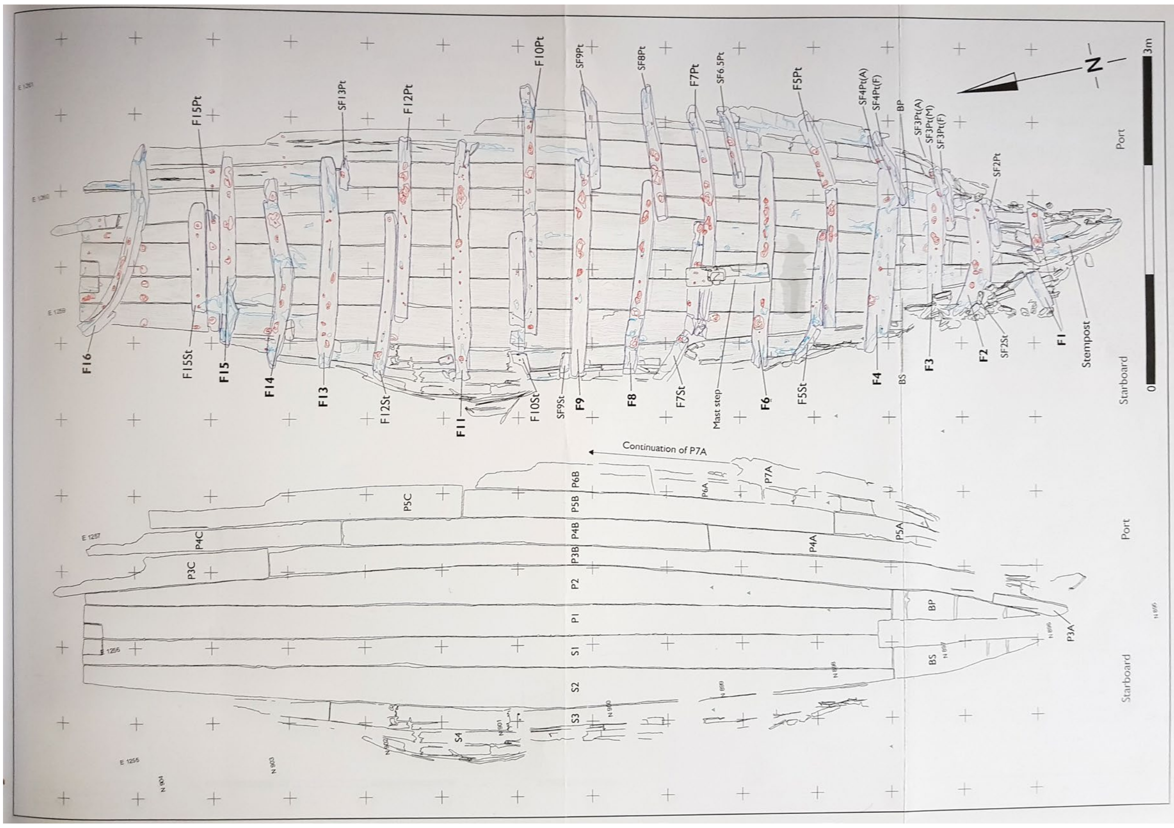

Figure 2-44 Barland's Farm photogrammetric survey plan (after Nayling and McGrail 2004)

Reconstruction of the boat used the reduced scale 1:20 drawings taken from the 'as found' model. During the documentation it was noted that strake P7 (7th strake on the port side) was the upper surviving limit of recovered evidence and this was set as an upper height limit and maximum width for the reconstruction. Other parameters which needed to be determined were the overall length, the original height of the posts, and the form of the stern and upper bow area. The run (curvature) of surviving strakes was extended until meeting an extension of the post, giving a forward limit to the boat. While adding a mirrored copy of the bow to the missing stern area would have provided a maximum possible overall length of circa 12.2 m, evidence from the remains suggested the boat had been fuller aft than forward.

A shorter 'version' of the stem post with the flat lower section removed was used, as it apparently coincided better with the projected strake runs. This provided a minimum reconstruction (Figure 2-46) with an overall length of circa 11.4 m, a beam of 3.16 m and a depth of 0.9 m (Nayling and McGrail 2004:166–168).

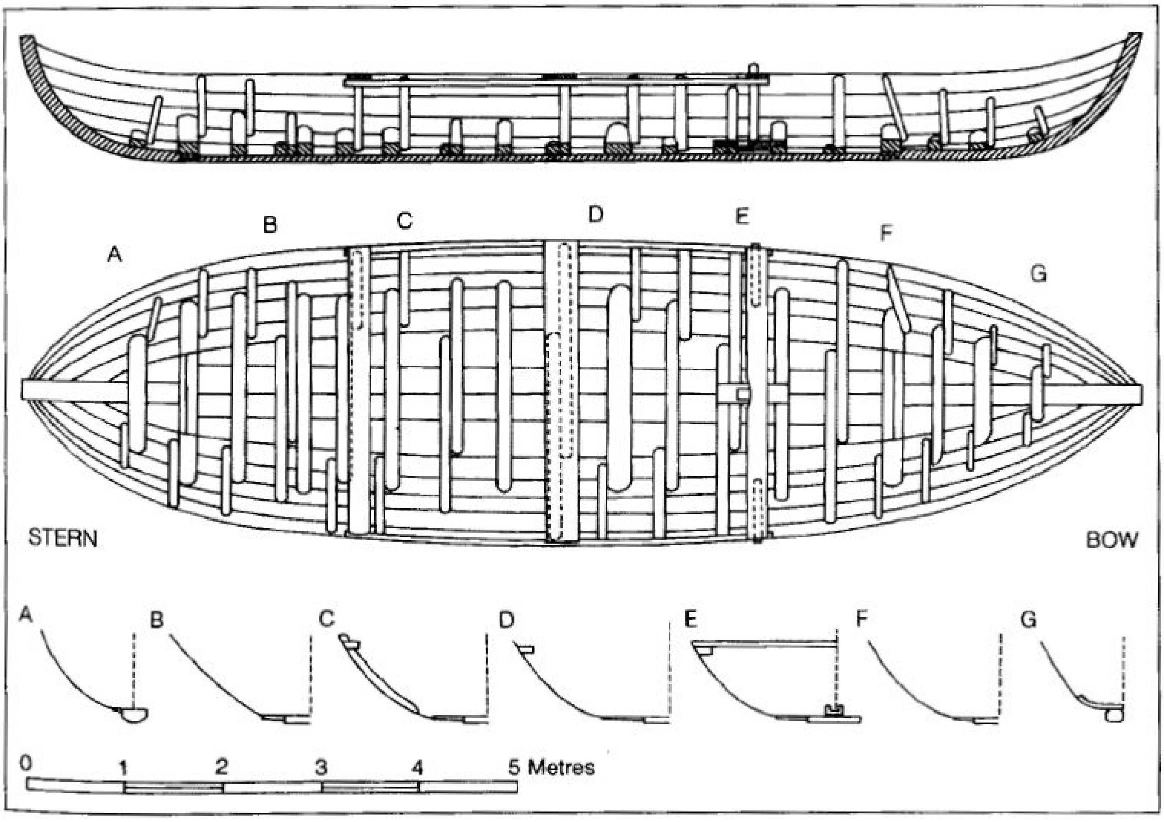

Figure 2-45 Barland's Farm reconstruction (after McGrail and Roberts 1999)

Data for the resulting reconstruction was tabulated by McGrail as 11.4 x 3.16 x 0.90 m (L x B x D), height at posts 1.3 m, Beam to Length ratio 1:3.6, Depth to Beam ratio 1:3.5, Depth to Length ratio 1:12.67, and a midship coefficient of 0.80. In comparing these, to definitions given by McKee (1983:81), McGrail describes the minimum reconstruction of the *Barland's Farm* boat, as being neither beamy (≤ 2.6), nor narrow (≥ 3.75), but in between, with a length-to-beam ratio of 3.6, having a shallow (≥ 3) cross section, rather than deep (≤ 2), and the midship sectional area is described as firm (0.8), rather than full (≥ 0.85) or easy (≤ 0.7) (Nayling and McGrail 2004:168). Owain Roberts estimates the boat to have weighed 2.08 tonnes, resulting in a draft of 0.18 m, with 0.72 m freeboard and a downflooding[25] angle of 24°. At 0.36 m draft, the remaining freeboard would be 0.54 m, resulting in a downflooding angle of 18° and the displacement would be 5 tonnes, allowing a cargo capacity of 3 tonnes. A draft and freeboard of 0.45 m (50% of the moulded depth) would result in a downflooding angle of 15° and a displacement of 7.1 tonnes, allowing a cargo capacity of 5 tonnes[26] (Nayling and McGrail 2004:179–191).

[25] For a definition of downflooding see Glossary of Terms.

[26] It is worth noting that Kahanov (2004:131) deemed the 14.4 m Ma'agan Mikhael vessel to be un-seaworthy with a freeboard of 0.65 m and downflooding angle of 24°. The reconstructed 11.4 m Barland's Farm boat has 0.72 m freeboard and the same 24° downflooding angle in an empty state, and Roberts is content to claim a cargo capacity of five tonnes resulting in a 0.45 m freeboard and 15° downflooding angle.

In 2012 Selina Ali carried out a reanalysis of the *Barland's Farm* boat. The first phase involved the creation of a digital three-dimensional model of the vessel (Figure 2-47) as represented in the published reconstruction drawings. The second stage used a combination of contact digitising and 3D laser scanning to record the available three-dimensional models of the same vessel. The 'as found' research model was recorded using 3D laser scanning (Figure 2-48), and the museum reconstruction model was recorded with contact digitising using a Faro Arm (Ali 2012).

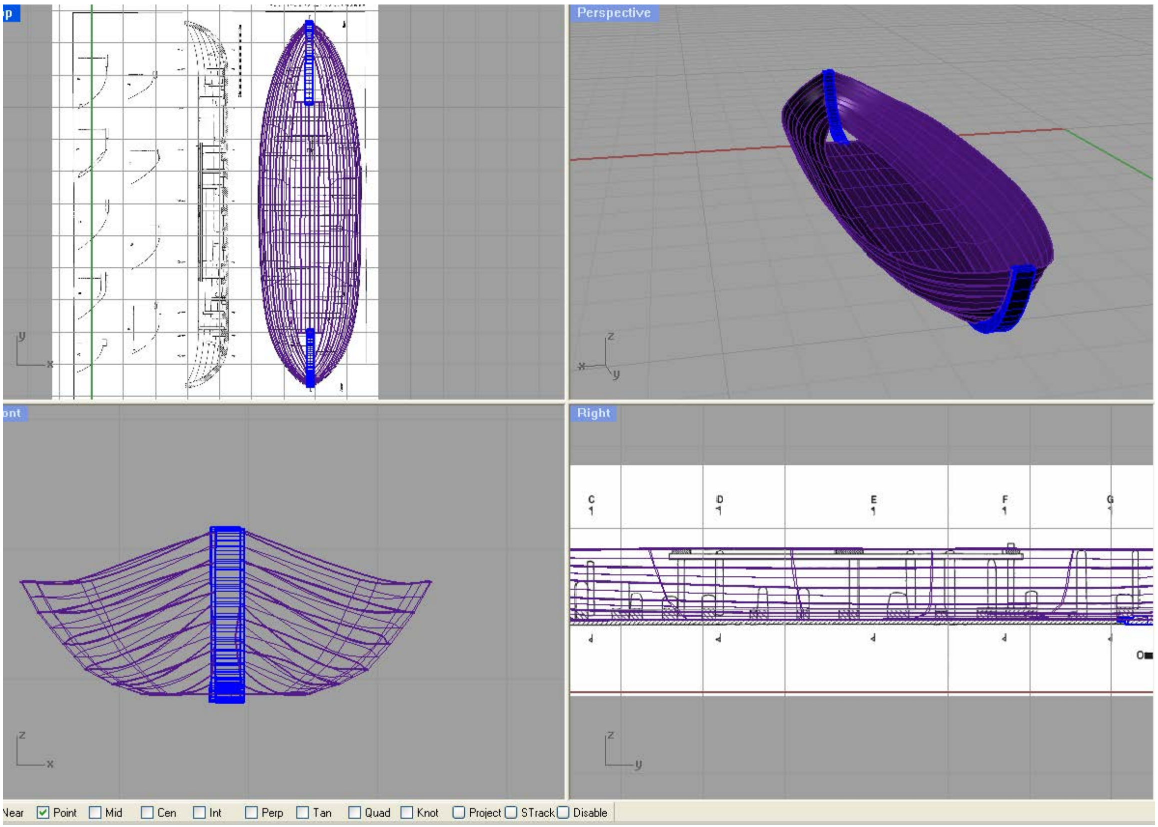

Figure 2-46 Digital model of the Barland's Farm reconstruction (after Ali 2012)

During the construction of the digital three-dimensional model, based on the reconstruction drawings, individual three-dimensional models of each frame were also created using the published catalogue of timbers (Nayling and McGrail 2004:235–307). An issue was found when the digital three-dimensional models of each frame were positioned in their respective locations within the overall digital reconstruction model. The framing elements which would be expected to have opened outwards, due to the relaxing of tension within the wood structure or flattening in-situ due to the weight of overburden, were in fact too tight for the reconstructed hull form as proposed (Ali 2012:15). None of the side portions of the frames (Figure 2-49), which should either touch or protrude through the hull sides if they had distorted, coincided with the proposed hull reconstruction shape.

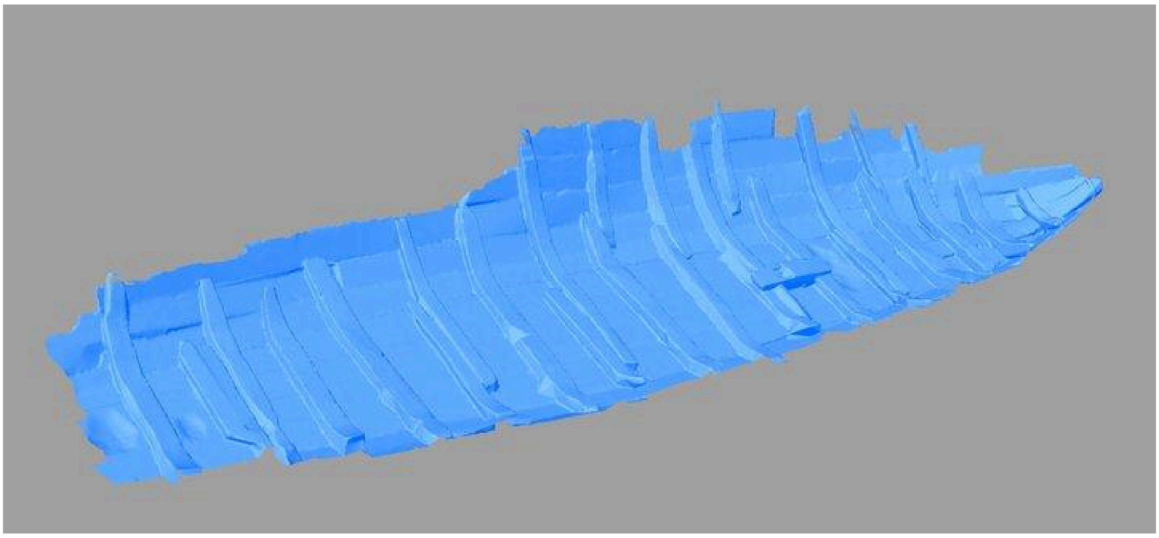

Figure 2-47 3D laserscan of the Barland's Farm 'as found' research model (after Ali 2012)

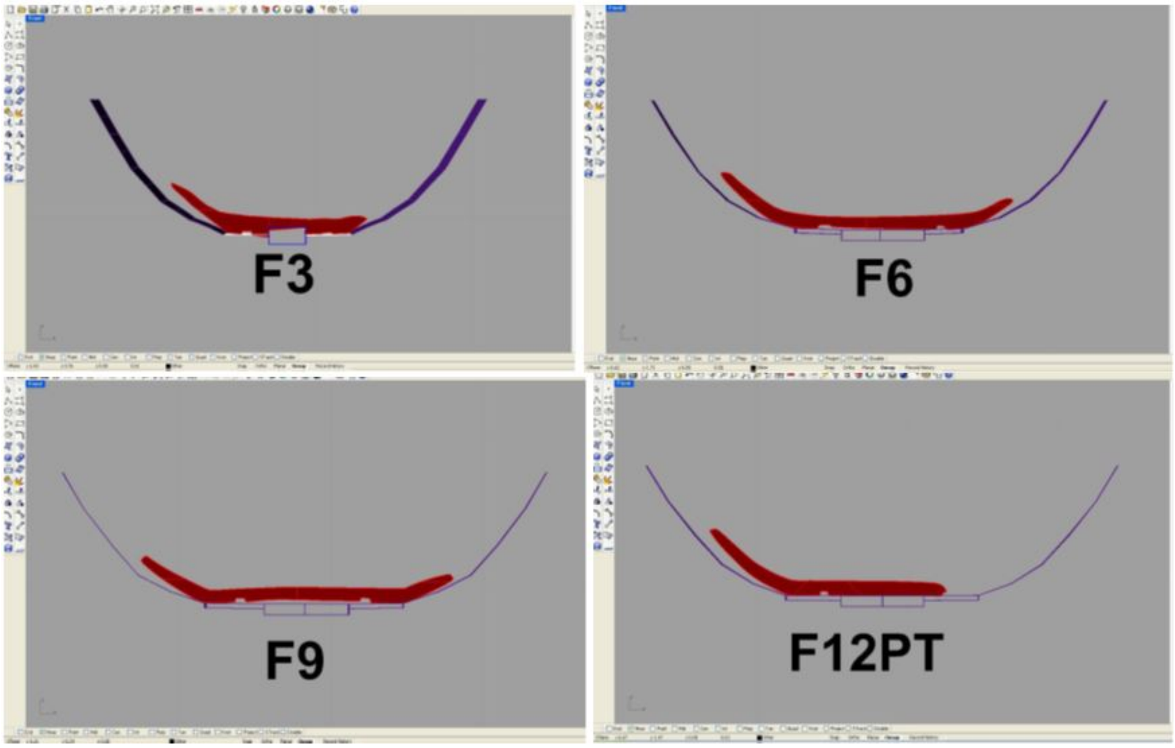

Figure 2-48 Digital frames models of Barland's Farm (after Ali 2012)

Comparing the three-dimensional frame models to the 3D laserscan of the ‘as found’ research model clearly illustrated (Figure 2-50) the frame shapes as recorded, and the constructed research model complied for the most part with one another, and the discrepancy lay with the reconstructed hull form drawings. Ali concludes that the reconstruction drawings put forward in the publication do not fit the archaeological record, and the proposed reconstructed form requires further investigation (Ali 2012:16).

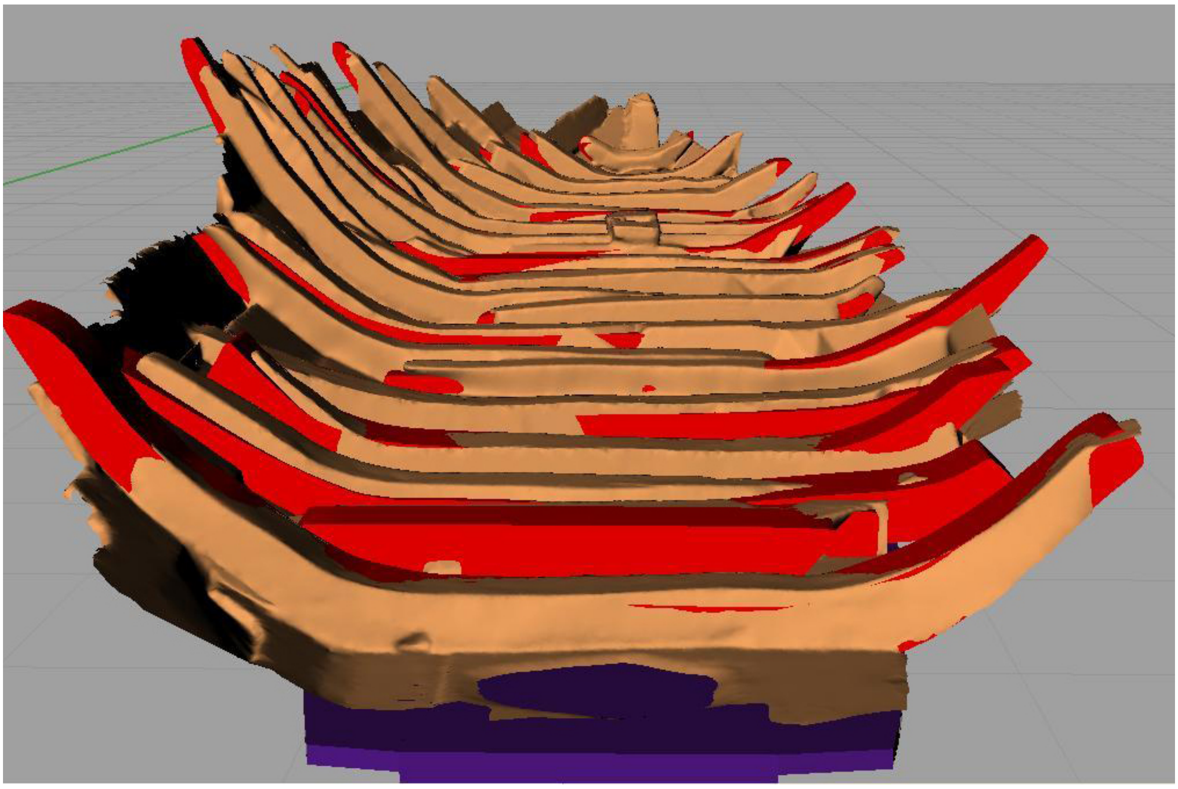

Figure 2-49 Comparing laserscan of 'as found' model to digital frame models (after Ali 2012)

For the Barland's Farm project, traditional survey using baselines and offsets to produce two-dimensional site sections and photogrammetry were used. Individual timbers were recorded using 1:5 scale drawings, which were subsequently reduced to 1:10 scale and used to create a 1:10 scale 'as found' model. The model was then measured to produce an 'original measured drawings' of the remains. Reduced scale, 1:20 drawings taken from the 'as found' model were then used for the reconstruction of the boat. Ratios of form, and hull form coefficients were calculated to evaluate capacity and sphere of operations. Which led McGrail to describe the vessel as being neither beamy nor narrow, but in between, having a shallow cross section, rather than deep, and the midship sectional area is described as firm, rather than full or easy.

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Appendix D Maritime Archaeology Conferences

1977 ISBSA 1 - Sources and Techniques in Boat Archaeology

In 1976 a conference titled **Sources and Techniques in Boat Archaeology** (McGrail 1977a) was held at Greenwich, which was to become the triennial International Symposium on Boat and Ship Archaeology (ISBSA), and consisted of an opening address by David Wilson, Wright setting the scene, a session of four papers dealing with wood degradation and conservation, two papers on ethnography and living tradition, and two papers on quantitative techniques, two papers on hypothetical reconstructions, three papers on experimental archaeology, and a session on ancient boatbuilding (see McGrail 1977b; Coates 1977; Coles 1977; McGrail 1977c). A unique aspect of this conference, was the fact that following each session, a one hour discussion took place which was recorded and transcribed in the subsequent publication giving a good overview of the 'current state' of the methods and techniques in use at that time.

1979 ISBSA 2 - The archaeology of medieval ships and harbours in northern Europe

Included sessions on 'Boats and Ships', 'Harbours','Sailing Ability and Rigging', and 'Iconographic Evidence'.

1980 Woodworking techniques before AD 1500

The recording of timbers, boatbuilding techniques, their technological change and analysis of attributes, working with unseasoned oak, the tools available to the medieval boatbuilder, as well as the marks those tools made as a means to identify the tools used, examples of Roman woodworking joints, as well as evidence of carpentry from the medieval Wood Quay site in Dublin and examples of wooden medieval artefacts were all matters under discussion at a conference held in Greenwich in 1980 (see Milne 1982; McGrail and Denford 1982; Darrah 1982; Walker 1982; Hewett 1982; Weeks and McGrail 1982; Wallace 1982; Hurley 1982). In a comment made during this conference Crumlin-Pedersen suggested that we needed to record the '*information a competent model builder would need to build a model of the structure so that it is correct in all detail'* (McGrail 1982:73).

1982 ISBSA 3 Post medieval boat and ship archaeology

The third ISBSA meeting held in Stockholm included a session with three papers on the '*Wasa*', Post medieval ship archaeological projects featured four papers, six papers on iconographic and documentary evidence, three papers on aspects of Naval architecture, five papers on local craft, and reports on current ship archaeology from; three from Sweden, Norway, Denmark, United

Kingdom, Canada, Holland, France, and Poland (see Crumlin-Pedersen 1985; Reinders 1985; Rieth 1985).

1985 ISBSA 4 Local Boats

held in Porto in 1985 – mainly regional vessels

1988 ISBSA 5 Carvel Construction Technique – skeleton-first, shell-first,

Held in Amsterdam in 1988 and featured 31 papers. The focus was primarily on the historical development of vessels, and focused on the skeleton-first, shell-first discussion (see Steffy 1991; Pomey 1991; Höckmann 1991; Arnold 1991; Green 1991; Hoving 1991)

1991 ISBSA 6 Crossroads in Ancient Shipbuilding

With 39 papers used a timeline and geographical locales to subdivide sessions into Prehistoric boats and ships, Roman and migration period boats, Viking and medieval ships of the North and East, Medieval ships of the West, Antique and later ships of the South, ships of the 15th and 16th centuries, local craft in Europe, local craft in America, naval architectural aspects of ancient ships, and a miscellaneous session.

1994 ISBSA 7 Shipbuilding and the river

Featured four sessions under the headings: Neolithic shipbuilding and shipbuilding in modern times, Ships and maritime shipbuilding from Mediterranean antiquity to modern times, Naval ethnography: European origin of local North American craft, and recent discoveries and research. Many French papers

1997 ISBSA 8 Down the river to the sea

held in Gdansk featured a session titled 'the central and eastern European scene', a session on 'the antique world', a session titled 'technical studies and reconstructions in ship archaeology' which contains two papers on the reconstruction of the Hjortspring boat, a paper on numerical hull shape reconstructions, also reconstructions of the Kampen cog from wreck OZ36 and the Mainz 3 wreckas well as the Viks boat. Paper on reverse clinker boatbuilding tradition in India by Lucy Blue, and 'Influences on Shipbuilding Technology' by Steffy. Difficult to get access to papers

2000 ISBSA 9 Boats, Ships and Shipyards

saw a large increase with 53 papers published, sessions included: Mediterranean ships, Reconstruction of ships, The shipyards, Island boats, The galleys, North European medieval and post-medieval ships, and Integrated evidence and replicas.

A Comparison Between the Earliest Testimonies of Venetian Construction Techniques and those of the Present Day

A New Look at the Utrecht Ship

2003 ISBSA 10 Connected by the Sea

held in 2003 at Roskilde again published 51 papers and focused on the connections between the land and sea, as well as long distance seafaring connecting different cultures. A section on experimental archaeology with 11 papers, and a section on the theoretical issues in the construction of ships with nine papers. Historical, iconographic and ethnographic approaches were combined in another section, and news from regional areas were in the final two sections.

1 Experimental archaeology and ships–principles, problems and examples

2 Experimental boat archaeology: Has it a future?

3 Experimental archaeology at the Viking Ship Museum in Roskilde

4 History written in tool marks

6 Trial voyages as a method of experimental archaeology: The aspect of speed

7 An example of experimental archaeology and the construction of a full-scale research model of the Cavalière ship's hull

9 The construction and trials of a half-scale model of the Early Bronze Age ship, Ferriby 1, to assess the capability of the full-size ship

10 The value of experimental archaeology for reconstructing ancient seafaring

16 Geometric rules in early medieval ships: Evidence from the Bozburun and Serçe LimanÏ vessels

18 Ship design in Holland in the eighteenth century

31 Early cogs, Jutland boatbuilders, and the connection between East and West before AD 1250

2006 ISBSA 11 Between the seas

held in Mainz in 2006, and published 54 papers, sessions included News from The Mediterranean, News from The Northern Seas, Inland New, Inland Navigation and Its Vessels, Research Methods, Interaction Inland-Sea, and Ship Construction.

Aspects of the Analysis of Structure and Strength of Pre-Historic Watercraft

The origin of the Clinker Hull construction. A technological intercourse of European dimension

Tracing technology: the material culture of maritime technology in the ancient Mediterranean and contemporary Indian Ocean

Two recent finds of medieval shipwrecks in the North of Germany

2009 ISBSA 12 Between Continents

held in Istanbul published 47 papers and began with two sessions covering News from the Mediterranean, and news from Northern Europe, followed by a section on the collection of shipwrecks discovered at Yenikapi, a section on Black Sea ships and seafaring was followed by a session on Ottoman shipbuilding. The final three sessions were on Ship construction, Experimental archaeology and Research methods.

Experimental Archaeology

36 Sea Stallion from Glendalough: Testing the Hypothesis

37 Travel Speed in the Viking Age: Results of Trial Voyages with Reconstructed Ship Finds

38 Waterways from the Varangians to the Greeks, Some results of experimental study on Medieval Navigation

39. Reconstruction and Sailing Performance of an Ancient Egyptian Ship

40 The jewel of Muscat Reconstructing a ninth century sewn-plank boat

Research Methods:

42 Development of an adaptive method for the rescue of 15 shipwrecks from a construction site in Oslo Harbour: need for speed

43 Recent Advances in Post-Excavation Documentation: Roskilde Method

44 Three-Dimensional Recording and Hull Form Modelling of the Newport (Wales) Medieval Ship

46 Hypothetical reconstruction of the Dramont E Shipwreck

47 Reconstruction of the Oseberg ship: evaluation of the hull form

2012 ISBSA 13 Ships and Maritime Landscapes

held in Amsterdam published a record 86 papers, 27 papers dealing with maritime landscapes, 5 papers on the subject of Regional watercraft, 5 papers on the subject of Design, 11 papers on the subject of Construction and Typology, 4 papers on Material applications, 3 papers on outfitting and propulsion, 5 papers on Reconstruction, and 26 papers on Current Research.

Construction and Typology

28. Connecting maritime landscapes. Or early modern news from two former 'Baltic Cogs'(Mecklenburg-West Pomerania, Germany) (Belasus 2017)

38. The Nydam ship finds (Denmark) and the crystallization of North European shipbuilding tradition during the Roman Iron Age

41 Transport with class. The large Nordic cargo ship from Karschau near Schleswig (Germany)

45. The medieval Utrecht ship type. Blending boatbuilding traditions in the cultural landscape of Europe's early medieval Migration Period

46. The devil is in the detail. The dilemma with classification and typology (Schweitzer 2017)

Reconstruction

11. Physical and digital modelling of the Newport medieval ship original hull form (England) (Jones et al. 2017)

22. The shipwreck (EP1-Canche) of a fluvial-maritime coaster of the first half of the 15th century from Beutin (Pas-de-Calais, France). Its nautical environment and functional context (Rieth 2017).

56 Emergency recording (October 2004-April 2005) of the 'barque' Neptune (Geneva, Switzerland)

57 3D Survey of the Archaic ship model H90 from Samos (Greece)

58. The Roskilde 6 ship (Denmark). Reconstructing the longest warship find of the Viking Age

59. Reconstructing the 15th-century Aber Wrac'h 1 ship (Brest, France)

60. The Arles-Rhône 3 project (Arles, France). From the excavation and raising of a Gallo-Roman barge to its documentation and 3D-modelling

Current Research

71.'The Ghost Ship'(Gotska Sandön Island, Sweden). Deep-water archaeology in the Baltic Sea

72. The Angra D wreck (Azores, Portugal). Study and reconstruction of an Iberian ship

74. Tracing 'The Ghost Ship' (Sweden). Can the hoekman reveal her construction date and origin?

77 The Dor 2006 shipwreck (Haifa, Israel). Construction details and tradition

78. The Phanagoria shipwreck (Taman Bay, Russia). First attempt at its identification

80 The Protis project (Marseilles, France). The construction of a sailing replica of an Archaic Greek boat

85 Numerous shipwrecks found in the Danish sector of the Nord Stream offshore gas pipeline (Baltic Sea)

86 A cog-like cargo vessel in the IJssel river near Kampen (the Netherlands)

2015 ISBSA 14 Baltic and Beyond

returned once again to Gdansk, Poland and published a total of 43 papers. The sessions were subdivided into: Ships and Ship finds from the Baltic; Maritime Landscapes and Harbour Installations; Recent discoveries of Remarkable Ship Finds or Significant Sources; Research Methods; Studies in ship construction; Experimental Archaeology; and Bark, Skin and Logboats.

Research Methods:

Block Models: change and control in early eighteenth century Royal Naval shipbuilding in Britain

22. 3D Laser-Scanning of a Mid-20th Century Basque Fishing Vessel: the Antxustegi, a model for the digital recording the Basque traditional fleet

23. The Accuracy of the Tonnage Formula, and the Correcting Coefficient

24. The Testing and Analysis of Hypothetical Ship Reconstructions

25. Early Cogs, at Home and Abroad

STUDIES IN SHIP CONSTRUCTION

27 A Missing Link in a Period of Change? Preliminary results of shipwreck U34 in Flevoland, the Netherlands

28. The EP1-Epagnette Wreck of the Mid-18th Century: an inland "flat-bottom" boat of the River Somme, France

29. Repairs on an Ancient Hull: direct evidence of bow section reconstruction from the Roman wreck of Marausa

Experimental Nautical Archaeology

30. Ships, Shot and Splinters: the effect of 17th-century naval ordnance on ship structure

31. The Prôtis Project: the Gyptis sailing trials

32. Building War Fleets: investigating resource management in late Viking Age Denmark

Posters

39. The Problems Involved in Reconstruction of the Original Hull Shape of a 14th-Century Venetian Galley

Appendix E Coefficients of Form

Descriptive use of coefficients

Coefficients of form are dimensionless descriptions of hull-form which allow comparison with other vessels independent of differences in size. The use of form coefficients as an analytical tool has been in use for at least two decades (McGrail 1987, 193-203). The data is relative in most cases and it is important to calculate the data, so it is at hand for any further studies. The nature of the archaeological find must also be considered. Obvious damage, shrinkage and distortions due to drying must be taken into account.

Slenderness coefficient (CS)

McGrail (1987, 194, 197) defines this as what is commonly known as the length to breadth ratio (L/B) as discussed by McKee (1983, 79, 81). It is a definition of the overall narrowness of the boat, a narrow boat having a coefficient 3.75 or higher. A high slenderness coefficient, 5 or more, is also indicative of high-speed potential (Rawson and Tupper 1976, 572). This last point is not necessarily applicable to all vessels some of which are man powered. A low slenderness coefficient is not indicative of directional stability. Directional stability is also reliant on the depth and area of the immersed body.

Beam/draught coefficient (B/D)

This is a definition of the general volume of the vessel. Boats with a low B/D can be considered as deep (Mckee 1983), or volume dominated (McGrail 1976). A high B/D means the boat is shallow and not volume dominated. Deep boats are good for carrying bulky cargos, and on the whole have good transverse stability and relative manoeuvrability.

Block coefficient (CB)

This is the ratio of the immersed volume of the hull to that of a rectangular block whose sides are equal to the extreme breadth, the mean draught and the length of the hull. The larger the value the greater the area of the hull that occupies the rectangular block. It can therefore be used to compare general hull shapes, eg a large oil tanker would have a CB of 0.88 and a racing yacht one of 0.34 (Barnaby 1969, 19). The oil tanker, which is slab-sided for most of its length, made more use of the area available within the block then the racing yacht which has fine lines fore and aft, and is not slab-sided. It is also generally accepted that a low value CB, less than 0.65, indicates good speed potential. This is relative to the size of the vessel. The wave-making resistance of a displacement vessel means longer vessels naturally have a higher speed potential despite their shape (Marchaj 1964, 248).

Prismatic coefficient (CP)

The CP is the ratio of the immersed volume of the area of the midship section multiplied by the waterline length. It gives an impression of how the hull-form fills the outline formed by its maximum sectional area projected over its length. In general, it exceeds 0.55 (Barnaby 1969, 25).

Coefficient of fineness of water plane (CW)

This is the ratio between the area of the water plane (waterline length x breadth) and a rectangle formed by the waterline length and breadth. A figure of 0.7 or less indicates a fine vessel whilst one of 0.9 indicates a slab-sided vessel. The CW of most pre-modern vessels is low compared to a modern-day equivalent (McGrail 1998, 197). This is due to the nature and restrictions of the method, material and level of technology used in the construction of such vessels.

Displacement volume

This is the volume of water displaced by the immersed volume of the vessel. It is otherwise known as the vessel's displacement. It can be calculated as a true working displacement or for the sake of study be standardised at the point when the waterline is 60% of the total depth of the same vessel. It is an indicator of relative size and load carrying potential.

Volumetric coefficient (CV)

This is the ratio between displacement and the cube of the waterline length. It has been shown that a vessel with sufficiently low CV it can be driven at relatively high speeds without excessive squat or wave making (McGrail 1978.137). This is not planning. It is also a useful indicator between deep draughted vessels and shallow draughted vessels.

Seaworthiness coefficient

A means by which the relative seaworthiness of a flat-bottomed vessel can be calculated. It is based on the premise that flared sides increase the transverse stability and buoyancy of a vessel the deeper she sits in the water. The effect of free-surface bilge water on transverse stability is lessened, as it is less than that of the flotation plane (McGrail 1987, 194). It is therefore important to the safety of a flat-bottomed vessel. The coefficient is a measurement of the flare of the sides of the vessel compared to the breadth of the bottom of the vessel.

Midship section coefficient

Coefficients of Form

The ratio of the midship section area to the area of a rectangle whose sides are equal to maximum breadth and draught. It usually exceeds 0.85 for ships other than yachts, the fin keels of which distort the overall rectangle. A low value, less than 0.85, indicates good speed potential (McGrail 1987, 197).

Log conversion percentage

A percentage of timber removed from the parent log in construction and therefore a relative indication of that process. It is the volume of the parent log, minus the remaining timber, divide by the volume of the parent log, the resultant of which multiplied by 10 (McGrail 1987, 311-12). A relatively high figure would suggest the log boat has excess timber whilst a lower percentage suggest a log boat has had more timber removed thus suggesting that the wood conversion phase was more effective. This can be used for vessels other than log boats.

Load space coefficient

A coefficient which compares the load carrying volume of the log boat with the overall volume of the parent log. It is a measure of the overall efficiency of construction in terms of load carrying potential (McGrail 1987, 10)

Centre of buoyancy

The fore and aft location where the buoyant forces acting on the hull have no rotational force. It expressed here as a percentage between the fore and aft most extent of the waterline.

Centre of floatation

The geometric centre of the area enclosed by the vessel's waterline. It is important for defining pitching motions.

Midsection coefficient

A ratio of the largest immersed area of any section of the hull to the product of the waterline beam and draught.

Displacement to length coefficient

A coefficient which gives an idea of the power/sail area required for the vessel and roughly how comfortable it would be. For sail power the following guide can be used:

Light Multi - Hulls 40 - 50
Ultra - Light Racers 100 - 150
Light Racers 150 - 200
Light Cruisers & Offshore Racers 200 - 275

Coefficients of Form

Medium Weight Cruisers 275 - 325
Heavy Cruisers 325 – 400

Power ratio

Light Displacement 75 - 200
Medium Displacement 200 – 300
Heavy Displacement 300 - 400

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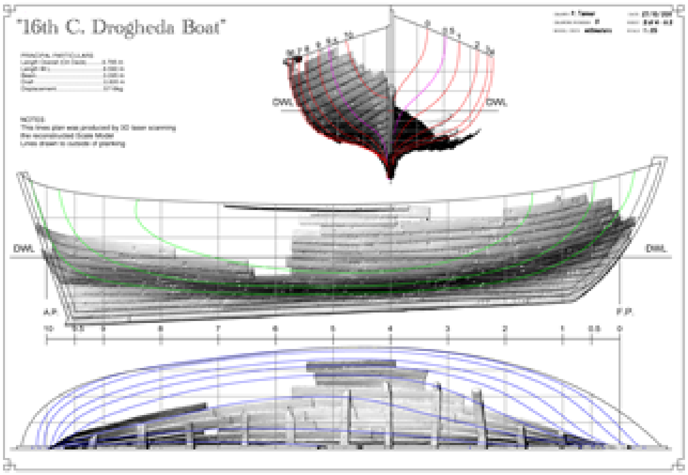
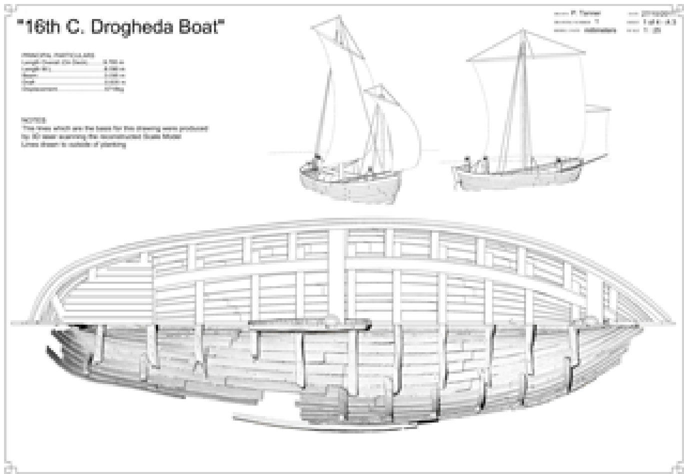
Appendix F Drogheda Boat





16th century Drogheda boat

Digital reconstruction and hydrostatic analysis

ABSTRACT

This is the draft version of chapter 4.6 of the Drogheda boat book.

Submitted to the Underwater Archaeology Unit, National Monuments Service, of the Department of Culture, Heritage and the Gaeltacht, Ireland.

The submission was made in October 2012.

Expected publication date: Tomorrow

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F.1 Introduction

The aim in reconstructing the hull shape is to generate a floating hypothesis for the vessel in order to ascertain linesplans and hydrostatic data such as displacement, sailing characteristics and cargo carrying capabilities.

To this end the recommendations as set out in “Principles for the Reconstruction of Ancient Boat Structures”(Crumlin-Pedersen and McGrail, 2006) have been followed and adhered to. These recommendations fall under five categories:

1. Deformation and its effects on the hull shape
2. The impact of modern naval architectural standards
3. The introduction of alien elements to complete the hull
4. The consideration of propulsion, steering and seaworthiness
5. The concept of minimum reconstruction

1 The issues of deformation have been dealt with already in chapter 4.6.2 whereby a reconstructed 1:10 scale model of the vessel was created from the “as-found” wreck using solid modelling and selective laser sintering techniques (see Plate 1).

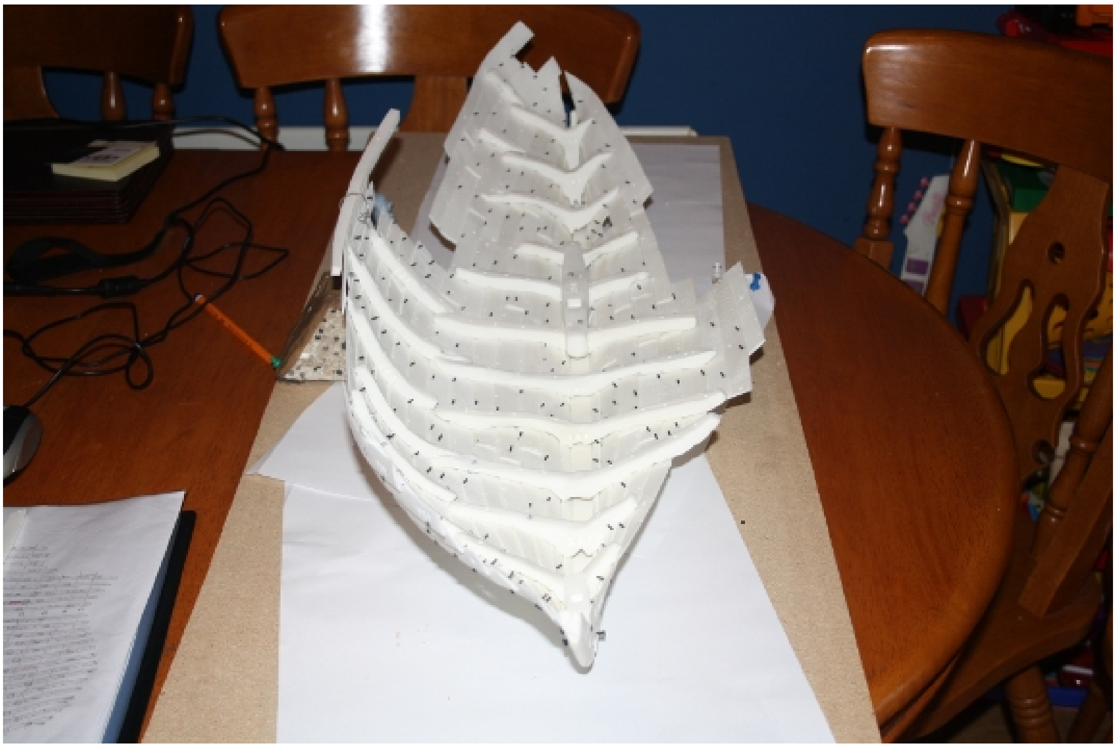


Plate 1: Reconstructed model 1:10 scale of “as-found” wreck. (P. Tanner)

This scale model represents a unique object in that it is neither the original as built vessel nor the vessel shape at time of sinking but a "post deposition" shape state (N. Nayling pers comm. 22/08/2012).

After several attempts at examining and measuring this physical model to determine shape, and distortion if any, a decision was made to "return" to the digital world to progress further (H Schweitzer pers comm. 07/2010). This physical scale model would then be examined for any twist or hogging and the missing portions "repaired" in order to produce a reconstructed hull shape.

2 With regard to modern naval architectural standards a conscious decision was made to try recreating the entire vessel as much as practicable based on recovered materials and contemporary iconography rather than what is considered “normal practice” by modern boatbuilding techniques.

> "a naval architect developing drawings for a ship or a boat will inevitably apply a rectilinear system of sections in order to 'cut up' the hull into manageable slices which can be represented in two-dimensional drawings."(Crumlin-Pedersen and McGrail, 2006,54)

The methodology used here does exactly the opposite in treating the object as a boat rather than separate slices or sections.

3 With regard to introducing alien elements to complete the hull again the recommendations have been adhered to, and the reconstructed hull has been mostly created by mirroring existing parts, or extrapolation from the preserved majority of the hull, any elements added to the hull for which no distinctive evidence has been found are in all cases clearly identified and reasons or explanations for their inclusion are given.

4 Steering, propulsion and seaworthiness will be dealt with later in this chapter.

5 With regard to the concept of minimum reconstruction this term is now used to describe one or more (partial) reconstructions based on the excavated evidence - as depicted in a 'torso/as-found' scale model or drawing in which allowances have been made for distortion, displacement and shrinkage- the proposed aim is to recreate a floating hypothesis and if possible, based on the recovered mast steps, an estimate of possible rigging and sail plan.

F.2 Intended Output

The intention is to create a traditional yacht lines plan in a two dimensional format, see Figure 1 together with hydrostatic data and form coefficients, a general arrangement or construction drawing where possible and visualisations of a completed vessel.

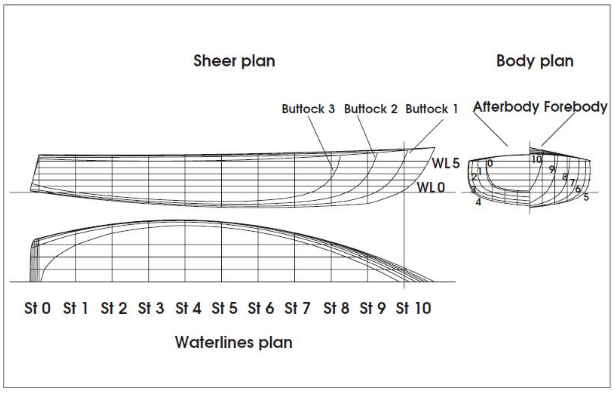


Figure 1 Typical Lines Plan

Lines Plan

In order for the plans to be useful for comparison purposes, the lines plan should be generated following standard conventions.

1. A Half Breadth or Plan View showing waterlines and deck edge with buttock spacing
2. A Sheer Plan or Profile View showing the buttocks, centreline profile and waterline spacing
3. Sections or Body plan with the forward sections on one side, usually the right and the after sections on the other side, again showing buttock and waterline spacing.

– Waterlines are lines parallel to the water surface
– Buttocks are lines parallel to the longitudinal axis and perpendicular to the waterlines
– Sections are parallel to the transverse axis and perpendicular to the waterlines

The normal procedure would be to divide the D.W.L.(Design or Datum Water Line) equally with station 0 at the forward end or F.P. and station 10 at the after end or A.P. This spacing is then continued to the ends of the vessel. Half stations can also be used at the fore and aft ends.

Waterlines and buttocks will normally follow traditional practice and be equi-spaced at say 12” intervals.

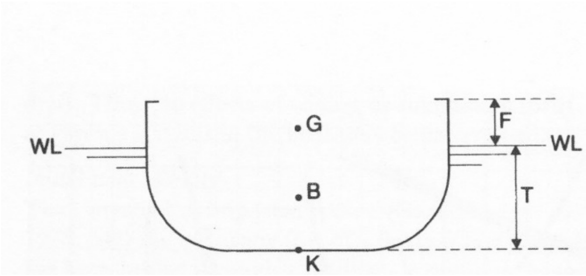
Waterlines above the D.W.L. may be double spaced to simplify the drawing and make it more legible.

Hydrostatic Data

It is important to remember that the main characteristics of a boat are: (1) its shape; (2) its weight distribution; (3) its construction; (4) its method of propulsion; and (5) its method of steering.

(1) and (2) determine its stability, (3) determines its strength, and all help to determine its performance, together with the seamanship of the master and crew. Theoretical stability and performance. The measure of the stability of a ship is its ability to right itself when heeled. (Marsden, 1993)

With regard to flotation and static stability, in order for a vessel to float it must displace a volume of water equal to its own weight. In this condition without any external influences the vessel is said to be floating in equilibrium whereby its centre of gravity "G" is located directly in line with its centre of bouyancy "B" see Figure 2.



G = centre of gravity (mass)
B = centre of bouyancy
F = Freeboard
WL = waterline
T = navigational draft
K = lowest point on hull

Figure 2 Body floating in equilibrium. (Diagram: NMM Greenwich.)

In addition other measurements such as freeboard "F", waterline "WL", navigational draft "T" and lowest point on the hull "K" can be recorded or measured.

For example a vessel which weighs (or displacement) 5700kg must therefore displace a volume of 5700 / 1025.9 (density of saltwater) = 5.56m³ and conversely a vessel which displaces 5.56m³ must weigh 5700kg. Therefore if two or more elements are known such as the underwater shape and the waterline position, the remaining variables can be calculated.

The weight of the vessel together with the longitudinal and transverse centres of gravity and buoyancy in various load states will need to be known before calculations of upright static stability can be undertaken. (McGrail 1998b,13)

The weights of displaced water at varying drafts are then plotted on a displacement curve, thereby allowing freeboard to be calculated for any loaded state.

Additional hydrostatic curves include

TPI or kg/cm tonnes per inch or centimetres per kilogram immersion plotted over a range of drafts to indicate how much a vessel will sink as loads are added.

LCB longitudinal centre of buoyancy against draft is plotted to help determine fore and aft trim or angular rotation.

Form Coefficients

In ship design it is often necessary to classify the hulls and to find relationships between forms and their properties, especially the hydrodynamic properties. The coefficients of form are the most important means of achieving this. By their definition, the coefficients of form are non-dimensional numbers.

Coefficients based on the underwater geometry of the hull may be used to give forecasts of performance (McGrail 1998b,193).

Some of the Coefficients examined later in this chapter include

Overall Dimensions

Length Overall, LOA: The length of the vessel, from forward end of stem to aft end of sternpost.
Length Extreme: The length of the vessel, including fixtures and fittings such as bowsprit and rudder
Beam Overall, BOA: The maximum beam of the vessel
Depth Overall, D: The maximum depth of the vessel, from the deepest point in the water to the highest point above the water.
Loa/Boa: The ratio of the Length Overall to the Beam Overall
Boa/D: The ratio of the Beam Overall to the Depth Overall

Waterline Dimensions
Waterline length, Lwl: The waterline length of the vessel
Waterline Beam, Bwl: The waterline beam of the vessel
Navigational Draft, T: The distance, perpendicular to the flotation plane, from the flotation plane down to the deepest point on the vessel

Lwl/Bwl: The ratio of the Waterline Length to the Waterline Beam.
Bwl/T: The ratio of the Waterline Beam to the Navigational Draft.
D/T: The ratio of the Depth Overall to the Navigational Draft

Volumetric Values
Displacement: the overall weight of the vessel, as defined in the input or calculated from the defined flotation condition.
Volume: The integrated underwater volume of the vessel
LCB: the longitudinal center of buoyancy of the resultant vessel orientation
TCB: the transverse center of buoyancy of the resultant vessel orientation
VCB: the vertical center of buoyancy of the resultant vessel orientation
Wet Area: the area of the underwater surfaces
Moment to Trim: the longitudinal moment required to trim the vessel between the fore and aft ends of the waterline.
Displ-Length Ratio: The displacement length ratio, which is always expressed in imperial units of long tons/ft^3. It is defined as (Displacement in long tons / (Length in feet/100)^3)
FB/Lwl: The ratio of LCB to LWL, measured from the forward end of LWL; a value less than 0.5 means that the LCB is forward of the midpoint of LWL.
TCB/Bwl: The ratio of the transverse center of buoyancy to the waterline beam.

Waterplane Values
Awp: the area of the waterplane of the resultant vessel orientation
LCF: the longitudinal centre of flotation of the resultant vessel orientation
TCF: the transverse centre of flotation of the resultant vessel orientation
Weight to Immerse: the weight required to sink the vessel one unit in the direction perpendicular to the equilibrium flotation plane.
FF/Lwl: The ratio of LCF to LWL, measured from the forward end of LWL; a value less than 0.5 means that the LCF is forward of the midpoint of LWL.
TCF/Bwl: The ratio of the transverse center of flotation to the waterline beam.

Sectional Parameters
Ax: the maximum underwater sectional area calculated using sections. The maximum value is interpolated from the sections, by fitting a parabola to the station of maximum sectional area and the two stations on either side of it.
Ax Location: The longitudinal location of the station of maximum area (see note on interpolation above)
Ax Location / Lwl: The ratio of Ax Location to LWL, measured from the forward end of LWL; a value less than 0.5 means that the Ax is forward of the midpoint of LWL.

Hull Form Coefficients
Cb: the block coefficient of the resultant vessel orientation due to the defined flotation condition, defined as (displaced volume / (LWL x BWL x T)), where T is the maximum navigational

Cp: the prismatic coefficient of the resultant vessel orientation, defined as (displaced volume / (LWL x Ax)), where Ax is the maximum sectional area
Cvp: the vertical prismatic coefficient of the resultant vessel orientation, defined as (displaced volume / (AWP x T)), where T is the maximum navigational draft
Cx: the maximum section coefficient of the resultant model orientation, defined as (Ax / (BWL x T)), where T is the maximum navigational draft
Cwp: the waterplane coefficient of the resultant vessel orientation, defined as (AWP / (LWL x BWL)).
Cws: the wetted surface coefficient of the resultant vessel orientation, defined as (wetted surface / SQRT(displaced volume * LWL)).

Static Stability Parameters

Zero righting arm will correspond to the heel angle at the equilibrium flotation plane.

The calculation of the righting arm allows the model to trim as it heels to maintain a true hydrostatic balance (this is true even if a Model Trim was entered to define the equilibrium flotation plane; the Model Trim is used to determine the center of gravity, which is then used as the model is heeled).

I (transverse): The transverse moment of inertia of the waterplane
I (longitudinal): The longitudinal moment of inertia of the waterplane
BMt: the transverse metacentric radius (distance from the vertical center of buoyancy to the transverse metacenter) of the resultant flotation condition
BMl: the longitudinal metacentric radius (distance from the vertical center of buoyancy to the longitudinal metacenter) of the resultant flotation condition
GMt: the transverse metacentric height (distance from the vertical center of gravity to the transverse metacenter) of the resultant flotation condition
GMl: the longitudinal metacentric height (distance from the vertical center of gravity to the longitudinal metacenter) of the resultant flotation condition
Mt: the height of the transverse metacenter in the resultant flotation condition, measured from the equilibrium flotation plane
Ml: the height of the longitudinal metacenter in the resultant flotation condition, measured from the equilibrium flotation plane

Construction Plans

The intention is to create a construction drawing of the reconstructed vessel showing the main structural elements in plan, profile and section views with the parts clearly coded to indicate the following:
recovered material coloured brown.
mirrored elements coloured grey.
parts which have been extrapolated from the preserved majority of the hull coloured blue.
interpreted items coloured green.
introduced items coloured red.

F.3 Recording the Hull Shape

3D Laser Scanning

As the component parts were recorded after lifting and prior to conservation, reassembled into the physical scale model and aligned using their original recorded fastenings, this created an accurate model of the post deposition vessel shape using only the recovered materials. (see Plate 1)

The next stage in analysing the overall vessel is to record this reassembled hull shape and generate lines plans and hydrostatic data. As the scale model is still relatively delicate, especially in the areas such as unfastened strake ends, touch probing would not provide as accurate a recording as a non-contact form of measurement such as 3D laser scanning.

The reconstructed 1:10 scale model was laser scanned using a Faro Platinum Arm and Laser-line Probe to capture a 3 dimensional point cloud (see Plate 2)

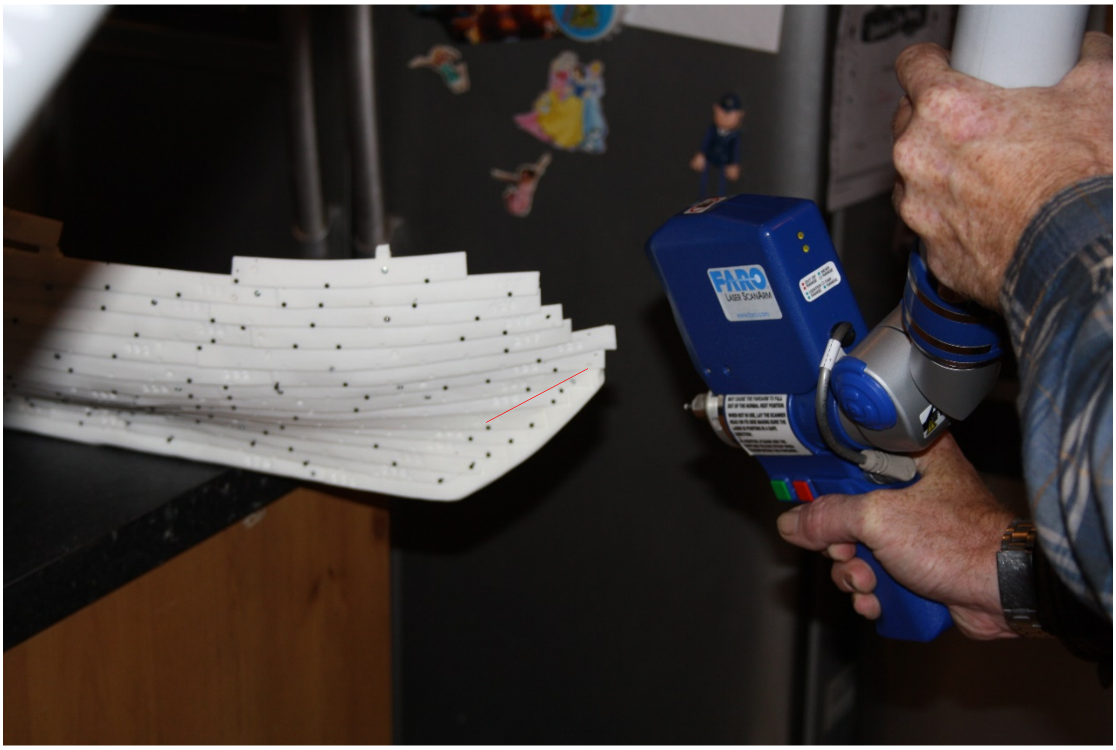


Plate 2: 3D Laser scanning the reconstructed scale model (H. Schweitzer)

The point cloud data for the Drogheda boat consists of 46.63 million points recorded at an accuracy of ± 0.076mm (see Figure 3).

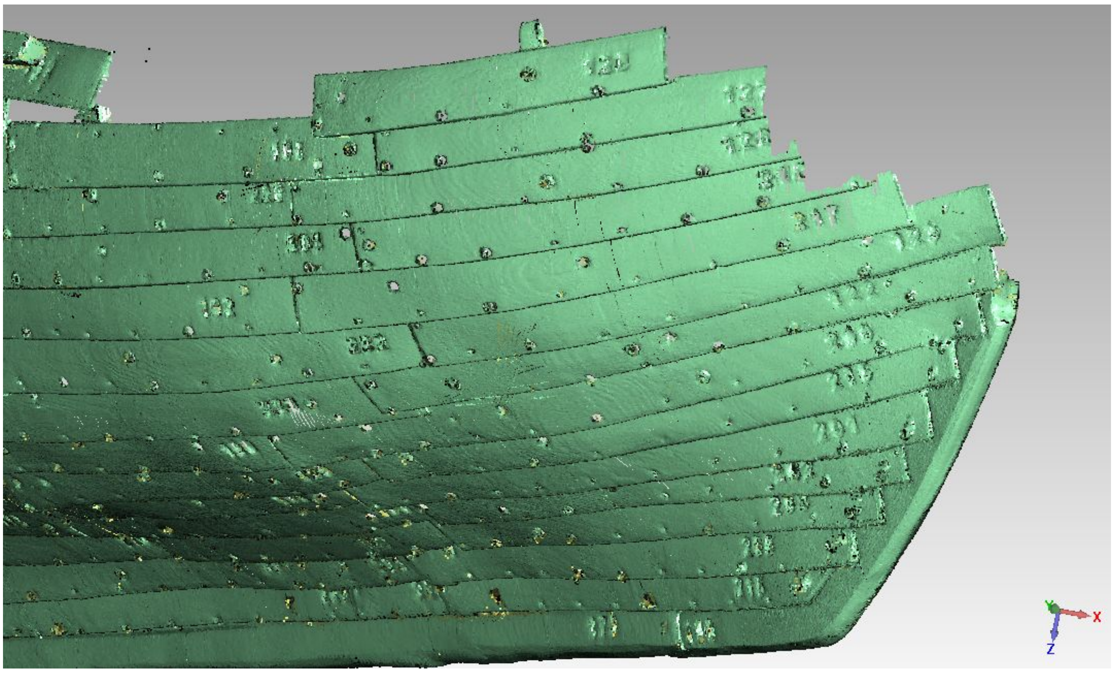


Figure 3 scanned 3D Point Cloud Data (P. Tanner)

Processing the scan data

The point cloud is refined using Geomagic Studio software to create a useable surface model of the recorded data. This is done by fitting a polygon mesh to the underlying point cloud data, followed by a smooth NURB (non-uniform rational b-splines) surface fitted to the polygon mesh.

This is where the current methodology differs from others to date whereby the recorded polygon mesh data has been used to extract a profile and longitudinal sections, plan sections and cross sections and group these together as buttocks, waterlines and stations to become a lines plan (Moreton et al., 2000,466).

In this process, the scanned data is used to generate an exact replica, computer model of the item scanned, in this instance a boat hull, and continues to treat it as such.

At all stages of this process the deviation between the surfaces and the original scanned point cloud data is checked to remain within the desired 0.080mm tolerances see Figure 4

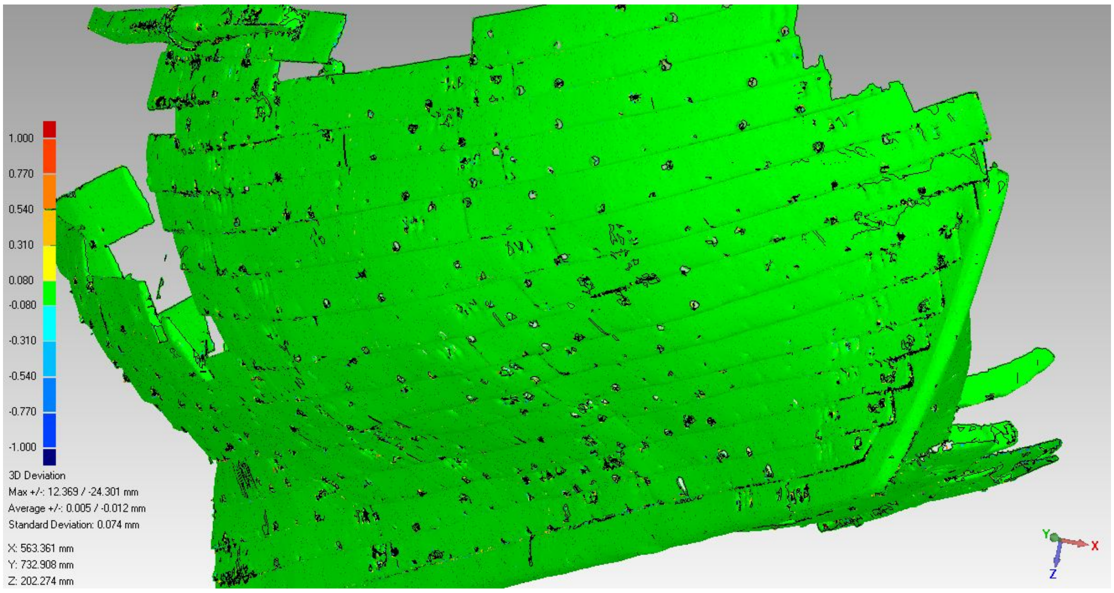


Figure 4 Checking deviation between generated surfaces and scanned data (P. Tanner)

By maintaining a tolerance of 0.080mm (80 microns) the resultant full size vessel measurements will be accurate to within 0.8mm, twice as accurate as traditional naval architecture surveys for taking linesplan which were typically carried out to $^{1}/_{16}$ inch (1.58 mm).

Once the scanned model has been processed, the polygon mesh and NURBs surface fitted, it is exported to Rhino and the required lines plan, main and additional dimensions, hydrostatic data and form coefficients can be extracted.

In the case of the Drogheda boat the design water line (DWL) was not clearly known, and to begin with, the model was orientated along its keel and a basic lines plan generated as a starting reference point (see Figure 5).

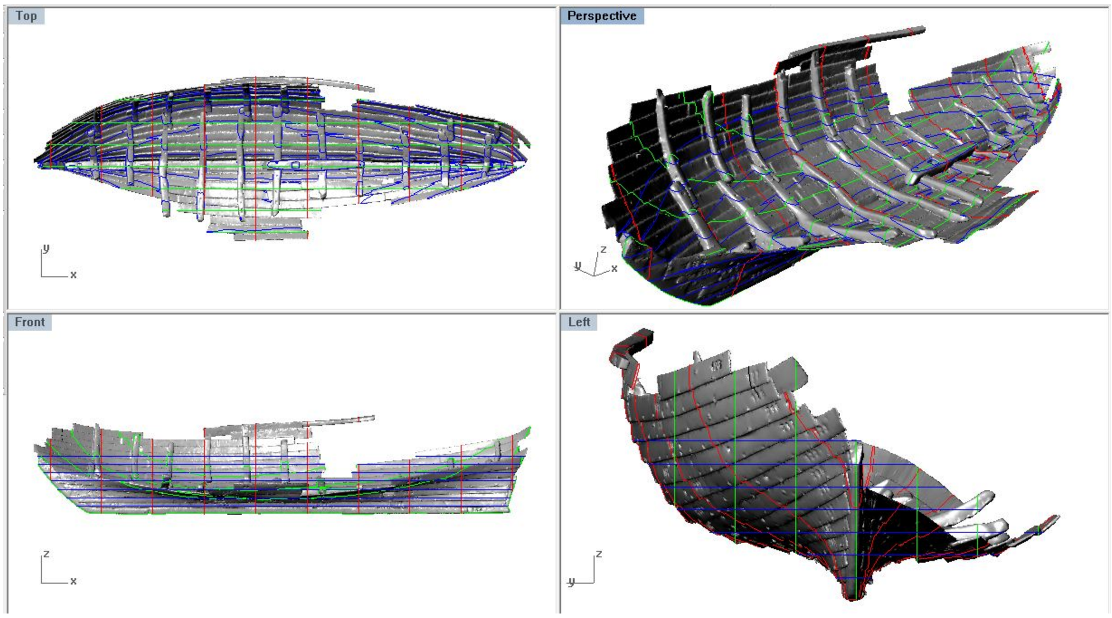


Figure 5 Basic lines plan with model aligned along its Keel. (P. Tanner)

As the model is incomplete and there is no datum, this set of lines plans is of little value and is created solely to record the shape and form of the reconstructed model. Obviously as large portions were not recovered, particularly the port side and the upper stem and sternpost, the reconstructed model was unsuitable for hydrostatic analysis at this stage.
In order to recreate a floating hypothesis, the model was re-scaled back to full size, by a factor of 10 in this case, and the process of reconstructing the hull commenced.

F.4 Reconstructing the Hull Shape

At this stage the remodelled vessel still did not represent a complete vessel so the missing parts would need to be interpolated and recreated.
These can be broken down into three main categories:

1 parts which are critical to creating a watertight hull which can function properly in the water.

2 items which would be considered necessary for the construction of the vessel, where some evidence of their existence remains even though the component part was not recovered.

3 items which were more than likely part of the complete vessel but no evidence of their existence was recovered.

Items falling into the first category include the stem extended up to gunwale level, the sternpost extended up to gunwale level and the remainder of the hull planking up to and including the gunwale.

The first stage was to check the computer model as recorded during 3D scanning for fairness as the re-scaling will have increased and errors or unfair regions by a factor of 10.
Fair is a term that is used whenever a boat is built. When wood is bent or curved or cut, or a line drawn, a boat builder must be concerned about fairness. A "fair curve" or line is one that is as smooth as it can be as it follows the path it must take around the hull of a boat. A fair line is free of extraneous bumps or hollows, and an unfair line needs to be faired, or smoothed out.

The recovered materials included 7 complete hull strakes and partial strakes up to a 15th strake on the starboard side (see Plate 1).

The top of the 15th strake was used as a provisional gunwale level and a height for the stem was estimated by extending the lines of each plank run, these lines were found by taking a series of sections through the recovered planking and again using fair curves in order to project the run of each strake to a point where it would naturally meet the stem. (see Figure 6)

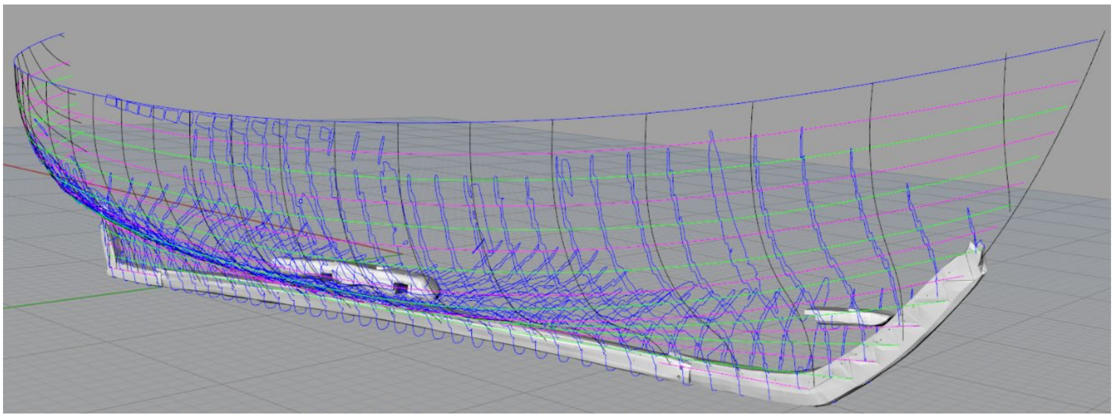


Figure 6 showing sections through planking from reconstructed model (P Tanner)

A curve representing the existing portion of the stem was created and extended as a fair curve to represent the missing portion (see Figure 7).

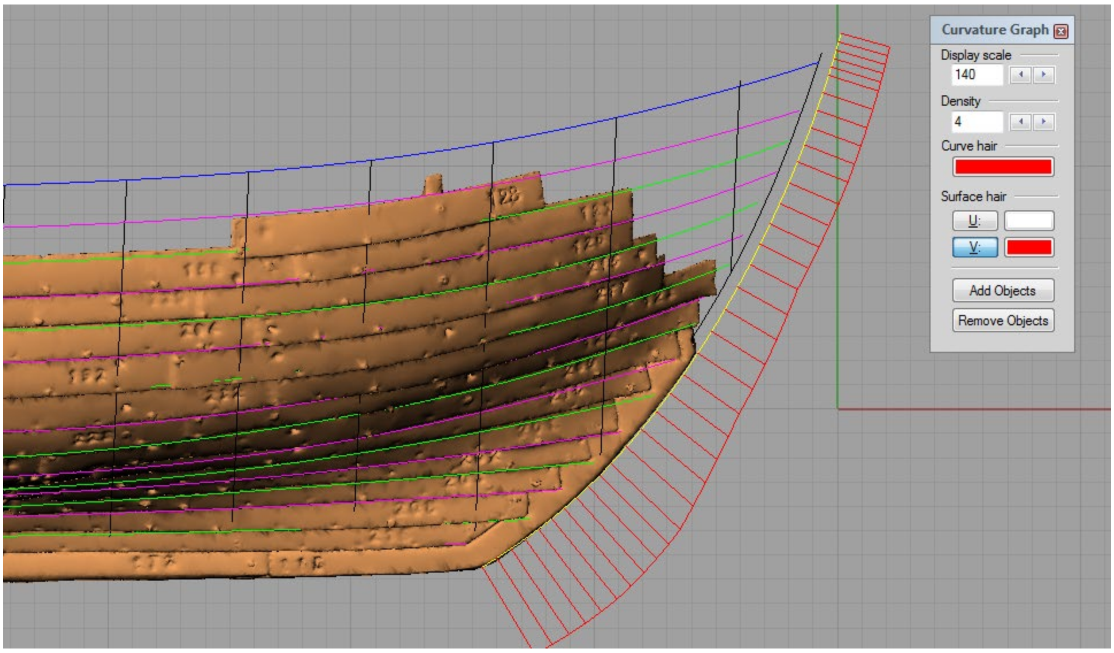
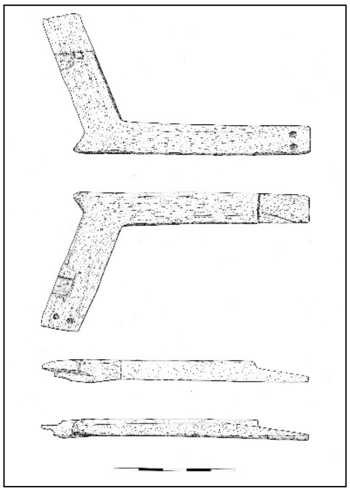


Figure 7 Showing stem curve extended to extrapolate missing stem (P. Tanner)



The sternpost was interpolated by examining the recovered sternhook (see Figure 8) and in particular the scarf at the top section of the stern hook which

indicated that the missing sternpost extended in a straight line continuing from the top of the sternhook up to gunwale level.

Figure 8 The stern hook (J. Ryan)

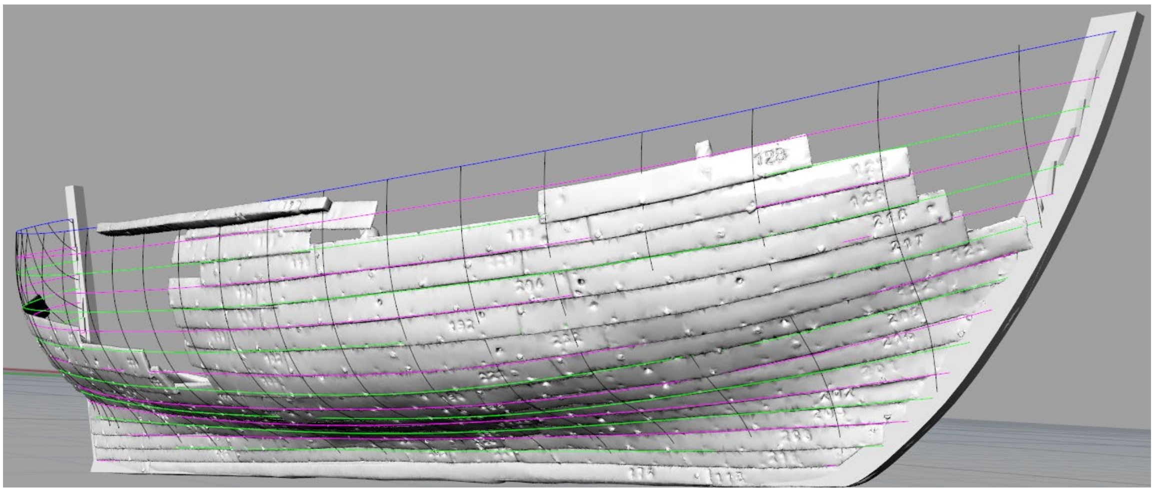


Figure 9 New keel, stem and stern post created (P. Tanner)

Figure 9 shows the newly created keel, stem and sternpost and Figure 10 shows the reconstructed curves used to interpolate completed vessel.

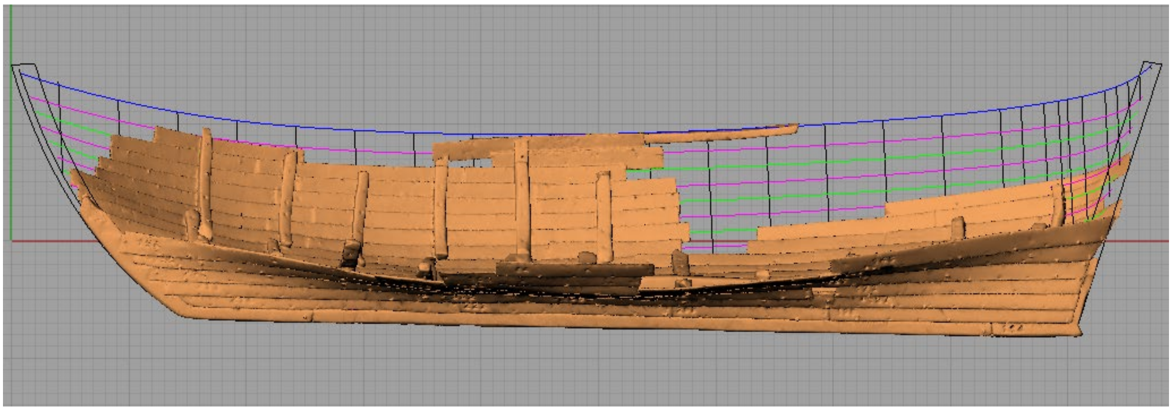


Figure 10 reconstructed curves used to interpolate completed vessel (P. Tanner)

The faired surface was then overlaid on the scanned reconstructed model to determine variations between the actual vessel and a faired surface (see Figure 11).

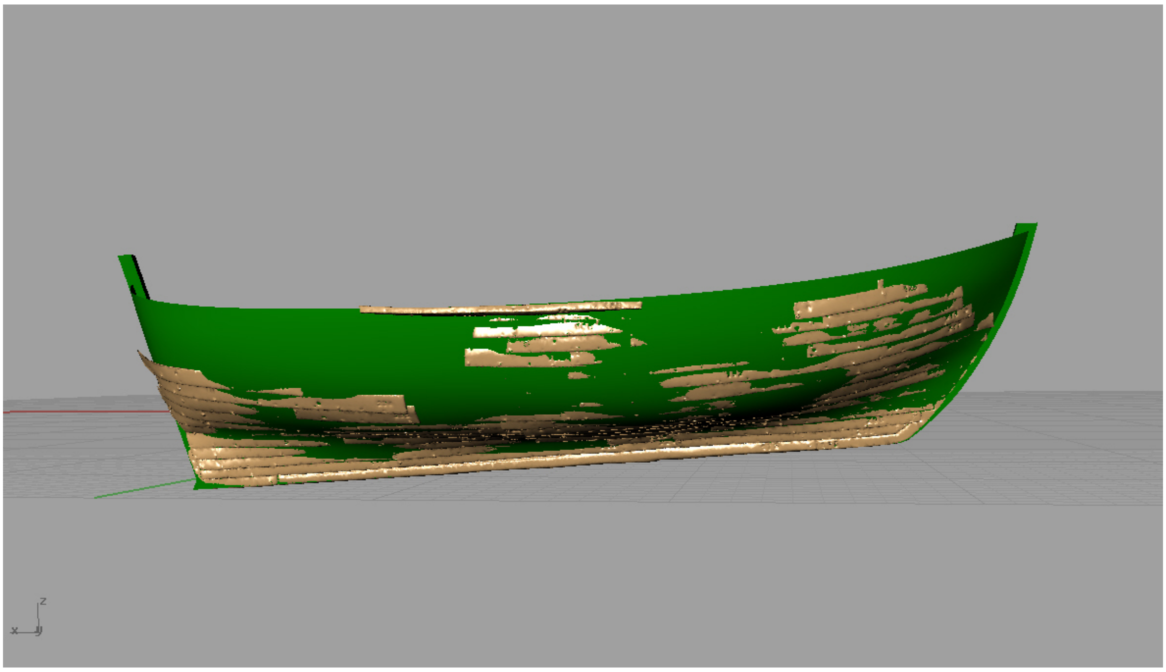


Figure 11 faired surface overlaid on scanned model (P Tanner)

At this stage each curve and surface was checked and re-faired using the curvature graph feature in Rhino (see Figure 12).

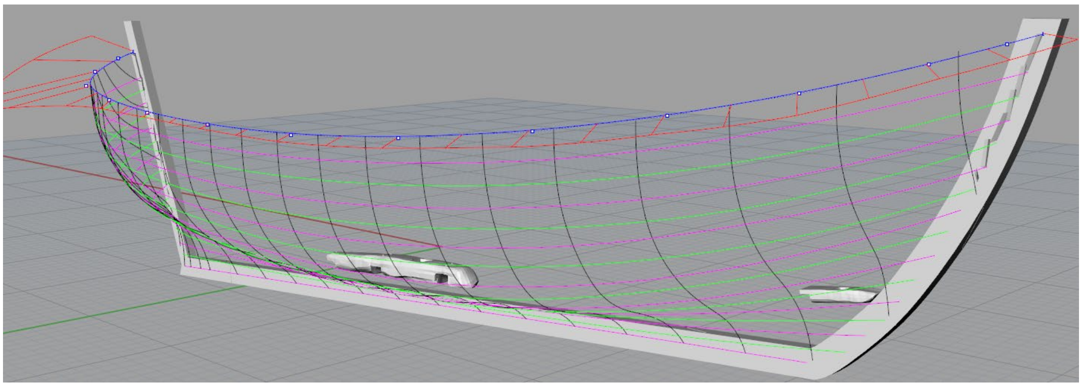


Figure 12 Sheer line curve checked using curvature graph (P. Tanner)

This process showed up several areas of unfairness or deformation in the reconstructed scale model and each area was closely examined for reasons prior to correcting or repairing, such as the port side hull planking mid-ships appeared to have sagged considerably (see Figure 13) but was more than likely as a result of a crack in frame No. 5.

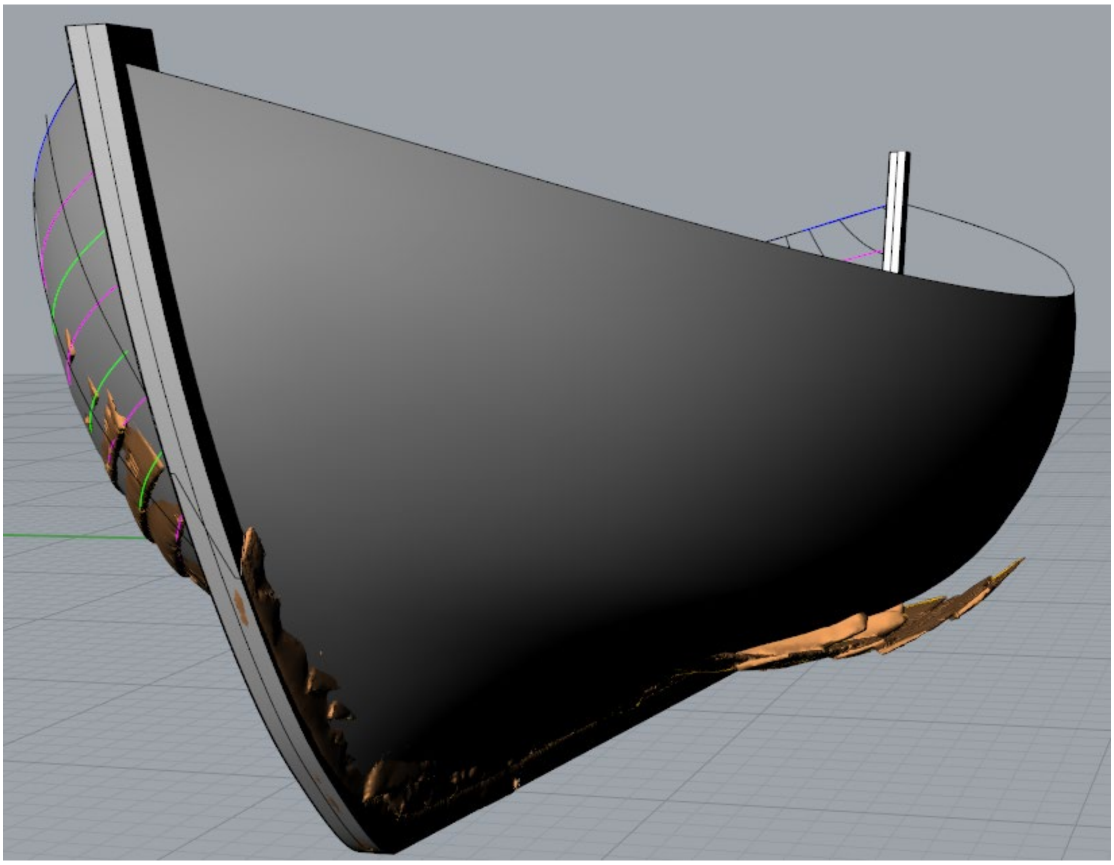


Figure 13 distortion to port side mid-ship (P. Tanner)

These localised regions of unfairness can be caused by many different factors including factors such as:

A slight difference in thickness or stiffness of an individual plank would create a hard spot (or hump) in an otherwise fair curvature run of a plank.

A badly made or fitted frame could cause a localised hollow by pulling in the previously fair curvature of the hull planking when fastened tightly.

Similarly, slight variations in the model rebuilding such as a screw being over tightened could cause a localised distortion.
Additionally, a working boat over the period of its lifetime will inevitably change shape slightly as a result of damage or wear and tear.

Once the existing surfaces were checked and faired these were then mirrored in order to create a more complete hull shape.

The concept of 'minimum reconstruction' as set out in "Principles for the reconstruction of ancient boat structures" (Crumlin-Pedersen and McGrail, 2006)" recommends that where considerable portions of the original vessel are excavated, as in this case, and full reconstruction appears to be a realistic aim, the problem is to determine one or more minimalistic ways to complete the hull and point to the most likely means of propulsion and steering for the vessel.

At this point the process of recreating the vessel up to the level of the 15th strake was completed, which provides a basic hull shape for the reconstructed vessel. In order to continue to examine the vessel and proceed to a full reconstruction, it will be necessary to establish how the vessel was intended to or actually, floated.

In order to establish a floatation condition for the vessel, three key facts are required, vessel hull shape in order to establish the centre of buoyancy B, vessel centre of gravity G to establish floatation trim and vessel weight in order to establish displacement.

We have the vessel hull shape based on the reconstruction methods already carried out, but a vessel weight and centre of gravity has not yet been established.

The most accurate method of determining the weight of a vessel is to weigh it in air and then carry out an inclining test to establish the position of G (McKEE, 1974,11-13), the inclining test is considered by many as the most accurate method of determining G and is still used today when recalculating for modifications or additional equipment added to an existing vessel.

In order to weigh the vessel and perform an inclining test a complete rebuilt vessel would be required, as this is not practical at this point in time, and the fact that we are still examining various hypothetical reconstructions an alternative approach will be used.

F.5 Establishing floatation condition

In the case of scanned vessels the 3D model is effectively free in space and we need to define how it is intended to float in order to go any further. As all the lines in a lines plan are related to the datum waterline this DWL must first be established on the 3 dimensional model.
This can be established by using known measurements such as waterline length and draft, or from actual markings such as painted or scribed lines on the original.

If the D.W.L. is unknown the model will need to be assessed to establish a floatation plane. The most accurate way to do this is to perform a weight analysis on the vessel.

In order to establish the D.W.L. each constituent part of the vessel is accurately modelled using Rhino solid modelling techniques and using the Orca Marine plug-in for Rhino a material is assigned to each part (see Figure 14).

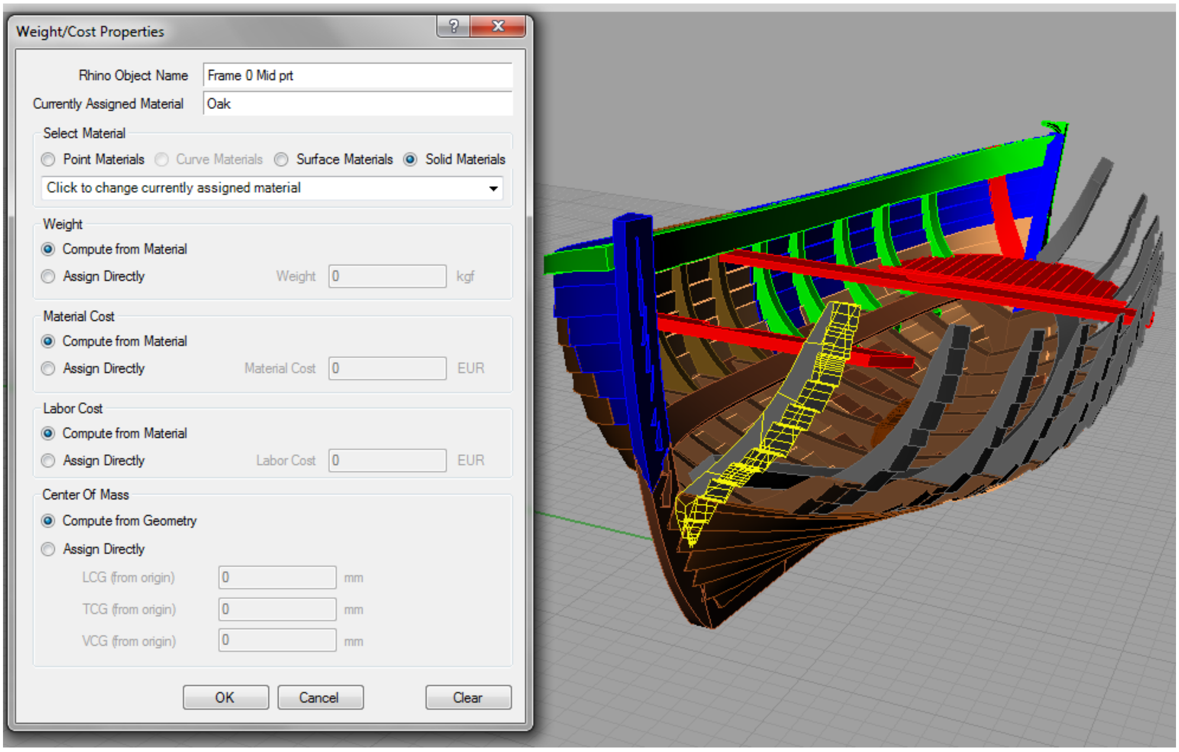


Figure 14 weights assigned to each constituent part (P. Tanner)

Orca Marine can use each component parts dimensions and the material assigned, to calculate the weight, longitudinal, transverse and vertical centre of gravity. When all of these constituent parts are combined an overall weight, centre of floatation and centre of buoyancy for the entire vessel is calculated.

With regard to the materials assigned for each element, as the density of timber varies significantly depending on various factors such as moisture content etc., an average density has been used in most cases. For example, Oak can vary between 600 and 900 kg per m^3, and in this case 750kg/m^3 has been used. Similarly, the barrels were calculated at between 193.5 and 245.65kg's so an average of 219.5 kg has been used.

The iron nails and roves were not individually modelled in the boat but have been included in the weight calculations on the basis of approx 40 nails per strake giving a total of 1360 nails at an approx total weight of 227kg. The treennails have not been modelled as these are basically a wooden dowel fitted to a pre drilled hole and would have no effect on the overall weight.

Once this floatation plane has been established it is then possible to create an accurate set of lines plans and Hydrostatic data for the rebuilt vessel.
As the floatation plane is calculated from the total weight, it is important to reconstruct as much of the overall vessel as possible by solid modelling each of the constituent parts and mirroring where necessary.

To begin with the backbone (keel, stem and sternpost) were modelled based on the recovered artefacts with the stem and sternposts extended up to sheerstrake height (see Figure 15).

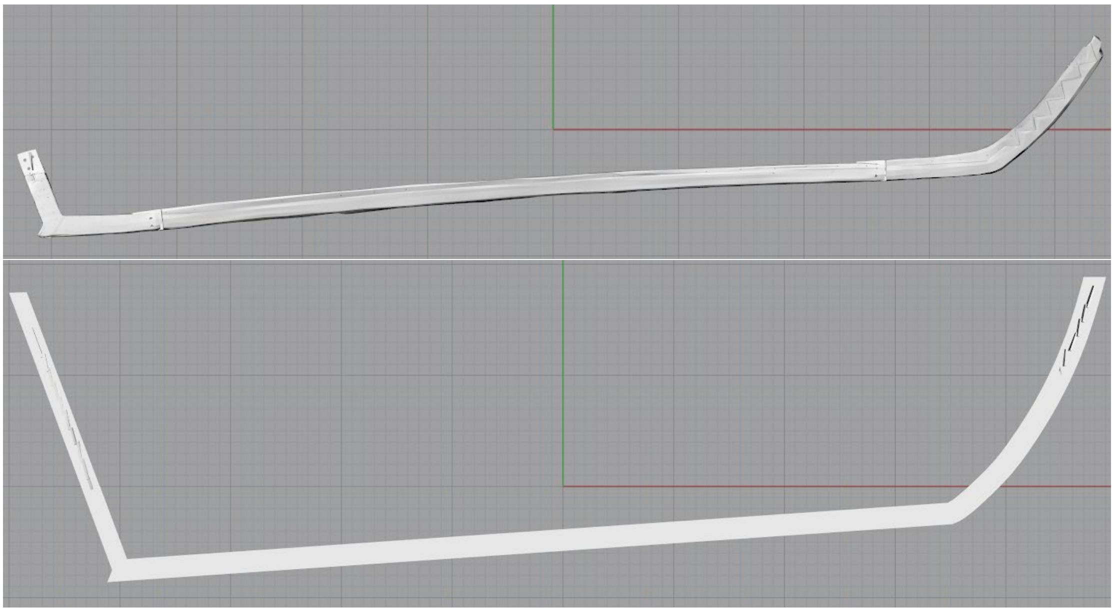
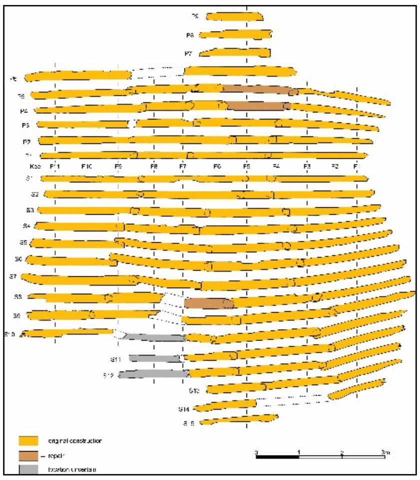


Figure 15 remodelled backbone (P. Tanner)



The recovered strakes (see Figure 16) were remodelled, following the faired curves from the reconstructed hull shape, and the additional strakes to form a watertight hull up to the 15th strake level were created (see Figure 17).

Figure 16 Diagram of recovered hull planking (H. Schweitzer)

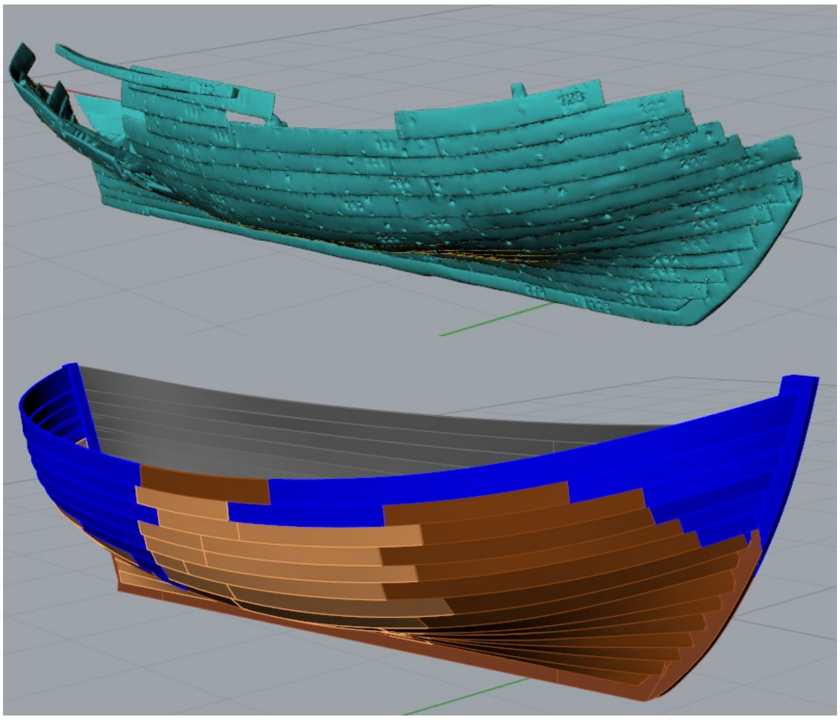


Figure 17 remodelled hull planking (P. Tanner)

The recovered frames were remodelled, again following the reconstructed hull shape, and the missing frame sections were added (see Figure 18)

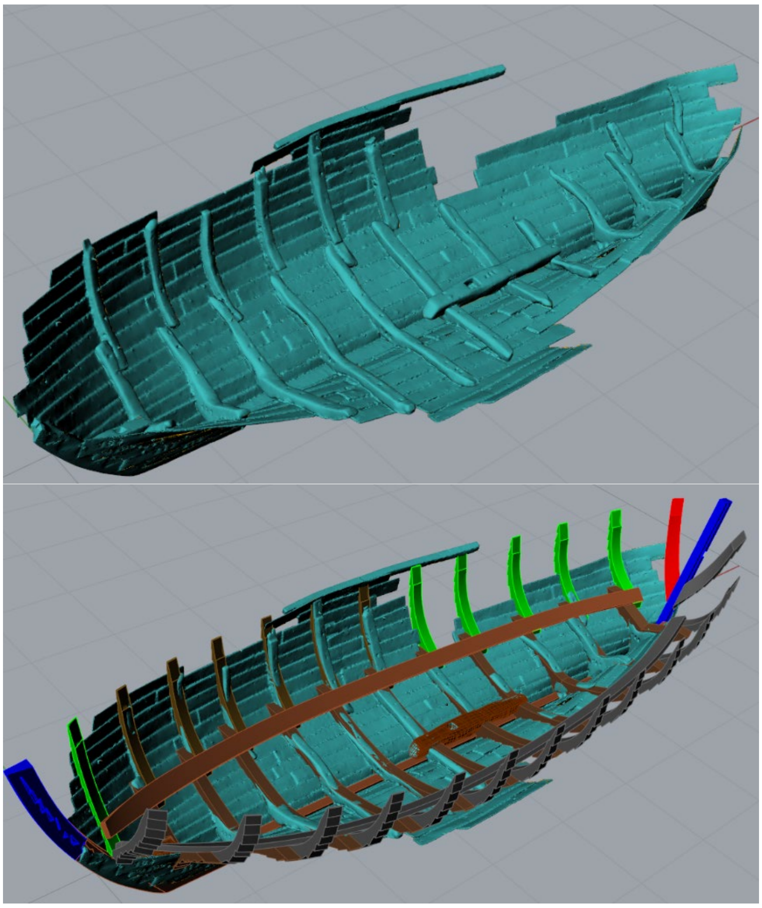


Figure 18 remodelled frames (P. Tanner)

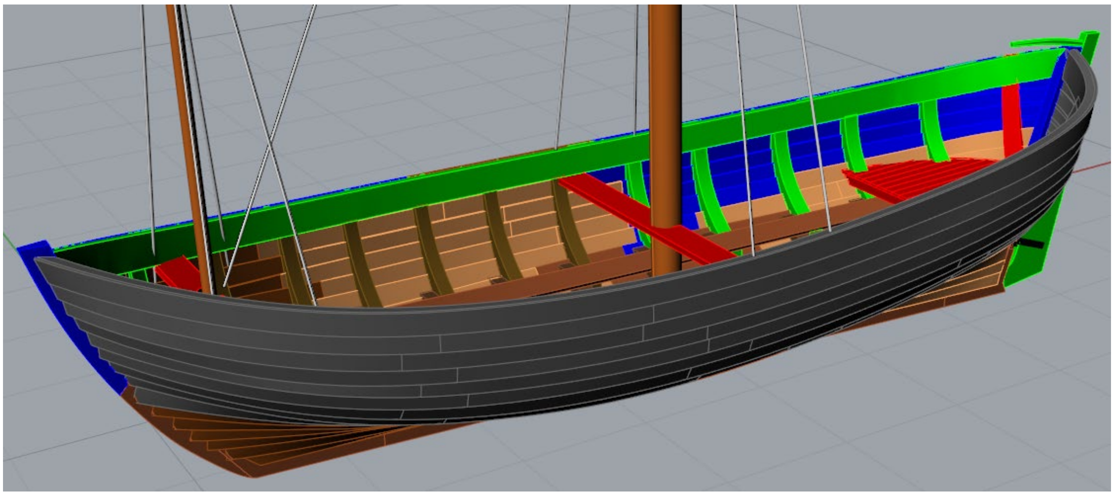


Figure 19 solid modelled reconstructed vessel (P. Tanner)

Figure 19 shows the remodelled vessel with the various parts colour coded as follows:

Brown colour represents items which were recovered.

Blue colour represents items necessary to create a watertight hull.
These include the upper stem post and upper stern post, and the remaining hull planking required to create a watertight vessel.

Shown in grey are items which have been mirrored. As the starboard side of the vessel was more complete this side was recreated and then mirrored to the missing port side.

Green colour represents items considered necessary to construct the vessel which were not recovered but evidence of their existence remains.
These items include the top or futtock sections of frames 7,8,9,10 and 11 as well as frame 0 which was added between frame 1 and the stem post in order to maintain frame spacing, additional evidence for frame 0 includes tree-nail holes at this position.
A sheer clamp or inwhale has also been added along the tops of the frames.
The tops of frames 1,4 and 5 have a scarf or rebate cut in either to take stanchions or this sheer clamp (this will be examined in more detail later).
A main mast, foremast, and rudder have also been added and these will be dealt with in more detail under considerations of propulsion, steering and seaworthiness.

Red colour represents items considered necessary but no evidence for their existence was discovered.
Items in this category include frame 11a which has been added between frame 11 and the sternpost in order to maintain frame spacing, although no evidence can be found for this frame as the hull planking in this area was not recovered.
Two thwarts have also been added to coincide with the mast positions. No evidence was recovered for these but they would be required to provide transverse strength to the hull and to provide support to both masts.

A cockpit sole has also been added in order to enable the helmsman reach the tiller.

When the entire vessel has been solid modelled in this fashion a total weight and centre of floatation for the vessel is calculated. When this is applied to the model it has the effect of orientating the vessel to its flotation condition.

The Drogheda Boat excluding any cargo or ballast (as built condition) weighs 2909 kg. With longitudinal centre of gravity (LCG) located 4322.5mm aft of the Forward end of the DWL (FP) and the vertical centre of gravity (VCG) located 516mm above the datum waterline, transverse centre of gravity (TCG) is 0mm located on the centre line as it is assumed the vessel is symmetrical.

F.6 Seaworthiness

The term "seaworthiness" is a very broad one, as it not only includes the physical state of the vessel but also extends to other aspects and factors. Consequently, it is not easy to define Seaworthiness in specific limited terms.

A thirteenth-century law defined a ship as seaworthy if she did not need to be bailed more than three times in 24 hours (Christensen 1968,138-9).

The Marine Insurance Act (1906) *states 'A ship is deemed to be seaworthy when she is reasonably fit in all respects to encounter the ordinary perils of the seas of the adventure insured'.*

NAVIGATION ACT 1912 - Definition of seaworthy

(1) A ship is to be treated as seaworthy under this Act if, and only if:

(a) it is in a fit state as to the condition of hull and equipment, boilers and machinery, the stowage of ballast or cargo, the number and qualifications of crew including officers, and in every other respect, to:

(i) encounter the ordinary perils of the voyage then entered upon; and

(ii) not pose a threat to the environment; and

(b) it is not overloaded.

Consequently seaworthiness can be defined as: *the fitness of the vessel in all respects, to encounter the ordinary perils of the sea; that could be expected on her voyage, and deliver the cargo safely to its destination.*

Evaluating whether a vessel would have been seagoing is an art as well as a science since a number of interacting factors have to be considered, factors such as the

strength, durability and integrity of the hull, as well as freeboard at operational drafts, stability and reserves of buoyancy (McGrail, 2001,6).
McGrail also states that an open boat below a certain size is unlikely to have been seagoing while a boat shaped underwater hull and a sheerline rising towards the ends suggest a seagoing vessel.

In order to determine seaworthiness, the vessel will be examined in varying floatation conditions. In "Ancient Boats in North-West Europe" (McGrail 1998b,13) these conditions are suggested as being influenced by 4 main factors:

1. Weight and centre of gravity of the vessel
2. Number and normal station of crew
3. Bulk density of cargo
4. Freeboard

1. The weight and centre of gravity for the Drogheda Boat has been calculated in the previous section for the as built or lightship condition

2. With regard to crew and stores, no evidence was recovered, but there is evidence of similar sized vessels being operated with as little as 2 crew (One man and a boy).

3 The evidence of cargo recovered was in the form of 12 casks which contained fish remains. As a result the vessel will be assessed using these casks as the main cargo, with various quantities to determine load carrying capabilities.

4.Freeboard, the distance between the gunnels or top edge, and the operational waterplane, will need to be examined. Ethnographic evidence suggests that for inland waters, small boats were loaded to very little freeboard (McGrail 1978,91). seagoing data is not readily available, however a medieval Icelandic Law states the minimum freeboard (F) of a cargo ship should be F=2D/5 where D=depth of hull amidships (Morken 1980,178).
In the case of the Drogheda Boat this would be F=2*1.66/5 = 0.664m.

Authors note: Interestingly this figure matches almost exactly with the "detailed hydrostatic data - loaded condition" used later in this chapter where the freeboard measures 0.662m.

McGrail also suggests the use of four "standard freeboards" (McGrail 1998b,199)

a) draft restricted to 300mm (minimum depth of water)
b) at a standard freeboard of 150mm (safety consideration)
c) minimum freeboard as a function of transverse stability (upper edge of sides awash at 10° heel)
d) maximum number of crew there is space for.

The Drogheda boat will now be examined to determine its floatation condition for four loading states.

Table 1 Floatation Condition for As built condition:

This is the empty vessel condition consisting of constituent parts of hull, and rigging only and excludes any crew, cargo or ballast.

Length overall	9795mm	Beam Overall	3095mm
Waterline length	8388mm	Waterline Beam	2306mm
Displacement	2900Kg	Draft	622.5mm
Prismatic Co-efficient	0.666	Freeboard	1117mm
Waterplane Area	12.56m²	Wetted Surface Area	19.55m²
Sinkage	152mm above datum waterline		

This gives a draft restricted floatation condition (a) of 622mm (excluding crew)

Table 2 Floatation Condition for Empty boat:

This is empty vessel condition consisting of constituent parts of hull and rigging plus 2 crew with 1 days store each, no cargo or ballast.

Length overall	9795mm	Beam Overall	3095mm
Waterline length	8372mm	Waterline Beam	2320mm
Displacement	3084Kg	Draft	684.5mm
Prismatic Co-efficient	0.675	Freeboard	1095mm
Waterplane Area	12.84m²	Wetted Surface Area	19.89m²
Sinkage	194mm above datum waterline		

This gives a draft restricted floatation condition (a) of 685mm (including crew)

Table 3 Floatation Condition for As found condition:

This consists of rebuilt vessel as shown, including hull and rigging together with 12 casks (as recovered) and notionally 2 crew, their stores for 1 day, anchor and warps.

Length overall	9795mm	Beam Overall	3095mm
Waterline length	8587mm	Waterline Beam	2627mm
Displacement	5718Kg	Draft	839.5mm
Prismatic Co-efficient	0.679	Freeboard	921mm
Waterplane Area	16.04m²	Wetted Surface Area	24.68m²
Sinkage	11mm below datum waterline		

This gives an as found floatation condition draft of 840mm (including crew)

Table 4 Floatation Condition for Notional fully laden condition:

This consists of rebuilt vessel as shown, including hull and rigging together with 42 casks (quantity that could fit within hull volume) and notionally 3 crew, their stores for 2 days, anchor and warps.

Length overall	9795mm	Beam Overall	3095mm
Waterline length	8955mm	Waterline Beam	2964mm
Displacement	12418Kg	Draft	1171mm
Prismatic Co-efficient	0.698	Freeboard	568mm
Waterplane Area	20.06m²	Wetted Surface Area	33.0m²
Sinkage	397mm below datum waterline		

This gives a maximum cargo floatation condition (d) draft of 1171mm

42 casks would represent approx 75,600 herring or 8,400kg weight of herring and a total weight of 9,219kg including casks. In addition this amount of cargo would result in a low freeboard of just 586mm, while this is still serviceable it would only be so in sheltered waters.

Sheer strake height:

There was initially a question regarding the sheer strake height, as a result of the visible scarf / rebates cut into the tops of frames 2,5 and 7. This scarf or rebate had two potential reasons, The first possible being a scarf joint to take stanchions, (an extension of the frames used to support additional hull planking usually forming bulwarks). The second possible reason being a rebate to take the sheer clamp or inwhale (a longitudinal stringer at the frame tops or gunwale level)
It was decided that the second option is the more likely of the two for the following reasons:

1. 15 strakes would be a reasonable number for a vessel of this size.
2. If the rebate was to receive stanchions this would potentially add two or more strakes to the height of the vessel. As already has been shown the vessel with its sheer at the fifteenth strake would be capable of carrying a considerable cargo in proportion to its size and this would lead to other difficulties with regard to propulsion
3. Looking at other working boats the internal volume of the vessel in comparison to its overall dimensions would appear to be in proportion with the sheer line set at the fifteenth strake.

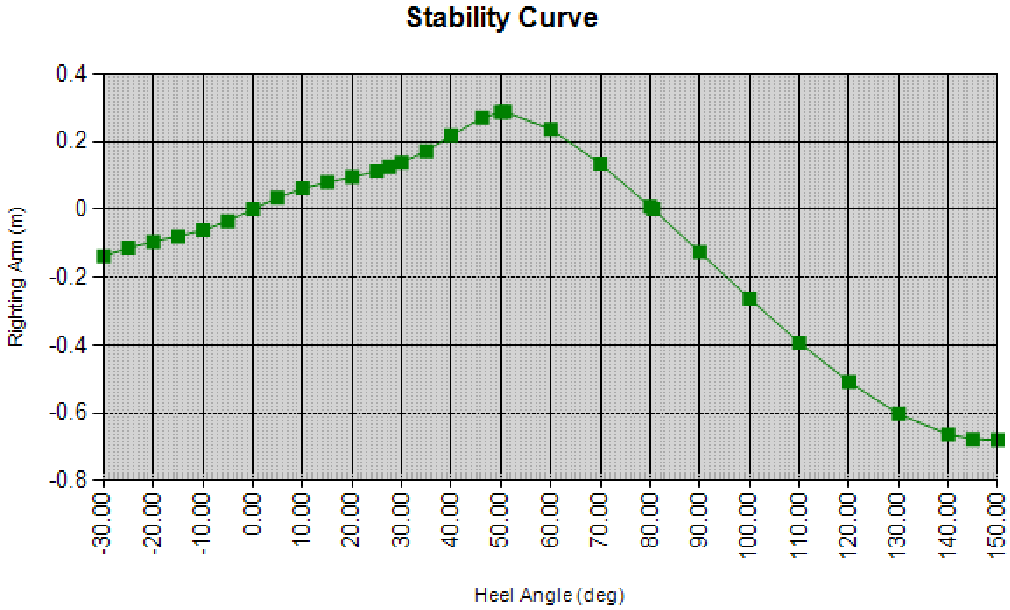
A detailed hydrostatic and static stability analysis below shows the different characteristics of the vessel in three different configurations.
These configurations are

1 Empty boat, fully rigged with 2 crew but no ballast or cargo.
2 As found boat, fully rigged with 12 casks, two crew and supplies for two days. This will be treated as the boats general service condition
3 Loaded condition, fully rigged with 32 casks, three crew and supplies for two days. This would represent a cargo of 75% the notional fully laden amount and still allow the vessel to operate in moderate to exposed conditions.

Detailed Hydrostatic Data - Empty boat

This is empty vessel condition consisting of constituent parts of hull, and rigging plus 2 crew with 1 days store each, no cargo or ballast.

Length overall	9795mm	Beam Overall	3095mm
Sinkage	194mm above datum waterline		
Waterline length	8372mm	Waterline Beam	2320mm
Displacement	3048Kg	Draft	684.5mm
Prismatic Co-efficient	0.675	Freeboard	1095mm
Waterplane Area	12.84m²	Wetted Surface Area	19.89m²
Downflooding angle	46.2deg	Righting moment 46.2°	823kgf-m



Heel(deg)	Trim(deg)	Righting Arm (m)	Righting Moment (kgf-m)
0	-1.155	0.000	0.0
5	-1.136	0.034	105.0
10	-1.090	0.061	187.4
15	-1.026	0.080	242.8
20	-0.944	0.095	289.8
25	-0.842	0.113	345.6
27.5	-0.783	0.125	380.3
30	-0.719	0.138	421.2
35	-0.572	0.172	524.2
40	-0.404	0.218	663.7
46.2	0.112	0.270	823.3
50	0.414	0.287	874.0
50.8	0.456	0.288	876.9
60	0.576	0.236	719.6
70	0.788	0.134	408.0
80	0.942	0.008	25.5
80.6	0.950	0.000	0.5
90	1.046	-0.127	-386.8

Heel(deg)	Point Name and Distance Above WL (m)	
0.000	Deck Edge	1.096
5.000	Deck Edge	0.968
10.000	Deck Edge	0.842
15.000	Deck Edge	0.718
20.000	Deck Edge	0.597
25.000	Deck Edge	0.477
27.500	Deck Edge	0.417
30.000	Deck Edge	0.359
35.000	Deck Edge	0.243
40.000	Deck Edge	0.131
46.225	Deck Edge	0.000

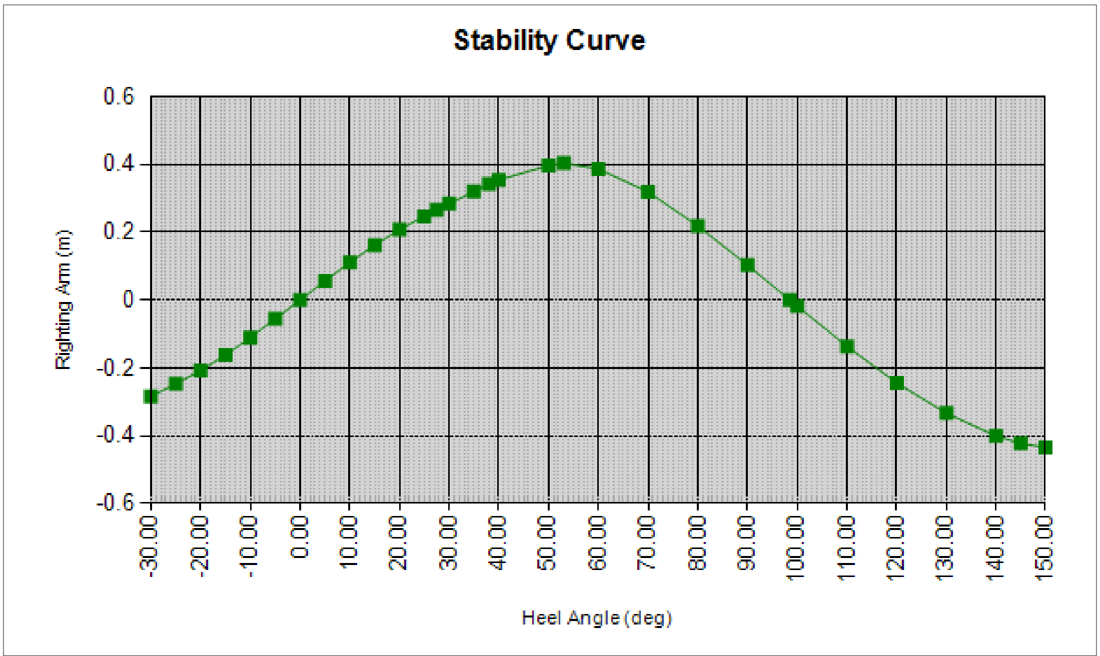
Stability Criteria - Sample Source, Open Water (meters)		
Name	**Actual**	**Pass / Fail**
GM At FreeEquil >= 0.15 meters	0.4102	Pass
GZ At 30 >= 0.2 meters	0.1382	Fail
Angle At GZmax > 25 deg	50.8	Pass
Area Between 0 and 30 > 3.15 meters-deg	2.2632	Fail
Area Between 0 and Flood > 5.15 meters-deg	5.5313	Pass
Area Between 30 and 40 > 1.72 meters-deg	1.7497	Pass
Area Between 30 and Flood > 1.72 meters-deg	3.2681	Pass

Conclusion:
Without regard to wind loading it would appear that in this condition the vessel, with a point of vanishing stability at approx 81° and the deck edge becoming submerged at 46.2° with very little righting moment (823kgf-m) the boat would be considered very tender or tippy.
If heeling due to wind loading was included this condition would probably be considered unsafe in all but the most protected waters.

Detailed Hydrostatic Data - As found condition

This consists of rebuilt vessel as shown, including hull and rigging together with 12 casks (as recovered) and notionally 2 crew, their stores for 1 day, anchor and warps.

Length overall	9795mm	Beam Overall	3095mm
Sinkage	11mm below datum waterline		
Waterline length	8587mm	Waterline Beam	2627mm
Displacement	5718Kg	Draft	839.5mm
Prismatic Co-efficient	0.678	Freeboard	922mm
Waterplane Area	19.02m²	Wetted Surface Area	24.68m²
Downflooding angle	38deg	Righting moment 38°	1953kgf-m



Heel(deg)	Trim(deg)	Righting Arm (m)	Righting Moment (kgf-m)
0	-1.496	0.000	0.0
5	-1.487	0.056	320.1
10	-1.459	0.111	632.5
15	-1.409	0.162	925.5
20	-1.341	0.207	1185.4
25	-1.261	0.247	1411.9
27.5	-1.217	0.265	1517.5
30	-1.170	0.283	1621.0
35	-1.064	0.320	1829.1
38.0	-0.994	0.342	1953.0
40	-0.950	0.354	2024.8
50	-0.740	0.396	2266.5
53.1	-0.675	0.403	2305.7
60	-0.376	0.386	2209.2
70	-0.319	0.318	1821.1
80	-0.140	0.218	1248.5
90	0.050	0.103	587.9
98.5	0.218	0.000	0.1
100	0.247	-0.018	-103.5

Heel(deg)	Point Name and Distance Above WL (m)	
0	Deck Edge	0.922
5	Deck Edge	0.793
10	Deck Edge	0.665
15	Deck Edge	0.537
20	Deck Edge	0.413
25	Deck Edge	0.293
27.5	Deck Edge	0.235
30	Deck Edge	0.178
35	Deck Edge	0.066
38.0	Deck Edge	0.000

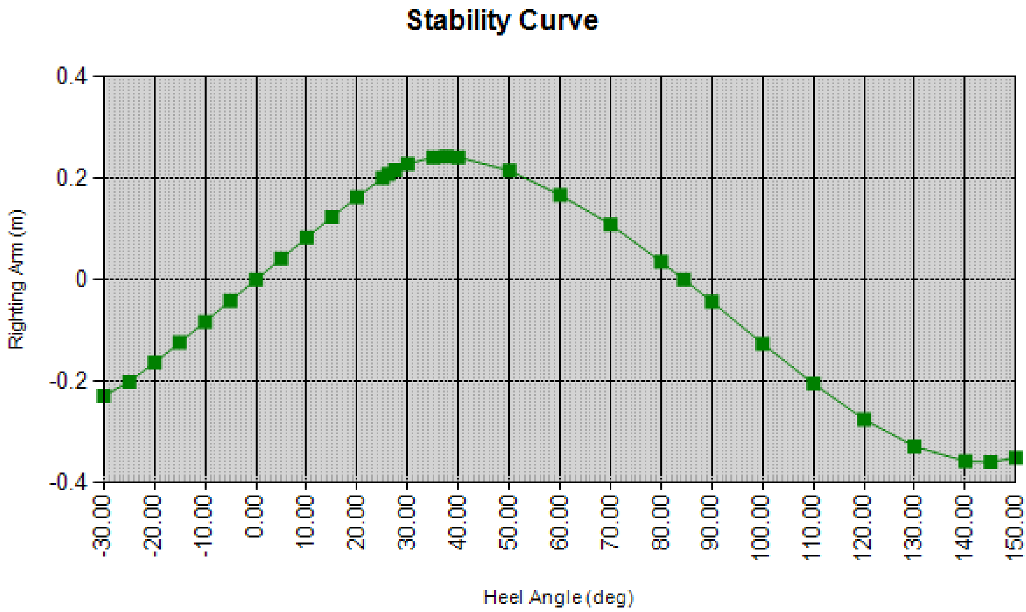
Stability Criteria - Sample Source, Open Water (meters)		
Name	**Actual**	**Pass / Fail**
GM At FreeEquil >= 0.15 meters	0.6439	Pass
GZ At 30 >= 0.2 meters	0.2835	Pass
Angle At GZmax > 25 deg	53.1	Pass
Area Between 0 and 30 > 3.15 meters-deg	4.6227	Pass
Area Between 0 and Flood > 5.15 meters-deg	7.1311	Pass
Area Between 30 and 40 > 1.72 meters-deg	3.1934	Pass
Area Between 30 and Flood > 1.72 meters-deg	2.5084	Pass

Conclusion:
Without regard to wind loading it would appear that in this condition the vessel, with a point of vanishing stability at approx 98.5°, the deck edge becoming submerged at 38° and a righting moment of 1953kgf-m the boat would be considered stable.

Detailed Hydrostatic Data – Loaded condition

This consists of rebuilt vessel as shown, including hull and rigging together with 32 casks (representing 75% notional fully laden) and 3 crew, their stores for 2 days, anchor and warps.

Length overall	9795mm	Beam Overall	3095mm
Sinkage	205mm below datum waterline		
Waterline length	8822mm	Waterline Beam	2880mm
Displacement	10223Kg	Draft	1139mm
Prismatic Co-efficient	0.700	Freeboard	662mm
Waterplane Area	19.03m²	Wetted Surface Area	30.49m²
Downflooding angle	26deg	Righting moment 26°	2124.6kgf-m



Heel(deg)	Trim(deg)	Righting Arm (m)	Righting Moment (kgf-m)
0	-0.701	0.000	0.0
5	-0.695	0.041	421.8
10	-0.677	0.082	842.6
15	-0.645	0.123	1259.5
20	-0.595	0.163	1665.0
25	-0.527	0.200	2046.6
26.1	-0.509	0.208	2124.6
27.5	-0.488	0.216	2209.5
30	-0.450	0.228	2333.4
35	-0.382	0.241	2465.3
37.5	-0.349	0.243	2480.0
40	-0.318	0.241	2466.2
50	-0.185	0.215	2197.5
60	-0.031	0.167	1709.0
70	0.158	0.108	1108.8
80	0.510	0.035	356.3
84.5	0.508	0.000	1.7
90	0.695	-0.043	-442.5

Heel(deg)	Point Name and Distance Above WL (m)	
0	Deck Edge	0.662
5	Deck Edge	0.533
10	Deck Edge	0.404
15	Deck Edge	0.276
20	Deck Edge	0.150
25	Deck Edge	0.027
26.1	Deck Edge	0.000

Stability Criteria - Sample Source, Open Water (meters)		
Name	Actual	Pass / Fail
GM At FreeEquil >= 0.15 meters	0.473	Pass
GZ At 30 >= 0.2 meters	0.2283	Pass
Angle At GZmax > 25 deg	37.5	Pass
Area Between 0 and 30 > 3.15 meters-deg	3.6252	Pass
Area Between 0 and Flood > 5.15 meters-deg	2.7795	Fail
Area Between 30 and 40 > 1.72 meters-deg	2.383	Pass
Area Between 30 and Flood > 1.72 meters-deg	-0.8433	Fail

Stability Criteria - Sample Source, Partially Protected Waters (meters)		
Name	Actual	Pass / Fail
GZ Between 0 and 30 >= 0 meters	0	Pass
FloodHt Between 0 and 20 > 0 meters	0.2433	Pass
Area Between 0 and 40 > 4.572 meters-deg	6.4493	Pass
Area Between 0 and Flood > 4.572 meters-deg	3.2628	Fail
Area Between 0 and GZmax > 4.572 meters-deg	6.2789	Pass

Stability Criteria - Sample Source, Protected Waters (meters)		
Name	Actual	Pass / Fail
GZ Between 0 and 25 >= 0 meters	0	Pass
FloodHt Between 0 and 15 > 0 meters	0.3706	Pass
Area Between 0 and 40 > 3.048 meters-deg	6.4454	Pass
Area Between 0 and Flood > 3.048 meters-deg	3.2654	Pass
Area Between 0 and GZmax > 3.048 meters-deg	6.2218	Pass

Conclusion:

Without regard to wind loading it would appear that in this condition the vessel, with a point of vanishing stability at approx 85°, the deck edge becoming submerged at 26° and a righting moment of 2124kgf-m the boat would be considered stable in protected waters, although the low freeboard of 662mm would probably make the vessel unsuitable for use in open waters and marginal in partially protected waters.

F.7 Assessment of Performance

For the purposes of assessing performance the vessel will be examined in the as-found or general service condition. This represents a vessel with an as built weight of approx 2900kg carrying a crew and cargo of approx 2800kg, a combined displacement weight of 5700kg.

Methods of assessment

Once a reconstruction drawing is available the performance of the boat it represents may be assessed in several ways (McGrail 1998b,192).
Using simple coefficients that are based on the boat's overall measurements, thus LOA/BOA and BOA/D summarise the overall proportions of the boat and as such give a relative assessment of the boats capabilities.
Using hydrostatic curves involves the definition of the waterline(s), underwater shape and calculations of displacements and sectional areas and coeffecients based on the underwater geometry may be used to give forecasts of performance.

Additional methods of assessment include scale models for tank testing and full size replica construction for undertaking sea trials testing.

Shape of the Hull

Naval architecture guidelines state the hull shape and dimensions give a boat buoyancy and stability as well as influencing other characteristics such as speed, manoeuvrability and load carrying capacity.
The underwater sections of a hull should have gentle sweeping curves in order to minimise resistance of water flow, while the general shape should also conform to the function of the vessel.
The transverse sections along the boat should have sufficient shape and volume to provide adequate buoyancy as required, while a fine entry forward combined with a smooth run aft will generally mean a greater speed potential requiring less driving force, whereas fuller bow sections will provide greater buoyancy ahead to help deal with steep seas and increase load carrying capacity.
Similarly a large gripe (connection between Keel and Stem) and large keel and deadwood will provide good lateral resistance in a sailing vessel. References to these design features can be seen in some of the descriptions used for vessels such as the "cods head, mackerel tail" design of traditional working boats, and another "apple cheek" bow indicating fuller forward sections.
If the stern is the same shape as the bow (a double ended vessel) the boat may be propelled in either direction which would be an advantage for an oared boat while a narrow stern may not provide adequate buoyancy to counteract the weight of a helmsman and might be swamped by a quartering or following sea, additionally a wider stern gives more space aft for the helmsman and sail trimming.
Flare (the angle the sides slope outwards) will provide for a drier vessel than a straight sided vessel, and have the added advantage of increasing displacement and transverse stability (load carrying capacity) as the draft increases.

An initial assessment of the Drogheda boat based on the lines plan shows a vessel with a reasonable fine entry forward, full length keel, long smooth run aft below the waterline, and changing to fuller sections above the waterline. This would indicate a vessel designed for sailing, intended to be reasonably fast and still have a load carrying capacity.

Size of the Hull

Length and Breadth:

A longer boat has a higher speed potential due to the increased waterline length, while a beamier boat should have a greater load carrying capacity due to its increased transverse stability.

(McKee, 1983,81) defined a beamy boat as LOA/BOA less than 2.6 and a narrow boat as LOA/BOA greater than 3.75

High values indicate large form stability, faster speeds (if light boat) and larger interior volume. Low values indicate gentler motions and normally safer blue water performance.

The Drogheda Boat has a LOA/BOA ratio of 3.165

Depth and Draft

The depth of the boat will determine the freeboard and draft at any given displacement.
The freeboard height is a measure of reserve buoyancy provided water does not come over the gunwale. The down flooding angle, the point at which the gunwale in an open boat dips below the waterline can also be found.
The Drogheda Boat in the as-found or general service floatation condition will have a draft (T) of 839.5mm and freeboard (F) of 922mm
The Drogheda Boat has a D/T ratio of 3.067
The down flooding angle is 38°

The LWL/T ratio is 10.29
The BWL/T ratio is 3.15

Speed Potential

The displacement Δ length ratio (DLR) is the most basic comparison of vessels, generally the vessel with the lower value will be the faster vessel.
At present DLR is classed as
50 and under is super Ultralight
50 to 120 is Ultralight
120 to 250 is light
250 to 320 is medium
320 to 380 is heavy
380 and over is very heavy
The Drogheda Boat has a DLR of 251.44

The prismatic coefficient C_p (displacement volume ∇ /(Ax*LWL)) may be used in the lower speed range of (V)/(√ LWL) between 0.6 and 1.1 to compare wave making resistance. A lower value indicates a lower resistance and therefore a potentially faster boat.
The Drogheda Boat has a C_p of 0.678

At lower speeds additional coefficients may be used to compare speed potential. Block Coefficient C_b (displacement volume ∇) / (LxBxT)) where values below 0.65 indicate good speed potential.
The Drogheda Boat has a C_b of 0.296

Midships Coefficient C_x (A_x)/(BxT) where values below 0.85 indicate good speed potential.
The Drogheda Boat has a C_x of 0.436

Slenderness Coefficient (LWL/BWL) where values above 5 indicate good speed potential.
The Drogheda Boat has a (LWL/BWL) ratio of 3.27

Volumetric Coefficient (displacement volume ∇) / $(LWL)^3$) where values above $2x10^{-3}$ 85 indicate good speed potential.
The Drogheda Boat has a Volumetric Coefficient of $8.79x10^{-3}$

Cargo Capacity and Tonnage

Tonnage

Medieval descriptions of the dimensions of ships may be rare, but references to their tun- nage or burthen are not. However, this does not mean that the use of tunnage figures is straight- forward. One immediate problem is that there were many different measures of ship capacity. In England the basis of measurement was the wine tun as wine was an important cargo, and it was enacted by statute that the wine tun should contain 252 gallons. In the Mediterranean the wine barrel was also used as a measure of tunnage, although the actual values accorded to the hotfa, or baril were varied (Zupko, 1977,29-30); (Lane, 1964,218-9). Zupko equates the tun of 252 gallons to 954 litres, 954 litres equates to 252 U.S. gallons whereas 252 imperial gallons equates to 1145 litres.

Bakers old rule (1582) for tonnage states *"length of keel excluding the false post multiplied by the greatest breadth within the plank and that product multiplied by the depth taken from the breadth to the upper edge of the keel produceth a solid number which divided by 100 gives the content in tons, into which add one third part for tonnage"*

Using this rule the Drogheda Boat would be 25.16 x 10.15 x 5.15 = 1315.18 / 100 = 13.15 plus one third (4.38) = 17.5 tons

The Builders Old Measurement (B.O.M.) was another system introduced in 1834-5 whereby it was not necessary to know the depth of the vessel (a measurement which was difficult to establish while the vessel was afloat) and was calculated as (L-3/5B) x B x 1/2B)/94

Using this rule, the Drogheda Boat would be

(32.13 - 3/5(10.15) x 10.15 x 1/2(10.15)) / 94

((32.13 - 6.09) x 10.15 x 5.08)/94 = 1342.67 / 94 = 14.28 tons

A third method of assessing cargo capacity is to examine the vessel shape and by modelling the casks which were recovered, then check what quantity of casks could physically fit within the hull.

A typical cask weighing 219.5kg and a volume of 230 litres was used and 42 of these would fit in the vessel.

This would give a total displacement weight including vessel, crew and rigging of 12418kg and when you subtract the lightship weight of the vessel which is 2900kg gives a gross deadweight of 9518kg equal to 9.4 tons

This would probably be an excessive loading as the vessel would have only 568mm freeboard and 1170mm draft.

A more suitable loading might be 75% of max loading which would mean 32 casks giving a total displacement weight including vessel, crew and rigging of 10223kg and when you subtract the lightship weight of the vessel which is 2900kg gives a gross deadweight of 7323kg equal to 7.2 tons

This would result in the vessel having a freeboard of 662mm and a draft of 1140mm.

These figures match well a medieval Icelandic Law in the Grågås Codex (Morken 1980,178).which states a cargo vessel is fully loaded when 2/5 of the total depth is freeboard.
In the case of the Drogheda Boat this would be 2/5 of 1.57m = 628mm.

F.8 Steering

Evidence was found of a rectangular rebate on either side of the sternhook as well as a groove on the aft face which confirm the existence of an iron gudgeon fitted to receive the mating pintle of a transom hung rudder. No evidence of the rudder was found so a basic representation has been used for modelling purposes.
A typical modern day formula for calculating rudder area for a traditional shape long keel sailing vessel would be 0.068 x waterline length x draft.
Using this formula would give 0.068 x 8.5 x 0.84 = 0.485m²
The actual rudder as shown has an area of 0.446m²

F.9 Propulsion

As little evidence of rig types or sails exists and no masts were recovered, they will have to be interpolated from contemporary iconography (see Plate 3 and Plate 4) combined with the use of modern calculations and formulas.

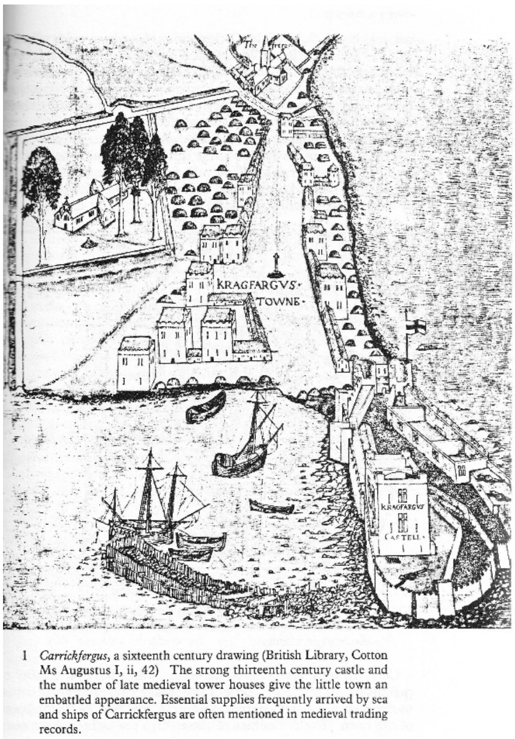


Plate 3: Carrickfergus
a sixteenth century drawing

Plate 4 Sixteenth Century Scheveningen Herring Buss (picture by Elandts in the Municipal Museum at The Hague)

Rigging Elements – Evidence recovered:

Evidence recovered included a mainmast heel block and a foremast heel block indicating that the vessel carried two masts for sailing purposes.

From the dimensions of the two mast steps, Mainmast step (see Figure 20) 180mm / 220mm moulded / sided and 1860mm in length with a rectangular mast heel socket of 140mm x 110mm and a depth of 85mm and the Foremast step (see Figure 21) 90mm / 130mm sided / moulded and 510mm length with a square mast heel socket of 80mm x 80mm and a depth of 40mm, this would suggest the foremast was smaller than the mainmast.

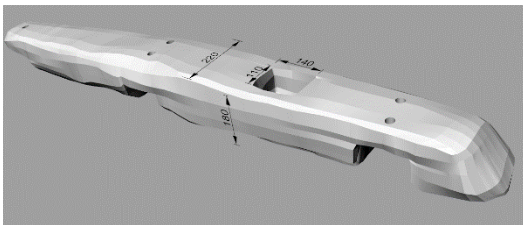


Figure 20 Main Mast Step (P. Tanner)

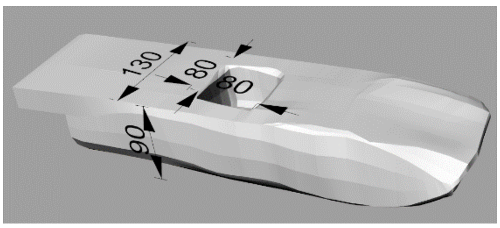


Figure 21 Fore Mast Step (P. Tanner)

A relatively small block (F289) was found broken but almost complete underneath stringer C37. This has been dealt with in detail in Chapter 4.1.8 and would appear to be a clew garnet block. (see Plate 5 and Figure 22)

Figure 22 Clew Garnet Block

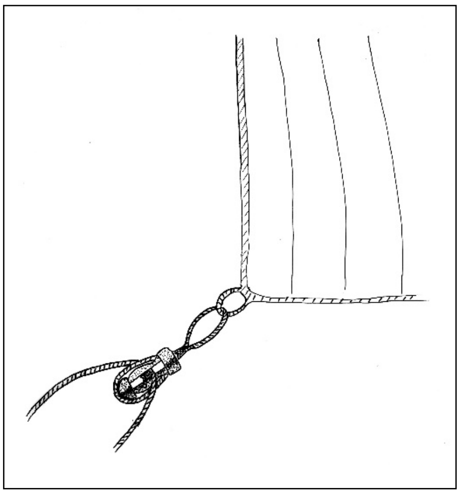


Plate 5 Small block F289 (Con Brogan)

Possible Parrel Truck

Parrels were devices attached to the yard and wrapped around the mast allowing for the yard to be moved up and down the mast.

The possible truck (F250) from the Drogheda Boat was found amongst material, which had collapsed into Cask 8, which was located immediately next to the starboard side of the mast step has been dealt with in more detail in Chapter 4.1.8. (see Plate 6 Figure 23 & Figure 24)

Plate 6: Parrel truck F250 (C. Brogan)

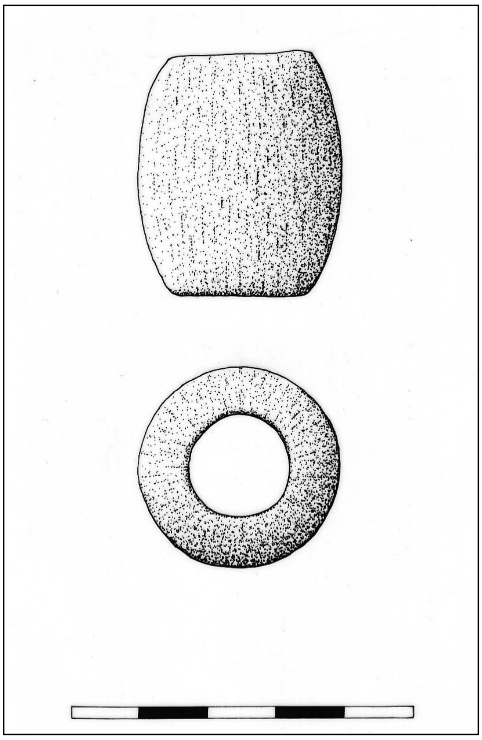


Figure 23 Parrel truck F250

(Illustration: J. Ryan)

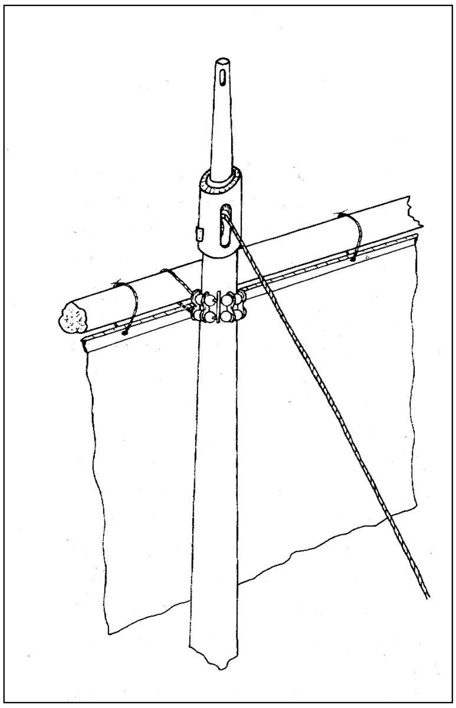


Figure 24 Schematic drawing showing a composite parrel of ribs and trucks (Drawing: Institute of Archaeology, Oxford)

For the purposes of assessing propulsion the vessel will be examined in the as found or general service condition. This represents a vessel with an as built weight of approx 2900kg carrying a crew and cargo of approx 2800kg a combined displacement weight of 5700kg.

For a displacement hull like the Drogheda Boat which is sitting in the water, as it moves forward it generates a bow and stern wave with the boat sitting in the trough between the two waves. As the boat accelerates to higher speeds a greater ammount of power is required to overcome this wave resistance, until a stage is reached where the power required to accelerate even more becomes enormous. This point is referred to as the displacement trap and a vessel intended to escape this displacement trap will either require unrealistic amounts of power or a hull shape specifically designed to "plane" on the water surface. This displacement trap results in a theoretical maximum hull speed, which is calculated as 1.34 times the square root of the waterline length (LWL) in feet. Boats which do achieve speeds where velocity (V)/(√ LWL)>1.40 may appear to be planning. 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 planning or skimming (Marchaj, 1964,fig 158).

Displacement boats like the Drogheda Boat can only exceed (V)/(√ LWL)=1.40 in ideal conditions or with excessive use of mechanical power.
Modern yachts generally operate around (V)/(√ LWL)=0.90 while cargo ships seldom exceed (V)/(√ LWL)=0.50 (Marchaj, 1964,254).
From 1.34 sqrt LWL the Drogheda boat has a theoretical max hull speed of 7.11kts.

Firstly, a target speed will need to be set for the vessel.
The Irish Sea, in and around Drogheda experiences a moderate tidal current with peak spring tidal currents between 2kts and 3.5kts
If the vessel is to work in an area with a tidal rate of two knots then the vessel will need to achieve a target speed of 4 to 5 knots or more in order to make progress when stemming a foul tide.

Displacement Hulls Speed / Length ratio from Gerr

Name:	**Drogheda Boat**				
LWL	28.182	feet	sq.rt LWL=	5.31	
Displacement	12566	lbs =	5.61	tons	
Target speed	4	knots	"Hull speed"=	7.1	kts
	4.61	mph			
S/L ratio =	0.75	RESULTS VALID BELOW 1.4 ONLY !			
10.665/(S/L)	14.154				
LB/SHP =	2835.7				
HP required =	4.43	hp			
kW required =	3.30	kW			

This would suggest that the boat would require 4.5hp to achieve a speed of 4kts.

Name:	**Drogheda Boat**				
LWL	28.182	feet	sq.rt LWL=	5.31	
Displacement	12566	lbs =	5.61	tons	
Target speed	5	knots	"Hull speed"=	7.1	kts
	5.76	mph			
S/L ratio =	0.94	RESULTS VALID BELOW 1.4 ONLY !			
10.665/(S/L)	11.323				
LB/SHP =	1451.9				
HP required =	8.65	hp			
kW required =	6.45	kW			

This would suggest that the boat would require 8.7hp to achieve a speed of 5kts.

Name:	**Drogheda Boat**				
LWL	28.182	feet	sq.rt LWL=	5.31	
Displacement	12566	lbs =	5.61	tons	
Target speed	6	knots	"Hull speed"=	7.1	kts
	6.91	mph			
S/L ratio =	1.13	RESULTS VALID BELOW 1.4 ONLY !			
10.665/(S/L)	9.436				
LB/SHP =	840.2				
HP required =	14.96	hp			
kW required =	11.15	kW			

This would suggest that the boat would require 15hp to achieve a speed of 6kts.

As we have no indication of the sail area carried by each mast on the boat the best estimate that can be made is a sail area of sufficient proportions to generate the required 8.7hp in a given wind speed of say 15kts.

Sail Wind Load is the force the apparent wind is placing on a sail.		
Load in Pounds = Sail Area * (Wind Speed)² * 0.00431		
Sail Area =	650	**Square Feet**
Wind speed =	10	**Knots**
Sail Wind Load =	280.15	**Pounds**
	2675.23	
approx	**4.86**	**hp**

From this table we can estimate that 650ft² (60m²) of sail area would generate approx.. 4.9hp with 10kts of wind and this could equate to 4.1kts boat speed

Sail Wind Load is the force the apparent wind is placing on a sail.		
Load in Pounds = Sail Area * (Wind Speed)² * 0.00431		
Sail Area =	650	**Square Feet**
Wind speed =	15	**Knots**
Sail Wind Load =	630.34	**Pounds**
	6019.26	
approx	**10.94**	**hp**

From this table we can estimate that 650ft² (60m²) of sail area would generate approx.. 10.9hp with 15kts of wind and this could equate to 5.4kts boat speed

A sail area of 60m² would give a sail area / displacement ratio of 19.2.

SA / D = Sail Area / (DV) 2/3

DV = Displacement volume in cubic feet

* Cruising Boats have ratios between 10 and 15. (Undercanvased)
* Cruiser-Racers have ratios between 16-20 (comfortable cruising)
* Racers have ratios above 20
* High-Performance Racers have ratios above 24.
* Racing multihulls have ratios above 28.
* True Planing vesels have ratios above 37.

A look at the comparison table (Figure 25 shows that these figures would be comparable with the averages for six other boats.

F.10 Size of Masts, Yards and Sail Areas

Masts:
The old English system of sparring ships is based on the length between the stem and sternpost on deck and the beam measured outside the wales. The length of the mainmast is found by adding the length plus the beam and half this number would give the mainmast length (Masting, Mast Making and Rigging of Ships Robert Kipping 1854).

With a length overall of 9.795m and a beam overall of 3.095m this would give a mainmast length of 6.45m. With a topmast being 3/5 mainmast this would add an additional 3.87m, topgallant mast adding ½ topmast length 1.95m and royal adding ¾ topgallant length 1.45m

The foremast is 8/9 the mainmast giving 5.73m, with a fore topmast being 8/9 main topmast this would add an additional 3.44m, fore topgallant mast adding ½ topmast length of 1.95m and royal adding ¾ topgallant length of 1.45m

The overall height for each mast can then be calculated once the size of the mastheads is known. This is the distance below the top of each mast at which the heel of the next mast is stepped. These are as follows:

Main and foremast heads, 5 inches (127mm) per yard (.914m) length of mast
All topmasts and topgallant mastheads 4 inches 101.5mm) per yard of mast length
Mainmast headheight of 0.9m, main topmast headheight of 0.43m
Foremast headheight of 0.8m, fore topmast headheight of 0.38m
Topgallant headheight of 0.22m and royal headheight of 0.16m

This would give a total mainmast height of 12.17m and a total foremast height of 11.17m for a fully rigged ship with the hull dimensions of the Drogheda boat.

Bowsprit:
The whole length of the bowsprit is 3/7 the mainmast (2.76m), with ¾ of its length (2m) outboard beyond the stem.
While there was no evidence recovered for a bowsprit it could be argued that one is required in order to give an attachment point at a suitable lead angle for the foremast forestay support.

Yards:
The main yard total length is 7/8 of the mainmast (5.64m), main topsail yard is 5/7 main yard (4.03m), main topgallant yard is 3/5 topsail yard (2.41m) and royal yard is ½ topsail yard (2.01m)
The foremast yard total length is 7/8 of the main yard (4.94m), fore topsail yard is 7/8 main topsail yard (3.53m), main topgallant yard is 3/5 topsail yard (2.41m) and royal yard is ½ topsail yard (2.01m)

Sails:
The dimensions of each sail can then be calculated
This would give the following sail areas

Mainsail	18.5m²
Main topsail	15.3m²
Main topgallant	5.5m²
Main royal	2.8m²
Foresail	14.4m²
Fore topsail	12.0m²
Fore topgallant	4.9m²
Fore Royal	2.8m²

Total Mainmast sail area of 42.1m² and total Foremast sail area of 34.1m²
Overall total sail area 76.2m².
This sail area would give a sail area / displacement ratio of 24.3 and would be considered excessive on a working boat of this size and would in fact be considered large or high performance racing on a modern racing yacht

Traditionally smaller vessels tended to not carry topgallants or royals as in the case of the bigger fully rigged ships, and frequently the topmast would also not be used relying instead on a single mainmast and foremast. Reasons for this include the relatively smaller sail area did not require the overall sail plan to be subdivided into these smaller more manageable and easier handled sizes, a massive reduction in the quantity of standing and running rigging required to operate these additional sails and less sails equated to less crew required for sail handling.
A smaller crew number had other advantages in that less stores and provisions were required and as with all financial considerations less crew resulted in a larger proportional share of the earnings for the smaller crew number. Many boats operated on this share system where the earnings were divided into equal shares with the boat itself taking one share to cover running costs, the owner or skipper earning one share and the crew earning a half share or less (this subdivision of earnings exists on many working and fishing boats right up to the present day).

In single masted working boats of the late 17th and 18th century the mast tended to be approx the same size as the length of the boat although this simple rule of thumb varied greatly and other examples would include, length of boat plus one foot.

With the topgallants and royals removed the resulting mast heights would be 9.42m and 8.37m for the mainmast and foremast respectively. This would result in a sail area of 33.8m² on the mainmast and 26.4m² on the foremast, giving a total sail area of 61.2m².
This would give a more manageable sail area with less requirements to reduce sail as the wind strength increased, and when compared to other known working boats the ratios such as sail area / displacement of 19.2 and sail area / wetted surface area of 2.4 compare well (see Figure 25).

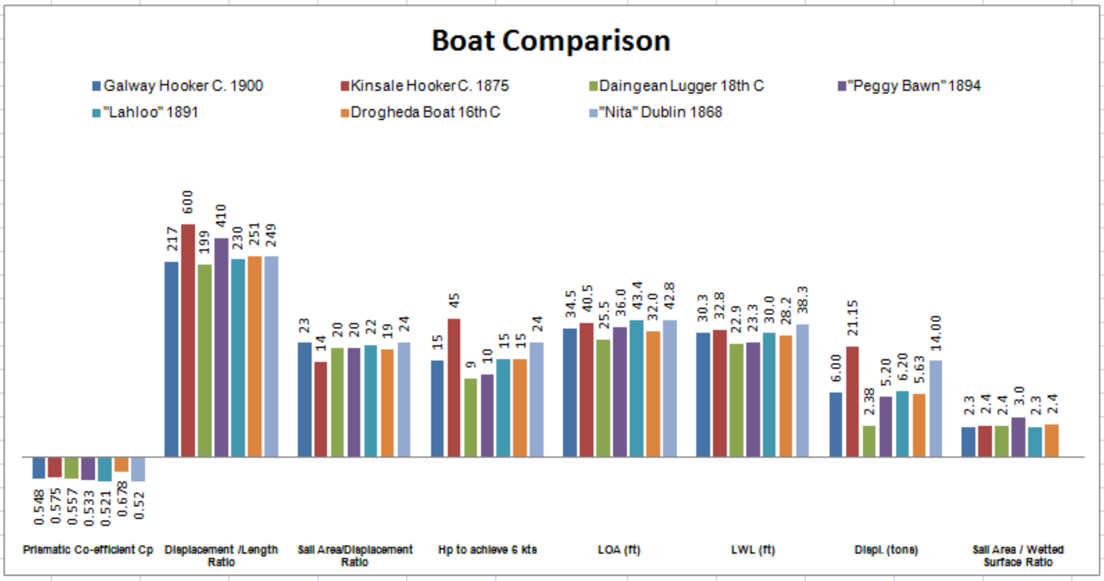


Figure 25 Some boat comparisons (P. Tanner)

It is also feasible that these sail areas be combined into a single sail on each mast, thereby further reducing rigging quantities and crewing requirements.

From the previous tables we can estimate that 61.2m² of sail area would generate approx. 11hp and a hull speed of 5kts requires 8.7hp while a hull speed of 6kts would require 15hp, resulting in a theoretical hull speed of approx. 5.7kts.

This would create a rigging and sail plan comparable to that of the sailing vessels shown in Plate 3, but this rig layout would appear to be unbalanced with too much sail area forward of the centre of lateral resistance (CLR) which is the pivot point of the boat and would therefore result in excessive or possibly dangerous lee helm.
It is normally preferable to have a slight amount of weather helm in a sailing vessel and this is often designed into the boat by having the centre of effort (CE) of the sails slightly aft of the CLR.

An alternative method of Estimating the rig size would be examining the two mast steps recovered which gives a mast tenon size for the main mast of 140mm x 110mm x 85mm and the mast heel block is 180mm sided dimension. If you take it that the mast base diameter is unlikely to be wider than the mast step, and also unlikely to be less than the longest dimension of the tenon, you could estimate the diameter at heel and hence the possible length (as these are usually related).
You could assume the mast diameter would be between 180 and 140mm; probably nearer 180; let's take 7 inches (178mm). A formula for a basic stayed mast would yield a mast length of 11.13m

The foremast on this basis would be about 90mm diameter at the heel; let's assume 3.5 inches (89mm); which would yield a mast length of 5.56m.

This would give a rigging size and sail plan that is more balanced, and comparable with the 16th Century herring busses as shown in Plate 4.

(**Authors note:** all of these power and speed calculations are affected by countless external influences including but not limited to factors such as sail canvas quality, crew handling skill, hull drag, actual displacement of vessel depending on cargo quantity carried, wind and wave conditions, etc, needless to say these results are indicative only and should be regarded as such)

F.11 Stability calculations for Empty boat with 15kts wind loading

Table 5 Floatation Condition for empty boat with 15kts wind loading

This is empty vessel condition consisting of constituent parts of hull, and rigging plus 2 crew with 1 days store each, no cargo or ballast.

Length overall	9795mm	Beam Overall	3095mm
Sinkage	194mm above datum waterline		
Waterline length	8372mm	Waterline Beam	2320mm
Displacement	3048Kg	Draft	684.5mm
Prismatic Co-efficient	0.675	Freeboard	1095mm
Waterplane Area	12.84m^2	Wetted Surface Area	19.89m^2
Downflooding angle	46.2deg	Righting moment 46.2°	823kgf-m
Heel angle	38.8deg	Resulting freeboard	159mm

Stability Criteria - Sample Source, Open Water (meters), Wind loading 15kts		
Name	**Actual**	**Pass / Fail**
GM At FreeEquil >= 0.15 meters	0.4103	Pass
GZ At 30 >= 0.2 meters	0.1382	Fail
Angle At GZmax > 25 deg	50.7662	Pass
Area Between 0 and 30 > 3.15 meters-deg	2.2635	Fail
Area Between 0 and Flood > 5.15 meters-deg	5.4971	Pass
Area Between 30 and 40 > 1.72 meters-deg	1.2345	Fail
Area Between 30 and Flood > 1.72 meters-deg	3.2336	Pass

With the boat heeled to 38.8° and the downflooding angle of 46.2° this would only leave 159mm of freeboard, in addition the relatively low righting arm moment of 823kgf-m means only a slight increase in wind pressure wouls cause the vessel to be swamped.

This indicates the boat when empty, would be unstable in a light to moderate wind and would almost certainly have carried some form of internal ballast.

F.12 Stability calculations for as found configuration with 15kts wind loading

Table 6 Floatation Condition for as found boat with 15kts wind loading

This consists of rebuilt vessel as shown, including hull and rigging together with 12 casks (as recovered) and notionally 2 crew, their stores for 1 day, anchor and warps.

Length overall	9795mm	Beam Overall	3095mm
Sinkage	11mm below datum waterline		
Waterline length	8587mm	Waterline Beam	2627mm
Displacement	5718Kg	Draft	839.5mm
Prismatic Co-efficient	0.678	Freeboard	922mm
Waterplane Area	15.64m²	Wetted Surface Area	24.31m²
Downfooding angle	38deg	Righting moment 38°	1890kgf-m
Heel angle	15.8deg	Resulting freeboard	497mm

Heel(deg)	Trim(deg)	Righting Arm (m)	Righting Moment (kgf-m)
0.000	-0.009	0.000	0.0
5.000	0.001	0.055	314.6
10.000	0.032	0.109	620.6
15.000	0.088	0.159	907.0
20.000	0.163	0.203	1163.4
25.000	0.243	0.243	1388.9
27.500	0.282	0.261	1493.9
30.000	0.322	0.279	1596.3
35.000	0.405	0.315	1801.1
37.171	0.444	0.331	1890.9
40.000	0.495	0.349	1997.2
50.000	0.727	0.390	2230.6
52.699	0.873	0.392	2241.6
60.000	1.295	0.378	2160.8
70.000	1.525	0.312	1782.2
80.000	1.790	0.213	1216.8
90.000	1.982	0.098	560.0
98.145	2.093	0.000	0.2
100.000	2.113	-0.022	-127.5

Stability Criteria - Sample Source, Open Water (meters), Wind loading 15kts		
Name	Actual	Pass / Fail
GM At FreeEquil >= 0.15 meters	0.6331	Pass
GZ At 30 >= 0.2 meters	0.2792	Pass
Angle At GZmax > 25 deg	52.6995	Pass
Area Between 0 and 30 > 3.15 meters-deg	4.5412	Pass
Area Between 0 and Flood > 5.15 meters-deg	6.5275	Pass
Area Between 30 and 40 > 1.72 meters-deg	3.1481	Pass
Area Between 30 and Flood > 1.72 meters-deg	2.1853	Pass

Conclusion:
With an average wind speed of 15kts the boat could potentially achieve a speed in the region of 5 to 5.5 knots at a heeling angle of up to 16° which would maintain approx. 500mm of freeboard and a righting moment in the region of 900kgf-m.
A sudden wind gust of 25kts would heel the boat to 36° while still maintaining a righting arm moment of approx1850kgf-m.
In this configuration the critical downflooding angle when the gunwale becomes submerged is at 38°.

F.13 Alternative methods of Propulsion

The boat would in all likelyhood have an alternative means of propulsion for use during periods of little or no wind and also for fine control manouvering.

Figures indicate the maximum output of a man rowing, on a fixed seat, is about 1hp (750 watts) sustainable for a short time and an average male can deliver approx 0.3 hp (250 watts) for 20 minutes.

Name:	**Drogheda Boat**				
LWL	28.182	feet	sq.rt LWL=	5.31	
Displacement	12566	lbs =	5.61	tons	
Target speed	1.7	knots	"Hull speed"=	7.1	kts
	1.96	mph			
S/L ratio =	0.32	RESULTS VALID BELOW 1.4 ONLY !			
10.665/(S/L)	33.304				
LB/SHP =	36939.7				
HP required =	0.34	hp			
kW required =	0.25	kW			

This would indicate that one man rowing could propel the Drogheda Boat at approx. 1.7kts

Name:	**Drogheda Boat**				
LWL	28.182	feet	sq.rt LWL=	5.31	
Displacement	12566	lbs =	5.61	tons	
Target speed	2.13	knots	"Hull speed"=	7.1	kts
	2.45	mph			
S/L ratio =	0.40	RESULTS VALID BELOW 1.4 ONLY !			
10.665/(S/L)	26.581				
LB/SHP =	18780.3				
HP required =	0.67	hp			
kW required =	0.50	kW			

This would indicate that two men rowing could propel the Drogheda Boat at approx. 2.13kts.With a potential rowing speed of between 1.7 and 2.2kts this would suggest the Drogheda Boat could be propelled by oar for close quarter manouvering, entering or leaving a port, or rounding a headland but would be unlikely to be used as a means of passage making.

F.14 Conclusions

The main characteristics of a boat are: (1) its shape; (2) its weight distribution; (3) its construction; (4) its method of propulsion; and (5) its method of steering.

All of these characteristics help to determine a boats performance, and when combined with the seamanship of the crew will give an indication of potential usage and areas of operation.

The reconstructed shape of the Drogheda Boat has been examined using the recovered evidence combined with the interpolated data.
The reconstructed vessel has the following principal dimensions when floating in its as found configuration.

Length overall LOA	9.795m
Beam Overall BOA	3.095m
Draft T	0.839m
Freeboard F	0.922m
Waterline length LWL	8.587m
Waterline Beam BWL	2.627m
Displacement	5718Kg
Prismatic Co-efficient	0.678
Waterplane Area	19.02m²
Wetted Surface Area	24.68m²
Downflooding angle	38deg
Righting moment 38°	1953kgf-m
Cargo (displ. - lightship)	2818kg

An initial assessment of the shape of the Drogheda boat based on the lines plan shows a vessel with a reasonable fine entry forward, full length keel, long smooth run aft below the waterline, and changing to fuller sections above the waterline. This would indicate a vessel designed for sailing, intended to be reasonably fast and still have a load carrying capacity.

A LOA/BOA ratio of 3.165 would be classed as average with a beamy boat defined as LOA/BOA less than 2.6 and a narrow boat as LOA/BOA greater than 3.75 (McKee, 1983,81)
The boat has a displacement/length ratio DLR of 251.44 which places it at the lower range of medium displacement category 250 to 320

The prismatic coefficient $C_{p\ of}$ 0.678 A lower value indicates a lower resistance and therefore a potentially faster boat.
Block Coefficient C_b of 0.296 where values below 0.65 indicate good speed potential.
Midships Coefficient C_x of 0.436 where values below 0.85 indicate good speed potential.

Slenderness Coefficient of 3.27 where values above 5 indicate good speed potential.

Volumetric Coefficient of 8.79×10^{-3} where values above 2×10^{-3} 85 indicate good speed potential.

In addition the hull shape above the waterplane provides adequate buoyancy at the ends with a moment to trim of 71.57kgf-m, a load of 350.5kgs required to trim the bow down by 10mm.

These figures indicate a vessel with a good speed potential and an easily driven form shape not requiring excessive sail areas, while still capable of carrying cargo.

Cargo

Evidence of 12 casks was recovered and these were used as a typical cargo for the vessel.

With a cargo of just the 12 casks recovered the boat would have an operational draft of 840mm and a freeboard of 922mm in the upright condition and a remaining freeboard of approx. 540mm when heeled while sailing in 15kts of wind.

A maximum possible number of casks was then fitted inside the hull to reveal a total quantity of 42 casks, this represents approx 75,600 herring or 8,400kg weight of herring. While this is still servicable it would not be so in exposed sea conditions, or on a long passage in rough weather.

A more suitable loading might be 75% of max loading which would mean 32 casks giving a total displacement weight including vessel, crew and rigging of 10223kg and when you subtract the lightship weight of the vessel which is 2900kg gives a gross deadweight of 7323kg equal to 7.2 tons

This would result in the vessel having a freeboard of 662mm and a draft of 1140mm in the upright condition and when heeled by wind loading while sailing would have sufficient freeboard remaining to undertake a coastal passage, although probably not enough to consider a long distance passage in exposed waters such as crossing the Irish Sea.

There was no evidence recovered for internal ballast save for one piece of limestone measuring c. 320mm by 180mm by 140mm, the stability analysis for the empty vessel shows that it would be unstable in this configuration and some form of internal ballast would be necessary, however it was common practice especially on the west coast of Ireland to carry a full cargo without ballast on the outbound or delivery leg of a trip and in the absence of a return load, to replace the cargo weight with locally sourced stone as ballast for the return leg of the trip.

An initial examination of the overall construction of the boat would suggest a vessel which was either roughly or quickly/cheaply constructed to function as a workhorse without regard for a high level of detail to finish and quality.

The use of grown timbers for the stem and stern hook, together with nicely formed tabled scarf joints indicate the builder had at least some knowledge of boat building techniques. However the location of these scarf joints, often directly above one another, would be alarming by modern boatbuilding rules which give exact locations and spacing rules. Clinker construction for modern vessels of 20 - 40ft (6 - 12m) inclusive requires the scarf spacing on adjacent strakes to be at least 72in (1.82m) with a scarf length of 4.5in (0.114m).

Grown floor timber spacing 24in (0.6m) and grown frame spacing 16in (0.4m).

The frame spacing on the Drogheda boat is at irregular intervals ranging from 0.52m to 0.83m with an overall average of 0.7m

Bilge drain holes in the aft end of both garboard planks indicate the boat was either hauled ashore or dryed out and left "draining" for a period of time.

Rigging

Examining the two mast steps recovered gave estimated mast heights of 11.13m for the main mast and 5.56m for the foremast.

Sail Area

From this a sail area of 650ft² (60m²) has been extrapolated which would generate approx 10.9hp with 15kts of wind and this could equate to 5.4kts boat speed
A sail area of 60m² would give a sail area / displacement ratio of 19.2.ratios between 10 and 15 Undercanvased while ratios between 16-20 comfortable cruising.

With an average wind speed of 15kts the boat could potentially achieve a speed in the region of 5 to 5.5 knots at a heeling angle of up to 16° which would maintain approx. 500mm of freeboard and a righting moment in the region of 900kgf-m.
A sudden wind gust of 25kts would heel the boat to 36° while still maintaining a righting arm moment of approx1850kgf-m.
In this configuration the critical downflooding angle when the gunwale becomes submerged is at 38°.

Rowing
With a potential rowing speed of between 1.7 and 2.2kts this would suggest the Drogheda Boat could be propelled by oar for close quarter manoeuvring, entering or leaving a port, or rounding a headland but would be unlikely to be used as a means of passage making.
These figures would suggest the Drogheda Boat was possibly a local fishing boat delivering its weekly catch of 12 casks of herring c. 2400kg to a local market, or could also serve the function of a lighter, a smaller vessel used to offload cargoes from a larger ship, restricted by its deep draft from entering a port. In this function the boat could easily carry a load of 32 casks c. 7300kg and potentially an even greater load of 42 casks representing 8400kg in sheltered waters.

It would also be capable of undertaking coastal voyages, within easy reach of a sheltered port or anchorage in the event of inclement weather or sea conditions but was probably unlikely to have undertaken long distance offshore voyages.

Lines plans and General Arrangement Drawing.

A general plan showing recovered material and the rebuilt vessel is shown on Page 53
A linesplan is shown on Page 54
A second linesplan showing the recovered material is shown on Page 55
The Construction drawing is shown on Page 56

The original report also included 11 additional appendices which have not been reproduced here:

The weight report as built is shown in Appendix 5
The weight report as found condition is shown in Appendix 6
The weight report with 32 casks is shown in Appendix 7
The weight report with 42 casks is shown in Appendix 8
The stability report empty is shown in Appendix 9
The stability report as found is shown in Appendix 10
The stability report empty with 15kts wind loading is shown in Appendix 11
The stability report as found with 15kts wind loading is shown in Appendix 12
The stability report with 32 casks in open water is shown in Appendix 13
The stability report with 32 casks in partially protected water is shown in Appendix 14
The stability report with 32 casks in protected water is shown in Appendix 15

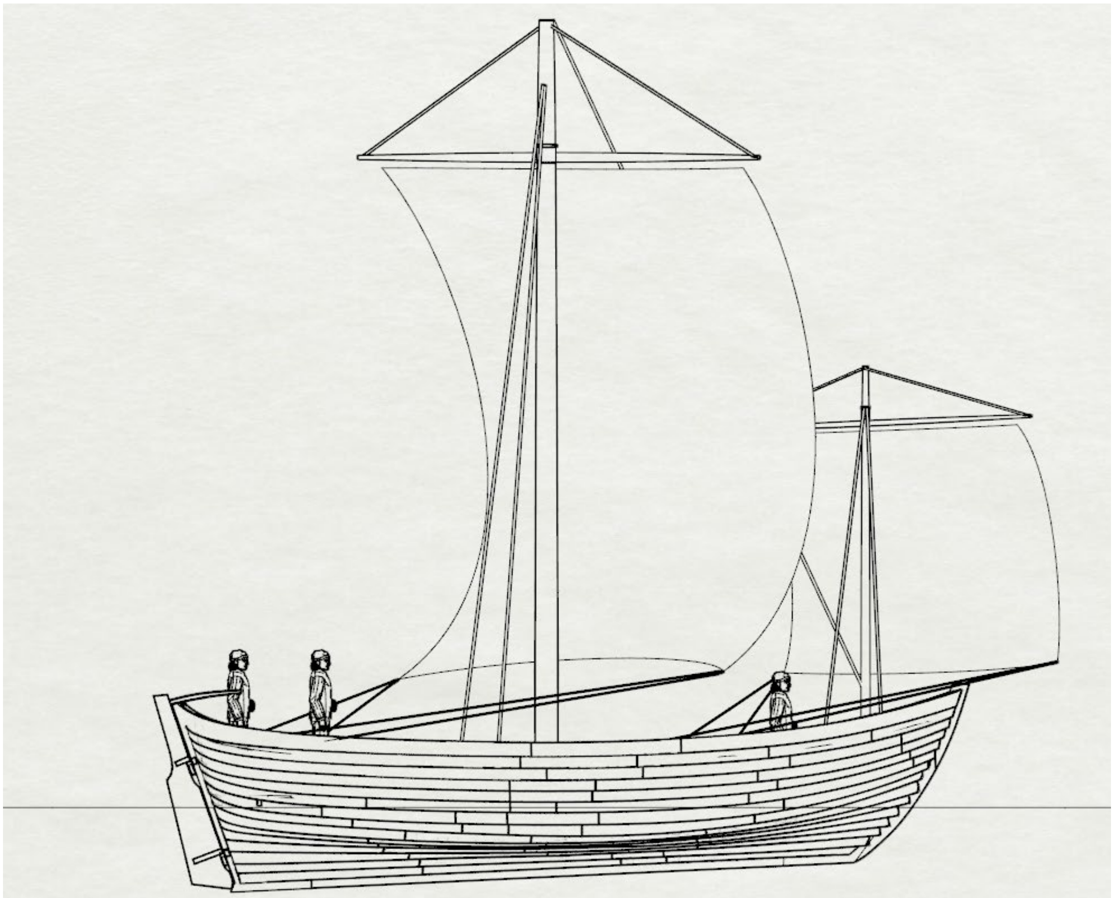


Figure 26 showing reconstructed vessel (P. Tanner)

Figure 27 showing reconstructed vessel (P. Tanner)

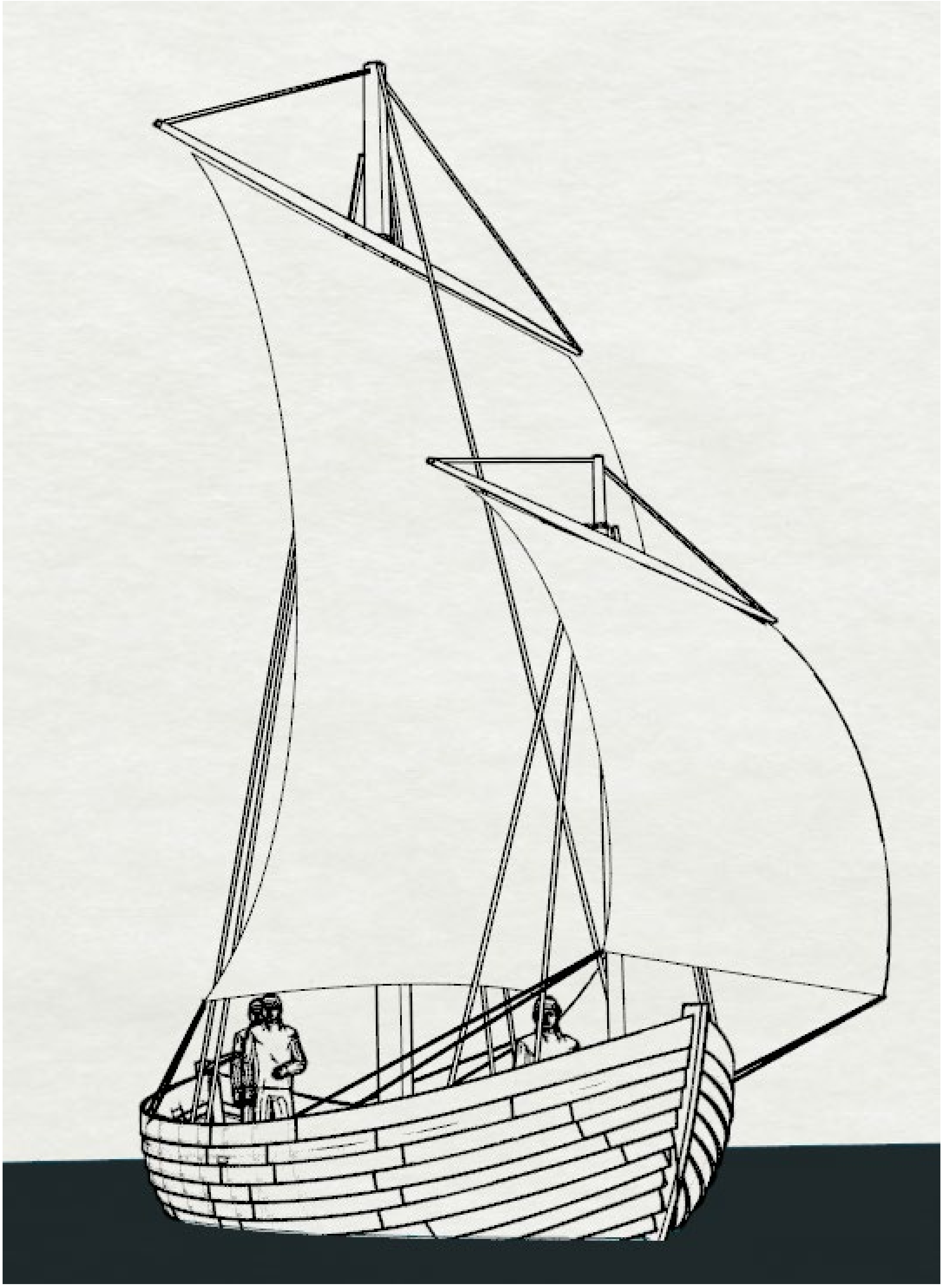


Figure 28 showing reconstructed vessel (P. Tanner)

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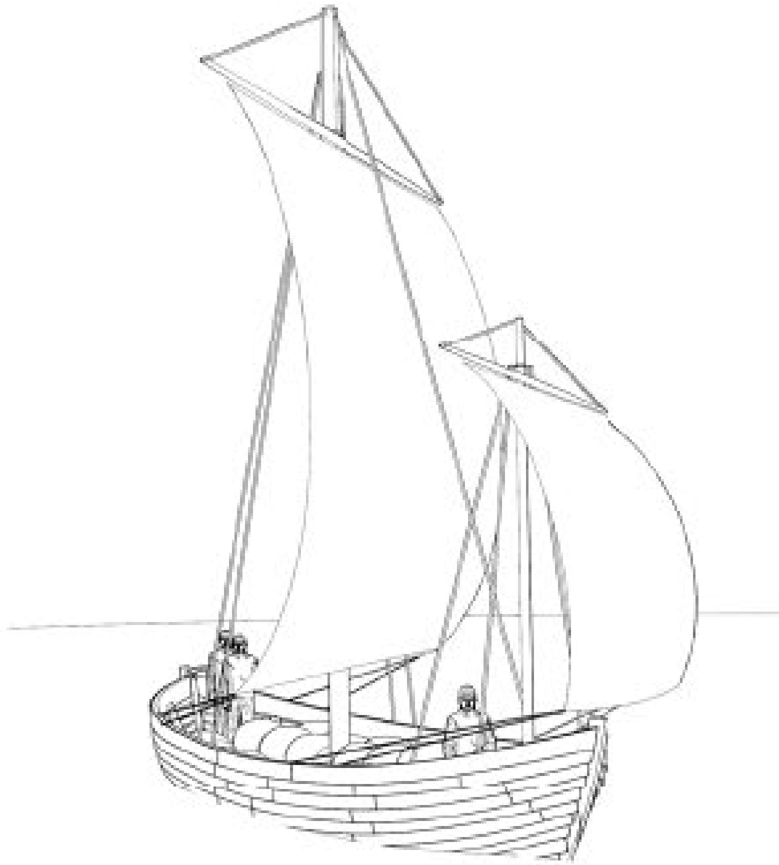
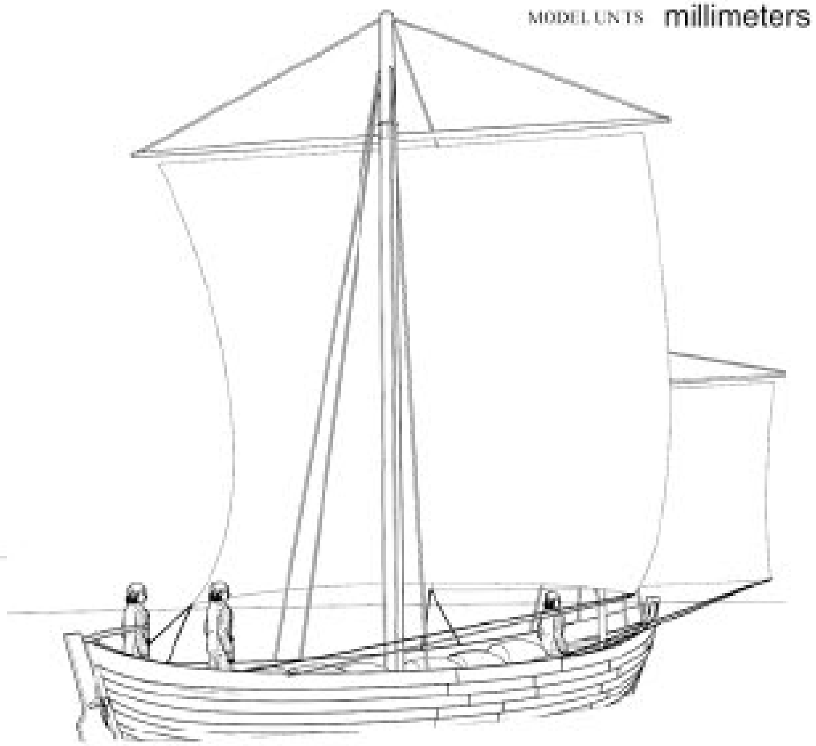
"16th C. Drogheda Boat"

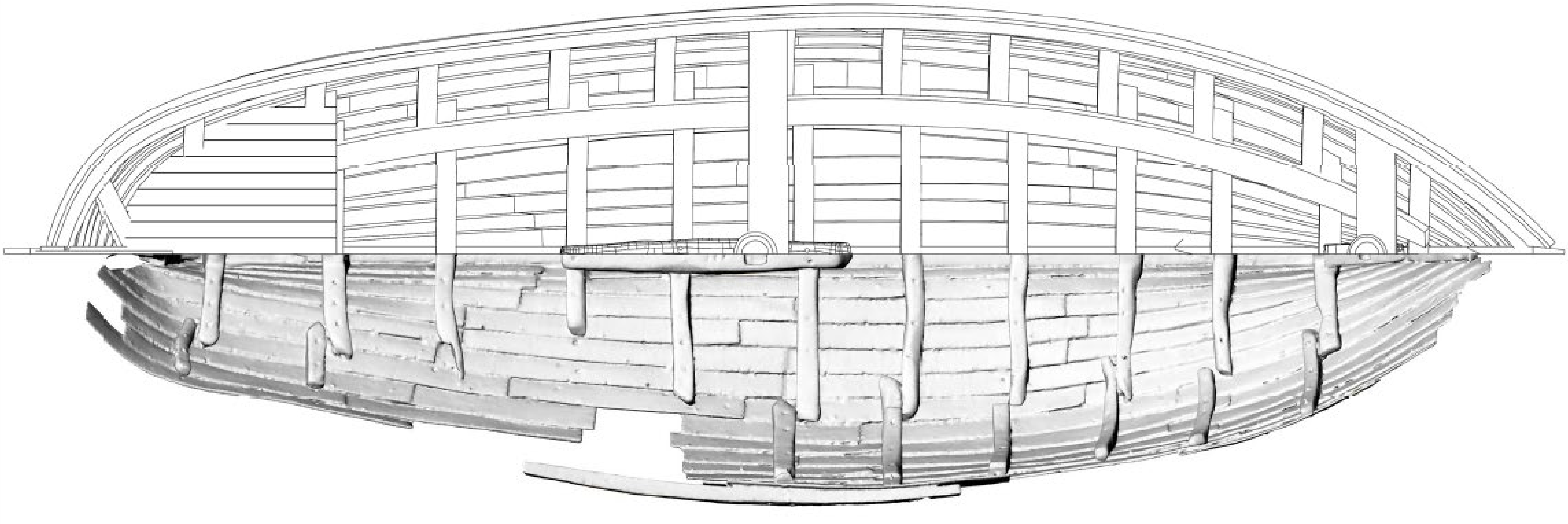
DRAWN	P. Tanner	DATE	27/10/2011
DRAWING NUMBER	1	SHEET	1 of 4 - A 3
MODEL UNITS	millimeters	SCALE	1 : 25

PRINCIPAL PARTICULARS
Length Overall (On Deck)..........9.795 m
Length W.L..................................8.590 m
Beam..3.095 m
Draft ....0.835 m
Displacement..............................5718kg

NOTES
This lines which are the basis for this drawing were produced by 3D laser scanning the reconstructed Scale Model
Lines drawn to outside of planking





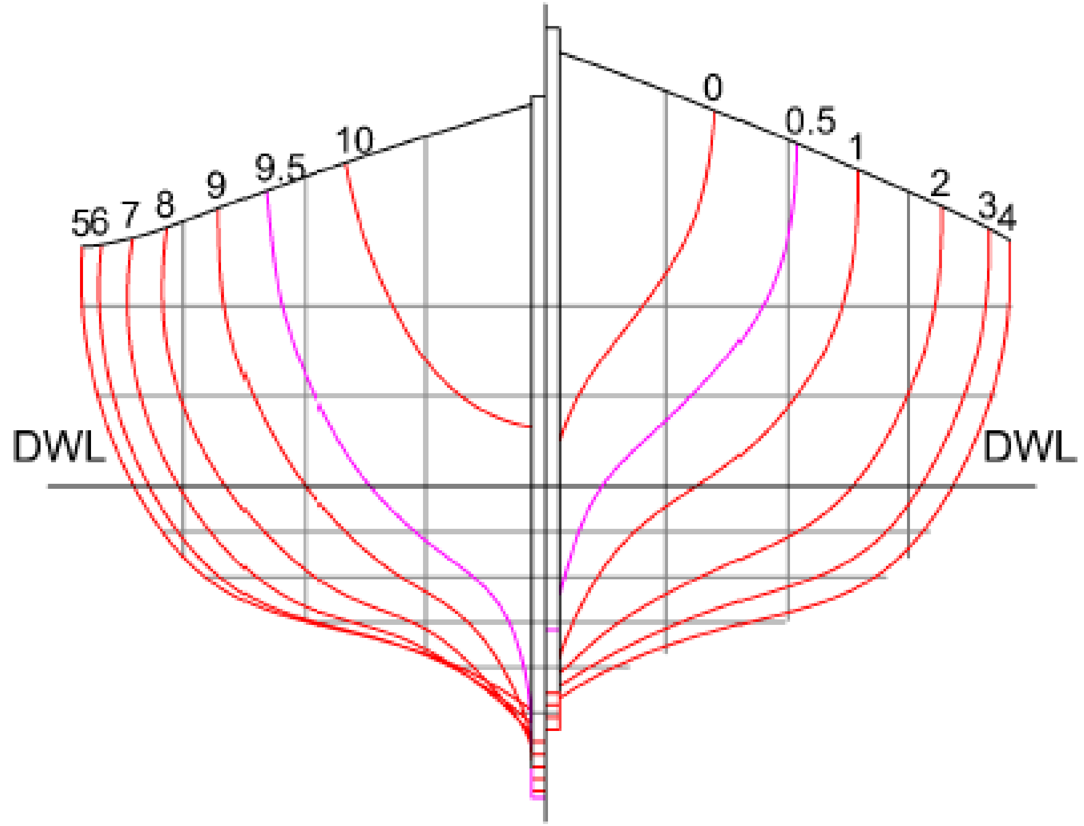


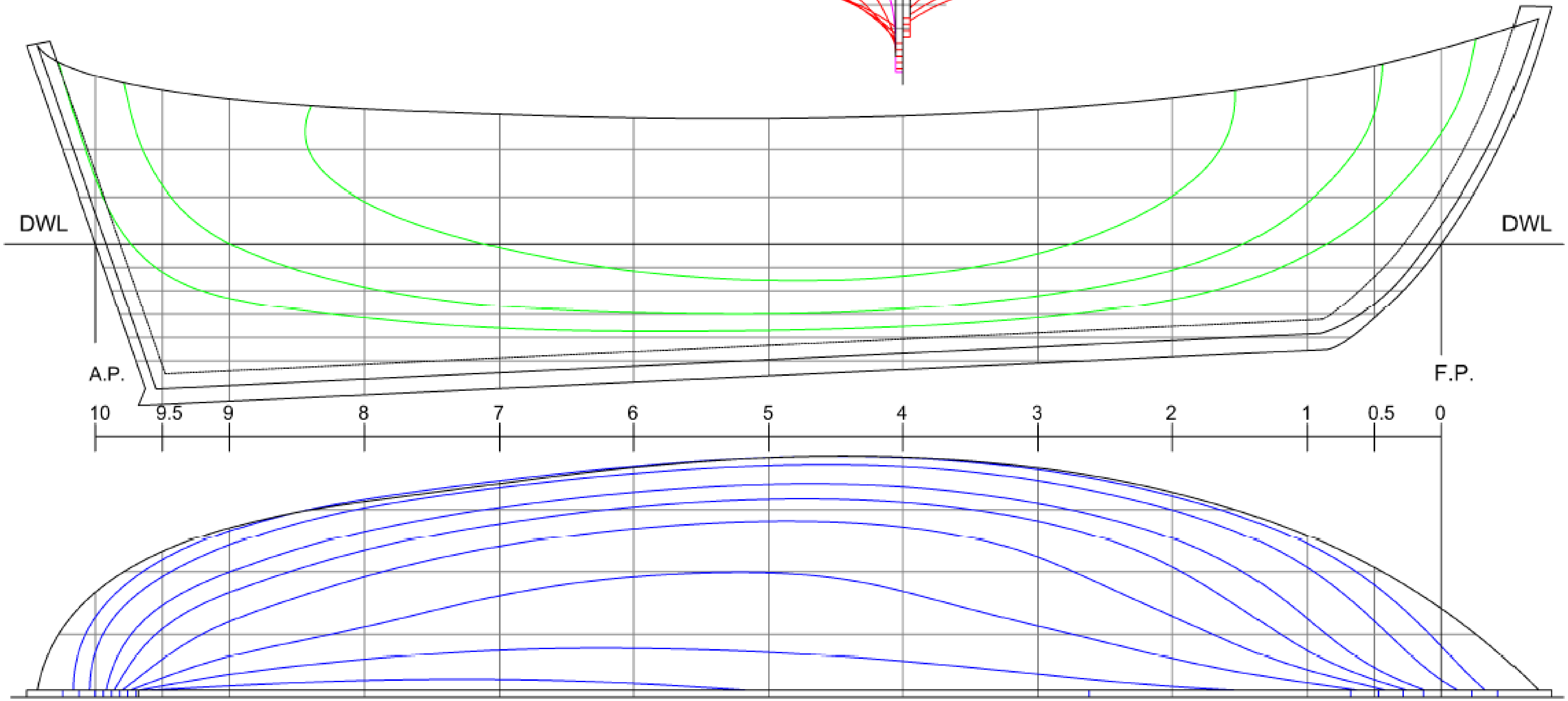
"16th C. Drogheda Boat"

DRAWN P. Tanner	DATE 27/10/2011
DRAWING NUMBER 2	SHEET 2 of 4 - A3
MODEL UNITS millimeters	SCALE 1:25

PRINCIPAL PARTICULARS
Length Overall (On Deck)..........9.795 m
Length W.L...................................8.590 m
Beam..3.095 m
Draft ....0.835 m
Displacement................................5718kg

NOTES
This lines plan was produced by 3D laser scanning
the reconstructed Scale Model
Lines drawn to outside of planking



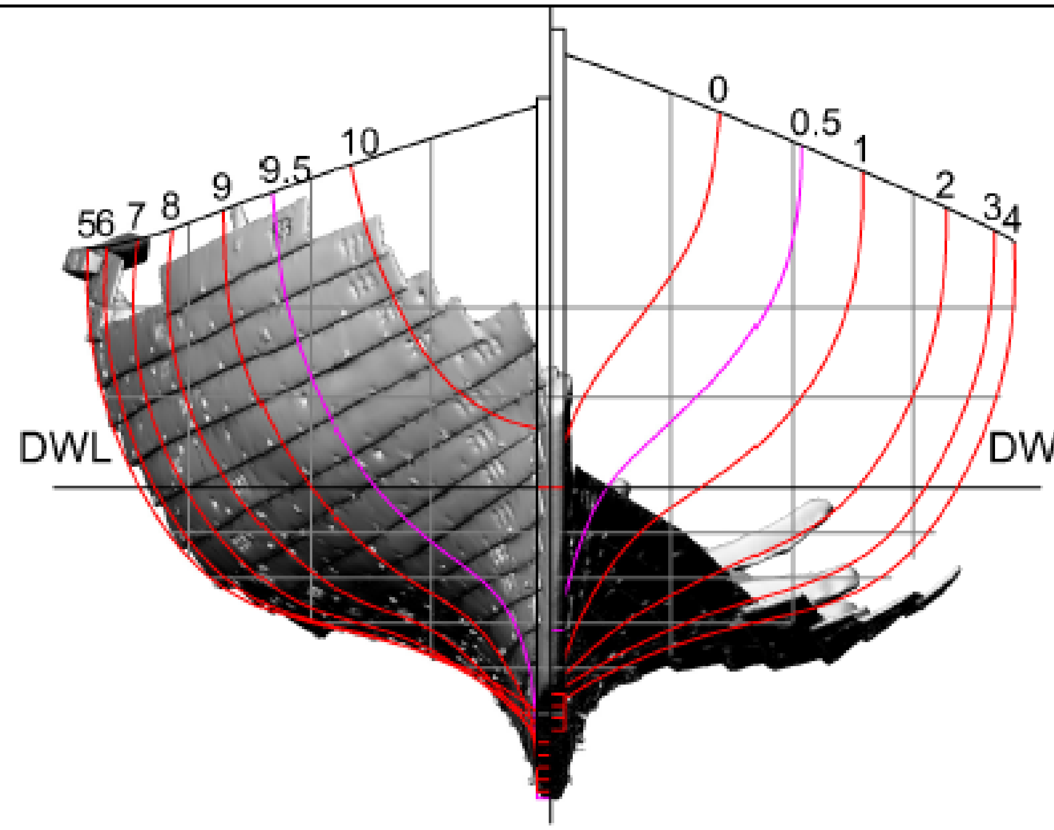


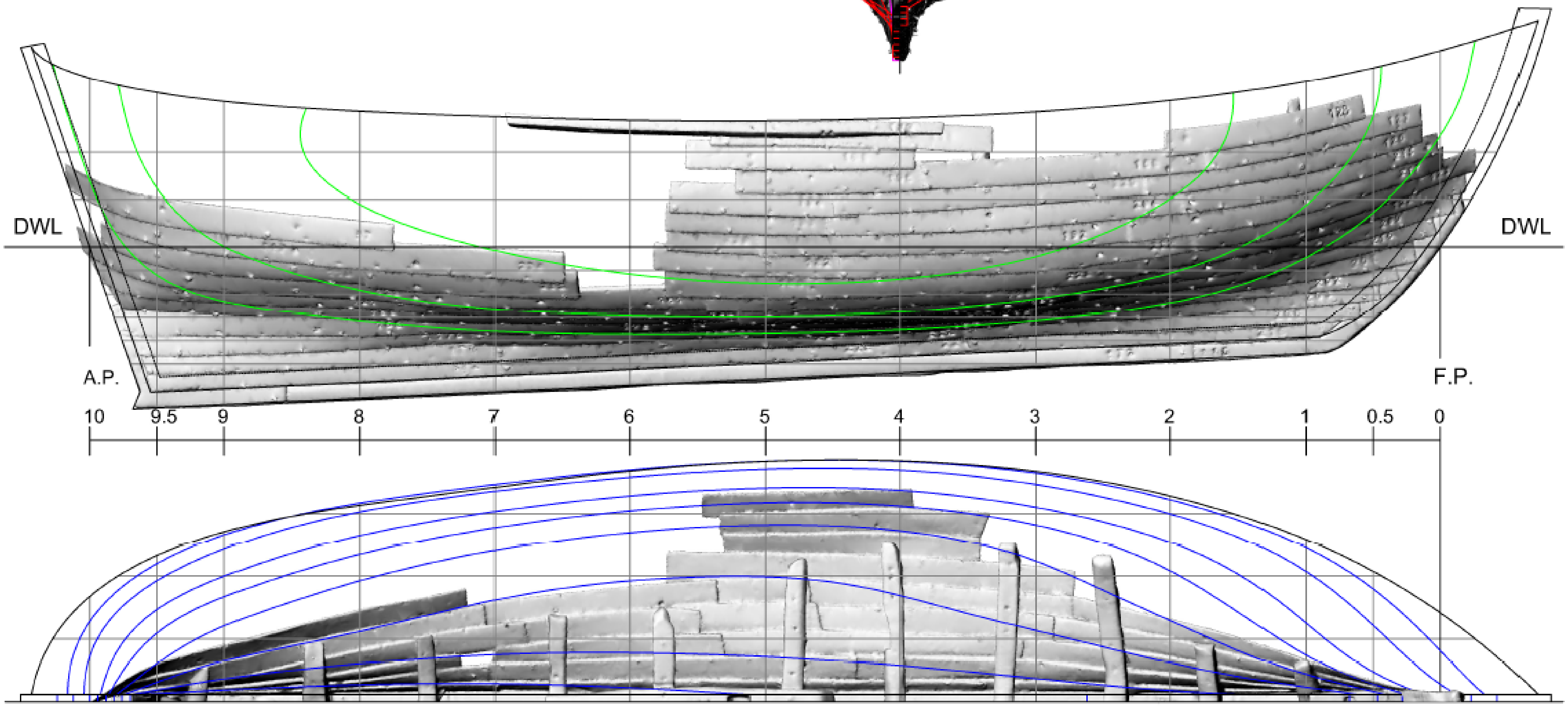
"16th C. Drogheda Boat"

DRAWN P. Tanner
DRAWING NUMBER 3
MODEL UNITS millimeters
DATE 27/10/2011
SHEET 3 of 4 - A3
SCALE 1 : 25

PRINCIPAL PARTICULARS
Length Overall (On Deck)..........9.795 m
Length W.L...................................8.590 m
Beam..3.095 m
Draft ....0.835 m
Displacement...............................5718kg

NOTES
This lines plan was produced by 3D laser scanning
the reconstructed Scale Model
Lines drawn to outside of planking



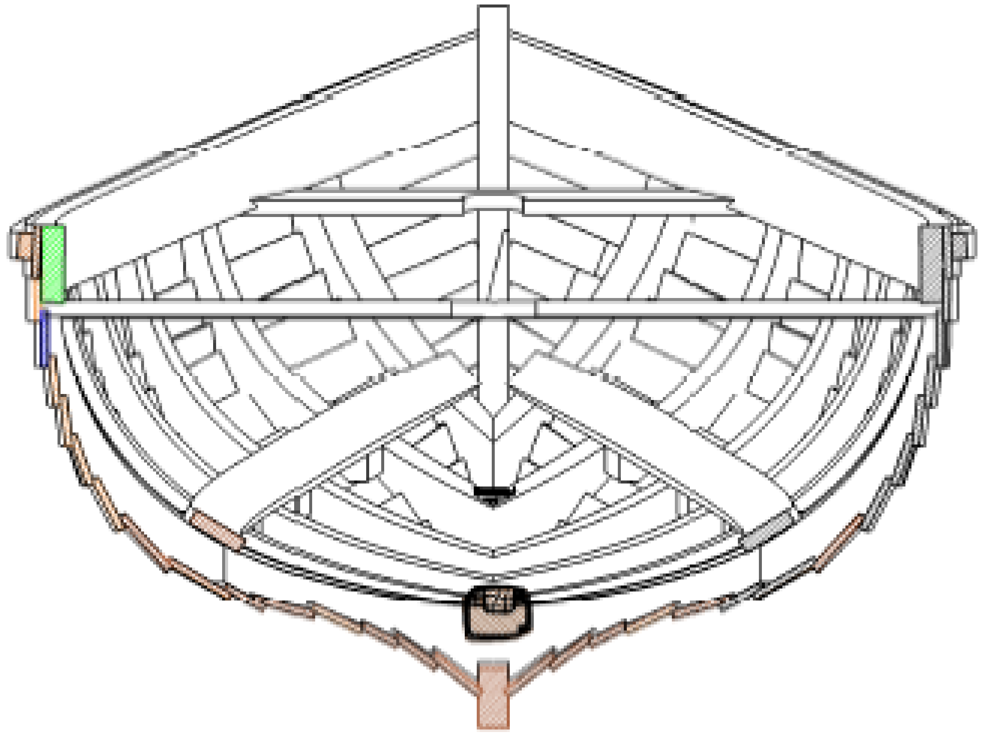


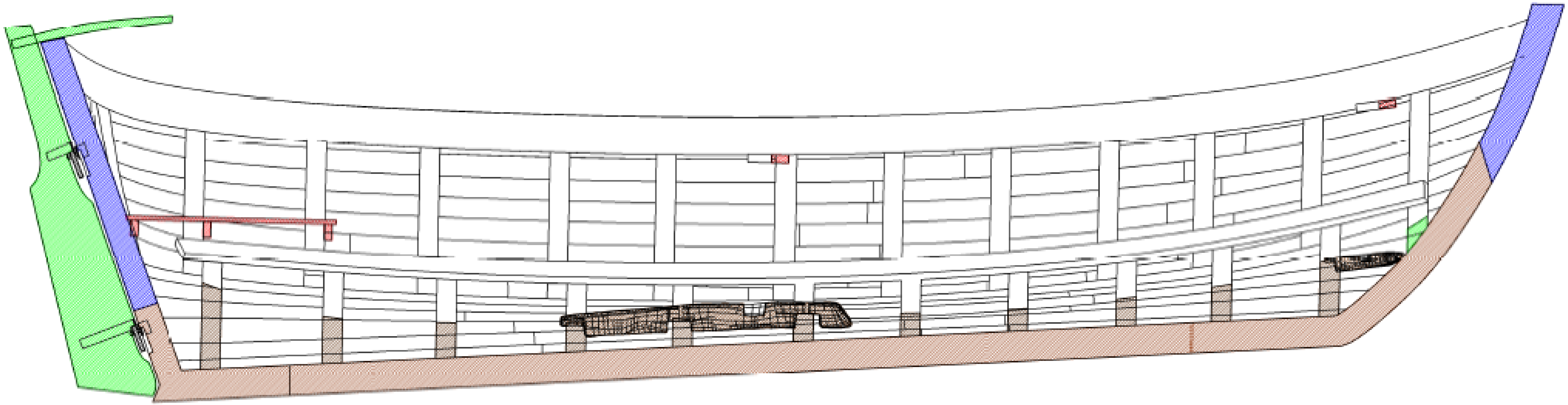
"16th C. Drogheda Boat"

DRAWN	P. Tanner	DATE	27/10/2011
DRAWING NUMBER	4	SHEET	4 of 4 - A3
MODEL UNITS	millimeters	SCALE	1:25

PRINCIPAL PARTICULARS
Length Overall (On Deck)..........9.795 m
Length W.L.................................8.590 m
Beam..3.095 m
Draft ....0.835 m
Displacement..............................5718kg

NOTES
This lines which are the basis for this drawing were produced
by 3D laser scanning the reconstructed Scale Model
Lines drawn to outside of planking





F.15 References for Appendix F

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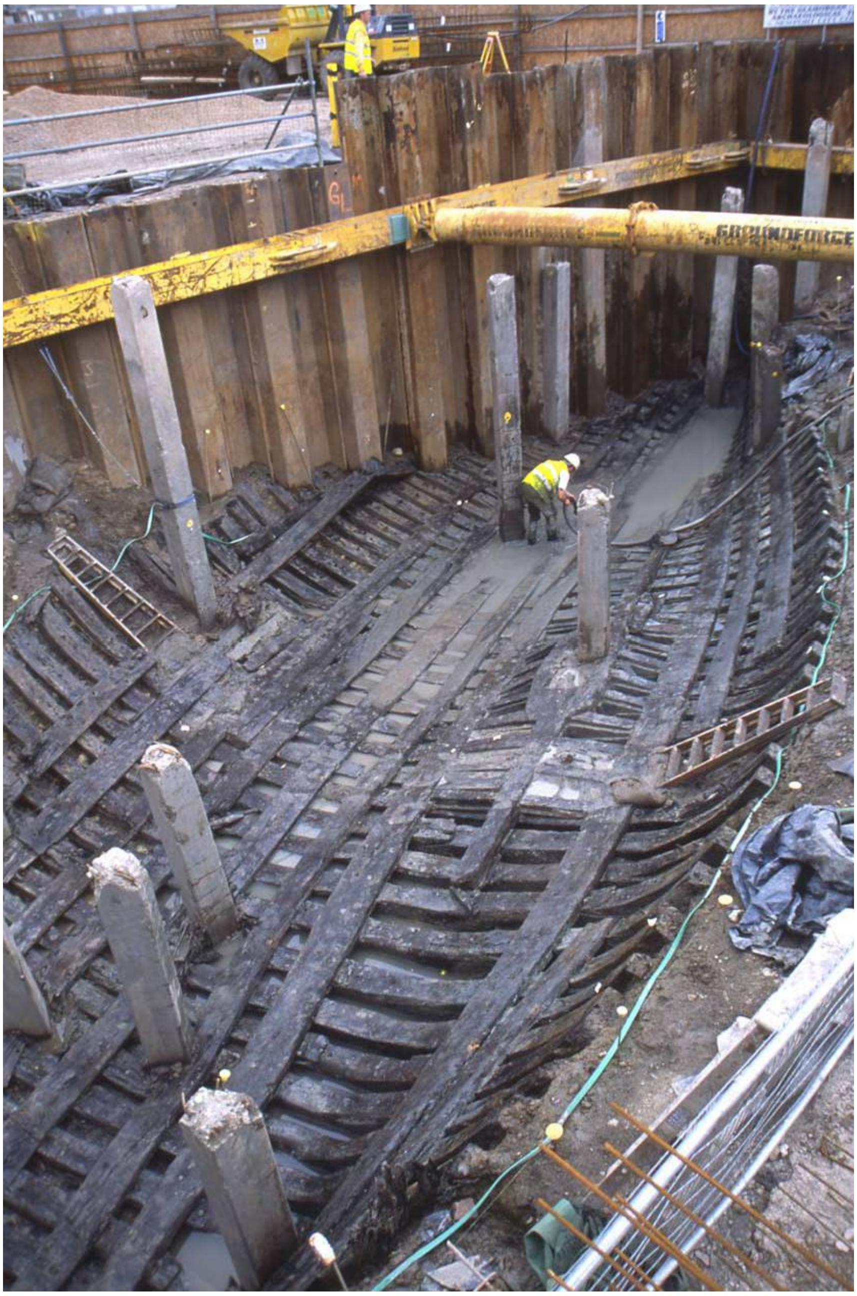
Appendix G Newport Phase 2 Capital Reconstruction

Newport Medieval Ship Project

Specialist Report:
Reconstructing the Hull Shape
Phase Two
Capital Reconstruction



Site number: GGAT 467

Site location: NGR: ST 31286 88169 Kingsway, Newport, South Wales, UK.

NEWPORT MEDIEVAL SHIP PROJECT

DIGITAL RECONSTRUCTION AND ANALYSIS OF THE NEWPORT SHIP

Phase Two

Capital Reconstruction

BY

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April 2014

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G.3 Introduction:

In 2002, during the construction of the Riverfront Theatre, on the banks of the River Usk in Newport, South Wales, an archaeological find of great significance was unearthed. While undertaking the excavations for the theatre's orchestra pit, the well-preserved remains of a 15th century clinker built merchant vessel were discovered, the incomplete remains measuring 22.8 x 7 x 3.6 m, and consisting of 1,700 ship timbers, and over 600 associated timbers and small finds were retrieved and catalogued.

The articulated structural remains consisted of a beech **keel**, truncated at the aft end by the site cofferdam, with the recovered portion having a recorded length of 19.8 m, and being of the beam type with a rebate for the garboard strake, with moulded dimensions between 170 mm and 240 mm and sided dimensions between 184 mm and 270 mm.

The **Stem** which was shattered into several pieces by the installation of the cofferdam and concrete piles was originally hewn from a single curving piece of oak and was scarphed to accommodate the keel as well as rebated to accept the planking hood ends.

Hull planking consisted of overlapping "clinker" radially split oak planking with an average thickness of 30-35 mm, fastened together with iron nails "*clenched"* (McGrail 2004a:152) over four sided iron roves (washers) with luting placed in the overlapping seams to ensure a watertight joint. The garboard (lowest) plank and the forward hood ends of subsequent planks were fastened to the keel and stem post using iron spike nails. The recovered planking represented 17 strakes from the port side and 35 strakes from the starboard side.

Oak **framing** consisted of floor timbers, and up to three futtocks having an average sided dimension of 244 mm, and an average of 121 mm spacing, with the average moulded dimension ranging from 354 mm at the centre line to 154 mm at the bilge and 130 mm at the recovered top. A total of 63 frame stations were recorded. Framing was fastened to the hull planking using both wooden treenails and iron spike nails. Frames were not fastened to the keel.

An oak **keelson** with a recorded length of 9.9 m was recovered, which included an integral swelling to accommodate the **mast step** included rebates on the underside to clamp over the floor timbers, and was treenailed to the floor timbers, and was braced in the central mast step area by ten oak **braces** fitted between the keelson and first stringer, and treenailed to the floor timbers.

Oak **stringers** recovered included the incomplete remains of three rows of stringers from the port side, and eight incomplete rows of stringers from the starboard side. The seventh stringer on the starboard side included substantial "swellings" to accommodate the dovetailed ends of the heavy transverse beams, and the eight stringer could possibly be relabelled to a **beam shelf** as it contained multiple rebates for the smaller deck beams. The stringers were generally fastened to the frames with two treenails at each frame station.

Ceiling planks and bilge boards, two or three rows of oak ceiling planks lined the interior of the hull between the keelson and first stringer, with a single row of ceiling planks between the first and second stringers, a single row of ceiling planks between the second and third stringers, and a single row of ceiling planks between the third and fourth stringers, finished with short loose ceiling boards fitted from the top of the fourth stringer outboard to the hull surface. The majority of ceiling boards were fastened to the inside face of the frames with iron spike nails. Loose fitted bilge boards filled the spaces between the keelson braces.

Four **riders** recovered in the bow area were oak and rebated to sit atop the stringers, ranging in size from 306 – 636 mm moulded and 100-261 mm sided.

Disarticulated elements included standing knees, transverse beams, deck elements including hatches, deck beams and carlings and a fragment of waterway, stanchions as well as other internal bracing elements.

This report deals with the issues raised following publication of the initial minimum reconstruction as published in "Newport Ship Specialist Report : Digital Reconstruction and Analysis of the Newport Ship" (Tanner 2013a).

Minimum reconstruction from Phase 1 (Tanner 2013a)

Experimental Boat and Ship Archaeology:

No more than fragments about the more remote past survive to be excavated, or as documents, inscriptions or icons. However, discoveries have recently been opening up lines of study of the maritime past and to learn from them more than is immediately obvious, it has become increasingly possible and at the same time necessary to formulate hypotheses which have to be tested to be tenable. Experimental Archaeology provides one way to investigate hypotheses about past technologies, artefacts and cultures. In Maritime Archaeology, such experiments can take the form of building, on full or reduced scale, models or making other simulations of ancient boats or ships, and testing them in repeatable sea trials, real or simulated.(Coates et al. 1995:293)

The very act of attempting to repair or reassemble the remains of a wreck, however slight the repair or repositioning of a part, is by definition hypothetical, unless it can be stated with 100% certainty that the repair or repositioning is accurate. This makes it experimental by nature. Otherwise what is produced, is nothing more than glorified surveying, and will do little to increase our knowledge of past technologies, artefacts and cultures.

The following reconstruction is by its very nature experimental, utilising digital documentation and digital reconstruction techniques. The reconstruction is conjectural for everything above the 35th strake, the transom, even the extrapolated shape of the stem. However, every step from the first timber being documented to the conjectural placement of the last piece of rigging, has been meticulously documented, and explained.

The physical scale model is the changeover point from definite, factual evidence, to hypothetical solutions. All of the data leading to that point as well as hypothetical solutions from that point onwards is available online via the archaeological data service (https://archaeologydataservice.ac.uk/archives/view/newportship_2013/), and future analysts can return to the reconstruction, to whichever point they may agree or disagree with, and continue from there in whatever new or alternate direction as they see fit.

G.4 Nomenclature :

Copies, Replicas, Reconstructions and Simulations:

These are all titles which have been used, sometimes indiscriminately, and rarely systematically, then add in prefixes such as hypothetical, experimental, partial, minimum, intermediate, contributory, capital and floating, how many more have I missed ? As noted by Crumlin-Pedersen (Crumlin-Pedersen 1995:303), discussions in IJNA have been centred primarily on problems of terminology in dealing with the various vessels built and some suggested solutions were proposed in the "replication debate" (Fenwick 1993:197). Similarly, Westerdahl notes the terms posed by McGrail, of copies or replicas for archaeological finds, and reconstructions or simulations for projects like the trireme based solely on documentary or iconographic evidence, will create serious confusion about the meaning of words. He cites Bill (1991) as a reconstruction in the true sense, and states because most wrecks do not survive beyond the upper parts, insufficient detail remains to enable talk of reconstruction or reproduction beyond this stage. Hypothetical rigging, experiments or sea trials carried out with alternative installations or techniques give the best meaning of the term floating hypothesis used by McGrail (Westerdahl 1993:205).

As-Found / Torso drawings:

'torso (Crumlin-Pedersen) / as-found (McGrail)' scale model or drawing in which allowances have been made for distortion, displacement and shrinkage-using valid comparative evidence to 'fill in' the missing parts, but without recourse to naval

architectural conjectures, alien elements, or anachronistic intrusions (Crumlin-Pedersen and McGrail 2006:57).
McGrail defines the "as-found" drawing, as being the hull as actually found, but with displaced timbers re-integrated, distorted timbers smoothed out, fragmented timbers re-assembled, and the hull rotated to its likely attitude when afloat. The as-found drawing or model does not include any reconstruction of missing parts. (McGrail pers. comm.)

Minimum Reconstruction:

The term 'minimum reconstruction' is now used to describe one or more (partial) reconstructions based on the excavated evidence-as depicted in a 'torso/as-found' scale model or drawing (Crumlin-Pedersen and McGrail 2006:57).

This author believes the 'As-Found' nomenclature, as used by McGrail, is a confusing and misleading label. *'As found' is often interpreted as referring to pristine condition, but "as found" means exactly that. It remains in the condition in which the current owner or consignee found it*. McGrail's definition, with re-integrated timbers, distortions repaired, fragments reassembled, and orientated to a floatation condition is far from the "as found" condition. In order to achieve the, re-assembled, re-integrated, smoothed and orientated condition described by McGrail either a preconceived shape, or a series of hypothetical reconstructions would be required in order to ascertain the correct shape and orientation.

Marsden (Marsden 1993:206–207) cautions against the use of the term "Replica", the dictionary definition being "*exact copy, especially a duplicate of a work, made by the original artist*". As most ship reconstructions are conjectural to some degree, it will be on the rarest occasion, or the bravest archaeologist who can correctly apply the term replica to a reconstruction. This author suggests the term replica be limited to use for individual elements, i.e. an exact copy of a single component, or be banished from the field of ship and boat reconstruction. If the label replica must be used, it should be quantified in the form "building a replica of a **hypothetical** 'whatever -named' vessel".

Capital Reconstruction:

Similarly, Steffy's label, “capital reconstruction” could be classed as misleading or confusing, as it is unclear what is meant by, and what level of importance or credibility, the term Capital adds to the reconstruction label.

Partial list of Fenwick's definitions:
Reconstruction Vessel constructed using the evidence from surviving elements to determine the form, dimensions, materials and technology originally employed;
Working model/Floating hypothesis An experimental three-dimensional form.
Restoration Alters a surviving vessel to represent an earlier condition
(Fenwick 1993:197)

For the purposes of this report the following nomenclature and labels will be used:

As Found Drawing:

Would be exactly that, a site survey drawing, either two or three dimensional, showing the material as found prior to any external influences such as repairing or reshaping.

Restored remains:

The hull as found, with displaced timbers re-integrated, distorted timbers smoothed out, fragmented timbers re-assembled, and the hull rotated to its likely attitude when afloat.

Working Model:
Any experimental three-dimensional form.

Floating Hypothesis:
The restored remains, only with missing materials added by mirroring existing parts, or extrapolation based on direct preserved evidence, to create a vessel capable of floating.
It should be noted that every subsequent stage, being based in whole or part on this floating hypothesis, is by definition hypothetical, and as such, each subsequent label could benefit from the inclusion 'hypothetical'.

Minimum Reconstruction:
The floating hypothesis version, with supplementary evidence based on contemporary finds and parallel iconographic evidence. Evidence from within the same tradition, but of a later date should, when used, be distinctly identified, and the relevance clearly argued. Following testing, this reconstruction is then published for review and criticism.

Intermediate or Revised Reconstruction:
The Minimum reconstruction version which has been modified or revised, as a result of comment or criticism following initial publication. Following testing, this revised reconstruction is again published for review and criticism.

Principal Reconstruction:
The combination of all preceding phases, in an iterative process, into a more definitive hypothetical reconstruction.

Abbreviations used:

IJNA	International Journal of Nautical Archaeology
D.W.L.	Design or Datum Water Line
L.C.G.	Longitudinal Centre of Gravity
T.C.G.	Transverse Centre of Gravity
V.C.G.	Vertical Centre of Gravity
GMt	Transverse metacentric height
DDM	Direct Digital Manufacturing
CAD	Computer Aided Draughting

G.5 Reconstruction Methodology:

Traditional Methods:

Recording:

Various techniques for the recording of wrecks have included methods such as:

- Sketch and scaled drawings created from direct measurements;
- Full scale tracing, where each element is washed, a polythene sheet is smoothed over the wet timber and features recorded using coloured felt pens (Valerie H. Fenwick 1972:179), the object being to produce a full size "paper pattern" of both sides of every plank;
- combinations of photography and transparent overlay tracing such as used during the excavation of the Batavia, which were subsequently redrawn at 1:4 scale (Baker and Green 1976:151), were reported by the authors as "fairly satisfactory, although not ideal" with details being inadvertently missed and errors introduced during the reduction to 1:4. The subsequent 1:10 scale model of ships timbers reported as unlikely to have an accuracy of more than ±5%;
- Elevated plane tracing, a technique developed at Roskilde to documents the Skuldelev timbers (Crumlin-Pedersen 2002d:53–56) uses the principles of projection by eye, recording onto transparent polyester film mounted on glass set above the timber, using differing colours and thickness of waterproof pens;

The Institute for Archaeologists guidelines (Institute for Archaeologists 2008b:7) states the record should contain data on the size, shape, material and condition of all elements of the vessels structure, fittings and ancillary components including a record of constructional features, all fastenings (size and type), tool marks (type and size), shipwrights marks, carpentry features (joints, bevels, chamfers), wood features, (grain, sapwood, knots, pins, bark), wear and compression marks, means of propulsion and steering, fittings (internal and external) and outer and internal coatings (paint, paying, caulking). Where sufficient remains are available this record should be to a standard to enable a reliable reconstruction.

Reconstruction:

A series of 10 or more articles were published in the IJNA spanning the period 1992 - 2007, (McGrail 1992; Goodburn 1993; Coates et al. 1995; Crumlin-Pedersen 1995; Roberts 1998; Crumlin-Pedersen 2006; Crumlin-Pedersen and McGrail 2006; Roberts 2006; Von der Porten 2006; McGrail 2007; Sanders 2007) proposing, discussing and criticising some of the guidelines and methodologies dealing with the complex nature of reconstructions. Some of the highlights of these articles are set out below.

McGrail states that copies or replicas are built of specific ancient boats, using excavated remains as the primary evidence, and reconstructions or simulations are built of some ancient type, known primarily from written and iconographic sources (McGrail 1992:354). McGrail also notes that both are valid research techniques, and the authenticity of the resulting vessel depends on the quality of the recorded data, the rigour of the arguments forming those data into a hypothesis of the form and structure of the original vessel and the appropriateness of the techniques used to turn such a hypothesis into a floating hypothesis or full scale replica. In addition, McGrail also emphasises the importance of full and widespread publication so as to allow critical appraisal, as it is only through the study of these publications that any claim of authenticity can be assessed. "Hypotheses must be investigated and tested by experiment, a process which lies at the foundation of all sciences. And after testing, the research must be published so that it may be criticized." ((McGrail 1992:355).

Goodburn lists the advantages of building reconstructions, both rigorous and otherwise, as exploring early boat and ship building in relation to specific hypothesis testing, as well as more subtle aspects such as labour investment, skills and resources. Exploring the performance, handling and rigging of early craft. Providing three dimensional displays and publications as well as several socio - economic benefits (Goodburn 1993:201–202).

In a jointly published paper by ten maritime archaeologists, discussing the need for experimental boat and ship archaeology (EBSA), the case for formulating hypotheses, which have to be tested to be tenable is clearly set out as a valuable way to learn more than is immediately obvious in the study of the maritime past. This paper states that experimental archaeology provides one way to investigate hypotheses about past technologies, artefacts and cultures, and in Maritime Archaeology such experiments can take the form of building full size or scale models, or creating other simulations of ancient boats and ships, and testing them in repeatable sea trials, real or simulated (Coates et al. 1995:293). The paper also states that if the right principles and methods can be established, then firm foundations will be laid to enable future projects formulate research designs, which will more securely enlarge our knowledge of maritime history and prehistory, with the overall aim of learning more than is immediately obvious from the direct evidence. In order to be valid EBSA must be a factual observation of the evidence, followed by a whole or partial hypothesis based on interpretation, which is then subjected to testing and evaluation, followed by publication for open criticism and subsequent re-assessments and further research. The paper sets out a six-stage method of enquiry:

1. Evidence: The quality of the evidence will normally be affected by the accuracy and completeness with which finds are recorded.
2. Interpretation: Definitive detail is limited by the quality and quantity of the evidence, any hypothesis cannot by definition be free of conjecture and assumptions, which arise from missing parts, distortion, displacement and fragmentation, and as such should be clearly stated and argued for each conjectural element so others can judge their validity. The task of deducing the vessel's original form and structure may be tackled in two stages:
   I. small scale models of individual timbers, brought together to build a coherent structure representing the pre-depositional state of those parts of the boat that were excavated.
   II. Using this as a basis, and other forms of evidence where appropriate, it may be possible to build up, by trial and error where necessary, one or more hypothetical reconstructions of the full form and structure of the original vessel, including propulsion and steering arrangements where warranted.
3. Tests: The tests of a reconstruction, whether hypothetical or real, must yield observations or physical measurements which can be directly compared with the predictions of the hypothesis. No experiment can ever

prove a hypothesis, it can either disprove it or produce results in agreement with its predictions. In the latter case the hypothesis remains tenable until disproved or accepted as a theory after having been established as an explanation of the evidence.

4. Evaluation of results: Result which directly address the hypothesis, as intended must be clearly distinguished from other, often unexpected results, and when evaluated in the light of the evidence may require the reworking of stages 1 to 4 before proceeding to publication.
5. Publication and criticism: Publication should be to as wide a readership as possible and must include a clear and unambiguous description of stages 1 to 4 in sufficient detail.
6. Re-assessment: The project should be re-assessed in light of criticism received and mature reflection

The paper also notes that terminology and descriptive terms are an issue, a reconstructed boat or ship, however reconstructed, should be defined in terms which imply no greater authenticity than can be justified by the evidence. Consequently different terms would have to be ascribed to different parts of a reconstructed ship owing to the disparities in the security of the evidence for each part and therefore in the authenticity of that particular part (Coates et al. 1995).

Crumlin-Pedersen notes that in order to fully exploit the potential of a ship find, a multidisciplinary approach as well as a wide range of skills are required, including but not exclusive to historians, wood specialists, environmentalists, naval architects, boatbuilders and sailors (Crumlin-Pedersen 1995:303). He further states that experimental archaeology provides an excellent opportunity to test the quality of the archaeological record and the relevance of the documentation in general against a reconstruction in terms of matching the original shape and structural layout, having the missing parts recreated following the construction principles and lines of the preserved part, and function as a seaworthy vessel in the correct setting.

In the paper "Some Principles for the Reconstruction of Ancient Boat Structures" (Crumlin-Pedersen and McGrail 2006) it has been suggested that a number of excavated boats and ships should be reappraised by a multi-phase process, undertaken by an independent interdisciplinary group of experienced maritime archaeologists, naval architects, craftsmen and sailors. The paper cautions against the influence of ideas from our modern world which may, unwittingly, be applied to the study. The issues of this impact are considered under five headings: deformation and its effects on the hull shape; the impact of modern naval architectural standards; the introduction of alien elements to complete the hull; the consideration of propulsion, steering and seaworthiness; and the concept of minimum reconstruction.

1. Deformation and its effects on the hull shape: Vessels which are excavated and recorded in-situ will normally show some degree of deformation and displacement. In addition, site formation factors acting on the vessel between deposition and archaeological recording, including the shape and nature of the underlying surface as well as the nature and weight of covering sediment will invariably add to the deformation, distortion, bending or displacement of the archaeological evidence. Consequently, all reconstruction work must take into account a competent assessment of the effects of deterioration, deformation and shrinkage.

2. The impact of modern naval architectural standards: Applying rectilinear systems of sections and assumptions such as straight-line keels require critical assessment when applied to ancient vessels. With the introduction of sawn timber for boatbuilding in northern and north-western parts of Europe, during the Roman period in Britain and not until the high or Middle Ages in Scandinavia, the starting point for fashioning a plank was not parallel sided boards but half logs or radially split wedge-shaped planks. Additionally, modern structural analysis can be unsuitable if the reference or standards used are based on modern steel or similar single skin vessels rather than ancient vessels with lashed or stitched fastenings which flex and twist when subjected to loading.

3. Introducing alien elements to complete the hull: It will usually be necessary to add elements to the hull for which no distinctive evidence has been found, so that the reconstructed vessel will be able to function properly in the water. This leaves room for a wide variety of proposals which should be narrowed down as much as possible to vessels of the same type and building tradition and of a similar or earlier date. Solutions based on evidence from other vessels or with a later date must be presented in detail and their relevance clearly argued.

4. Considering propulsion, steering and seaworthiness: The strong modern interest in yachting and sailing ship nostalgia, tend to focus interest on the potential of an ancient hull to carry one or more sails and preferably be capable of tacking against the wind. Limited leeway and ample stability under sail are prerequisites for a hull to be suitable for this type of propulsion, and this should not be the only method considered.

5. The concept of "minimum reconstruction": The term minimum reconstruction is now used to describe one or more (partial) reconstructions based on the excavated evidence, as depicted in a "torso" (Crumlin-Pedersen) or "as-found" (McGrail) scale model or drawing, in which allowances have been made for distortion, displacement and shrinkage, and using valid comparative evidence to "fill in" the missing parts, but without recourse to naval architectural conjectures, alien elements, or anachronistic intrusions. Where considerable portions of a vessel are excavated, and full reconstruction appears to be a realistic aim, the problem is to determine the most likely complete hull. In such cases there may be more than one valid solution, and one or more hypotheses should be presented for further discussion.
(Crumlin-Pedersen and McGrail 2006)

McGrail states, after the evidence has been re-appraised, small-scale models of every excavated plank and timber should be made and fitted together until a model is formed of the boat as found, but with distortions and compressions removed, displaced elements replaced, fragmented timbers made whole, and the hull rotated to its deduced attitude when afloat. This ‘as-found’ or ‘torso’ model, or a measured drawing developed from it, then becomes the basis for an attempt to ‘fill in' the missing pieces, a process which may lead, if the surviving evidence allows, to a rigorously-argued reconstruction of the original boat. An agreed reconstruction may subsequently be used to deduce the original boat's performance, including her seagoing potential or, if justified, a full-scale model may be built and tested at sea (McGrail 2007:255). In 1977-8 the National Maritime Museum at Greenwich re-appraised eight or so reconstructions of *Ferriby boat 1* and built small scale reconstruction models of four of them. McGrail noted that *" Excavated wooden objects seldom retain their original shape; between deposition and excavation significant changes are to be expected. A flat bottom recorded on a boat during excavation does not mean that such was necessarily her shape when in use; conversely, a longitudinally curved bottom on excavation does not necessarily imply that the boat was built with rocker. In both cases, the original, pre-depositional shape has to be logically deduced and presented for criticism."* ((McGrail 2007:256). McGrail states the shape of the Ferriby 1 remains when excavated, has yet to be determined by an impartial and informed examination of all of the evidence, and whatever that shape proves to have been will then become the basis for a taphonomic study to establish the form that the surviving parts of the boat had on deposition.

In the Minimal, Intermediate and Maximum Reconstructions of the Dover boat (Von der Porten 2006) the author notes three published articles (Crumlin-Pedersen 2006; Crumlin-Pedersen and McGrail 2006; Roberts 2006) discussing possible reconstructions for ancient boat structures, the most contentious being the Bronze-Age boat found at Dover almost a decade and a half earlier, illustrates the ongoing problem: to what degree should a boat or ship find be reconstructed? The author further states that:

"Legitimate caution, and sometimes fear of criticism, encourage a minimalist approach. It is easy simply to show what was found and what can be comfortably extrapolated from what was found, then let other professionals and members of the public interpret it as they will."

Von de Porten notes that reconstructions are sometimes called minimal when enough is added to the find to make it look like a complete boat or ship. Consequently, the public is given the impression that the boat's overall appearance is known and that she originally did not consist of much more than what was found, neither of which is demonstrably true in the Dover Boat reconstruction. And suggests it would be better to call this an intermediate reconstruction rather than a minimal reconstruction. It is open to criticism that it is both too much reconstruction in relation to what is known, and too little reconstruction in relation to what might have existed originally. He further suggests that perhaps this is a craft that would be better exhibited and interpreted 'as found', admitting that we do not have enough information to reconstruct her in any configuration with any confidence given the present state of knowledge.

Steffy Method:

Not until Dick Steffy 's first tentative contact with George Bass in 1963 was it fully appreciated that the fragmented and usually flattened hull remains which characterise most wrecks, although meticulously plotted, recovered, conserved and recorded, could lead to reliable three-dimensional reconstructions in what became known as the 'Steffy Method' (Martin 2013:242).

Steffy states that, in the interpretation of shipwrecks, research and reconstruction are practically synonymous. The reconstruction evolves continuously as the research progresses. (Steffy 1994:214). He also notes that ship and boat reconstruction in the archaeological sense, is the partial recreation of the remains of sunken or abandoned vessels, and the people and processes that influenced them. Partial recreation being the key phrase in that no recreation can be absolutely complete. Steffy lists three basic types of reconstruction: graphic, three-dimensional and physical.

1. Graphic being most frequently used on, but not limited to, sparsely preserved wrecks are two dimensional in scope. Research includes archival information, computer data and graphic programs, mathematical analyses, drafting and photography. Publication is in graphic form as reports composed of text, photographs and drawings.
2. Three dimensional when used increases the research potential through the added dimension. Research in addition to 1 above also included models, replicas, and experimental devices to solve problems and recognise details which may not be accomplished in graphic forms. Presentation is similar to 1 above as well as potential reuse of research models as exhibits or teaching aids.
3. Physical reconstructions are considered the deluxe method of reconstruction at its best and most complex. Actually, rebuilding the vessel full size while studying the work of the original craftsmen during each stage. Presentation is the reconstructed vessel, as well as models and published articles. If the reconstruction is a fully functioning vessel, sea trials, daily usage and ongoing maintenance are sources for additional research (ibid: 214-215)
4.

Recording Method:

Steffy notes that regardless of the nature of the project, all the recorded hull information will ultimately have to be compiled into some orderly collection, which he calls the hull catalogue. He also states that ideal shipwreck recording employs a liberal combination of photographs and drawings, and begins by setting out a labelling system for the component parts based on their function. With regard to drawings he recommends a wreck plan illustrating the distribution of hull timbers and artefacts. Irrespective of the method used to create the wreck plan it should reveal framing plans, planking seams, visible scarf and butt joints, scattered fragments and any other structural information. Regarding fragment or timber drawings Steffy notes the important factor is carefully examining each surface, often repeatedly as an indispensible step in accumulating all the information the wreck has to offer, and as with the wreck plan, the method whether contact tracing, elevated plane tracing or directly scaled drawings, is not as important as the result, a manageable drawing at a scale large enough for accuracy but small enough for convenience.

Steffy also notes [writing in 1994] that eventually rugged field type computers with sophisticated transfer devices and limitless memory will become practical enough to draw the hundreds of hull fragments directly onto a graphic system at the excavation site or the conservation lab. When such systems become economical and easy to manage, most hull recorders will abandon the above methods. But the basics will remain the same.

Reconstruction:

In his book "Wooden Ship Building and the Interpretation of Shipwrecks" Steffy set out his general approach to reconstructions. The first step was to gather all of the available information, site plans, photographs, drawings, sketches and the hull catalogue. These he calls the raw materials, amounting to an inventory of what was seen or excavated. The next step being to convert those raw materials into the reconstruction. His methodology included a list of objectives: Construction; Design; Technology; Cargo and artefacts; Economics; and People, the objective being to combine these avenues of research with the raw materials, into a good steffy reconstruction. Steffy categorised vessel remains into contributory and capital reconstructions. Capital reconstructions he identified as those resulting in hull lines or elaborate construction plans, making a major contribution to shipbuilding or seafaring history and incorporating extensive research procedures. He cites the Cheops boat, Kyrenia ship, Skuldelev vessels, and Madrague de Giens wreck as examples of capital reconstructions. Contributory reconstructions he identifies as those from less extensively preserved wrecks, supplying new information but lacking the potential to provide elaborate design or construction contributions. He cites the Molasses Reef and Highborn Cay wrecks as examples of contributory reconstructions.

For contributory reconstructions his general approach was to analyse the timber catalogue, and possibly construct a partial scale model, in order to produce a text or graphical reconstruction of that portion of the excavated remains. To this he then added additional information gleaned from other sources, cargo where available or evidence of such, as may result from analysis of the so called "bilge grunge" culminating in a publication, which depending on the extent of the preserved wreck could be as little as several paragraphs describing a handful of timbers assembled in a particular fashion, and only hints at potential cargo or usage. The next step being the search for parallels, including dating, construction methods, and materials used. While all of these materials could be found in other contemporary wrecks, they may not be in the same combination. This being the case the project may be "parked" for years or even decades, until a parallel would be published, whereby the original project can be subsequently reassessed.

Capital reconstruction are usually enormous undertakings, the logistics involved in simply handling the recorded material for some of these vessels is staggering. Many represent tons of timber, thousands of fragments and fastenings and tens of thousands of dimensions. Proper handling and arrangement of recorded information is critical. Ideally for a wreck subject to a capital reconstruction, all recording should be completed first, followed by compiling a formal catalogue, and then the step by step reconstruction process, ending with a completely reassembled vessel displayed is a museum and a final publication describing the vessel (ibid: 215-220).

Regarding structure and design, Steffy states

> "the idea [of reconstruction] is to investigate the wooden structure found on the seabed and to convert it into its original form, or one that is as complete as possible."

And in the case of a broken or scattered wreck can be somewhat akin to assembling a jigsaw puzzle with missing or badly fitting pieces. A preliminary set of lines is considered the logical next step, taken directly from the hull if the wreck has maintained its shape, or in the case of a broken up hull, following shifting of frame shape and planking widths until you have reasonable satisfied the excavated evidence. For the next phase Steffy states that

"a ship is a three-dimensional structure, so why not research it in three dimensions."

Finding the proper location for all of the hull fragments and the shapes they produce for a flattened or scattered hull is quite involved and, in such cases, the three-dimensional perspective is a necessity. This can be achieved either using digital computer modelling or physical scale research models. If using digital computer modelling Steffy notes, a good graphics system capable of producing isometrics, and moving fragments around as required is essential. Additionally, the program should include a data system with wood and fastening properties and ideally the catalogue database system. Steffy goes on to state;

"many of us either do not have access to such exotic [1994] equipment or lack the funding or the expertise to alter the program as required. For us the best research medium is models. People working on computers may want to try using some of these models on the screen" (ibid: 221).

The various models and their contribution to reconstructions are set out below:

Mould-and-Batten Models:

Steffy notes these are probably the most helpful in reconstructing vessels, especially one that broke up or flattened after sinking, as they overcome the drawback of pure graphical, two dimensional drawings. Being a variation of the eighteenth and nineteenth century builder's half models, they are quickly and easily made, and have many uses. The primary one being to help correct and expand on the preliminary set of hull lines. Additionally, these mould-and-batten models can be used to develop rising and narrowing lines, study planking arrangements, and analyse buttock lines and waterlines. While this model produces a set of three-dimensional curves which conform to the excavated data, and extend the hull where material is sparsely recovered, they represent one set of lines which merely prove the lines are workable, and approximate to the original vessel. It confirms the surviving timbers will fit this curvature, but will they do so and properly align all the fastenings and butts or scarfs. And will the projected areas beyond the areas of hull survival accept construction synonymous with the existing structure.

Planked Model:

Next planking shapes are cut from thin sheets of wood, with features such as fastenings, frame locations, scarf or butt joints and other pertinent features redrawn or reprinted to scale and taped onto the wooden plank cut-outs. These scaled planks are then attached to the model, with the existing battens, moulds or frames adjusted and repositioned to suit. Steffy states:

"This is not a precise method of alignment, because it does not take advantage of planking edge angles and internal timber alignment, nor does it account for the repairs or unusual planking alignments sometimes found on hulls. When the original ship is finally assembled in the museum, adjustments will probably still have to be made. In addition, where rotten seams were cut out and replaced with new planks, or where unknown problems or unknown logic caused the shipwright to adopt some strange planking shape, the above method is not always reliable. It is however still more accurate than graphic reconstructions under the same difficulties."

"Sometimes the slightest angular differences between laboratory reconstructions and that of the actual remains will become big variations by the time you reach the stern or caprail."

Fragment Models:

In the case of extremely fragmented wrecks, each fragment of appreciable size is duplicated precisely, including fastenings and angles in their correct location, and assembled. Such models lack a certain amount of precision due to the scaling down process, and the difficulty in precisely reproducing the broken or damaged edges. It has advantages over the planked model in utilising the fastenings as well as planking edge angles and internal timber alignment, and also can serve as a dress rehearsal of the assembly of the original vessel.

Other Research Models:

Sometimes it is necessary to model an individual timber or device, such as mast step, pump, capstan or particular timber joint to understand it better. Interdisciplinary study can be aided by sectional models, such as examining the relationship between cargo, artefacts and hull timbers. Three-dimensional site models or dioramas may help to study hull or artefact dispersion. Dynamic, handling and sailing tests can be made in model form using tank testing under controlled laboratory conditions (ibid: 221-230).

Roskilde Method:

Recording:

During 1998 at the Centre for Maritime Archaeology, Roskilde, initial trials were carried out using various devices for digital documentation (Holm 1998:31) and subsequently a Faro Arm digitiser or coordinate measuring machine (CMM) was purchased in 2000 (Hocker 2003) and combined with the Rhinoceros CAD software. By directly contact tracing the artefact [ships timber] using the touch probe mounted on a pistol grip located on the end of the Faro Arm, the edges and features are recorded and directly drawn as three dimensional curves in the Rhinoceros software (Ravn 2012:314). A layering system within the Rhinoceros software (Jones 2013) is used to organise the recorded data under categories relevant to the vessel being recorded, such as: original edge; damaged edge; sapwood; grain; planking land; cracks; clinker nails and roves; additional nails; nail angles; treenails; wooden spikes and plugs; wear marks; compression marks; tool marks (subdivided by type if required); intentional marks; and a surface cross section at regular intervals (Ravn et al. 2011:233–236).

The benefits of this system are immediately apparent, the timbers are accurately (a well calibrated Faro Arm records at sub-millimetre accuracy) recorded at full size, using contact tracing or digitising, thereby removing any scaling errors, other interpretive or by-eye errors are also eradicated. As the timber is recorded three dimensionally, there can be no error in the matching up of different views as all "views" are automatically orientated into a three-dimensional wireframe model. Additionally, the recorded surface cross sections, which are traced or digitised directly along the surface at regular intervals, generate rapid dimensionally accurate timber cross sections, something which is difficult to achieve by other means. This layering system also gives the user the option of viewing as much or as little data as necessary, when re-examining a particular element, the item can be view as a simple outline drawing displaying only the recorded shape, or a detailed view showing the subject of interest such as intentional builders marks, or additional nail fastenings.

Reconstruction:

The free-hand or digitiser-generated drawings are printed on paper at the desired scale, showing among other things, the outline, cross section, nail holes, treenail holes, cracks, lands, and scarfs. These drawing are cut out and glued to cardboard that is scaled to the thickness of the ship element. The planks are then fitted together using pins through original fastening holes, with site excavation plans, field notes and photographs used to assist in the process. Frames are similarly attached lining up the treenail holes. After creating a three-dimensional model of the preserved remains, informed decisions are made to determine the lines not preserved based on the preserved lines and hull form, as well as through comparisons to contemporary vessels and iconographic and written sources. The completed physical cardboard model is then digitised to produce an inner-edge lines drawing. Based on this inner-edge lines drawing, a torso drawing of the hull is made showing all of the preserved parts. Additionally, a plank-expansion drawing is created from the drawings which shows the character of the planks; their shape, width, length and thickness; the bevel of the overlap; and framing distance. Finally if possible a construction drawing of the whole ship, complete with rigging is made (Ravn et al. 2011:237–238).

There are, however, issues with this methodology, as noted by Ravn, when transforming the three-dimensional digital data into two dimensional prints. Including how to deal with twisted planks, where it is necessary to "flatten out" the three dimensional shape, in order to avoid distortion of dimensions, prior to printing and gluing to cardboard (Ravn 2012:316). Another issue discovered during the full size reconstruction process, was the need to re-adjust or alter the original inner-edge line drawing due to the fact that oak planks do not behave in exactly the same way as the material used in the scale model (Ravn et al. 2011:240).

Another often overlooked issue is that paper is subject to considerable irreversible shrinkage due to changes in humidity (Uesaka et al. 1989), as much as 0.5 % within 24 hours. While 0.5 % might not appear significant, when applied to a scaled drawing, the effect is magnified by the scale factor, for example a drawing at 1:10 scale could change as much as 5%, and a 1:20 scaled drawing could be affected as much as 10%. Taking a recovered 2.8 m long plank drawn at 1:10 scale on A4 paper, the result after shrinkage could be as much as 1.4 cm on paper resulting in a 14 cm difference when rescaled in a full-size reconstruction.

A line drawn on paper is a geometrical representation in graphical format of a connection between two points. By definition, a point is recorded in X, Y and Z coordinates, but has zero size, that is zero length, zero width and zero height. A line connects two or more points, it has zero width and zero height, it does not have a thickness, it is only given a thickness in graphical representations, and as such that graphical thickness results in erroneous measurements when scaling from a drawing, often adding millimetres or centimetres depending on the scale. Conversely, a digital version, using CAD software, where the paper-space is endless, and the object is drawn full size, with lines recorded mathematically, and only represented graphically on screen to aid the operator, all measurements between lines are independent of graphical representations or scale, and by nature 100% accurate in relation to the recorded shape.

In 2007 a working group was established to develop common standards in digital documentation, and share developments for three dimensional documentation and reconstruction: FRAUG (Faro Rhino Archaeology Users Group) consisting in 2009 of the Vasa Museum, the Norwegian Maritime Museum, the Newport Medieval ship Project, the Drogheda Boat Project, the Yenikapi Shipwrecks Project, and the Viking Ship Museum in Roskilde, and since growing into a pan-European phenomenon with approximately 20 members (Ravn et al. 2011:245; Ravn 2012:315). The 2014 8th annual meeting of FRAUG will be attended by more than 30 people. In 2011 Ravn notes Direct Digital Manufacturing (DDM) of the three dimensional documentation may replace the cardboard planks and frames of the reconstruction scale model and future computer technology may even allow a reconstruction to be made in virtual reality (Ravn et al. 2011:246).

Ravn also notes that since a reconstruction process aims to reconstruct artefacts in their functional use, the damaged or distorted parts should be repaired or reshaped to the former original design before manufacturing digital solids (Ravn 2012:316). However, attempting to repair or reshape an individual artefact in isolation from its parent structure - the vessel, may prove difficult or inaccurate.

Some examples of this modern approach include: the Norwegian Maritime Museum Barcode 6 reconstruction, which used a hybrid version of DDM for the framing elements and two dimensional drawings on cardboard for the hull planking; and both the Drogheda Boat Project and the Doel Cog which used DDM for all of the recovered elements. This method of direct digital manufacturing the constituent elements, using the accurately recorded three-dimensional documentation, is somewhat akin to the Steffy plank model or fragment model methods, but with the added precision and accuracy, resulting from the direct process.

G.6 Planned Approach:

In the case of the Newport Medieval Ship, an amalgamation of the perceived best practices or techniques from the above articles was combined in an attempt to reach a more definitive "Principal Reconstruction". As set out in the earliest articles (McGrail 1992; Coates et al. 1995) 6(McGrail 1992) phases were decided on for the reconstruction, being:

1. Evidence
2. Interpretation and formation of a hypothesis
3. Testing of the hypothesis
4. Evaluation of the results
5. Publication so as to allow critical appraisal,
6. Re-assessment

It was also agreed that phases 2 through 6 would be repeated as necessary in the search for a definitive hypothetical reconstruction.

Evidence:

All of the articles are consistent in stressing the importance of the accuracy and completeness of the recorded evidence. On site documentation included; recording the position and context of artefacts, disarticulated timbers and hull remains were recorded with traditional scaled drawings, photogrammetry, photography and videography, with an eye toward documenting individual timbers in a high degree of detail at a later date (Nayling and Jones 2014).

Site plans were hand drawn usually at 1:10 scale, annotated with timber codes, using a site grid aligned to the centre line of the ship and annotated with spot heights related to OD (Ordnance Datum) which included plans and site sections. These drawings were complimented with two phases of photogrammetric surveys, the first including the stringers and framing, the second when framing had been removed to reveal the planking, keel and stem, which allowed the extraction of three-dimensional line data (Nayling and Jones 2014).

Post excavation documentation involved a pilot study comparing laser scanning, 1:1 elevated plane tracing and contact digitising (Barker and Nayling 2004), laser scanning being dropped due to the resultant point cloud lacking interpretation and requiring extensive post processing. The benefits of elevated plane tracing and contact digitising were compared by drawing representative ship timbers, with digitising proving more efficient. This contact digitising produced an extremely accurate three dimensional record of every ship timber (Jones 2009a; Jones 2009b; Jones and Nayling 2011). These timber records were supplemented with handwritten timber recording sheets, including observations made and notes on wood science; digital photography; laser scanning and physical casting of special features. Additionally details about each timber, including function code, description and its progress through the documentation phase were tracked in a database (Nayling and Jones 2014).

This formed what Steffy refers to as the "raw materials" or "inventory of what has been seen or excavated" and consisted of:

Site Drawings, Records and Photographs
Three-dimensional site photogrammetry data
Hull Catalogue - 3D timber records
Artefacts

Interpretation:

As per the above recommendations which suggest a multi-phase process (McGrail 2004b:433) or a multidisciplinary approach (Crumlin-Pedersen 1995:303; Crumlin-Pedersen and McGrail 2006:53) the recorded artefacts was subdivided by category resulting in 24 specialist reports which would form part of the overall interpretation.

G.7 Formation of a hypothesis:

In order to create a hypothesis all of the articles are consistent in their recommended approach, using the recovered remains to create a scaled model as a starting point, only the methodology varies in each method, and a brief synopsis is listed below:

a) In the article "Experimental Boat and Ship Archaeology: Principles and Methods" (Coates et al. 1995:295–297) the authors suggest using small scale models of individual timbers, brought together to build a coherent structure representing the pre-depositional state of those parts of the boat that were excavated.

b) The 'Steffy Method' of the fragmented model, where each fragment of appreciable size is duplicated precisely, including fastenings and angles, and assembled in their correct location, using the recorded fastening positions.
c) The 'Roskilde Method' of flattening the three-dimensional data, printing on paper at a reduced (1:10) scale, gluing to appropriate cardboard stock and re-bending to for a reassembled scale model.

For method (a) the authors state, it is essential that the model builder is experienced and is either the same person as, or is supervised by, the archaeologist to ensure that he keeps to the evidence (Coates et al. 1995:296).
For method (b) Steffy notes that such models, lack a certain amount of precision due to the scaling down process, and the difficulty in precisely reproducing the broken or damaged edges (Steffy 1994:223).
For method (c) Ravn noted issues, including when dealing with twisted planks, where it is necessary to "flatten out" the three dimensional shape, in order to avoid distortion of dimensions, prior to printing and gluing to cardboard (Ravn 2012:316), and the need to re-adjust or alter the original inner-edge line drawing due to the fact that oak planks do not behave in exactly the same way as the material used in the scale model (Ravn et al. 2011:240).

In remembering the quote by Steffy "a ship is a three dimensional structure, so why not research it in three dimensions." (Steffy 1994:221), the question was asked, why take an apparent step backwards in flattening the recorded three-dimensional shape, to a two-dimensional print, and subsequently recreate a three-dimensional shape. The Newport Medieval Ship's three dimensional timber catalogue provided a unique opportunity, as each timber was accurately recorded in three dimensions, the option to produce traditional two dimensional drawing of each timber to form a 'traditional' timber catalogue existed, but the option also existed to create either scaled or full size, three dimensional digital and physical solid models using direct digital manufacturing. This direct digital manufacturing would produce dimensionally accurate 1:10 scale solid parts directly from the full-scale recorded data.

Creating a Working Model:

A range of rapid prototyping or direct digital manufacturing technologies were assessed during a pilot study, with final selection being selective laser sintering, which produced a fine surface detail, using a robust, appropriately flexible nylon (polyamide 12) material (Nayling and Jones 2012:323). This approach dealt with two of the above-mentioned issue, the precision of the scaled parts (Steffy) and the issue of dealing with distorted dimensions in twisted or curved timbers (Ravn). The third issue (Coates et al) was dealt with by having all of the recorded timbers complete with fastening holes modelled, forming essentially a large three dimensional jigsaw puzzle or Airfix® style kit ready for assembly by archaeologist, using a combination of the recorded timber function codes printed on each part as reference, by alignment of fastening holes and consultation of site records and photographs. The reconstructed physical scale model was assembled in the perceived order of construction using only recovered material with the emphasis on allowing the hull planking to determine the original hull form. No attempt was made to flatten distorted timbers. This process created a unique object or shape state, that is neither the original as-built vessel nor the vessel shape at time of sinking but a "post-deposition" shape state (Jones et al. 2013:123).

The completed Working model (Figure 1) contained all of the articulated structural ship timbers found during the excavation with the exception of the ceiling planks, which were omitted for clarity. No attempt was made to create models for missing timbers.

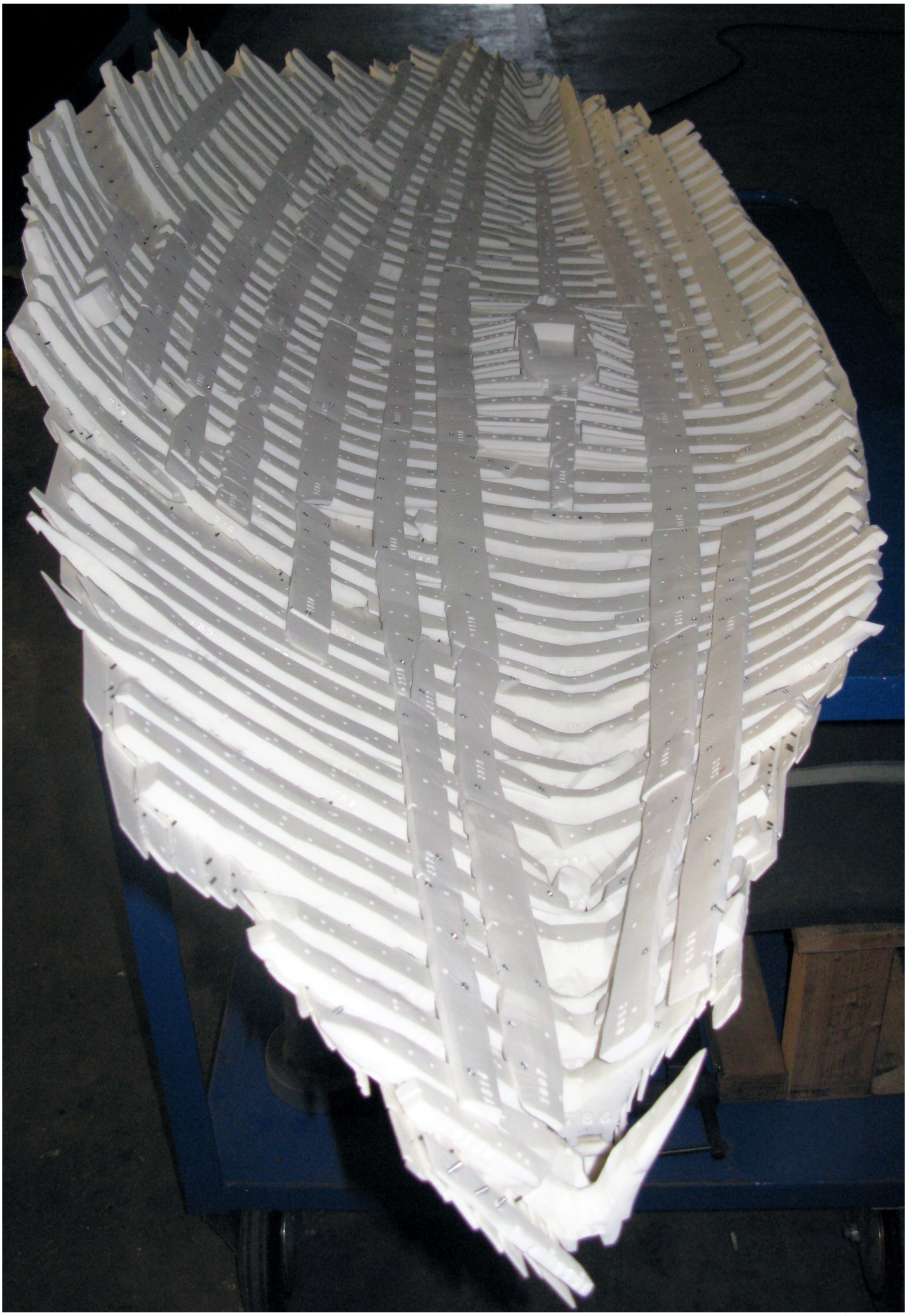


Figure 1 The 1:10 scale Physical Model (ceiling planks omitted for clarity) (Photo courtesy of Newport Museum and Heritage Service)

The Drogheda Boat project, which had closely followed the same digital documentation and subsequent physical scale modelling process (Schweitzer 2012:225–231; Schweitzer Forthcoming), but at circa 9 m length, reached completion at an earlier date, was the subject of a digital hypothetical reconstruction by this author (Tanner 2013b), and presented at the annual FRAUG (Oslo 2011) conference. The Newport Ship team, keen to capitalize on the completed three dimensional nature of the recording and modelling stages foresaw potential of this emerging digital reconstruction methodology, and invited the author, a boatbuilder and sailor with over twenty years' experience to consult on the reconstruction phase of the Newport Medieval Ship. On examining the physical scale model it was immediately apparent that this shape did not represent the pre-depositional shape (as mentioned in the EBSA article), as the model had significant twist in both the bow and stern areas as well as localised areas of distortion, probably due to the asymmetric nature of the material recovered, as well as the nature of the surface the vessel came to rest on, coupled with between five and seven meters of post deposition overburden. This post deposition shape scale model was considered to be a more definite starting point for the formation of a hypothetical reconstruction, as this shape represented, as accurately as possible, the recorded remains devoid of any interpretation or preconceptions.

Creating a Floating Hypothesis:

Definition: The restored remains, only with missing materials added by mirroring existing parts, or extrapolation based on direct preserved evidence, to create a vessel capable of floating.

Discussions regarding potential reconstructions methods included using the physical scale model, with lightweight battens attached to extrapolate the extent of the missing hull, as well as the possibility of a wholly digital approach as used on the Drogheda Boat project. As the Drogheda Boat project, the only known example of a wholly digital reconstruction, which was created using faired curves to extrapolate the missing portions of the hull (Tanner 2013b:140), a digital version of the Steffy mould and batten method, was still awaiting publication and subsequent criticism, a hybrid approach was decided upon, whereby the vessel would be digitally reconstructed, with each stage tested in the form of battens on the physical model as a real world reality check.

"Where considerable portions of the original vessel are excavated, and full reconstruction appears to be a realistic aim, the problem is to determine one or more minimalistic ways to complete the hull and point to the most likely means of propulsion and steering for the vessel."(Crumlin-Pedersen and McGrail 2006:57)

It was decided from an early stage in the reconstruction process that the approach would be incremental:

- Create a minimal floating hypothesis bases solely on the recovered material, extrapolated to the ends in order to create a watertight hull (Figure 2);
- Test the validity of this floating hypothesis and if successful;
- Create a minimum reconstruction based on the floating hypothesis with additional material only added if evidence for its existence survived in the articulated remains, or valid contemporary solutions were available from vessels of the same type and building tradition and of a similar or earlier date;
- Test the validity of this Minimum Reconstruction hypothesis and if successful;

- Publish results and await feedback;
- Revise Minimum Reconstruction based on feedback retest and republish;
- Create Principal Reconstruction following feedback on earlier versions;
- Possible creation of alternative reconstructions.

The detailed methodology, and a step by step process have already been published in the 'Digital Reconstruction and Analysis of the Newport Ship' (Tanner 2013a), and a brief overview of this process is set out below.

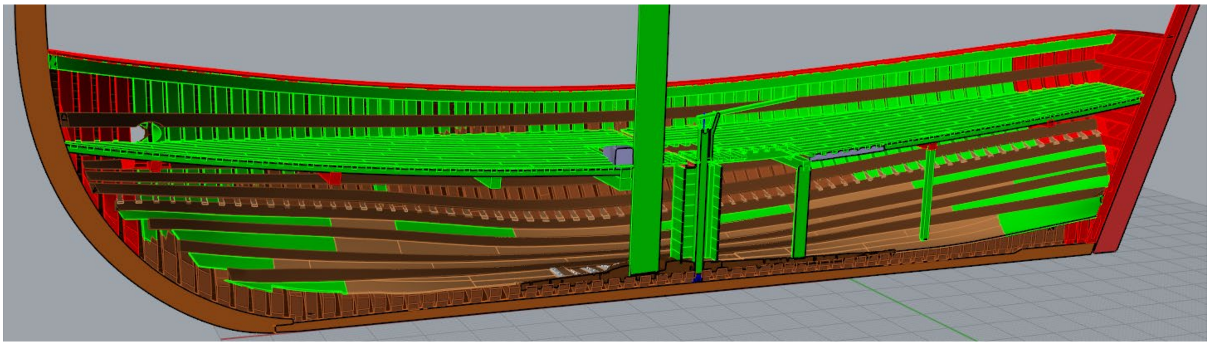


Figure 2 Floating Hypothesis

The 'working model' was 3D laser scanned, and the resulting point clouds were processed to create a digital polygon mesh model, which was a three-dimensional version of the 'working model'. This digital working model was then rescaled back to full size, which would allow the importation and alignment of the originally recorded individual ships timbers. The result being all work in relation to positioning, reshaping, or repairing distortion, was executed at full size, in order to reduce any errors caused by working at a small scale. The next stage was to gather all of the available resources, what Steffy referred to as the raw materials or inventory, this included: the original two-dimensional site drawings; site records and photographs; three dimensional site photogrammetry data; and the three dimensionally recorded ship timbers. Each of these was imported into the digital working model file, and orientated in relation to each other, which created a rather large file, but a comprehensive visual view of the entire recorded project to date. A layering system was used to enable the display or hiding of pertinent data as required. The benefit of this became immediately apparent when examining the working model during reconstruction, if an area of distortion was detected, the relevant site section or record could be simply 'switched on' or unhidden to better analyse and understand the underlying cause, or the original timber recording could be viewed, in position, to examine other causes such as original damage, timber degradation, or intentional feature. This provided an unprecedented research and analysis tool, which previously involved consulting, often thousands of separate documents and drawings. An example of this is shown in Figure 3 where the three-dimensional recorded stem and keel timbers, and a copy of the hand drawn two dimensional site sections have been re-orientated to align with the working model. A copy of the site sections was used in order to preserve the original site section alignment for further analysis. This process of copying or duplicating the recorded material prior to any modification, was deemed an important and beneficial feature of the digital reconstruction process, as it retained an original 'as recorded' copy of each element, allowing further analysis or if necessary, a step back point in what was now a hypothetical process.

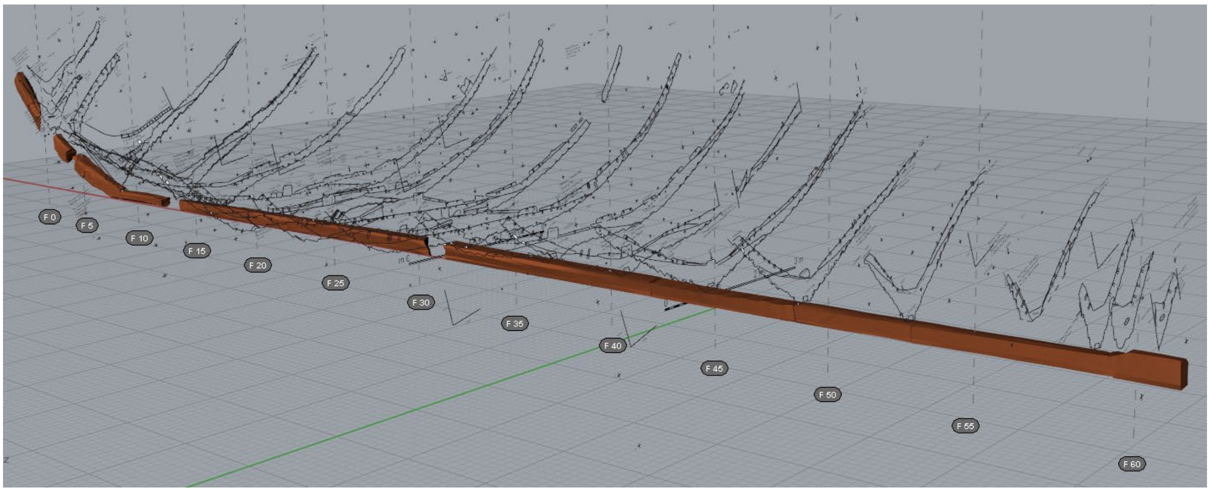


Figure 3 Re-orientated keel and stem timbers with hand drawn site sections orientated to match

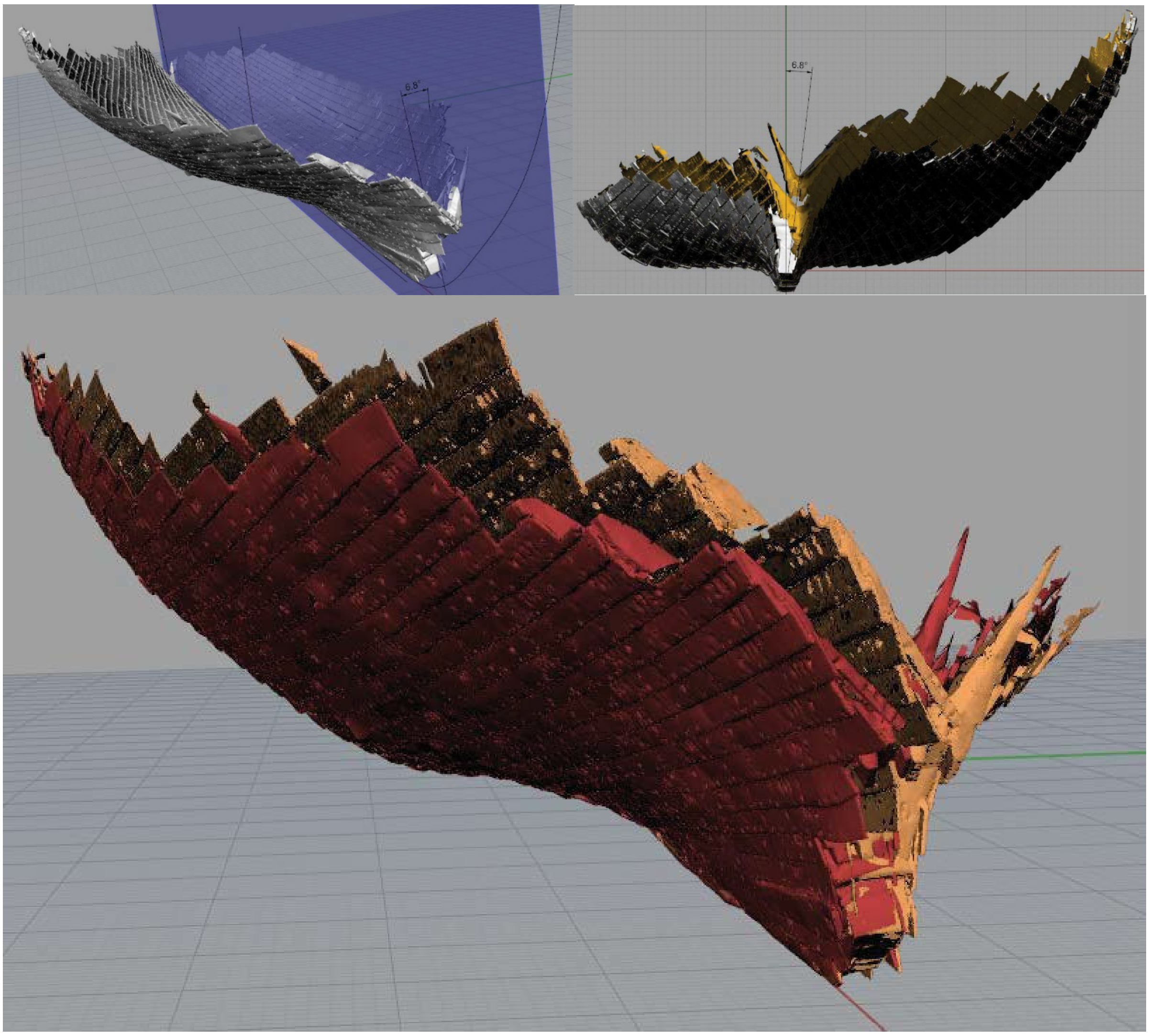


Figure 4 Fitting Symmetry plane and digital working model, original in red, repaired in brown

Global distortion and symmetry were examined by fitting a centreline plane to the digital working model to access the degree of twist and distortion is the surviving remains. This twist was measured as 8.4° and 6.8° in the bow and stern areas respectively, and this was digitally repaired (Figure 4). Localised distortion and extending the recovered partial remains to determine the hypothetical extents of the hull was done by projecting curves onto the digital working model to coincide with every fourth strake run. These curves were duplicated prior to fairing and extending creating a digital fairing ribbands (Figure 5), similar to the Steffy 'mould and batten' method. The surviving remains included the lower edge of a 35th strake, and additional analysis of the remains revealed the partial remains of a beam which provided a deck height based on the recovered but disarticulated deck beams. A hypothetical sheer line was set at 1.2 m above this known deck height.

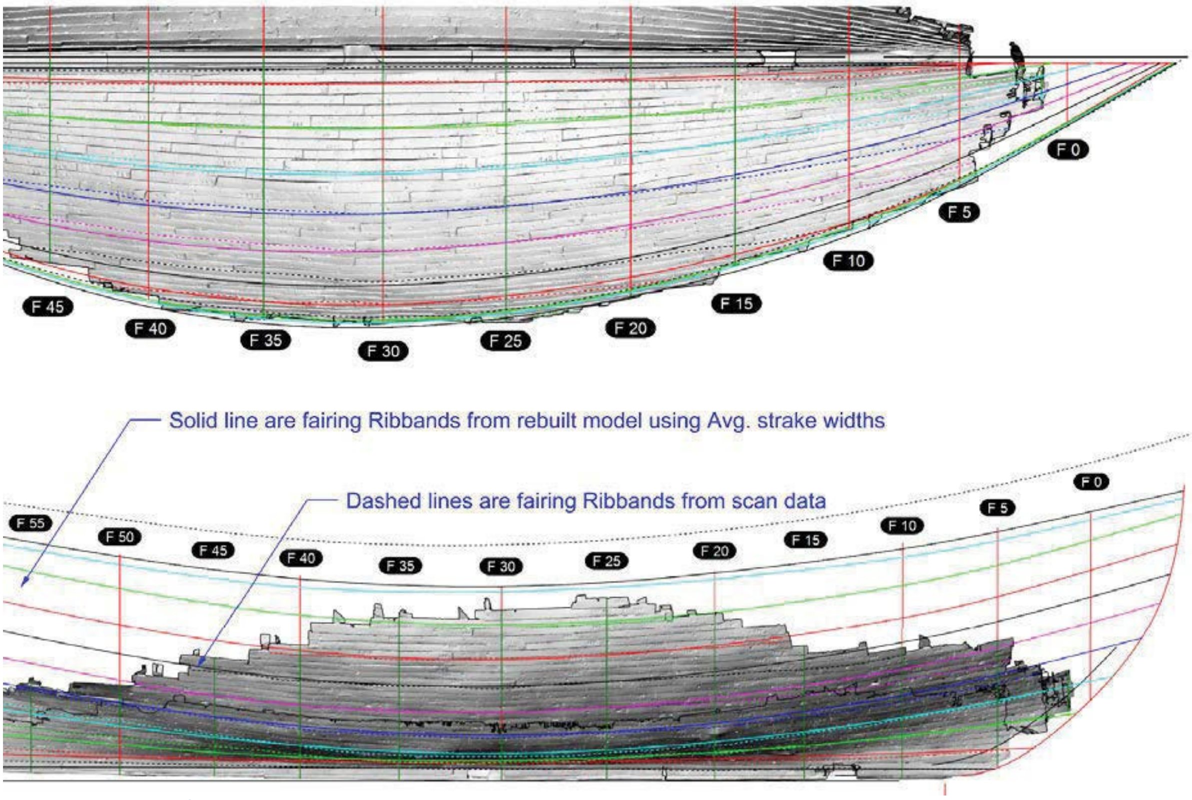


Figure 5 Digital fairing battens

To determine the extremities at the bow and stern, the plank lengths making up each strake were examined to determine both shortest and longest lengths used in the building of the vessel. These lengths were then overlaid on the existing strakes from the preceding complete scarf end. Taking a maximum and minimum plank length created a probability box inside which the final plank hood end should lay. For the bow a curve representing the recovered portion of the stem was extended, passing through this probability box to determine the hypothetical bow shape. At the stern, a stern post at the determined 110° angle (taken from archaeological and historical parallels) was then created to fit within the probability box (Figure 6).

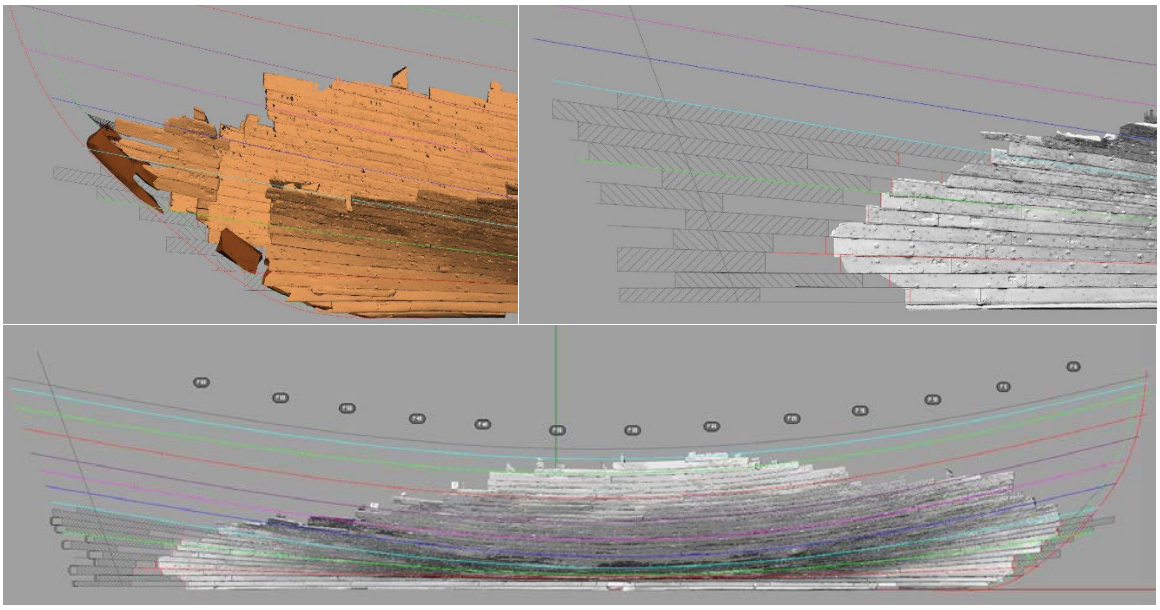


Figure 6 Probability box to determine extremities

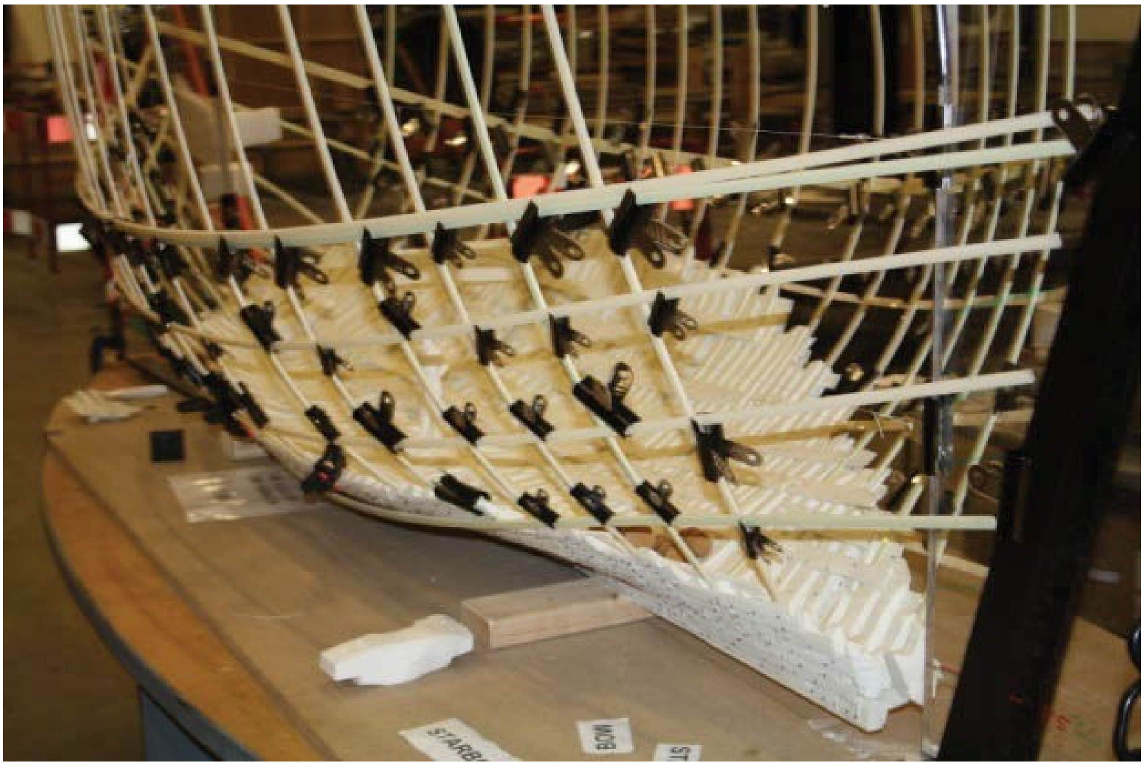


Figure 7 Fairing battens added to the Physical scale model

In a check on the emerging hull shape the digital fairing curves were added to the physical working model (Figure 7), as fairing battens. Again, all of these battens were attached using temporary removable fastenings to allow revision or reversion. In an additional check, each of the individual recorded timbers was then repositioned or repaired to conform with the emerging hypothetical hull reconstruction. At this stage it was found that by 'grouping' the three dimensional recorded data together with the digital solid model the two previously separate sets of records, could be modified in unison, which gave the added advantage of aligning the original recorded data with the emerging hull form.

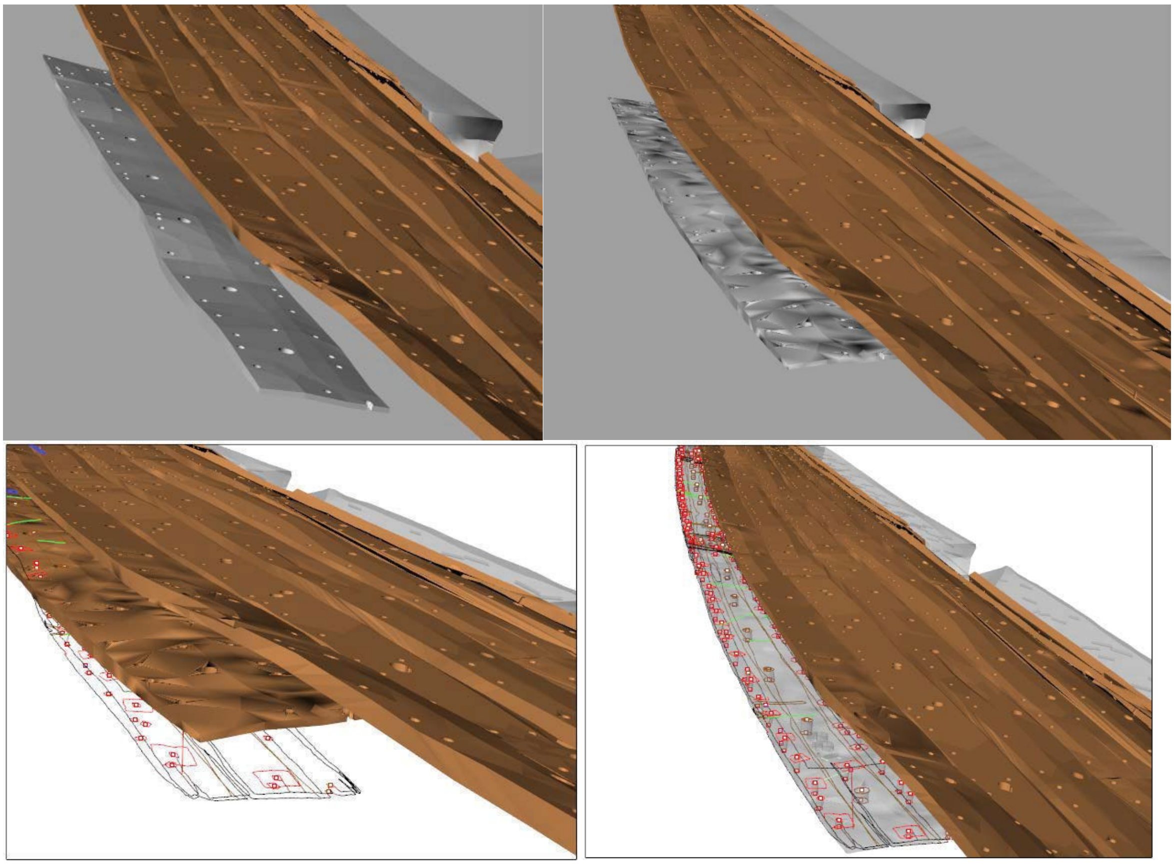


Figure 8 Aligning a modelled strake (8_4 CT557) and associated recorded data with the emerging hull shape

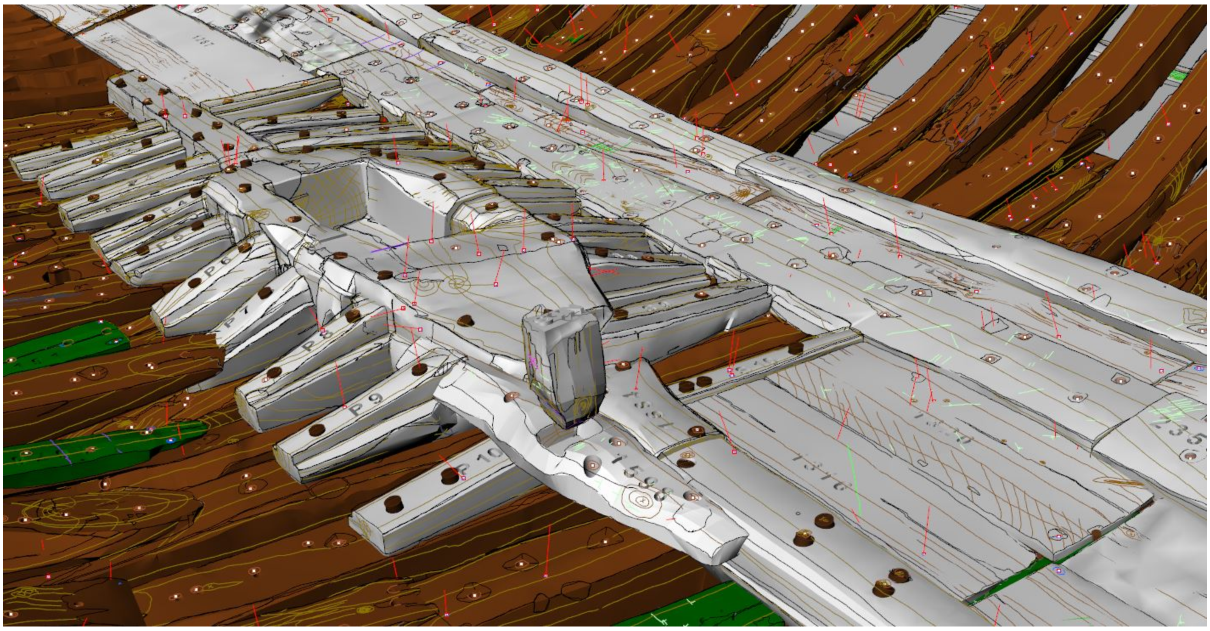


Figure 9 Adding additional recorded material to the digital working model

Additional recorded material, such as ceilings, which were not included in the physical 1:10 scale working model, were then added to the digital working model (Figure 9). This process resulted (after several iterations) in the formation of a floating hypothesis (watertight hull), which was then ready for analysis in terms of steering and propulsion.

Steering and Propulsion:

No evidence of steering gear was recovered, however the centreline rudder hung on pintle and gudgeons and attached to a sternpost are relatively common by the mid fifteenth century, and as a result a basic representation has been used for modelling purposes. A typical modern-day formula for calculating the rudder area of a traditional shape, long keel sailing vessel would be 0.068 x waterline length x draft.

Using this formula would give

$0.068 \times 25.9 \times 2.6 = 4.58m^2$

The rudder used in the hypothetical floating hypothesis has an area of $4.6m^2$

In keeping with the minimalistic approach, and using only recovered articulated material, the only evidence recovered for propulsion is the keelson with its integral mast step. Nineteen wooden artefacts and forty pieces of cordage were recovered from the site, but no proof of these forming part of the original vessel could be clearly established. Consequently, as part of the floating hypothesis it was decided to limit the hypothetical reconstruction to a single mast fitted with a single square sail. With the mast step area of the keelson having a maximum width of 73 cm and a disarticulated mast partner indicating a similar 73 cm diameter, this was believed to be a reliable starting point for the hypothetical mast. Previous Cog reconstructions, other contemporary reconstructions, as well as 16th century manuscripts were consulted to determine proportions for the mast, yard and sail dimensions. This resulted in a hypothetical mast 23.5 m in height, with a diameter of 0.75 m, a yard length of 18 m resulting in a potential sail area of 265 m^2.

G.8 Testing of the hypothesis:

The "complete hull", floating hypothesis (1 deck, 1 mast and no castles) (Figure 10), based on recovered materials, with additional components added to complete a watertight hull, was accurately digitally modelled to include each component part. Each individual component was then assigned a material, oak with a density of 800 kg / m^3 (being a typical density for oak at 27% moisture content) was used, and the Orca 3D software computed the weight, longitudinal, transverse and vertical centres of gravity for each component part (Figure 11), to provide a combined total weight and location for the longitudinal transverse and vertical centres of gravity.

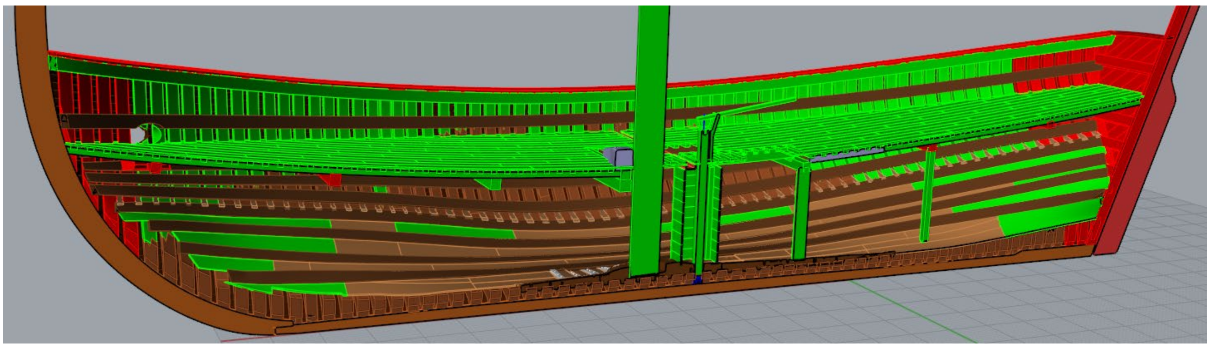


Figure 10 "Complete Hull" Floating Hypothesis

Object Name	Material	Weight (kgf)	LCG (mm)	TCG (mm)	VCG (mm)	Weight Basis
Cap Rail Transom	Oak @ 800 kg (27% M.C.)	35.246	-9277.963	-1099.408	5653.180	0.044 m^3
Frame 69	Oak @ 800 kg (27% M.C.)	21.411	-8681.195	-2210.639	4982.631	0.027 m^3
Frame 68	Oak @ 800 kg (27% M.C.)	56.372	-8294.251	-2041.232	4286.406	0.070 m^3
Frame 67	Oak @ 800 kg (27% M.C.)	113.179	-7907.031	-1592.637	3542.371	0.141 m^3
Fashion Piece Stb.	Oak @ 800 kg (27% M.C.)	163.068	-8360.361	-1194.675	3280.917	0.204 m^3
Strake 38 Stb	Oak @ 800 kg (27% M.C.)	144.210	4574.258	-3202.977	4634.623	0.180 m^3
stringer 7 stb a	Oak @ 800 kg (27% M.C.)	22.768	16227.150	-630.828	3596.064	0.028 m^3
stringer 7 stb b	Oak @ 800 kg (27% M.C.)	27.012	12664.588	-2389.014	3133.123	0.034 m^3
stringer 7 stb c	Oak @ 800 kg (27% M.C.)	28.145	-2242.038	-2954.975	3114.478	0.035 m^3
stringer 7 stb d	Oak @ 800 kg (27% M.C.)	27.743	-5768.202	-2230.178	3539.716	0.035 m^3
Stem	Oak @ 800 kg (27% M.C.)	530.837	16754.449	4.135	2739.149	0.664 m^3
Bilge Pump Base	Oak @ 800 kg (27% M.C.)	7.073	4122.083	-85.772	380.334	0.009 m^3
Bilge Pump Spear Valve	Oak @ 800 kg (27% M.C.)	0.373	4122.126	-85.772	876.759	0.000 m^3

Figure 11 Portion of Orca 3D weight analysis

This has the effect of orientating the remodelled hull shape to its lightship or empty flotation condition, as well as defining the centre of floatation, centre of buoyancy and centre of gravity. For all of these calculations a reference point or baseline was set as the bottom aftermost end of the reconstructed keel.
The results of the component model were as follows:
Weight 60,865 kg, L.C.G. 11.76 m, T.C.G. 0.0 m, V.C.G. 2.47 m.

Creating a simplified Hull Model:

A common practice used in naval architecture when designing, or modifying a hull during the initial phases, is to use average weights to analyse how the developing hull designs will float and react. One method of doing this is to take an average of the hull construction weight, such as the hull planking and framing and "smear" this average weight onto a simplified single surface hull, rather than modelling each separate component. This allows a simplified single surface model of the hull to be analysed and tweaked rapidly and relatively simply, in order to achieve the desired goals. Once the design is approaching the desired results, the individual components are then accurately modelled to produce more accurate and realistic floatation characteristics, and then tweaked or modified as necessary.

For the Newport Medieval Ship, the average strake thickness is 31 mm. Approximately 50% of the hull planking is double thickness as a result of the overlapping clinker construction, resulting in a notional strake thickness of 46.5 mm. The framing has an average moulded dimension of 195 mm. Average sided dimensions are 230 mm with an average inter-frame spacing of 118 mm. Taking half the frame moulded dimension of 97.5 mm plus the notional strake thickness of 46.5 mm gives a notional solid hull thickness of 145 mm.

This allowed the creation of a simplified single skin surface model, and the notional solid hull thickness of 145 mm was assigned again using oak with a density of 800 kg / m^3. A reduced notional solid thickness of 120 mm was used for the deck surface.

Newport Medieval Ship
Orca3D Weight and Cost Report
3D Scanning Ireland Ltd.
Report Time: 15 March 2014, 10:53:21
Model Name: C:\Users\Pat Tanner\Desktop\Meters_Newport Hull Shape.3dm

Weight Items

Object Name	Material	Weight (kgf)	LCG (m)	TCG (m)	VCG (m)	Weight Basis
All Items						
Clench Nails - Stb.	Clench Nails	941.113	11.794	-2.085	2.174	0.000 N/A
Clench Nails - Port	Clench Nails	941.113	11.794	2.085	2.174	0.000 N/A
Spike Nails - Stb.	Spike Nails	399.031	11.915	-1.859	2.075	0.000 N/A
Spike Nails - Port	Spike Nails	399.031	11.915	1.859	2.075	0.000 N/A
Rudder	Oak @ 800 kg (27% M.C.)	517.613	-1.279	0.000	2.424	0.647 m^3
Tiller	Oak @ 800 kg (27% M.C.)	70.468	-1.346	0.000	5.757	0.088 m^3
Anchors	None	* 1850.000	23.523	0.000	4.178	N/A
Anchor warps	None	* 200.000	21.475	0.000	3.841	N/A
Additional Strakes Port	145mm Oak	2540.594	11.656	2.880	4.574	22.483 m^2
Recovered Hull Stb	145mm Oak	10811.864	13.080	-1.809	1.221	95.680 m^2
Repaired Hull Stb	145mm Oak	4383.710	2.678	-2.116	2.915	38.794 m^2
Transom Hull	145mm Oak	5.640	21.532	-0.049	0.053	0.050 m^2
Repaired Hull Stb	145mm Oak	2108.979	22.228	-1.635	3.506	18.664 m^2
Repaired Hull Port	145mm Oak	11186.114	10.911	2.304	2.636	98.992 m^2
Transom Hull	145mm Oak	5.640	21.532	0.049	0.053	0.050 m^2
Recovered Hull Port	145mm Oak	6118.439	12.745	1.065	0.636	54.145 m^2
Additional Strakes Stb	145mm Oak	2543.456	11.640	-2.876	4.575	22.508 m^2
Main Deck	120mm Oak	15936.417	11.253	0.000	3.513	171.359 m^2
SubTotal		60959.222	11.772	0.000	2.656	
Totals		**60959.222**	**11.772**	**0.000**	**2.656**	

Figure 12 Weight report minimum hull reconstruction without rigging

The results (Figure 12) of the simplified surface model were as follows: Weight 60,959 kg, L.C.G. 11.77 m, T.C.G. 0.0 m, V.C.G. 2.66 m, and with the differences being marginal at a weight decrease of 94 kg, an increase of 12 mm in the longitudinal centre of gravity and an increase of 190 mm rise in the vertical centre of gravity, are considered to be close enough to the component model version for the purposes of initial shape and overall size calculations.

When the vessel is orientated to its flotation condition in this configuration (Figure 13) it has a draft of Aft of 1.42 m, a draft Forward of 1.22 m and a freeboard midship of 2.83 m

Condition Summary

Load Condition Parameters

Condition	Weight / Sinkage	LCG / Trim	TCG / Heel	VCG (m)
LightShip Un-Rigged	60959.000 kgf	11.770 m	0.000 m	2.66

Resulting Model Attitude and Hydrostatic Properties

Condition	Sinkage (m)	Trim(deg)	Heel(deg)	Ax(m^2)
LightShip Un-Rigged	1.421	-0.451	0.000	4.94

Condition	Displacement Weight (kgf)	LCB(m)	TCB(m)	VCB(m)	Wet Area (m^2)
LightShip Un-Rigged	60959.097	11.756	0.000	0.911	118.987

Condition	Awp(m^2)	LCF(m)	TCF(m)	VCF(m)
LightShip Un-Rigged	88.939	11.906	0.000	1.328

Condition	BMt(m)	BMl(m)	GMt(m)	GMl(m)
LightShip Un-Rigged	3.354	35.918	1.605	34.169

Condition	Cb	Cp	Cwp	Cx	Cws	Cvp
LightShip Un-Rigged	0.265	0.491	0.559	0.540	3.119	0.474

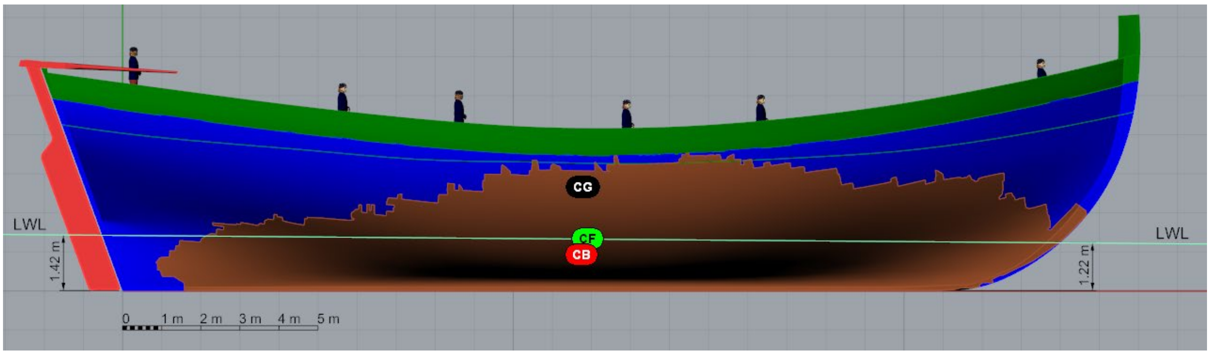
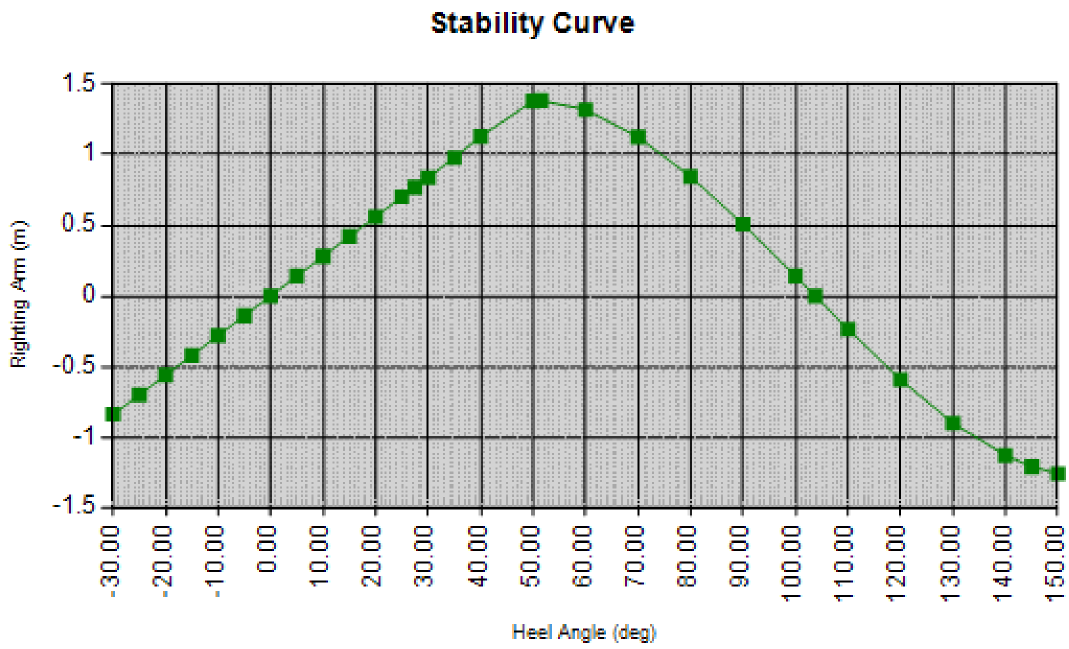


Figure 13 Floatation Condition Floating Hypothesis simplified hull version



Stability Criteria - Bureau Veritas, Intact Stability					
Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Area Between FreeEquil and 30 > 3.151 meters-deg	0	30	3.151	12.6118	Pass
Area Between FreeEquil and 40 > 5.157 meters-deg	0	40	5.157	22.4239	Pass
Area Between 30 and 40 > 1.719 meters-deg	30	40	1.719	9.8121	Pass
GZ At 30 > 0.2 meters	30		0.2	0.8382	Pass
Angle At GZmax > 25 deg	51.563		25	51.563	Pass
GM At FreeEquil > 0.15 meters	0		0.15	1.6051	Pass

Figure 14 Bureau Veritas Intact Stability Results - Floating Hypothesis - simplified hull version

The results in Figure 14 show that the vessel in this configuration has a good stability curve, with the transverse righting moment, GM_t, being 1.605 m, and comfortably passing all of the modern Bureau Veritas intact stability requirements, with the cap rail becoming submerged at 41°. This would indicate that the vessel, reconstructed to this level and shape, would function adequately.

Obviously the vessel in this condition does not resemble any of the medieval vessels, as depicted in contemporary iconography, but, as all good structures depend on good foundations, it was deemed a valuable stage in the reconstruction process, as it confirms that this lower portion of the reconstruction, based solely on articulated recovered material, does in fact function as a vessel.

Floating Hypothesis - Single Mast:

Intact Stability:

This analysis was then repeated for the floating hypothesis with a single mast and rigging (Figure 15), a weight report (Figure 16) was generated to include the mast and rigging, and the vessel was analysed for intact stability (Figure 17 and Figure 18).

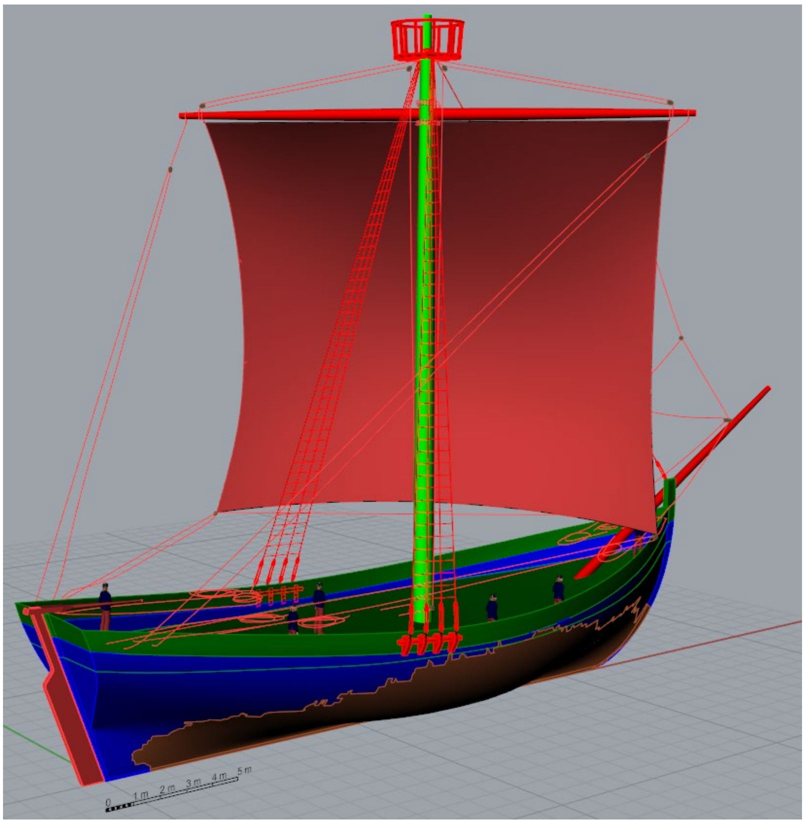


Figure 15 Floating hypothesis with Single Mast

Weight Items

Object Name	Material	Weight (kgf)	LCG (m)	TCG (m)	VCG (m)	Weight Basis
All Items						
Rudder	Oak @ 800 kg (27% M.C.)	517.613	-1.279	0.000	2.424	0.647 m^3
Tiller	Oak @ 800 kg (27% M.C.)	70.468	-1.346	0.000	5.757	0.088 m^3
Rigging CG Mainmast	None	* 5962.590	14.316	0.000	12.125	N/A
Additional Strakes Port	145mm Oak	2540.594	11.656	2.880	4.574	22.483 m^2
Recovered Hull Stb	145mm Oak	10811.864	13.080	-1.809	1.221	95.680 m^2
Repaired Hull Stb	145mm Oak	4383.710	2.678	-2.116	2.915	38.794 m^2
Transom Hull	145mm Oak	5.640	21.532	-0.049	0.053	0.050 m^2
Repaired Hull Stb	145mm Oak	2108.979	22.228	-1.635	3.506	18.664 m^2
Repaired Hull Port	145mm Oak	11186.114	10.911	2.304	2.636	98.992 m^2
Transom Hull	145mm Oak	5.640	21.532	0.049	0.053	0.050 m^2
Recovered Hull Port	145mm Oak	6118.439	12.745	1.065	0.636	54.145 m^2
Additional Strakes Stb	145mm Oak	2543.456	11.640	-2.876	4.575	22.508 m^2
Main Deck	120mm Oak	15936.417	11.253	0.000	3.513	171.359 m^2
SubTotal		62191.524	11.633	0.000	3.537	
Totals		**62191.524**	**11.633**	**0.000**	**3.537**	

Figure 16 Weight Report Floating hypothesis with Single Mast

Condition Summary

Load Condition Parameters

Condition	Weight / Sinkage	LCG / Trim	TCG / Heel	VCG (m)
LightShip Single Mast	62191.500 kgf	11.630 m	0.000 m	3.64

Resulting Model Attitude and Hydrostatic Properties

Condition	Sinkage (m)	Trim(deg)	Heel(deg)	Ax(m^2)
LightShip Single Mast	1.489	-0.713	0.000	5.02

Condition	Displacement Weight (kgf)	LCB(m)	TCB(m)	VCB(m)	Wet Area (m^2)
LightShip Single Mast	62191.600	11.596	0.000	0.921	120.008

Condition	Awp(m^2)	LCF(m)	TCF(m)	VCF(m)
LightShip Single Mast	89.634	11.805	0.000	1.342

Condition	BMt(m)	BMl(m)	GMt(m)	GMl(m)
LightShip Single Mast	3.341	35.660	0.622	32.941

Condition	Cb	Cp	Cwp	Cx	Cws	Cvp
LightShip Single Mast	0.257	0.493	0.563	0.522	3.116	0.458

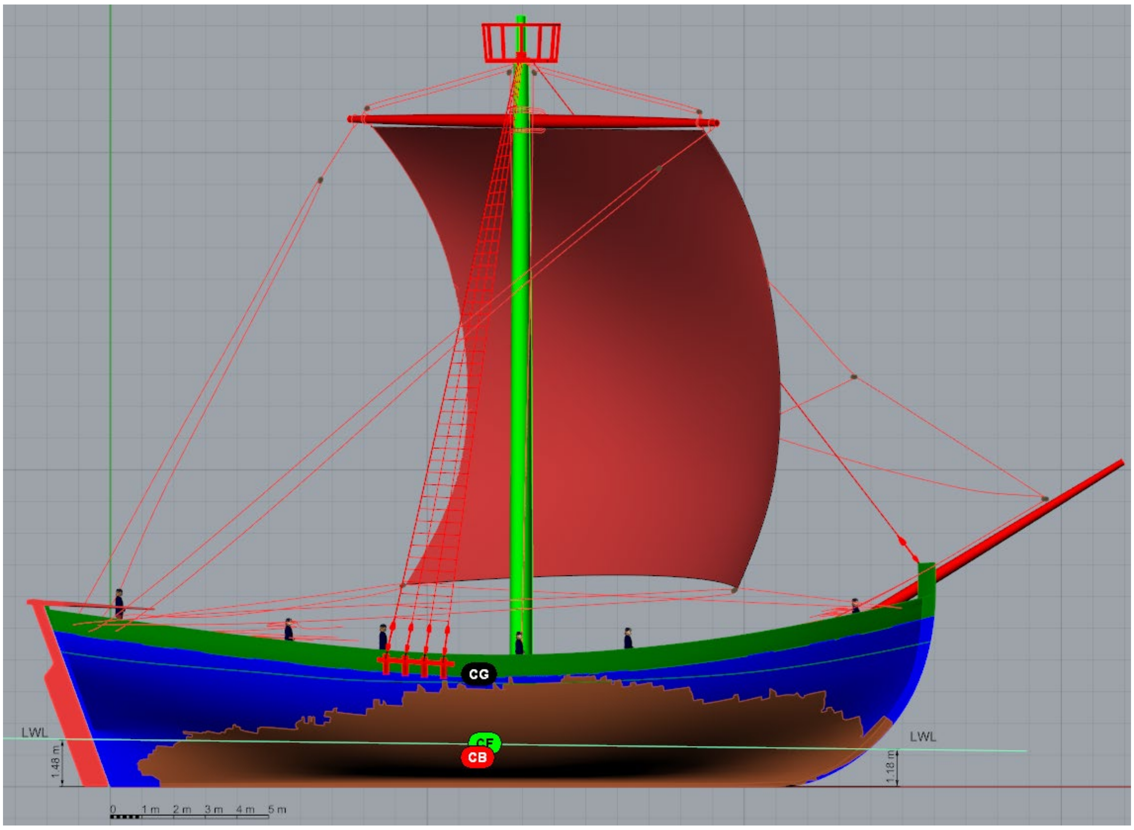
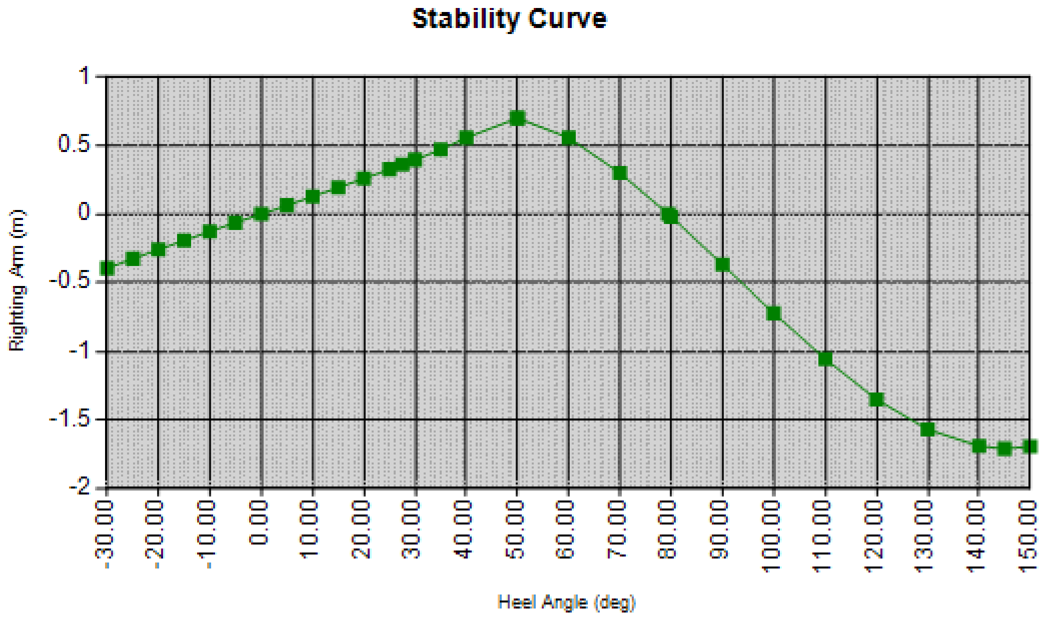


Figure 17 Floatation Condition for Floating Hypothesis with Single Mast



Stability Criteria - Bureau Veritas, Intact Stability					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Area Between FreeEquil and 30 > 3.151 meters-deg	0	30	3.151	5.8319	Pass
Area Between FreeEquil and 40 > 5.157 meters-deg	0	40	5.157	10.5652	Pass
Area Between 30 and 40 > 1.719 meters-deg	30	40	1.719	4.7332	Pass
GZ At 30 > 0.2 meters	30		0.2	0.3957	Pass
Angle At GZmax > 25 deg	49.987		25	49.987	Pass
GM At FreeEquil > 0.15 meters	0		0.15	0.7222	Pass

Figure 18 Bureau Veritas Intact Stability Results - Floating Hypothesis - Single Mast

In this single mast configuration, the vessel has the following flotation characteristics:
Weight 62,191 kg, L.C.G. 11.63 m, T.C.G. 0.0 m, V.C.G. 3.54 m,
Draft Aft of 1.48 m, Draft Forward of 1.18 m and a freeboard midship of 2.82 m.

Wind and Wave Stability:

In order to determine the effect of wind loading on the vessel the lateral projected area needs to be calculated. The vessel was configured in the worst-case scenario condition with regard to wind loading, which would represent a "beam on" wind, with the sail sheeted in tight. This is not a normal sailing configuration but represents the worst possible case scenario. To establish this lateral projected area, the yard and sail was rotated as close as possible to the centre line plane, allowing for normal restrictions such as shroud placement. The projected sail area combined with the above water hull surface area was then calculated (Figure 19). This results in a lateral projected surface area, including hull, spars and sails of 245.3 m².

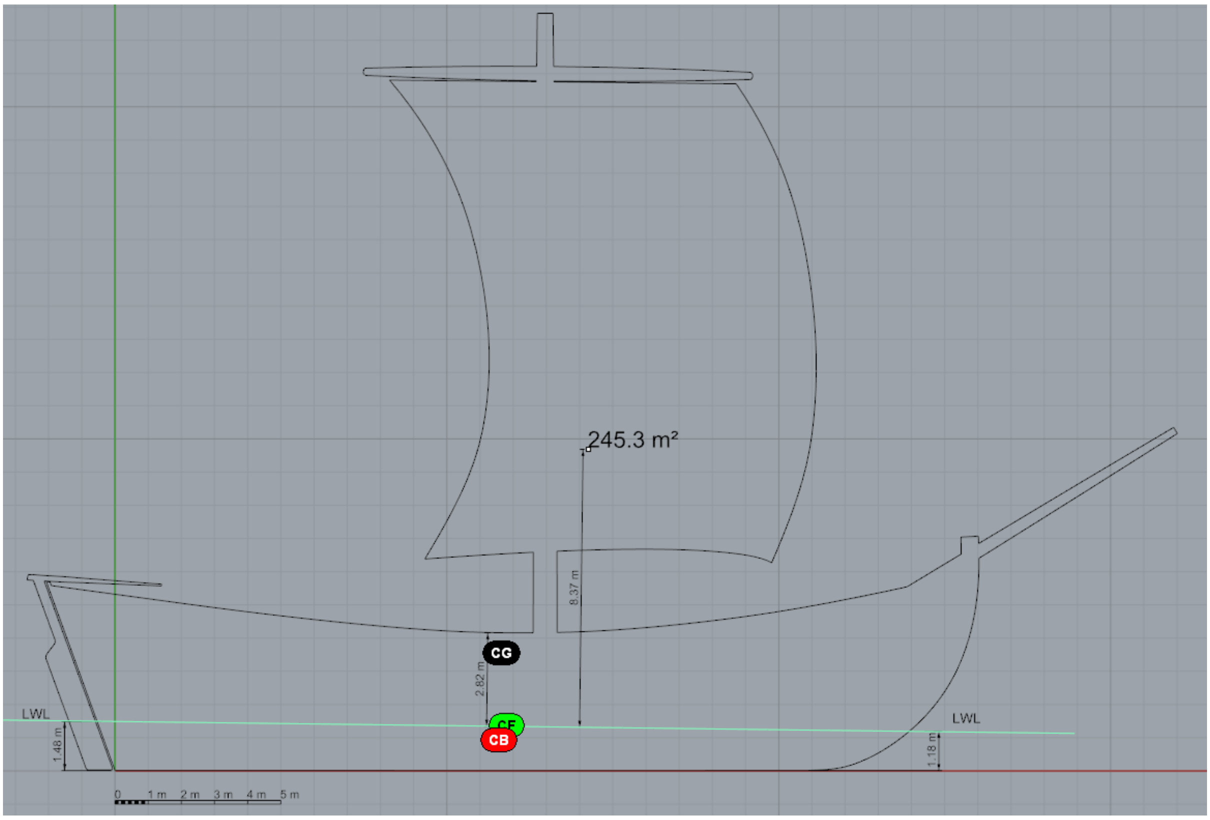


Figure 19 Lateral surface area for wind loading

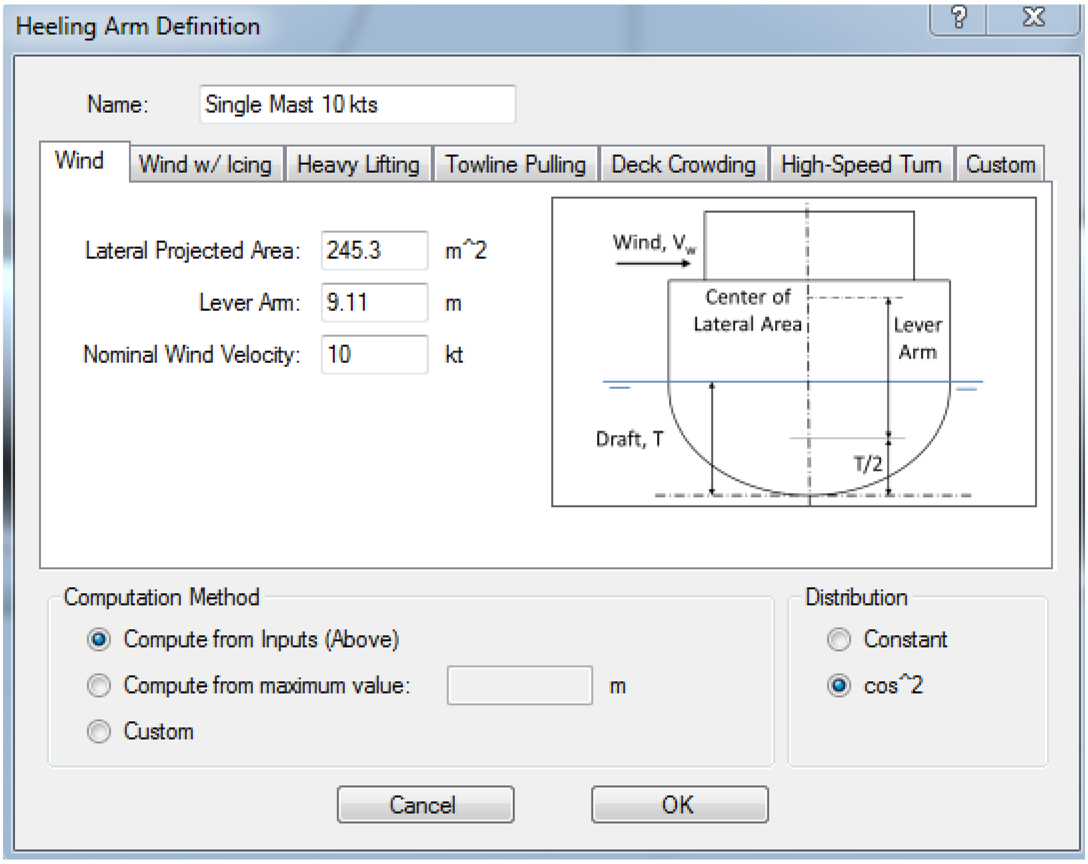


Figure 20 Wind loading criteria for Single Mast

With the centre of lateral area 8.37 m above the LWL (load waterline) and a draft of 1.48 m the resulting lever arm is 9.11 m (Figure 20).

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, Single Mast 5 Kts					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Angle At SteadyEquil <= 16 deg	1.3841		16	1.3841	Pass
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-23.6159	40.7231	1	2.6082	Pass
ResRatio Between SteadyEquil-25 deg and Flood > 1	-23.6159	40.7378	1	2.6102	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-23.6159	50	1	4.094	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	1.3841		32.5785	1.3841	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, Single Mast 10 kts					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Angle At SteadyEquil <= 16 deg	5.4874		16	5.4874	Pass
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-19.5126	40.7231	1	2.2233	Pass
ResRatio Between SteadyEquil-25 deg and Flood > 1	-19.5126	40.7378	1	2.2253	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-19.5126	50	1	3.6646	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	5.4874		32.5785	5.4874	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, Single Mast 15 Kts					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Angle At SteadyEquil <= 16 deg	11.8419		16	11.8419	Pass
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-13.1581	40.7231	1	1.5915	Pass
ResRatio Between SteadyEquil-25 deg and Flood > 1	-13.1581	40.7378	1	1.5933	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-13.1581	50	1	2.8844	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	11.8419		32.5785	11.8419	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, Single Mast 20 Kts					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Angle At SteadyEquil <= 16 deg	19.3144		16	19.3144	Fail
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-5.6856	40.7231	1	0.8988	Fail
ResRatio Between SteadyEquil-25 deg and Flood > 1	-5.6856	40.7378	1	0.9001	Fail
ResRatio Between SteadyEquil-25 deg and 50 > 1	-5.6856	50	1	1.9219	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	19.3144		32.5785	19.3144	Pass

Figure 21 Stability results for Floating hypothesis with a single mast

G.9 Evaluation of the results:

The floating hypothesis hull with a single mast passes the modern Bureau Veritas stability rules for wind and rolling waves in all but 20 knots of wind. This is the vessel tested in the "worst possible" scenario, and as every sailor knows the sheets should have been eased or sail shortened in order to decrease the lateral projected area and as a result would also pass the 20 knot test.(Figure 21). With the Caprail submerged at 40.7°, the angle of maximum stability at 50.3° and the angle of vanishing stability at 79.4°, this reconstruction would be deemed as passing the modern test criteria.

G.10 Creating a Minimum Reconstruction:

Internal consultation, combined with feedback from a number of external archaeologists, concluded the floating hypothesis was a valid hypothetical solution, and with the inclusion of castles, in-line with contemporary iconography, would represent a minimum reconstruction.

Iconography:

Iconography which pre-dated the Newport ship was initially consulted as a potential resource for the hypothetical bow and stern castles, and as both castles were conjectural, a simplified reconstruction of both was added to the floating hypothesis model to create a hypothetical minimum reconstruction ready for testing. Some examples of the iconography used are shown in Figure 22 and Figure 23.

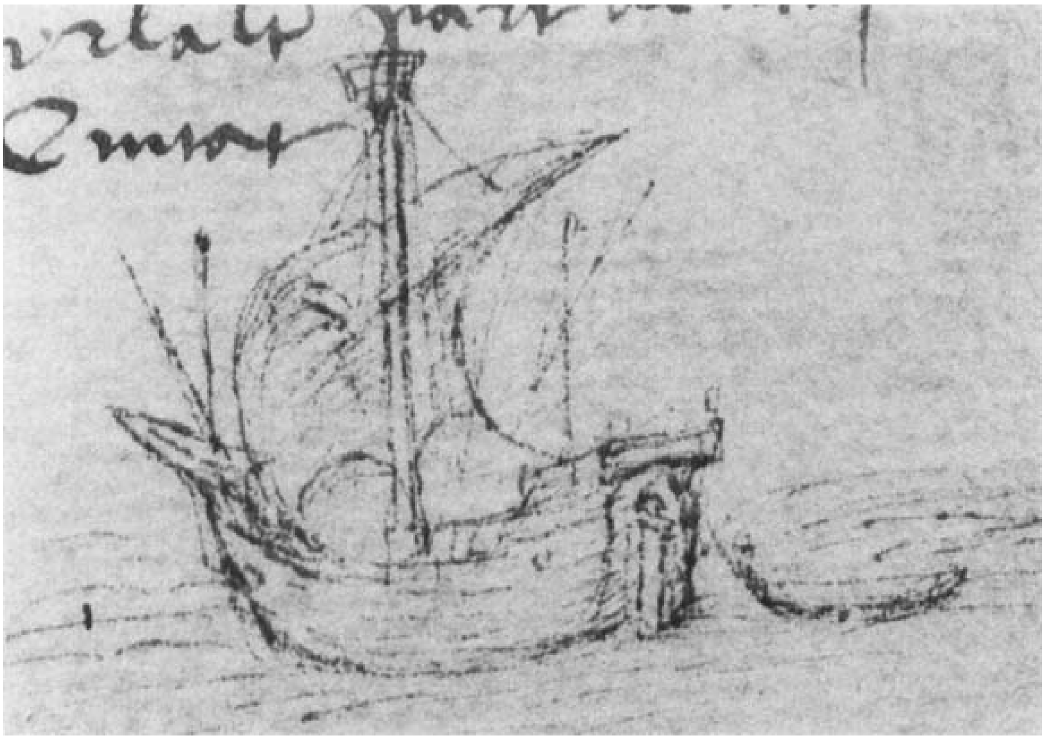


Figure 22 Depiction of a three masted ship

Mott notes this depiction of a three masted ship located in the Municipal Archives of Barcelona, dates to 1409, as well as the adoption of a mizen mast in the Mediterranean around 1350 as indicated by a drawing on a Venetian map by Pizigani dated 1366 (Mott 1994:40).

King's Lynn bench end showing two masted vessel circa 1415

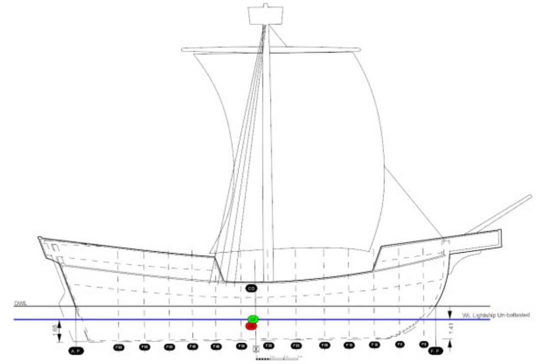
Michael of Rhodes manuscript circa 1440

Figure 23 King's Lynn bench and Michael of Rhodes image

Figure 24 Minimum Reconstruction

G.11 Testing the Minimum Reconstruction:

The hypothetical minimum reconstruction (Figure 24) was then tested in various loading conditions (Table 1) to analyse the validity of the reconstruction.

<table>
<tr>
<td>
Model Name: D:\Lightship Un_ballasted.3dm
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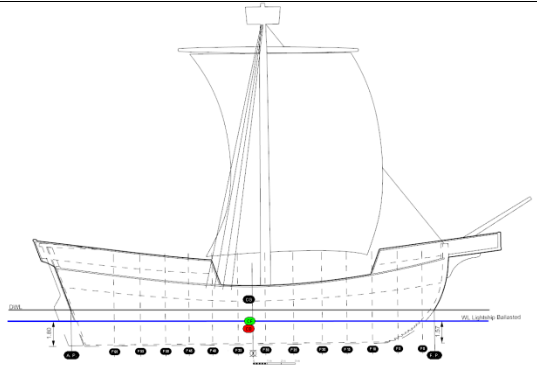
<td>
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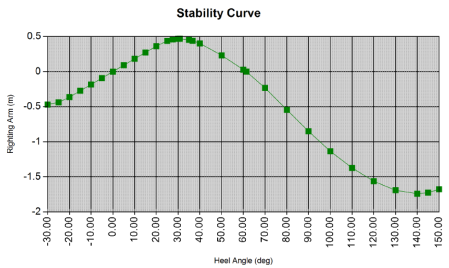
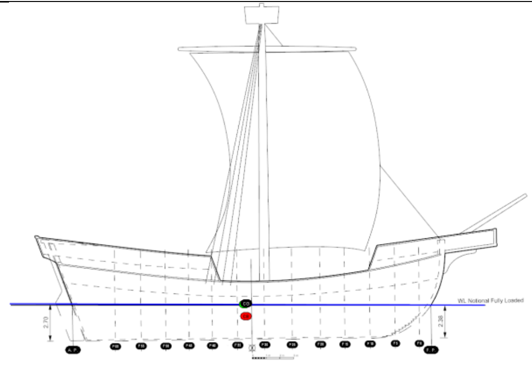
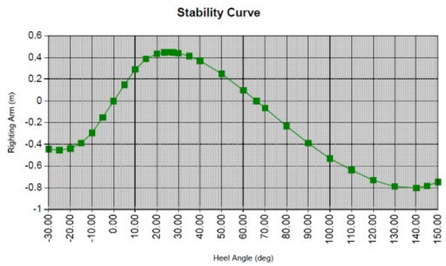
</td>
<td>
Model Name: D:\Notional Fully Loaded.3dm
</td>
</tr>
<tr>
<td>Minimum Reconstruction Unballasted
Draft aft of 1.65 m
Draft forward of 1.41 m with a
Metacentric height GMt of 0.53 m
Freeboard of 2.88 m.</td>
<td>Minimum Reconstruction Ballasted
Draft aft of 1.8 m
Draft forward of 1.57 m
Metacentric height GMt of 1.05 m Freeboard of 2.72 m.</td>
<td>Minimum Reconstruction Fully Loaded
Draft aft of 2.7 m
Draft forward of 2.38 m
Metacentric height GMt of 1.72 m
Freeboard of 1.86 m.</td>
</tr>
<tr>
<td>While this would indicate a reasonably stable condition with a GMt of 0.53 m exceeding the modern requirement of 0.15 m, the vessel considered unsafe by modern criteria with the area under the righting arm curve being insufficient.</td>
<td>This condition would be considered stable by modern standards</td>
<td>Considered unstable, with the stability between the 30° heel angle and the downflooding angle being insufficient. However this condition would satisfy a common sense criteria (Tanner 2013a:113–121).</td>
</tr>
</table>

Table 1 Test results for Minimum Reconstruction

G.12 Publication:

Initial publication included the Newport Ship Expert Panel group, and FRAUG, a collaboration group of over twenty maritime archaeologists, from numerous pan European institutions. Criticisms and comments received following this initial publication included :

- More masts would be most likely, probably three masts.
- An explanation of the torso drawing; - the criticism was the inclusion of reconstructed or missing parts in this drawing.
- Physical scale model; definition required to clarify status, why is it labelled as 'reconstructed' physical scale model ?
- clear arguments regarding propulsion and steering.
- logical explanation required of each step.

G.13 Re-assessment:

It was decided, in keeping with the incremental approach, and complying with the self imposed rule, to only use articulated material from the recovered wreck, that the minimum reconstruction would be revised, based on the feedback received, to include a fore and mizen mast. This revised minimum reconstruction would then be republished to a wider audience, and await additional feedback before proceeding in an attempt at a complete or principal reconstruction.

G.14 Revised Minimum Reconstruction -Three Masts:

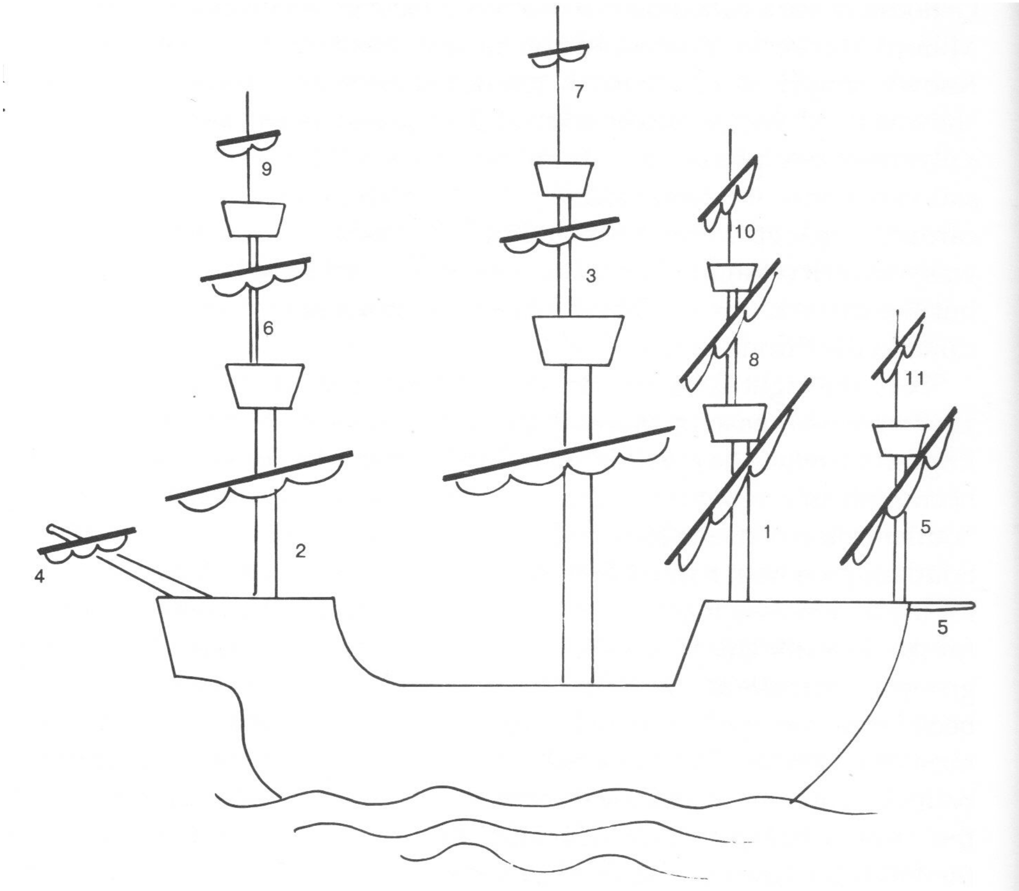


Figure 25 Schematic diagram of European rig development (after Friel:1995)

1: Mizzenmast by 1350 Mediterranean and by 1416 N. Europe
2: Foremast by 1435 N. Europe and by 1453 Mediterranean
3: Main TopMast by 1465
4: Sprit Yard by 1465
5: Bonaventure Mast and Outligger (Outrigger) by late 1470's
6: Fore Topmast by 1495
7: Main TopGallant by 1495
8: Mizzen TopMast by 1514
9: Fore TopGallant by 1514
10: Mizzen TopGallant by 1514
11: Bonaventure TopMast by 1514

Based on the timeline used for the rig development in Europe by Friel above, the Newport Ship falls within the first 2 stages, indicating that a fore and mizen mast would have been likely on a vessel of this size.

The analysis was then repeated for the same floating hypothesis hull with three masts (Figure 26) a weight report (Figure 27) was generated to include the mast and rigging.

The vessel was then analysed for intact stability (Figure 28 and Figure 29).

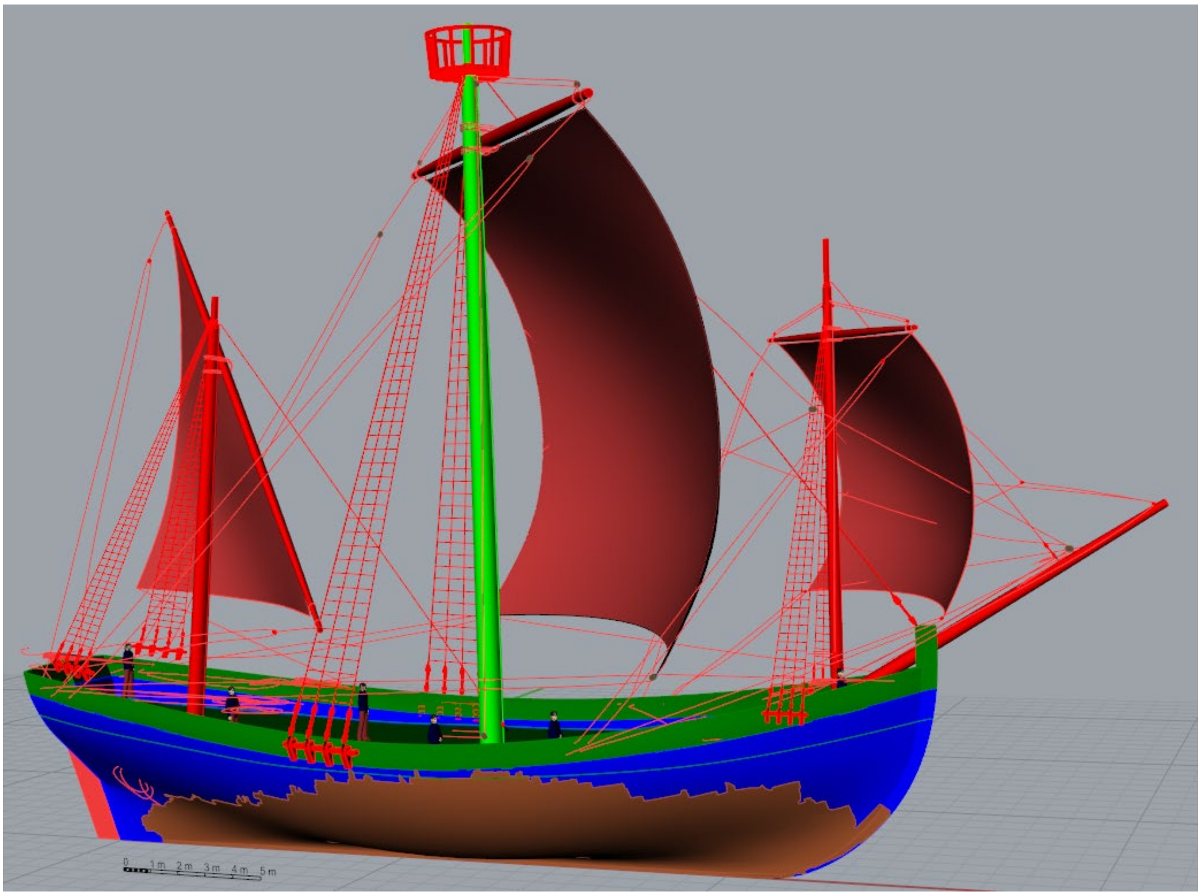


Figure 26 Revised Minimum Hull reconstruction with Three Mast

Weight Items						
Object Name	**Material**	**Weight (kgf)**	**LCG (m)**	**TCG (m)**	**VCG (m)**	**Weight Basis**
⊟ All Items						
Clench Nails - Stb.	Clench Nails	941.113	11.794	-2.085	2.174	0.000 N/A
Clench Nails - Port	Clench Nails	941.113	11.794	2.085	2.174	0.000 N/A
Spike Nails - Stb.	Spike Nails	399.031	11.915	-1.859	2.075	0.000 N/A
Spike Nails - Port	Spike Nails	399.031	11.915	1.859	2.075	0.000 N/A
Rudder	Oak @ 800 kg (27% M.C.)	517.613	-1.279	0.000	2.424	0.647 m^3
Tiller	Oak @ 800 kg (27% M.C.)	70.468	-1.346	0.000	5.757	0.088 m^3
Anchors	None	* 1850.000	23.523	0.000	4.178	N/A
Anchor warps	None	* 200.000	21.475	0.000	3.841	N/A
Rigging CG Mizenmast	None	* 1869.000	3.644	0.000	9.709	N/A
Rigging CG Mainmast	None	* 5962.590	14.316	0.000	12.125	N/A
Rigging CG Foremast	None	* 754.770	23.351	0.000	9.439	N/A
Additional Strakes Port	145mm Oak	2540.594	11.656	2.880	4.574	22.483 m^2
Recovered Hull Stb	145mm Oak	10811.864	13.080	-1.809	1.221	95.680 m^2
Repaired Hull Stb	145mm Oak	4383.710	2.678	-2.116	2.915	38.794 m^2
Transom Hull	145mm Oak	5.640	21.532	-0.049	0.053	0.050 m^2
Repaired Hull Stb	145mm Oak	2108.979	22.228	-1.635	3.506	18.664 m^2
Repaired Hull Port	145mm Oak	11186.114	10.911	2.304	2.636	98.992 m^2
Transom Hull	145mm Oak	5.640	21.532	0.049	0.053	0.050 m^2
Recovered Hull Port	145mm Oak	6118.439	12.745	1.065	0.636	54.145 m^2
Additional Strakes Stb	145mm Oak	2543.456	11.640	-2.876	4.575	22.508 m^2
Main Deck	120mm Oak	15936.417	11.253	0.000	3.513	171.359 m^2
SubTotal		69545.582	11.898	0.000	3.731	
Totals		**69545.582**	**11.898**	**0.000**	**3.731**	

Figure 27 Weight Report Revised Minimum Reconstruction with Three Mast

Load Condition Parameters				
Condition	Weight / Sinkage	LCG / Trim	TCG / Heel	VCG (m)
LightShip Three Masts	69545.600 kgf	11.900 m	0.000 m	3.73

Resulting Model Attitude and Hydrostatic Properties				
Condition	Sinkage (m)	Trim(deg)	Heel(deg)	Ax(m^2)
LightShip Three Masts	1.474	-0.261	0.000	5.56

Condition	Displacement Weight (kgf)	LCB(m)	TCB(m)	VCB(m)	Wet Area (m^2)
LightShip Three Masts	69545.708	11.887	0.000	0.968	125.680

Condition	Awp(m^2)	LCF(m)	TCF(m)	VCF(m)
LightShip Three Masts	93.548	11.974	0.000	1.419

Condition	BMt(m)	BMl(m)	GMt(m)	GMl(m)
LightShip Three Masts	3.294	34.151	0.531	31.389

Condition	Cb	Cp	Cwp	Cx	Cws	Cvp
LightShip Three Masts	0.281	0.495	0.567	0.568	3.074	0.495

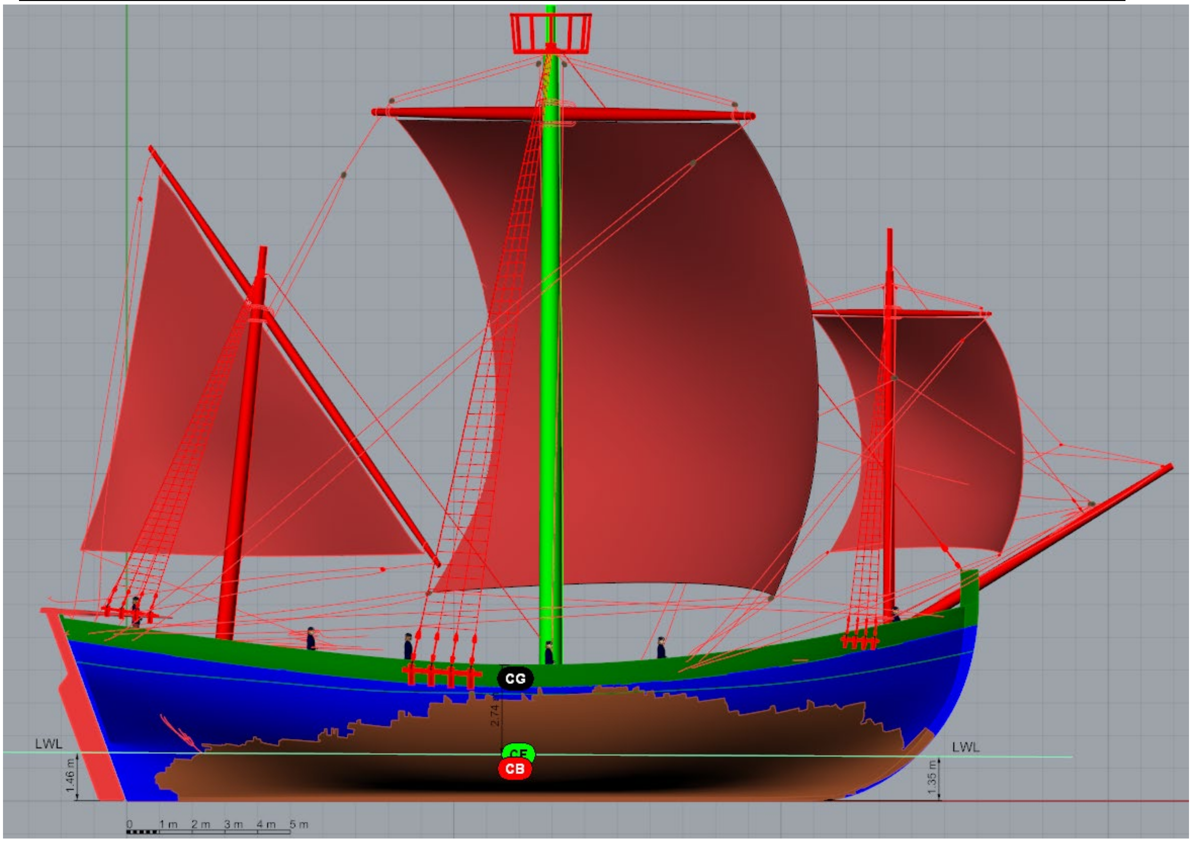
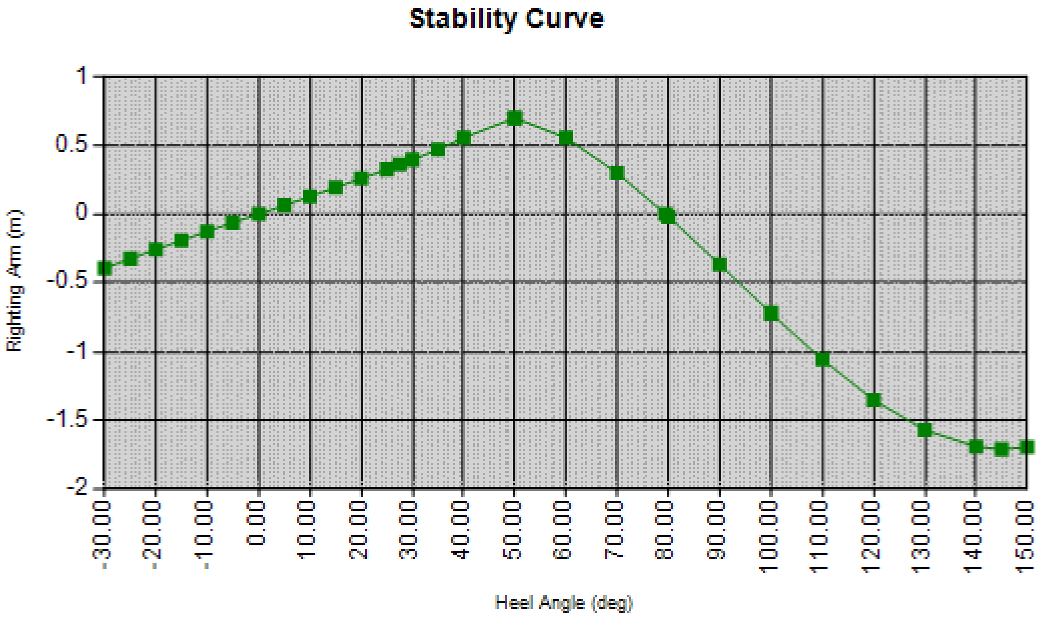


Figure 28 Minimum Hull reconstruction with Three Masts



Stability Criteria - Bureau Veritas, Intact Stability					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Area Between FreeEquil and 30 > 3.151 meters-deg	0	30	3.151	5.8319	Pass
Area Between FreeEquil and 40 > 5.157 meters-deg	0	40	5.157	10.5652	Pass
Area Between 30 and 40 > 1.719 meters-deg	30	40	1.719	4.7332	Pass
GZ At 30 > 0.2 meters	30		0.2	0.3957	Pass
Angle At GZmax > 25 deg	49.987		25	49.987	Pass
GM At FreeEquil > 0.15 meters	0		0.15	0.7222	Pass

Figure 29 Bureau Veritas Intact Stability Results - Minimum Reconstruction - Three Masts

In this three-mast configuration, the vessel has the following flotation characteristics:
Weight 69,545 kg, L.C.G. 11.90 m, T.C.G. 0.0 m, V.C.G. 3.73 m,
Draft Aft of 1.46 m, Draft Forward of 1.35 m and a freeboard midship of 2.74 m.

Wind and Wave Stability

The vessel was again configured in the worst-case scenario condition with regard to wind loading, which would represent a "beam on" wind, with the sails sheeted in tight. This is not a normal sailing configuration but represents the worst possible case scenario. To establish this lateral projected area, the yards and sails were rotated as close as possible to the centre line plane, allowing for normal restrictions such as shroud placement. The projected sail area, combined with the above water hull surface area was then calculated (Figure 30) .This results in a lateral projected surface area, including hull, spars and sails of 345.47 m².

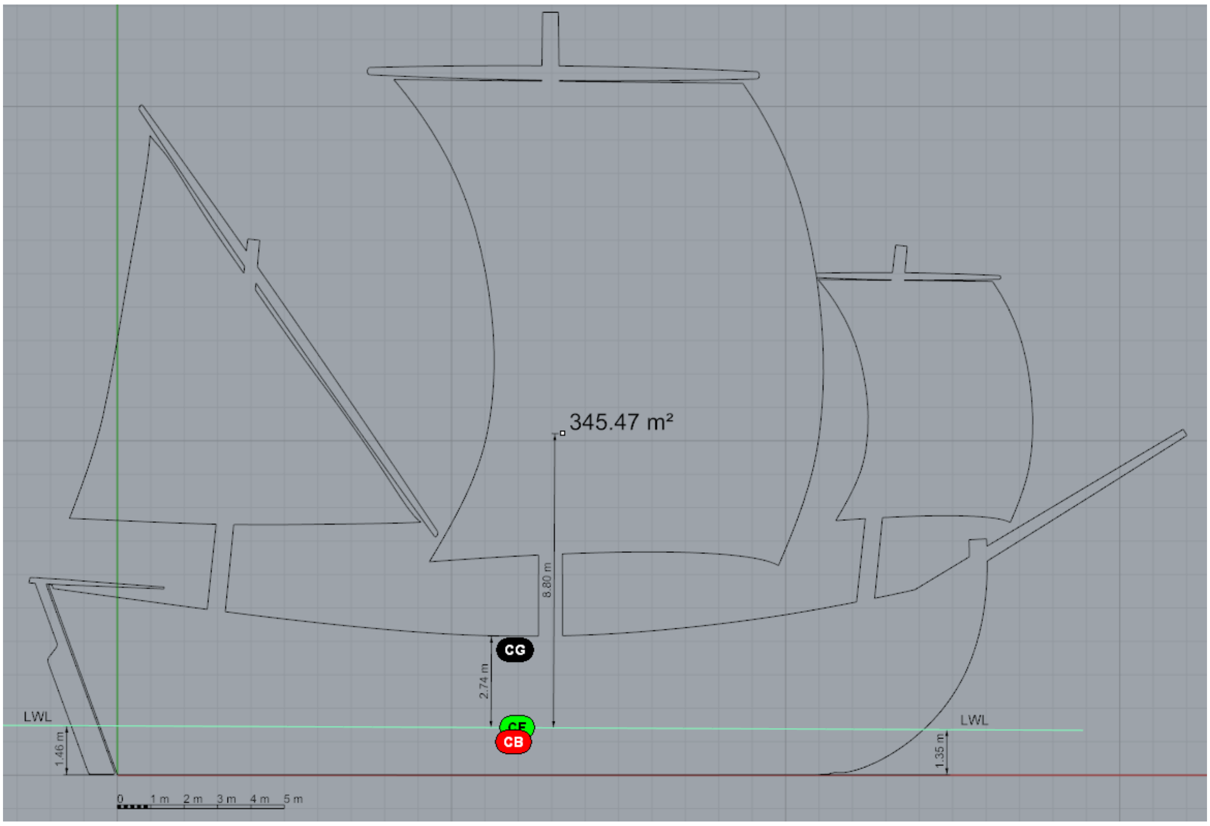


Figure 30 Lateral surface area for wind loading with Three Masts

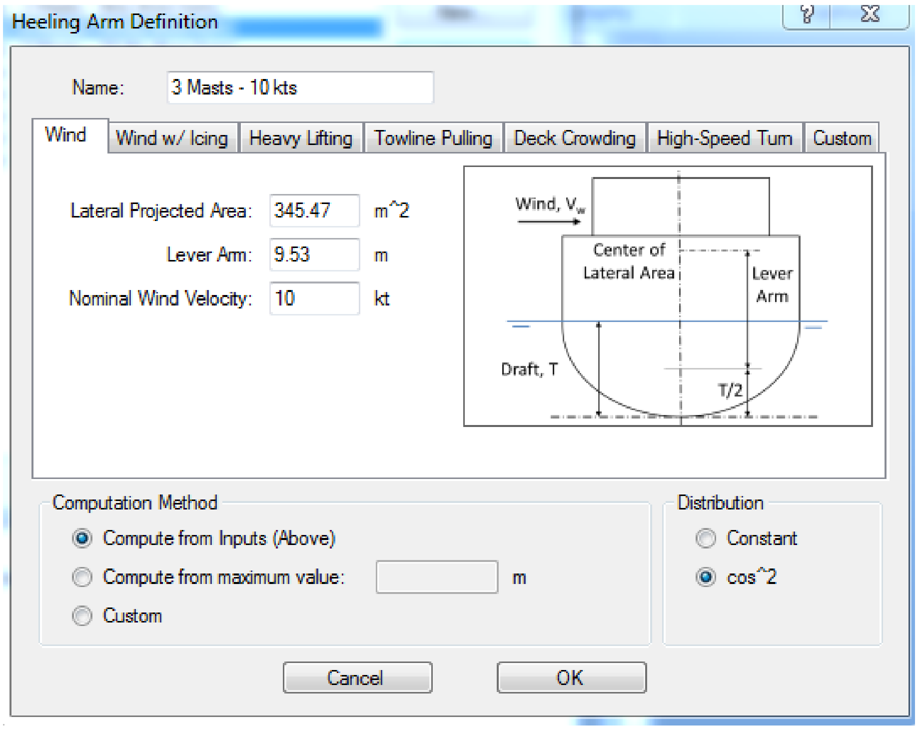


Figure 31 Wind Loading Criteria for Three Masts

With the centre of lateral area 8.8 m above the LWL (load waterline) and a draft of 1.46 m the resulting lever arm is 9.53 m (Figure 31).

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 5kts					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Angle At SteadyEquil <= 16 deg	2.0396		16	2.0396	Pass
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-22.9604	40.7231	1	2.5426	Pass
ResRatio Between SteadyEquil-25 deg and Flood > 1	-22.9604	40.7378	1	2.5446	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-22.9604	50	1	4.0247	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	2.0396		32.5785	2.0396	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 10 kts					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Angle At SteadyEquil <= 16 deg	7.987		16	7.987	Pass
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-17.013	40.7231	1	1.97	Pass
ResRatio Between SteadyEquil-25 deg and Flood > 1	-17.013	40.7378	1	1.9719	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-17.013	50	1	3.3648	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	7.987		32.5785	7.987	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 15 Kts					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Angle At SteadyEquil <= 16 deg	16.587		16	16.587	Fail
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-8.413	40.7231	1	1.1277	Pass
ResRatio Between SteadyEquil-25 deg and Flood > 1	-8.413	40.7378	1	1.1292	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-8.413	50	1	2.2569	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	16.587		32.5785	16.587	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 20 kts					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Angle At SteadyEquil <= 16 deg	25.6912		16	25.6912	Fail
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	0.6912	40.7231	1	0.4417	Fail
ResRatio Between SteadyEquil-25 deg and Flood > 1	0.6912	40.7378	1	0.4426	Fail
ResRatio Between SteadyEquil-25 deg and 50 > 1	0.6912	50	1	1.2054	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	25.6912		32.5785	25.6912	Pass

Figure 32 Stability results for minimum reconstruction with Three masts

The minimum reconstruction hull with three masts passes the modern Bureau Veritas stability rules for wind and rolling waves in all both 5 and 10 knots of wind. The vessel "fails" the 15 knots wind test, but only on the resultant heel angle criteria, in that it heels to 16.5° when the requirement is 16°, which could be deemed as a pass. The vessel fails the 20 knot wind test, but it must be remembered that this is tested in the "worst possible" scenario, and the sail area would have been reduced in reality. With the Caprail submerged at 40.7°, the angle of maximum stability at 50.3° and the angle of vanishing stability at 79.4°, this reconstruction would be deemed as passing the modern test criteria.

Consequently, this stage of the minimum reconstruction can be deemed as functional.

Figure 33 Revised Minimum Reconstruction

The revised minimum reconstruction with fore and mizen masts is shown in Figure 33, and a key drawing (Figure 34) showing the extent of the archaeological evidence, as well as the hypothetical portions shown red, used in creating the minimum reconstruction.

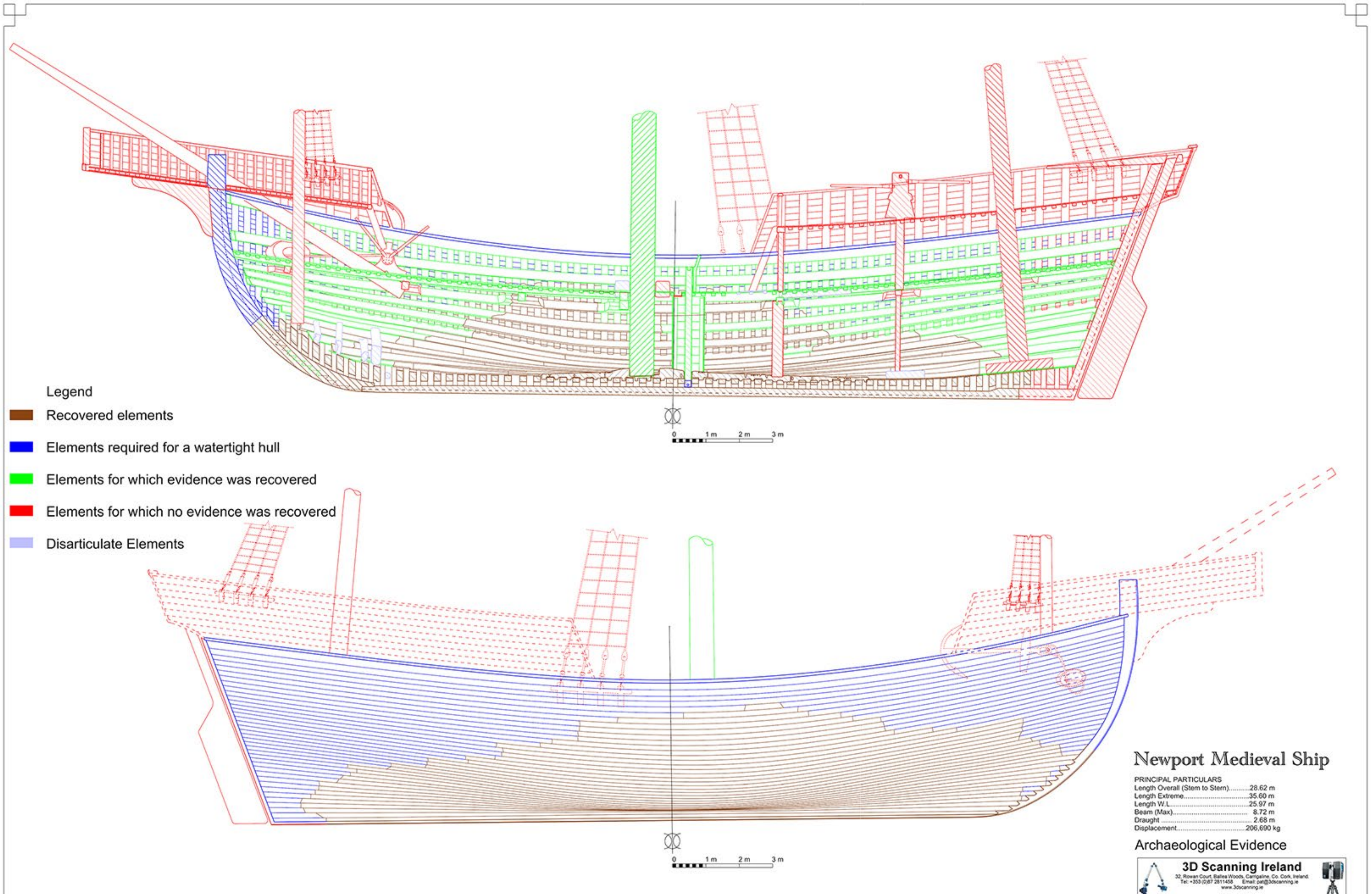


Figure 34 Revised Minimum Reconstruction showing recovered elements and hypothetical additions

G.15 Subsequent Publication:

All of the reconstruction drawings, specialist reports, as well as the entire Newport Medieval Ship database of records, recorded material, and photographs was then published online with the Archaeological Data Service, and is publicly available on-line at:
http://archaeologydataservice.ac.uk/archives/view/newportship_2013/index.cfm
as well as a paper and poster session at ISBSA 12; a paper for the SHA Underwater Archaeology Proceedings 2013; and two papers in the IJNA forthcoming.

Criticisms and comments received following subsequent publication:

- Sheer line too low
- Looks like a big boat rather than a ship
- Upperworks look modern when compared to Beauchamp images
- Inclusion of cannons is required
- Upperworks do not resemble the 'Zumaia' tapestries
- Recovered stem not included in the model
- Diagram required showing levels with ground, and tidal levels
- Keel at 4m OD means ship floats on any tide
- Suggestion to call fig 33a (photo of physical scale model) the Minimum reconstruction and not 33b (photo of minimum reconstruction superimposed on Model)
- Some real issues surrounding reconstructed section shapes
- One comment regarding the transom, can't see proof and therefore should be bluff double ended

Symmetry:

One of the early comments received was the question of assumed symmetry in the original vessel.
Due to the nature of nautical archaeological remains longitudinal symmetry is often considered theoretically justifiable, though caution should always be expressed prior to late 19th-century industrial standardisation or when recording vernacular/ethnographic vessels (Institute for Archaeologists 2008b:8)
In order to validate this assumption, the substantial floor timbers which should be less affected by sagging or distortion were examined for symmetry.
This symmetry was examined using three criteria,

1. Centre line dimensional symmetry
   The widths to the strakes either side of a notional centre-line
2. Flare or angular symmetry
   The difference in angle of the hull either side.
3. Strake height difference
   Whether the same strake is gaining or losing height between port and starboard.

When building a vessel, it is important to try and keep the strakes on either side at the same vertical height, as any difference will be clearly noticeable especially where the strakes meet at the stem and stern posts. Traditionally the strake would be hung on the first side and the planking stock for the same strake on the opposing side would be selected based on the maximum dimensions of the already hung strake. This mirrored strake would then be trimmed to size in order to prevent any "gain" in height. The significance of this gain becomes apparent the more strakes that are added to the hull. Any minor increase in each plank width will culminate in a large difference higher up on the hull which could result in a significantly narrower plank width, or even worse, an uneven number of planks between one side and the other. While an increase of single digit proportions might seem insignificant in the overall height, being less than 1%, when you take the individual width of each strake this difference could be as much as 10 or 20%.

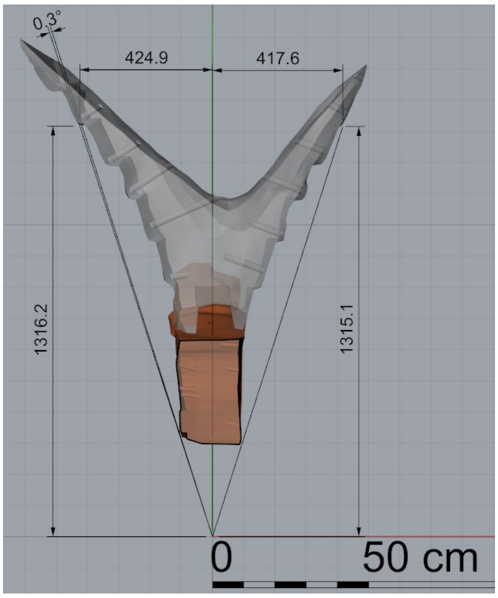


Figure 35 Symmetry at Frame 5

Frame 5

1. 2 mm at Keel, 7.3 mm at 7th strake
2. 0.3° at 7th strake (1315 mm above baseline)
3. 1.1 mm at 7th strake (1315 mm above baseline) equates to 0.08 % gain

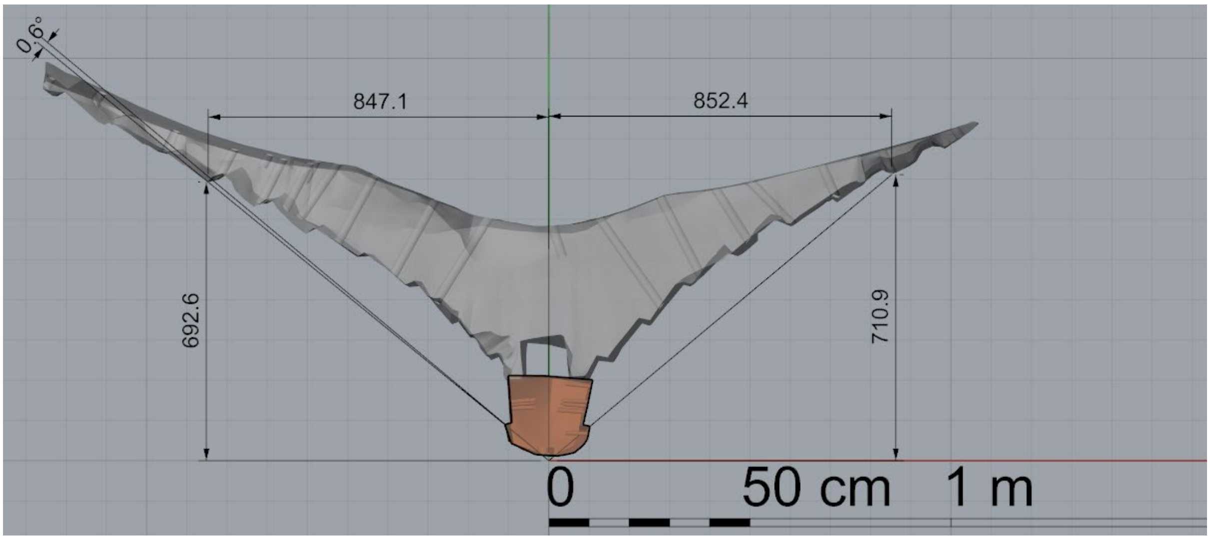


Figure 36 Symmetry at Frame 15

Frame 15

1. 2 mm at Keel, 5.3 mm at 7th strake
2. 0.6° at 7th strake (692 mm above baseline)
3. 18.3 mm at 7th strake (692 mm above baseline) equates to 2.6% gain

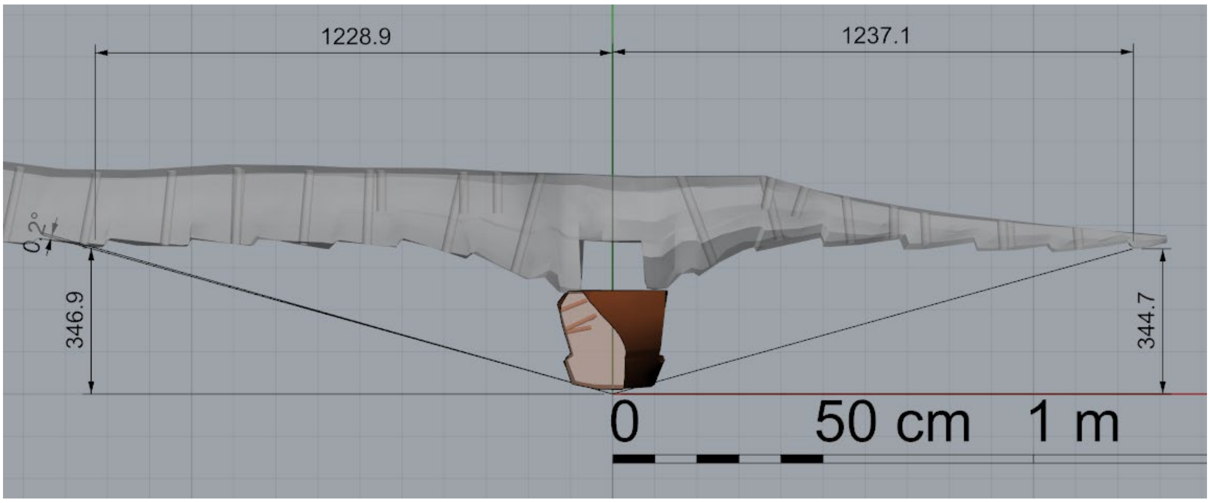


Figure 37 Symmetry at Frame 30

Frame 30

1. 2 mm at Keel, 8.2 mm at 7th strake
2. 0.2° at 7th strake (345 mm above baseline)
3. 2.2 mm at 7th strake (345 mm above baseline) equates to 0.63 % gain

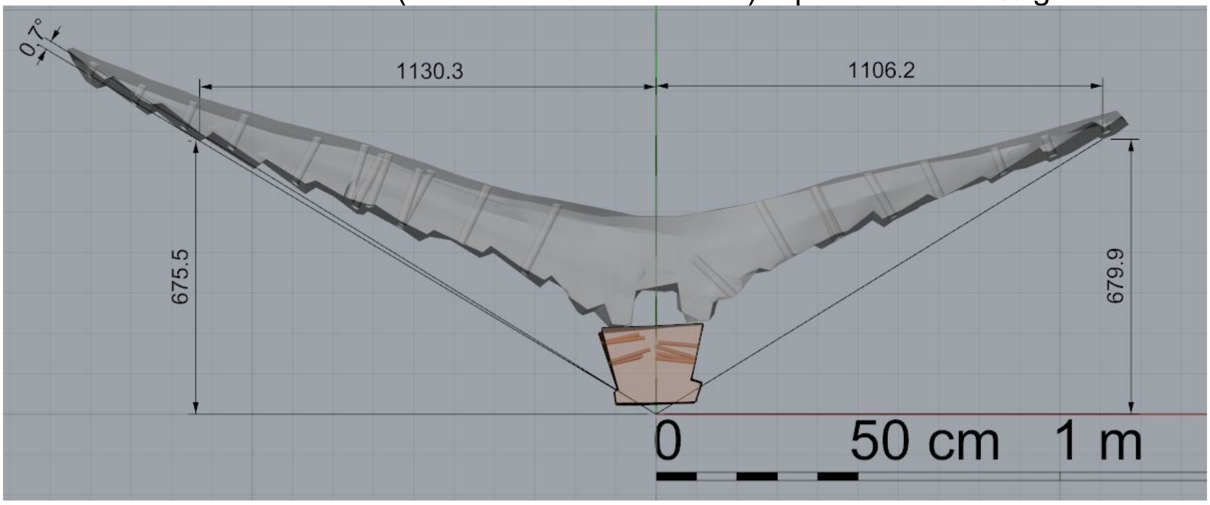


Figure 38 Symmetry at Frame 45

Frame 45

1. 1.6 mm at Keel, 24.1 mm at 8th strake
2. 0.7° at 8th strake (675 mm above baseline)
3. 4.4 mm at 8th strake (675 mm above baseline) equates to 0.65 % gain

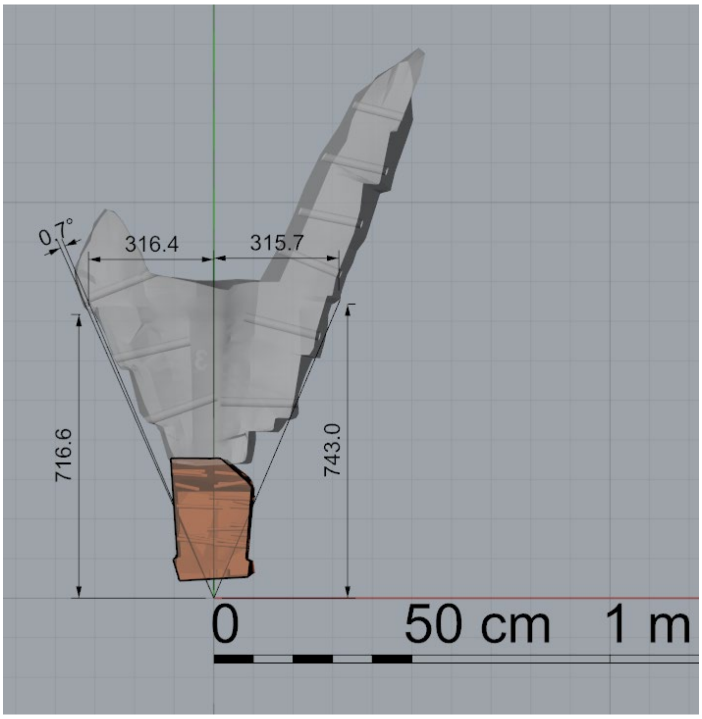


Figure 39 Symmetry at Frame 60

Frame 60

1. 1.6 mm at Keel, 0.7 mm at 3rd strake
2. 0.7° at 3rd strake (716 mm above baseline)
3. 26.4 mm at 3rd strake (716 mm above baseline) equates to 3.7 % gain

This would indicate that the original intention was to build a symmetrical vessel.

G.16 Testing Criteria:

Modern Stability Calculations:

A second comment or criticism which is often asked of hypothetical reconstructions is, what criteria is used in the testing?

Once a reconstruction drawing is available the performance of the boat it represents may be assessed in several ways using simple coefficients that are based on the boat's overall measurements, thus LOA/BOA and BOA/D summarise the overall proportions of the boat and as such give a relative assessment of the boats capabilities. Using hydrostatic curves involves the definition of the waterline(s), underwater shape and calculations of displacements, sectional areas and coefficient based on the underwater geometry, may be used to give forecasts of performance. (McGrail 1998b,192).

A problem exists when attempting to examine the stability and performance of an archaeological reconstruction. What "rules" should be used as a reference? It is unlikely that any "stability rules" were in force during the original construction of the vessel, other than common sense and possibly to some extent "trial and error". A hypothetical reconstruction "fails" for many of the floatation configurations when using modern stability criteria. However, the main criteria which fail are;

1. the area under the Gz curve between 30° heel and the downflooding angle.
2. the area of positive stability being less than the area of negative stability when rolling due to wave action is taken into consideration.

Modern rules for the stability of ships are formulated by the International Maritime Organisation (IMO), and it is at the discretion of inspectorates or classification societies to adopt these rules or make them even more stringent. Bureau Veritas (BV) is one such classification society founded in Antwerp in 1828, originally Belgian but now a French society (Bureau Veritas 2012:81–97).

The stability testing carried out in the following sections use the Bureau Veritas criteria:

The main stability rules are the same for IMO and BV

Area GZ_{0-30}	> 0.055 m-rad or 3.151 m-deg
Area $GZ_{0-40(f)}$	> 0. 009 m-rad or 5.157 m-deg
Area $GZ_{30-40(f)}$	> 0. 003 m-rad or 1.719 m-deg
Height GM_0	> 0.1 m
Angle GZ_{max}	> 25° (preferably >30°)

Many of the modern criteria have been developed and refined in an effort to "force" stability and safety into the design of a vessel so as to reduce the potential for catastrophic failure due to "pilot" error, a need which has arisen in part due to the increase in "amateur" or inexperienced sailors having relatively easy access to sailing or boating in general. Criteria such as GZ_{30} and GZ_{40}, while working for smaller vessels are more difficult to achieve with a larger sailing vessel. In addition not many large (25 m plus) sailing vessels would even consider operating at these angles of heel.

If the Newport Medieval ship were to be tested under Bureau Veritas modern rules, with a load waterline length (LWL) exceeding 24 m, it would be assessed for certification under four categories. Sheltered areas, Coastal areas, Navigation limited to within 60 nautical miles of a coastline or unrestricted navigation. For certification under the first three categories the vessel would be required to comply with the Intact stability rules,

2.1.2 GZ curve :

The area under the GZ curve to be not less than 0.055 m-rad or 3.151 m-deg up to 30° angle of heel,

The area under the GZ curve to be not less than 0. 009 m-rad or 5.157 m-deg up to 40° angle of heel or the downflooding angle if this is less than 40°,

The area under the GZ curve between 30° and 40° heel angle to be not less than 003 m-rad or 1.719 m-deg,

2.1.3 Minimum Righting Lever:

The righting lever GZ to be not less than 0.2 m at a heel angle equal or greater than 30°,

2.1.4 Angle of Maximum Righting Lever

The maximum righting arm is to occur at angle greater than 25° and preferably greater than 30°,

2.1.5 Initial Metacentric Height

The initial metacentric height GM_0 is to be not less than 0.15 m,

3.1.3 Wind and Wave rolling

The area above the heeling curve and below the GZ curve must equal to or greater than the area above the GZ curve and below the heeling curve. The heel angle resulting from steady wind to be less than 16° or 80% of the angle of deck immersion, whichever is less.

For unrestricted navigation, a vessel would also be required to comply with the rules for Damage Stability, which examines flooding control by the inclusion of watertight bulkheads or subdividing the hull using compartmentation. All of the inspectorates and classification societies also give the option for "alternative" compliances and will accept lower values by agreement on a case by case basis. An example of this from Bureau Veritas:

> "In cases of ships with a particular design and subject to the prior agreement of the flag Administration, the Society may accept an angle of heel GZmax less than 25° but in no case less than 15°, provided that the area "A" below the righting lever curve is not less than the value obtained, in m.rad, from the following formula:
>
> A = 0,055 + 0,001 (30° - GZmax)"

This indicates a level of common sense approach to the problem of classifying a vessel which does not meet the predetermined criteria.

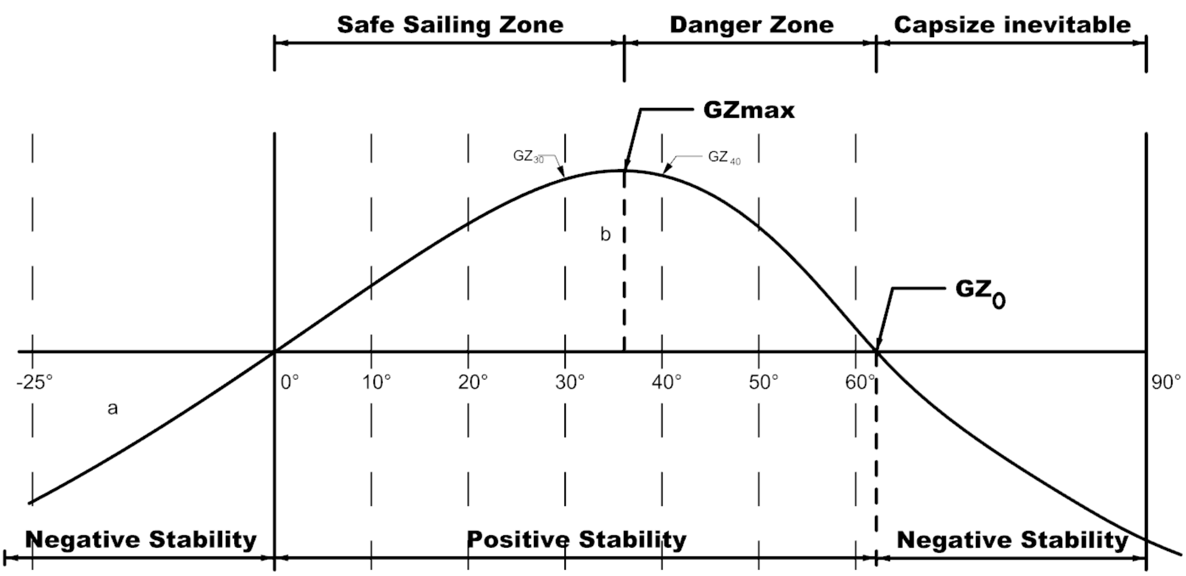


Figure 40 A generic stability curve

Taking the fictitious stability curve (Figure 40) for a generic sailing vessel, once the sails are set the vessel will begin to heel, due to the wind heeling moment, until a state of equilibrium is reached, whereby the righting arm moment balances the wind heeling moment. As long as this state of equilibrium occurs between 0° and the angle of GZ_{max}, which differs for every vessel, the vessel is sailing in the "safe sailing zone" where the heeling moment will be opposed by an increasing righting moment, and all is good in the world.

The problems begin when the vessel heels beyond the angle of GZ_{max} where the amount of righting moment is decreasing, in this "danger zone" a small increase in heeling moment caused by a slight wind speed increase, or even, a seemingly insignificant crew movement causing a centre of gravity shift, will result in a large heel angle increase which could overwhelm the decreasing righting moment, and in this zone between GZ_{max} and GZ_0 the sails should be eased or reduced to decrease the Wind heeling arm. Failure to reduce the heeling moment within this "danger zone" will quickly result in the vessel heeling beyond the angle of GZ_0 which will result in an inevitable capsize.

The real danger for a sailing vessel, is one where the vessel can still sail in apparent comfort, such as the deck edge not yet underwater, but beyond the angle of GZ_{max}, whereby a slight increase in healing moment could lead to undesirable consequences. Attempts to reduce these dangers have led to the introduction of "general rules" such as GZ_{30}, GZ_{40} and GZ_{30-40} and generic wave roll loading such as equilibrium -25°.

This criteria is using a generic 25° wave roll angle.
Angle of roll, in degrees, to windward due to wave action, is calculated as follows:
$\theta_1 = 109kX_1X_2 \sqrt{rs}$
Where k, X_1, X_2 and s are coefficients defined in the Bureau Veritas handbook,
r = 0,73 ± 0,6 (OG) / T_1 - where OG = distance between centre of gravity and the waterline, and T_1 = mean moulded draft.
The actual wave roll angle for the reconstructed Newport Medieval Ship is 14.59°, rather than the generic 25°.

Bureau of Medieval Common Sense:

A proposed set of criteria to assess the medieval reconstruction could be simplified to examine the vessel using a common sense approach while still ensuring a reasonable margin of safety. These rules should ensure the vessel sails within the "safe sailing zone" with a clear visual indicator of when the vessel heels beyond the angle of GZ_{max} and enters the "danger zone";

1. Steady Equilibrium less than GZ_0
2. Steady Equilibrium less than Downflooding
3. Steady Equilibrium less than GZ_{max}
4. GZ_{max} greater than Downflooding
5. Steady Equilibrium + 14.6° less than Downflooding

Rule 1: This would have the effect of ensuring the resultant heel angle, due to wind loading, is not in the negative stability zone where capsize is inevitable.

Rule 2: The caprail atop the bulwark will remain above water at the resultant heel angle.

Rule 3: The resultant heel angle will be within the safe sailing zone.

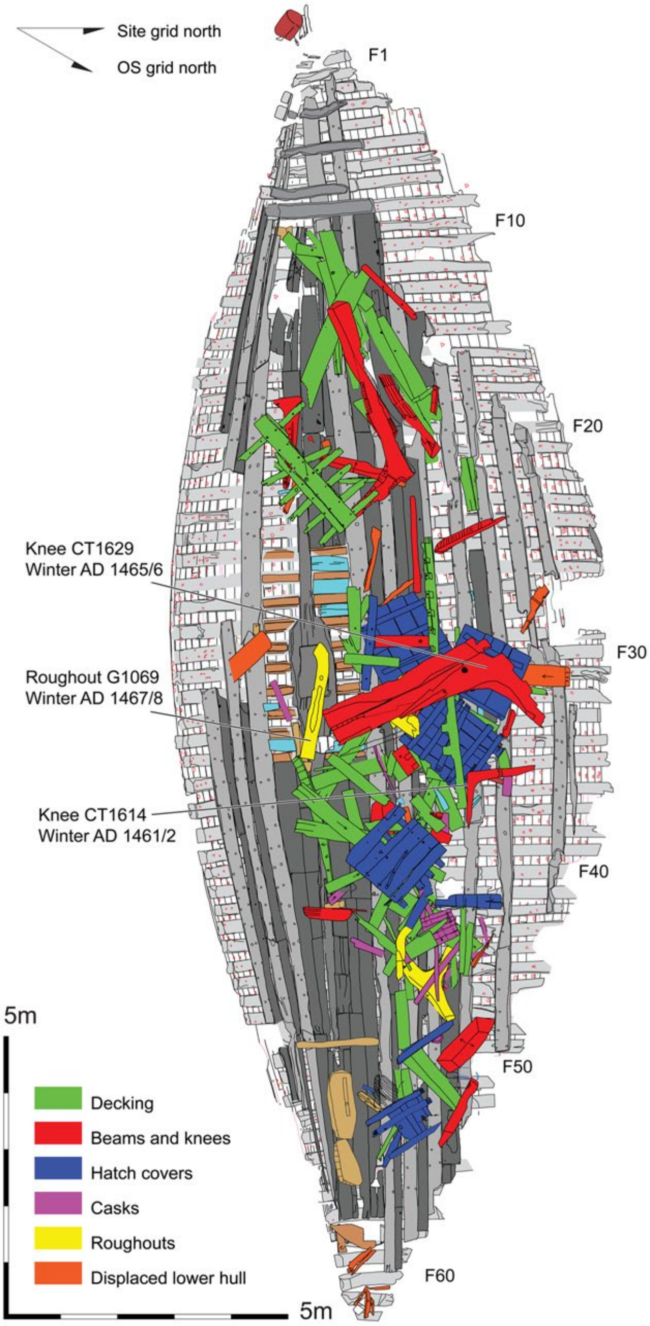
Rule 4: The caprail atop the bulwark reaching the water being a clear visual indication of the vessel heeling to the GZ_{max} angle and as such a warning to reduce sail area.

Rule 5: The caprail is still above the water with the vessel heeled by the wind and wave roll.

The Steady Equilibrium angle is the resultant angle of heel of the vessel, when the forces of heeling due to wind load are balanced by the forces of the righting moment.

It should also be noted that the Downflooding angle for each reconstructed version of the Newport Medieval Ship has been notionally set at the Caprail height amidships and with the recovered evidence of the hatch covers being caulked, this would indicate, at least an attempt at waterproof decks. The actual downflooding angle could be significantly higher, especially if the deck hatches were located only along the centre line of the vessel.

This vessel is then tested using these criteria, for each floatation condition in a given wind strength as well as that same wind strength with a wind gust loading of 150%.



G.17 Additional or Capital Reconstructions

Several hundred disarticulated timbers were found during the excavation, many of which resembled ship timbers (Jones and Nayling 2011:59). These disarticulated elements (Figure 41) which were recovered from within and around the hull area, but were not attached to the vessel remains, were then examined and hypothetically placed in an attempt to create a more complete or capital reconstruction.

This hypothetical placement was informed by analysing find location, parallel / comparable archaeological evidence, iconography and ship building knowledge.

Figure 41 Disarticulated elements within the hull structure (Nigel Nayling)

As the hull shape was repaired, refined, and increasingly filled out, it became possible to position large numbers of these disarticulated elements in their original perceived positions.

Disarticulated Elements:

A large quantity of components, included four standing knees, beam fragments including carlings and a fragmented beam shelf, stanchions, deck elements and five articulated but displaced hatch covers as well as other unidentified components were recovered from within or around the vessel remains.

Beam Shelf:

A partial beam shelf fragment CT1526 (Figure 42 and Figure 43) was recovered which was disturbed by the sheet piling but still partially attached to the recovered framing timbers above the 7th stringer, thereby giving an accurate indication of the deck height.

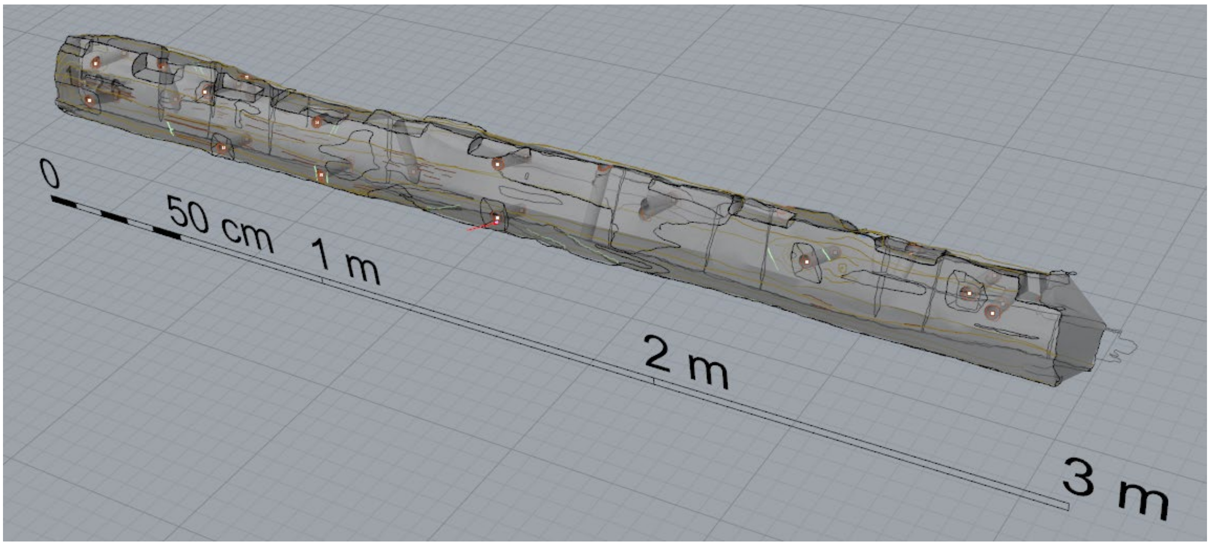


Figure 42 Beam Shelf Fragment CT1526

Figure 43 Detail of beam Shelf fragment CT1526 (Newport Museums and Heritage Service)

A recovered fragment of a carling beam CT1539 measuring circa 265 x 200 mm, with three rebates circa 85 x 46 mm to take ledges or deck beams, could be associated with these carlings.

Deck Beams:

Several disarticulated deck beams (Figure 44) were recovered which had average dimensions of 115 mm wide x 95 mm high and were not straight, typically having a curvature with a rise of 15 mm over 1.2 m distance indicating the deck was cambered.

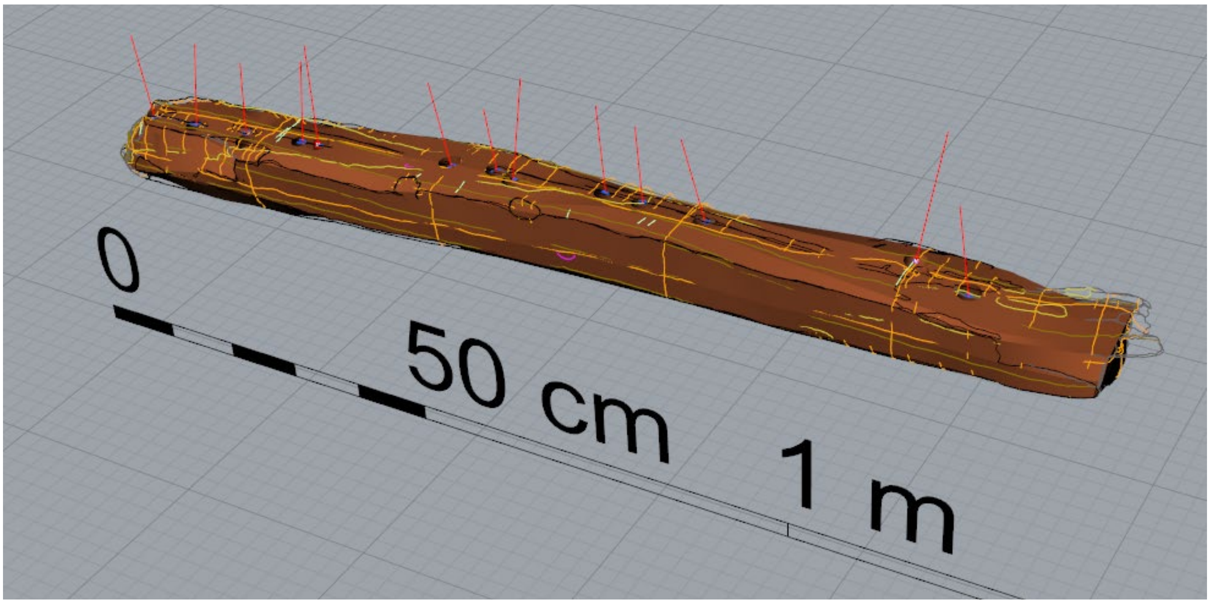


Figure 44 Deck Beam CT1235

Carlings:

A fragment of a carling beam (Figure 45), 2.1 m long x 180 mm high x 155 mm wide, was recovered which contained rebates of dimensions similar to the recovered deck beams.

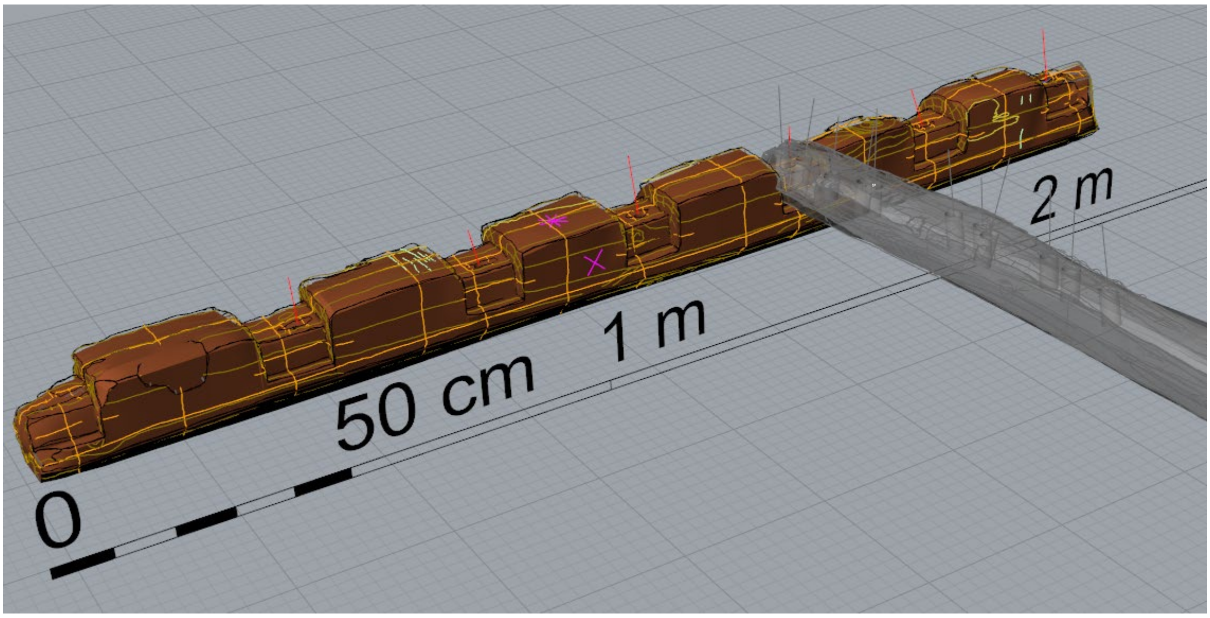


Figure 45 Carling Beam fragment CT1131

Standing Knees:

One of the largest disarticulated elements was a composite beam-standing knee assembly (Figure 47) which was recovered just aft of midships on the starboard side of the vessel. This assembly comprises of lower and upper transverse large beams circa 320 mm moulded x 245 mm sided and 260 mm moulded x 215 mm sided respectively. The lower beam CT003 was a single piece while the recovered portion of the upper beam comprised two separate sections CT001 and CT002 which were jointed using stepped or locking scarf joints. Both beams were through connected with four iron bolts, and the standing knee CT1629 was then fitted again with a locking or stepped scarf and initially fastened to the transverse beam assembly with iron toe nails prior to drilling and final fixing with two iron through bolts (Figure 46).

The standing portion of this knee was again toe nailed to the inboard mating surface of the frame prior to drilling and final fastening with two wooden treenails. Two blind treenail holes as well as seven spike nail holes indicate the presence of additional unknown items fastened to the inboard surface of this standing knee. The outboard end of the lower transverse beam terminated in a dovetail tennon which closely matched the dimensions of the dovetailed mortice rebates on the beam swelling of the recovered seventh stringer (Figure 48), thereby indicating the height or vertical positioning of this element. Initially it was thought this large knee and beam assembly was associated with the beam swelling on the seventh stringer midships between frames 29 and 30.

However closer examination of the outboard end of both the beam and knee revealed the end had not been cut square, but tapered aft, indicating the assembly was located further aft, probably associated with the beam swelling (Figure 48) recorded on the seventh stringer between frames 40 - 41. The inboard end of this composite beam was roughly hacked in antiquity, presumably during the salvage of ships timbers, so the centreline location is not apparent, however a rebate measuring circa 285 mm wide by 95 mm deep on both the forward and aft faces, was probably associated with large longitudinal carling beams.

While the standing knee CT1629 was identified as British oak with a felling date of the winter AD 1465/6, and is thought to be a repair, and not an original part of the vessel, it is being treated as a like for like replacement of an earlier element.

Figure 46 Iron forelock bolts associated with Knee CT1629 (Newport Museums and Heritage Service)

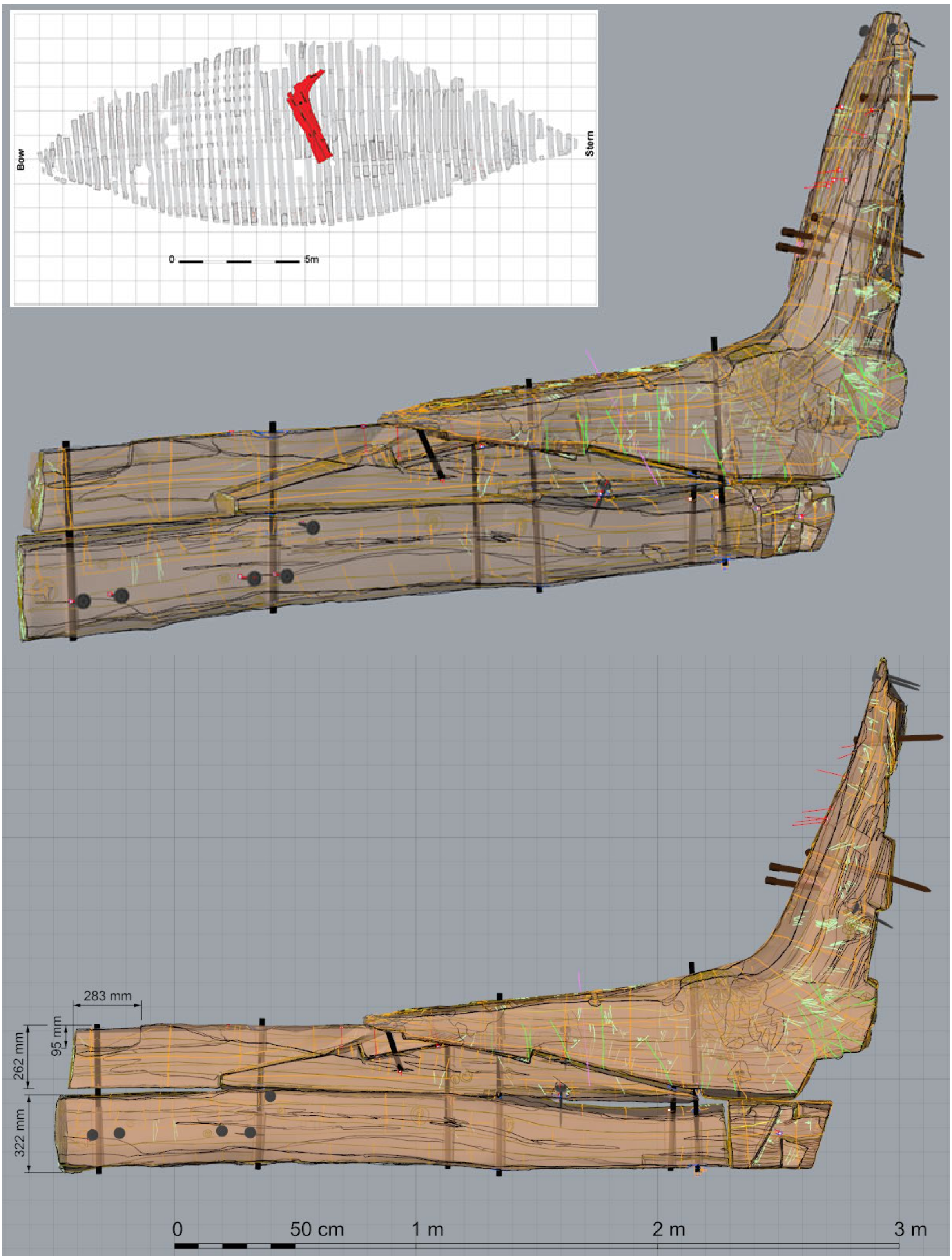


Figure 47 Composite Beam Knee assembly

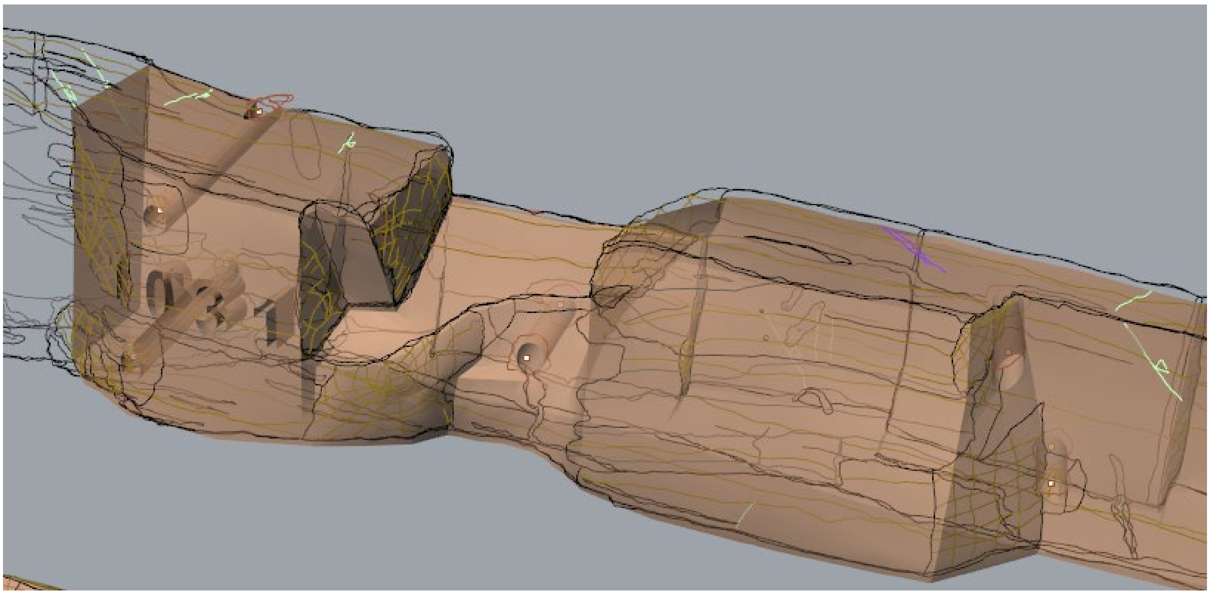


Figure 48 Detail of a Beam Swelling on Stringer STRS 7.1- CT1031

A second substantial standing knee CT1638 and transverse beam CT1615 (Figure 49) were recovered from within the vessel on the starboard side in the area of frame 20. This beam and standing knee were not assembled to each other when recovered as they were substantially damaged by the insertion of two concrete piles prior to excavation, but closely resemble the shape and scantling size of the composite beam-standing knee assembly.

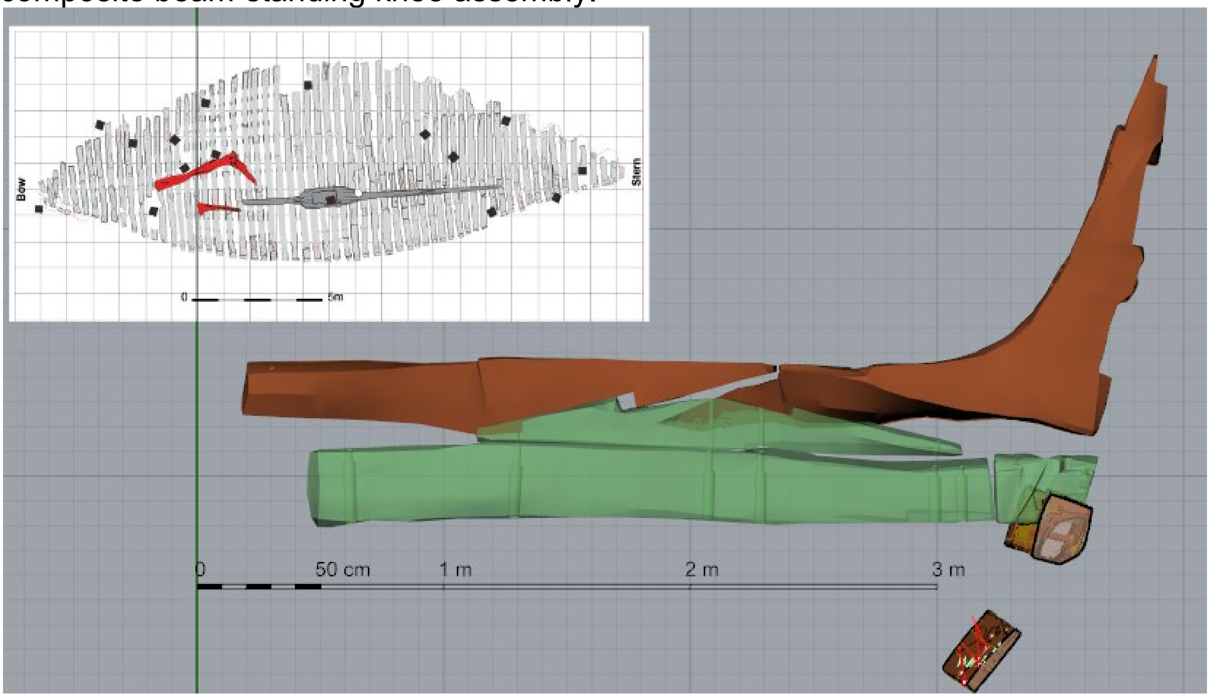


Figure 49 Standing Knee CT1638 and Beam CT1615

Figure 49 shows the beam CT1638 and associated standing knee CT1615 repositioned to coincide with the beam swelling and dovetail rebate located between frames 20 and 21. The transverse beam shown green in figure 15 is a copy of the transverse beam CT003 which forms part of the composite beam standing knee assembly from frame 40-41 in order to illustrate the similarities. Both of these standing knees CT1638 and the bigger knee CT1629 have their upright leg angled or flared outboard following the curvature of the lower hull.

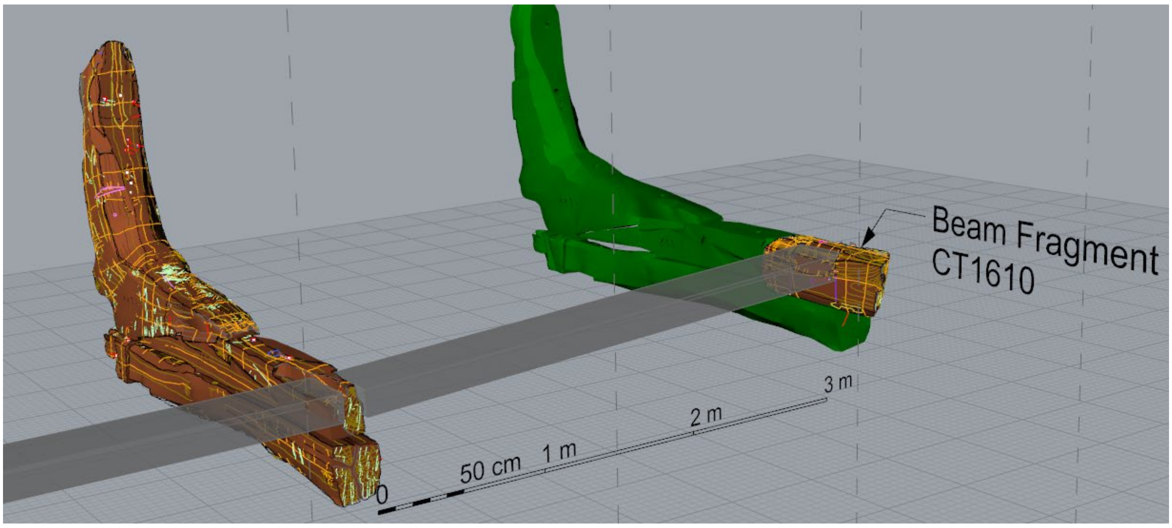


Figure 50 Transverse beams with rebates for Carling Beams

The standing knee and transverse beam assembly (Figure 50), repositioned within the reconstruction, showing the probable position of beam fragment CT1610, the green beam knee assembly in Figure 50 is a duplicate copy of the one recovered, with two large carlings shown grey. These carlings are based on the 285 x 95 mm rebate in the transverse beam CT001 and the beam fragment CT1610 which is of similar dimensions to CT001 and has a matching similar sized rebate on forward face only. This could indicate the aft extremity of the heavy carling beams.

Hatch Covers:

A total of 5 articulated but displaced hatch covers were recovered from within the vessel. Two hatches context 148 and 150 measured 1.4 m wide x 1.6 m long, with the supporting beams underneath measuring 1.25 m. Hatch cover context 143, measured 1.4 m wide x 1.3 m long and had a timber cleat circa 2.5 cm square partially displaced, running in a fore and aft direction which was interpreted as being a toe rail or foot brace (Figure 51). Hatch cover context 147 measured 1.4 m wide x 1.2 m long and the fifth hatch cover context 144 measured 1.3m wide with a recovered (potentially partial) length of 0.9 m. All of these deck hatches featured caulking between the deck planks, which indicates an attempt at waterproofing and could suggest a watertight deck.


Figure 51 Hatch Cover context 143 (Newport Museums and Heritage Service)

Mast Partner:

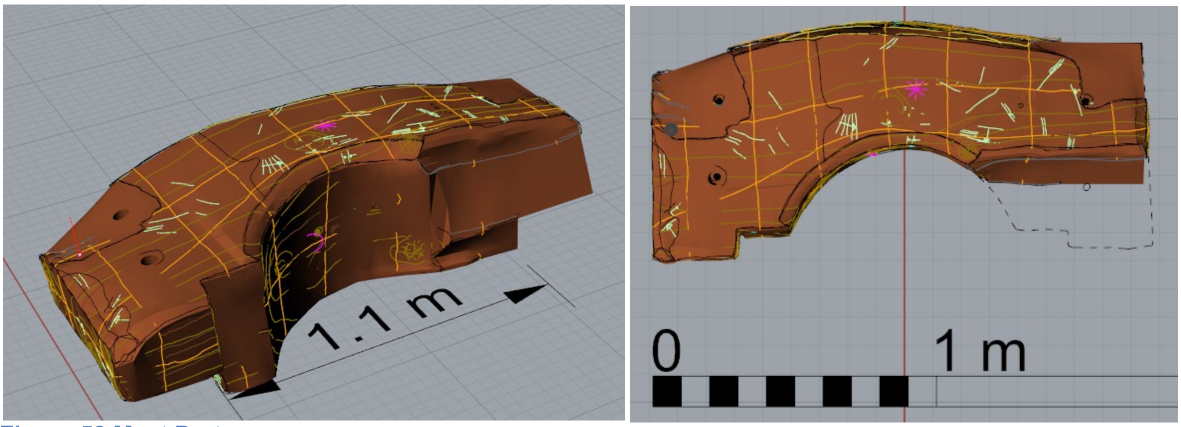


Figure 52 Mast Partner

A displaced mast partner fragment was recovered from within the vessel, which had been roughly hacked in antiquity, through one of the four iron bolt fastening positions. The presumed extent of the missing portion is shown dashed in Figure 52. The curved rebate on the aft face, to accommodate the mast indicated a diameter in the region of 815 mm (circa 4 palmos from Table 4). A rebate of circa 305 mm wide x 135 mm deep on the underside of each end was probably used to clamp over the heavy carling beams.

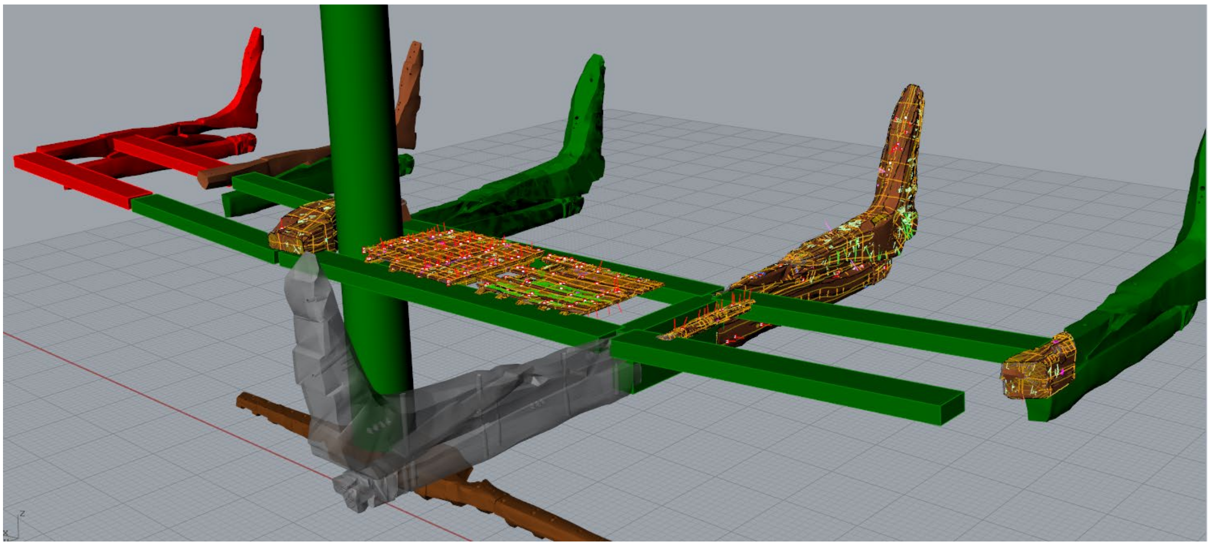


Figure 53 Deck Structure reconstruction between frames 10 - 50 with standing knees included

With these beam knee assemblies and associated carling beams (Figure 53) positioned within the reconstruction and mirrored to the port side, a centreline width of 1.1 m between the two heavy central carling beams results. This matches the width of the rebated section on the underside of the mast partner (Figure 52) and also the widths of deck hatches context 148 and context 150, both of which have been provisionally positioned just aft of the main mast. This layout of off-centre heavy carlings with ledges or deck beams running outboard to a beam shelf is a typical feature of deck construction, and similar layouts can be seen in both the San Juan and Mary Rose records. This also gives an accurate indication of the width measurement for the vessel at this height.

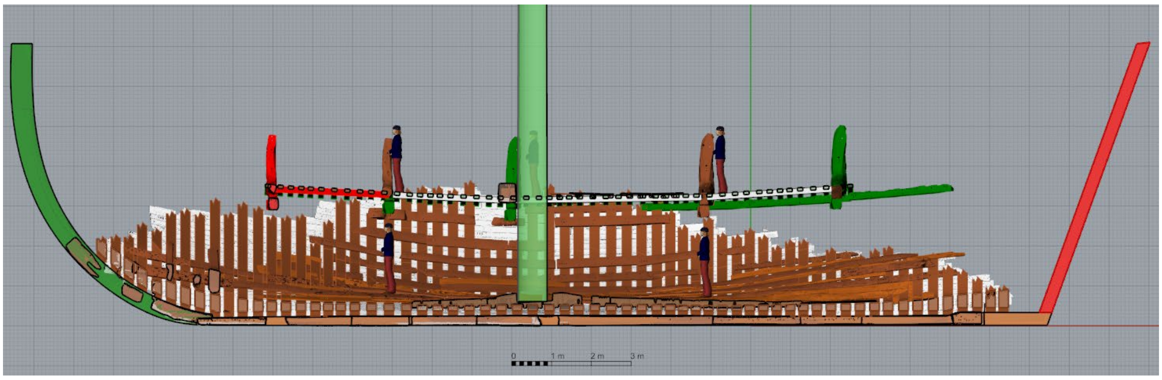


Figure 54 Longitudinal Section with standing knees added

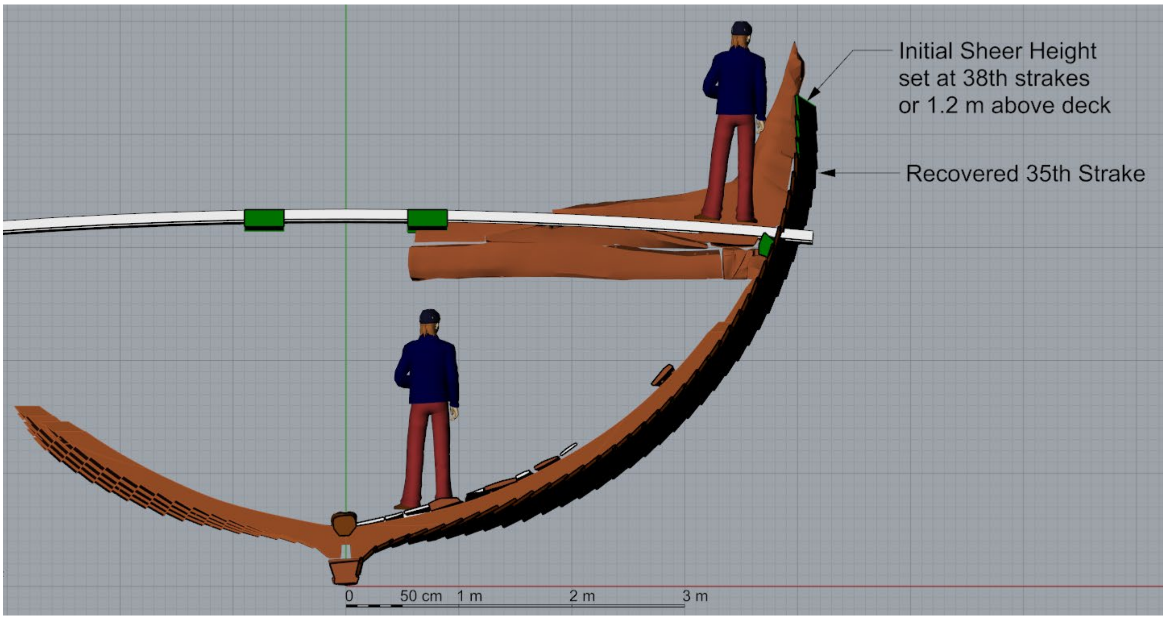


Figure 55 Section at Frame 40 with Standing Knee CT1629 and beam assembly added

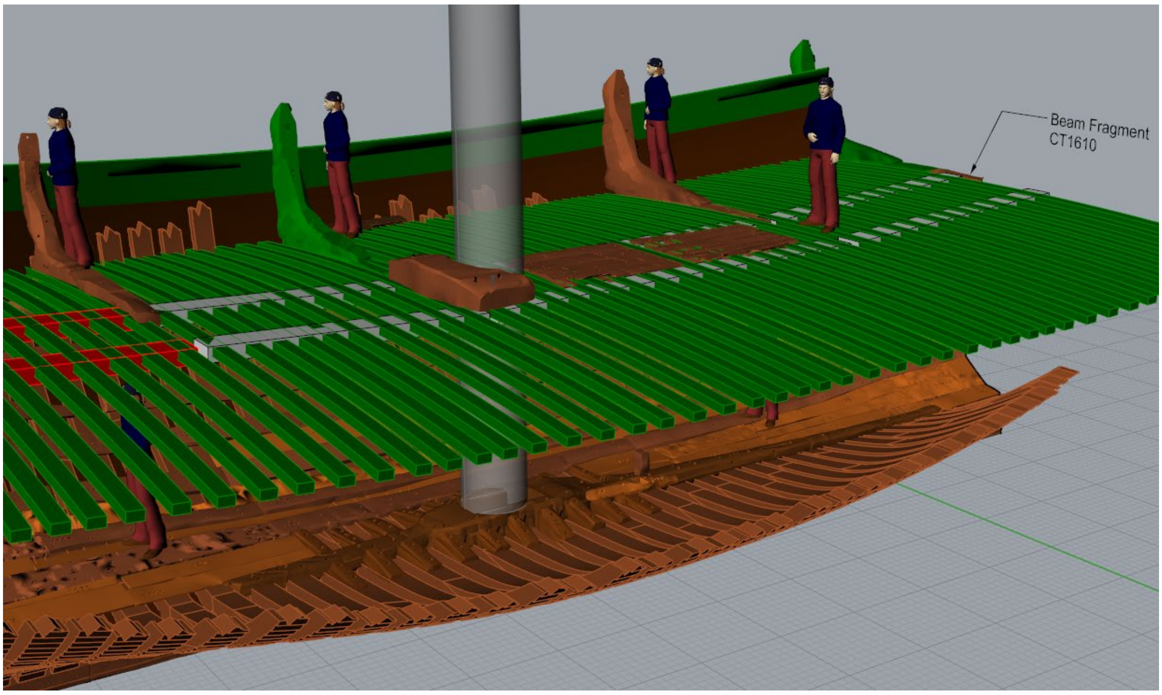


Figure 56 Reconstructed Deck structure between frames 20 to 50

The inclusion of both standing knees, CT1629 at frame 40 and CT1615 at frame 20 creates an issue with the revised minimum reconstruction. This reconstruction used the recovered 35 strakes, plus a notional three additional strakes in order to generate a sheer height of circa 1.2 m above the deck height, which was set by the recovered beam-shelf fragment CT1526 located between frames F30 - F36. With both of the recovered standing knees included in a hypothetical reconstruction the sheer height needs to extend to a minimum of 41 strakes, which would equate to 1.65 m above deck height (Figure 54 to Figure 56). This would appear too high for practical purposes and would indicate the presence of a second deck. Additional evidence for this second higher deck can be found in the shape and size of standing knee CT1547.

Additional Standing Knees:

Standing knee CT1547 and beam CT1542 (Figure 57) which were both recovered from outside the vessel on the starboard side in the vicinity of frame 40 are similar in features and shape to the composite beam standing knee assembly, however a smaller scantling size for this beam of 205 mm sided by circa 175 mm moulded as opposed to 260 mm x 215 mm for the composite beam CT003 together with the near vertical angle of 4° inboard for the standing portion of the knee CT1547 point towards these elements coming from a second higher level in the vessel where the hull curvature has transitioned from an outboard flare to a vertical or slight inboard (tumblehome) shape (Figure 58 and Figure 59). The standing knee CT1547 also has two rebates on the forward face, presumably to accommodate carling beams and two mortises on the horizontal leg, presumably to accommodate vertical stanchions which could support a stern-castle deck above.

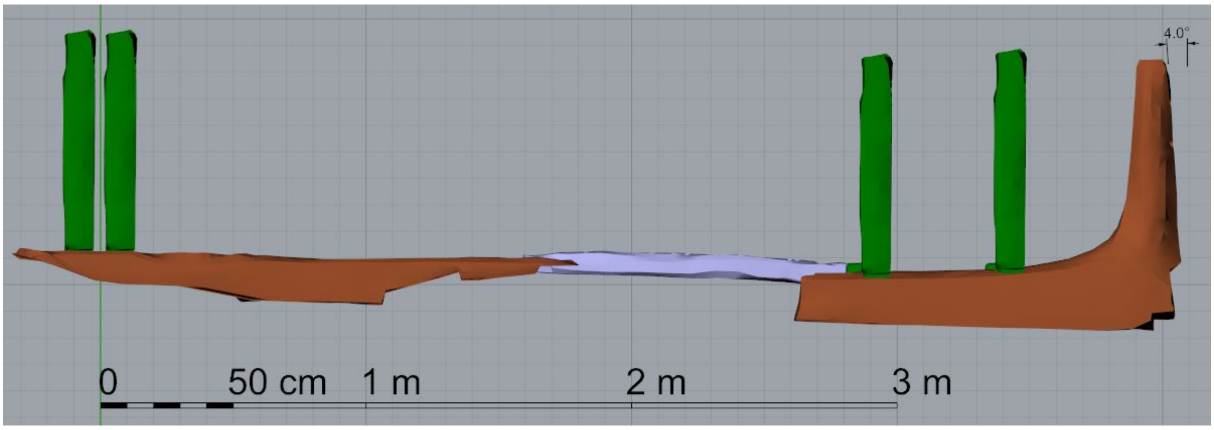


Figure 57 Standing Knee CT1547 and beam CT1542

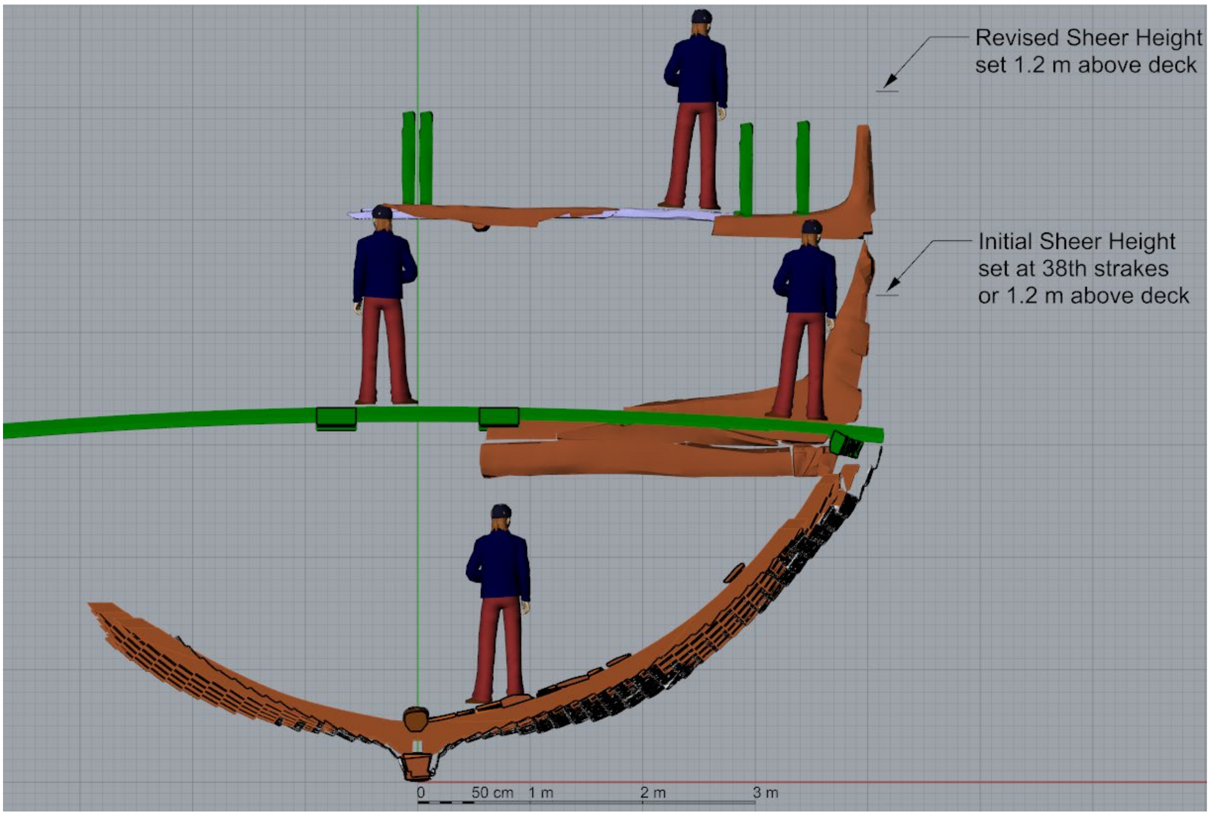


Figure 58 Section at Frame 40: Minimum Reconstruction with Standing Knee CT1547 added

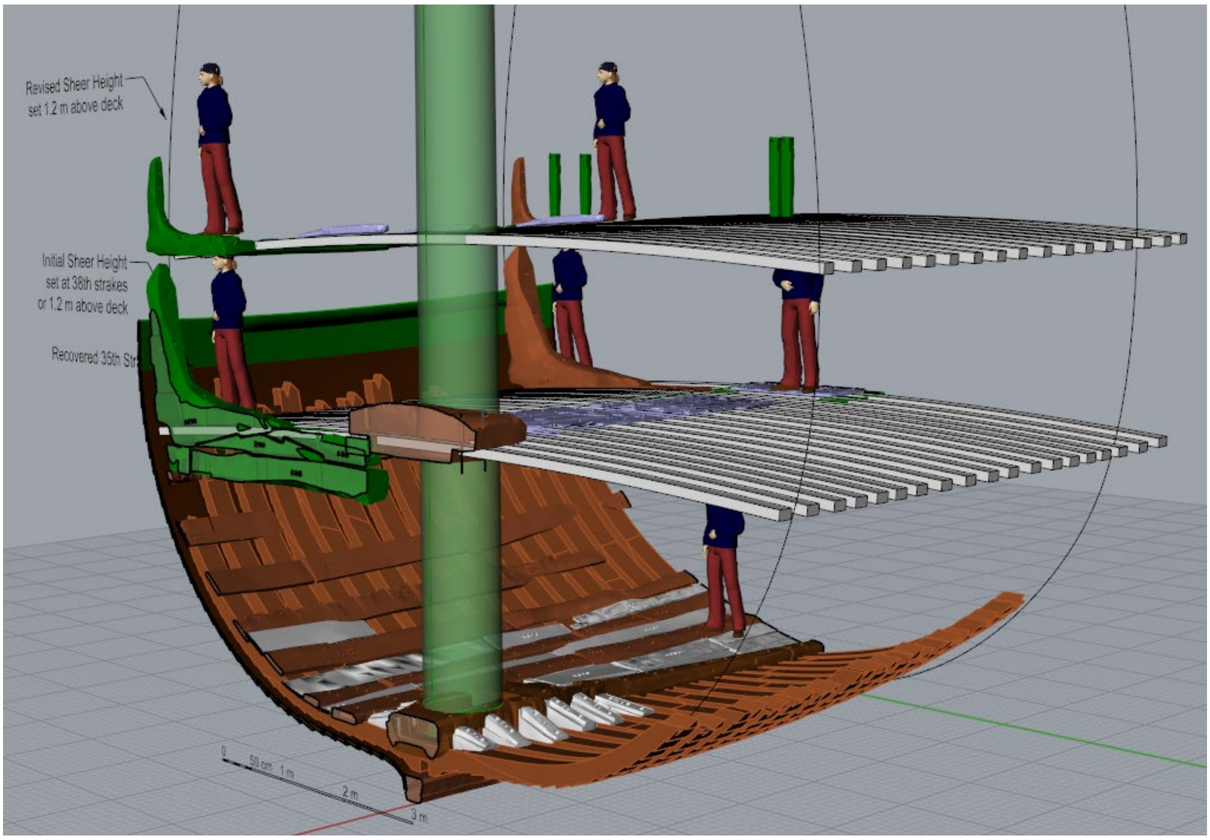


Figure 59 Main and Upper Deck reconstruction between frames 20 - 40 with standing knees included

Knee CT1605 (Figure 60) was recovered from within the vessel in the region of frame 20. A scantling size of 185 mm sided x 145 mm moulded and the inboard angle of 14° indicates that this knee did not function as a standing knee at the height of the main or upper decks. Equally this knee could not function as a hanging knee at any of the transverse beam location as the outboard angle does not match the hull shape. This knee possibly used as a standing knee, coming from a third, higher location within the vessel where the hull curvature has transitioned from a near vertical to a more pronounced inboard (tumblehome) shape.

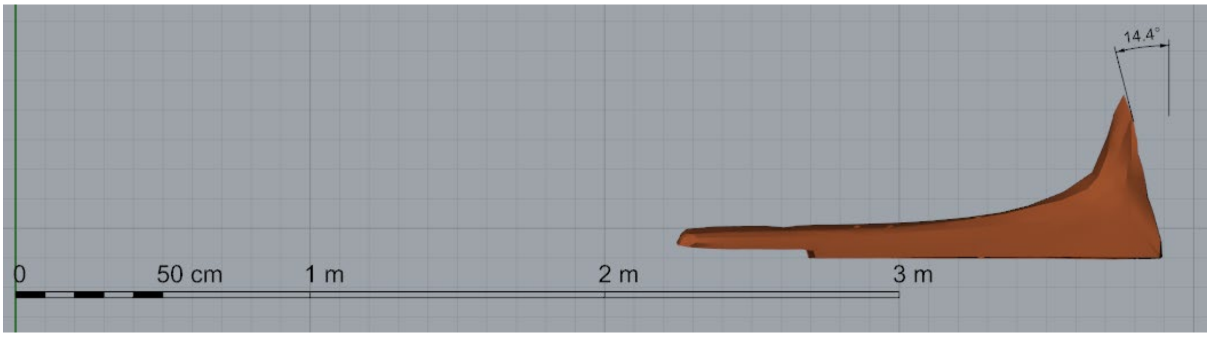


Figure 60 Knee CT1605

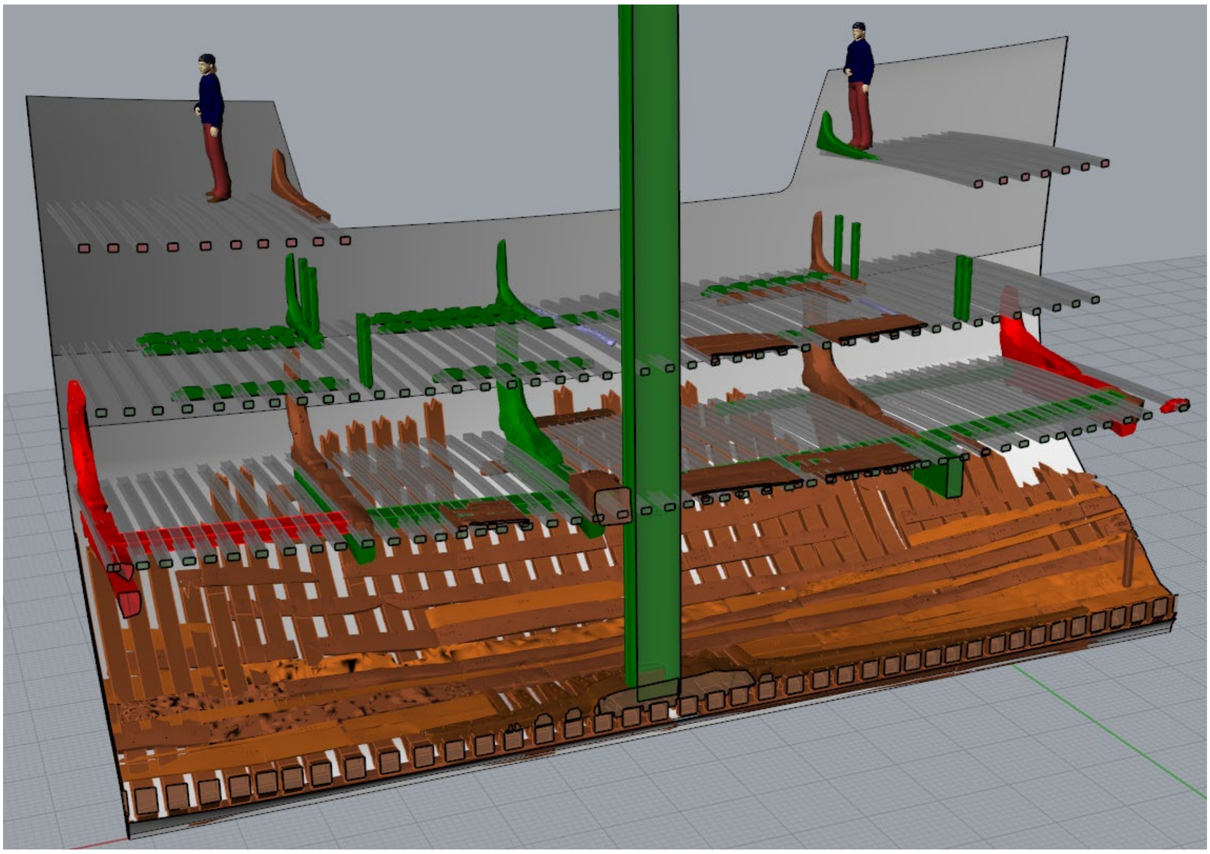


Figure 61 Main, Upper and Castle Deck reconstruction between frames 10 - 50

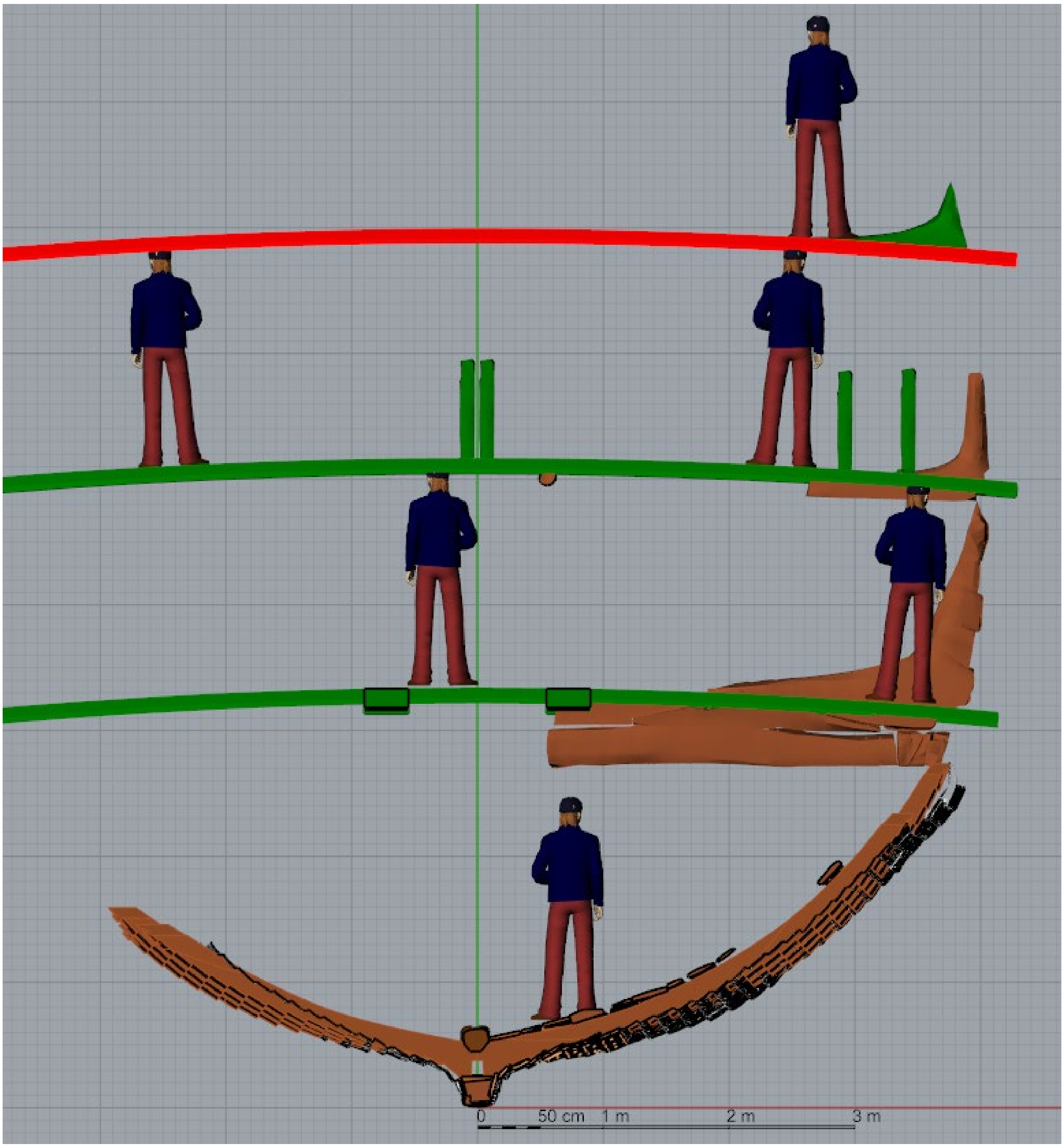


Figure 62 Section at Frame 40: Minimum Reconstruction with Standing Knee CT1605 added

A reduction in scantling size as the elements rise higher in the vessel construction is standard practice in order to keep the centre of gravity as low as possible. Evidence of this can be clearly seen in both the Mary Rose and San Juan records. This would lend more credence to the belief that the smaller knees and beams are positioned higher within the reconstruction is valid.

Frames 26, 30, 35 and 42 included a recovered third futtock, however all third futtock fragments recovered were hacked in antiquity, leaving only short lower end fragments, the longest surviving being 1.2 m. The highest surviving, complete second futtock, is located at frame 26, with a recorded height above the keel of 3.3 m. For the recovered futtocks, the shortest recorded length, excluding scarf is 1.6 m and the longest recorded complete length excluding scarf is 2.7 m. Assuming a similar dimension for the fragmented third futtock, a single long third futtock, would be sufficient to reach the proposed caprail height associated with a second deck level in the midships or waist area (Figure 63). Similarly, if three of the recovered long futtocks were used, they would be sufficient to reach the proposed caprail height in the bow and stern castle areas.

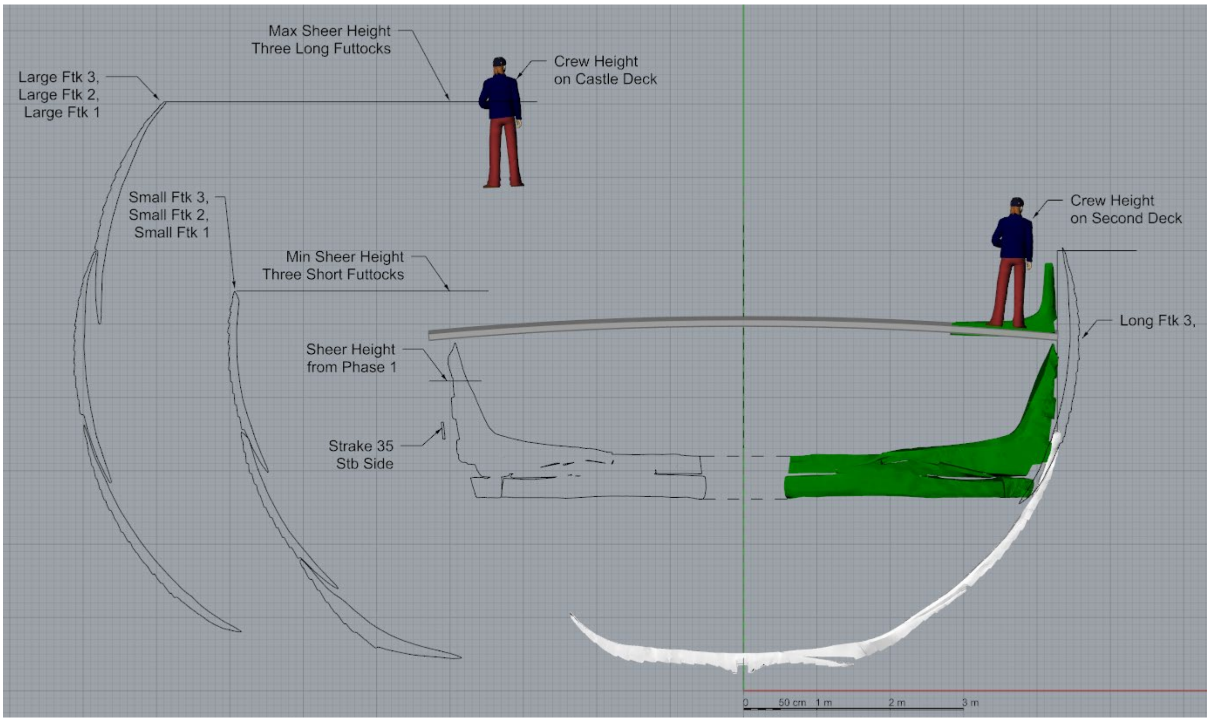


Figure 63 Possible Futtock Sizes

The use of three futtocks gives a potential caprail or sheer height of 8 m above the baseline (Figure 64), as opposed to the 5.5 m height used in the floating hypothesis reconstruction. This gives a hypothetical maximum extent of the hull reconstruction, and as such sets the upper limits for the hypothetical Principal Reconstruction.

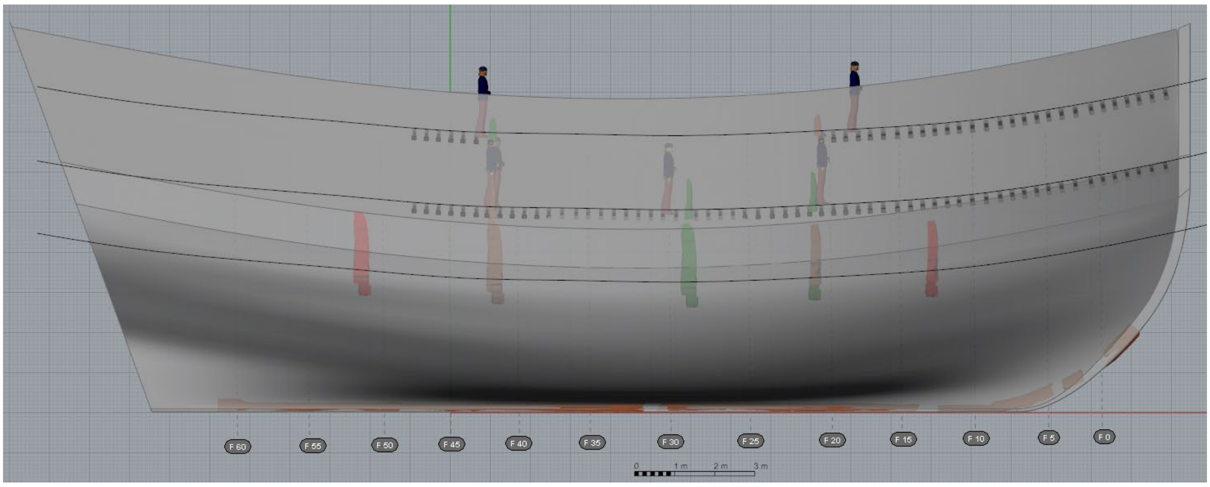


Figure 64 Potential Sheer height based on three futtocks

Another thought to be considered, is the percentage of materials recovered, in comparison do the quantity of materials in the total vessel. In a time when recycling ships timbers for other uses was commonplace, at what point do the reclaimers call a halt to the reclamation process. If you picture the recovered remains laying on its starboard side, as being the last, lower single figure, or low teen percentage of the entire vessel, being the parts lowest down, in the most difficult area to work, and the most effort required for further reclamation, possibly subject to tidal or continual flooding, as evidenced by the series of 7 drainage holes bored outwards through the lower starboard side of the hull on strake 19_6 and 19_7 . Perhaps the recovered remains is the point whereby the reclaimers decided they had recovered enough, and what was initially considered to be the substantial remains of a large ship, is in fact the partial remains of a much larger Medieval ship.

Iconography:

In addition to the iconography used earlier in the creation of the floating hypothesis and minimum reconstruction, additional fifteenth century iconography was analysed, in order to adjust the maximum hull extents to a contemporary medieval shape and style.

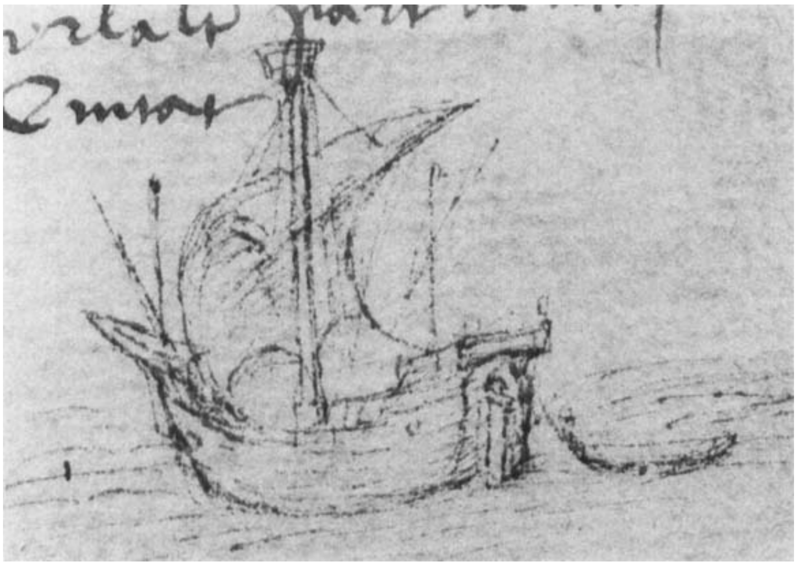


Figure 65 Depiction of a three masted ship (Mott 1994)

From the depiction of a three masted ship (Figure 65) the image shows a large three masted vessel, with a two tier stern castle, potentially a two tier forecastle, and the sheer cut much lower in the midship or waist area, based on the proportion of the image the vessel could have two decks midships as the freeboard looks high in comparison. The vertical line drawn from the aft corner of the stern-castle vertically down to the waterline could be to indicate a transom. This vertical line is not shown in the 'W A Kraeck' engraving (Figure 66), thereby indicating a double ended vessel up to the transom beam level, and likewise is not shown in the 'Beauchamp' images (Figure 69), which also would appear to be representing double ended vessels. The 'Zumaya' images (Figure 67) have been interpreted as representing both transom and double ended vessels.

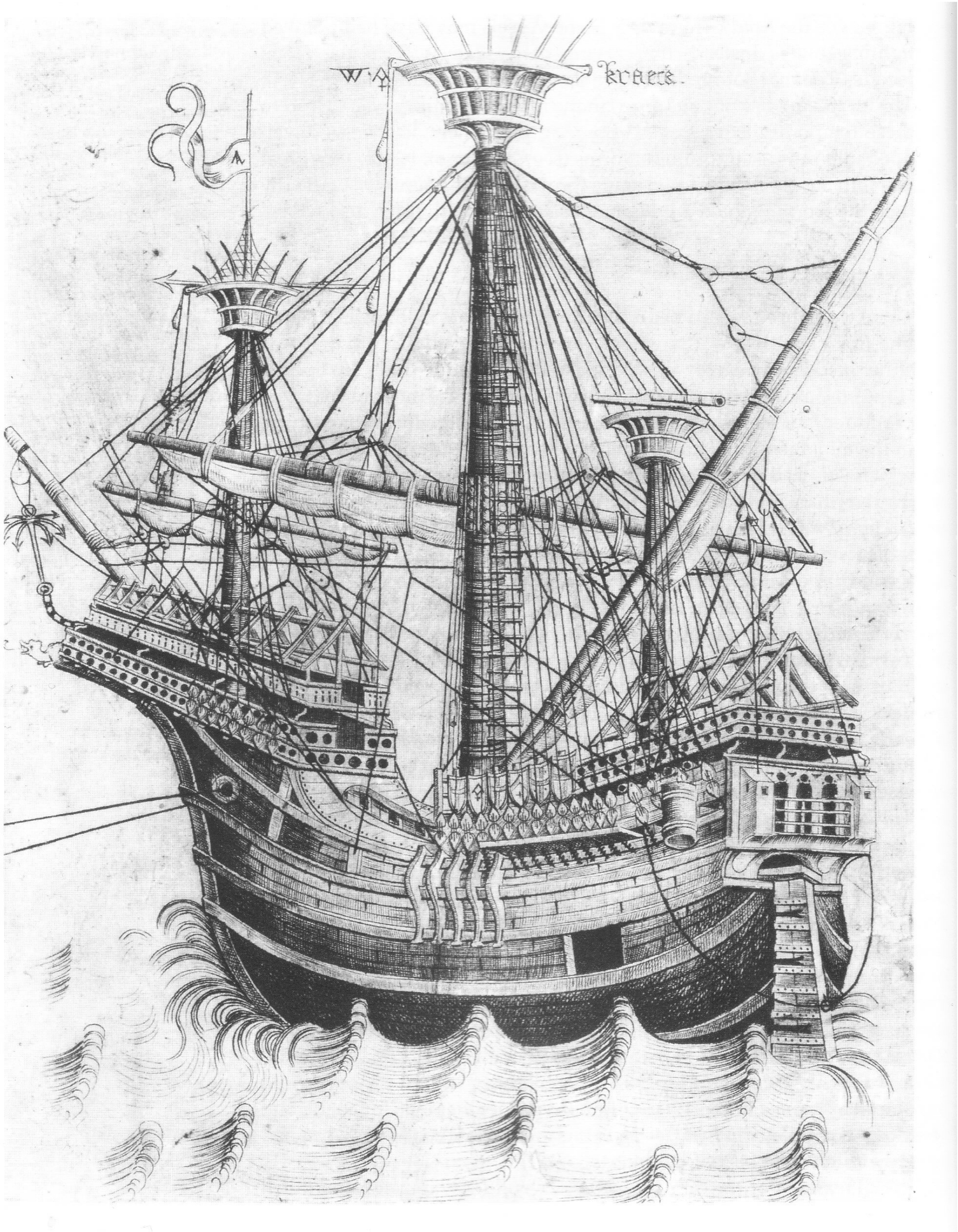


Figure 66 W A Kraeck engraving 1470

Friel notes that the W.A engraving of a Kraeck (Carrack) (Figure 66) is evidently a skeleton built ship based on the smooth hull planking and the large wales which serve to strengthen the structure. The open landing port near the stern suggest at least two decks, with two stages in both the fore and after castles, both of which are topped with roof like structures, which could have supported canvas shelters or anti boarding netting similar to that depicted in the foretops. Armaments include four cannons visible in the after castle as well as a swivel gun in both the main and mizen tops (Friel 1995:83). Also notable in the engraving is the quantity and complexity of the rigging with 8 shrouds per side for the foremast, 18 for the main mast, the foremast truck with four sets of parrals and main mast truck with 5 sets of parrals. Ratlines are absent, replaced with a Mediterranean style Jacob's ladder.

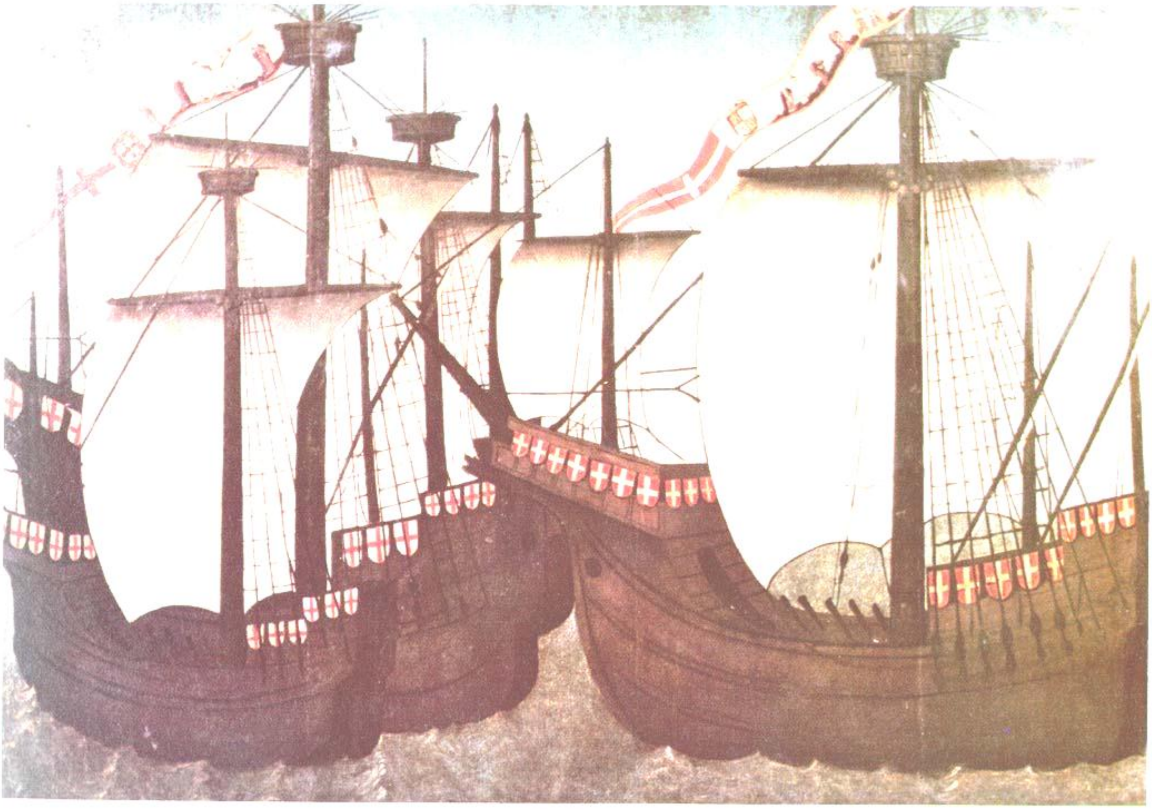


Figure 67 Zumaya images dating from 1475 of a Basque ship known as the Juan Martinez de Mendaro ship.

Figure 68 Detail from "The Punishment of Korah" by Botticelli 1482

Figure 69 Five images from the Beauchamp pageant 1485

All of these images are reasonably consistent in the overall shape and proportions of the vessel profile, that is, a relatively high, probably two-tier fore and stern castles, with a sheerline dropping low in the central waist area. Other similar features include the absence of mast tops in the fore and mizen masts in all but the

'W A Kraeck' engraving. Figure 68 clearly shows two large centre line hatches, one forward of the main mast, with possibly a bilge pump, and / or, a capstan behind the mast and the second hatch forward of the mizen mast.

G.18 Principal Reconstruction:

Based on these images it was decided to cut down or lower the sheerline in the central waist area to a height commensurate with the second deck level, and the addition of 1.6 m to the sheer would create adequate height for the proposed castles (Figure 70).

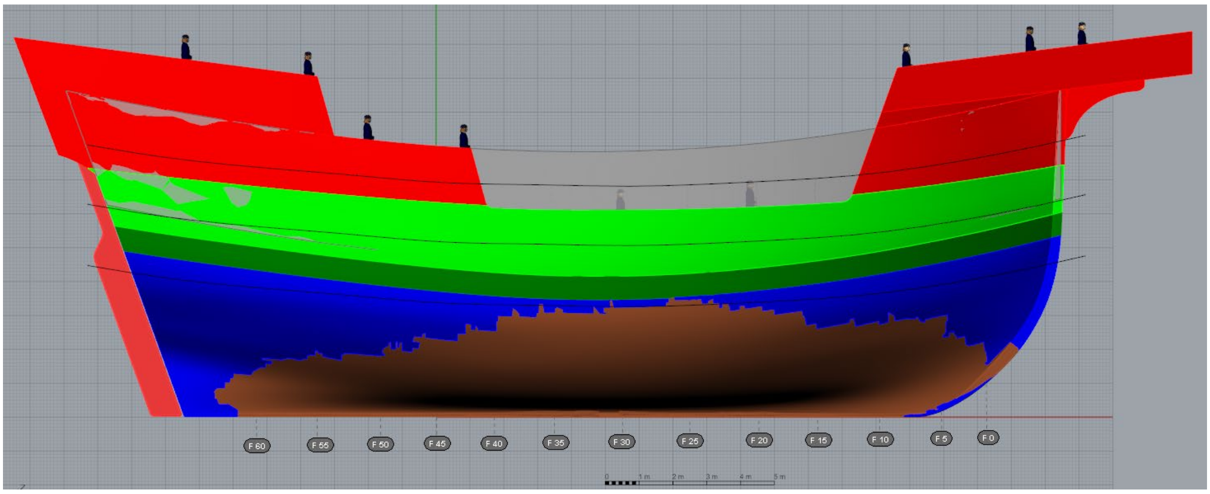


Figure 70 Developing Primary Reconstruction Hull extents based on Contemporary Iconography

Figure 70 is colour coded as follows:

- Brown indicates recovered materials
- Blue is material used to create a watertight hull
- Dark Green is material based on recovered evidence
- Light green is additional material where only slight evidence recovered
- Red indicates hypothetical material where no evidence was recovered

G.19 Testing the Principal Reconstruction:

This hypothetical principal reconstruction (Figure 71) was then tested and analysed, a weight report (Figure 72) was generated to include the masts and rigging, and the vessel was analysed for intact stability (Figure 73).

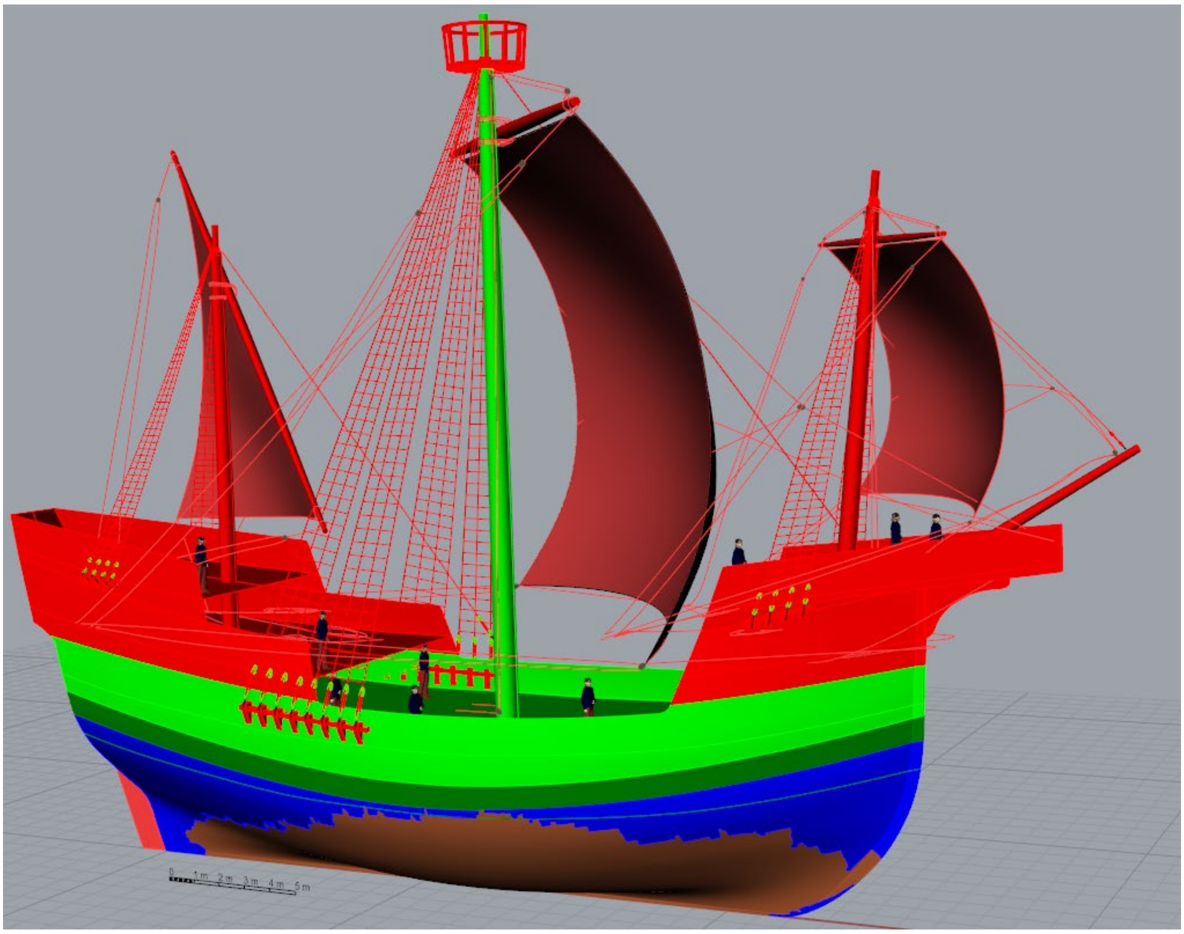


Figure 71 Principal Reconstruction

Object Name	Material	Weight (kgf)	LCG (m)	TCG (m)	VCG (m)	Weight Basis
All Items						
Rudder	Oak @ 800 kg (27% M.C.)	866.324	-1.717	0.000	3.524	1.083 m^3
Tiller	Oak @ 800 kg (27% M.C.)	132.975	-2.175	0.000	8.374	0.166 m^3
Spike Nails - Stb.	Spike Nails	399.031	11.915	-1.859	2.075	0.000 N/A
Spike Nails - Port	Spike Nails	399.031	11.915	1.859	2.075	0.000 N/A
Clench Nails - Stb.	Clench Nails	941.113	11.794	-2.085	2.174	0.000 N/A
Clench Nails - Port	Clench Nails	941.113	11.794	2.085	2.174	0.000 N/A
Anchors	None	* 1850.000	22.297	0.000	6.003	N/A
Anchor warps	None	* 200.000	21.996	0.000	5.687	N/A
Rigging CG Foremast	None	* 1484.184	24.061	0.000	12.789	N/A
Rigging CG Mizenmast	None	* 1867.888	3.145	0.000	13.196	N/A
MainMast CG	None	* 6731.060	13.954	0.000	12.961	N/A
Main Deck	120mm Oak	17312.756	10.990	0.000	5.342	186.159 m^2
Lower Deck	120mm Oak	16525.405	11.232	0.000	3.518	177.693 m^2
SternCastle Upper deck	120mm Oak	3778.735	0.424	0.000	9.400	40.632 m^2
SternCastle Lower deck	120mm Oak	7008.425	3.302	0.000	7.327	75.359 m^2
ForeCastle Lower deck	120mm Oak	1678.659	22.033	0.000	7.563	18.050 m^2
ForeCastle Upper deck	120mm Oak	2155.629	23.847	0.000	9.560	23.179 m^2
UpperWorks	120mm Oak	8411.180	0.416	0.000	8.588	90.443 m^2
UpperWorks	120mm Oak	6138.309	24.445	0.000	9.126	66.003 m^2
Main Hull	145mm Oak	10948.709	13.061	-1.869	1.209	96.891 m^2
Main Hull	145mm Oak	59.836	22.661	-0.070	0.426	0.530 m^2
Main Hull	145mm Oak	4417.242	2.648	-2.209	2.916	39.091 m^2
Main Hull	145mm Oak	2459.534	11.198	-3.074	4.509	21.766 m^2
Main Hull	145mm Oak	0.000	14.494	-4.326	3.525	0.000 m^2
Main Hull	145mm Oak	0.000	14.411	-4.333	3.521	0.000 m^2
Main Hull	145mm Oak	2090.443	22.235	-1.728	3.559	18.499 m^2
Main Hull	145mm Oak	12729.120	10.831	0.000	5.715	112.647 m^2
Main Hull	145mm Oak	59.836	22.661	0.070	0.426	0.530 m^2
Main Hull	145mm Oak	6229.272	12.734	1.118	0.622	55.126 m^2
Main Hull	145mm Oak	11227.108	10.853	2.393	2.644	99.355 m^2
Main Hull	145mm Oak	2459.548	11.198	3.074	4.509	21.766 m^2
SubTotal		131502.466	11.039	0.000	5.431	
Totals		**131502.466**	**11.039**	**0.000**	**5.431**	

Figure 72 Weight Report Principal Reconstruction

Load Condition Parameters				
Condition	Weight / Sinkage	LCG / Trim	TCG / Heel	VCG (m)
Condition 1	131502.466 kgf	11.039 m	0.000 deg	5.431

Resulting Model Attitude and Hydrostatic Properties				
Condition	Sinkage (m)	Trim(deg)	Heel(deg)	Ax(m^2)
Condition 1	2.360	-2.202	0.000	9.19

Condition	Displacement Weight (kgf)	LCB(m)	TCB(m)	VCB(m)	Wet Area (m^2)
Condition 1	131502.756	10.880	0.000	1.286	164.227

Condition	Awp(m^2)	LCF(m)	TCF(m)	VCF(m)
Condition 1	122.350	11.109	0.000	1.935

Condition	BMt(m)	BMl(m)	GMt(m)	GMl(m)
Condition 1	3.021	29.395	-1.127	25.247

Condition	Cb	Cp	Cwp	Cx	Cws	Cvp
Condition 1	0.288	0.557	0.646	0.518	2.898	0.446

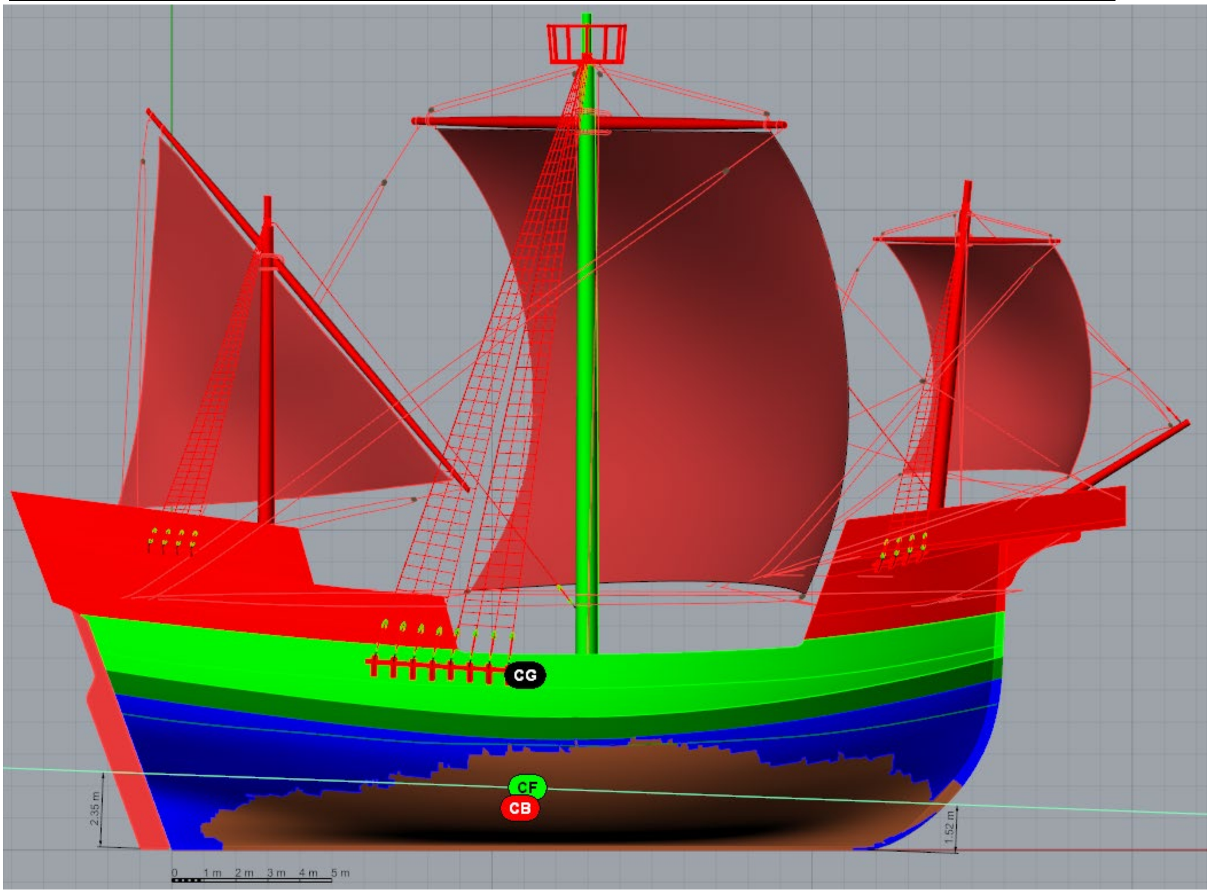


Figure 73 Principal Reconstruction - unballasted

In this configuration, the vessel has the following flotation characteristics:
Weight 131,502 kg, L.C.G. 11.04 m, T.C.G. 0.0 m, V.C.G. 5.4 m,
Draft Aft of 2.35 m, Draft Forward of 1.52 m and a freeboard midship of 4.19 m.

It should be noted that the vessel in this configuration has a negative transverse metacentric height (GMt) of -1.127 m. This is caused by the ships centre of gravity being too high, located above the metacenter. Even with a negative metacentric height vessels certain hull forms still find a position of stable equilibrium at an angle of heel that does not immediately endanger them, and will remain permanently heeled at this angle called angle of loll. However as the ship is inclined, negative Righting Arms (called upsetting arms) are created which tend to capsize the ship (Figure 74). It would be impossible for the vessel to sail in this condition without internal ballast being added to lower the centre of gravity and thereby generating a positive metacentric height.

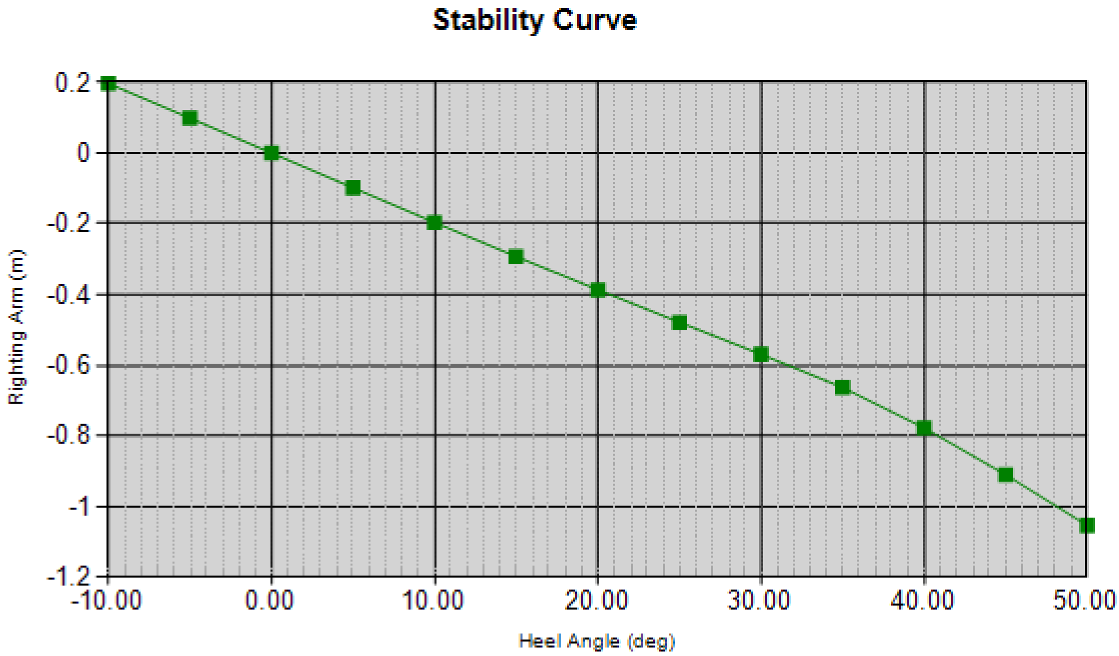


Figure 74 Un-Ballasted Stability Results

Several stability criteria were then run with varying quantities of ballast to determine a sufficient ballast to enable the vessel to operate under full sail in up to 15 knots of wind. Internal ballast of stone was positioned inside the vessel on top of the ceiling planking. The quantity required to allow the vessel to operate under full sail in 15 knots of wind was determined to be a depth of 0.6 m (Figure 75).

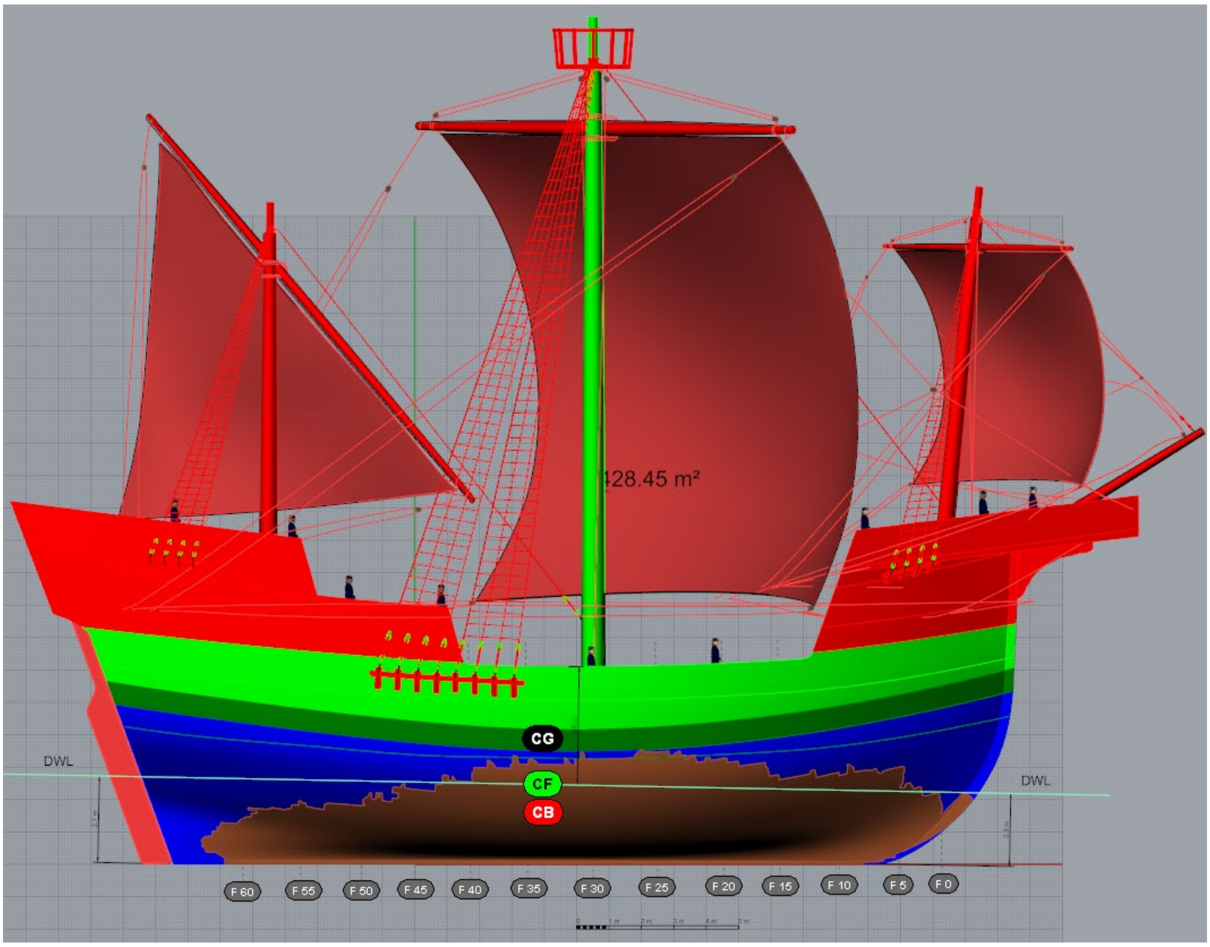


Figure 75 Principal Reconstruction - Ballasted to 0.6 m

In this configuration, the vessel has the following flotation characteristics:
Weight 205,377 kg, L.C.G. 11.4 m, T.C.G. 0.0 m, V.C.G. 3.85 m,
Draft Aft of 2.7 m, Draft Forward of 2.3 m and a freeboard midship of 3.6 m.

Condition Summary

Load Condition Parameters				
Condition	Weight / Sinkage	LCG / Trim	TCG / Heel	VCG (m)
Equilibrium, Bureau Veritas, Intact Stability	205377.573 kgf	11.409 m	0.000 m	3.855

Resulting Model Attitude and Hydrostatic Properties				
Condition	Sinkage (m)	Trim(deg)	Heel(deg)	Ax(m^2)
Equilibrium, Bureau Veritas, Intact Stability	2.721	-1.289	0.000	13.52

Condition	Displacement Weight (kgf)	LCB(m)	TCB(m)	VCB(m)	Wet Area (m^2)
Equilibrium, Bureau Veritas, Intact Stability	205377.858	11.358	0.000	1.607	201.670

Condition	Awp(m^2)	LCF(m)	TCF(m)	VCF(m)
Equilibrium, Bureau Veritas, Intact Stability	144.266	11.335	0.000	2.467

Condition	BMt(m)	BMl(m)	GMt(m)	GMl(m)
Equilibrium, Bureau Veritas, Intact Stability	2.784	25.022	0.535	22.774

Condition	Cb	Cp	Cwp	Cx	Cws	Cvp
Equilibrium, Bureau Veritas, Intact Stability	0.347	0.574	0.678	0.605	2.806	0.512

Stability Criteria - Bureau Veritas, Intact Stability					
Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Area Between FreeEquil and 30 > 3.151 meters-deg	0	30	3.151	3.8587	Pass
Area Between FreeEquil and 40 > 5.157 meters-deg	0	40	5.157	6.648	Pass
Area Between 30 and 40 > 1.719 meters-deg	30	40	1.719	2.7893	Pass
GZ At 30 > 0.2 meters	30		0.2	0.2416	Pass
Angle At GZmax > 25 deg	64.7245		25	64.7245	Pass
GM At FreeEquil > 0.15 meters	0		0.15	0.536	Pass

Figure 76 Intact Stability with 0.6 m Ballast

Wind and Wave Stability:

The vessel was again configured in the worst-case scenario condition with regard to wind loading, which would represent a "beam on" wind, with the sails sheeted in tight. This is not a normal sailing configuration but represents the worst possible case scenario. To establish this lateral projected area, the yards and sails were rotated as close as possible to the centre line plane, allowing for normal restrictions such as shroud placement. The projected sail area combined with the above water hull surface area was then calculated (Figure 77). This results in a lateral projected surface area, including hull, spars and sails of 428.45 m².

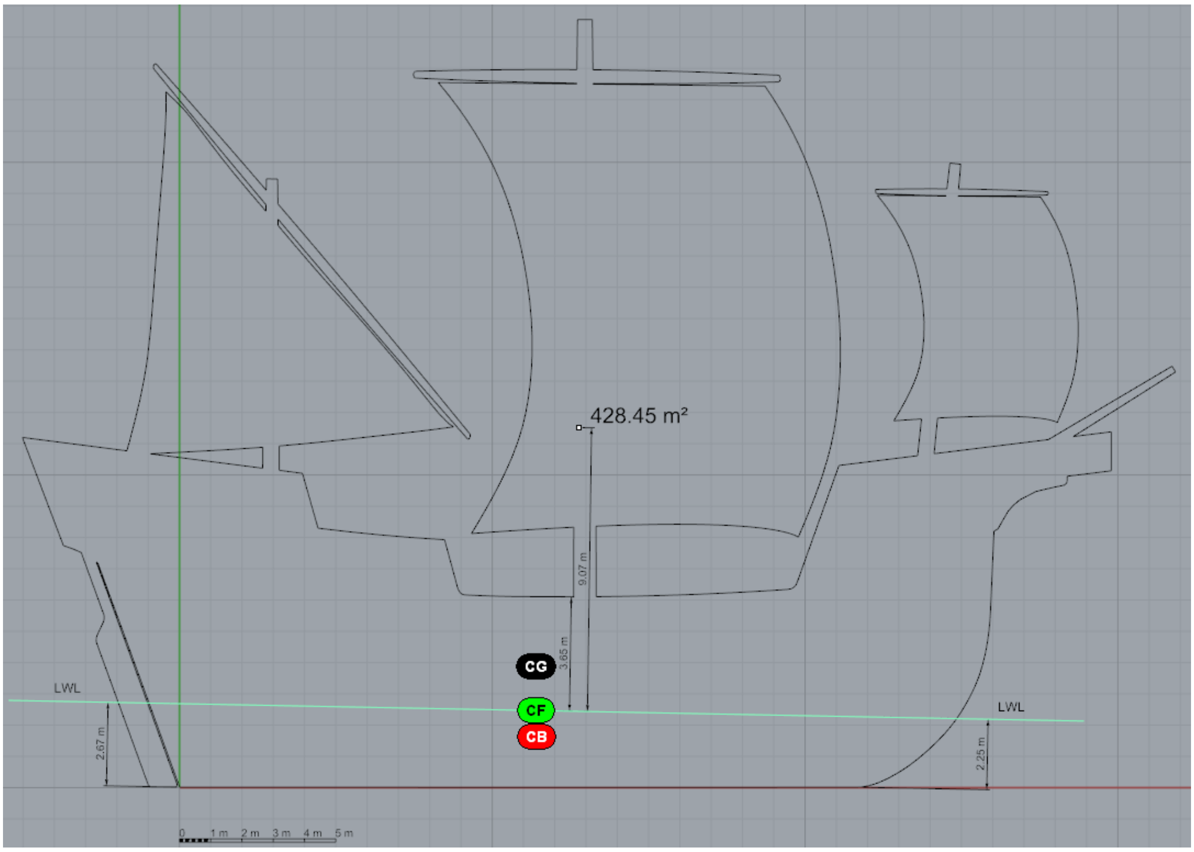


Figure 77 Lateral surface area for wind loading Principal Reconstruction

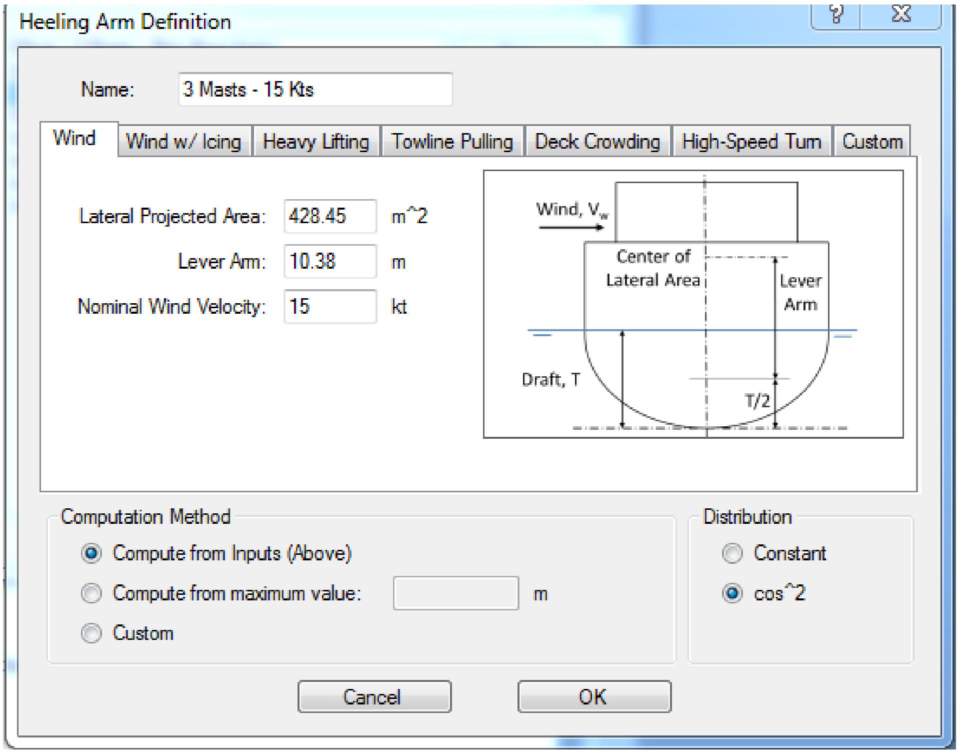


Figure 78 Wind Loading - Principal Reconstruction

With the centre of lateral area (Figure 77) 9.07 m above the LWL (load waterline) and a draft of 2.67 m the resulting lever arm is 10.38 m (Figure 78).

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 5kts					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Angle At SteadyEquil <= 16 deg	1.1347		16	1.1347	Pass
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-23.8653	23.4986	1	0.8022	Fail
ResRatio Between SteadyEquil-25 deg and Flood > 1	-23.8653	45.6671	1	2.9878	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-23.8653	50	1	3.6001	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	1.1347		18.7988	1.1347	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 10 kts					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Angle At SteadyEquil <= 16 deg	4.5154		16	4.5154	Pass
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-20.4846	23.4986	1	0.5688	Fail
ResRatio Between SteadyEquil-25 deg and Flood > 1	-20.4846	45.6671	1	2.548	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-20.4846	50	1	3.1277	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	4.5154		18.7988	4.5154	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 15 Kts					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Angle At SteadyEquil <= 16 deg	10.0707		16	10.0707	Pass
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-14.9293	23.4986	1	0.2781	Fail
ResRatio Between SteadyEquil-25 deg and Flood > 1	-14.9293	45.6671	1	1.926	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-14.9293	50	1	2.4531	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	10.0707		18.7988	10.0707	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 20 kts					
Name	**Angle 1**	**Angle 2**	**Required**	**Actual**	**Pass / Fail**
Angle At SteadyEquil <= 16 deg	17.5641		16	17.5641	Fail
ResRatio Between SteadyEquil-25 deg and DeckImm > 1	-7.4359	23.4986	1	0.0543	Fail
ResRatio Between SteadyEquil-25 deg and Flood > 1	-7.4359	45.6671	1	1.2737	Pass
ResRatio Between SteadyEquil-25 deg and 50 > 1	-7.4359	50	1	1.7335	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	17.5641		18.7988	17.5641	Pass

Figure 79 Stability results for Principal Reconstruction

The Principal Reconstruction passes the modern Bureau Veritas stability rules for wind and rolling waves in all 5 to 15 knots of wind, except for the stability ratio between -25° and the steady wind heel angle (Figure 79). These criteria are using a generic 25° wave roll angle.

Angle of roll, in degrees, to windward due to wave action, calculated as follows:

$\theta_1 = 109kX_1X_2 \sqrt{rs}$

Where k, X_1, X_2 and s are coefficients defined in the Bureau Veritas handbook,

r = 0,73 ± 0,6 (OG) / T_1 - where OG = distance between centre of gravity and the waterline, and T_1 = mean moulded draft.

The actual wave roll angle for the reconstructed Newport Medieval Ship is 14.59°. The vessel "fails" the 20 knots wind test, on the same stability ratio between -25° and the steady wind heel angle, and on the wind heel angle.

The wind heel angle is only 1.5° more than the arbitrary 16° set in the criteria. Again, this heel angle would in fact reduce by shortening sail, which would be standard practice in a 20 knot wind strength.

With stability retested using a wave rolling angle of 14.6 and the Caprail submerged at 45.7°, the angle of maximum stability at 64.75° and the angle of vanishing stability at 96.1°, this reconstruction could be deemed as passing the modern test criteria (Figure 80).

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 5kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil <= 16 deg	1.1347		16	1.1347	Pass
ResRatio Between SteadyEquil-14.6 deg and DeckImm > 1	-13.4653	23.4986	1	2.2623	Pass
ResRatio Between SteadyEquil-14.6 deg and Flood > 1	-13.4653	45.6671	1	8.4361	Pass
ResRatio Between SteadyEquil-14.6 deg and 50 > 1	-13.4653	50	1	10.1629	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	1.1347		18.7988	1.1347	Pass

Stability Criteria - Bureau Veritas, Wind and Rolling Waves, 3 Masts - 10 kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil <= 16 deg	4.5154		16	4.5154	Pass
ResRatio Between SteadyEquil-14.6 deg and DeckImm > 1	-10.0846	23.4986	1	1.6134	Pass
ResRatio Between SteadyEquil-14.6 deg and Flood > 1	-10.0846	45.6671	1	7.2378	Pass
ResRatio Between SteadyEquil-14.6 deg and 50 > 1	-10.0846	50	1	8.8822	Pass
Angle At SteadyEquil < DeckImm*0.8 deg	4.5154		18.7988	4.5154	Pass

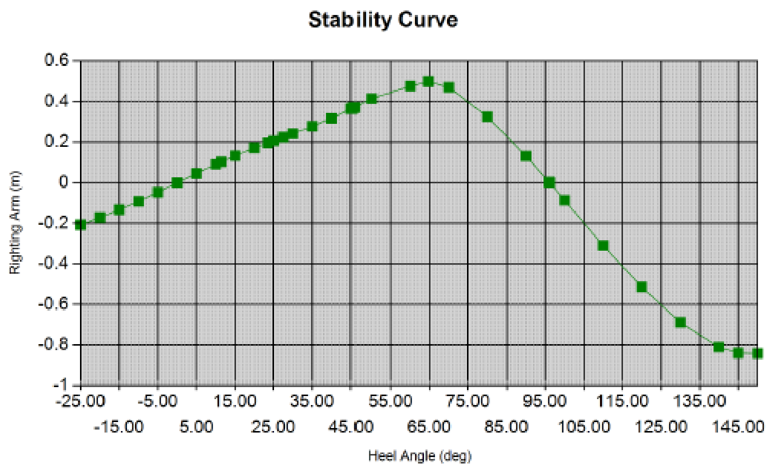


Figure 80 Stability results for Principal Reconstruction revised wave roll angle

Cargo Capacity:

Ethnographic evidence suggests that for inland waters, small boats were loaded to very little freeboard (McGrail 1978,91). Seagoing data is not readily available, however a medieval Icelandic Law in the Grågås Codex states the minimum freeboard (F) of a cargo ship should be F=2D/5 where D=depth of hull amidships (Morken 1980,178).

In the case of the Newport Medieval Ship this minimum freeboard would be F=2 x 6.1 / 5 = 2.46 m. This would result in a draft aft of 3.88 m and a draft forward of 3.46 m (Figure 83). This results in a displacement value of 392,500 kgf (Figure 81). With a ballasted deadweight of 205,377 kg and a displacement value of 392500, this means the Newport Medieval Ship would be capable of carrying circa 187,122 kg of cargo.

Load Condition Parameters

Condition	Weight / Sinkage	LCG / Trim	TCG / Heel	VCG (m)
Medieval Loadline	3.690 m	0.000 deg	0.000 deg	None available

Resulting Model Attitude and Hydrostatic Properties

Condition	Sinkage (m)	Trim(deg)	Heel(deg)	Ax(m^2)
Medieval Loadline	3.690	0.000	0.000	23.83

Condition	Displacement Weight (kgf)	LCB(m)	TCB(m)	VCB(m)	Wet Area (m^2)
Medieval Loadline	392494.772	11.745	0.000	2.360	277.772

Condition	Awp(m^2)	LCF(m)	TCF(m)	VCF(m)
Medieval Loadline	169.673	11.347	0.000	3.690

Condition	BMt(m)	BMl(m)	GMt(m)	GMl(m)
Medieval Loadline	1.973	18.327	None Available	None Available

Condition	Cb	Cp	Cwp	Cx	Cws	Cvp
Medieval Loadline	0.442	0.595	0.722	0.742	2.734	0.612

Figure 81 Medieval Load Line Characteristics

Tidal Range:

With the Severn Estuary having the biggest tidal range in Europe, this could have been a deciding factor in the choice of location for careening or repairing a large sailing vessel.

Figure 82 The River Usk close to where the Newport Medieval Ship was discovered

The highest ground level within the Pill where the Newport Medieval Ship was discovered, was located between midships and frame 26 and was recorded as 3.98 m above OD (ordnance datum).

Location	Bottom of Keel - Height above OD
Frame 2	4.35 m (Underside of Stem)
Frame 9	3.71 m
Frame 22	3.93 m
Frame 29	3.95 m
Frame 41	3.46 m
Frame 49	3.27 m
Frame 61	2.93 m

Table 2 Recorded Keel heights relative to Ordnance Datum

	Chart Datum	Newport Difference	O.D.
Highest astronomical tide	13.36	-5.81	7.55
Mean high water springs	12.14	-5.81	6.33
Mean high water neaps	8.97	-5.81	3.16
Mean low water neaps	3.12	-5.81	-2.69
Mean low water springs	0.51	-5.81	-5.3
Lowest astronomical tide	-0.59	-5.81	-6.4

Table 3 Tidal Range Data for Newport (present day)

Source: National Oceanography Centre. (http://www.ntslf.org/tides/hilo?port=Newport)

From the above table, with the heights corrected from chart datum to ordnance datum, chart datum for Newport being 5.81 m below OD, although based on current records, it can be seen that the vessel had an available draft of 2.38 m above the highest point within the Pill, at high water during spring tides.

With a draft aft of 3.88 m and a draft forward of 3.46 m the Newport Medieval Ship, based on current tidal data could not enter the 'Pill' in a fully laden condition.

With a deadweight draft aft of 2.7 m, and draft forward of 2.3 m it would appear from Figure 83 that the vessel entered the 'Pill', in a deadweight or "ballast only" condition, during a high spring tide and looking at the recreated ground level was manoeuvred as far in as possible until the keel grounded at or close to frame 29. Using the rule of twelfths, whereby the tide drops by 1/12 the first hour, 2/12 the second hour, then 3/12, 2/12 and 1/12 up to the sixth hour, when it reaches low water, would mean the ship remained permanently dry during neap tides, and was only "wet" for a maximum of 2.5 to 3 hours on the two days either side of high water springs. With the time between spring and neap tides being approximately seven days, and the range between spring and neap high tides at Newport being 3.2 m which would result in the neap high tide level increasing by 0.46 m each day, the vessel would remain completely dry for four days during each neap tide cycle.

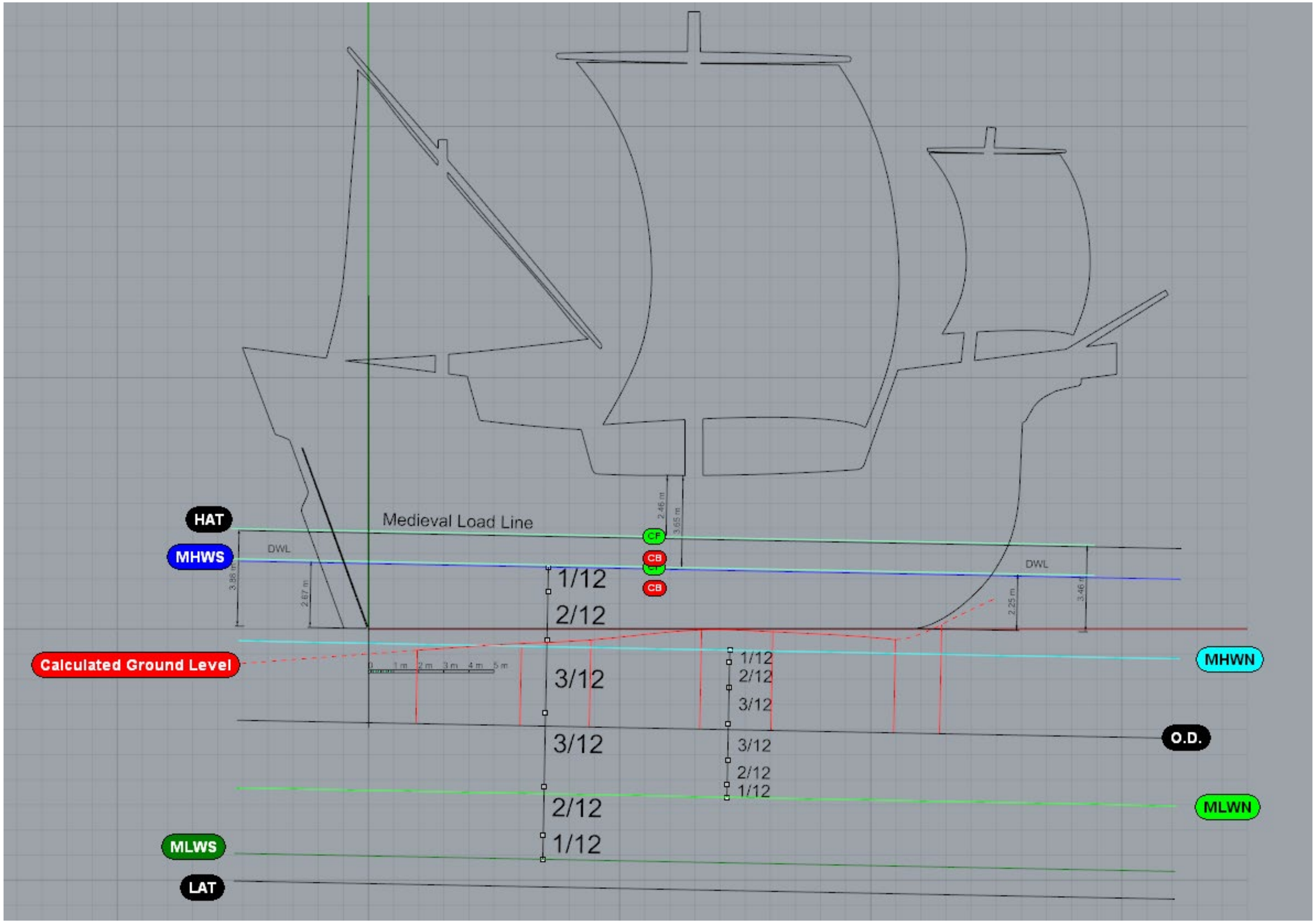


Figure 83 Tidal Heights

G.20 Conclusion:

McGrail states that no experiment can ever prove a hypothesis, it can either disprove it or produce results in agreement with its predictions (Coates et al. 1995). This series of tests examining both unballasted and ballasted stability, cargo capacity, and the deadweight floatation plane in relation to the available draft inside the pill would indicate the Principal Reconstruction hypothesis, when ballasted with 0.6 m of stone would appear to function satisfactorily as a sailing vessel, capable of carrying circa 187 metric tonnes of cargo, and capable of entering the 'Pill' on a high spring tide, which ultimately became her final resting place.

An Iberian Ship?

The dendrochronology reports for the Newport Medieval Ship point towards strong Iberian connections (Nayling 2013) (Nayling and Susperregi 2014).

Iberian Units of Measure

Castro notes that with the most basic pieces of information for comparison, even the units of measure were not consistent throughout the Iberian Peninsula. The codo measured approximately 55.7 cm in Andalusia (codo castellano) and 57.5 cm in the Basque country (coco cantábrico). This Basque codo eventually being adopted for the whole country after 1590 (Castro 2008:68–69). These values were also subdivided into palmos and dedos (Table 4).

Spanish and Portuguese Shipbuilding Units in the Sixteenth Century		
Unit	Metric System Equivalent	Country
Codo castellano	55.7 cm	Spain (Basque)
Codo cantábrico	57.5 cm	Spain (Andalusia)
Vara castellana	83.6 cm	Spain
Palmo	20.9 cm	Spain
Dedo	1.74 cm	Spain
Tonelada de carga	1.382 m^3	Spain
Tonel macho	1.521 m^3	Spain
Rumo	154 cm	Portugal
Goa	77 cm	Portugal
Palmo de goa	25.667 cm	Portugal
Vara	220 cm	Portugal
Palmo de vara	22 cm	Portugal
Dedo	1.83 cm	Portugal
Tonel	1.275 m^3	Portugal

Table 4 Spanish and Portuguese shipbuilding units in the 16C

(Castro 2008:69)

Loewen notes the deck heights in the San Juan, Red Bay wreck, at intervals of 4 codos, 3 codos, and 3 codos offers an understanding of Michael Barkham's observation, based on construction contracts, that 16th-century Gipuzkoan deck heights were standardised and did not vary according to the ships size (Loewen in Grenier et al. 2007:III-149–151). Loewen gives a height of 2.3 m (4 codos) up to the Lower deck, 4.02 m (7 codos) to the Main deck and 5.75 m (10 codos) to the Upper deck and 7.5 m (13 codos) up to the fourth or Fore and Stern castle decks. This gives a height of 2.3 m for the Lower deck and 1.73 m height for the subsequent decks. It should be noted that Loewen appears to use the Codo cantábrico (Basque) equivalent to 0.575 m for these measurements.

The height of the lower deck in the Newport Medieval Ship is predetermined by the location of the beam swellings on the seventh stringer, and measures 2.58 m above the ceiling. The logical height for a second deck, based on positioning a beam shelf and the Standing Knee CT1547 as close as practical above the lower deck standing knee would be 1.83 m circa 3 ¼ codos. Based on the dimensions of the hypothetical Principal Reconstruction, when Iberian measurement unit are applied to these dimensions (Figure 84) the conversion results in whole, half and quarter 'Codo' measurements to within 1 cm.

Figure 84 Iberian measurements applied to Principal Reconstruction

Castro notes that:

> "*Thomas Oertling has proposed the existence of an Iberian shipbuilding tradition based on a cluster of 11 traits. His hypothesis is based on archaeological evidence found on several shipwrecks. There are scholars who support Oertling's findings and those who do not. The detractors argue that although the sample shipwrecks were engaged in Iberian trade, there is no way to confirm that they were all actually built in Iberia.*" (Castro 2008:77).

Eric Rieth (1998:178–180) argues;

'when common traits appear in a large enough number of shipwrecks from the same cultural horizon, they comprise "architectural signatures" that constitute the defining characteristics of a shipbuilding tradition.'

The Oertling Trait Cluster is the "architectural signature" of Iberian shipbuilding.

Iberian Atlantic Vessels: Characteristics proposed by Oertling (2001)

1 A given number of pre-assembled central frames bearing dovetail joints.
Newport Medieval Ship does not have pre-erected frames

2 Carvel planking fastened with a combination of nails and treenails.
Newport Medieval Ship has clinker planks fastened with both nails and treenails.

3 A knee joining the after end of the keel and the sternpost (*couce*).
No evidence recovered.

4 A single piece deadwood knee over the *couce* upon which sit the y-frames (*coral*).
No evidence recovered.

5 Y-frames tabbed into the deadwood knee.
No evidence recovered.

6 Keelson notched over the floors.
Yes

7 Mast step is an expanded portion of the keelson, part of which is cut to seat the ship's pump.
Yes

8 Buttresses supporting the mast step against the footwale.
Yes

9 Ceiling extending only over the floors, the last strake notched to receive filler planks.
Yes

10 Teardrop-shaped iron strop accepting a deadeye attached to two or three lengths of chain, the last link through an eyebolt.
Yes - deadeye for iron strop recovered, but not the iron strop.

11 Flat transom with proud sternpost.
No evidence recovered.

From the evidence recovered, the Newport Medieval Ship definitely has traits 6,7,8,9 and 10. For traits 3,4,5 and 11 there was insufficient recovered evidence to confirm or deny the existence of these traits. With regard to trait 2, plank fastening is, as per the proposed Iberian Atlantic vessel characteristics, even though the planking is clinker rather than carvel, so this could be classed as at least a half match.

Regarding the framing, while the Newport Medieval Ship did not have pre-erected frames, there is a change in "style" for the central portion of the vessel. The frames from F19 forward all have a central V shaped floor, consisting of symmetrically shaped arms of approx. equal lengths. The frames from F20 aft to F46 exhibit a symmetrical shape with a long and short arm alternating between port and starboard sides. The frames from F47 aft to F63 all return to a central V or Y shape with symmetrically shaped arms of equal lengths.

While Oertling was discussing carvel-built vessels, Adams in discussing the St Peter Port Guernsey wrecks noted;

"a clinker hull with this degree of internal coherence in its framing would have been relatively easy to convert to carvel as is known to have happened in England in the case of the *Great Bark*, built clinker in 1515 and rebuilt carvel as the *Great Galley* in 1523 (Anderson, 1962: 62), an example of both technological and conceptual flexibility." (Adams and Black 2004:235)

Of the St Peter Port Guernsey wrecks, Guernsey 6 has a beam of 7+ m and Guernsey 8 has a length of circa 25 m, which puts them both in roughly similar size category as the Newport Medieval Ship. St Peter Port 3 and 6 have transverse beams terminated on a stringer or beam shelf (Adams and Black 2004:233–238) just like Newport Medieval Ship, as opposed to the through hull beams associated with the cog like vessels. St Peter Port 6 planks dated to felling dates between AD 1229 - AD 1261. Very close rings less than 1 mm, potentially from southern England, and St Peter Port 7 included buttresses against the footwale either side of keelson, treenailed to frames, and a Keelson expanded to form the mast step exactly like Newport Medieval Ship.

Regarding the 11th trait of a flat transom and proud sternpost, Castro (2008:78) notes;

> "The eleventh trait calls for flat stern panels. These first appear in the Basque iconography in the last quarter of the 15th century and then again around 1500 in a view of the port of Venice by Jacopo Barbari (Taras Pevni 2002, pers. comm.) (Casado Soto 1995:40; Bash 2000). In the mid-16th century, flat panels appear on a Basque whaling ship at Red Bay, Labrador, but at the same time, contemporary iconography shows what seems to be both round and flat sterns (Figure 3) (Grenier et al. 1994). This may be an example of a trait that shifts through time or of a specific style of vessel."

From Figure 67 both round and square sterns were in existence in iconography before 1475 based on the 'Zumaya' tapestry.

Therefore I submit that the Newport Medieval Ship, with the dendrochronology pointing towards strong Iberian connections, a partial match to two of Oertling's traits, a definite match to five more, and insufficient evidence recovered to confirm or deny a match to the remaining four, is potentially a predecessor or early exemplification of this so called "Iberian Atlantic Vessel". Table 5 illustrates more comparisons between Newport Medieval Ship and some contemporary vessels. Figure 86 illustrates Newport Medieval Ship overlaid on the Red Bay or San Juan vessel of 1565.

Vessel	Age	Total Length	Construction	Total Beam	Keel Length	Keel Cross-Section	Length to Beam Ratio	Avg. Frame Dimensions/ Joinery	Frame Spacing centres	Mast Step Expanded Keelson	Keelson Notched Over Floors	Mast Step Reinforcement	Outer Hull Planking Thickness	Timber Origin	Comments / Unusual Features	Additional Sources
Culip VI Catalonia	Early 14th century	16.35 m	?	4.11 m	12.86 m	9 cm sided x 7 cm moulded	1:3.9	11 cm sided x 13 cm moulded Joinery: unknown	24.5 cm	Yes	Yes	No	3 cm		Mediterranean type coaster	
Sandwich Wreck Kent, UK	1332-61	20+ m	Clinker, Iron nails and □ roves	7-8 m	?	?	?	33 cm sided x 23 cm moulded	?	?	?	?	7.5 cm	British		
Ria de Aveiro A North / Central coast of Portugal	Mid 15th century	*c.* 17m			12.35 m	12 cm sided x 12 m moulded	1:4.8	12 cm sided x 12.5 cm moulded Joinery: mortise-and-tenon with treenails and iron nails	33 cm	Yes	Yes	Bilge stringers	5-5.5 cm			
Cais do Sodré	15th century	unknown			27.72 m	27 cm sided x 25 cm moulded	unknown	19.3 cm sided x 30.5 cm moulded Joinery: dovetail mortise-and-tenon with long iron nails	unknown	unknown	Yes	Bilge stringers	7.5 cm			
Copper Wreck W5	Early 15th century 1399 ?	c. 25 m	Clinker, Iron nails and □ roves	8 m	16.34 m	20-40 cm sided x 25 cm moulded	1:3.1	20 cm sided 17-23 cm moulded Wedged treenails to planking	30 - 40 cm				5 cm		Through hull ("Cog-Like") transverse beams 28 cm moulded x 24 cm sided @ 1.65 m crs Inner and Outer sternposts Planking nails driven from inboard	(Litwin 1980)
Skaftö Western Sweden	1437	c. 25 m	Clinker, Iron nails and □ roves	?	poss. 14 m	45 cm sided x ? moulded	?	15 cm sided x 11 cm moulded Treenailed to planking	35 - 40 cm	Not Recorded	Not Recorded	Not Recorded	3.5 - 4 cm	Gdansk, NE Poland Baltic Coast	Through hull ("Cog-Like") transverse beams Rudder recovered in-situ	(von Arbin 2009)
Aber Wrac'h Aber Wrac'h, France	1435	c. 25+ m	Clinker, Iron nails and □ roves	c. 8 m	?	?	Circa 1:3.1	15 - 25 cm square Treenailed to planking one per strake	28 cm	?	?	Small quadrangular blocks	5 cm	?	Through hull ("Cog-Like") transverse beams Also included cant frames	(L'Hour and Veyrat 1989)
NEWPORT MEDIEVAL SHIP **Newport, Wales**	**1450 - 1470**	**28.6 m** **34.8 m** **Incl. Castles**	**Clinker,** **Iron nails and □ roves**	**8m**	**c. 21.5 m**	**23 cm sided x 25 cm moulded**	**1:3.5** **Or** **1:4.3**	**25 cm sided** **13 - 35 cm moulded** **Treenailed to planking**	**36 cm**	**Yes**	**Yes**	**Buttress and Stringers**	**3 cm**	**Basque**	**Planking also iron spike nailed to framing** **4 Riders in Bow area**	**Author**
U 34 IJsselmeerpolders, Netherlands	1528 ±9	30 m	Clinker, Iron nails and roves, plus treenails in bottom	9 m	25.5 m	?	Circa 1:3.3	18-34 cm sided 16-35 cm moulded Wedged treenails to planking	45 to 52 cm	No	?	6 "frame-like" Riders per side	6 cm and 5 cm	South East Poland and Baltic	Quadrangular opening interpreted as a gun port Wooden lath and sintels over caulking bottom only	(Overmeer 2007)
Highborn Cay Bahamas	Early 16th century	19 m			12.6 m	15-16.5 cm sided x 21 cm moulded	Circa 1:3.5	16 cm sided x 16.5 cm moulded Joinery: dovetail mortise-and-tenon with treenails and iron nails	40 cm	Yes	Yes	Buttresses and stringers	6 cm			
Cattewater Plymouth, England	Early to mid 16th century	27.7 m			19.8 m	28 cm sided x 30 cm moulded	1:2.8	20 cm sided x 20 cm moulded Joinery: dovetail mortise-and-tenon	37 cm	Yes	Yes	No	6-7 cm			
Molasses Reef Turks & Caicos Isl	Early 16th century	20 m			unknown	unknown	1:2.6	16cm sided x 16 cm moulded Joinery: dovetail mortise-and-tenon with treenails and iron nails	32.5 cm	unknown	unknown	unknown	4.5 cm			
San Esteban	Mid 16th century	20.12 m			14.48 m	31 cm sided x 27 cm moulded	1:3.6	21 cm sided x 25 cm moulded Joinery: unknown	unknown	unknown	unknown	unknown	10 cm			
San Juan *Red Bay, Labrador, Canada*	1565	22 m	Carvel		14.75 m	unknown	1:2.9	20 cm sided x 22 cm moulded. Joinery: dovetail mortise-and-tenon	25-30 cm	Yes	Yes	Buttresses and stringers	unknown	Basque		

Table 5 Newport Ship compared to contemporary vessels (Revised after Schwarz 2008; Auer and Maarleveld 2011)

G.21 Alternative Reconstruction:

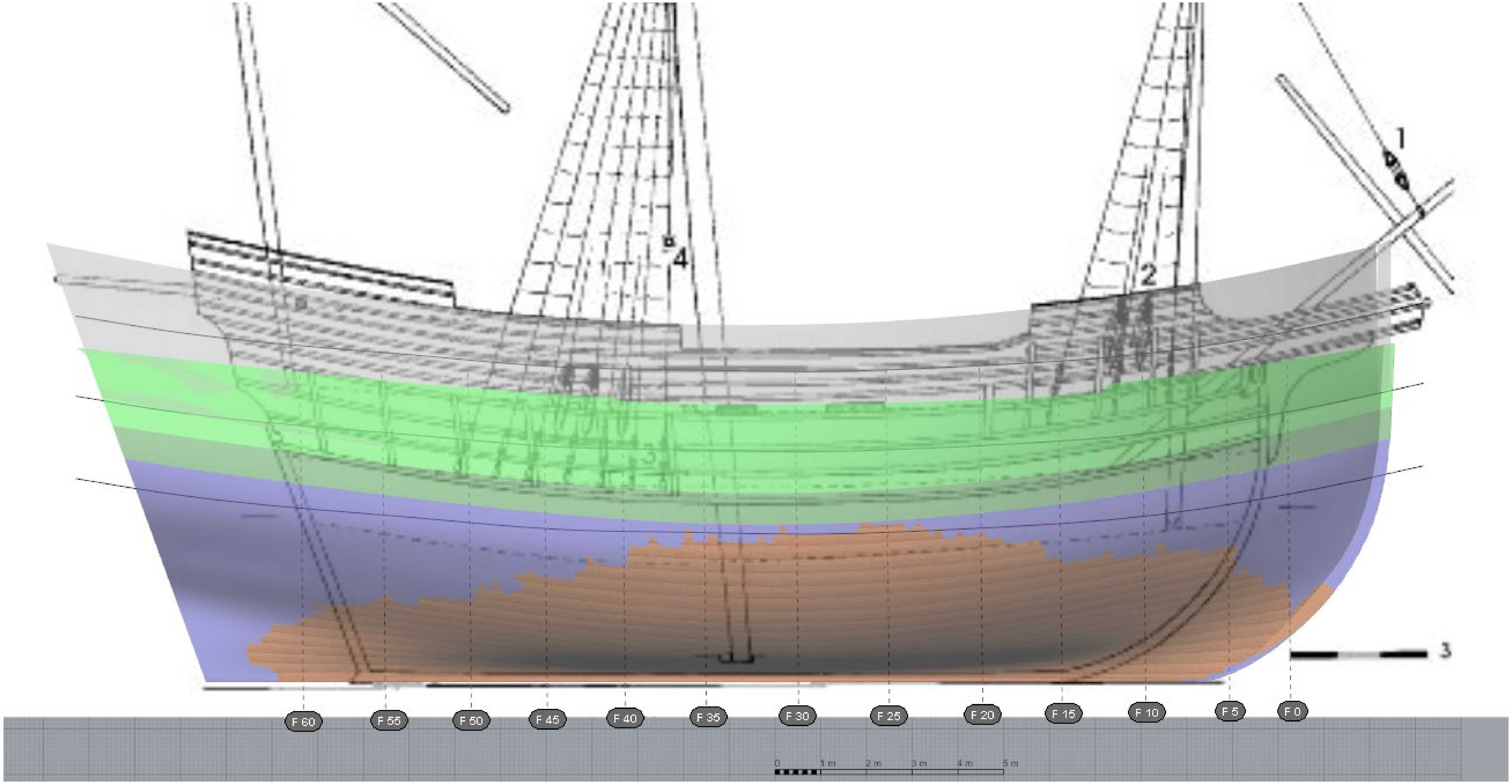


Figure 85 Alternative Reconstruction

San Juan, Red Bay 1565

G.22 References for Appendix G

Adams, Jonathan, and Jennifer Black
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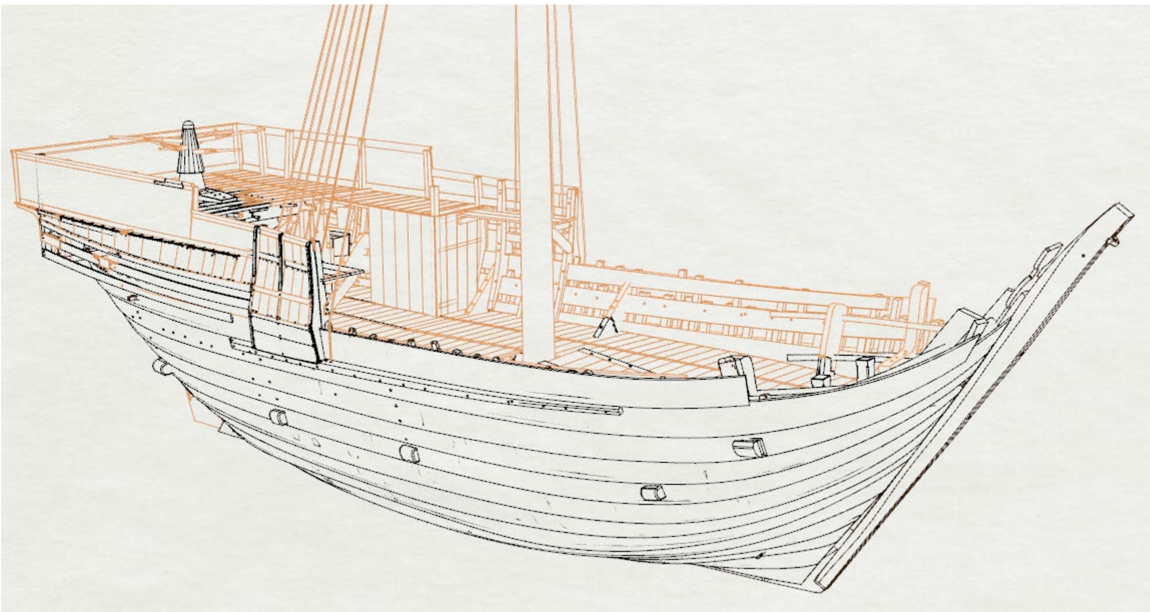
Appendix H Bremen Cog reanalysis

The Bremen Kogge

Still a Cog

but not as we knew it



Prepared by
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Contents

Bremen Kogge

H.1 Introduction

To examine the potential variations in hull shape of the Bremen Kogge, I began by assembling all of the available data sets as a starting point in order to determine how the shape and form of the hull shape had changed or deteriorated over the past years while on display in the museum. It quickly became apparent that discrepancies existed even in the initial (1985-1990) paper drawings of the recorded shape of the vessel. As well as subsequent deformation of the hull shape over time. Lahn described how several of the floor timbers sagged under the weight of subsequent timbers during the physical reconstruction, but the drawings as published, are unclear whether the deformed floor shape or a repaired "idealised" shape was chosen to represent the hull shape. Further detailed examination of the available drawings indicated inconsistencies between the individual drawings, with discrepancies ranging from -1.2cm and +15.6cm. It would appear to this author that some drawings represent exact shape measurements, while other drawings appear to represent an ideal or faired hull shape, however this is unclear as the drawings are not labelled as such.

Further examination of the newer (2011-2014) 3D recorded data showed significant further changes to the overall hull shape and form. Discrepancies ranging between -4.8cm to +21.7cm were measured. With the Bremen Kogge being a significant example of the Kogge type vessel, it is considered an important aspect of this project to attempt to determine the most accurate and viable reconstruction shape for the vessel.

H.2 Available data sets

2D Drawings:

There are two separate types of drawings in this set,

- Drawings by either C. Nord or Rita Schultze from W. Lahn's reconstruction
- Drawings prepared by Hanover University based on a Photogrammetry Survey of the reconstructed Kogge, carried out in 1980

The drawings based on Lahn's reconstruction appear to be an idealised reconstruction, while the drawings from University of Hanover appear to be a measured survey of the resulting physical shape of the reconstructed Kogge.

There appears to be a variation in the overall profile heights of the Kogge between the idealised reconstruction drawings and the recorded shape in the photogrammetry drawings. The reconstructed drawing shape in profile view is between 30 mm in the bilge area and up to 80 mm near the sheer (Table 1), higher than the Photogrammetric survey drawing of the reconstructed vessel carried out in 1989 (Figure 1). This is possibly explained in the written section by Lahn, describing how some of the floor timbers sagged under the weight of subsequent timbers during the physical reconstruction of the Kogge.

Position	A	B	C	D	E	F	G	H
Height Diff.	+32 mm	+15 mm	+23 mm	+86 mm	+82 mm	+66 mm	+19 mm	0 mm

Table 1 Differences between Lahn reconstruction and the 1980 photogrammetric survey

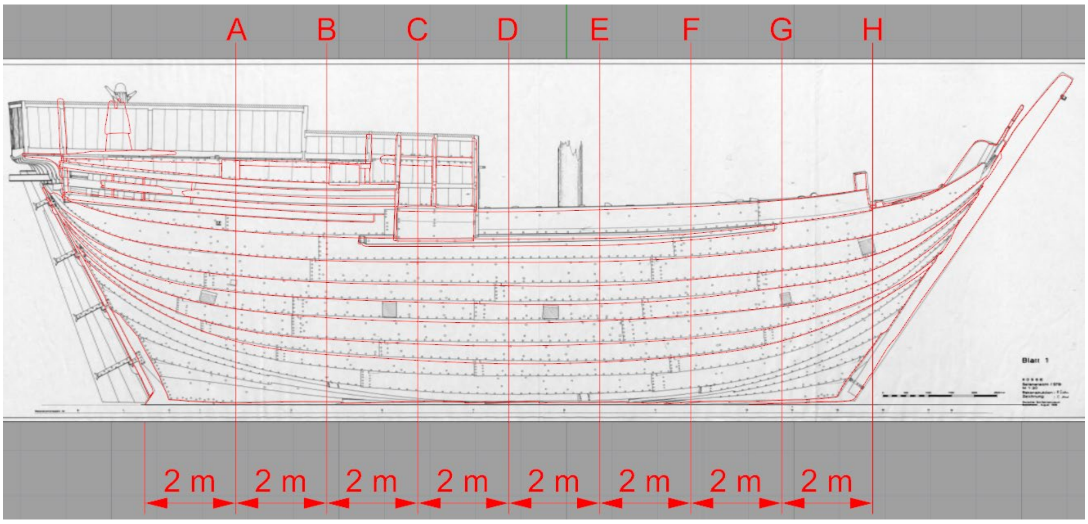
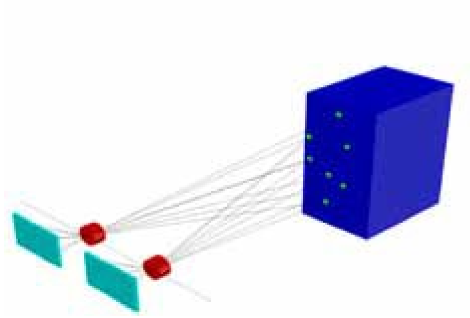


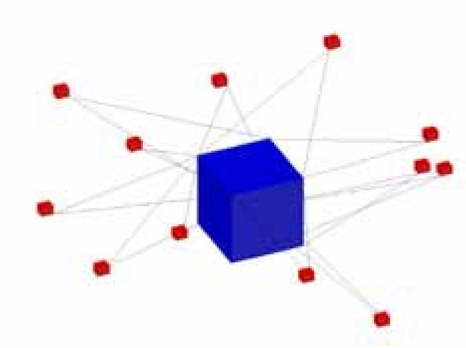
Figure 1 Photogrammetry outline overlaid on Profile Drawing

3D Data capturing surveys:

3D laser scanning uses a laser ranging device that send an active eye safe laser beam to a target, and records either the time of flight or phase shift in the laser beam returning to a camera lens, resulting in millions of points with accurate x, y, z dimensional measurements.

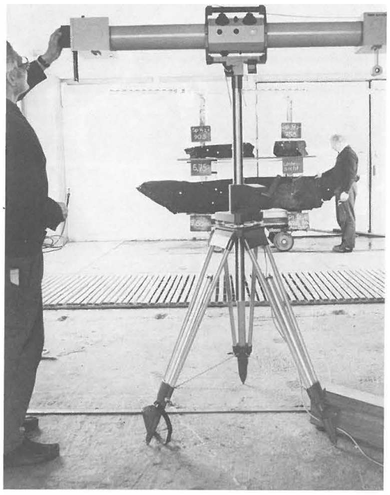
Photogrammetry can be subdivided into two main formats,





Stereo paired Photogrammetry

Multi image photogrammetry

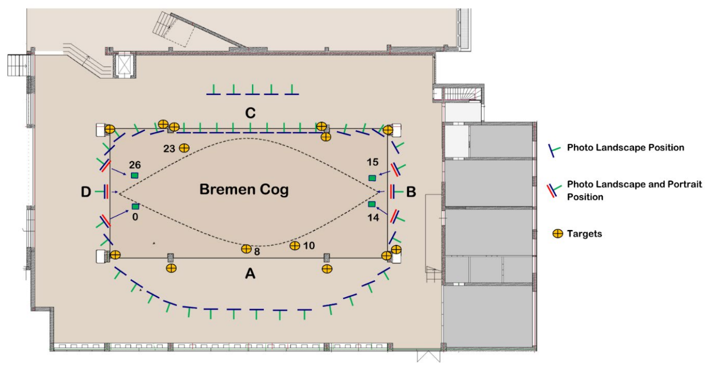


Stereo paired Photogrammetry uses stereo paired, dedicated photogrammetric cameras, mounted at a known separation distance and thereby generating images with a known fixed overlap, to allow the use of trigonometry to generate three dimensional data points.

Illus. 33:Measuring the parts with a stereogrametric camera.

Photo:G. Meierdierks/DSM The Hanse Cog of 1380

Multi-image based photogrammetry typically using a single SLR camera to record multiple images of the target object from various viewpoints, and uses mathematical matching of the pixels within the images to generate three dimensional co-ordinates.



Location of camera positions during the 2014 photogrammetry survey

Image J Guery

3D Scan 2011:

These files consisted of:

3D point cloud of circa 1.2 million data points and a

3D polygon mesh model of 944,361 triangles, generated from a reduced subset of the original data, as well as several files in the proprietary Polyworks® compressed file format.

I was able to extract the raw data from the Polyworks® file format and import the scan data into Geomagic Studio software. This allowed the generation of an accurate detailed polygon mesh model based on the raw 2011 3D scan data (Figure 2). The result being a highly detailed 3D mesh model of circa 2.5 million triangles, albeit only of the interior surfaces of the Kogge as there was no data of the external surfaces recorded in the 2011 data.

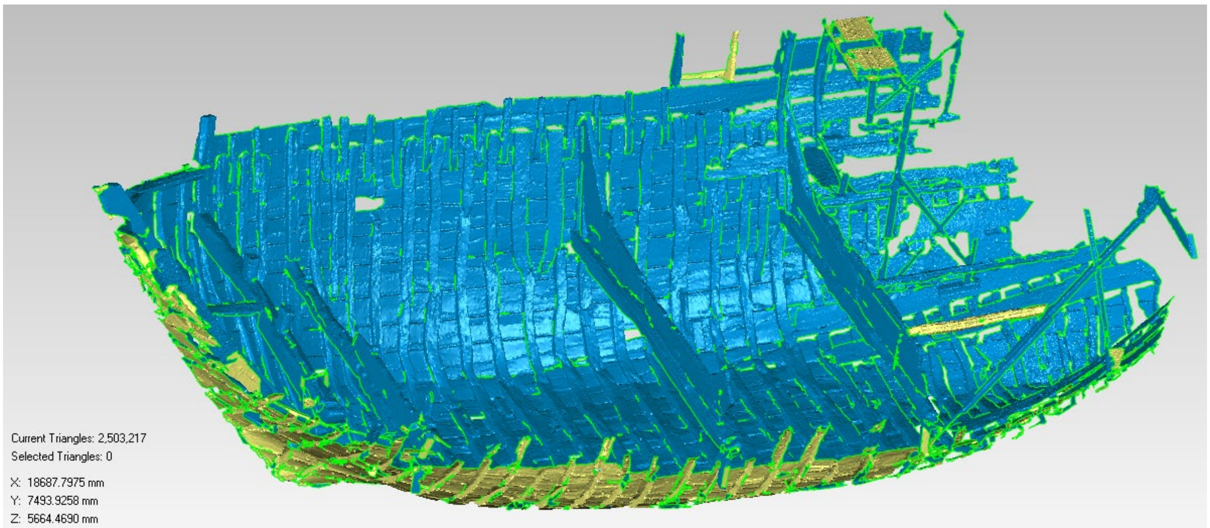


Figure 2 Cleaned Polygon Mesh model from 2011 3D scan

The 2011 scan data was then imported into Rhinoceros 3D modelling software and aligned correctly in order to examine any shape deviation between the recorded shape and the previously recorded known data (Figure 3).

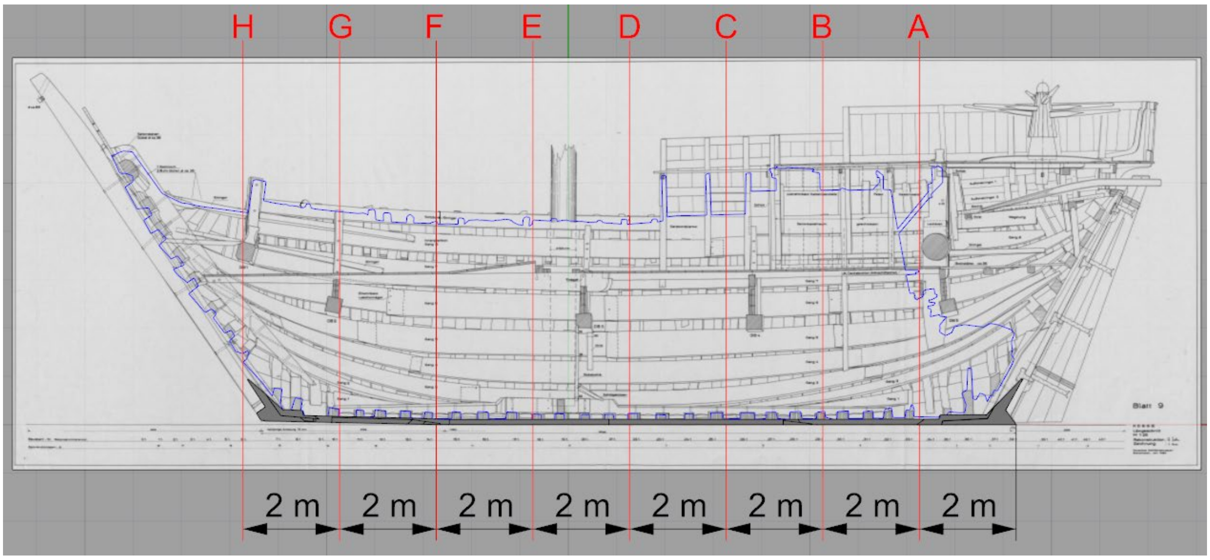


Figure 3 Outline of 2011 3D scan overlaid on Longitudinal Section Drawing

The top position of the uppermost sheer strake was then measured every 2m from the aft face of the keel and the amount of sagging compared to both the Lahn reconstruction drawings and the 1980 photogrammetry survey Table 2.

Position	A	B	C	D	E	F	G	H
Height Diff. 1	No Data	-61mm	-70mm	-203mm	-153mm	-170mm	-132mm	-79mm
Height Diff. 2	No Data	-46mm	-47mm	-117mm	-71mm	-104mm	-113mm	-79mm

Table 2 Differences between the 2011 3D scan data and the Lahn reconstruction line 1, and 1980 photogrammetric survey line 2

SFM October 2014:

This data set consisted of three data files and a PDF report

- DenseCloud - NIR - BremenCog Facea.ply 04/11/2014
- DenseCloud - NIR - BremenCog.ply 31/10/2014
- DenseCloud - NIR - BremenCog.stl 21/08/2014

Some 200 photographs were recorded of the Kogge, and using Agisoft® Photoscan a point cloud of 7.7 million data points was generated.Both files are in point cloud format, and were imported into Geomagic Studio in order to generate polygon mesh data 3D models (Figure 4).

The DenseCloud - NIR - BremenCog.ply contained a 3D point cloud of 12.27 million points

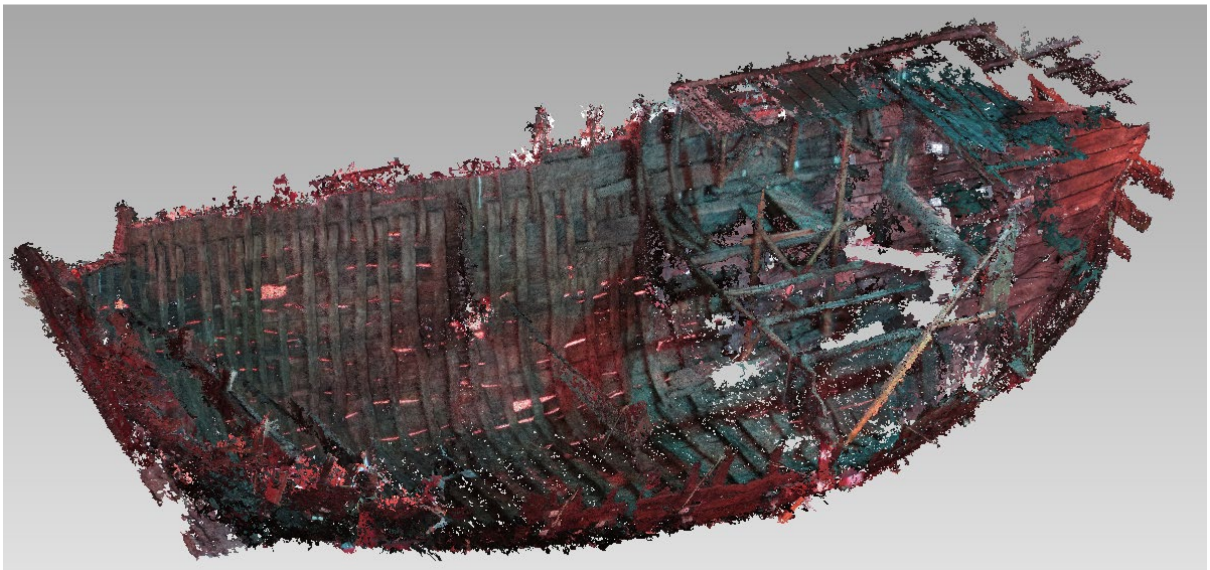


Figure 4 Point Cloud data converted to 22 million polygon mesh model

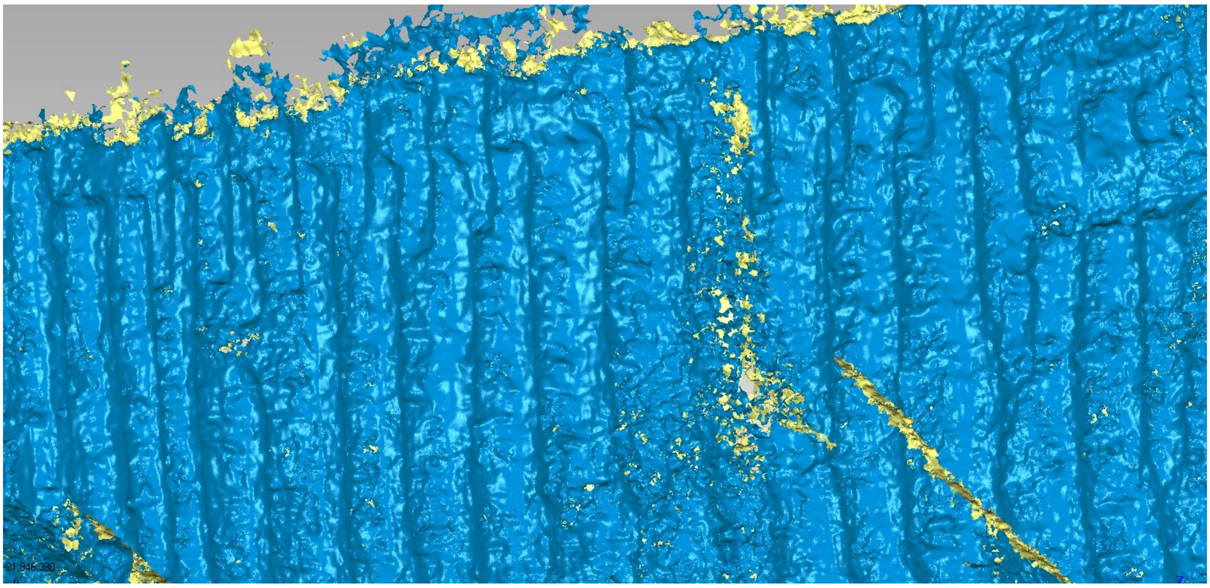


Figure 5 The same 22 million polygon mesh with the texture removed showing the lack of geometric detail in the 3D model

While the 3D model created using the SFM data provides a visual coloured three dimensional model, when the texturing is removed from the file to examine and measure the underlying geometric shape of the 3D model, the resolution of the mesh data is insufficient to provide accurate dimensional results (Figure 5).

This data while useful for viewing the overall model is of little use for dimensional analysis other than overall general measurements (Figure 6) and checking the overall dimensions listed in Table 3.

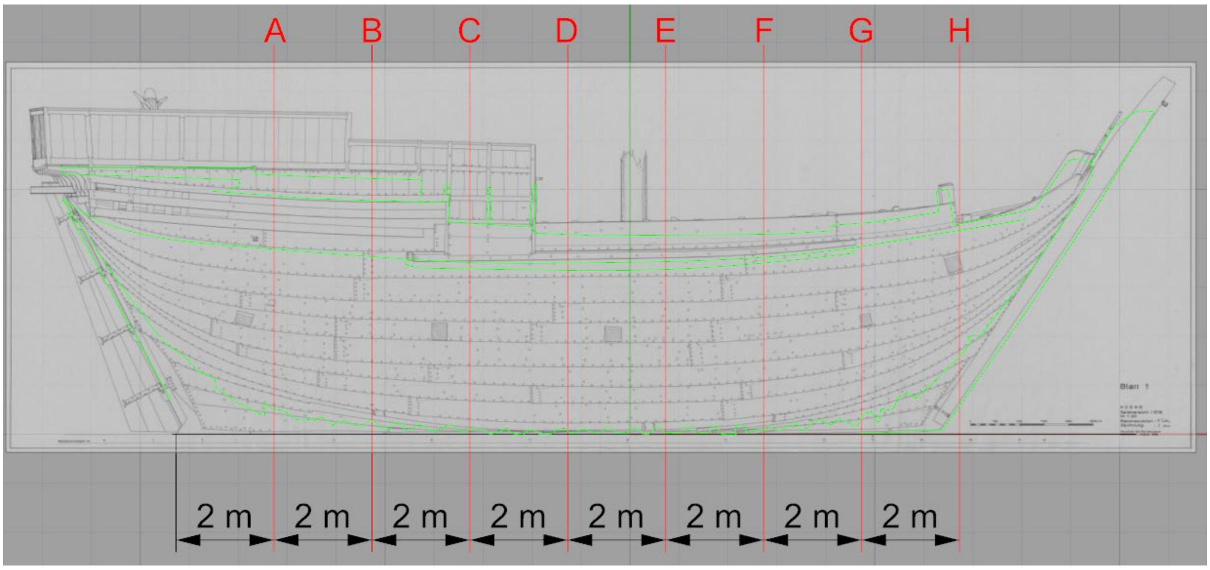


Figure 6 Outline of SFM October 2014 overlaid on Profile Drawing

Position	A	B	C	D	E	F	G	H
Height Diff. 1	-98mm	-73mm	-81mm	-227mm	-200mm	-201mm	-162mm	-92mm
Height Diff. 2	-66mm	-58mm	-58mm	-141mm	-118mm	-135mm	-143mm	-92mm

Table 3 Differences between the SFM Oct 2014 3D data and the Lahn reconstruction line 1, and 1980 photogrammetric survey line 2

3D Scan 2014:

This data set consisted of two files

- Kogge_SFM_mit.ply 27/04/2014
- kogge_unified_1cm.stl 19/01/2014

Kogge_SFM_mit.ply contained a 3D point cloud of 29 million data points of a partial recording of the starboard side external surface only. This data set was imported into Geomagic and a polygon mesh model created from the 3D Point Cloud data (Figure 7).

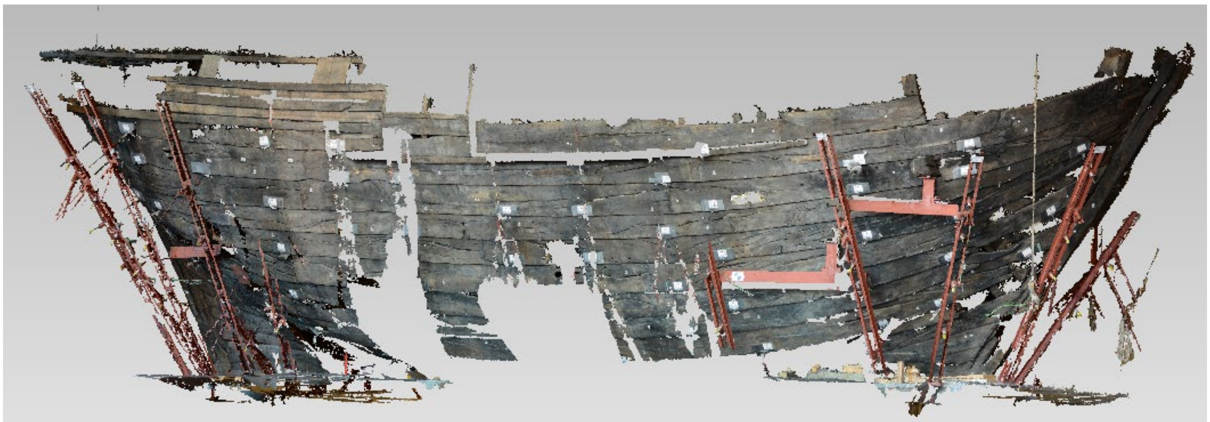


Figure 7 Polygon Mesh model generated from 3D Point Cloud data

This data is saved at some peculiar scale resulting in overall dimensions of 18.7 m long, 7.4 m wide and 6.2 m high. With the reconstructed Kogge measuring 22.65 m between posts there is an obvious error in this data set. However the geometric detail once the texturing is removed appears of a high detail (Figure 8).

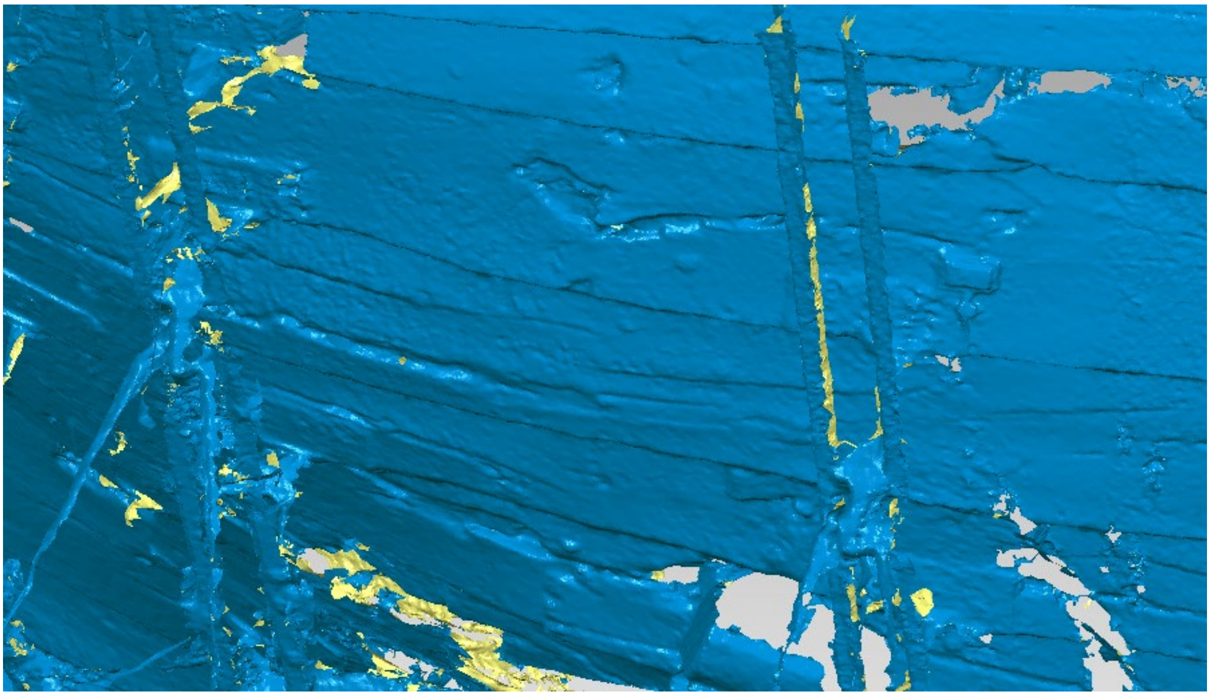


Figure 8 Texture removed from the Kogge_SFM_mit.ply data to reveal underlying geometry detail

Kogge_unified_1cm.stl appears to be a decimated polygon mesh model, where the quantity of polygons in the model has been reduced in order to minimise the final file size (Figure 9).

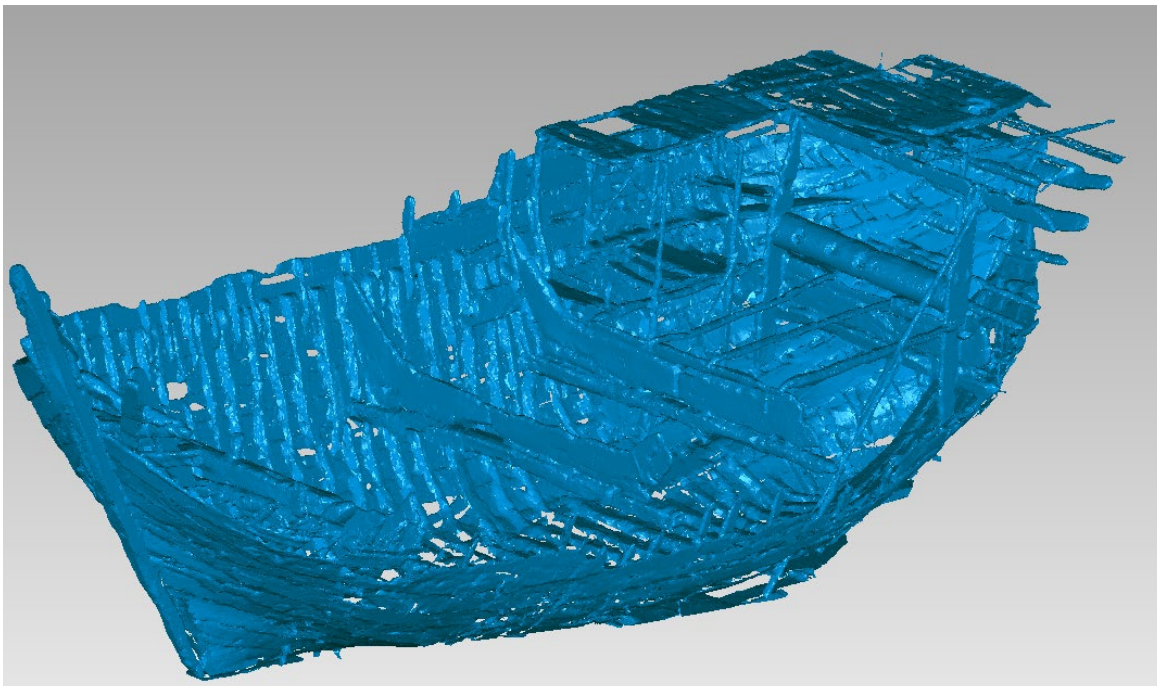


Figure 9 Polygon Mesh model from kogge_unified_1cm.stl

Considering the interior only 3D scan from 2011had 2.5 million polygons this 2014 scan would have benefitted from maintaining a higher polygon count in order to preserve the geometric shape data. The height changes for the top surface of the sheer strake were measured and compared with both the Lahn drawing and the photogrammetric survey (Figure 10) and the results set out in Table 4.

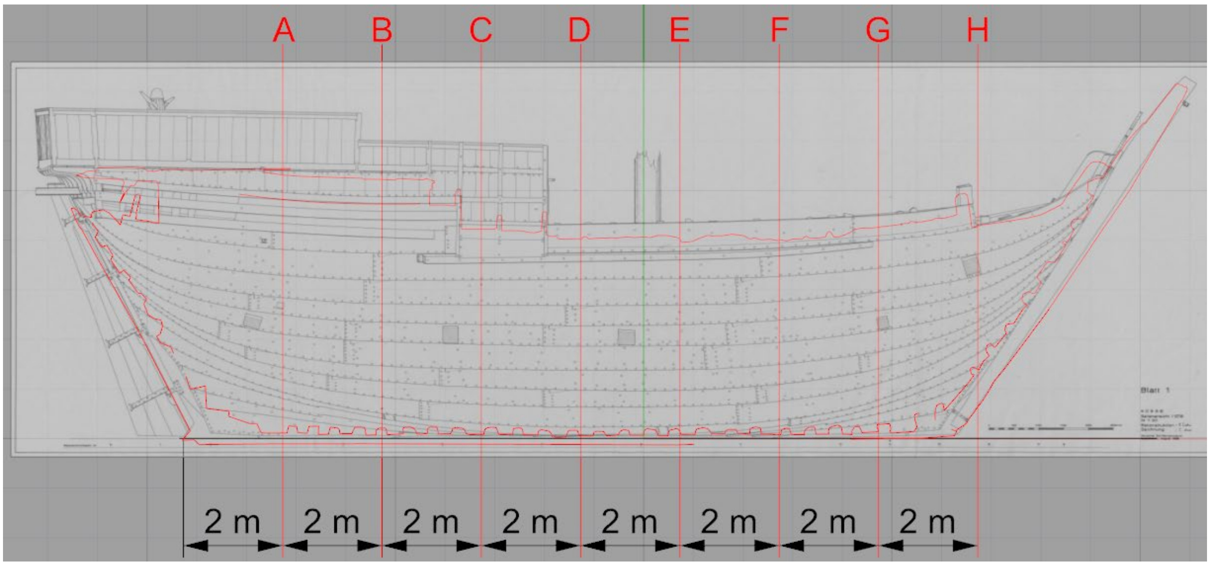


Figure 10 Outline of 3D Scan 2014 overlaid on Profile Drawing

Position	A	B	C	D	E	F	G	H
Height Diff. 1	-137mm	-118mm	-125mm	-255mm	-220mm	-222mm	-204mm	-99mm
Height Diff. 2	-105mm	-103mm	-102mm	-169mm	-138mm	-156mm	-185mm	-99mm

Table 4 Differences between the 3D Scan 2014 3D data and Lahn drawing line 1, and 1980 photogrammetric survey line 2

Position	A	B	C	D	E	F	G	H
Photogrammetric Survey 1980	0	0	0	0	0	0	0	0
Lahn Drawing 1985	+32 mm	+15 mm	+23 mm	+86 mm	+82 mm	+66 mm	+19 mm	0 mm
3D scan 2011	No Data	-46mm	-47mm	-117mm	-71mm	-104mm	-113mm	-79mm
SFM Oct 2014	-66mm	-58mm	-58mm	-141mm	-118mm	-135mm	-143mm	-92mm
3D scan 2014	-105mm	-103mm	-102mm	-169mm	-138mm	-156mm	-185mm	-99mm

Table 5 Comparing 4 surveys to Lahn drawing

The results set out in Table 5 show the changing shape of the hull over a period of 30 years.

H.3 Two Dimensional Lahn Drawings

All of the available two-dimensional drawings were imported into Rhinoceros modelling software, scaled back to full size dimensions, and correctly orientated, in order to be used as a guide for the overall three dimensional shape of the reconstructed Kogge (Figure 11).

As the paper is subject to some shrinkage and the additional potential errors resulting from digitising the plans, each plan was checked and scaled using only the scale bars or actual dimensions directly on the drawings. The most reliable of these drawings were the cross section plans which had measured dimensions in both the width and height axis. All of the profile and plan drawings had dimensions only in the longitudinal axis and these drawings were scaled to match these dimensions.

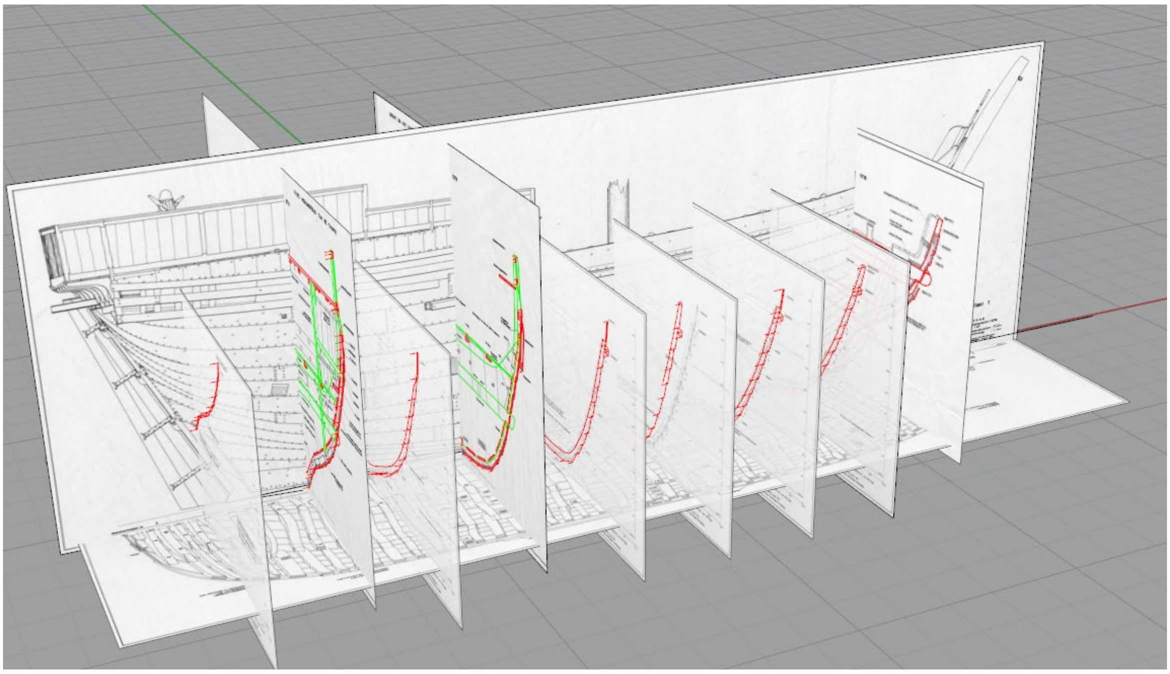


Figure 11 Lahn Two Dimensional drawings scaled and positioned in 3D space

However when the cross section drawings are compared to the longitudinal profile drawings there are some discrepancies in the height measurements as shown in Table 6. The heights of each strake were then taken from the cross section drawings and projected onto the profile views (Figure 12).

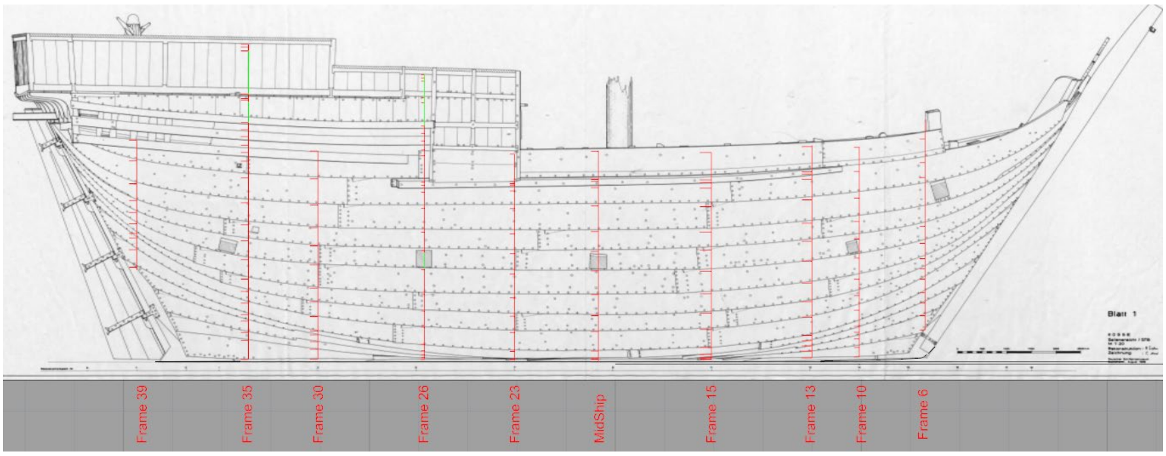


Figure 12 Heights from Cross Section drawings projected onto Profile drawings

Location	Overall Height	Reconstructed Profile Blatt 1	Photogrammetry Blatt 25	Measurement Point
Frame 6	4522mm	+147 mm	+163 mm	Washboard
Frame 10	4354mm	+156 mm	+156 mm	Washboard
Frame 13	4369mm	+ 84 mm	+ 53 mm	Washboard
Frame 15	4250mm	+129 mm	+ 66 mm	Washboard
MidShip	4273mm	+ 64 mm	- 24 mm	Washboard
Frame 23	4216mm	+ 87 mm	+ 17 mm	Washboard
Frame 26	5260mm	+128 mm	+ 23 mm	Upper Deck
Frame 30	4280mm	- 12 mm	- 39 mm	Washboard
Frame 35	5343mm	+ 85 mm	+ 28 mm	Upper Deck
Frame 39	4498mm	+ 30 mm	+ 34 mm	Strake 14

Table 6 Difference between Reconstruction Drawing Cross Section Sheer Heights

The strake heights on the body plan (Blatt 35) appear to coincide with the strake heights in the profile drawings (Blatt 1,5,6,7 and 9), with the exception that the heights on Blatt 35 Body Plan are all uniformly circa 35mm too low in comparison to the profile views Blatt 1,5,6,7 and 9. However this discrepancy could be explained by scaling issues, a 35 mm difference at full size is equivalent to a 1.75 mm difference on the scale drawings. It would appear that the section drawings (Blatt 29 to 34) are based on the actual recorded shape, while the Body Plan (Blatt 35) and the profile views (Blatt 1,5,6,7 and 9), as well as the section drawings (Blatt 3) are based on a faired or idealised reconstruction shape.

Lahn states:

> "We can say with complete conviction that any difference between the cog we built and the original from 1380 can be measured in millimetres. There may be deviations of up to 30 millimetres in individual parts but the overall shape is not affected by these differences which are the result of distortions in the wood." "The data collected form a basis for a precise reconstruction and a scholarly evaluation - a comprehensive task for future years." (Kiedel & Schnall 1989, p.39).

The shaded data in Table 6 shows the overall height discrepancy between each of the sections drawings represented on Blatt 3 and the corresponding point on the profile drawing. These are discrepancies between the same points from different views taken from the completed reconstruction drawings.

As discussed in great detail by Dick Steffy, lines drawings and construction plans are graphic descriptions of the shape of the hull as reconstructed. No single two-dimensional drawing can accurately or full present the three dimensional shape of the object it represents. A plan view will describe the length and width, without any height reference, just as a profile or section drawing will describe the width and height without any depth information. The side (sheer plan) or profile view, the (half breadth) plan view and the (body plan) sections views, all represent the same side of the same hull, and except for reasons of clarity or special circumstances, all lines shown on one plan must be shown on the other two as well (Steffy 1994, pp.15–20, 244–250).

From the two-dimensional data available, there would appear to be three separate potential hull shapes for the vessel.

- The hull shape created from the Body Plan drawings
- The hull shape created from the cross-section drawings
- The hull shape created from the photogrammetric survey and reconstructed profile drawings
- and potentially a fourth shape if average dimensions were to be used.

Body plan or Lines Plan drawings Blatt 35, 36 and 37

While the fixation on symmetry tends to be a modern concept with little or no supporting evidence recovered from medieval wrecks (F. Hocker, 2016, pers. comm., 30 Sep.), no boatbuilder ever intentionally sets out to construct a ship or boat which is asymmetrical athwartships, that is, the same shape on both sides, with a few notable exceptions such a venetian gondola or a proa. Figure 13 shows the level of symmetry achieved, as recorded from the reconstructed shape.

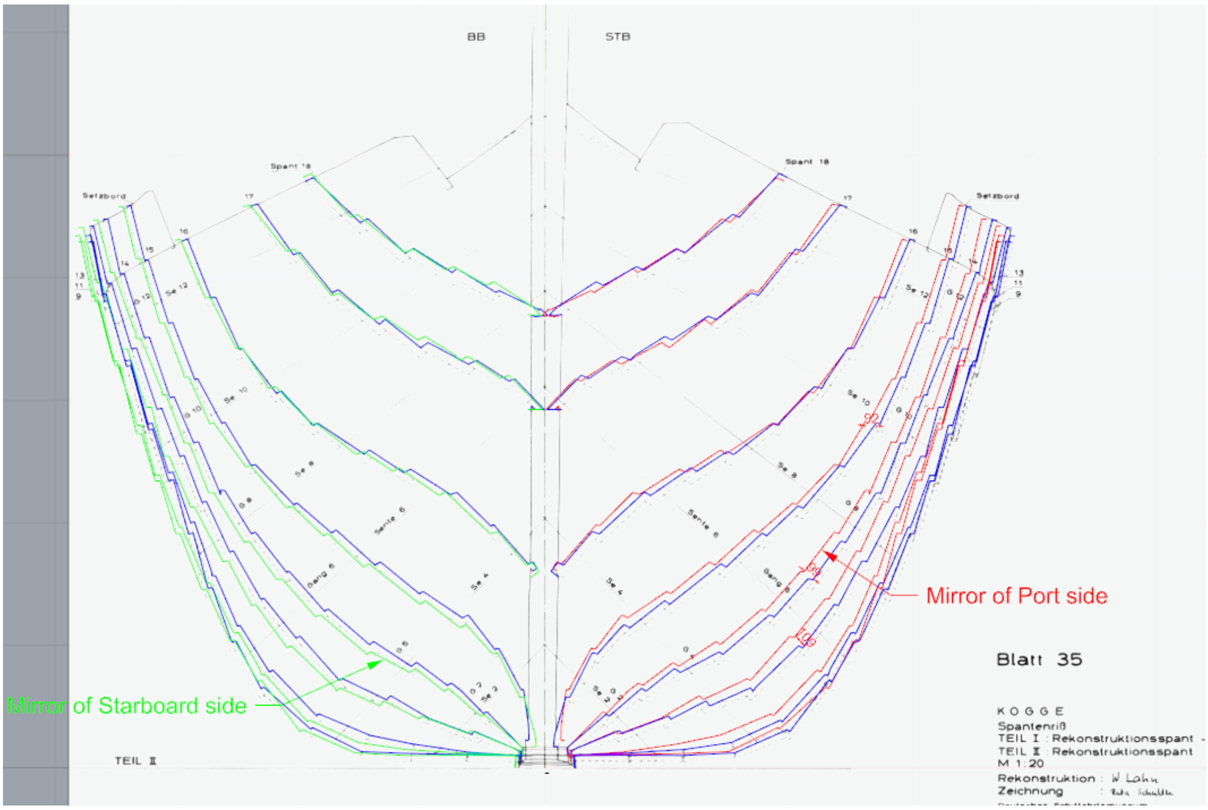


Figure 13 Body Plan drawing showing asymmetry between port and starboard sides of the hull, measured at up to 109 mm in places

A digital three dimensional model of the hull shape (Figure 14) was created using the measurements from the Body Plan drawing (Blatt 35). This three-dimensional digital hull shape was then compared to the various two dimensional drawings. The photogrammetry profile drawings from 1980 were overlaid on the 3D model to compare the hull shape between the 1980 photogrammetric survey and the hull shape derived from the Body Plan drawings (Figure 15) and the results set out in Table 7.

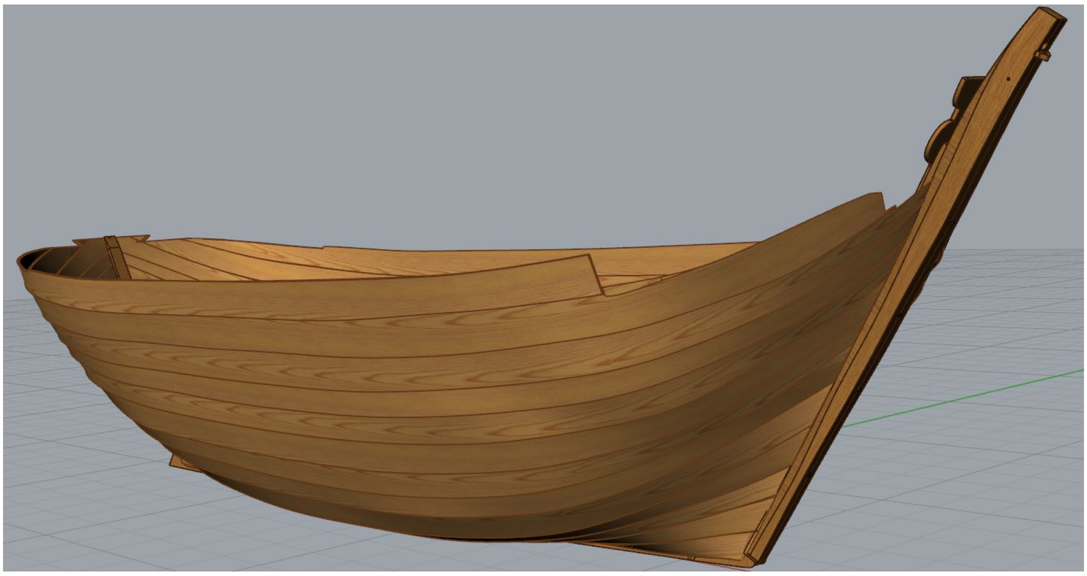


Figure 14 Hull Shape derived from Body Plan Drawing (Blatt 35, 36 and 37)

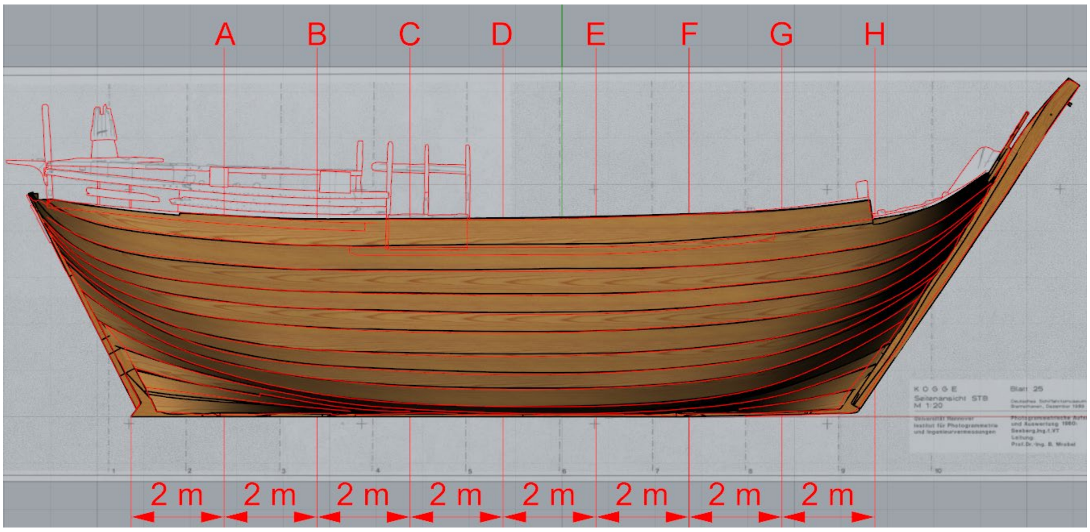


Figure 15 Photogrammetry profile 1980 overlaid on Faired Body Plan Hull

	A	B	C	D	E	F	G	H
Sheer	+3	-50	-23	-41	-24	-9	+43	+53
WashBoard	+24	- 1	-44	-73	-73	-50	+21	+41
Strake 12	+33	- 7	-36	-48	-52	-8	+11	+41
Strake 11	+3	- 6	-28	-39	-43	+6	+17	+24
Strake 10	-13	+ 3	-31	-39	-50	-23	+24	+65
Strake 9	+4	-19	-42	-42	-13	+34	+9	+45
Strake 8	-34	- 3	-45	-62	-33	-18	+8	+62
Strake 7	-46	-19	-45	-58	-26	-14	+12	-18
Strake 6	-25	+ 7	-31	-36	-19	-16	+20	+21
Strake 5	+6	+ 7	+24	+6	-18	-26	+2	No data
Strake 4	-30	-16	No data	No data	No data	No data	No data	No data
Strake 3	-16	0	No data	No data	No data	+7	-4	No data
Strake 2	+51	+13	No data	No data	No data	No data	-9	No data
Strake 1	0	0	0	0	0	0	0	0

Table 7 Difference between 1980 Photogrammetry Profile and 3D Body Plan model

	A	B	C	D	E	F	G	H
Sheer	-24	-38	-29	-45	-47	-48	-60	-56

Table 8 Difference between 3D Body Plan model and Profile Drawing Blatt 1

Table 8 shows the height differences between the 3D body plan model and the matching profile view drawing from Blatt 1.

The same three dimensional model of the hull shape (Figure 14) was then compared to the previously recorded 3D Scan 2014 data. The 3D scan was overlaid on the 3D body plan model to compare the hull shape as recorded in 2014 to the hull shape derived from the Body Plan drawings (Figure 15) and the results set out in Table 9.

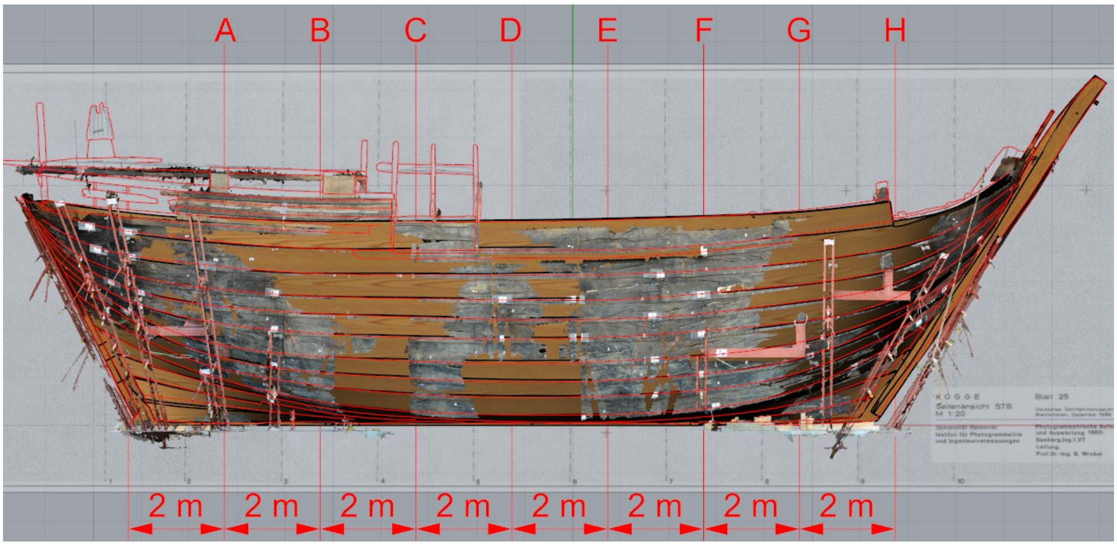


Figure 16 3D scan November 2014 overlaid on Body Plan Hull

	A	B	C	D	E	F	G	H
Sheer	No data	-50	-129	-153	-168	-169	-131	-73
WashBoard	-47	- 78	-122	-148	-140	-152	-95	-69
Strake 12	-61	- 53	-102	-138	-138	-117	-80	-75
Strake 11	-84	- 63	-96	-130	-117	-114	-64	-77
Strake 10	-100	-81	-98	-128	-120	-109	-79	-41
Strake 9	-78	-79	-107	-141	-106	-123	-83	-28
Strake 8	-93	- 77	-110	No data	-25	-99	-80	-39
Strake 7	-56	0	-50	No data	-36	-95	-84	-20
Strake 6	0	+ 21	-34	No data	-20	-95	-28	-50
Strake 5	+24	+ 7	-11	No data	-42	-70	-45	No data
Strake 4	+8	-16	No data	No data	No data	No data	No data	No data
Strake 3	+6	No data	No data	No data	No data	No data	-33	No data
Strake 2	+45	No data	No data	No data	No data	No data	-44	No data
Strake 1	0	0	0	0	0	0	0	No data

Table 9 Difference between 3D scan 2014 and Faired Body Plan model

It should be noted that all the dimensions set out in Table 9 are vertical measurements only. This is an indication of how much the current (2014) shape of the hull has sagged vertically, the hull has also spread horizontally and an indication of this can be seen from the various section slices shown in Figure 17 to Figure 20.

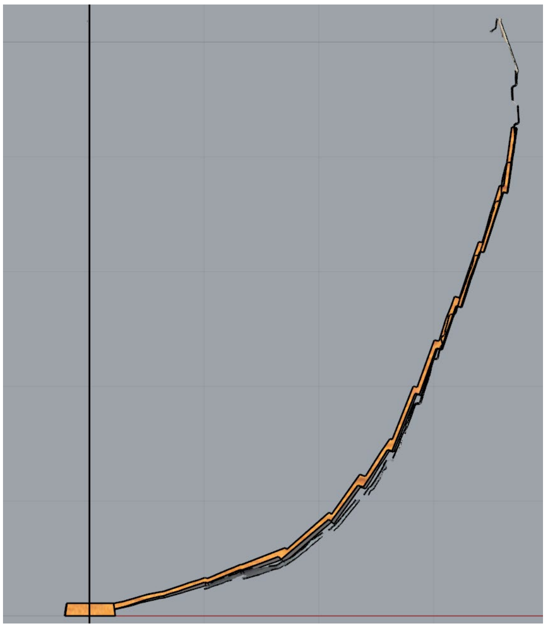


Figure 17 Section at Measurement Point B

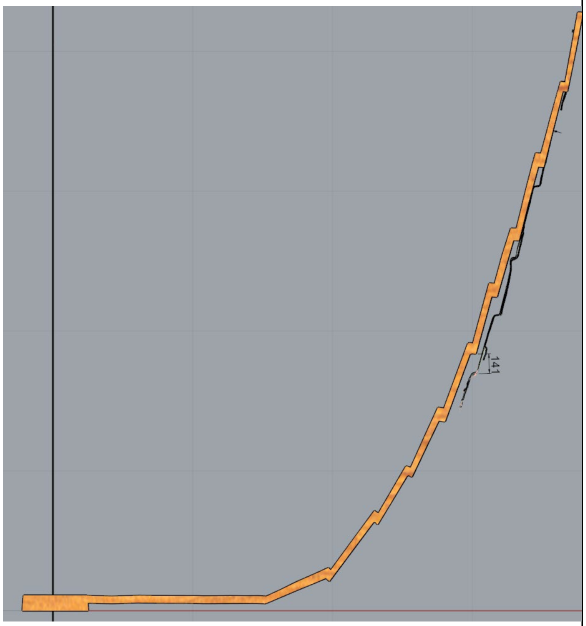


Figure 18 Section at Measurement Point D

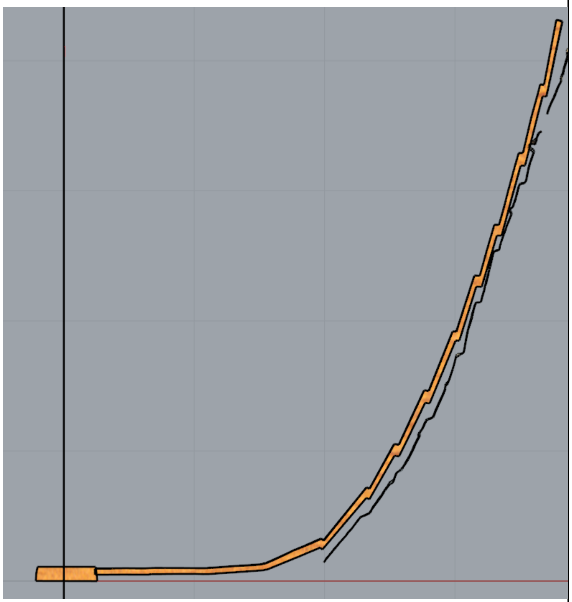


Figure 19 Section at Measurement Point E

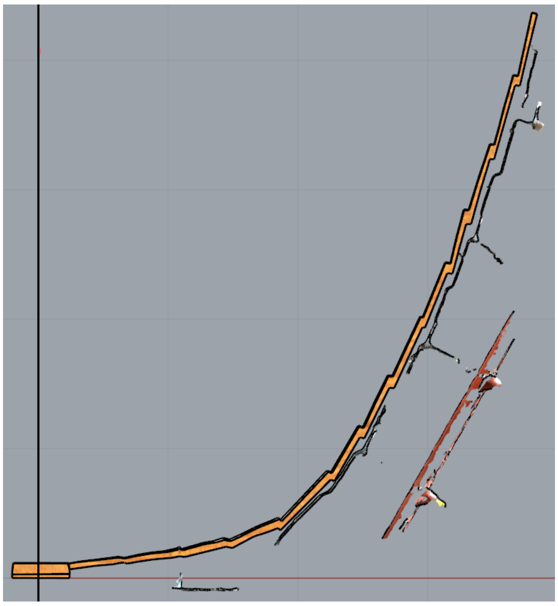


Figure 20 Section at Measurement Point F

From Table 9 and the sections shown in Figure 17 to Figure 20, it is clearly apparent that the hull shape of the Kogge as recorded in the 3D scan 2014 is not the same shape as that of the three dimensional model created from the Body Plan (Blatt 35) drawing.

Additionally based on the measurements in Table 7 it is apparent that the recorded shape of the hull from the photogrammetric survey carried out in 1980 is not the same as the three dimensional shape indicated from the Body Plan drawing, and the question must be asked if the reconstructed hull ever achieved the shape indicated by these (Body Plan) drawings.

While Figure 21 demonstrates that the three dimensional hull shape derived from the Body Plan drawings complies with the Midship Section drawing (Blatt 4), Figure 22 to Figure 24 show there are some positional inconsistencies with the other sections at frames 10, 26 and 35 from Blatt 3.

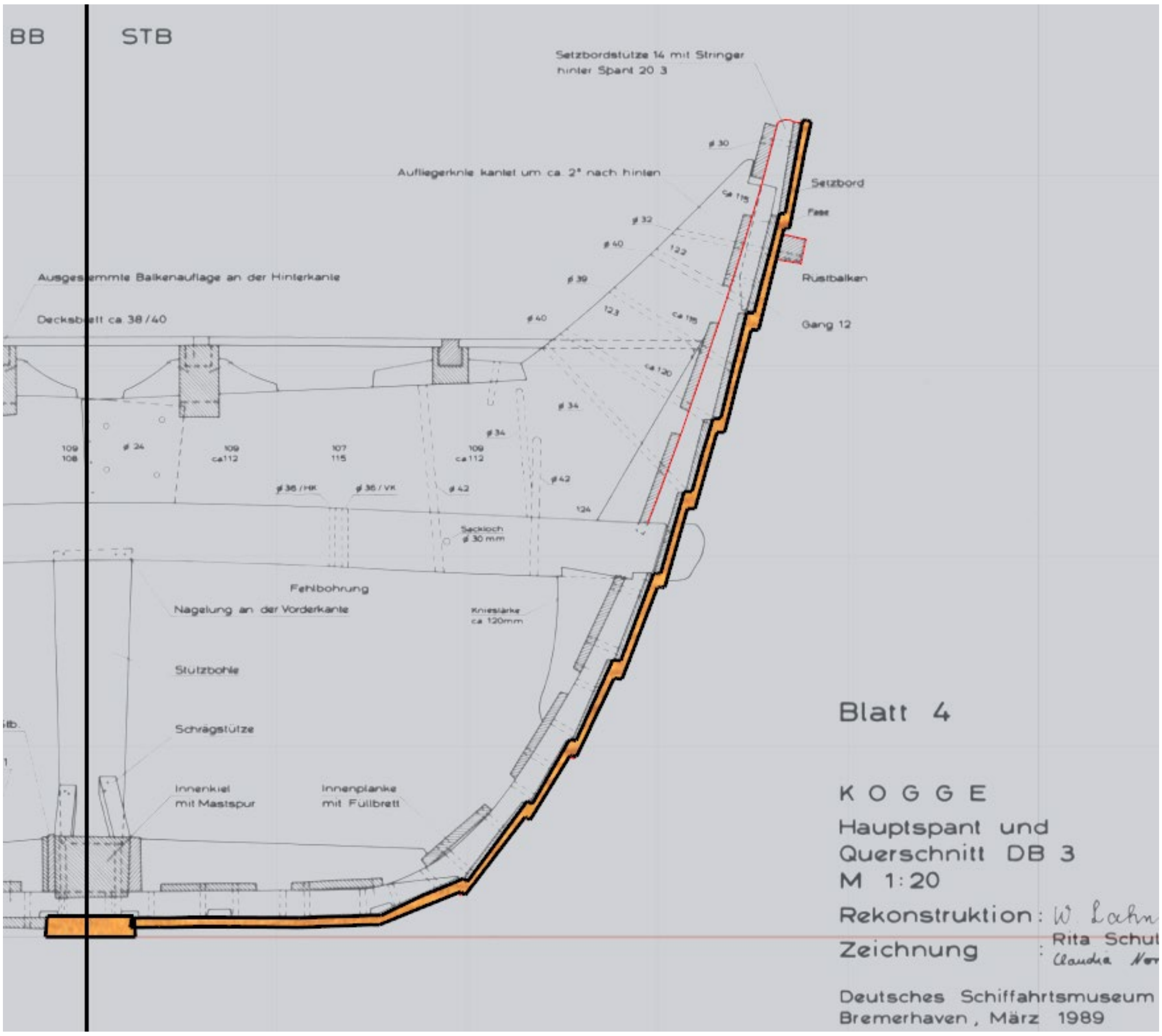


Figure 21 Section showing relationship between Body Plan hull shape and Midship Section Drawing (Blatt 4)

There appears to be an additional issue with the cross section drawn at Frame 10. The shaded planks (Figure 22) are the digital 3D body plan model from the drawing as shown on Blatt 35. While both the Body Plan (Blatt 35) and the Cross Section drawing from Blatt 3 have the same starting point at the keel and garboard plank, the cross sectional shape and heights of the subsequent strakes, 2 through 8 vary significantly (up to 132 mm at strake 4) before conforming in shape again at strake 10, with the body plan heights (Blatt 35) remaining up to 115 mm higher for the subsequent strakes 11,12 and 13.

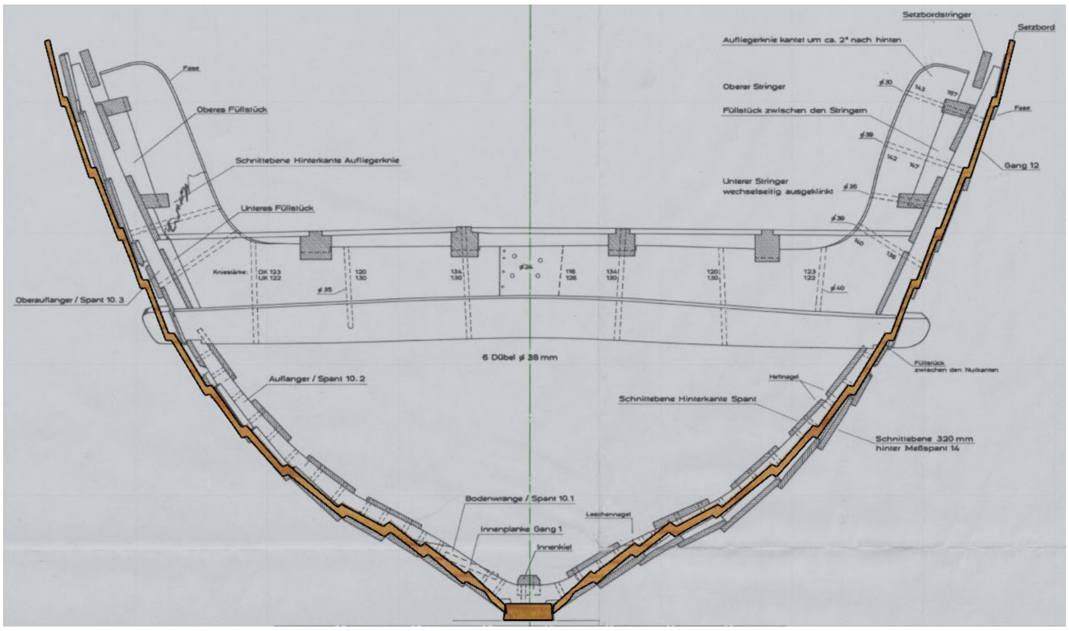


Figure 22 Section showing Body Plan hull shape (brown) at Frame 10

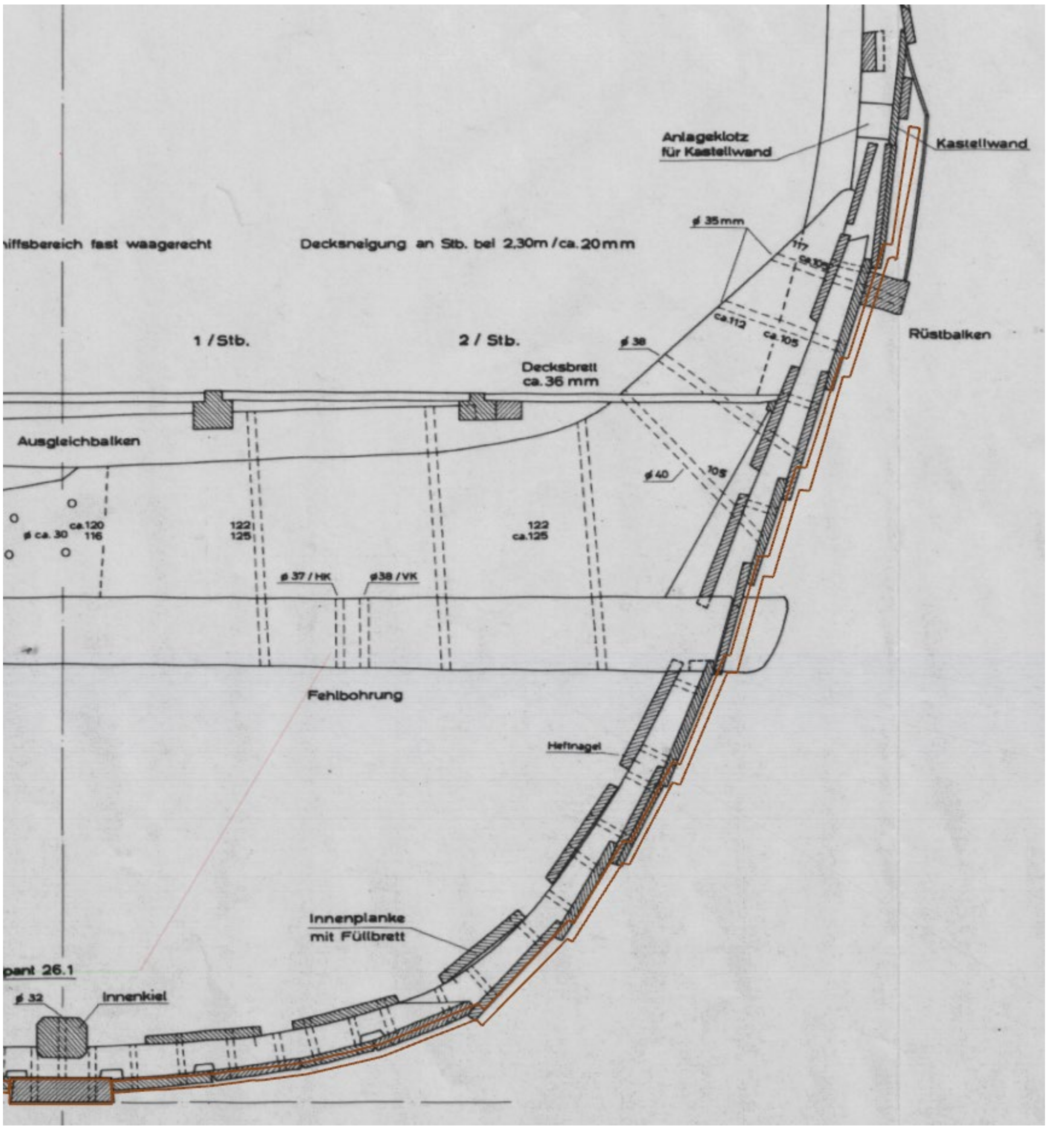


Figure 23 Section showing Body Plan hull shape (brown) at Frame 26

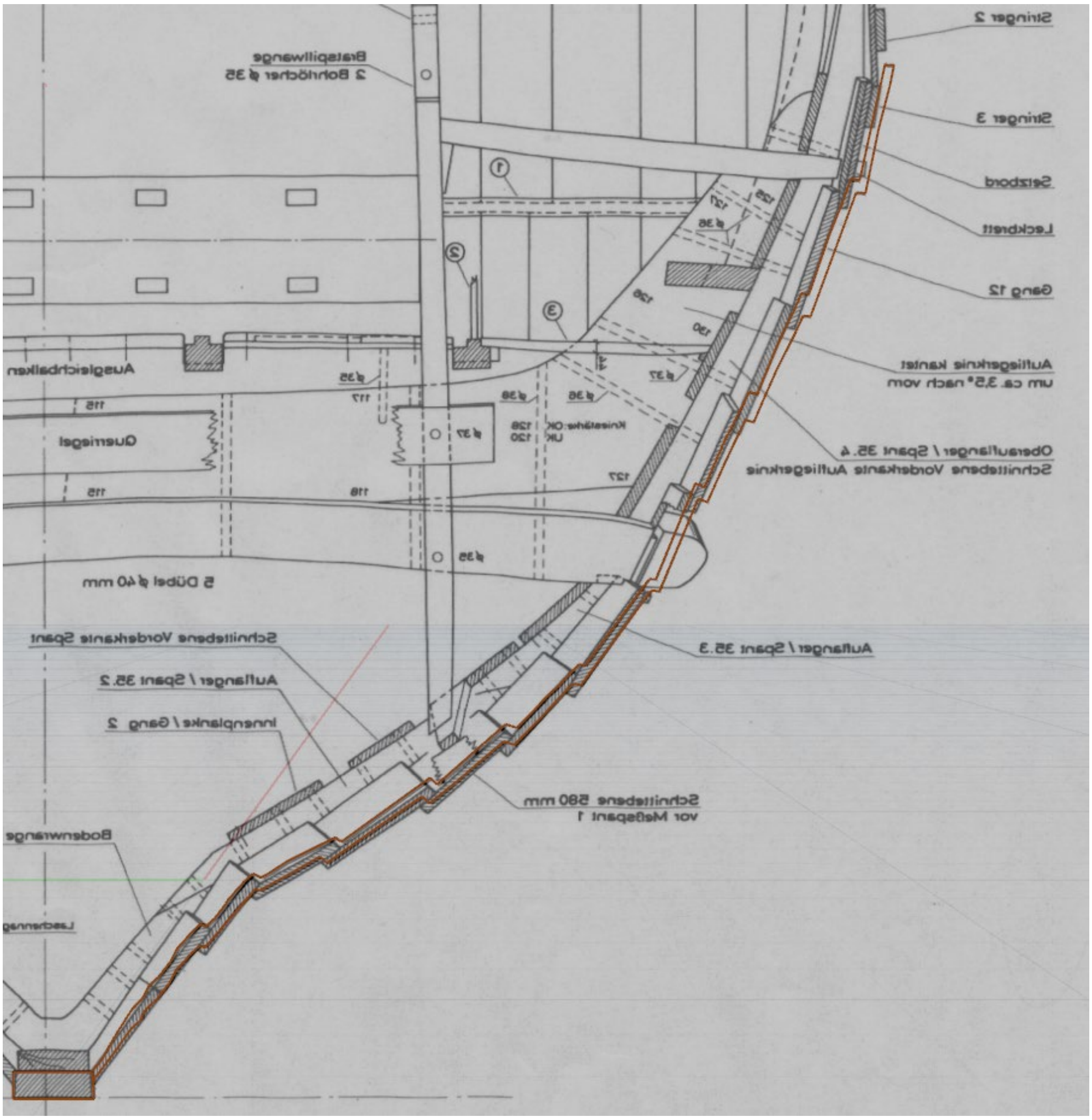


Figure 24 Section showing Body Plan hull shape (brown) at Frame 35

Hull shape derived from section drawings

When a set of digital strakes are lofted through the measurement points from the section drawings:

> frames 6,10,26 and 35 on Blatt 3; frame 13 (Blatt 34); frame 15 (Blatt 33); frame 19 (Blatt 32); frame 23 (Blatt 31); frame 30 (Blatt 30); and frame 29 (Blatt 29)

the longitudinal run of the strakes creates an extremely distorted unfair shape (Figure 25), especially in the region between frames 23 and 39 on the upper strakes from 6 to the wash board strake. It would therefore appear that the section drawings (Blatt 29 to 34) represent the "recovered" or "as found" shape of the timbers with little or no repair to distortion or deformation.

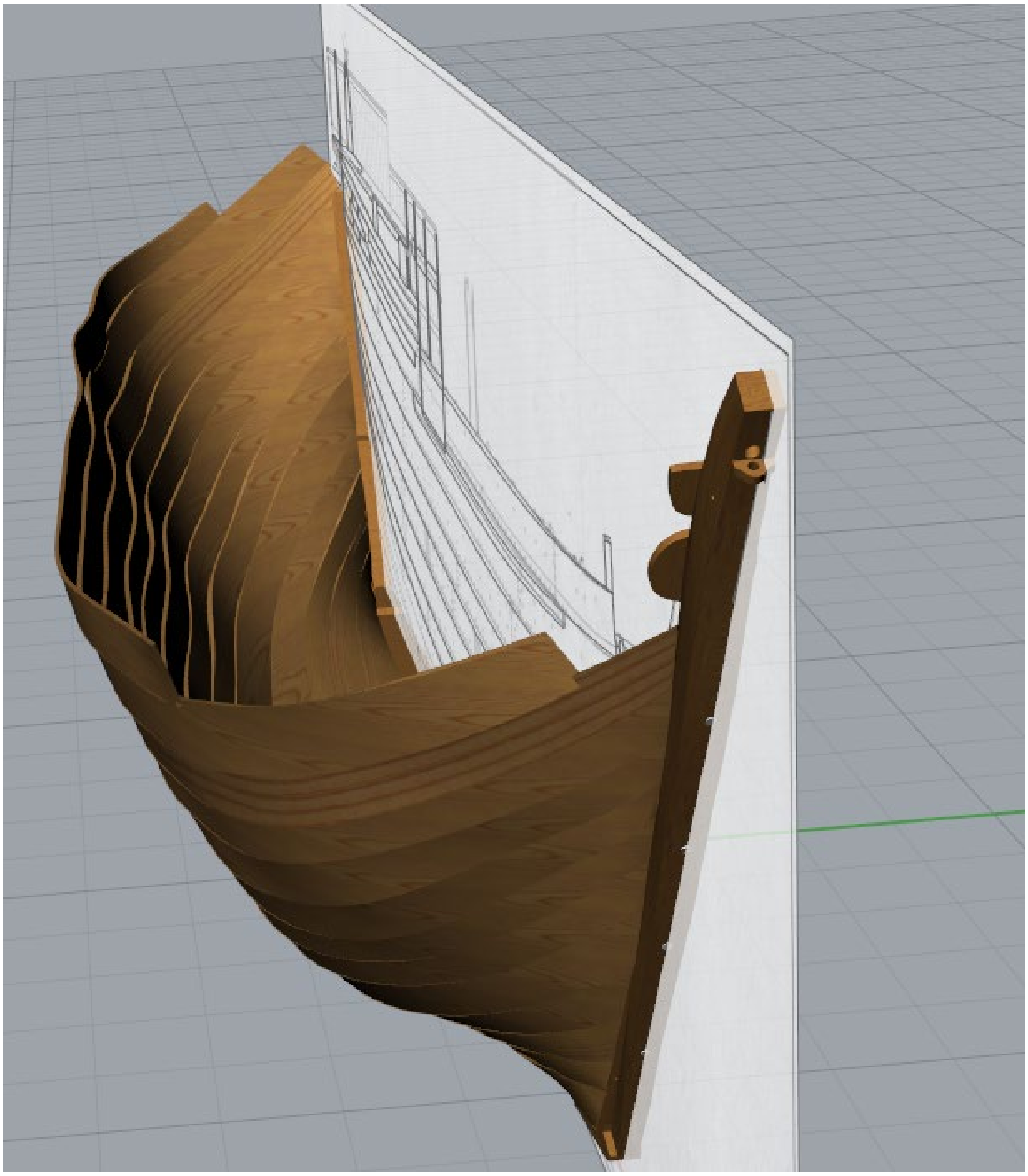


Figure 25 Digital strakes lofted through the measured points from the Section Drawings

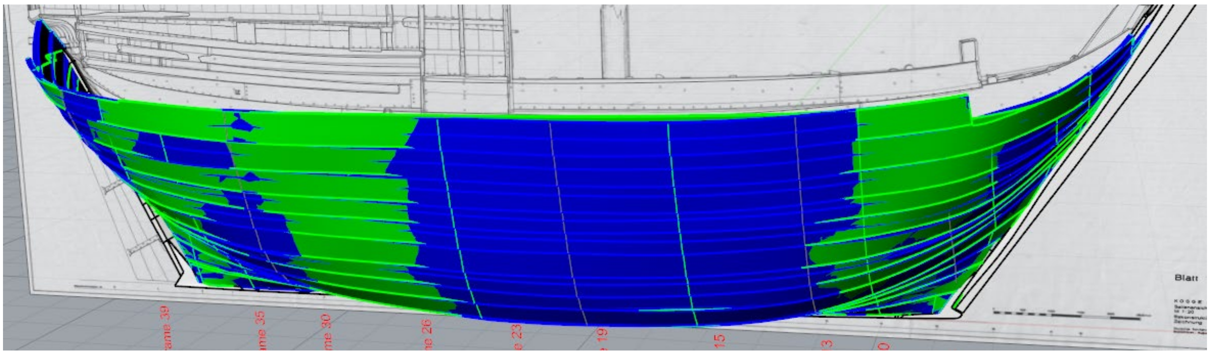


Figure 26 Body Plan Hull shape (green) overlaid on Frame Section hull shape (blue)

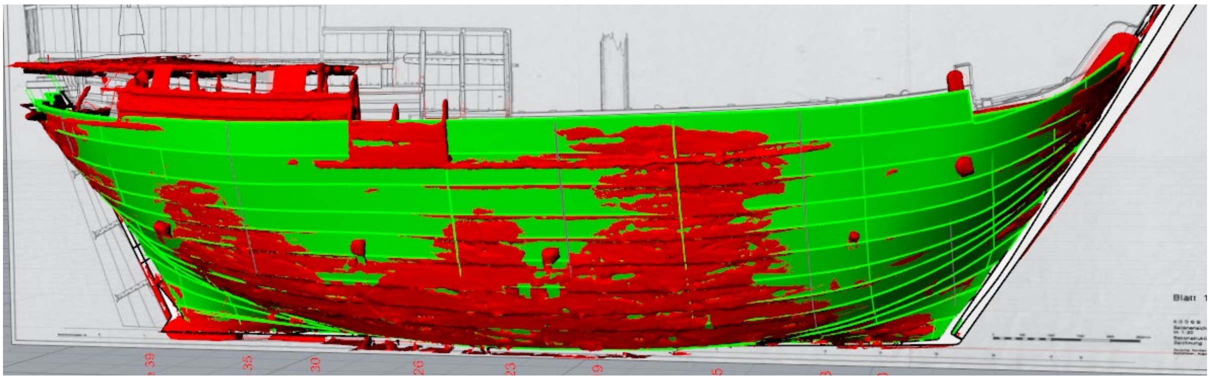


Figure 27 Body Plan Hull shape (green) with 3D scan 2014 (red) overlaid

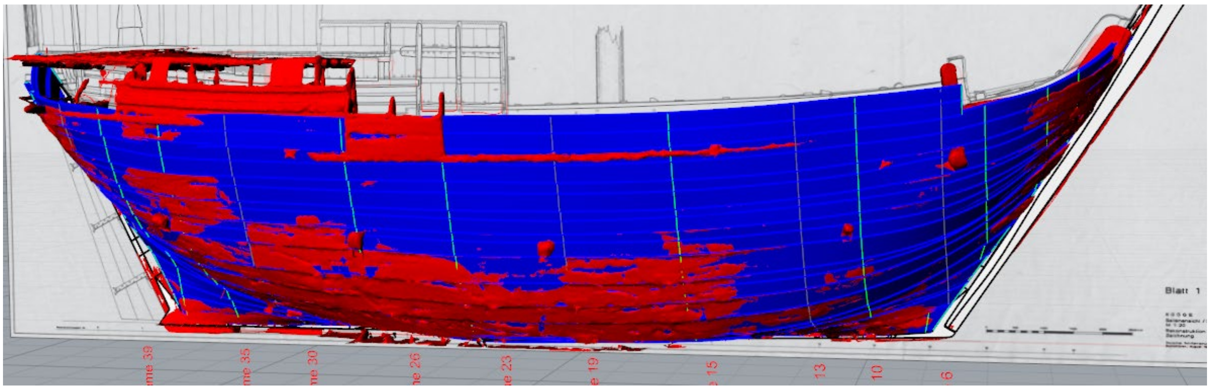


Figure 28 Frame Section Hull shape (blue) with 3D scan November 2014 (red) overlaid

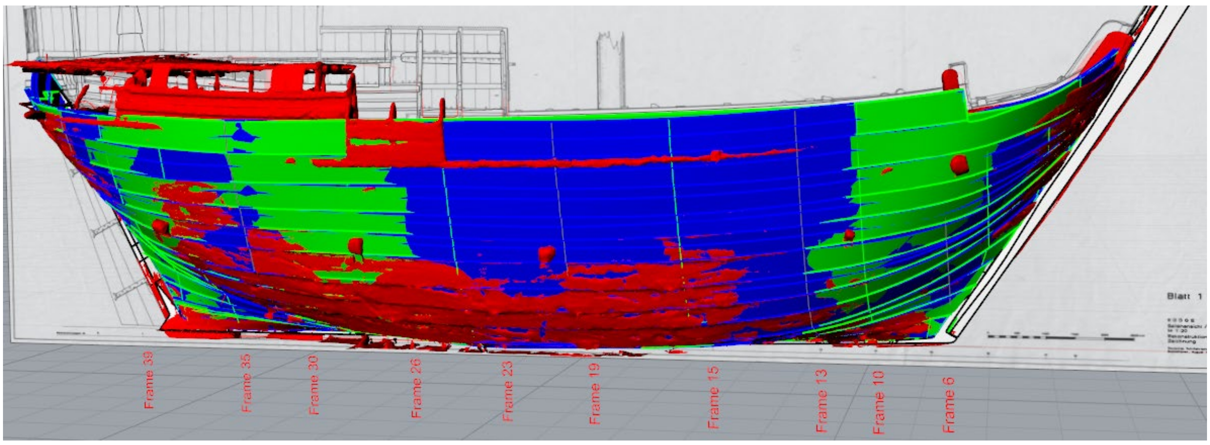


Figure 29 Body Plan Hull shape (green) with Frame Section Hull shape (blue) and 3D scan 2014 (red) overlaid

It is apparent from Figure 26 to Figure 29 that the two versions of the hull shape, the Body Plan (Blatt 35) hull shape, and the Frame Section (Blatt 3 and 29 to 33) hull shape, vary significantly in several areas along the length of the hull. In addition, the measurements from Table 6 show the discrepancies between the profile and section reconstruction drawings. Table 8 shows the height discrepancies between the body plan (Blatt 35) and the section reconstruction drawings (Blatt 3), and Figure 22 to Figure 24 shows the shape discrepancies between the same drawings.

All of the cross section drawings appear to have discrepancies in the heights when compared to the original photogrammetry survey drawing and the reconstructed profile (Blatt 1) and planking (Blatt 5) drawings. These discrepancies (Table 6) range from minus 39mm to plus 163mm.

H.4 Original Reconstruction drawing hull shape:

Blatt 1 Starboard Profile and Blatt 5 Starboard Planking would appear to be taken directly from the photogrammetry survey drawing of December 1989 judging by how the strake runs follow exactly to each other except in the central area from frame 19 aft to frame 28. As noted on Blatt 31 and 32, the floor timbers 19.1, and 23.1, had a turn of the bilge of circa 30 mm. Following installation, the ends of these timbers sank under the weight of the planks and timbers above.

The reconstructed profile drawing appears to have taken this issue into account, and all the strake runs in the area between frame 19 and 28 were raised (blue curves in Figure 30). However as the strake runs were only raised in this localised area, when the naturally fair strake runs (red curves in Figure 30) taken from the photogrammetry survey drawing are overlain on the reconstructed profile drawing it clearly illustrates the reverse curvature, or hump, in the area between frames 15 and 26.

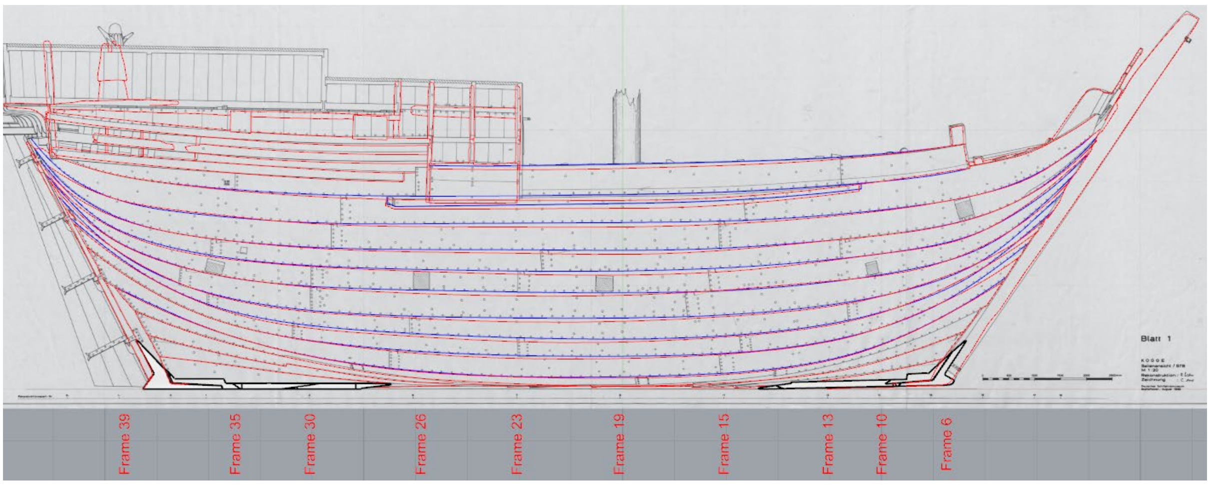


Figure 30 Locally distorted strake runs

Sagging Frames

On the drawing of frame 19 (Blatt 32) and frame 23 (Blatt 31) there is a note stating that timbers 19.1, and 23.1, the floor timbers, had a turn of the bilge of circa 30 mm. Following installation the ends of these timbers sank under the weight of the planks and timbers above.

Blatt 26 is a photogrammetric or stereoptic analysis of frames 9,16,19 and 23, and would appear to be a record of these frame shapes prior to installation and subsequent deformation under the weight of planking and frame timbers. Based on the recorded shape (Figure 31) of frame 23 from Blatt 26 the amount of sagging would appear to be closer to 40mm. When the 3D scan 2014 data is compared to this original frame shape (Figure 32) the hull would appear to have sunk by as much as 63 mm in the area of the third strake.

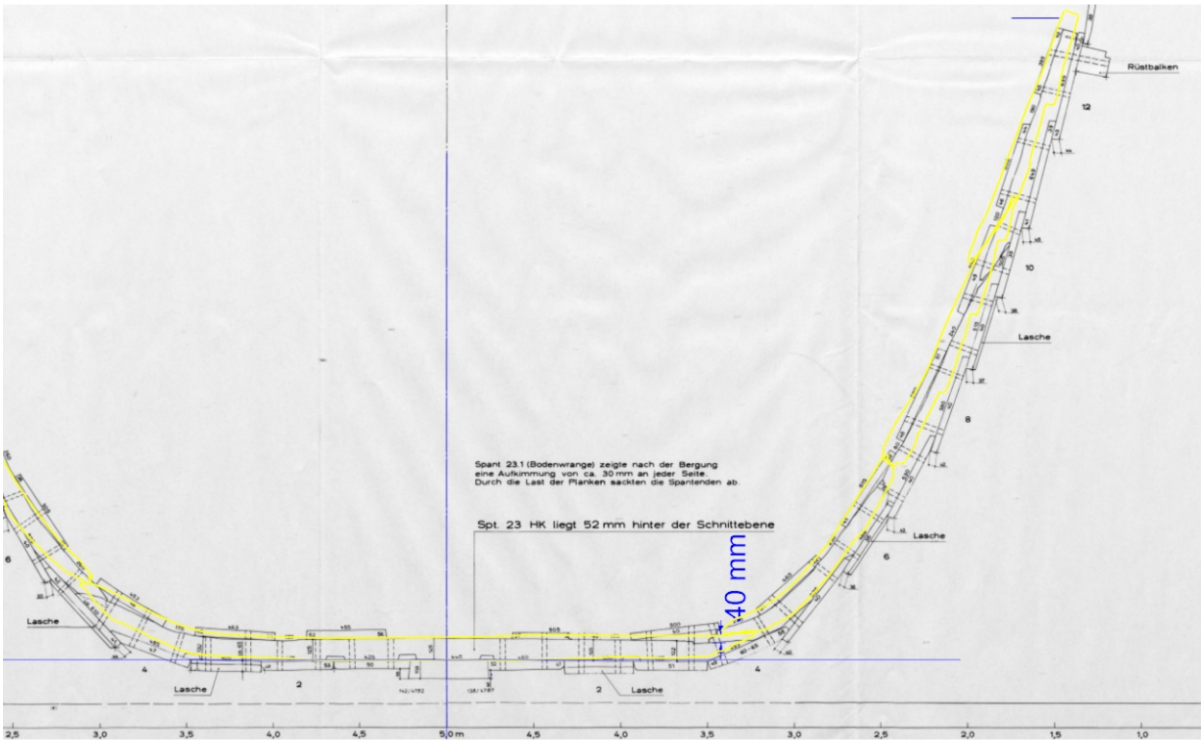


Figure 31 Recorded shape of Frame 23 (yellow) overlaid Section Drawing Blatt 31

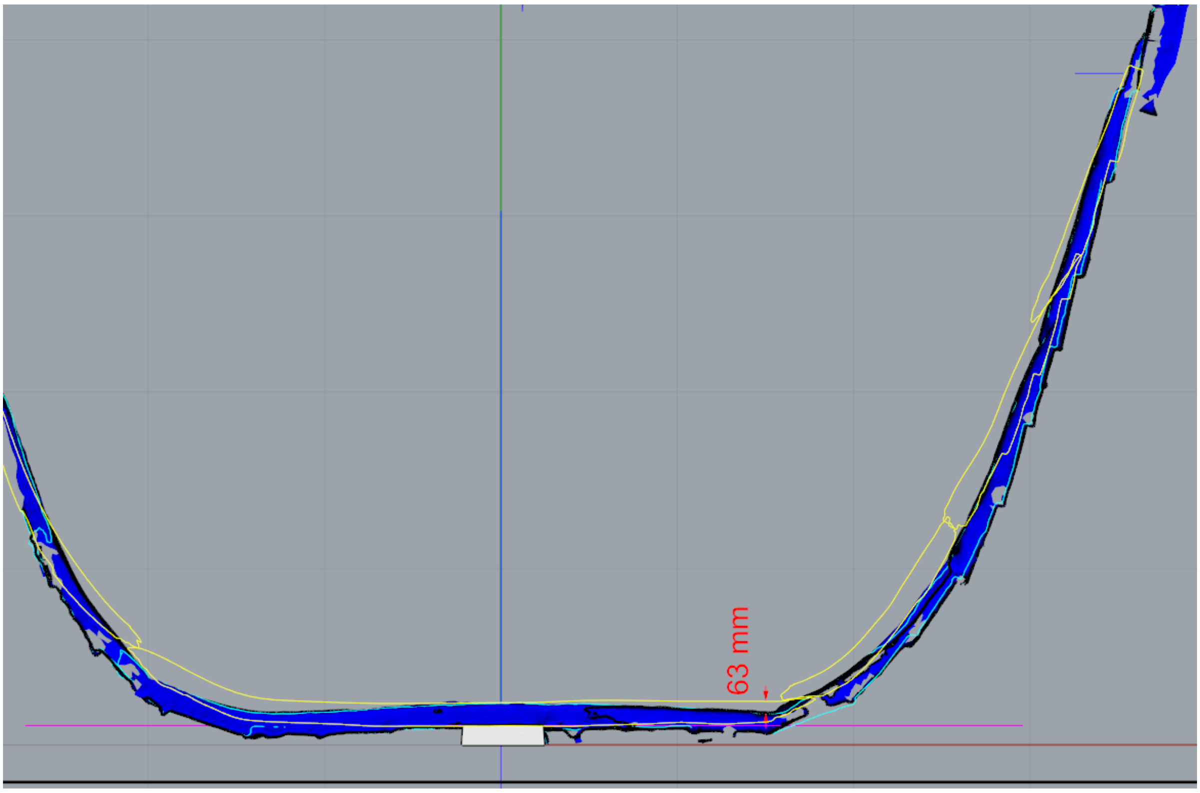


Figure 32 Recorded shape of Frame 23 (yellow) overlaid on 3D scan data

If this "as recorded" frame shape were to be used at Frame Station 19 it would potentially have the effect of raising strake 2 by 15 mm, strake 3 by 23 mm and strake 4 by up to 64 mm. The compounded result would have the effect of raising the top of the washboard strake by as much as 70 mm. This would also have the effect of increasing the deadrise by 1.3°.

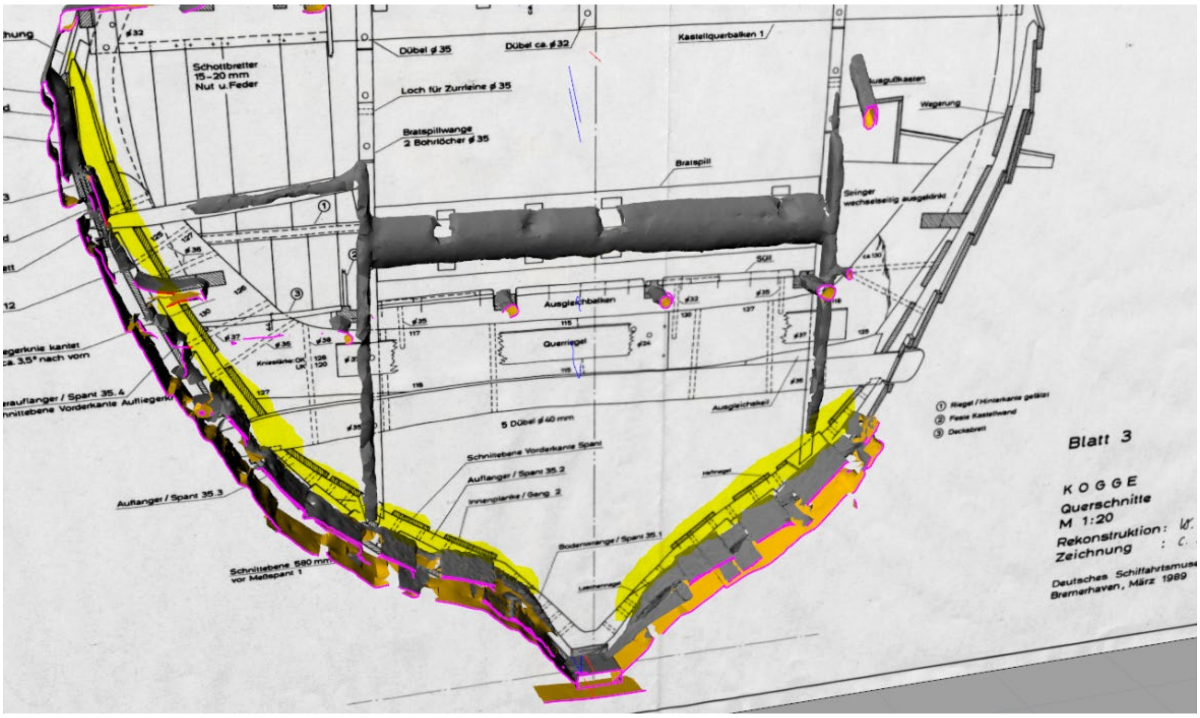


Figure 33 Drawing of Section at Frame 35 positioned over 2011 3D scan

Strake Runs

There appears to be an inconsistency with the strake runs as illustrated in the Starboard profile view (Blatt 1) and the Starboard planking view (Blatt 5). A digital 3D model of strake 9 (Figure 34) was created using the heights taken from the reconstructed drawings Blatt 1Starboard profile view, and Blatt 5 Starboard planking, and the widths used from Blatt 8 reconstructed framing plan. In both the profile (Blatt 1) and plan (Blatt 8) views, the curvature of this reconstructed strake appears as smooth fair curves.

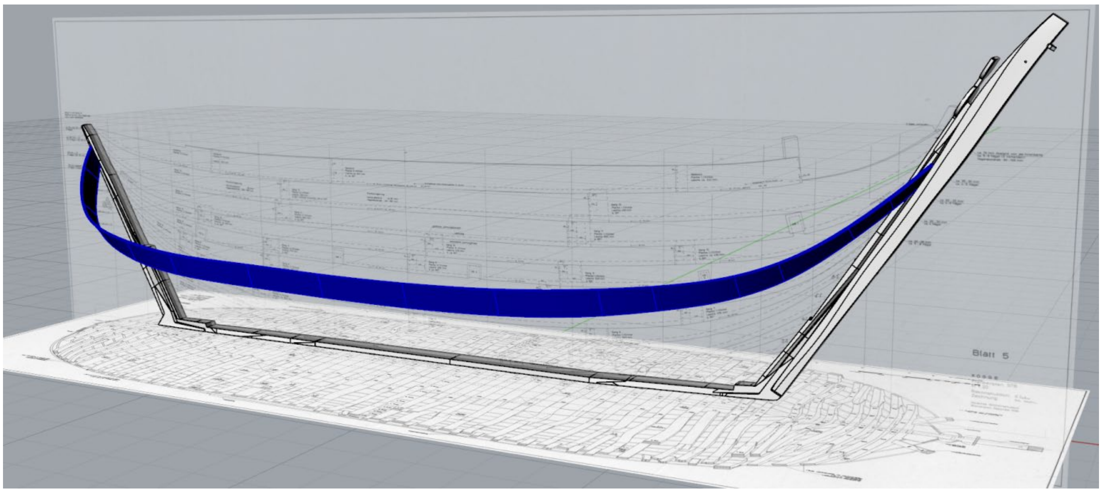


Figure 34 3D digital model of reconstructed strake 9

However the three dimensional strake created from these measurement points has an unusual distortion between frame 6 and the stem post. When this digital strake is compared to the 3D laser scan taken in November 2014 (Figure 35), the run of the digital strake follows that of the actual strake in the scan data, albeit some 165mm higher due to the current sagged hull shape, as far as frame 6 before stepping up significantly. It would appear that the curves drawn to represent the strake runs included a drafting error, and skipped or jumped a strake in this area when being lifted from the photogrammetry survey.

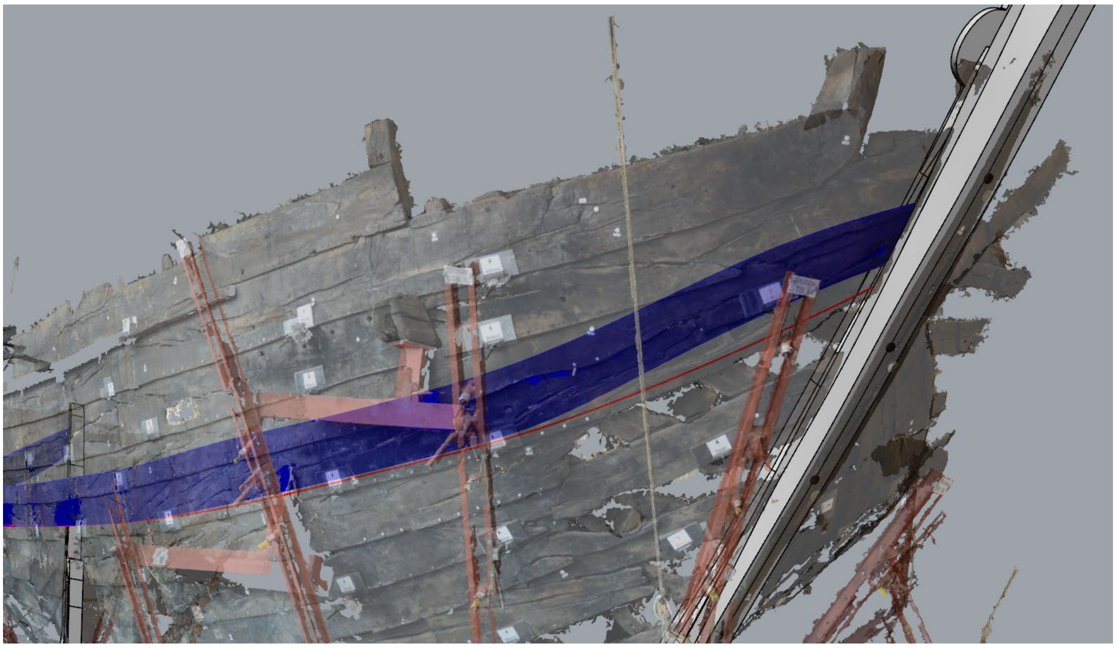


Figure 35 Comparing digital reconstructed strake to actual scan shape

An exact digital version of strake 9 (red in Figure 36) was then created from the November 2014 scan data and compared to the version (blue in Figure 36) created from the reconstructed profile drawings. This clearly illustrates the erroneous forward end of the reconstructed profile drawing strake, with the strake as originally drawn, measuring 117mm longer than the actual physical strake.

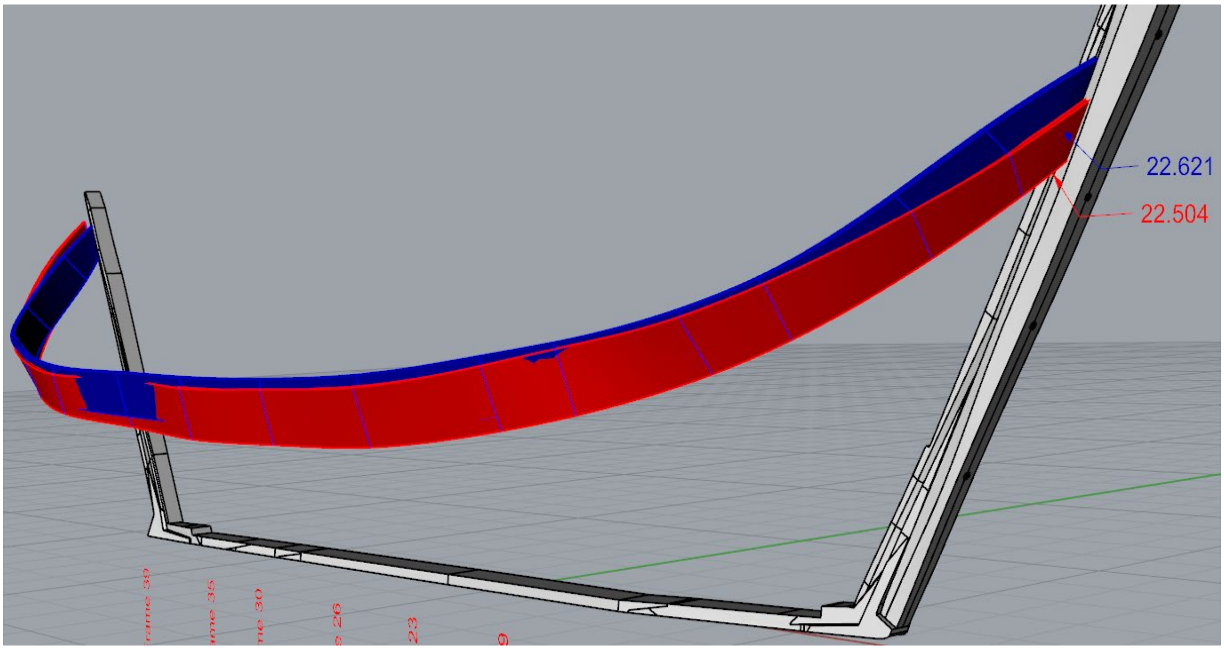


Figure 36 Comparing actual strake to reconstructed version

H.5 Stern Castle:

The starting point for the stern castle reconstruction (Figure 37) was the windlass cheeks over deck beam 5 and the recovered castle crossbeam 1. Two additional beams running parallel to the castle crossbeam and three crosspieces for each of the side decks (Lahn 1992, p.126).

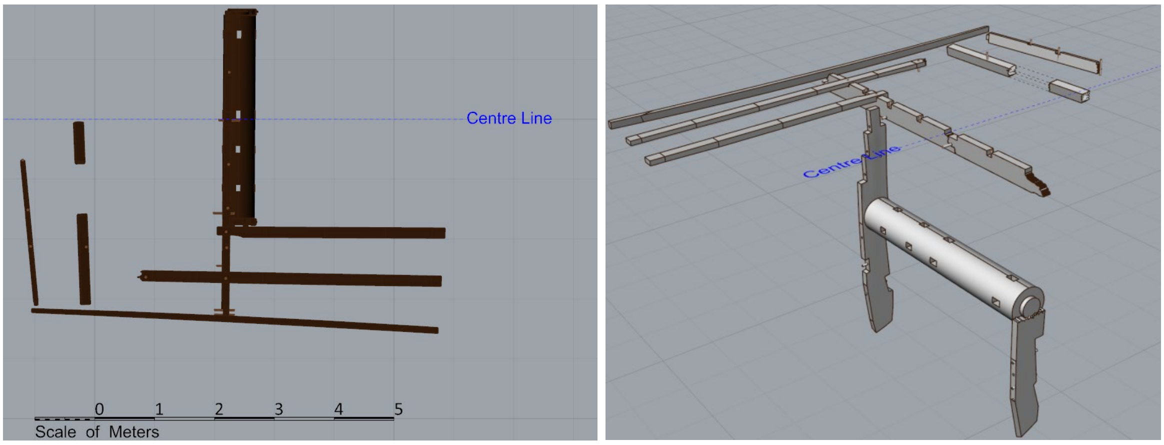


Figure 37 Recovered main structural elements of Stern Castle

Windlass:

The starboard windlass cheek and the windlass were recovered in their entirety, but only the lower half of the port windlass cheek was recovered. A rabbet containing a dowel hole on the lower starboard cheek, together with a corresponding dowel hole on the port cheek indicated the existence of a cross piece brace. The upper portion of the starboard cheek was mirrored to recreate the missing port segment (Figure 38).

The entire windlass assembly was securely fastened to crossbeam DB5 and its bevel knees with two dowels per side. A blind dowel hole 103mm deep was recorded on the starboard windlass cheek, located circa 86mm above the main deck surface, indicated the presence of some unexplained element.

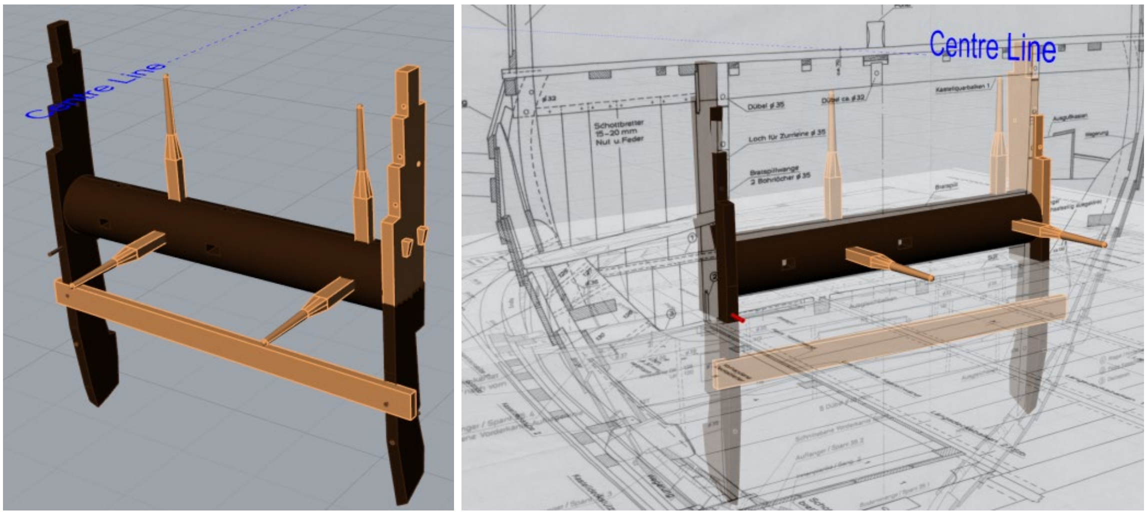


Figure 38 Reconstructed portions of windlass

Castle crossbeam 1:

Castle crossbeam number one is described by Lahn as being puzzling in that there is nothing unusual about the underside, but the topside, the surface of which sets the camber of the deck, is described as having an unusual 20mm upward projection in the otherwise straight line of the surface (Lahn 1992, p.129), which Lahn explained as a distortion. Lahn recreated this beam from its two partial fragments as a perfectly flat topped beam, which drooped by 52mm (0.4°) towards port (Figure 39).

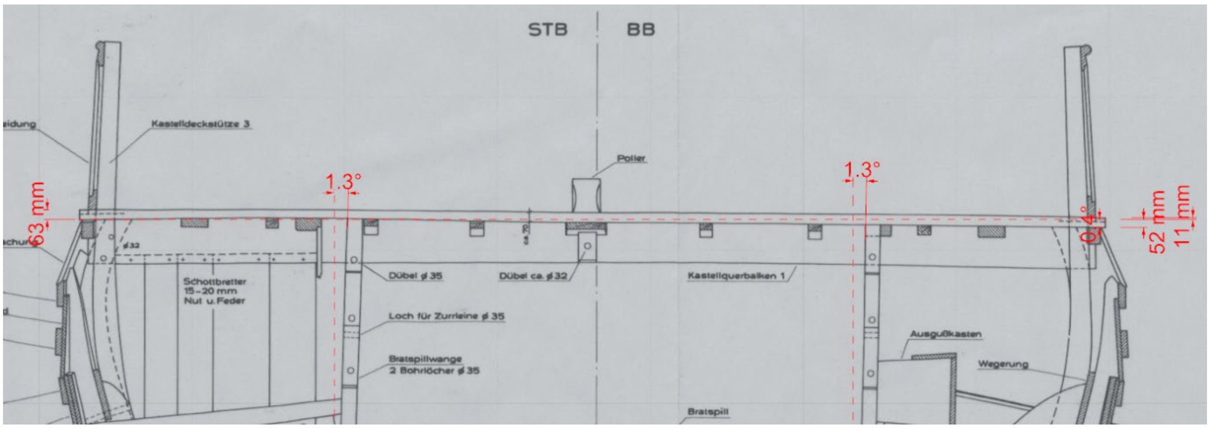


Figure 39 Castle crossbeam 1 fitted in-situ

Lahn states the carling beams were all let into castle crossbeam 1 to a depth such that the upper surfaces were flush (Lahn 1992, p.154). With the deck camber at the forward end determined by the upper surface of the castle crossbeam, the beam as reconstructed, being perfectly straight, results in no deck camber at the forward end. It should be noted that he already would have known at this stage in the reconstruction, that the main deck had been constructed with deck camber which measured 92mm. Therefore the stern castle deck, with its caulking to create a watertight roof over the enclosed spaces below, would be more than likely to have some degree of camber in order to reduce the possibility of standing water remaining on the surface.

The beam as reconstructed with its straight top and bottom surfaces (Figure 40) removes any possibility of deck camber in this area. The height of the beam as reconstructed is 22mm less at the missing port end, with little or no evidence to support this reduction, and no explanation given.

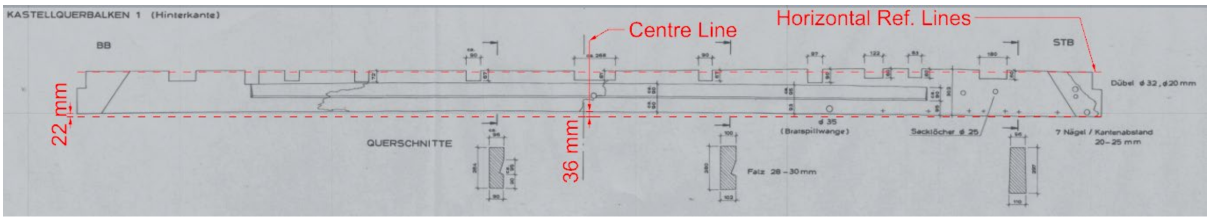


Figure 40 Reconstructed castle crossbeam 1

Channel wale and stanchions

In order to continue with the placement of the stern castle elements, the channel wale stanchions were next fitted to the reconstruction. Of the six stanchions, the three outer stanchions and two inner stanchions were recovered (Figure 41), as well as two of the three crosspieces and the two lower boards installed to protect the shrouds.

The castle wall which was completely destroyed, was reconstructed based on small fragments and nail holes. It is estimated to have been circa 600mm wide, 25 - 27mm thick and running from the aft channel wale to frame 36. The castle wall was clinker fastened to the washboard strake with a landing of circa 60mm. A ceiling strake made up of two planks was fastened internally, and was considered to be non structural on the basis of having mainly nail fastenings.

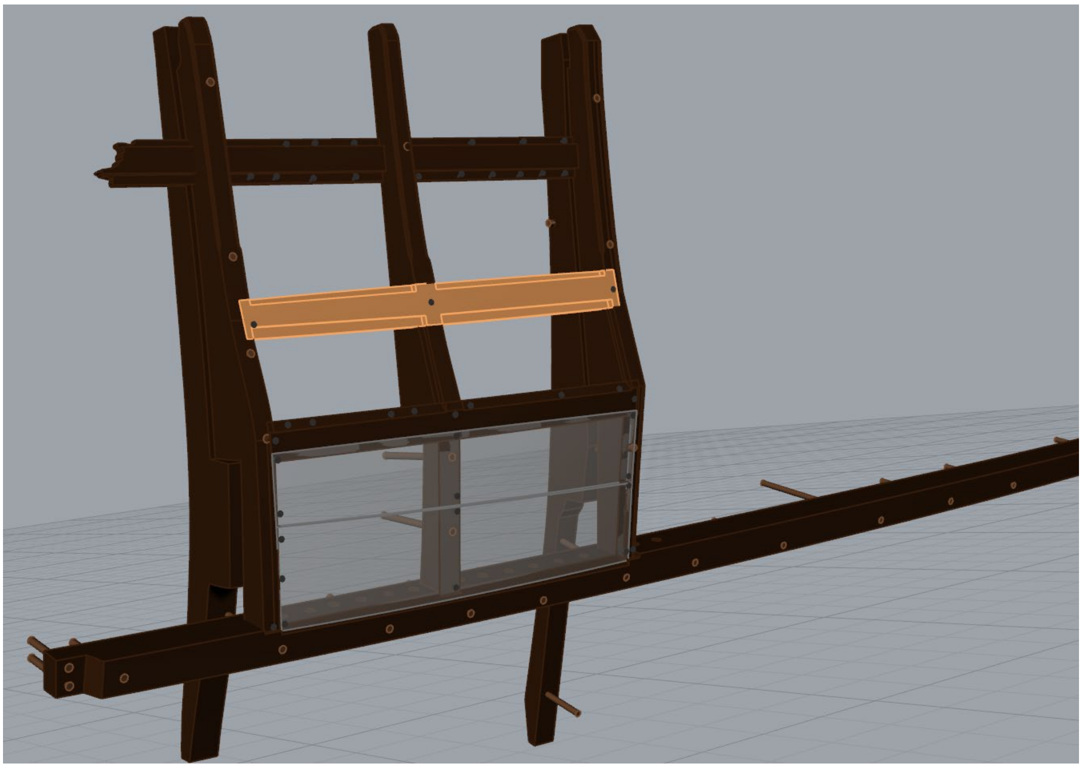


Figure 41 Channel wale and stanchions

Castle-deck support 1:

Castle deck support 1 located just aft of the inner channel wale stanchion, was fitted to the shape of the inner planks (stringers) and the ceiling plank. It was dowelled to the inner and outer planks, with its head protruding above the castle deck level by 620mm. With it's through hull fastenings, this element, together with the channel stanchions, form a definitive starting point for the stern castle reconstruction.

Castle-deck supports 2 and 3:

Castle deck support 2 which was lost, stood 1.32m aft of the first support, with its base nailed to the afterbody stringer. It was not dowelled through the hull, and its height above deck was derived from the height of castle deck support 5.

This recovered broken castle deck support 3 is noted as resting against the aft face of deck beam five bevel knee, with its base resting on the afterbody stringer, and its outer surface resting against the inner and ceiling planks, and sloping considerably (3°) towards the fore (Lahn 1992, p.138). Lahn states that as this support was broken it is not known how far it extended above the deck (ibid, p 135), but notes on p.138 that the head of this support including the reconstructed rail, extends 1.15m above the deck (Figure 42).

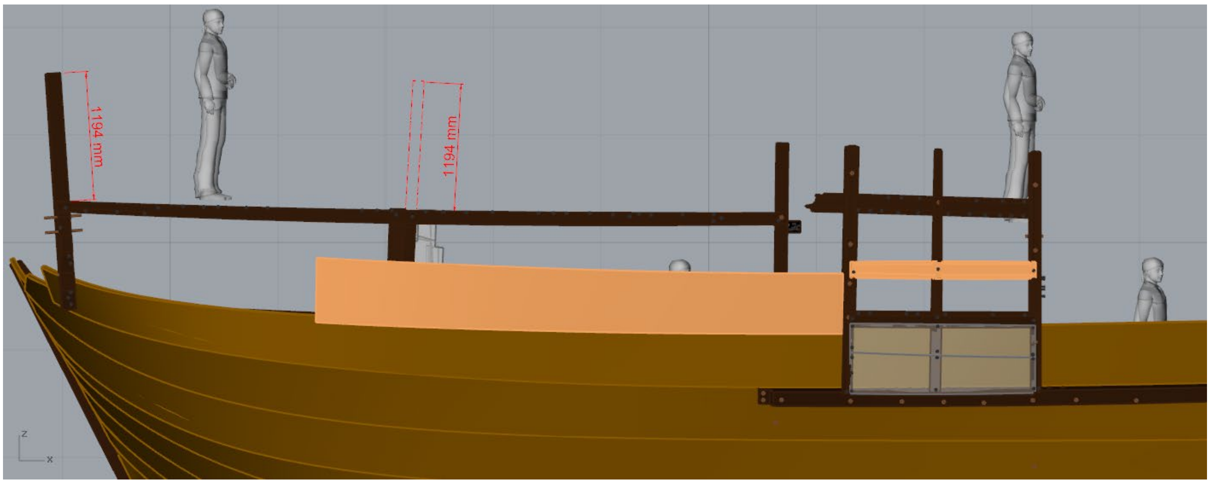


Figure 42 Castle deck supports

Castle deck support 3 is illustrated in the cross section drawing (Figure 43) taken at frame 35 (Blatt 3: Spant 35 mit Querbalken DB 5). However this illustration shows the top of castle deck support 3 located 1.094m above the deck. With the castle deck support located circa 90mm behind the position of this section illustration, and with the afterbody stringer on which the support sits, rising as it runs aft, the support should be positioned higher than shown in the illustration.

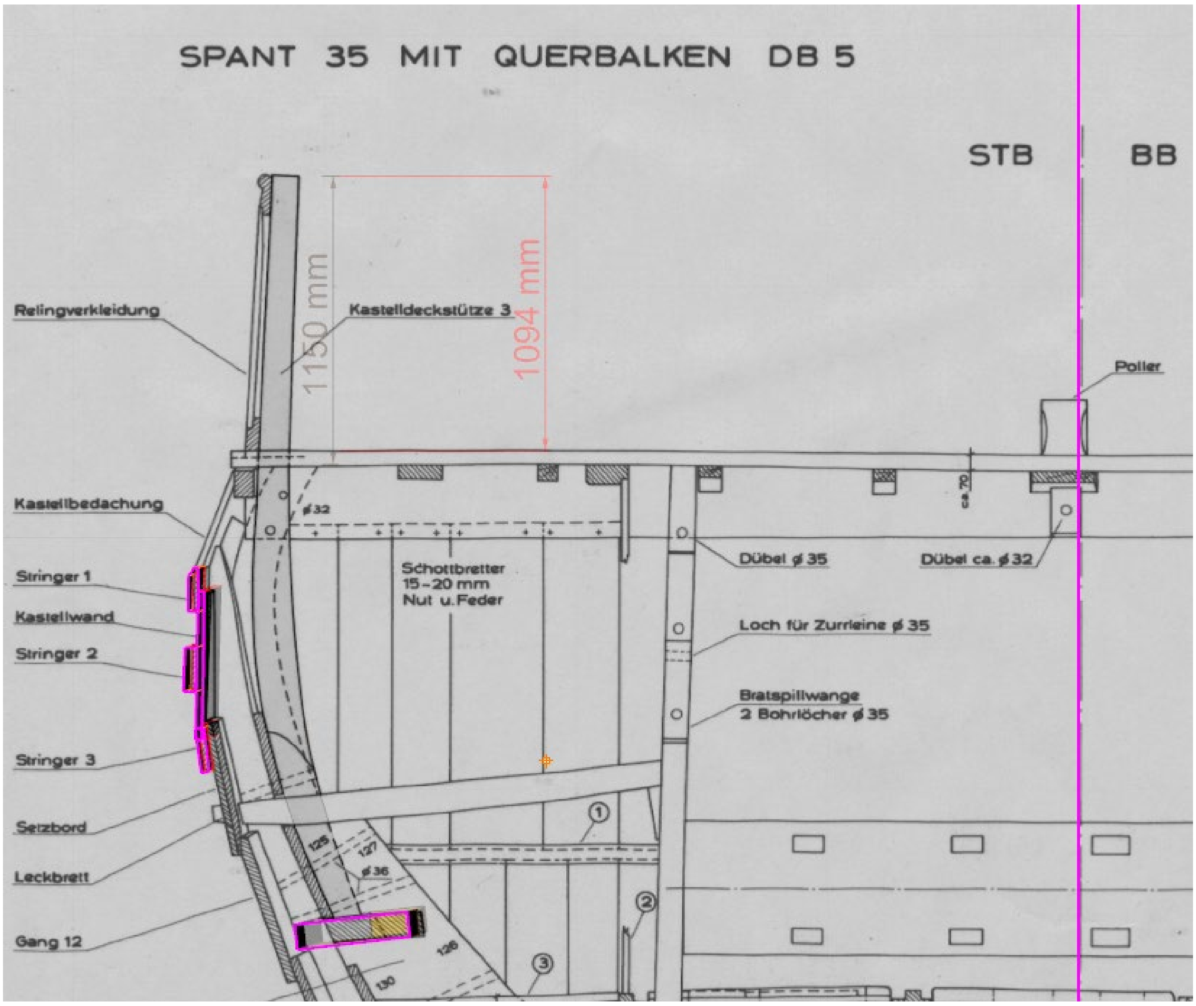


Figure 43 Castle deck support 3

Castle-deck support 4:

Castle-deck support 4 was lost, but its position and cross sectional shape were estimated based on the cut-out at deck level, with its base resting in a mortice in lower castle crossbeam 2 resulting in an estimated height of 2.18m and dimensions of 150mm wide (sided) by 140mm thick (moulded). The relationship between the deck cut-out and lower castle crossbeam 2 results in a 7° tilt towards the fore.

Castle-deck support 5:

Castle-deck support 5 and the starboard half of the associated upper castle crossbeam number three were the only elements recovered of the stern framework. Three half-lap joints were let into the outer face to take the castle outer stringers, as well as another half-lap rabbet to accommodate the castle-deck outer beam. The inner face has two mortises to accommodate the recovered upper castle support beam, and the missing lower castle support beam, as well as a rabbet to house a hanging knee supporting the missing lower castle support beam, forming the stern framework. The aft face has a rabbet with two dowel holes to accommodate a hanging knee to support the cantilevered aft portion of the castle deck.

Lahn states castle-deck support 5, was positioned in precise alignment with the three forward castle deck supports (Lahn 1992, p.141). However with castle deck supports 2 and 4 lost, then only castle deck support 1, and the broken lower end of castle deck support 3 remained (Figure 44). Therefore in aligning support 5 with the three forward supports, he was using one existing support and two extrapolated positions.

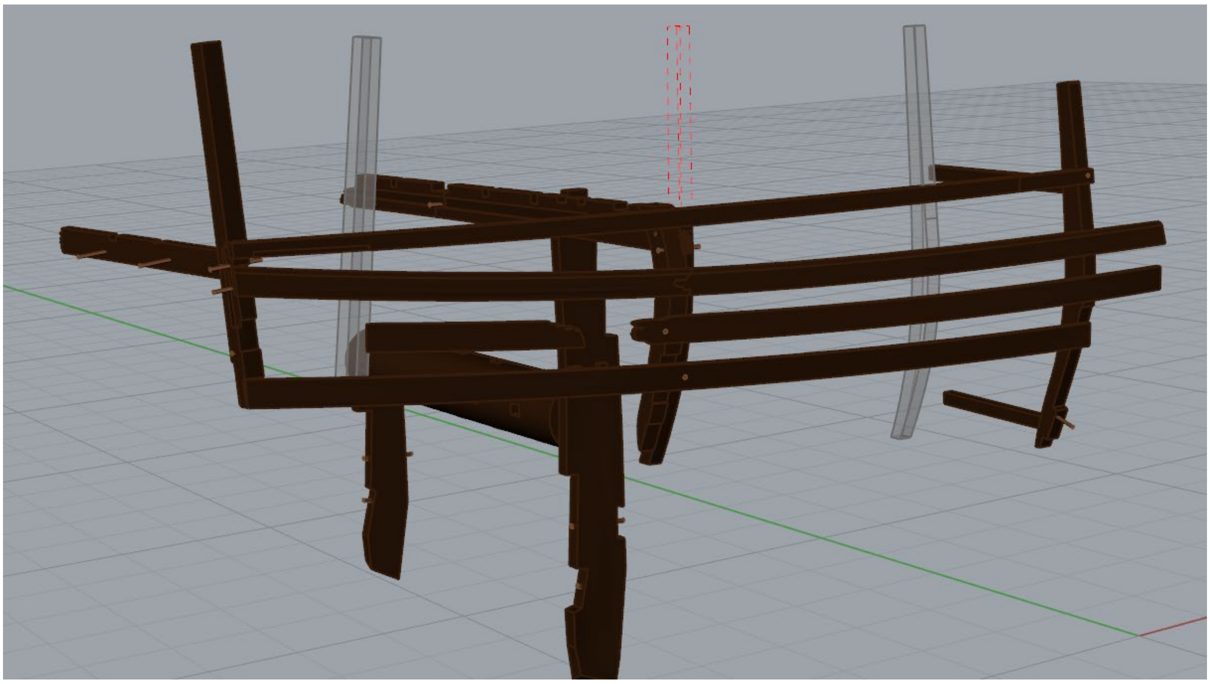


Figure 44 Positioning castle deck support 5

Castle-deck outer beam:

The starboard outer deck beam was recovered in its entirety with the exception of the short forward scarphed end section. This beam was nailed and doweled to castle deck support 1, rested in the rabbet let into the end of castle crossbeam 1, nailed to the castle deck support 3, with nails recorded corresponding to the positions of the missing castle supports 2 and 4.

Lahn notes that when this starboard outer castle beam was installed, it ran an absolutely straight course, bending neither upward, downward nor side to side (Lahn 1992, p.142). If the aft support at castle deck support 5 was positioned in precise alignment with the other supports there could be no other result for the positioning of this beam.

Lower crossbeam 2:

The middle of the beam was supported by a sturdy 167mm wide by 113mm thick vertical support pillar. As the recovered portion of the beam passed the midship line, it is possible to measure the camber as 39mm. From the drawing (Blatt 14) lower crossbeam 2 was installed drooping to port by 35mm (0.3°), with the port end some 330mm further aft than the starboard end.

Upper crossbeam 2:

Two badly eroded fragments of the coniferous upper crossbeam 2 were recovered, measuring circa 140mm by 145mm, but were estimated to be potentially 5mm larger in both dimensions. The ends of this crossbeam were let into a 70mm deep mortise in the missing castle-deck support 4. In the reconstruction this beam was recreated as a straight parallel sided beam, which drooped by 68mm towards port.

The stern framework:

Lower crossbeam 3:

No part of this beam was recovered, from the impressions remaining around the mortice on the inside face of castle deck support 5, the tenoned lower crossbeam was 143mm wide and 150mm high at the connection to the vertical member. The beam was assumed to be 240mm wide in the vicinity of the sternpost in order to support the planks on the inside and evidence for vertical reinforcement supports is explained by the presence of two dowel holes in the upper beam (Lahn 1992, p.141). A rabbet in the aft inside face of castle deck support 5 indicated the existence of a hanging knee to support the crossbeam.

Upper crossbeam 3:

Upper crossbeam 3 receives no written description in Lahn's report, other than to mention the two dowel holes which were presumed to accommodate the vertical support pillars in the framework. Only the starboard portion (circa 40%) was recovered. Dimensions noted on the drawing (Blatt 14) state 170mm by 50mm for this beam, with a doweled tennon set into the corresponding mortice in castle deck support 5.

From the drawing (Blatt 14) lower crossbeam 3 was installed perfectly level, while the upper crossbeam 3 was installed drooping to port by 28mm (0.2°).

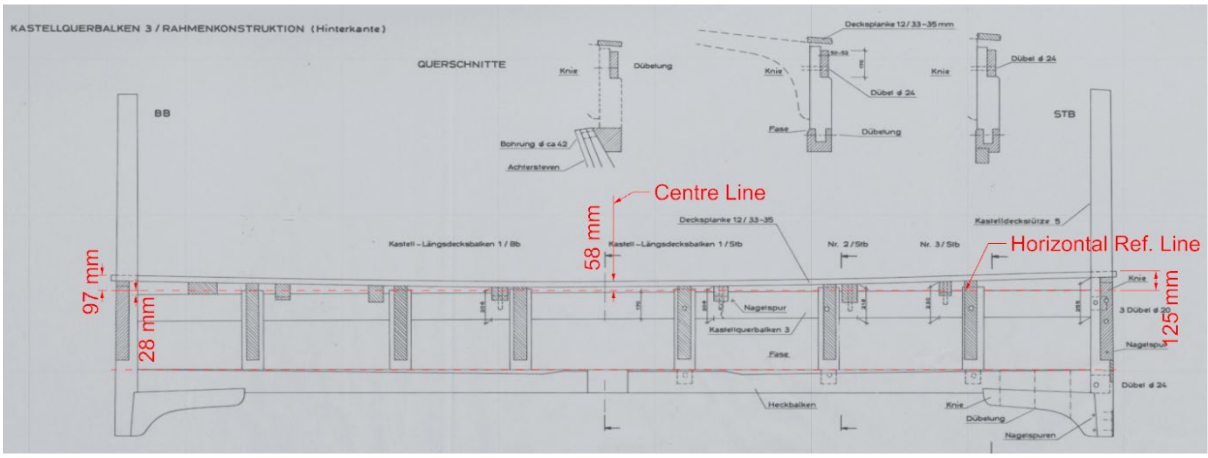


Figure 45 The stern framework

In discussing the stern framework (Figure 45) Lahn states "The slight downward slope of upper crossbeam 3 towards port corresponds to the position of castle crossbeam 1 further forward. The entire castle deck presumably sloped downward towards port by 40mm." Lahn also notes the hole at the head of the sternpost is too high for a bolted connection between it and lower crossbeam 3.

Measurements taken by Lahn indicate the port corner of the framework would have been circa 610mm further aft than the starboard corner and as such the framework position differs substantially in regard to the other crossbeams (Lahn 1992, p.141).

Additionally the entire framework is tilted aft by circa 4°, although no reason or explanation is stated for this, while the stanchion at crossbeam 2 is tilted circa 7° to the fore as a result of lying against the face of crossbeam DB5, and the stanchion at crossbeam 1 is tilted 4° to the fore.

Longitudinal deck beams (carlings):

As well as the longitudinal outer deck beam already installed, four of the main castle longitudinal deck beams were recovered, as well as two from the starboard side deck. The transverse positions for these carling beams was predetermined by the surviving eight rebated cut-outs in the top of castle crossbeam 1 at the fore and the three rebated cut-outs in castle crossbeam 3 to the rear.

The four recovered longitudinal main castle deck beams are described by Lahn as increasing in length from starboard to port, with measurements listed in the report as being 4.24m, 4.43m, 4.53m and 4.60m (Lahn 1992, p.149). These measurements are reconstructed lengths, and these increasing lengths are used as part of the justification for the trapezoidal plan form of the stern castle. The actual measured lengths of the recovered deck beams are 4.22m, 4.27m, 4.42m and 4.25m.

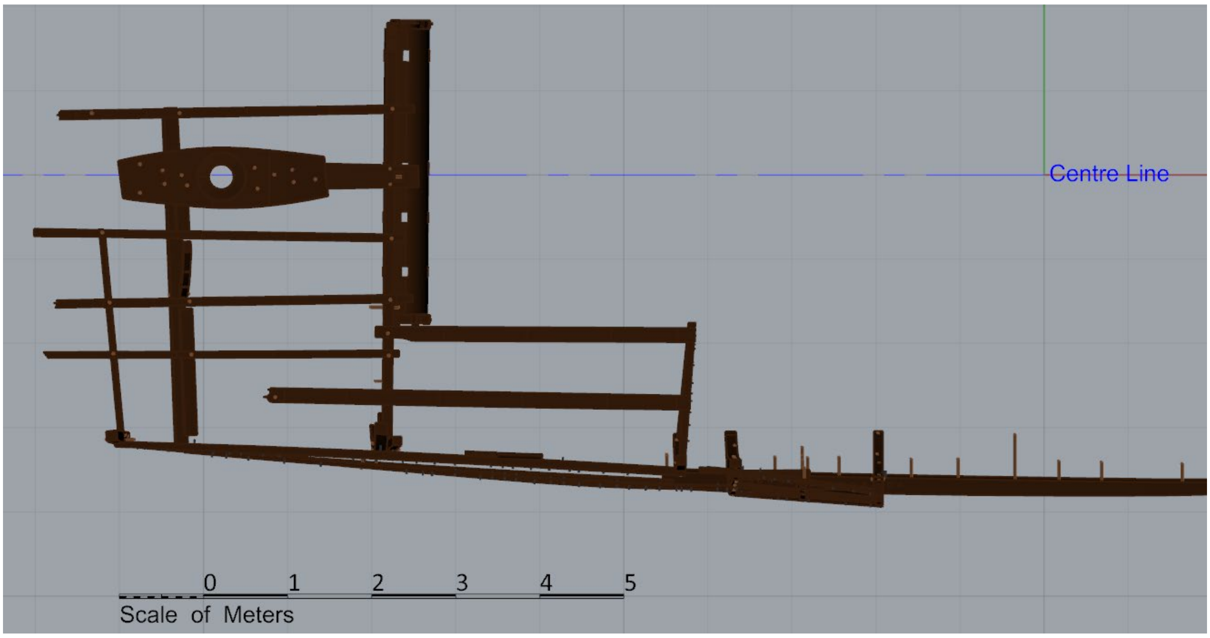
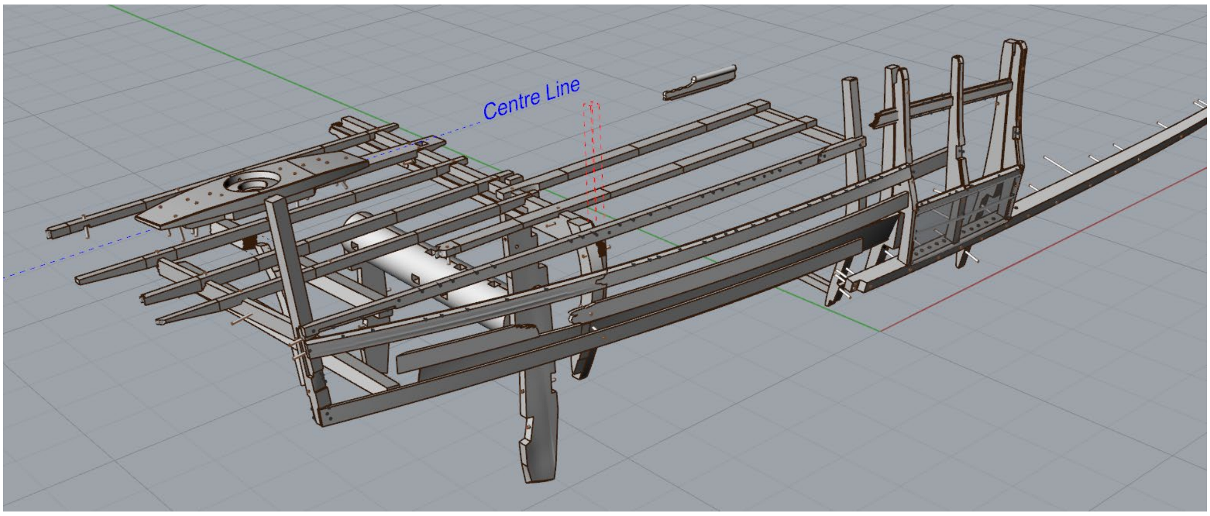


Figure 46 Recovered structural elements of the Stern Castle



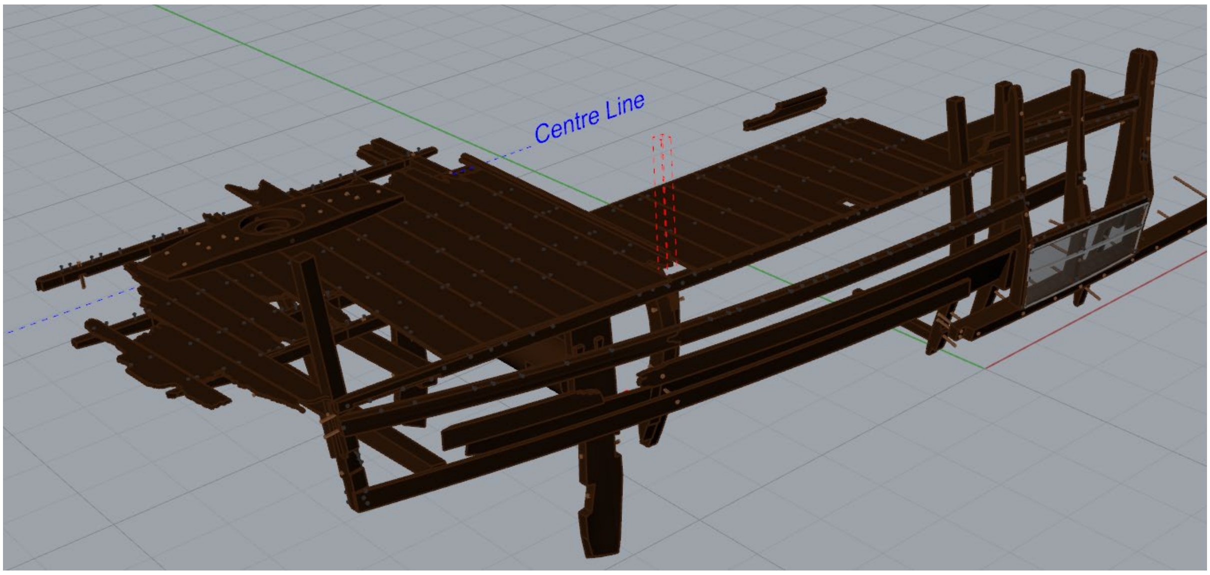


Figure 47 The recovered stern castle with deck planks

Handrail:

The only parts recovered and interpreted as being parts of a handrail were a short piece of the handrail, a knee, and two rail sections (Lahn 1992, p.126). The basis for the reconstruction was thus limited to these four pieces and contemporary book illustrations.

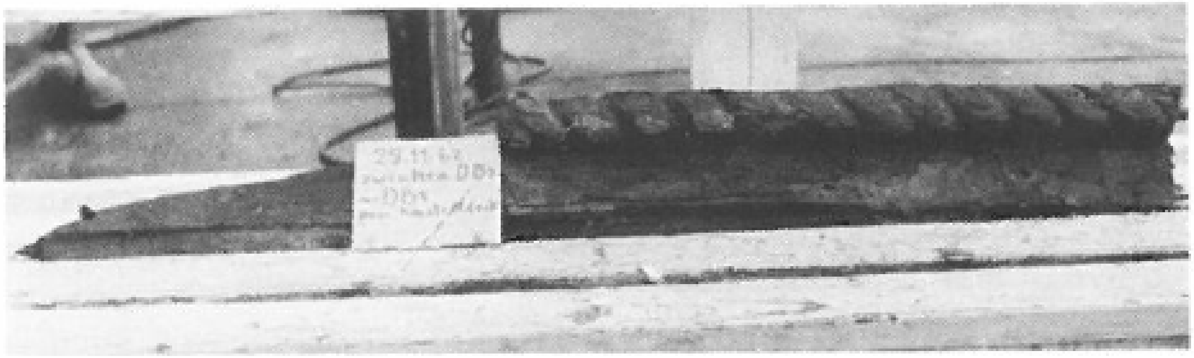


Figure 48 Recovered small portion of carved handrail (Photo K. Schierholz/Focke-Museum)

H.6 Reconstructed Stern Castle

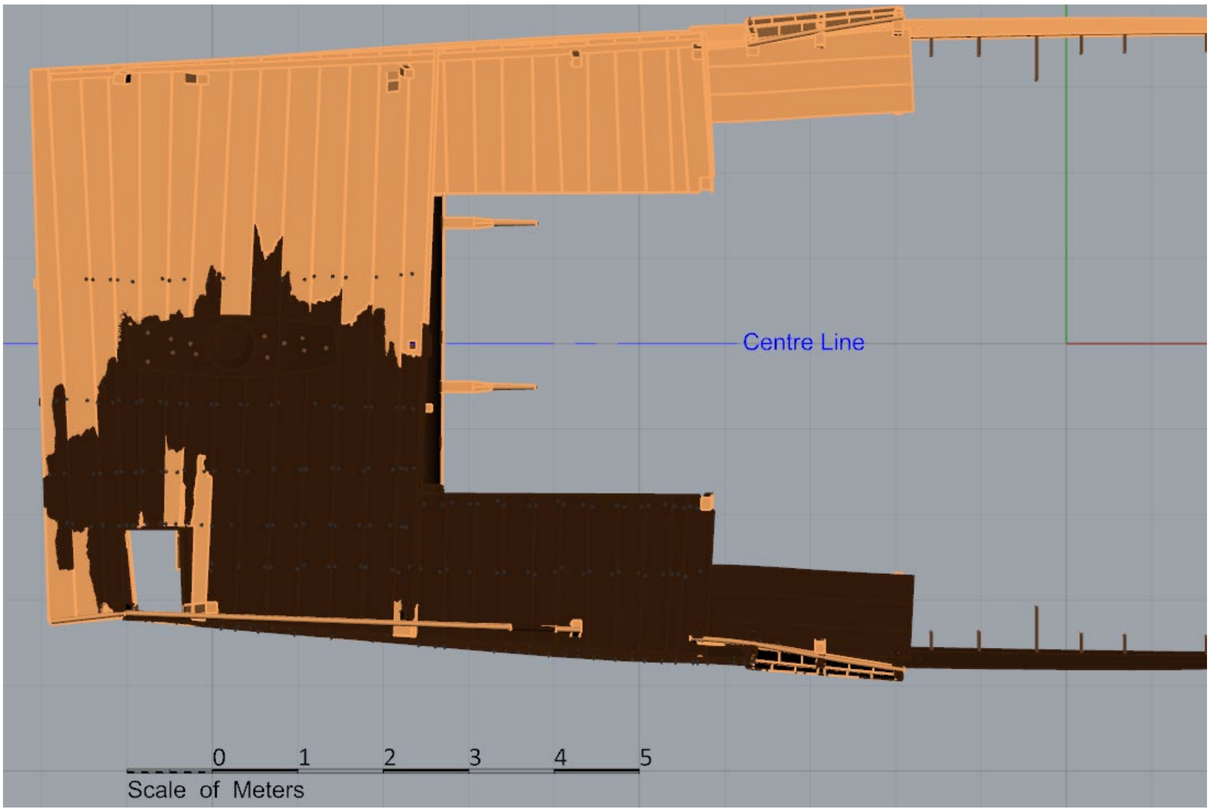


Figure 49 Plan view of the reconstructed stern castle

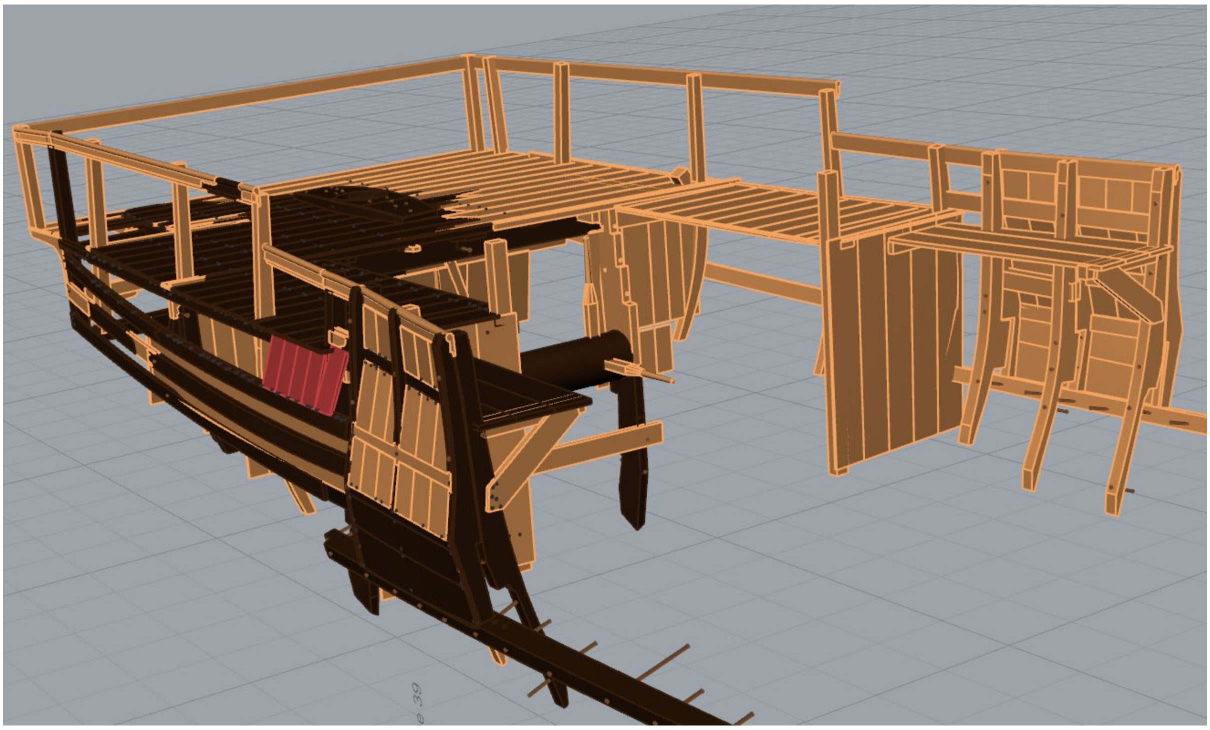


Figure 50 The reconstructed Stern Castle

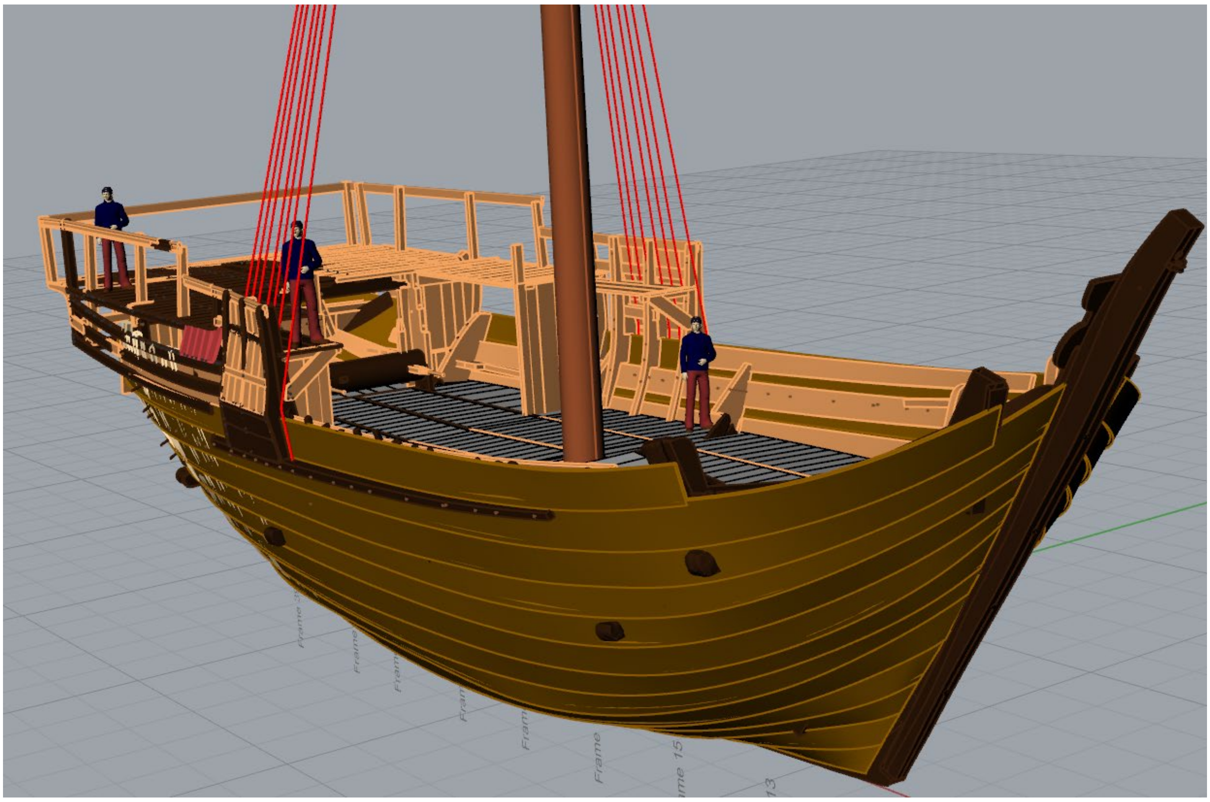


Figure 51 Digital model of the Lahn Reconstruction

H.7 Summary of the Lahn Reconstruction:

With all of the drawings dating from 1984 to 1990 it would appear these drawings were created or edited after the ship reconstruction process was completed in 1979. It appears that the reconstruction drawings were created based on the process of re-assembling the cog hull. Lahn notes that when the reconstruction began in early 1972, the process commenced with an immense number of cog parts, with the reference points being some drawings made by Lahn and photos taken during salvage operations. The individual parts were laid out in the gallery, divided according to characteristics which indicated their position within the ship. Salvage conditions meant it was not always possible to be decisive, with only 8% of the starboard side parts reliably labelled. For many elements an incredible number of fragments had to be re-assembled, and Lahn states these were firmly fixed together to form an original part, prior to insertion into the hull (Kiedel & Schnall 1989, p.33), the question must be asked, how was the original form and shape of these parts known or recreated.

Modern three dimensional modelling and analysis techniques as developed during the Drogheda boat reconstruction (Tanner 2013a), further refined and developed during projects such as the Newport Medieval Ship (Jones et al. 2013; Tanner 2013b), and the re-analysis of the Poole Iron Age logboat (Tanner 2017). The accuracy of this digital modelling approach has been set out in the forthcoming paper 3D Scanning, Contact Digitising and Advanced 3D Digital Modelling for the reconstruction and Analysis of Boats and Ships (Tanner 2016).

Recreating the Lahn reconstruction as a digital 3D model (Figure 51) has shown the interrelationship of the many constituent components, as well as that of the published drawings, has highlighted some of the issues which had to be considered and overcome during the initial reconstruction of the many fragmented parts of the recovered ship and also highlighted certain inconsistencies.

In discussing recovered elements, Lahn typically describes the element in great detail, including dimensions, presence or lack of sapwood, number and position of fastening holes, and any other relevant features. However when it comes to discussing these elements being fitted, he often switches to a hypothetical mode, describing in detail how the element was fastened using either a dowel or nail to the mating dowel or nail hole in the related existing element at one end, then describing how the element was fastened to the unrecovered supporting element at the opposing end in the same level of detail.

Consequently with many of the elements, and more specifically the fastenings shown on the drawings, it is difficult or impossible to determine whether or not these are original components, or items recreated by the reconstructor. An example of this can be seen in Blatt 14 which clearly illustrates the recorded features of castle deck support 5, including overall dimensions, size and location of rabbets, positions of nail and dowel fixings. However the same drawing clearly shows (Figure 52), in precisely the same format and style, the position and size of elements, such as lower crossbeam 3, complete with tenons and dowels, as well as the expanded width of this beam in order to mate with the sternpost, even when these elements were not recovered, or no real evidence exists.

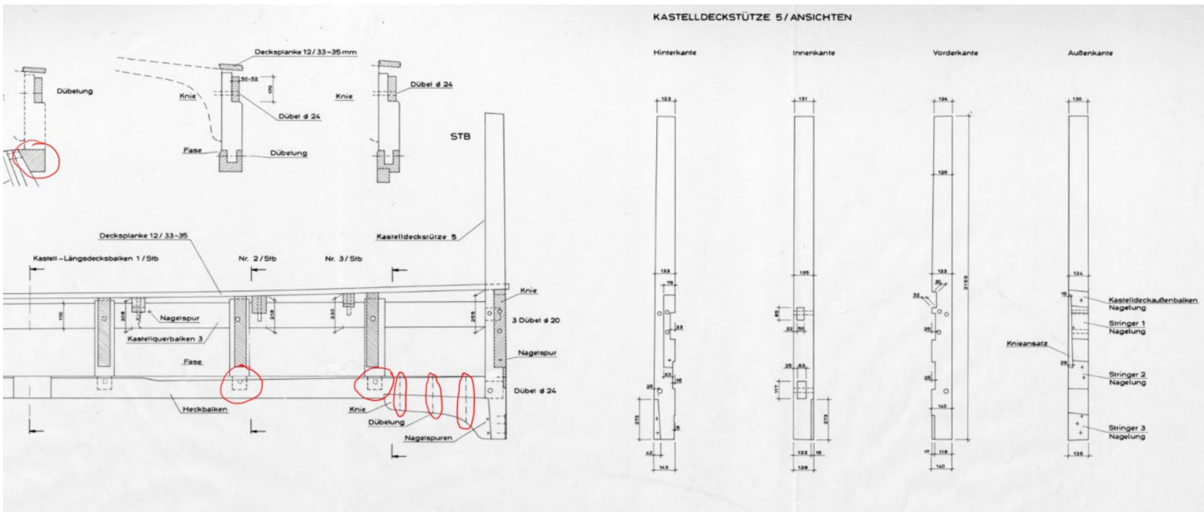


Figure 52 Drawing of reconstructed stern framework

Lahn states that based on the reconstructed positions of certain elements, the outermost side castle deck beam had to be supported by an additional support block at upper crossbeam 2 in order to attain the correct height. The deck camber was determined by castle crossbeam 1 at the fore, and by the heights of the longitudinal deck beams at the aft end. No evidence for these supporting blocks was recovered.

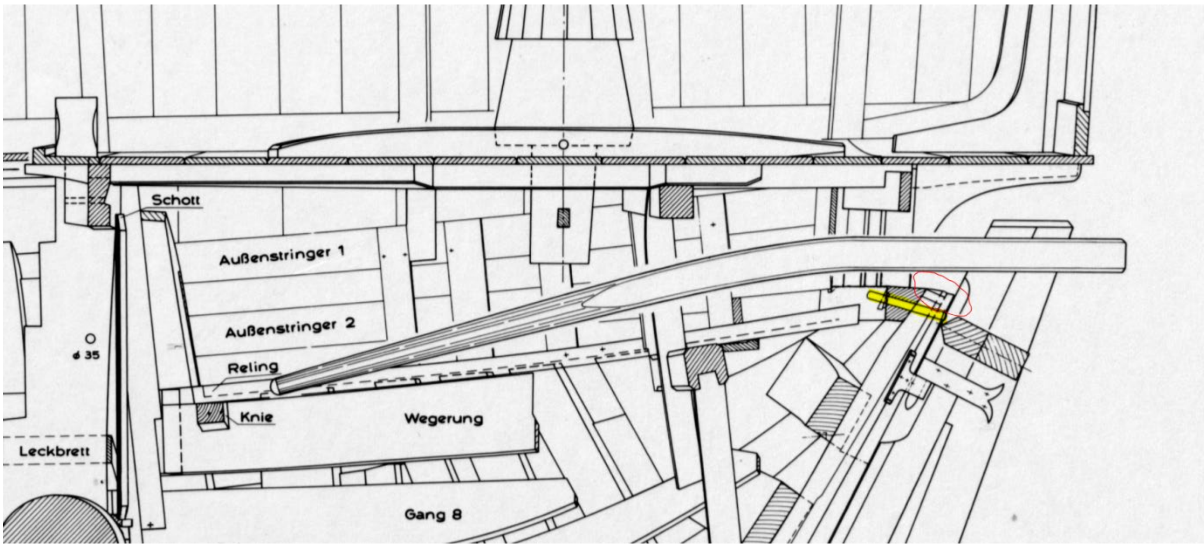


Figure 53 Bolted connection to stern framework

Lahn notes the 40mm diameter hole (circled red) at the head of the sternpost (Figure 53) is too high for a bolted connection between it and the lower crossbeam 3, and, as such a connection would be logical, he introduces a bolt 80mm lower down (highlighted yellow) even though no evidence for such a hole exists in the recovered sternpost. This would suggest that at this junction, where there is obvious evidence for some form of a bolted connection, either the reconstructed beam is 80mm too low, or the beam as reconstructed does not mate with the sternpost as shown.

If the beam is installed 80mm to low, the resulting elevation change would remove the reverse camber (Figure 54), or hollowed deck shape, which Lahn describes as being reminiscent of modern offshore ocean racing yachts with self draining cockpits.

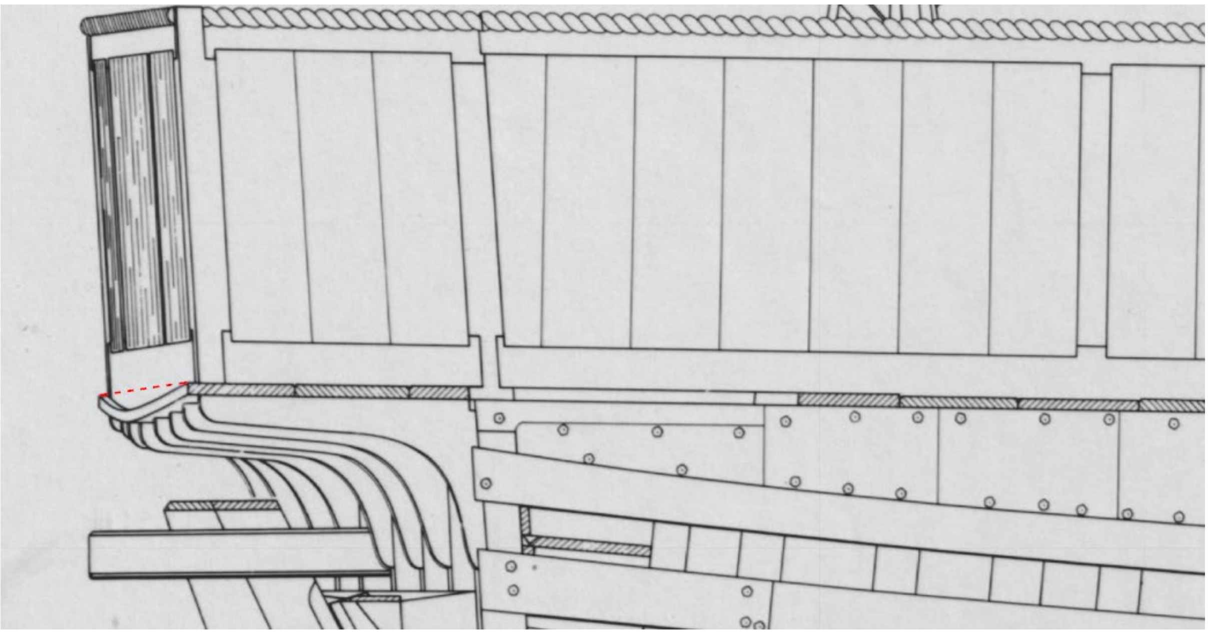


Figure 54 Hollow deck

In discussing the method of reconstructing the ship, Lahn states the hull planks were joined to the ribs using conical oak dowels (treenails), and a conical drill was used to drill the old holes deeper. Because of their shape these dowels fitted every hole, and where no old joints existed, new holes and dowels were installed to match the existing (Kiedel & Schnall 1989, p.39). As a result it is now difficult or impossible to distinguish with confidence original fastenings from the newer reconstructed fasteners (M. Belasus 2016, pers. comm., 3 Nov.).

It would appear that the published reconstruction drawings and the associated text (Lahn 1992), would benefit from what the London Charter (Denard 2009, p.8) describes as:

> Documentation of knowledge claims, where it is made clear to the audience what is represented, for example the existing state, evidence based restoration or hypothetical reconstruction.
>
> Documentation of process or Paradata, where the evaluative, analytical, deductive, interpretive and creative decisions are made.

H.8 Alternative Reconstruction

Recreating the Original Hull Shape

The aim in reconstructing the hull shape is to generate a floating hypothesis for the vessel in order to arrive at lines plans and hydrostatic data such as displacement, sailing characteristics and cargo carrying capabilities. In the paper Some Principles for the Reconstruction of Ancient Boat Structures (Crumlin-Pedersen & McGrail 2006) the authors suggest general principles that should be observed and considered under five headings: (1) deformation and its effects on the hull shape, (2) the impact of modem naval architectural standards, (3) the introduction of alien elements to complete the hull, (4) the consideration of propulsion, steering and seaworthiness, and (5) the concept of minimum reconstruction.

Deformation and its effects on the hull shape can be clearly seen in Figure 25 which illustrates the hull form created by simply lofting strakes through the as documented cross section shapes, thereby creating an extremely unfair, distorted hull form. The effects of modern naval architecture standards are described by the authors as naval architects, applying a rectilinear system of sections to 'cut up' the complex three dimensional curved body forming the hull shape, in order to represent the shape as a series of two dimensional drawings. Three dimensional modelling of the hull shape would circumvent this rectilinear approach.

The introduction of alien elements, considered necessary where partial or incomplete hull remains are recovered, should be limited to elements recorded from vessels of the same type, of the same building tradition and from the same or earlier dates. With the extensive quantity of remains recovered for the Bremen Cog, the almost complete starboard side, including partial upper works and stern castle structure, the missing elements from the damaged port side should be possible to recreate by mirroring. It should therefore be possible to recreate an almost complete hull form with the addition of little or no alien elements.

Consideration of propulsion, steering and seaworthiness should be included at the earliest stages of the reconstruction process, as illustrated in Figure 51 where the red coloured shrouds in the earlier reconstruction do not sit naturally when run from the mast head as positioned, to the fixing points in the outer channel wale. Additional further hydrostatic and seakeeping analysis should be carried out on the completed hypothetical reconstruction.

Minimum reconstruction is described by the authors as one or more (partial reconstructions based on the excavated evidence. In which allowances have been made for distortion, displacement and shrinkage, and valid comparative evidence used to supplement the missing portions. Where a considerable portion of the vessel survives, and full reconstruction is a realistic aim, a minimalistic way to complete the hull and determine the most likely means of propulsion and steering is required. The resulting hypothetical reconstruction(s) needs to be analysed in a non biased way, judged not by today's standards, but the standards prevailing at the time when the original vessel was built, in order to produce a fully functional reconstruction.

The three dimensional analysis of the previously published reconstruction drawings highlighted certain inconsistencies upon close examination, as set out in the preceding sections. Comparisons between the published drawings (green lines in Figure 55), the 1980 photogrammetry survey (red lines in Figure 55) and the 2014 laser scan recorded from the actual reconstructed vessel (blue lines in Figure 55), demonstrated some of the shape deformation which has, and continues to occur. Consequently it is believed by the author, that neither the original drawings, nor the current museum exhibit accurately represent the original hull form of the vessel and a renewed attempt at a more convincing, evidence based, hypothetical reconstruction would be beneficial.

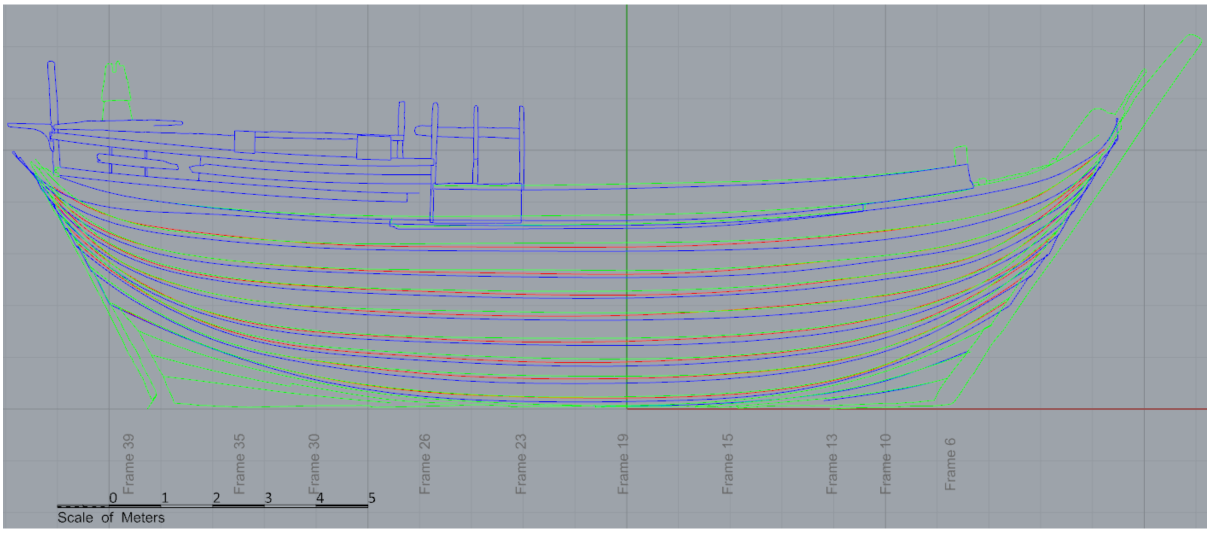


Figure 55 Profile differences between published drawings and 2014 3D scan

H.9 Available data

As all of the original recorded data was not available for the renewed hypothetical reconstruction, a combination of the published drawings from the 1980's and the subsequent three dimensional scans, both photogrammetric and laser scans, which were carried out over a 4 year period between 2011 and 2014 were used as the basis for the renewed reconstruction attempt.

While this renewed reconstruction attempt does not benefit from the advantages of handling, inspecting and accurately measuring each constituent component, such as the previously completed the 16C Drogheda Boat (Tanner 2013a) and the 15C Newport Medieval Ship (Jones et al. 2013) reconstructions, the data available from the above sources, together with this authors sailing and shipbuilding experience, should, when combined with the digital testing methodology (Tanner Forthcoming; Tanner 2017), lead to a more refined and enhanced alternative reconstruction.

The first stage in the renewed reconstruction approach was to assess the dimensional data available. All of the written dimensions from the 1980's drawings were taken to be correct, and presumably an accurate record of the dimensional size of the element (presumably in a waterlogged state) at that point in time. Where printed dimensions were not available, or the published drawings did not correlate, measurements were taken either from the original drawings which were digitally rescaled back to full (1:1) size in order to reduce error margins, or directly from the three dimensional survey data recorded between 2011 and 2014.

H.10 Shrinkage

A sampling of 16 timbers from the Newport Medieval Ship were initially documented in a waterlogged state, and subsequently re-documented post conservation, using in both cases, a Faro Arm contact digitiser capable of three dimensional sub millimetre recording accuracy. During the conservation process the timbers were treated initially with Di-ammonium Citrate to remove soluble iron salts, followed by soaking in a solution of PEG200 and 3350 to predetermined levels (15% v/v PEG200 and 5% w/v PEG3350 for the planks, and 15% v/v PEG200 and 20% w/v PEG3350 for the frames) over a period of 12 to 24 months. Following PEG treatment the timbers were dried using accelerated vacuum freeze-drying (VFD) to a moisture content of between 10 and 15% and subsequently stored at 54%RH and 20°C. The comparison of pre and post conservation dimensions provided consistent results demonstrating the planks are shrinking on average,

Variations in length of between 0 and 0.2% with less than 0.1% on average were recorded. Radial shrinkage (thickness in the case of radially split planks) measured between 2 and 4.1% with an average of 3%. Tangential shrinkage (width in the case of radially split planks) ranged between 4.4 and as much as 15.1% with an 8% average (Jones & Panter 2016).

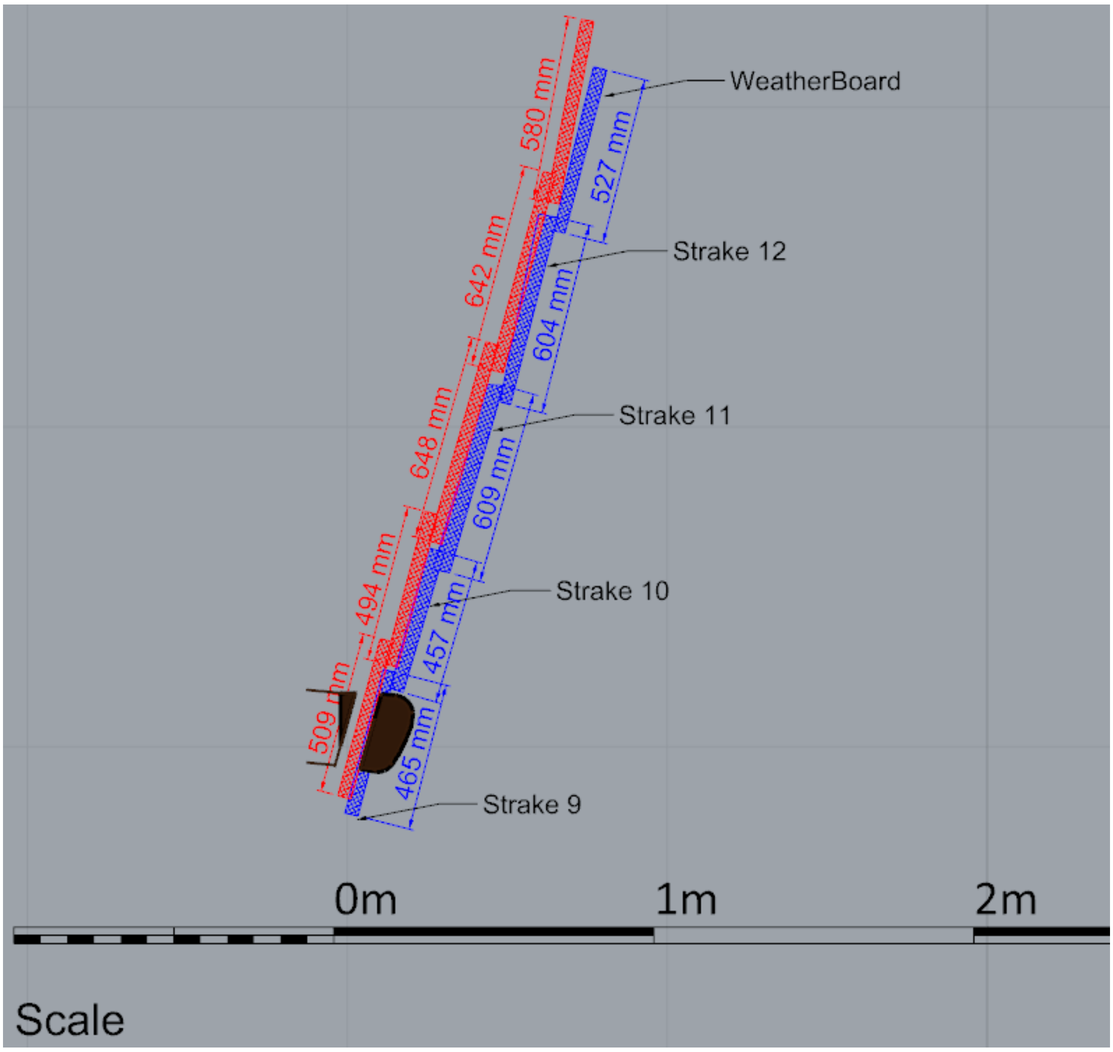


Figure 56 Tangential Shrinkage in the Strakes at frame 19

Figure 56 shows the tangential or width dimensions of the upper five strakes at frame 19 with the current dimensions taken from the 2014 laser scan shown in blue and the original (waterlogged ?) dimensions as documented on the Lahn drawings of 1980 shown in red. The differences between the original documented dimensions and the dimensions measured from the 2014 laser scan are set out in Table 10

Location	Lahn Measurement 1980	2014 Laser Scan dims.	Difference mm	%
WeatherBoard @ F19	580 mm	527 mm	53 mm	9.1 %
Strake 12 @ frame 19	642 mm	604 mm	38 mm	5.9 %
Strake 11 @ frame 19	648 mm	609 mm	39 mm	6.0 %
Strake 10 @ frame 19	494 mm	457 mm	37 mm	7.5 %
Strake 9 @ frame 19	509 mm	465 mm	44 mm	8.6 %
WeatherBoard @ F23	574 mm	537 mm	37 mm	6.4 %
Strake 12 @ frame 23	635 mm	577 mm	58 mm	9.1 %
Strake 11 @ frame 23	649 mm	581 mm	68 mm	10.5 %
Strake 10 @ frame 23	505 mm	457 mm	48 mm	9.5 %
Strake 9 @ frame 23	515 mm	474 mm	41 mm	8.0 %

Table 10 Shrinkage measured between 2014 scan and 1980 dimensions

With the figures from Table 10 giving a shrinkage rate comparable to the tangential shrinkage documented for the Newport Medieval Ship timbers, it can be assumed that the radial at 3%, and longitudinal shrinkage at 0.1% would be similar for the Cog. A 3% radial shrinkage would result in a 1.2mm change and is considered negligible for the purposes of hull form reconstruction. Similarly a 0.1% longitudinal shrinkage over a strake-length of 22.5m, resulting in a 22.5mm change, should not result in significant change to the overall hull shape.

Strake widths as printed on the published drawings were used for the hypothetical reconstruction in preference to the measured 2014 widths, which were subject to significant shrinkage.

As all of the drawings published in the 1980's were flat two-dimensional projected views of the complex three dimensional curved body forming the hull shape, it was not possible to determine an accurate length for the three dimensional, compound curve, strake lengths. The actual strake lengths were measured from the 2014 three dimensional scanned data, with the caveat that the dimensions recorded were potentially 0.1% shorter due to shrinkage (Figure 57).

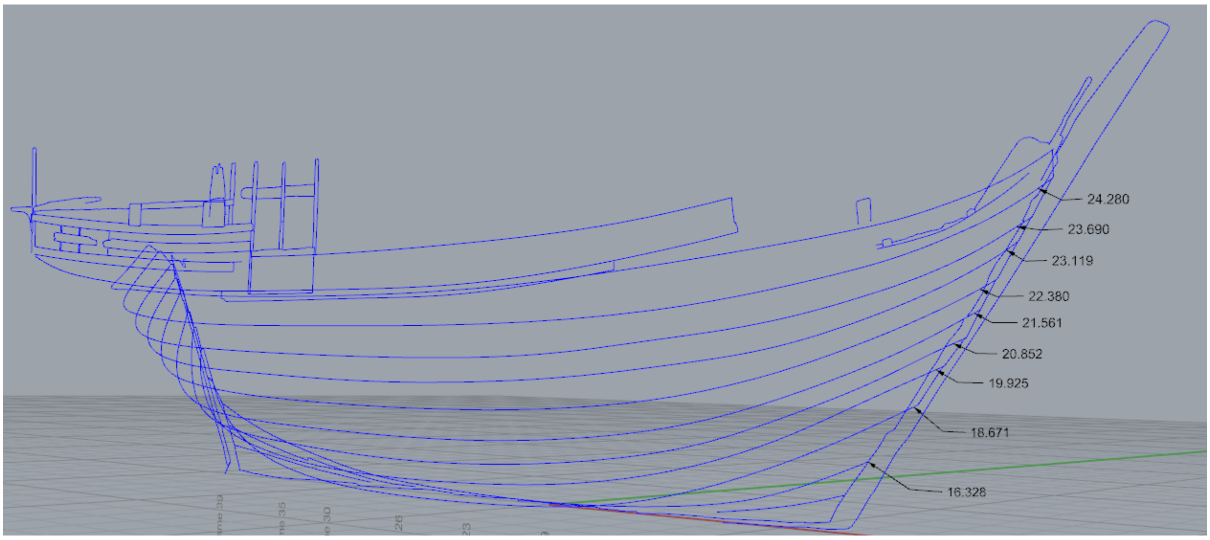
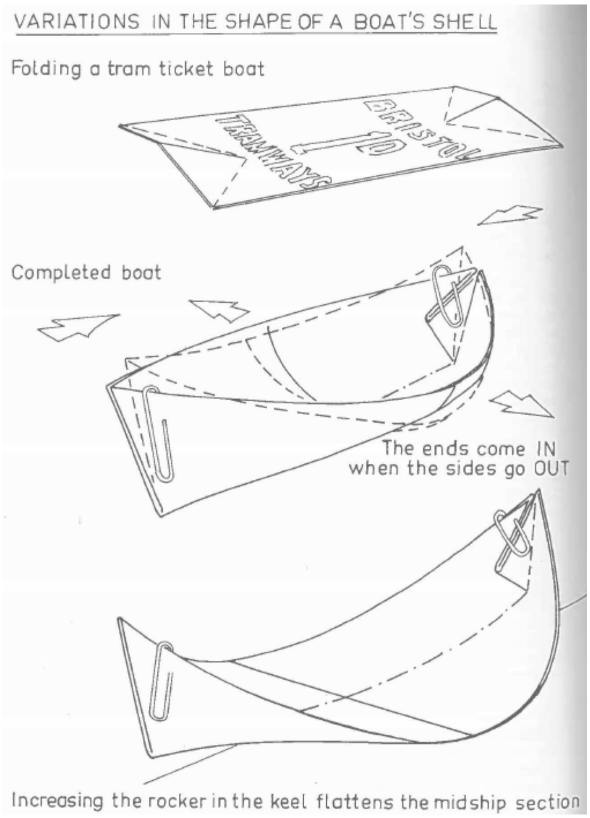


Figure 57 Actual three dimensional strake lengths

This three dimensional length of the bottom edge of each strake, which is easily measured using the CAD software, would be the same as straightening and flattening each strake, in order to measure its actual physical length.

It must be noted that when reconstructing a three dimensional shape such as a vessel hull form, no single point can be modified in a single view in isolation, as each point when shown in a single two dimensional view is actually forming part of a three dimensional curve. Reconstruction of a three-dimensional shape means that all corrections involve simultaneous changes in all three planes.



The task of making, recording and keeping track of all these on the sheer, body and half-breadth plans together, is foreboding and liable to all sorts of errors, particularly when one considers the fact that the shell of a boat can adopt a number of different but related shapes until one or more dimensions are fixed (Figure 58).

The sides will come together if the ends are forced apart, such as altering the rake of the stem or stern post, and if the rocker is increased the midship section will flatten.

By creating a digital three dimensional model of the strakes forming the vessel's hull shape, any modification to a single point in any one of the three planes, longitudinal, transverse or vertical, will automatically update the corresponding points position in the other two planes.

Figure 58 Variations in the shape of a boat's shell Drawing: after McKee in (Fenwick 1978, p.268)

Similarly if the position of the end posts is known, thereby fixing the start and end points of each strake, and the overall physical length of each strake is also known, the potential variations in overall shape is greatly reduced. Taking the upper edge of the hull in McKee's example above (Figure 58), if the start and end points are predetermined by knowing the position of both end posts, and the curve length is known from the physical strake length, the curvature and subsequent hull shape is predetermined to a certain extent. Increasing the height of the sheer curve would result in a corresponding reduction in overall hull width to match the fixed overall length of the stake, just as increasing the hull width would cause a reduction in the sheer height.

H.11 Developing the Hull Form

With the overall length, widths, start and end points known for the first or garboard strake, there is little shape variation possible during the reconstruction. The fact that the lower edge of this garboard strake must conform to the keel profile shape, further limits the potential variations in overall form. The known overall length of the subsequent strake number 2 will add additional constraints to the potential shape variations for the upper edge of this garboard strake. The combined effect of these constraints, results in a shape form for the garboard strake with an extremely high level of confidence. The only possibility for altering this shape form is to increase or decrease the rocker (longitudinal curvature) of the keel.

As each subsequent strake is added to the evolving hull form, the overall strake length, combined with the necessity to mate to the upper edge of the preceding strake, results in a profile shape with a high degree of confidence.

However, the ability to induce twist into each subsequent strake as it is added, creates the potential to slightly alter the overall evolving hull form. This twist would either increase the vertical height while decreasing the width, or vice versa. While the size of this potential alteration is slight for each subsequent strake added, the cumulative total could potentially add several centimetres to the overall height or width of the completed hull form.

Any additional surviving elements of the vessel, which give indications of the height or width for a point on the hull, will further aid in determining the confidence of the evolving hull form. Elements such as transverse beams, thwarts (seats) or deck boards can provide a known width, or vertical elements such as stanchions or knees can provide a known height.

If the complete strake length is known, and the width (post thickness) and height (cumulative height of preceding strakes) for the start and end point are fixed, the only possible variables are the overall width and the overall height for the strake. Setting either one of these variables, will subsequently regulate the other.

Cross Beams

With the start and end points of strake 9 pre-set by their positions on the end posts, the overall physical length of the strake known (22.38m + 0.224m allowance for 0.1% shrinkage) from the surviving archaeological evidence, and four additional locations reasonably predetermined by the widths of each of the main deck cross-beams, the only variable is the heights of each deck cross-beam. These heights are pre-set by the combined widths of the lower eight strakes, and can only be varied a minute amount by altering the cross sectional shape of the hull at each of the four locations. Consequently a faired curve, magenta in Figure 59, with a known start and end point, known length and passing through four pre-determined positions, can have little or no alternative profile shapes.

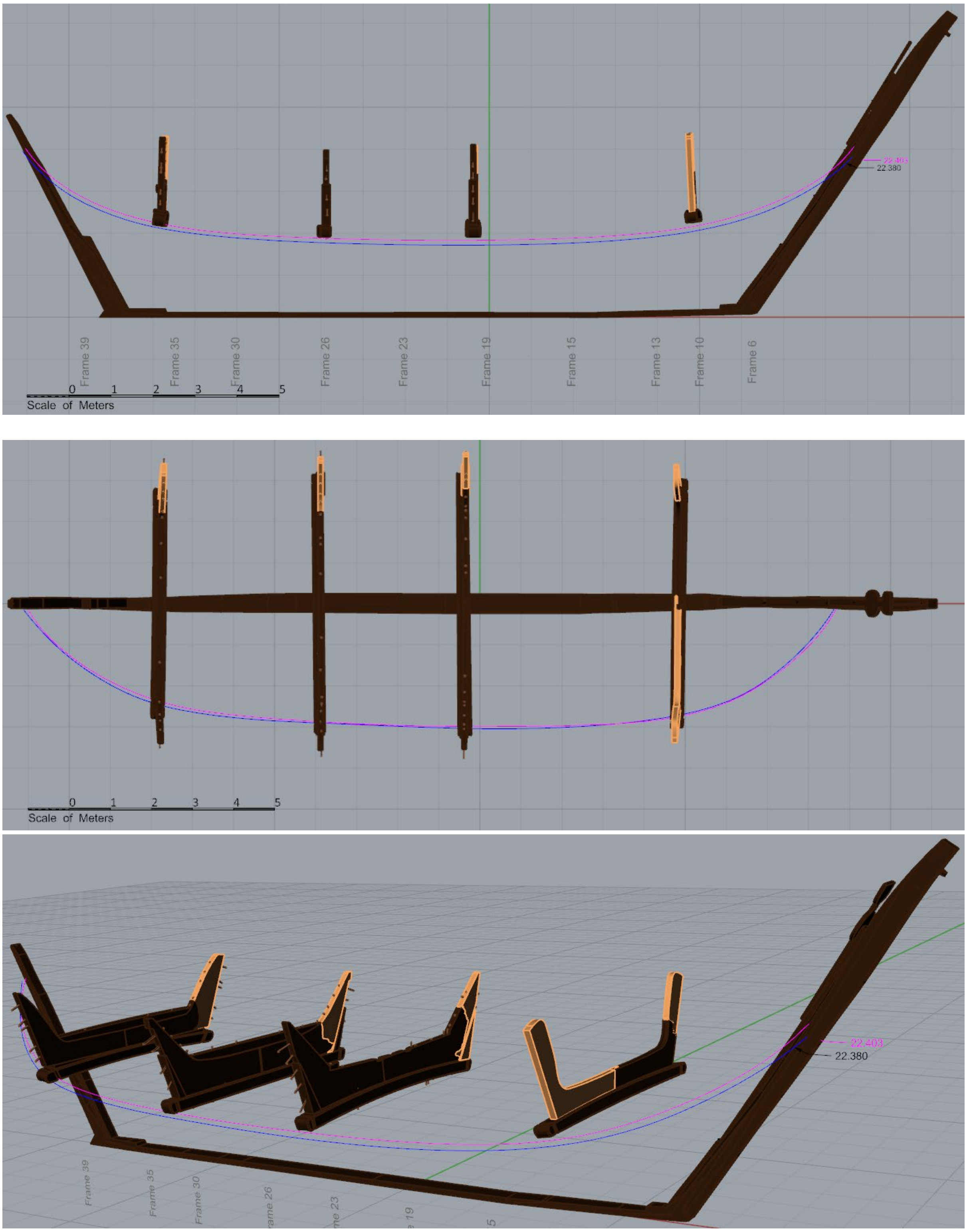


Figure 59 Three Dimensional Shape of Strake 9

By creating a curve of known fixed overall length, where the start and end points are known, transverse and vertical positions are somewhat predetermined by the preceding and subsequent strakes, in order to facilitate the required clinker land or overlap, and the known widths of each strake enables the generation of a three dimensional shape for each strake with little or no potential shape variation.

This process was then used to recreate the required three dimensional shape for each subsequent strake, magenta curves in Figure 60, thereby recreating the overall hull shape.

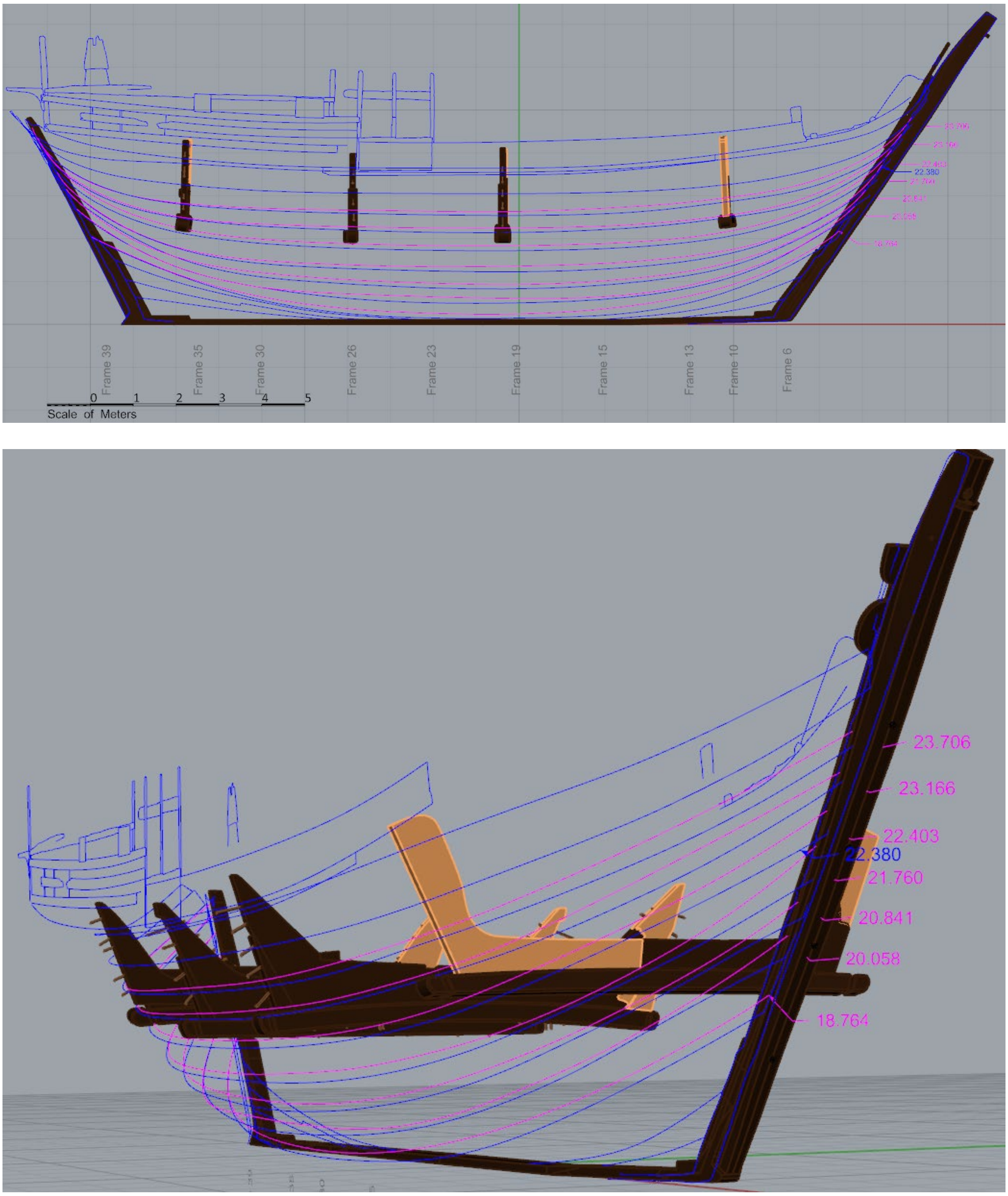


Figure 60 Recreating three dimensional strake curves

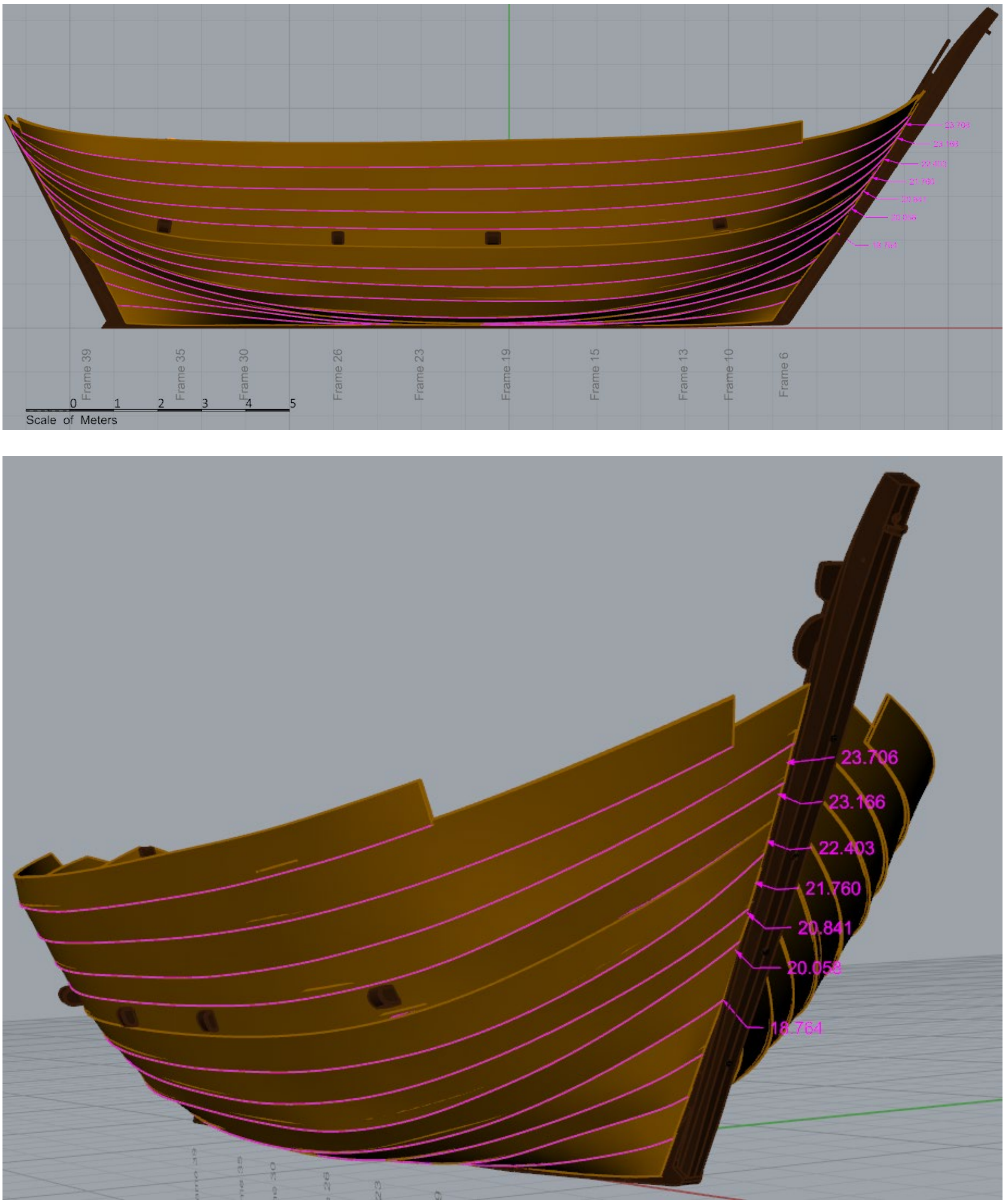


Figure 61 Strake widths lofted through three dimensional curves

The previously documented strake widths are then lofted through the 3D curves (Figure 61). While this process may not recreate the exact hull shape, as fairing the curves does not take into account localised minor distortions or imperfections in the wood, it does recreate the idealised or 'design intent' of the hull shape based on the recovered archaeological materials, and in the opinion of this author, complies with the term 'Minimum Reconstruction' which is described as one or more (partial) reconstructions based on the excavated evidence, in which allowances have been made for distortion, displacement and shrinkage (Crumlin-Pedersen & McGrail 2006, p.57).

Frames

The main deck cross-beams and frames were positioned in accordance with the locations as recorded from the initial reassembly of the ship (Figure 62). The frames were smaller in their moulded dimension compared to the sided dimensions, and as such were more susceptible to transverse deformation. Consequently the refined hull shape, developed thus far is believed to be a more accurate representation of the original hull shape for the purposes of this hypothetical reconstruction.

Experience gained to date from projects such as the Newport Medieval Ship, and the Drogheda Boat, have demonstrated that even substantial framing timbers are susceptible to significant shape distortion and cannot be reliably used as a shape template. Consequently the refined hull was taken as a more definitive form and transverse deformation in the frames was digitally repaired to match the refined hull shape, while observing the location of documented features such as joggle positions and treenail fastenings. Missing elements (light brown in Figure 62) were mirrored where necessary.

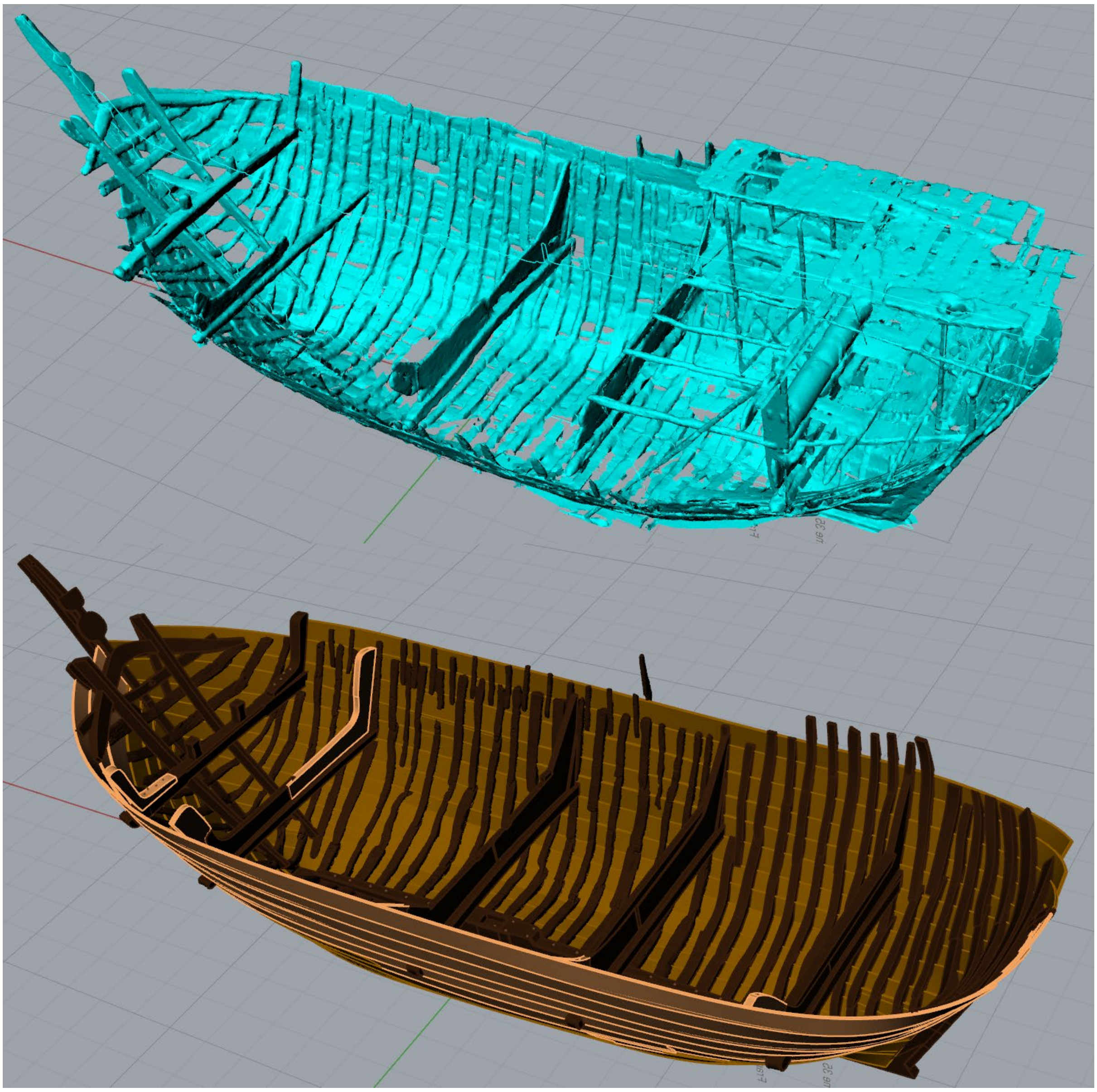


Figure 62 2014 3D laser scan above, and 'repaired' digital reconstruction below

Longitudinal Beams

The longitudinal deck beams or carlings, fore and aft stringers and ceiling planks were then fitted to the reconstruction (Figure 63), based initially on the published drawings, but also taking into account positional changes resulting from the refined hull form.

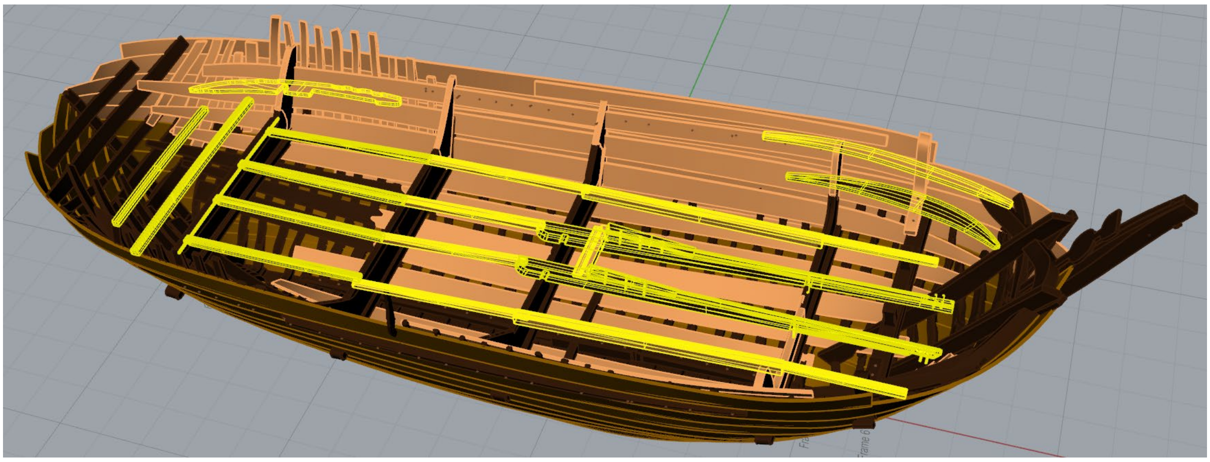


Figure 63 Additional elements such as stringers and deck beams added

Windlass

The windlass and its side cheeks form one of the main supports for the forward end of the stern castle, and during the initial reassembly, this feature was used as the main starting point for the entire stern castle reconstruction. When installing castle crossbeam 1, Lahn notes the beam rests on the shoulder rebate formed in the top of the starboard windlass cheek (Lahn 1992, p.127) which matches both the width and height of the crossbeam. However with top half of the port windlass cheek not recovered, the starboard side was mirrored to port, and the castle beam positioned on top of the mirrored shoulder rebate. There is no evidence to prove the port shoulder rebate was identical to that of the recovered starboard side, and the unexplained height reduction to port of the reconstructed castle crossbeam results in the entire beam drooping to port by 52mm when installed.

Castle Crossbeam 1

A closer inspection of the beam as documented, shows the upper surface rising by as much as 25 mm (Figure 64) as it crosses from the starboard extremity towards the ships centreline. The lower surface would also appear to follow the same upward direction. If this shape were mirrored to the missing port side, and then extended to its natural crown point at midships, the height increase would be at least 37mm (Figure 65), which matches the recorded dimension of 36mm from the existing archaeological evidence at the underside of the beam. Interestingly this also matches the recorded camber measured in the recovered lower crossbeam 2. The consequence would be a slight deck camber in the forward end of the castle deck, rather than the flat camber-less deck proposed by Lahn in this area.

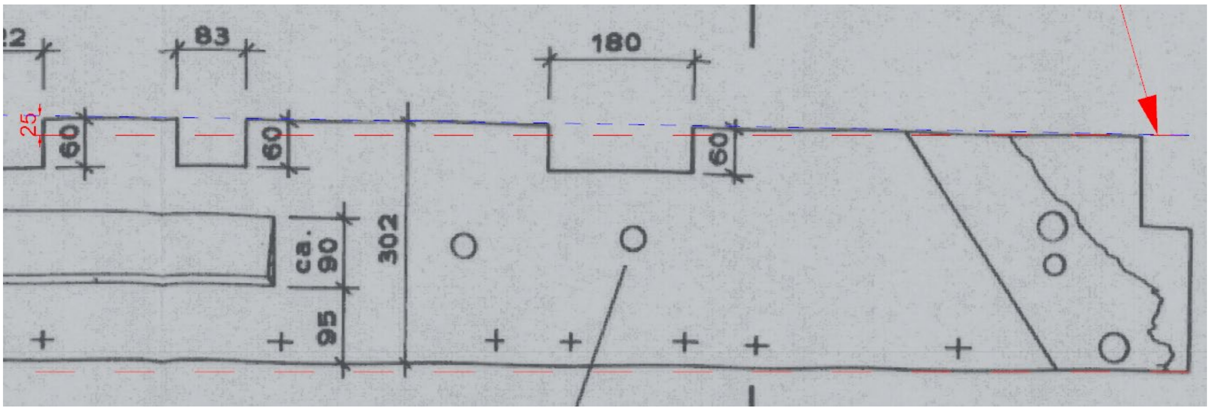


Figure 64 Detail of recovered starboard end of castle crossbeam 1

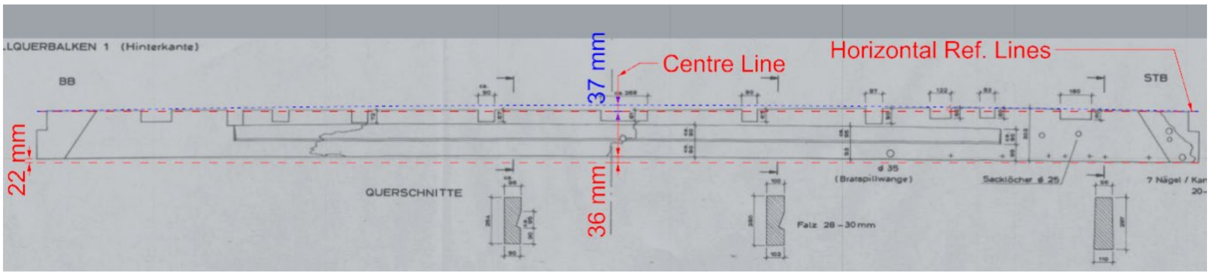


Figure 65 Alternative castle crossbeam 1 reconstruction

Mirroring the extant castle crossbeam end (Figure 65) would reduce this droop to 30mm, and a simple minor alteration by the cog builder, to the shoulder height of the port windlass cheek, would have easily resulted in the beam being installed level (Figure 66) at either end. While no archaeological evidence exists for this beam having been installed level, even less evidence exists for its drooping installation.

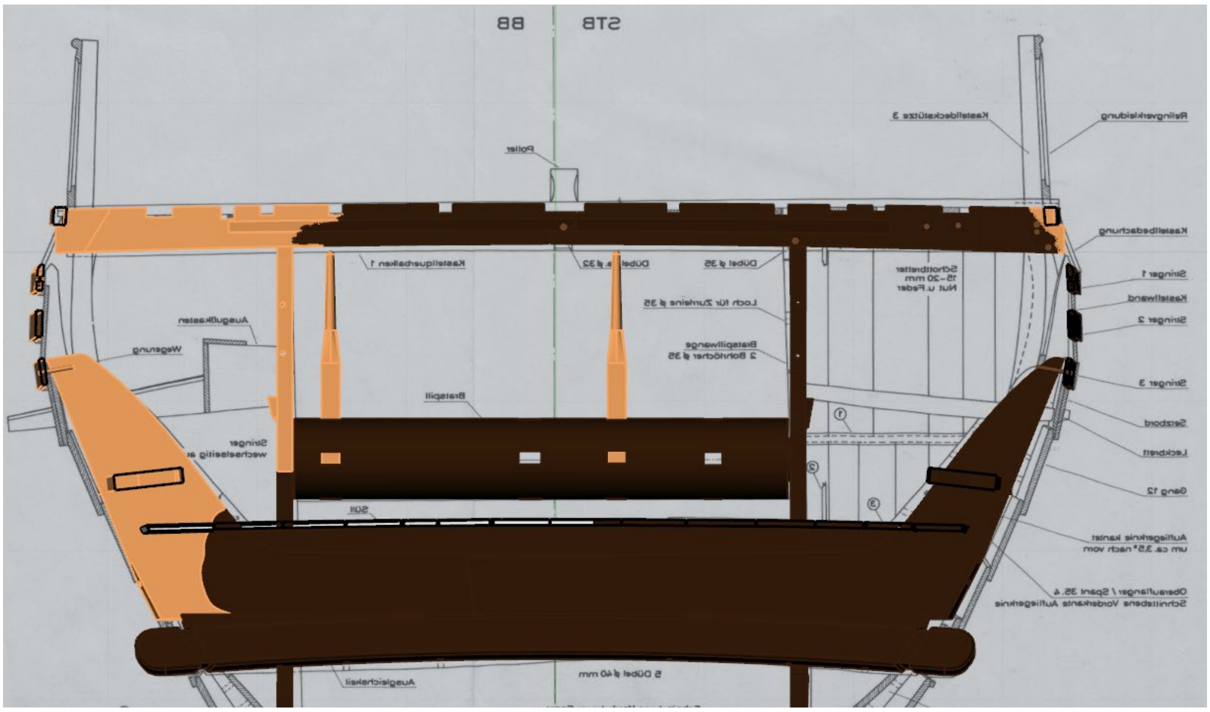


Figure 66 Alternative reconstruction of Castle Crossbeam 1

From the two dimensional section drawing (Blatt 3) and the 3D scan data, the windlass cheeks supporting the castle deck are both angled to the port side by 1.4°, and the horizontal castle beam is sagging to port by 1.7° (Figure 67). This is potentially distortion in the reconstructed vessel, caused by the incomplete and unsupported port side. It would appear that the damaged incomplete port side of the hull has sagged causing the two support stanchions and the windlass to be angled to port.

The windlass cheek which supports castle crossbeam 1, dictates not only the forward position of the stern castle, but also the width and perimeter shape of the stern castle. The foremost starboard corner of the stern castle is accurately positioned by the recovered channel wale stanchions, which position the forward end of the castle deck outer beam highlighted in Figure 68.

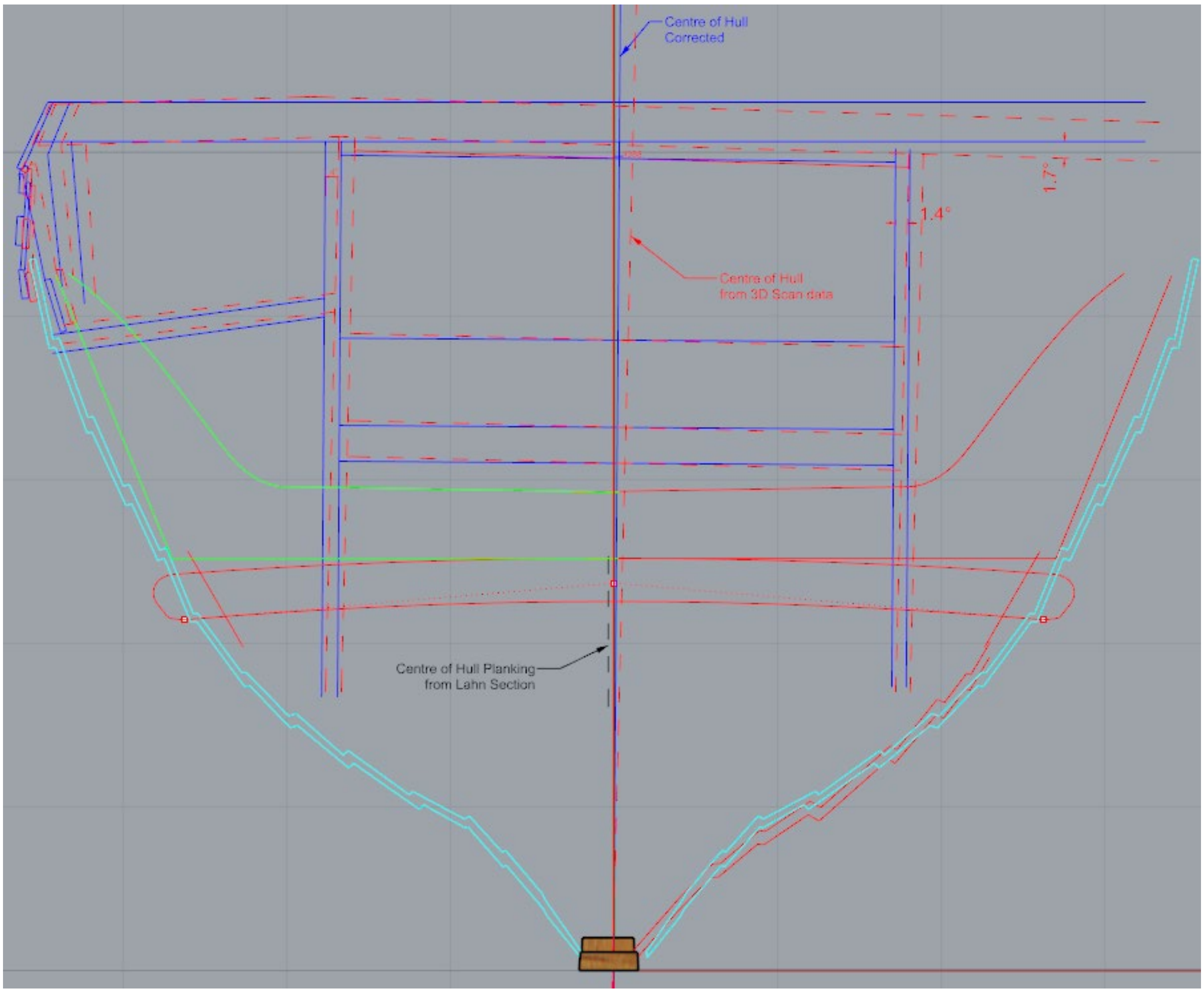


Figure 67 Alternative Cross Section shape

Castle deck outer beam

Lahn noted that when the starboard castle deck outer beam was installed, it ran an absolutely straight course, bending neither upward, downward nor side to side (Lahn 1992, p.142). The aft end of this absolutely straight beam was then used to locate the upright stanchion forming the aft end of the stern framework.

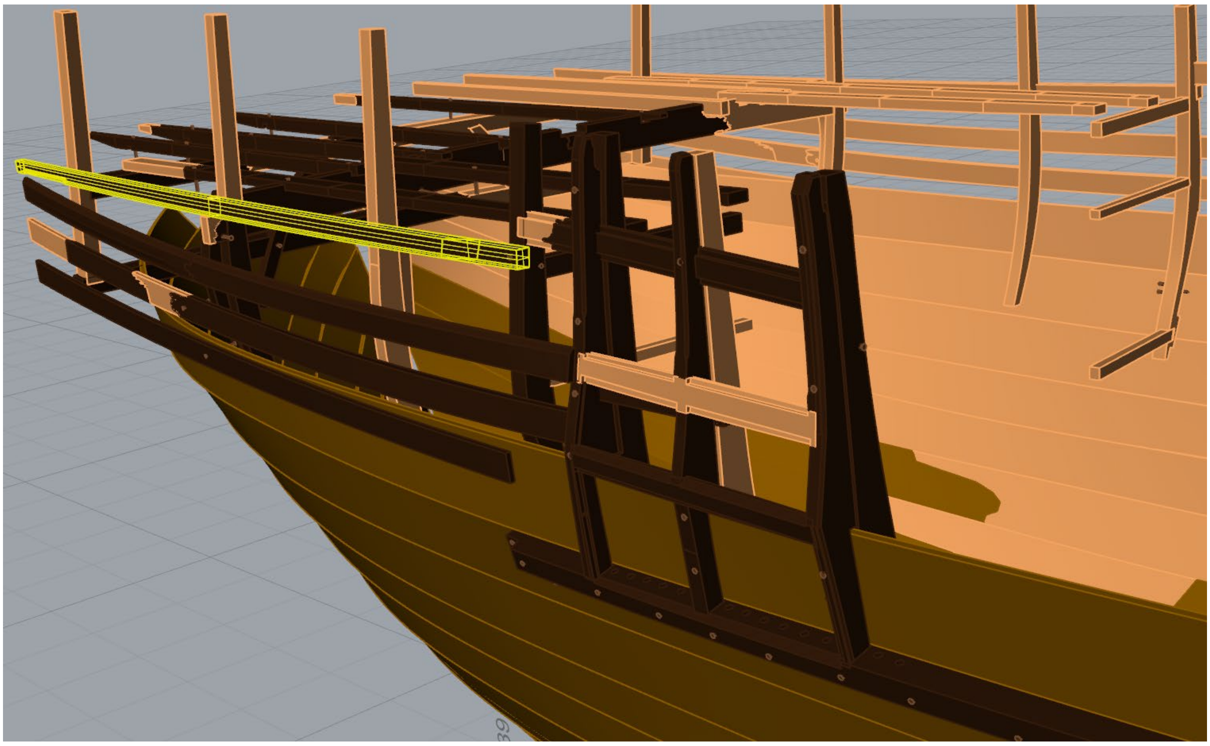


Figure 68 Channel wale stanchions with castle deck outer beam

This beam if so installed, is unique in that it is the singular, solitary, item without some degree of curvature, in the entire ship. When compared to its neighbouring features, the castle outer stringers, which follow reasonably the upward sweeping form of the sheer curve, in addition to curving inboard as they run aft, this straight beam creates something of a visual anomaly and creates the appearance of drooping or hogging (Figure 69).

Figure 69 Drooping Castle outer beam

If the windlass is installed vertical (Figure 70), this has the effect of moving the starboard end of castle cross-beam 1 outboard by 68mm, which in turn creates some longitudinal curvature in the previously straight castle deck outer beam.

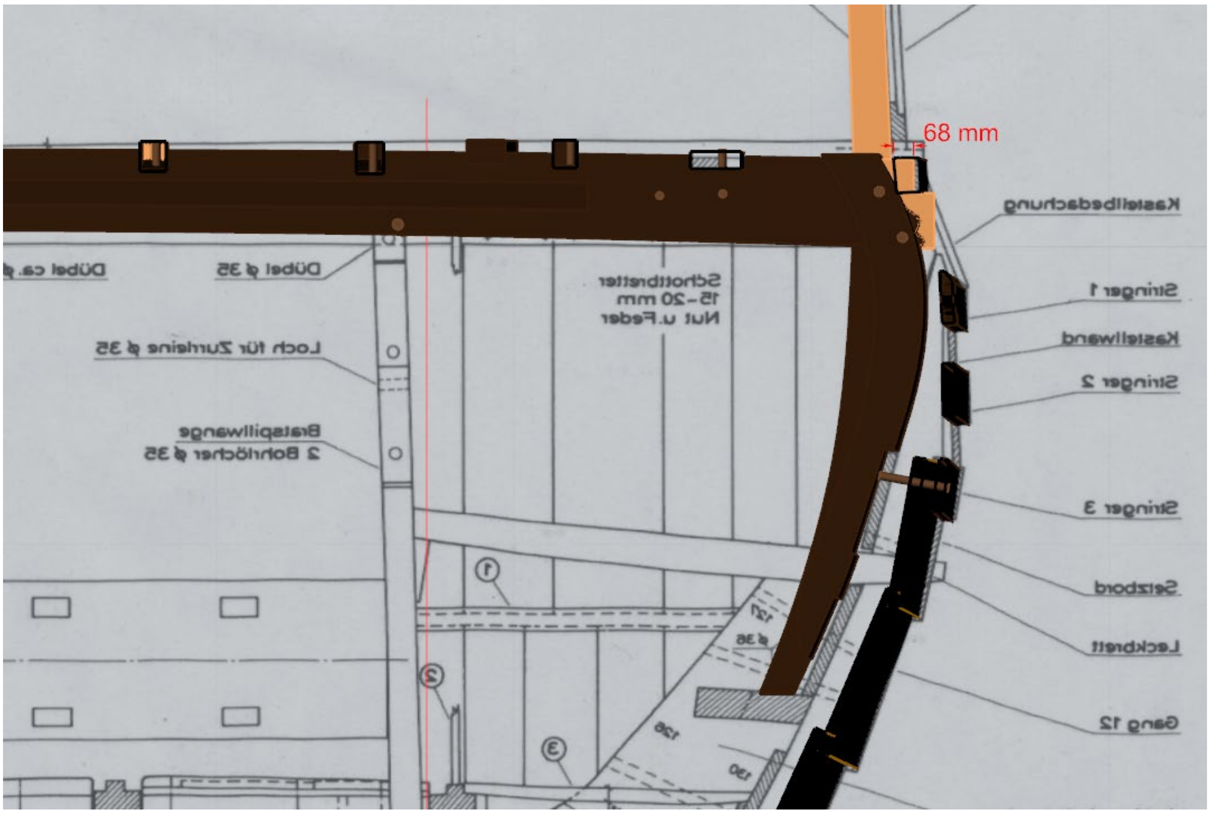


Figure 70 Effect of installing the windlass vertical

Stern Framework

In the original reconstruction drawings, Lahn recreated the stern castle with the stern framework rotated aft by 5.3° (Figure 71) based on what he described as the increasing lengths of the castle deck beams (Figure 72), and possibly the decision that this framework was fastened directly to the stern post, even though he notes the fastening hole in the stern post is 80mm to low as reconstructed (Figure 53).

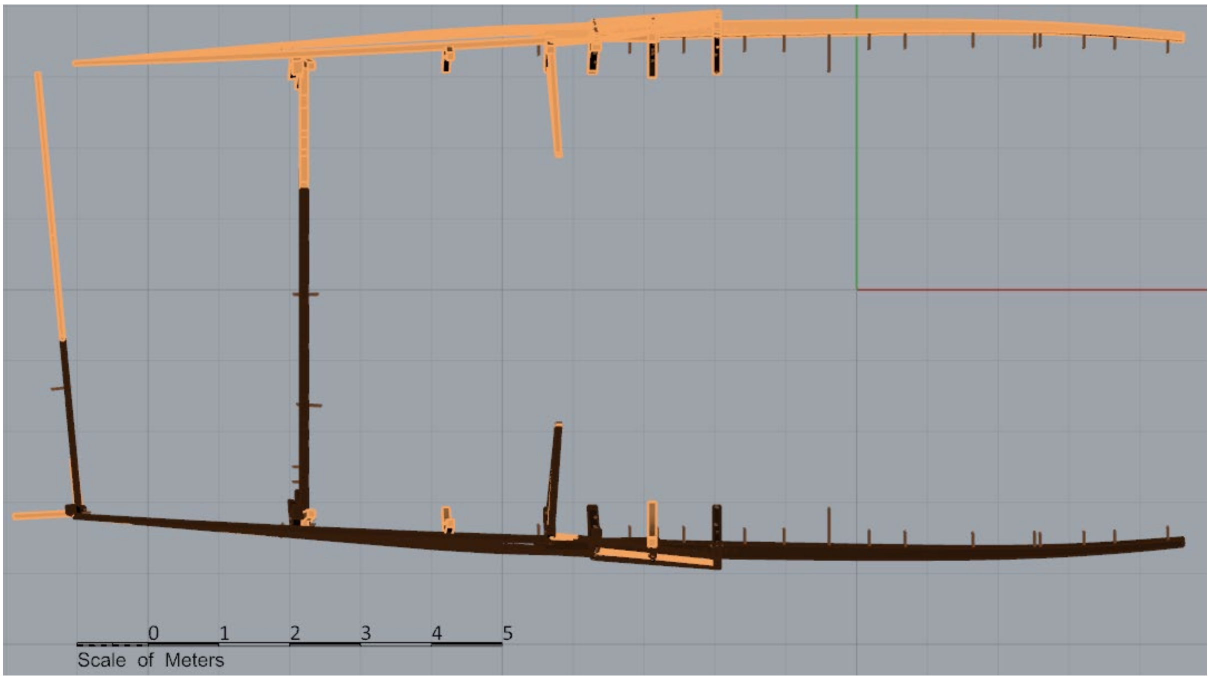


Figure 71 Angled stern framework

The rotation of the stern framework with the port end some 610mm further aft than the starboard end is noted by Lahn as differing substantially in regard to the other crossbeams (Lahn 1992, p.141), but is justified by the increasing deck beam lengths towards port (Figure 72), however this increase is only in the reconstructed lengths.

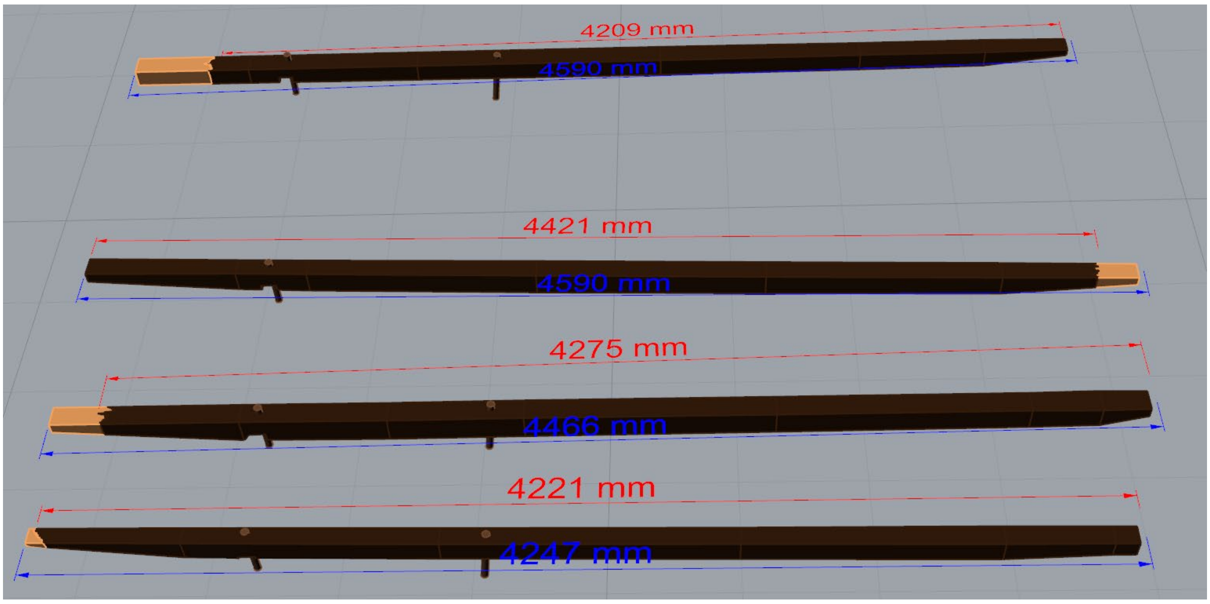


Figure 72 Increasing deck beam lengths

Additionally the entire framework is tilted aft by circa 4°, although no reason or explanation is stated for this, while the stanchion at crossbeam 2 is tilted circa 7° to the fore as a result of lying against the face of crossbeam DB5, and the stanchion at crossbeam 1 is tilted 4° to the fore. A close examination of the half lap rebates between the castle outer stringers and the castle deck support 5 stanchion (Figure 73) reveals these joints to be open and gaping with the stern framework tilted aft and rotated towards the stern.

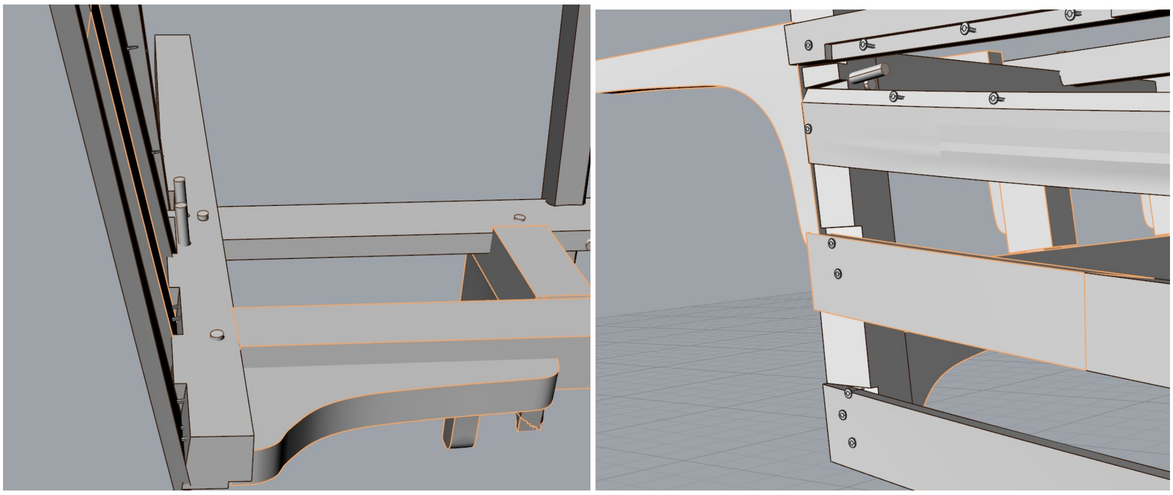


Figure 73 Connection between outer stringers and castle deck support 5

Closing these joints would rotate the stern framework towards the fore, into a more transverse orientation. This existing archaeological evidence would indicate the stern framework should be straightened in both the vertical and horizontal planes in order to close these joints.

Stern Castle Deck

Further justification for the trapezoidal castle deck is given in the form of the recovered deck planks, the seven after most of which all widen as they run from starboard to port. However none of the full width portions of these seven tapered deck planks cross the ships centre line, and if these boards were mirrored to the missing port side, creating transversely curving deck boards, the need for the oblique angled after end to the stern castle is removed

Perhaps a combination of the two solutions, which would appear to be more in keeping with the archaeological evidence, would result in a more traditional, and visually pleasing, plan shape for the stern castle (Figure 74), as well as creating the required deck camber to aid with draining the caulked deck planks.

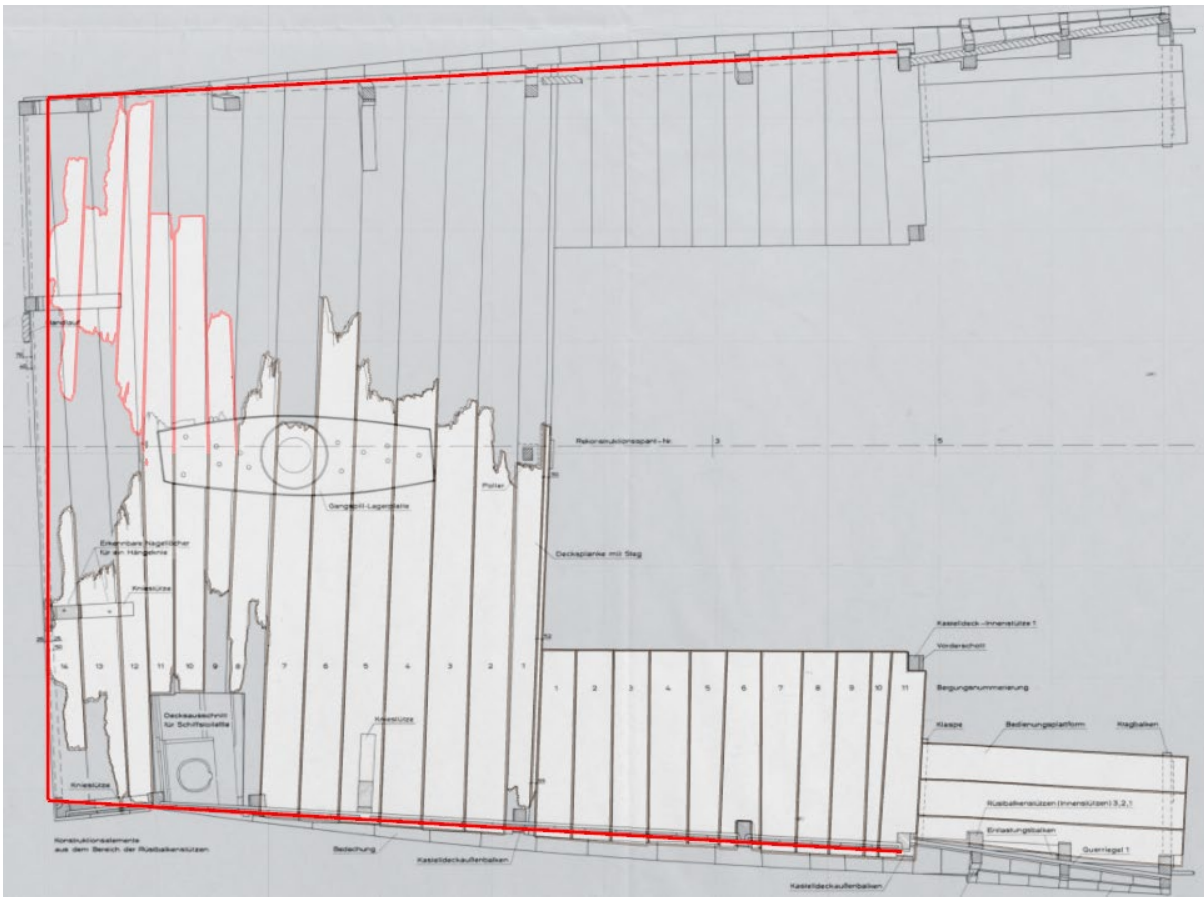


Figure 74 mirroring the deck planks to create an alternative stern castle end

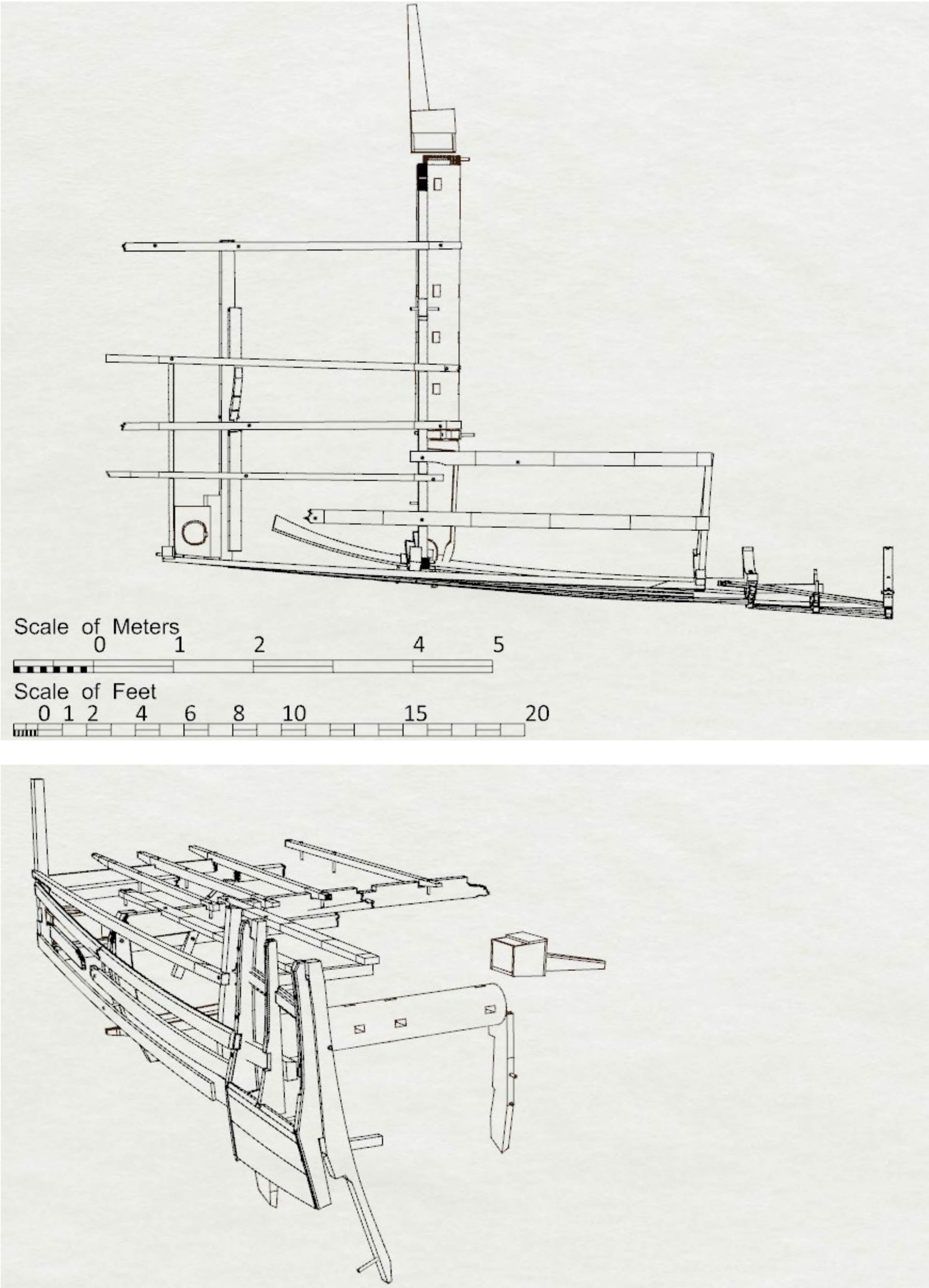


Figure 75 Recovered stern castle supports repositioned

With the recovered stern castle elements rotated and repositioned to close the joints in the stern framework assembly (Figure 75) the missing elements shown brown in Figure 76 were mirrored and reconstructed to complete the stern castle support structure.

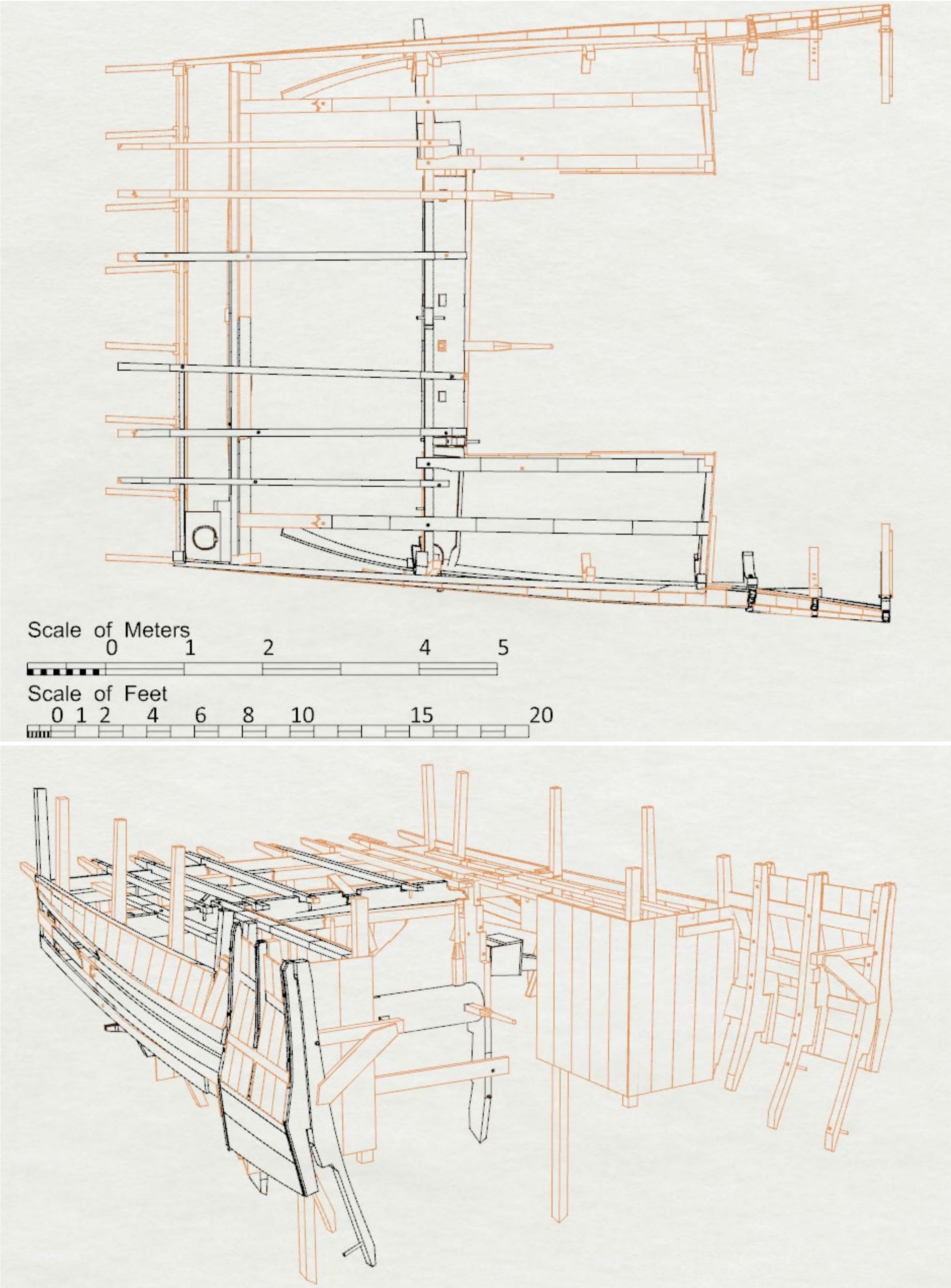


Figure 76 Reconstructed castle deck support structure

The recovered deck planks were then mirrored to the port side and any missing portions reconstructed (Figure 77).

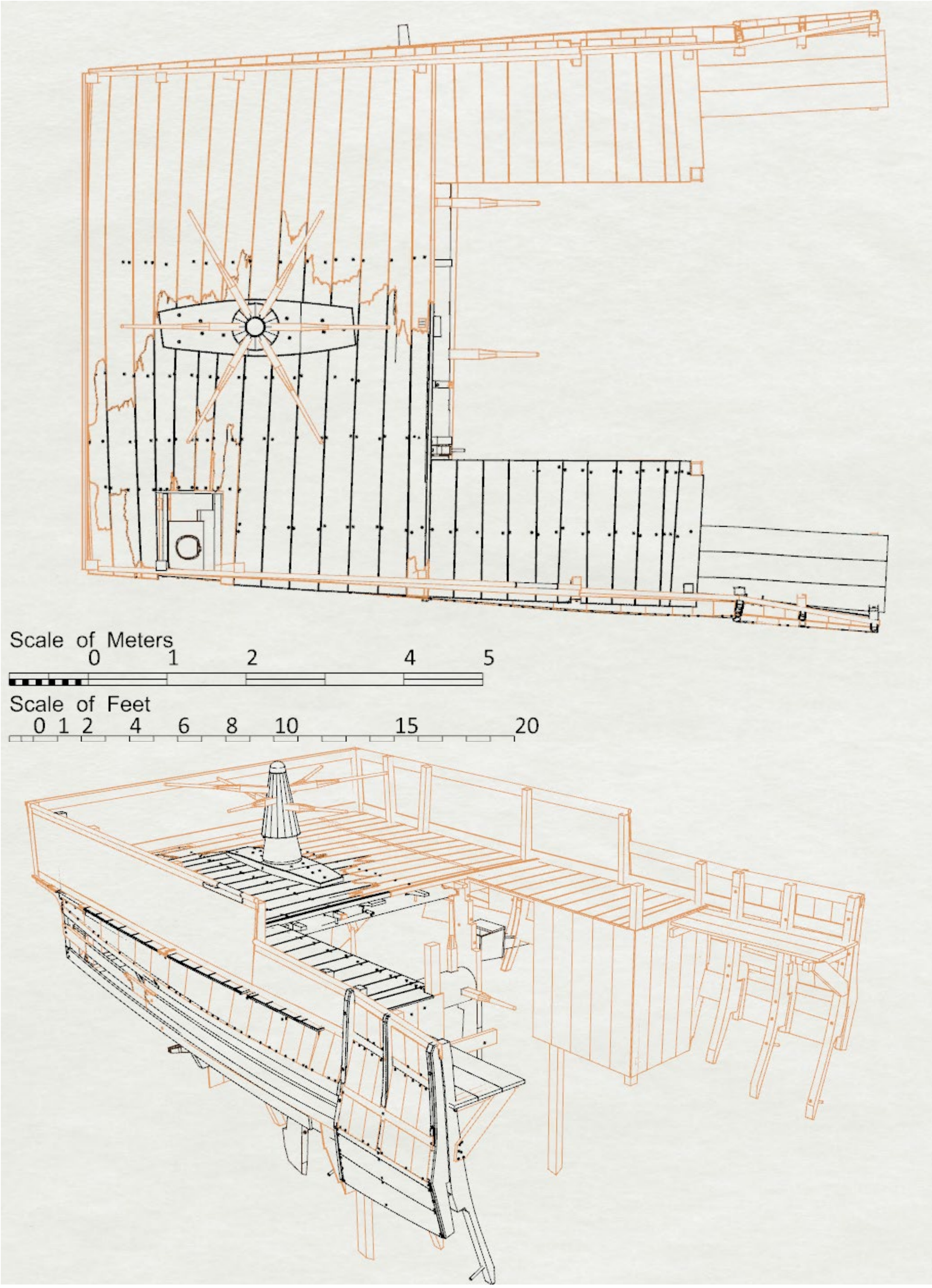


Figure 77 Stern castle deck planks reconstructed

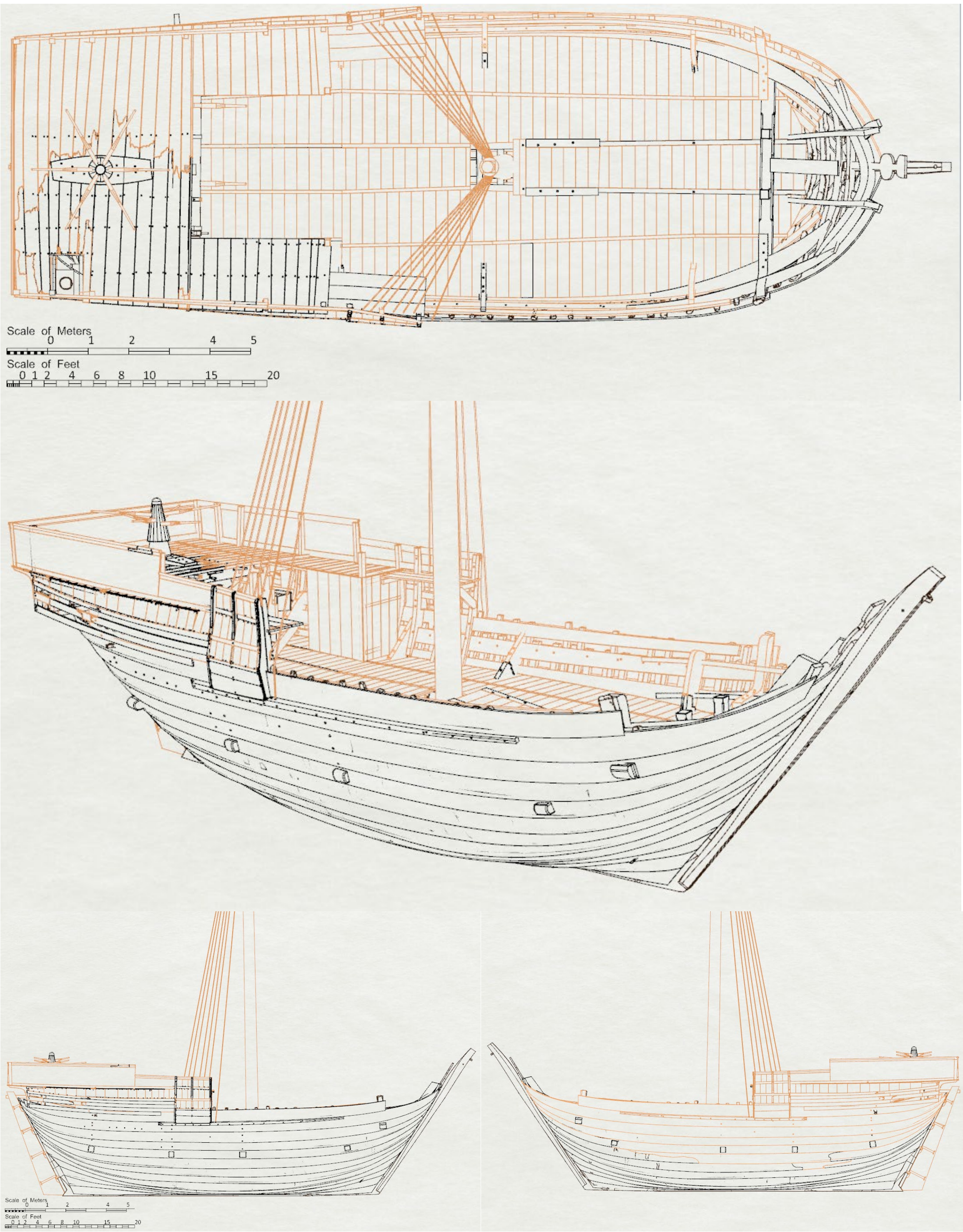


Figure 78 Completed reconstruction

The weight of all the timber as shown in the reconstruction (Figure 78), including mast and main shrouds is 43.77t. The centre of gravity is located 7.547m forward and 3.175 above the aft lower extremity of the keel. An allowance of circa 15t for additional elements such as iron fastenings, yard, sails and running rigging, anchors and warps, and sundry equipment would bring the total vessel deadweight to 58.7t.

H.12 Conclusion

As previously discussed in the summary of the original reconstruction, the quantity and often fragmented condition of the many constituent parts posed a particular set of difficulties during the initial reconstruction process. With 37 published drawings and the accompanying 250 plus page report (Lahn 1992), it has still proven difficult some 25 years later to accurately determine exactly which elements of the reconstruction were original documented components, and which elements form part of the hypothetical reconstruction. It would appear that the process employed during the initial reconstruction was to reassemble the vessel components and document the evolving hull form based on this reconstructed shape. Efforts were then (apparently) made to correct issues which arose during the reassembly process in the publications.

Advances in three-dimensional digital modelling have highlighted some issues with the original reconstruction, in addition to highlighting some of the archaeological evidence, which was apparently not included in the reconstruction.

The alternative reconstruction described above, clearly takes all of the archaeological evidence into consideration, while also considering important additional factors such as timber shrinkage, and distortion in the reconstructed hull form as well as in that of the recovered elements. The techniques employed throughout this alternative reconstruction clearly identify and distinguish between recovered and reconstructed elements. Colour coding has been used throughout this report and the accompanying large format drawings to clearly distinguish between recovered and reconstructed components.

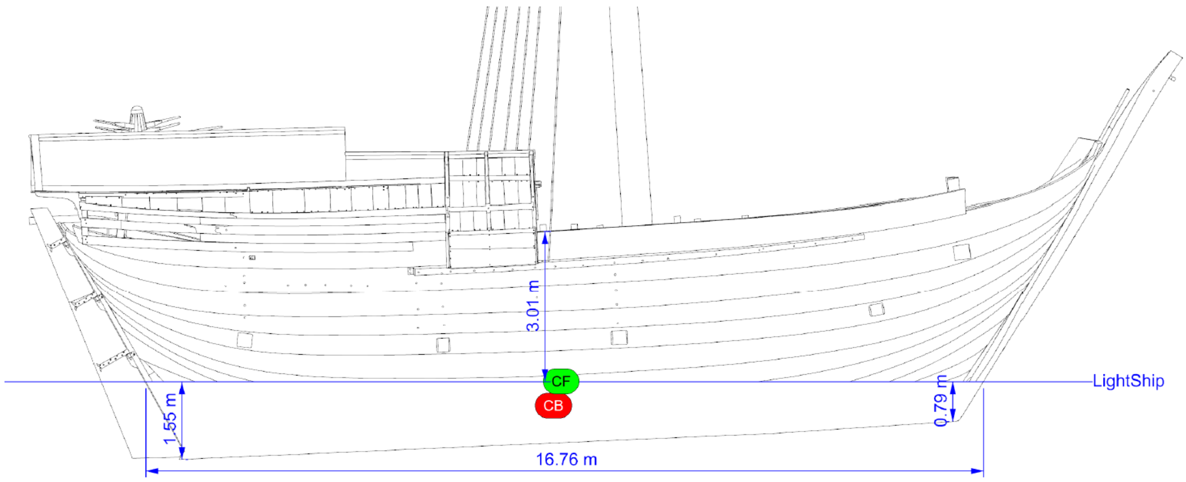


Figure 79 Lightship Condition

With the cog completely empty, the deadweight of 58.7t would result in the vessel floating as shown in Figure 79. This would result in a draught aft of 1.55m, a draught forward of 0.79m and a freeboard of 3.01m. The vessel would be completely unstable in this condition with the centre of gravity too high, and would require some form of internal ballast to sail safely.

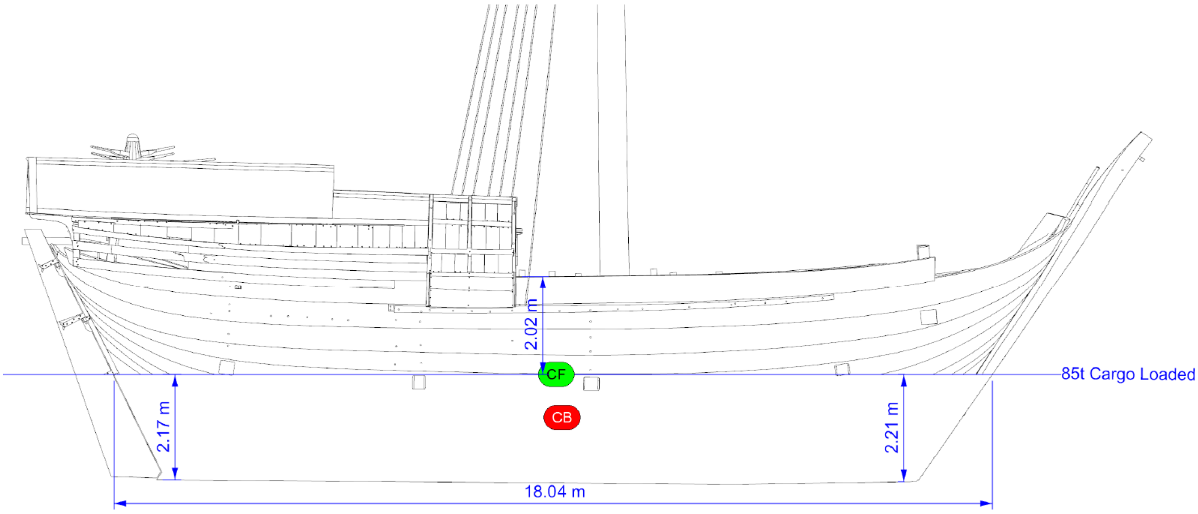


Figure 80 85t Cargo Loaded

With the cog loaded to 85t of cargo, as suggested in The Hanse Cog of 1380 (Kiedel & Schnall 1989, p.81), and the deadweight of 58.7t, resulting in a total displacement of 144t the vessel floats as shown in Figure 80. This would result in a draught aft of 2.17m, a draught forward of 2.21m and a freeboard of 2.02m. This would result in deck beams one and five to sit just at the waterline, while deck beams two and three would be completely submerged.

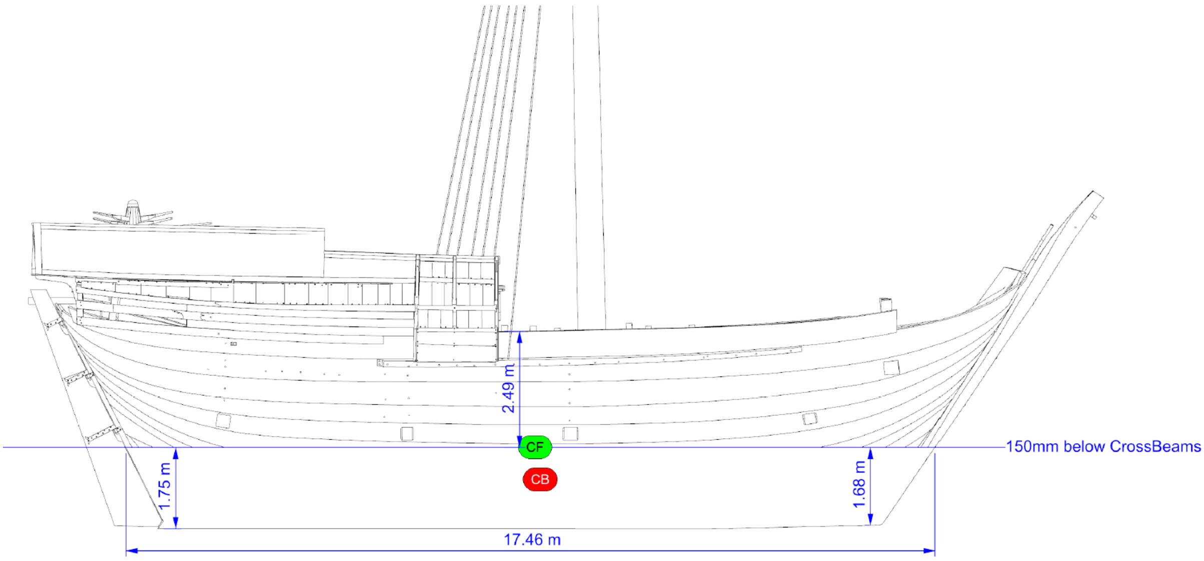


Figure 81 Loaded without submerging deck beams

With the cog loaded to maintain the deck beams above the waterline, and the deadweight of 58.7t, results in a total displacement of 87t and the vessel floats as shown in Figure 81Figure 80. This would result in a draught aft of 1.75m, a draught forward of 1.68m and a freeboard of 2.49m. However this would limit the total cargo capacity to 28.3t.

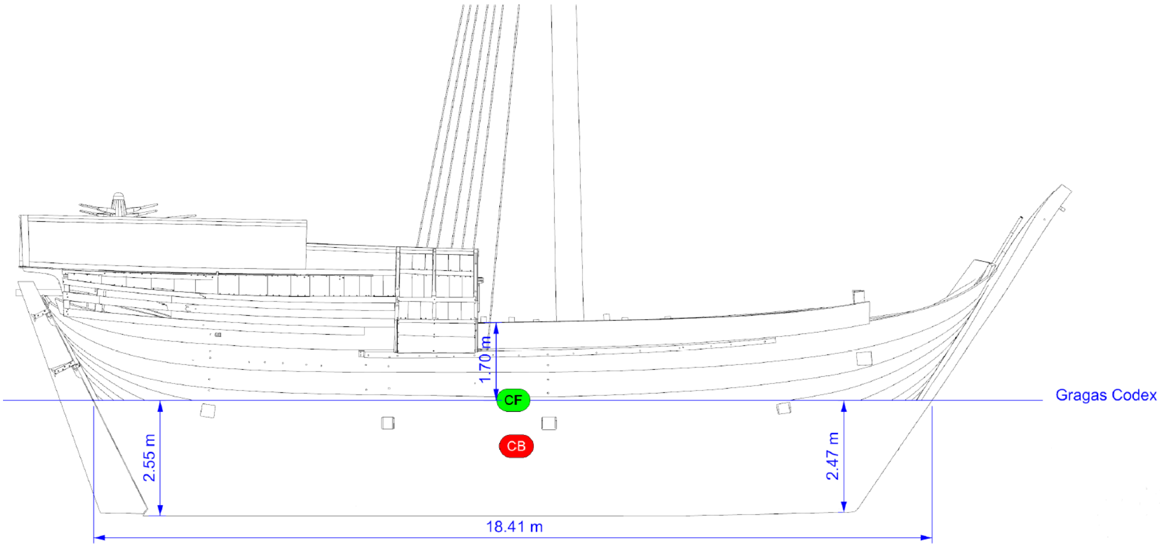


Figure 82 Loaded to Medieval Waterline Law

Loading the cog to the earliest known rules, a medieval Icelandic Law in the Grågås Codex from ca 1280, states the minimum freeboard (F) of a cargo ship should be F=2D/5 where D=depth of hull amidships (Morken 1980,178). For the cog this would be a freeboard of 1.7m. This would result in a total displacement of 154.6t, and the deadweight of 58.7t, results in a total cargo capacity of 96t. IT should be noted that in this condition four of the five deck beams which protrude through the hull are completely submerged.

This raises the question of the purpose for the wedge or pointed timbers elements typically found secured to the hull forward of the protruding ends of these deck beams, and often described as fenders to protect the protruding beam ends. Possibly these wedge shaped timbers could be installed as fairing blocks to improve the water flow around the protruding, submerged beam ends.

Is the cog the international trading ship of the Hanseatic League? In the opinion of this author, with many years of boat building and offshore sailing experience, probably not, more likely, a coastal trading vessel than an international sea-going trader. However, given that the Hanse traded with among others Iceland, further research is required to determine the exact sea-keeping capabilities and suitability of the cog as an offshore trading vessel.

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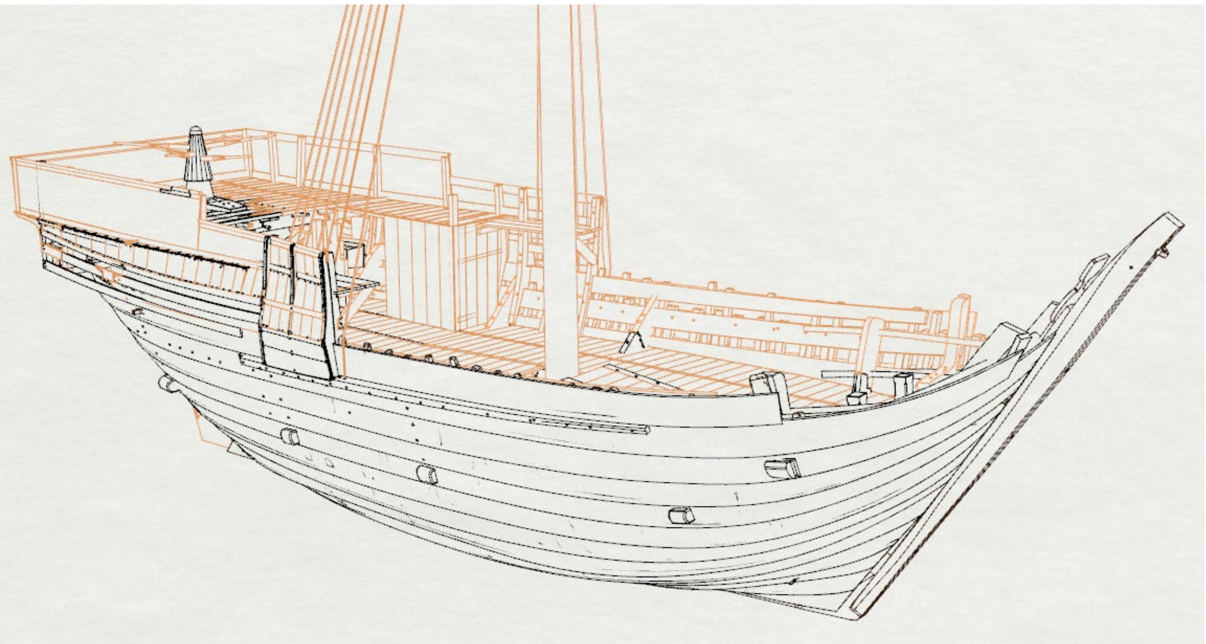
Appendix I Bremen Cog Seakeeping, Stability and Performance analysis

The Bremen Kogge
A Seakeeping, Stability and Performance Analysis



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I.1 Introduction

As previously discussed in the technical report examining the original reconstruction, the quantity and often fragmented condition of the many constituent parts posed a particular set of difficulties during the initial reconstruction process. With 37 published drawings, and the accompanying 250 plus page report (Lahn 1992), it has still proven difficult some 25 years later to accurately determine exactly which elements of the reconstruction were original documented components, and which elements form part of the hypothetical reconstruction. It would appear that the process employed during the initial reconstruction was to reassemble the vessel components and document the evolving hull form based on this reconstructed shape. Efforts were then (apparently) made to correct issues which arose during the reassembly process in the subsequent publications.

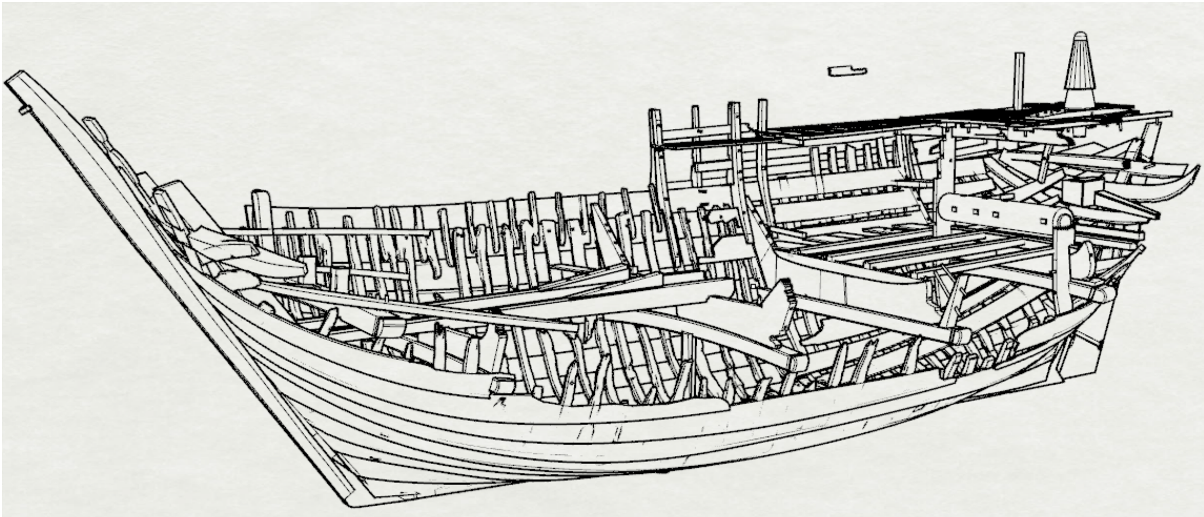


Figure 1 Recovered elements of the original vessel

Advances in three-dimensional digital modelling have highlighted some issues with the original reconstruction, in addition to highlighting some of the archaeological evidence, which was apparently not included in the reconstruction.

The alternative reconstruction (Figure 2) described in that technical report, clearly takes all the archaeological evidence into consideration, while also considering important additional factors such as timber shrinkage, and distortion in the reconstructed hull form as well as in that of the recovered elements. The techniques employed throughout this alternative reconstruction clearly identify and distinguish between recovered and reconstructed elements. Colour coding has been used throughout this report and the accompanying large format drawings to clearly distinguish between recovered and reconstructed components.

A brief description of the weight units used:

The tun, ton and tonne are probably the most mis-used and misunderstood unit of measurement known to humanity, often indiscriminately substituted, and generally leading to utter confusion.

The tun is based on the old cask measurement system and as such is a measure of volume rather than weight.

Ton or imperial ton is equal to 2240 pounds (abbreviated lbs), while in the United States US ton means 2,000 U.S. pounds. Consequently, came the development of the Long Ton or British ton at 2240 pounds, and the short ton at 2,000 pounds.

Tonne or metric tonne, often abbreviated to ton, is equal to 1,000kg.

Throughout this document weights will be given as kilograms (abbreviated kg) or metric tonne, unless specifically noted otherwise.

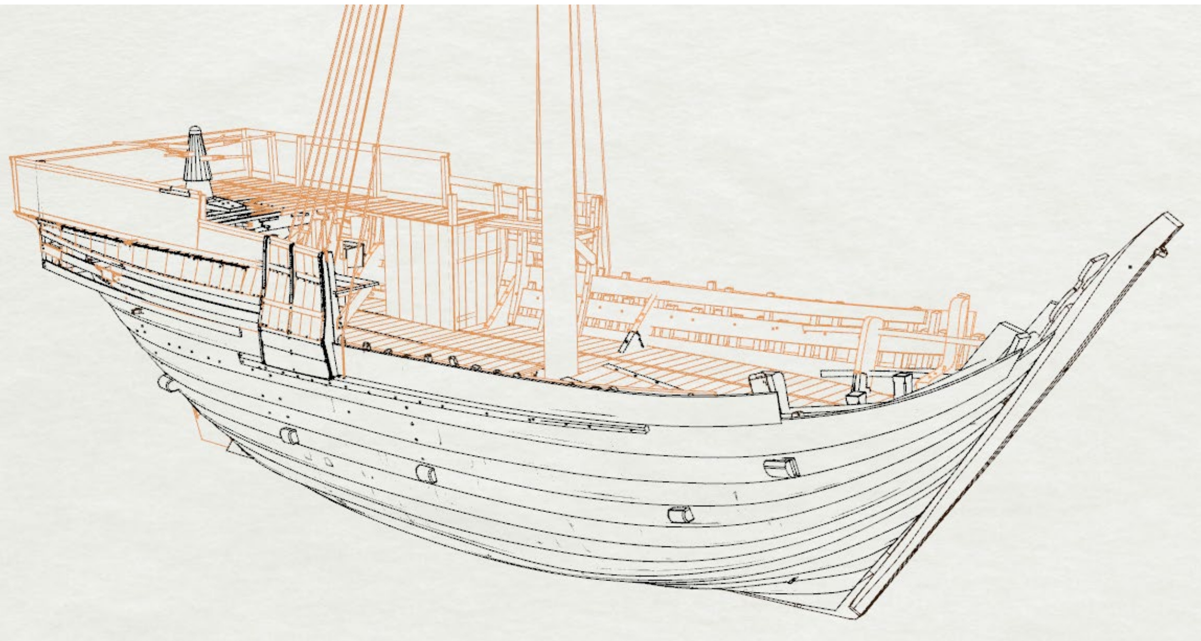


Figure 2 Alternative Reconstruction of the Bremen Cog

I.2 Analysis of the Alternative Reconstruction

McGrail (1988, p. 35) suggests the performance of ancient boats may be assessed in several ways; a: by eye, using general assessments of an experienced seaman, boatbuilder or naval architect. b: Using simple coefficients such as length/breadth, midship coefficient and block coefficient can give some idea of a boat's capabilities. c: Using hydrostatic curves to deduce performance based on underwater geometry. d: Small scale models to be used in tank and wind tunnel testing. e: Computer analysis as an effective way to investigate certain aspects of performance, especially when there are alternative reconstructions to be investigated. f: Building full size replicas and undertaking sea trials.

In Ancient Boats in North-West Europe (McGrail, 1998a, pp. 195–198) the author states the assessment of performance of excavated examples of early boats and ships is difficult, but by making certain assumptions it is possible to give broad answers to such questions as how fast was that boat? And what was her cargo capacity? Suggested approaches include

Speed estimates:

Prismatic coefficient:

(displacement volume (∇)) / (cross section area(A) x waterline length(LWL))

may be used in the range of speed equivalent to (speed) / ($\sqrt{}$ waterline length) equal to between 0.6 and 1.1. A low value of 0.55 to 0.53 indicates low resistance and hence a potentially fast boat.

At lower speed ranges the following coefficients may be used to compare speed potential.

Slenderness Coefficient: (waterline length) / (beam). High values (> 5) indicate good speed potential.

Midship Coefficient: (cross section area m²) / (beam x draft). Low values (< 0.85) indicate good speed potential.

Block Coefficient: (displacement volume (∇)) / (beam x waterline length x draft). Low values (< 0.65) indicate good speed potential.

Cargo Capacity:

Assessments of tonnage included traditional formulas such as Builders Old Measurement (BOM):

$$\text{tonnage} = \frac{\left(L - \frac{3}{5}B\right) \text{x B x} \frac{1}{2}B}{94}$$

where L = waterline length and B = waterline Beam.

In medieval times the problem of equating weight with volume in terms of standard unit of cargo had to be resolved to give an accurate indication of a vessel's capacity for costing and taxation purposes. As such '*tuns burthen'* is more a measure of internal volume, or 'standard units' a boat could carry, than an accurate measurement of load capacity.

Deadweight Coefficient = (deadweight kg) / (displacement force kg) measured the ability of a boat to carry cargo, ideally suited for heavy or high-density cargoes.

Once a reconstruction drawing or model is available, the performance of the boat it represents may be assessed in several ways using simple coefficients that are based on the boat's overall measurements, thus LOA/BOA and BOA/D summarise the overall proportions of the boat and as such give a relative assessment of the boats capabilities.

Empty bare hull and superstructure

Principal Dimensions

Length overall (LOA):	23.16m
Beam overall (BOA):	7.68m
Waterline Length (LWL):	16.49m
Waterline Beam (BWL):	5.15m
Navigational Draft (T):	1.25m
Displacement:	43,248kg
Keel Length:	15.6m

I.3 Assessment of Performance

Using these basic dimensions for the analysis of the alternative reconstruction would provide the following results:

Prismatic coefficient: (displacement volume (∇)) / (cross section area(A) x waterline length(L))
0.627

Slenderness Coefficient: (waterline length) / (beam). High values > 5 indicate good speed potential.
3.202

Midship Coefficient: (cross section area m²) / (beam x draft). Low values < 0.85 indicate good speed potential.
(4.074m²) / (5.15 x 1.25) = 0.633 0.634

Block Coefficient: (displacement volume (∇)) / (beam x waterline length x draft). < 0.65 indicate good speed potential.
0.398

Builders Old Measurement (BOM):

$$\text{tonnage} = \frac{\left(L - \frac{3}{5}B\right) \text{x B x} \frac{1}{2}B}{94}$$ = 199.5 tuns

From these results it would suggest the vessel with a:
'*Slenderness Coefficient*' of 3.202, does not have good speed potential.

'*Midship Coefficient'* result of 0.633 is less than the baseline value of 0.85, which would suggest the vessel has good speed potential.

'*Block Coefficient*' value of 0.398 being below the baseline value of 0.65 would also suggest a vessel with good speed potential.

In summary these coefficients would suggest the vessel is a 200 tun ship, with a speed potential somewhere between below average and good.

Clearly, this is not an accurate assessment of the vessels characteristics. The adjective "good" does little to describe the actual vessel. As a definition "good" can simply mean; of a high quality, standard or level; pleasant or enjoyable; better than or an improvement on;

Good is a relative adjective, but what is it relative to? What is the baseline against which it is measured?

Using hydrostatic curves involves the definition of the waterline(s), underwater shape and calculations of displacements, sectional areas and coefficient based on the underwater geometry (of a vessel), and may be used to give forecasts of performance (McGrail, 1998a, p. 192).

In order to use hydrostatic curves, underwater shape, and the sectional areas and coefficients of the underwater geometry of a vessel, it is first required to define what that underwater shape is. To establish the underwater geometry of a vessel it is firstly necessary to establish how the vessel floats in order to determine what portion of the vessel is under water.

Establishing a flotation condition

To establish a floatation condition for the vessel, three key facts are required,

(1) vessel hull shape to establish the centre of buoyancy (B),
(2) vessel weight to establish displacement.
(3) vessel centre of gravity (G) to establish floatation trim.

Vessel Hull Shape

The vessel hull shape has been established based on the reconstruction methods already employed in the previous technical report.

As there was little or no evidence of the rigging or internal fittings for the vessel, the ship will be analysed in the following conditions:

1 Empty bare hull and superstructure (Figure 4)
2 Rigged and crewed (Principal or Capital Reconstruction)
3 Minimum Ballast
4 Minimum Freeboard

Empty Bare Hull and Superstructure

Vessel Weight and Centre of Gravity

The most accurate method of determining the weight of a vessel is to weigh it in air and then carry out an inclining test to establish the position of centre of gravity (McKee, 1974, pp. 11–13). To weigh the vessel and perform an inclining test, a complete, rebuilt vessel would be required. As this is not practical, and the fact that various hypothetical reconstructions are still being examined, an alternative approach was used.

Every constituent part of the vessel was accurately modelled using Rhinoceros 3D solid modelling techniques, and, using the Orca 3D plug-in for Rhinoceros 3D, a material is assigned to each part. Orca 3D can use each constituent part's dimensions and assigned material, to calculate the weight, longitudinal, transverse and vertical centre of gravity for the entire vessel.

With regard to the materials assigned for each element, as the density of timber varies, an average density is used. For example, oak can vary between 600 and 900 kg per m^3, and in this case an average of 800 kg per m^3 is used, being the average density for oak at 27% moisture content. The treenails have not been modelled as these are basically a wooden dowel fitted to a pre-drilled hole and would have no effect on the overall weight.

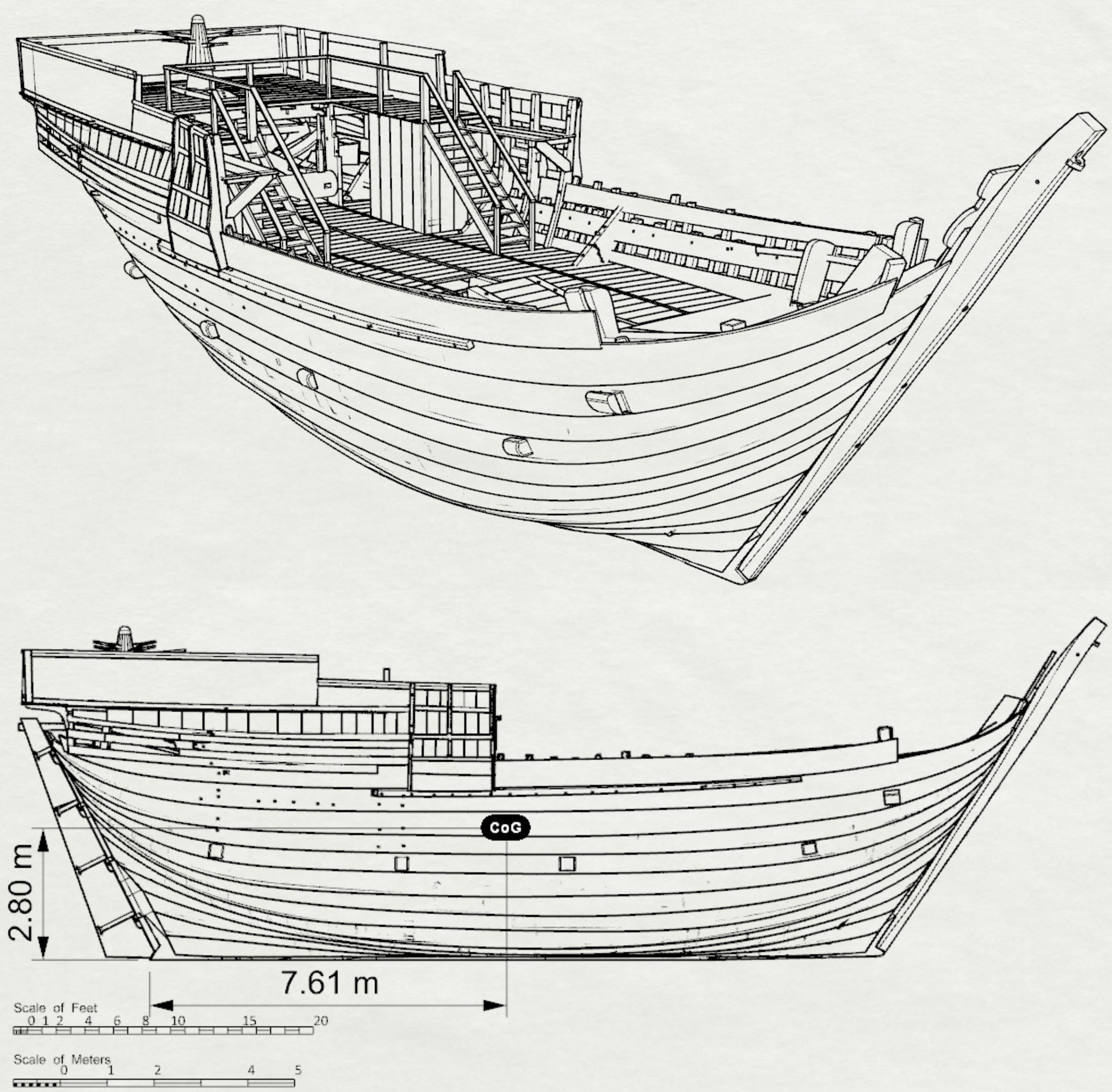


Figure 3 Empty Bare Hull and Superstructure

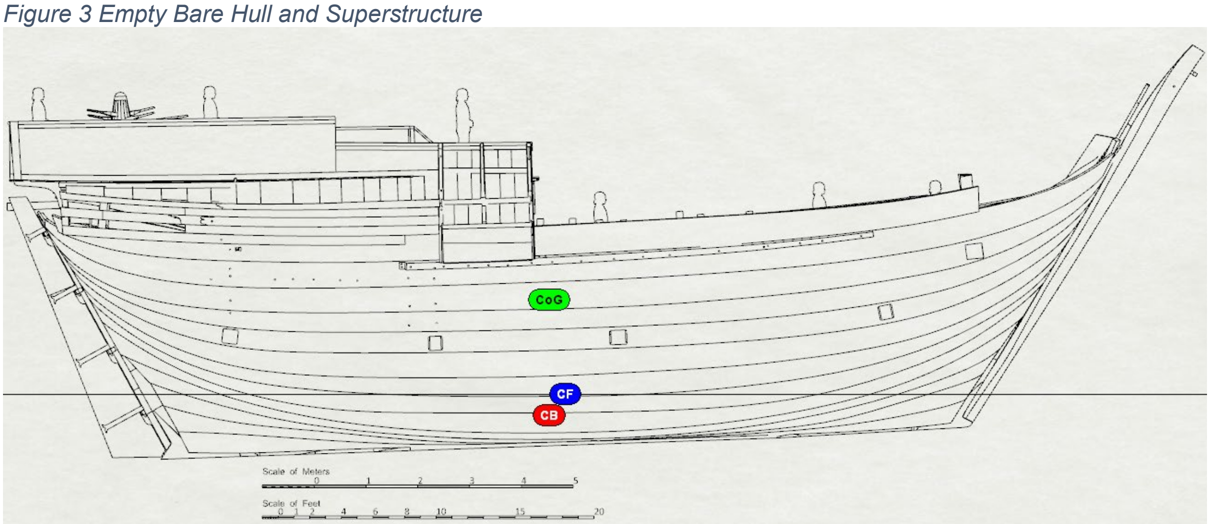


Figure 4 Flotation condition for the empty bare hull and superstructure

The iron nails were not individually modelled in the reconstructed vessel, but calculations based on average nail spacing indicates some 3,300 nails were used fastening the hull planking with a further 600 used on the castle deck area. to be included in the weight calculations. At an average of 0.18kg per nail the combined weight would be an additional 700 kg.

In this configuration the empty bare hull and superstructure weighs 43,248 kg. The centre of gravity (CoG) is located 7.61m forward and 2.80m above the aft lower edge of the keel. The vessel floats with a 2° stern down trim (Figure 4). The draft is 0.64m at the bow and 1.25m at the stern. The vessel has 3.1m freeboard aft, 3.26m amidships and 3.47m at the bow. The vessel can heel to 49.5° before water floods over the gunnel. The angle of maximum righting moment GZmax is 46.5° and the angle of vanishing stability GZ_0 is 68°.

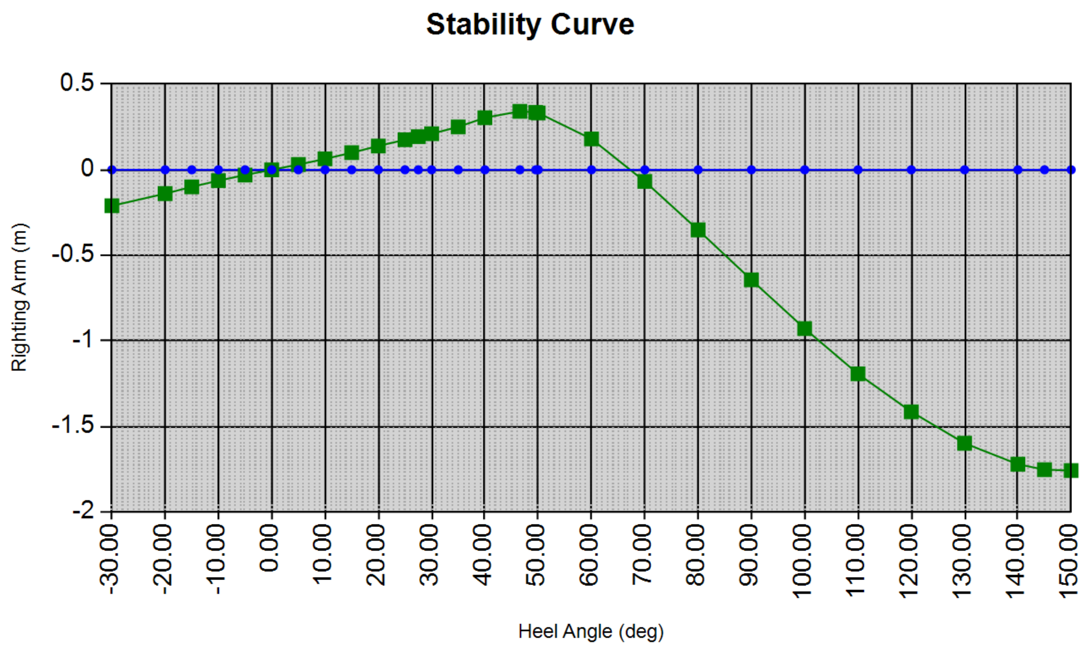


Figure 5 Stability curve for bare hull and superstructure

However, with such a small area of initial reserve stability (Figure 5), a gentle 10 knot breeze would cause 2 degrees of heel. Just 4 people standing at the edge of the deck would cause the vessel to heel by 3.5°. If a one-tonne weight were also added the angle of heel would increase to 16.4°. The addition of a second one-tonne weight would increase the heel angle beyond 61° and result in a catastrophic capsize of the vessel.

This would indicate that the completed hull and superstructure could be launched and moved to a floating berth to facilitate rigging and final fit-out, but the vessel would be incredibly 'tender' in this condition and great care would be needed.

Is this a potential clue to the final fate of the Bremen Cog, and an explanation for its seemingly unfinished construction state?

I.4 Principal or Capital Hypothetical Reconstruction

The aim in reconstructing the hull shape is to generate a floating hypothesis for the vessel in order to ascertain lines plans and hydrostatic data such as displacement, sailing characteristics and cargo carrying capabilities.

Once the hull and basic superstructure have been finalised based on the recovered archaeological evidence, it is necessary to include the additional elements such as rigging and internal fitout, required to generate a capital reconstruction or floating hypothesis.

"Principles for the Reconstruction of Ancient Boat Structures" (Crumlin-Pedersen and McGrail, 2006) set out a series of recommendations under five categories:

1. Deformation and its effects on the hull shape
2. The impact of modern naval architectural standards
3. The introduction of alien elements to complete the hull
4. The consideration of propulsion, steering and seaworthiness
5. The concept of minimum reconstruction

Both recommendations 1 and 2 have been dealt with in the previous report dealing with the reconstructed shape of the recovered vessel. Figure 3 represents a reasonably complete vessel with the exception of the standing rigging, mast, yard and support shrouds, and any internal fixtures or fittings.

Introduction of alien elements to complete the hull

In 1991 a master shipwright led a project to construct the *Hansekogge*, a full-size replica of the Bremen vessel with advice provided by Hoheisel and Lahn. The hull was built as authentically as possible, while rigging and sails were calculated according to the Timbotta manuscript of 1445.

From the Timbotta manuscript the standing rigging would have proportions of:
Mast = Beam (7.62m) x 4 = 30.48m, and Yard = 4/5 of Mast = 24.57m.

Hoffmann notes the mast standing 24m above deck, and based on recommendations from Roskilde, the single square sail was reduced in width, resulting in a yard of 14.6m length and a total sail area of 199m² for the *Hansekogge* replica.

At the same time the *Hansekogge* was built in Kiel, another replica the *Ubena* was built in Bremerhaven based on the same drawings by Werner Lahn. For the *Ubena* cog it was decided to carry a much longer yard and a sail 4m wider than the *Hansekogge* in order to more closely reflect the recommendations of the Timbotta manuscript.

A third replica the *Roland von Bremen* was also constructed in 2000, but due mainly to increased mast and hull planking thickness the total displacement is listed at 120 tonnes (Table 1), significantly more than that of the other two replicas. In addition Hoffmann (2009, p. 293) notes an inability to obtain information on the sailing qualities of the *Roland von Bremen*, the replica with the smallest rig and sails, and states the vessel has probably never really been subjected to sea trials and proper sailing tests.

	Ubena	*Hansekogge*	*Roland von Bremen*
Length amidships incl. stern castle	23.23m	23.27m	23.27m
Maximum Beam	7.62m	7.62m	7.62m
Length of Keel	15.6m	15.6m	15.6m
Height of Mast	23m	24m	22.5m
Length of Yard	18m	14.6m	18m
Sail Area	150m² + 3 bonnets of 50m² each	100m² + 3 bonnets of 33m² each	90m² + 2 bonnets of 30m² each
Total Sail Area	300m²	199m²	150m²
Displacement	c.75 tonnes, incl. 35 tonnes lead ballast	60 tonnes, incl. 22 tonnes stone ballast	120 tonnes, incl. 20 tonnes lead ballast
Draft	2.25m	1.6m	2.25m
Engine	400hp Volva Penta with propeller	2 Schottel water-jet units	2 Schottel water-jet units
Equipment	All modern safety and navigation equipment	All modern safety and navigation equipment	All modern safety and navigation equipment
Installations	16 comfortable bunks in cabins, elec. Lighting, heating, WC, Shower, Pantry	12 bunks in cabins, 12 bunks in Hold, elec. Lighting, heating, WC, Shower, Pantry	11 simple bunks, elec. Lighting, heating,2 WCs, Pantry
Construction	45m³ Seasoned Oak keel and planking 110m³ Green Oak Frames and Interior	56m³ Oak for hull Larch for Mast and Yard	90 tonnes Oak
Fastenings	7,000 hand-forged stainless-steel nails	11,000 hand-forged stainless-steel nails	10,000 hand-forged stainless-steel nails
Crew	12 + Captain	10 + Captain	6 + Captain
Sailing Area	North and Baltic Seas	North and Baltic Seas	Rivers and Inland waters Germany

Table 1 Comparative Data for the three Replicas after (Hoffmann and Hoffmann, 2009, p. 291)

Certain anomalies and pertinent facts are immediately obvious from the above table of comparative data. The *Roland von Bremen* replica is significantly (77%) heavier than the other two and has a far lesser sail area. A direct means of comparison would be the Sail Area/Displacement ratio, which is, 184 for *Ubena*, 142 for *Hansekogge* and only 67 for the *Roland von Bremen*. This is a direct, power to weight comparison, between each of the three replicas.

Furthermore, if all three replicas are in fact built to the same drawings, it is physically impossible for the same hull shape to have the same draft and have a 77% increase in displacement. Modern digital analysis of the Lahn hull shape results in the following draft / displacement values:

60 tonnes displacement = 1.53m draft
75 tonnes displacement = 1.75m draft
120 tonnes displacement = 2.33m draft

In addition to the above-mentioned anomalies, certain elements such as engine, safety and navigation equipment, electric lighting, heating and showers are certainly not contemporaneous with the original Bremen Cog, and it is doubtful any of the modern luxuries such as 'comfortable bunks in cabins' would have featured onboard the original vessel.

A 400hp Volva Penta engine weighs circa 660kg and has a fuel consumption of circa 52 litres per hour, a 5,000-litre fuel tank would not be considered extreme. This would only allow for five days continuous motoring or a range of 600 nautical miles.

This gives a combined total weight of 5,660kg which would need to be replaced with ballast in the original vessel.

For the other two replicas, twin Schottel water-jet units weigh circa 470kg each, and with a similar 5000 litre fuel tank would result in a combined weight of 5,940kg which would need to be replaced with ballast in the original vessel.

This would result in a reduced total weight, of the empty vessel including rigging and internal fillings, for the *Ubena* replica of 34.34 tonnes, 32.06 tonnes for the *Hansekogge* replica and 94.1 tonnes for the *Roland von Bremen* replica.

The digital reconstruction of the empty bare hull and superstructure weighs 43,248 kg excluding rigging, internal ballast and any form of interior fitout. This would indicate some further anomalies with the data reproduced in Table 1. Indeed, the *Hansekogge* lists a total fully laden weight of 84 tonnes (Hoffmann and Hoffmann, 2009, p. 291), and with the removal of engines and ballast this would further reduce to 56.1 tonnes.

Rigging Reconstruction:

Details as described in ‘Sailing the Bremen Cog’ (Hoffmann and Hoffmann, 2009) are to be used in creating a reconstruction of the sailing rig. Hoffman notes the mast position was fixed from the archaeological evidence with the recovery of the mast step, as were the shroud fixing points in the channel wale and stem-head. Dimensions for the standing rigging were based on a manuscript dating to 1445, which describes the mast of an Italian coche as being four times the hull’s beam. The yard-to-mast ratio should be 4:5 and the sail should be twice as wide as it is deep. Bonnets (extra panels attached to the bottom of the mainsail) would allow for an almost square mainsail in light weather conditions.

The authors also note the hypothetical rigging reconstruction developed by Hoheisel, a naval architect and director of the Deutches Shiffahrtmuseum, was tested by students at the University of Hamburg in a wind-tunnel. Conclusions suggested the cog would be capable of tacking to windward, but the authors note the experiments did not include wave force or seaway. A student at the university of Berlin tested the hull shape using an idealised set of lines plans and calculated stability for various cargo loads. Results indicated the ballasted or loaded ship displayed sufficient stability, but not unballasted with the mast stepped.

From Table 1 the three replicas have a mast height of 23m, 24m and 22.5m, a yard length of 18m, 14.6m and 18m, and a sail area of 300m², 199m² and 150m² for the *Ubena*, *Hansekogge* and *Roland von Bremen* respectively.

As part of the principal or capital reconstruction a mast height of 23.5m was chosen, with a yard length of 18m and a sail area of 199m² comprising of a mainsail of 100m² with three additional bonnets of 33m² each.

While it would be unreasonable to claim the digital reconstruction represents an exact copy of the exact rigging employed on 14th century Cog type sailing vessels, the elements modelled represent what could be classed as the bare minimum required for the mast, yard and sails to be operated in a functional and seaman like manner. This is based on this authors more than 30 years of offshore sailing on various modern and traditional sailing craft. With these elements accurately modelled and materials assigned, the Orca 3D software is able to determine an accurate weight and centre of gravity for all of the rigging components. Some examples of weights determined from the digital reconstruction of the rigging are:

Mast – Spruce, 2,334kg: Yard – Spruce, 442kg: Standing Rigging – forestay and shrouds, 158kg: Running Rigging – halyards, sheets etc., 237.8kg

Two anchors – Iron and oak (incl. anchor warps), 265kg each.

The combined total for the standing and running rigging as modelled is 3,861kg and would appear to be in some agreement with figures quoted in “Sailing The Bremen Cog” (Hoffmann and Hoffmann, 2009, p. 289) *.. because, on the replica, at least five*

people are needed to operate the barrel-winch and to handle the 300-kg yard.

The centre of gravity of the rigging is 10.46m ahead of and 10.48m above the aft lower edge of the keel. When these weights are combined with the vessel the net result is a combined weight of 47,019kg and the combined centre of gravity shifts vertically by 0.624m and towards the fore by 0.24m (Figure 6).

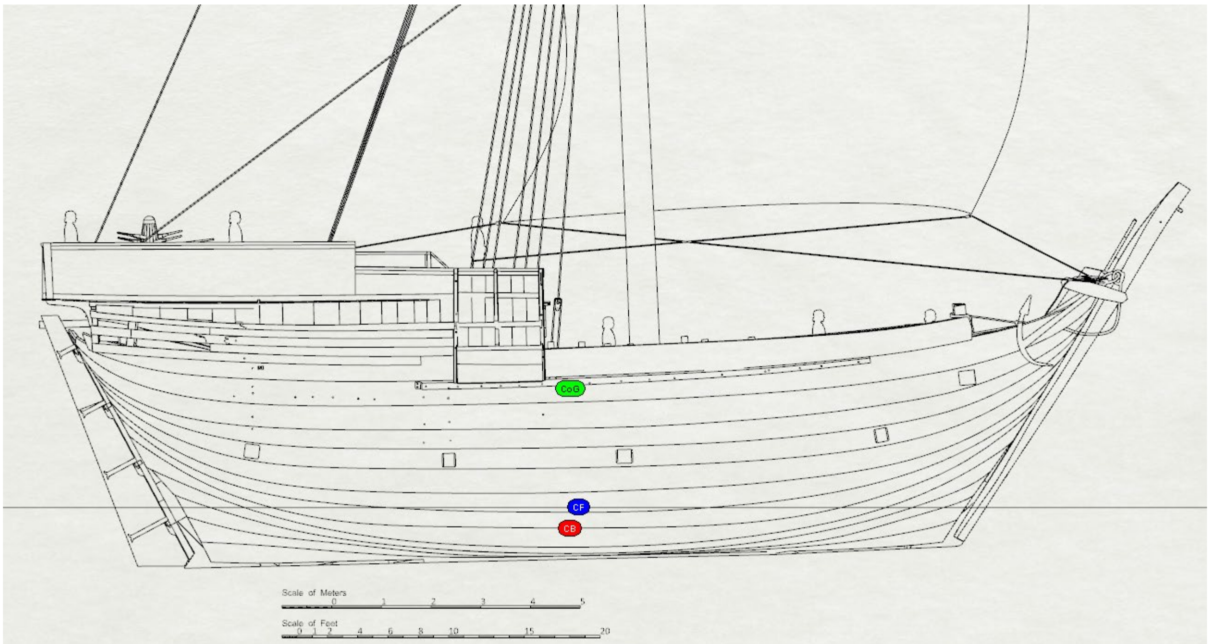


Figure 6 Flotation Condition with mast and rigging

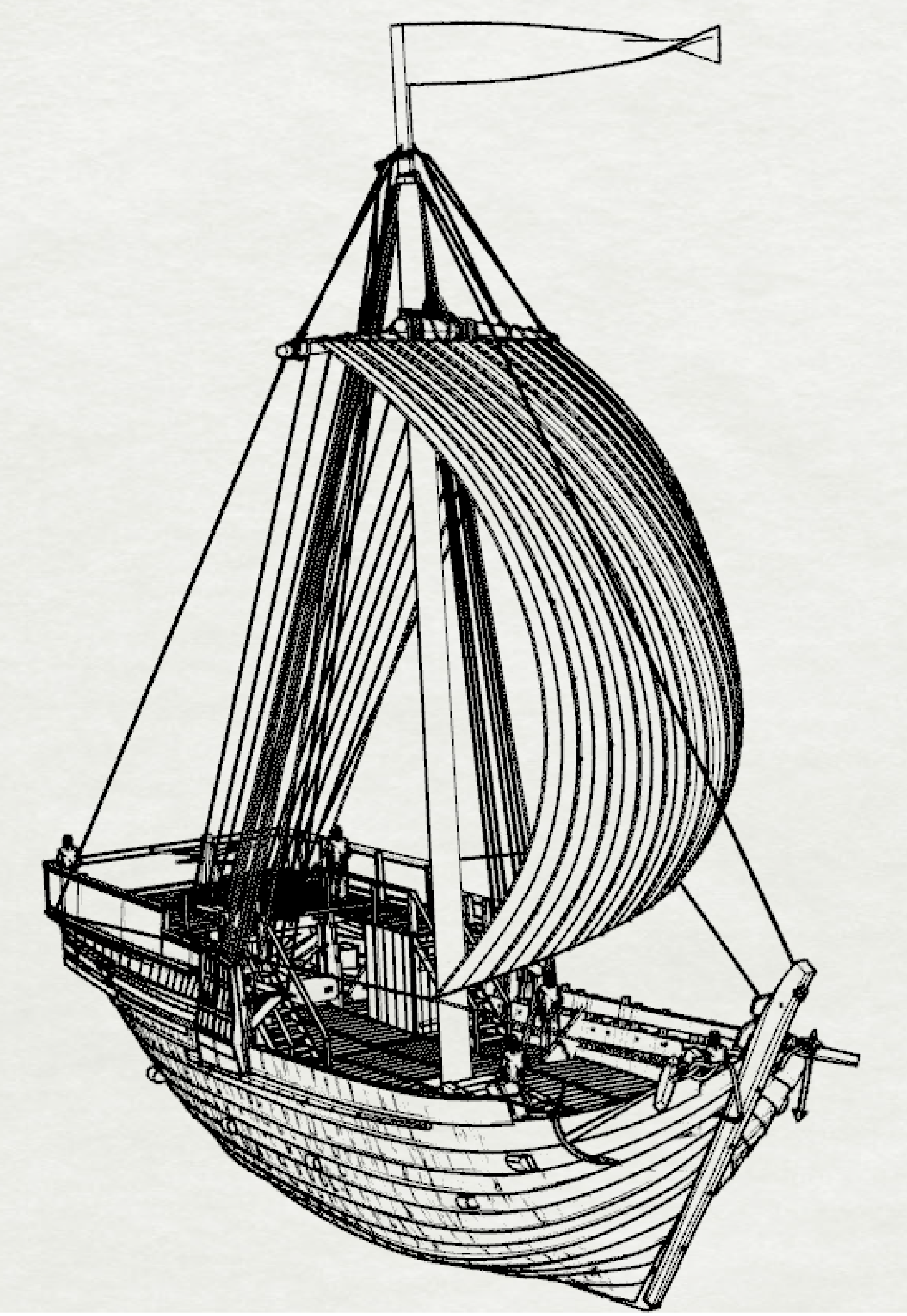


Figure 7 Principal Reconstruction with mast and rigging added

In this configuration (Figure 7), the complete hull, superstructure, mast, yard and running rigging, but no internal fittings or ballast, the vessel weighs 47.294 tonnes, and the centre of gravity is located 3.4m above the keel. This causes the vessel to have a negative transverse metacentric height GM_T of -0.292m.

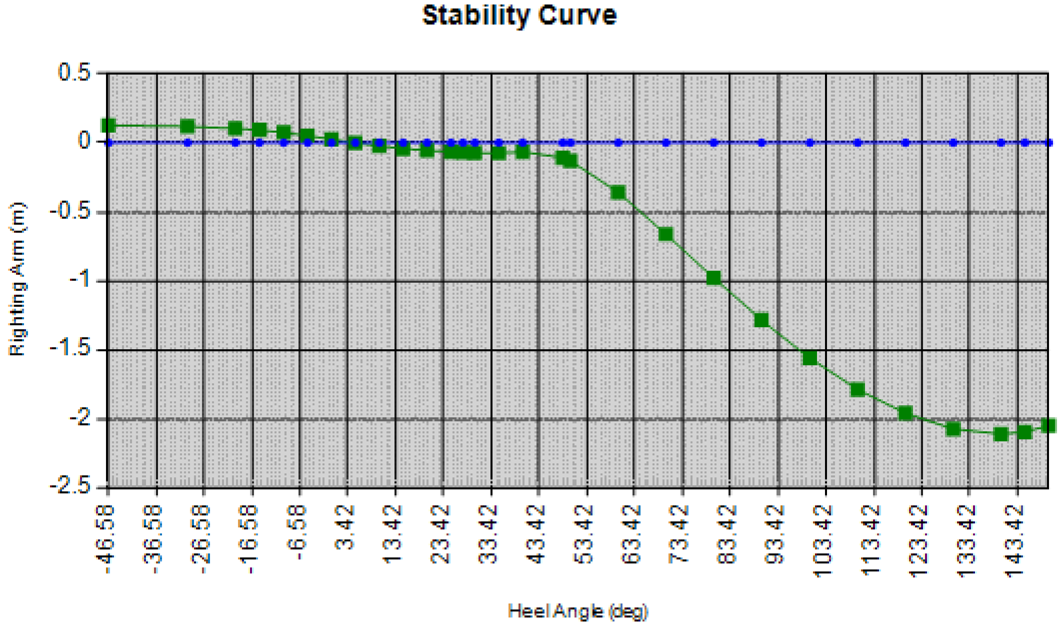


Figure 8 Stability Curve fully rigged vessel

A vessel with a negative metacentric height is not stable in an upright condition, which leads to a heeling moment. This heeling moment will cause the vessel to heel or lean up to an angle where the righting moment and righting lever both become zero. That angle in this configuration is 4.7°. However due to the convex downward curvature of the stability curve (Figure 8), the righting lever will only increase its negative value as the vessel heels further. Any slight heeling moment, such as a single person stepping aboard, or a gentle wind will capsize the ship.

Stability Criteria - Bureau Veritas, Intact Stability

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
GM At FreeEquil >= 0.15 meters	4.7033		0.15	-0.2896	Fail
GZ At 30 >= 0.2 meters	30		0.2	-0.0749	Fail
Angle At GZmax >= 25 deg	-46.5788		25	-46.5788	Fail
Area Between 0 and 30 >= 3.151 meters-deg	0	30	3.151	-1.084	Fail
Area Between 30 and 40 >= 1.1719 meters-deg	30	40	1.1719	-0.7307	Fail
Area Between 0 and 40 >= 5.157 meters-deg	0	40	5.157	-1.8146	Fail
Area Between 0 and Flood >= 5.157 meters-deg	0	48.4032	5.157	-2.5503	Fail
Area Between 30 and Flood >= 1.1719 meters-deg	30	48.4032	1.1719	-1.4664	Fail

Figure 9 Stability Criteria Fully rigged vessel

Figure 9 indicates it would be physically impossible to rig the ship without some quantity of internal ballast to lower the ship's centre of gravity.

Minimum Ballast

A ballast of 24 tonnes was calculated as being necessary, based on the weight of stones found in the Vejby Cog found in Denmark. Professor Harro Postel of the Institute for Shipbuilding in Kiel undertook tank-towing tests, and noted the cog appeared stable, but did not believe it would be capable of tacking. His experiments showed the ship could only sail to within 90° of the true wind and Postel describes the vessel as a 'beam wind sailor' provided it is suitably ballasted and in calm waters (Hoffmann and Hoffmann, 2009, pp. 287–289).

Ballasting the vessel to improve stability

During the research and construction of the Hanse cog replica a figure of 24 tonnes ballast was deemed necessary based on the on the weight of stones found in the Vejby Cog discovered in Denmark (Hoffmann and Hoffmann, 2009, pp. 287–289).

The book "On the Stowage of Ships and Their Cargoes" (Stevens, 1863, p. 11) suggests a figure of one ton of ballast per ten of tonnage. With the Builders Old Measurement of 200 tuns for the Bremen cog, this would indicate 20 tonnes of ballast. Discussing ballast Stevens notes there is no specific rule for the quantity required by a ship, and a general rule would be half her tonnage (builder's old measurement). Sand should never be taken when stone is available, but if compelled to use sand, every means should be used to prevent it entering the limber holes or pumps (Stevens, 1863, p. 34). Granite or limestone are a common form of ballast stone and while both have a density of circa 2,700kg per cubic meter, Stevens suggest a figure of 1,016kg per m^3 for rough stone.

Clearly some quantity of internal ballast is required for the vessel to function safely. For any cargo vessel the internal volume or cargo capacity is its most valuable commodity. As internal ballast is generally not a valuable or marketable commodity, it is desirable to keep the volume to a minimum. To this end the least volume of internal ballast is the preferred option, and for maximum effect should be as heavy (dense) and positioned as low as practicable inside the vessel.

The least practicable quantity of internal ballast would be a sufficient weight to resist the overturning moment generated by the vessel while under sail. As already discussed in the rigging reconstruction, the hypothetical reconstruction would carry a mast of 23.5m, with a yard length of 18m and a sail area of 199m^2 comprising of a mainsail of 100m^2 with three additional bonnets of 33m^2 each. Typically, the "Full Sail" of 199m^2 (Figure 7) would be used in light to moderate wind conditions, with the sail area being reduced by removing bonnets, down to the minimum or "reefed" sail area of 100m^2 (Figure 10), as the wind strength increases.

I.5 Method of Assessment

Modern rules for the stability of ships are formulated by the International Maritime Organisation (IMO), and it is at the discretion of inspectorates or classification societies to adopt these rules or make them even more stringent. Bureau Veritas (BV) is one such classification society founded in Antwerp in 1828, originally Belgian but now a French society (Bureau Veritas 2012:81–97). The stability testing carried out in the next sections uses the Bureau Veritas criteria:

The main stability rules are the same for IMO and BV

Area GZ_{0-30} > 0.055 m-rad or 3.151 m-deg Height GM_0 > 0.15 m
Area $GZ_{0-40(f)}$ > 0. 009 m-rad or 5.157 m-deg Angle GZ_{max} > 25° (preferably >30°)
Area $GZ_{30-40(f)}$> 0. 003 m-rad or 1.719 m-deg

These are the minimum intact stability criteria, and for unrestricted navigation, such as ocean voyages, the additional weather criterion including wind loading and rolling waves are to be complied with. These include:
Height GM ≥0.30m Wind Heel Angle ≤ 16° or 20º for sailing vessels
Righting Lever GZ ≥0.20m at 30° heel angle
Righting Lever GZ ≥0.50m at 50° heel angle

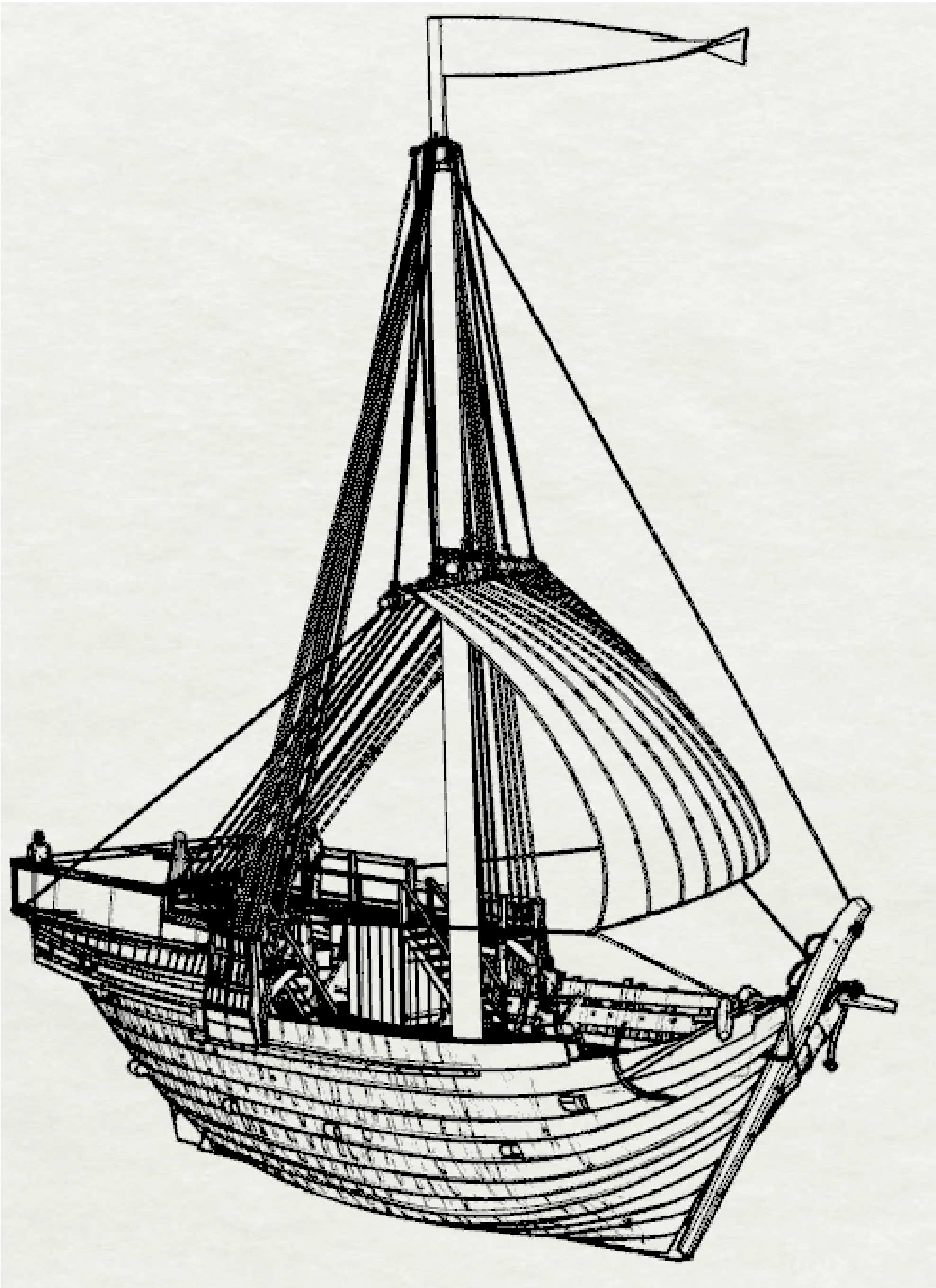


Figure 10 Fully Reefed Sail Area

The vessel was tested with varying quantities of internal stone ballast and analysed with the Orca 3D software using ‘modern’ Bureau Veritas stability criteria.

To begin a depth of 25cm resulting in 7,230 kg of ballast was tested, with each additional 5cm of stone adding circa 2,900 kg to the total ballast.

A total depth of 41cm resulted in 15,090 kg of internal ballast. This resulted in a combined total vessel weight of 62,294 kg, which included all of the hull and superstructure (stern castle), mast, yard and sail, standing and running rigging, anchors and warps, and “permanent” internal stone ballast. This would be classed as the Lightship displacement condition (Figure 11), which is the fully rigged vessel excluding cargo, crew or stores.

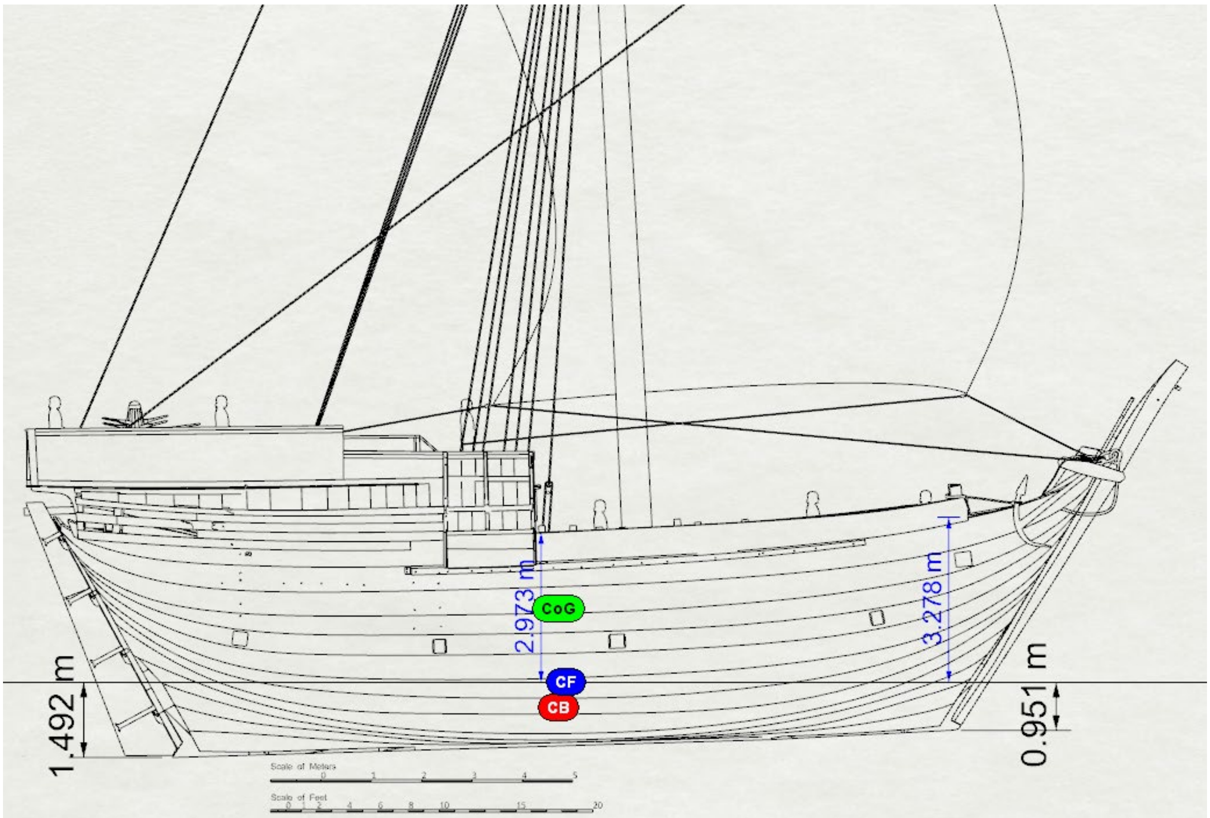


Figure 11 Lightship Flotation Condition

In this configuration the vessel which weighs 62,294 kg floats with 1.49m draft aft, 0.95m draft forward and has 2.97m freeboard amidships. The centre of gravity is located 7.68m ahead and 2.95m above the lower aft edge of the keel.

Principal Characteristics

Length overall (LOA):	23.16m	Prismatic Coefficient:	0.653
Beam overall (BOA):	7.68m	Block Coefficient:	0.446
Waterline Length (LWL):	16.83m	Midship Coefficient:	0.684
Waterline Beam (BWL):	5.42m	Slenderness Coefficient:	3.105
Navigational Draft (T):	1.49m	Waterplane Area:	70.1m²
Displacement:	62,294kg	Wetted Surface Area:	94.2m²
Keel Length:	15.6m	Metacentric Height GM_t:	0.338m
Freeboard amidships	2.98m	Sail Area (100m² reefed):	199m²
Ballast:	15,090kg		

Stability Criteria - Bureau Veritas, Intact Stability

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
GM At FreeEquil >= 0.15 meters	0		0.15	0.3385	Pass
GZ At 30 >= 0.2 meters	30		0.2	0.2598	Pass
Angle At GZmax >= 25 deg	41.2531		25	41.2531	Pass
Area Between 0 and 30 >= 3.151 meters-deg	0	30	3.151	3.3472	Pass
Area Between 30 and 40 >= 1.1719 meters-deg	30	40	1.1719	3.1453	Pass
Area Between 0 and 40 >= 5.157 meters-deg	0	40	5.157	6.4926	Pass
Area Between 0 and Flood >= 5.157 meters-deg	0	44.7235	5.157	8.1425	Pass
Area Between 30 and Flood >= 1.1719 meters-deg	30	44.7235	1.1719	4.7953	Pass

Stability Criteria - Bureau Veritas, Wind with Rolling Waves, Full Sail 5Kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil < Flood deg	2.1699		44.7235	2.1699	Pass
Angle At SteadyEquil +25 deg < Flood deg	27.1699		44.7235	27.1699	Pass
GZ From 30 to GZmax > 0.2 meters	30	41.2531	0.2	0.3233	Pass
Area Between FreeEquil and 30 > 3.151 meters-deg	0	30	3.151	3.3472	Pass
Area Between FreeEquil and 40 > 5.157 meters-deg	0	40	5.157	6.4926	Pass
Area Between FreeEquil and Flood > 5.157 meters-deg	0	44.7235	5.157	8.1425	Pass
Area Between 30 and Flood > 1.719 meters-deg	30	44.7235	1.719	4.7953	Pass
Angle At GZmax > 25 deg	41.2531		25	41.2531	Pass
GM At FreeEquil > 0.15 meters	0		0.15	0.3642	Pass
ResRatio Between SteadyEquil-25 deg and Flood > 1	-22.8301	44.7235	1	3.6617	Pass
FloodHt At SteadyEquil > 0.5 meters	2.1699		0.5	2.7447	Pass
Angle At SteadyEquil <= 20 deg	2.1699		20	2.1699	Pass

Stability Criteria - Bureau Veritas, Wind with Rolling Waves, Full Sail 10Kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil < Flood deg	8.0944		44.7235	8.0944	Pass
Angle At SteadyEquil +25 deg < Flood deg	33.0944		44.7235	33.0944	Pass
GZ From 30 to GZmax > 0.2 meters	30	41.2531	0.2	0.3233	Pass
Area Between FreeEquil and 30 > 3.151 meters-deg	0	30	3.151	3.3472	Pass
Area Between FreeEquil and 40 > 5.157 meters-deg	0	40	5.157	6.4926	Pass
Area Between FreeEquil and Flood > 5.157 meters-deg	0	44.7235	5.157	8.1425	Pass
Area Between 30 and Flood > 1.719 meters-deg	30	44.7235	1.719	4.7953	Pass
Angle At GZmax > 25 deg	41.2531		25	41.2531	Pass
GM At FreeEquil > 0.15 meters	0		0.15	0.3976	Pass
ResRatio Between SteadyEquil-25 deg and Flood > 1	-16.9056	44.7235	1	3.2071	Pass
FloodHt At SteadyEquil > 0.5 meters	8.0944		0.5	2.4122	Pass
Angle At SteadyEquil <= 20 deg	8.0944		20	8.0944	Pass

Stability Criteria - Bureau Veritas, Wind with Rolling Waves, Full Sail 15 Kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil < Flood deg	15.8933		44.7235	15.8933	Pass
Angle At SteadyEquil +25 deg < Flood deg	40.8933		44.7235	40.8933	Pass
GZ From 30 to GZmax > 0.2 meters	30	41.2531	0.2	0.3233	Pass
Area Between FreeEquil and 30 > 3.151 meters-deg	0	30	3.151	3.3472	Pass
Area Between FreeEquil and 40 > 5.157 meters-deg	0	40	5.157	6.4926	Pass
Area Between FreeEquil and Flood > 5.157 meters-deg	0	44.7235	5.157	8.1425	Pass
Area Between 30 and Flood > 1.719 meters-deg	30	44.7235	1.719	4.7953	Pass
Angle At GZmax > 25 deg	41.2531		25	41.2531	Pass
GM At FreeEquil > 0.15 meters	0		0.15	0.5753	Pass
ResRatio Between SteadyEquil-25 deg and Flood > 1	-9.1067	44.7235	1	2.0845	Pass
FloodHt At SteadyEquil > 0.5 meters	15.8933		0.5	1.8963	Pass
Angle At SteadyEquil <= 20 deg	15.8933		20	15.8933	Pass

Stability Criteria - Bureau Veritas, Wind with Rolling Waves, Full Sail 20Kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil < Flood deg	23.0361		44.7235	23.0361	Pass
Angle At SteadyEquil +25 deg < Flood deg	48.0361		44.7235	48.0361	Fail
GZ From 30 to GZmax > 0.2 meters	30	41.2531	0.2	0.3233	Pass
Area Between FreeEquil and 30 > 3.151 meters-deg	0	30	3.151	3.3472	Pass
Area Between FreeEquil and 40 > 5.157 meters-deg	0	40	5.157	6.4926	Pass
Area Between FreeEquil and Flood > 5.157 meters-deg	0	44.7235	5.157	8.1425	Pass
Area Between 30 and Flood > 1.719 meters-deg	30	44.7235	1.719	4.7953	Pass
Angle At GZmax > 25 deg	41.2531		25	41.2531	Pass
GM At FreeEquil > 0.15 meters	0		0.15	0.8705	Pass
ResRatio Between SteadyEquil-25 deg and Flood > 1	-1.9639	44.7235	1	1.0198	Pass
FloodHt At SteadyEquil > 0.5 meters	23.0361		0.5	1.4038	Pass
Angle At SteadyEquil <= 20 deg	23.0361		20	23.0361	Fail

Stability Criteria - Bureau Veritas, Wind with Rolling Waves, Reefed Sail 20 kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil < Flood deg	16.0697		44.7235	16.0697	Pass
Angle At SteadyEquil +25 deg < Flood deg	41.0697		44.7235	41.0697	Pass
GZ From 30 to GZmax > 0.2 meters	30	41.2531	0.2	0.3233	Pass
Area Between FreeEquil and 30 > 3.151 meters-deg	0	30	3.151	3.3472	Pass
Area Between FreeEquil and 40 > 5.157 meters-deg	0	40	5.157	6.4926	Pass
Area Between FreeEquil and Flood > 5.157 meters-deg	0	44.7235	5.157	8.1425	Pass
Area Between 30 and Flood > 1.719 meters-deg	30	44.7235	1.719	4.7953	Pass
Angle At GZmax > 25 deg	41.2531		25	41.2531	Pass
GM At FreeEquil > 0.15 meters	0		0.15	0.58	Pass
ResRatio Between SteadyEquil-25 deg and Flood > 1	-8.9303	44.7235	1	2.0569	Pass
FloodHt At SteadyEquil > 0.5 meters	16.0697		0.5	1.884	Pass
Angle At SteadyEquil <= 20 deg	16.0697		20	16.0697	Pass

Stability Criteria - Bureau Veritas, Wind with Rolling Waves, Reefed Sail 25 kts

Name	Angle 1	Angle 2	Required	Actual	Pass / Fail
Angle At SteadyEquil < Flood deg	21.5892		44.7235	21.5892	Pass
Angle At SteadyEquil +25 deg < Flood deg	46.5892		44.7235	46.5892	Fail
GZ From 30 to GZmax > 0.2 meters	30	41.2531	0.2	0.3233	Pass
Area Between FreeEquil and 30 > 3.151 meters-deg	0	30	3.151	3.3472	Pass
Area Between FreeEquil and 40 > 5.157 meters-deg	0	40	5.157	6.4926	Pass
Area Between FreeEquil and Flood > 5.157 meters-deg	0	44.7235	5.157	8.1425	Pass
Area Between 30 and Flood > 1.719 meters-deg	30	44.7235	1.719	4.7953	Pass
Angle At GZmax > 25 deg	41.2531		25	41.2531	Pass
GM At FreeEquil > 0.15 meters	0		0.15	0.8143	Pass
ResRatio Between SteadyEquil-25 deg and Flood > 1	-3.4108	44.7235	1	1.2191	Pass
FloodHt At SteadyEquil > 0.5 meters	21.5892		0.5	1.5029	Pass
Angle At SteadyEquil <= 20 deg	21.5892		20	21.5892	Fail

Figure 12 Lightship Stability Results

For this flotation condition, the vessel passes all the 'modern' Bureau Veritas stability criteria (Figure 12), including wind loading and rolling waves for wind strengths of 5 (F2 or 2.6m/s), 10 (F3 or 5.1m/s) and 15kts (F4 or 7.7m/s) with a full sail area. With full sail area and 20kts (F5 or 10.3m/s) wind speed the vessel fails the rolling wave criteria and the maximum wind heel angle criteria.

However common sense would dictate that the sail area be reduced or "reefed" as the wind strength increases (Figure 10), and with the reduced sail area the vessel passes all criteria for 20kts (F5 or 10.3m/s) wind strength and with a wind strength of 25kts (F6 or 12.9m/s) only fails for the rolling wave and wind heel angle.

It should be noted that the test criteria were examined for a worst-case scenario, that is with a beam on wind and the sails sheeted in fully to capture the maximum wind. As the wind increases the sheets would normally be eased out to ease pressure and reduce the wind heel angle. This would easily reduce the heel angle by the required 3° and 1.5° for full sail in 20kts and reduced sail in 25kts respectively.

The only criteria on which the vessel fails the modern standards is the rolling wave criterion, which states the vessel should not heel to a point where the deck is immersed, when an additional 25° to allow for wave rolling is added to the wind heel angle.

This 25° wave roll angle, is a standard "margin of safety" figure applied by the modern licencing and safety authorities. All the inspectorates and classification societies also give the option for "alternative" compliances and will accept lower values by agreement on a case by case basis. An example of this from Bureau Veritas:

> "In cases of ships with a particular design and subject to the prior agreement of the flag Administration, the Society may accept an angle of heel GZmax less than 25° but in no case less than 15°, provided that the area "A" below the righting lever curve is not less than the value obtained, in m.rad, from the following formula:
> A = 0,055 + 0,001 (30° - GZmax)"

This indicates a level of common sense approach to the problem of classifying a vessel which does not meet the predetermined criteria, or is marginal in complying with the pre-defined limits.

Calculating Actual Wave Roll Angle

$\theta_1 = 109kX_1X_2\sqrt{rs}$

k : Coefficient equal to 1.0 for a round-bilged yacht having no bilge or bar keels, 0.7 for a yacht having sharp bilge or defined in Table 2 for a yacht having bilge keels, a bar keel or both. X_1, X_2 and s are coefficients defined in Table 2.

r = 0.73 ± 0.6(OG) / T_1 where OG is the distance in m, between the centre of gravity and the waterline (positive if above and negative if below).

$\frac{A_K \times 100}{L \times B}$	k:	B/T_1	X_1	C_B	X_2	T_R	S
0,0	1,00	≤ 2,4	1,00	≤ 0,45	0,75	≤ 6	0,100
1,0	0,98	2,5	0,98	0,50	0,82	7	0,098
1,5	0,95	2,6	0,96	0,55	0,89	8	0,093
2,0	0,88	2,7	0,95	0,60	0,95	12	0,065
2,5	0,79	2,8	0,93	0,65	0,97	14	0,053
3,0	0,74	2,9	0,91	≥ 0,70	1,00	16	0,044
3,5	0,72	3,0	0,90			18	0,038
≥ 4,0	0,70	3,1	0,88			≥ 20	0,035
0,0	1,00	3,2	0,86				
		3,4	0,82				
		≥ 3,5	0,80				

Table 2 Coefficient values for wave roll

A_K: Total overall area, in m², of bilge keels, or area of the lateral projection of the bar keel, or sum of these areas, or area of the lateral projection of any hull appendages generating added mass during yacht roll.
B: Beam in m, of the vessel
T_1: Mean moulded draft of the vessel.
L_W: Length in m, of the vessel waterline.
C_B: Total block coefficient = $\frac{\text{displacement}}{1025\ \text{L}\ B_{WL}\ \text{T}}$
$T_R = \frac{2\ \text{C B}}{\sqrt{\text{GM}}}$ where $C = 0.373 + 0.023\frac{B}{T_1} - 0.043\frac{L_w}{100}$
GM: Metacentric height in m, of the vessel.

K = 0.7 the coefficient for a sharp bilged vessel
X_1 = 0.8, as B(7.68m) / T_1(1.25m) = 6.144 being greater than 3.5 gives 0.8 from Table 2.
X_2 = 0.75 as a C_B of 0.398 being less than 0.45 gives a value of 0.75 from Table 2
r = 0.73 +- 0.6(1.5m) / 1.25 = 0.73 + 0.72 = 1.45
T_R = 13.13 as $\frac{2\ \text{C B}}{\sqrt{\text{GM}}} = \frac{7.7909}{0.59329}$
s = 0.06 from Table 2 as T_R = 13.13

Therefore, $\theta_1 = 109\ k\ X_1\ X_2\sqrt{rs} = 9.58°$

The actual wave roll angle for the hypothetical reconstruction is 9.58º. When this is applied to the Bureau Veritas criteria the combined heel angle is 23.04° wind heel angle plus 9.58° wave roll angle = 32.62° which is less than the deck immersion angle of 48.04°.

Therefore, the vessel with 15,090kg of internal stone ballast satisfies all of the stability criteria.

As the vessel was tested using ‘modern’ stability criteria, these figures are not definitive, however with any decrease in ballast quantity, the skill level required of the master and crew, as well as the likelihood of an unsuccessful voyage increase exponentially.

I.6 Seaworthiness

The term seaworthiness is a very broad one, as it not only includes the physical state of the vessel but also extends to other aspects and factors. Consequently, it is not easy to define seaworthiness in rigorous terms.

A 13th century law defined a ship as seaworthy if she did not need to be bailed more than three times in 24 hours (Christensen 1968,138-9).

A medieval Icelandic Law in the Grågås Codex states the minimum freeboard (F) of a cargo ship should be F=2D/5 where D=depth of hull amidships (Morken 1980,178).

In the case of the Bremen Cog this minimum freeboard would be
F=2 x 4.35 /5 = 1.74 m.

The Marine Insurance Act (1906) states ‘A ship is deemed to be seaworthy when she is reasonably fit in all respects to encounter the ordinary perils of the seas of the adventure insured’ (Chalmers and Ivamy, 1976).

Consequently, seaworthiness can be defined as the following: the fitness of the vessel in all respects, to encounter the ordinary perils of the sea, that could be expected on her voyage, and deliver the cargo safely to its destination.

Evaluating whether a vessel would have been seagoing is an art as well as a science since a number of interacting factors have to be considered, including the strength, durability and integrity of the hull, the freeboard at operational drafts, the stability and reserves of buoyancy (McGrail, 2001, p. 6). McGrail also states that an open boat below a certain size is unlikely to have been seagoing while a boat-shaped underwater hull and a sheerline rising towards the ends suggest a seagoing vessel.(McGrail, 2001, p. 6)

In order to determine seaworthiness, the vessel must be examined in varying floatation conditions. These conditions are suggested as being influenced by the following four main factors (McGrail 1998,13)

1. Weight and centre of gravity of the vessel,
2. Number and normal station of crew,
3. Bulk density of cargo,
4. Freeboard, the distance between the gunwale or top edge, and the operational waterplane, will need to be examined.

The weight and centre of gravity of the vessel have been calculated in the previous section. This creates the lightship displacement condition which satisfies the stability criteria, and should under the above definition be classed as seaworthy.

The number and normal station of the crew, in the case of a vessel of this size with a minimum suggested crew of 12, would not have a significant bearing on the flotation condition.

As the bulk density, or even quantity of cargo cannot be definitively stated due to lack of archaeological evidence, the only alternative is to calculate the quantity of cargo the vessel can carry. The maximum quantity of cargo a vessel can carry is determined by the available stowage space, the bulk density of the cargo being carried, and the remaining freeboard (distance between the water and the top edge of the hull) of the vessel.

With no clear evidence of what freeboard "rules" were in use, a logical choice would be either the through hull beam ends kept above the water level (Figure 13), or the medieval Icelandic law from the Grågås Codex, which is a minimum freeboard of 1.74m for this vessel.

Figure 13 Through Hull beam ends

The seaworthiness for the vessel will be analysed for the following three load conditions:

Lightship Displacement (Figure 11)

Through Beams @ waterline

Medieval load-line law (Grågås Codex)

A single square sail of 100 m^2, plus three additional bonnets of 33m^2 each gives a total sail area of 199 m^2. A sail area of 199m^2 would generate the following power for a given wind strength

Force 3: 9-10 knots: Power 0.118 kW/m^2 x Sail Area 199 m^2 = 23.48 kW
Force 4: 13-15 knots: Power 0.161 kW/m^2 x Sail Area 199 m^2 = 32.04 kW
Force 5: 19-21 knots: Power 0.312 kW/m^2 x Sail Area 100 m^2 (reefed) = 31.2 kW
Force 6: 25-27 knots: Power 0.559 kW/m^2 x Sail Area 100 m^2 (reefed) = 55.9 kW
(Gerr, 1995, p. 164)

I.7 Lightship Displacement (Figure 11)

Principal Characteristics

Length overall (LOA):	23.16m	Prismatic Coefficient:	0.653
Beam overall (BOA):	7.68m	Block Coefficient:	0.442
Waterline Length (LWL):	16.83m	Midship Coefficient:	0.684
Waterline Beam (BWL):	5.42m	Slenderness Coefficient:	3.105
Navigational Draft (T):	1.49m	Waterplane Area:	70.1m²
Displacement:	62,294kg	Wetted Surface Area:	91.29m²
Keel Length:	15.6m	Metacentric Height GM_t:	0.371m
Freeboard amidships	2.98m	Sail Area (100m² reefed):	199m²
Ballast:	15,090kg	Cargo	0kg

Weight to immerse 719kgf per cm.

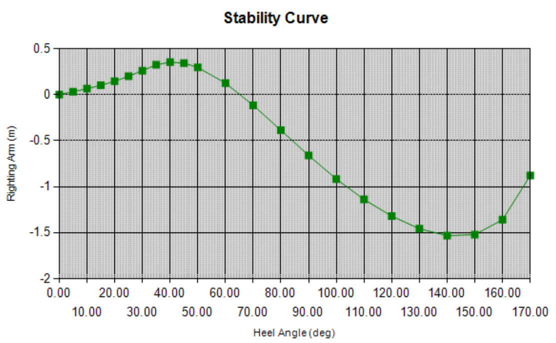


Figure 14 Lightship Stability Curve

Speed	Power Required
1 knot	0.1 (kW)
2 knots	0.2 (kW)
3 knots	0.7 (kW)
4 knots	1.6 (kW)
5 knots	3.1 (kW)
6 knots	5.8 (kW)
7 knots	11.5 (kW)
8 knots	24.7 (kW)
9 knots	42.1 (kW)

Table 3 Lightship Displacement powering requirement

From the Orca 3D stability analysis, using the Bureau Veritas criteria, the hypothetical reconstruction, in lightship displacement configuration, has sufficient stability at lower angles of heel.
The angle of maximum righting moment GZ_{max} is 41.1°.
The angle of vanishing stability GZ_0, beyond which capsize would be inevitable, is 65.6°.
The angle at which water passes over the side rail is 44.6°.

While the angle of vanishing stability is low by modern standards (120°) the vessel has sufficient stability to resist the overturning moments generated by wind loading and rolling waves. As such the vessel could be deemed seaworthy under the Marine Insurance Act (1906) and satisfies Bureau Veritas stability criteria.

Speed Potential

Wind Strength	Power Generated	Sail Efficiency 70%	40%	WindHeelAngle	Freeboard Remaining	GustHeelAngle 150% Avg Wind	Freeboard Remaining
Force 3: 9-10 knots	23.48 kW	7.45 knots	6.75 knots	7.98°	2.42 m	15.71°	1.92 m
Force 4: 3-15 knots	32.04 kW	7.85 knots	7.15 knots	15.71°	1.92 m	26.01°	1.21 m
Force 5:19-21 knots	31.2 kW	7.80 knots	7.1 knots	15.80°	1.91 m	16.11°	1.20 m
Force 6:25-27 knots	55.9 kW	8.85 knots	7.82 knots	21.3°	1.53 m	32.4°	0.79m

Table 4 Lightship Ballasted Resultant Sailing Parameters

I.8 Beam Ends Freeboard (Figure 16)

Principal Characteristics

Length overall (LOA):	23.16m	Prismatic Coefficient:	0.681
Beam overall (BOA):	7.68m	Block Coefficient:	0.476
Waterline Length (LWL):	17.47m	Midship Coefficient:	0.699
Waterline Beam (BWL):	5.96m	Slenderness Coefficient:	2.937
Navigational Draft (T):	2.07m	Waterplane Area:	83.89m²
Displacement:	105,639kg	Wetted Surface Area:	116.9m²
Keel Length:	15.6m	Metacentric Height GM_t:	0.826m
Freeboard amidships	2.45m	Sail Area (100m² reefed):	199m²
Ballast:	15,090kg	Cargo	43,345kg

Weight to immerse 860kgf per cm.

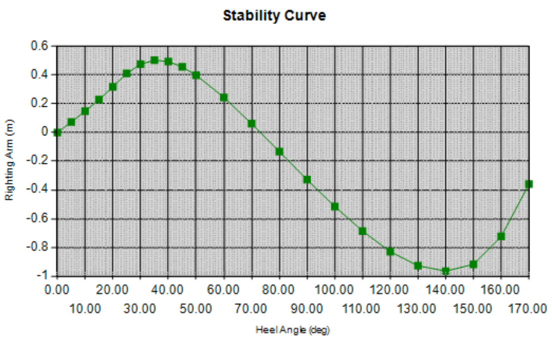


Figure 15 Beam-Ends Stability Curve

Speed	Power Required
1 knot	0.2 (kW)
2 knots	0.7 (kW)
3 knots	2.5 (kW)
4 knots	5.3 (kW)
5 knots	10.1 (kW)
6 knots	17.5 (kW)
7 knots	29.9 (kW)
8 knots	56.3 (kW)
9 knots	92.2 (kW)

Table 5 Lightship Displacement powering requirements

From the Orca 3D stability analysis, using the Bureau Veritas criteria, the hypothetical reconstruction, in Beam Ends freeboard displacement configuration, has sufficient stability at lower angles of heel.
The angle of maximum righting moment GZ_{max} is 35.9°.
The angle of vanishing stability GZ_0, (capsize) is 73.5°.
The angle at which water passes over the side rail is 35.7°.

While the angle of vanishing stability is low by modern standards (120°) the vessel has sufficient stability to resist the overturning moments generated by wind loading and rolling waves. As such the vessel could be deemed seaworthy under the Marine Insurance Act (1906) and satisfies Bureau Veritas stability criteria.

Speed Potential

Wind Strength	Power Generated	Sail Efficiency 70%	40%	WindHeelAngle	Freeboard Remaining	GustHeelAngle 150% Avg Wind	Freeboard Remaining
Force 3: 9-10 knots	23.48 kW	5.9 knots	4.9 knots	0.8°	1.54 m	4.47°	2.05 m
Force 4: 3-15 knots	32.04 kW	6.5 knots	5.5 knots	4.47°	2.05 m	9.67°	1.76 m
Force 5:19-21 knots	31.2 kW	6.4 knots	5.4 knots	4.42°	2.05 m	9.60°	1.76 m
Force 6:25-27 knots	55.9 kW	7.4 knots	6.4 knots	6.84°	1.92 m	14.17°	1.49m

Table 6 Beam Ends Freeboard Resultant Sailing Parameters

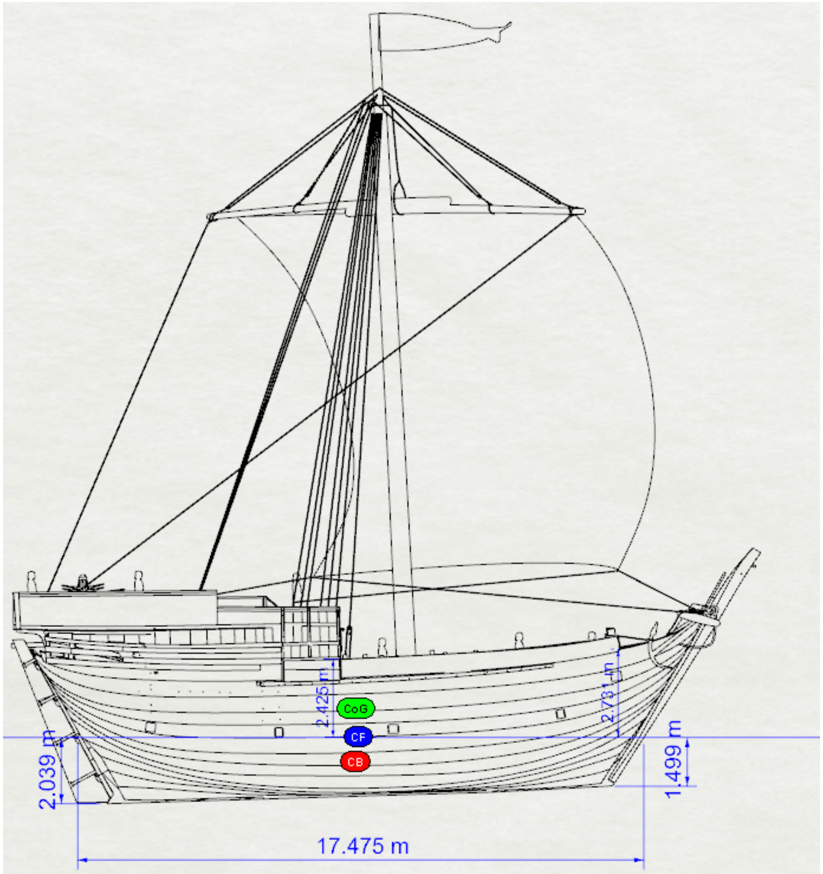


Figure 16 Beam End Displacement

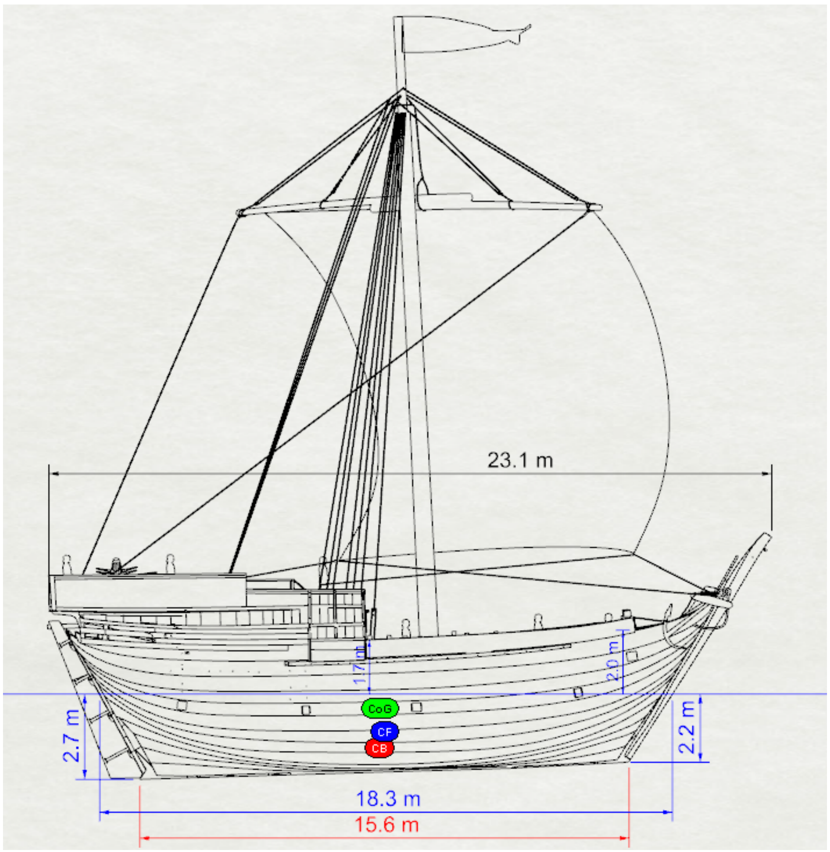


Figure 17 Grågås Codex displacement

I.9 Grågås Codex Freeboard (Figure 17)

Principal Characteristics

Length overall (LOA):	23.16m	Prismatic Coefficient:	0.703
Beam overall (BOA):	7.68m	Block Coefficient:	0.502
Waterline Length (LWL):	18.31m	Midship Coefficient:	0.714
Waterline Beam (BWL):	6.50m	Slenderness Coefficient:	2.82
Navigational Draft (T):	2.77m	Waterplane Area:	99.80m²
Displacement:	170,297kg	Wetted Surface Area:	149.8m²
Keel Length:	15.6m	Metacentric Height GM_t:	1.30m
Freeboard amidships	1.75m	Sail Area (100m² reefed):	199m²
Ballast:	15,090kg	Cargo	108,003kg

Weight to immerse 1023kgf per cm.

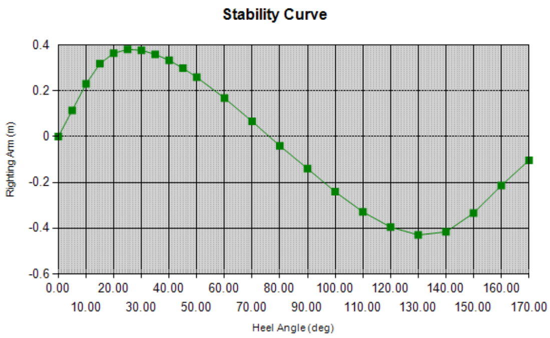


Figure 18 Grågås Codex Stability Curve

Speed	Power Required
1 knot	0.2 (kW)
2 knots	1.3 (kW)
3 knots	4.1 (kW)
4 knots	9.5 (kW)
5 knots	18 (kW)
6 knots	31.6 (kW)
7 knots	55.5 (kW)
8 knots	110.8 (kW)
9 knots	208.7 (kW)

Table 7 Lightship Displacement powering requirements

From the Orca 3D stability analysis, using the Bureau Veritas criteria, the hypothetical reconstruction, in Grågås Codex freeboard displacement configuration, fails the stability criteria.

The angle of maximum righting moment GZ_{max} is 26.3°.

The angle of vanishing stability GZ_0, (capsize) is 76.2°.

The angle at which water passes over the side rail is 24.5°.

The vessel fails the '*modern*' stability criteria as the wind heel angle plus 25° generic wave roll angle is greater than the flooding angle of 24.5°, and the stability at 30° of heel is insufficient.

As already calculated, the actual wave roll angle for this vessel is 9.58°, and with wind heel included, would not pass above the flooding angle of 24.5°.

Speed Potential

Wind Strength	Power Generated	Sail Efficiency 70%	40%	Wind Heel Angle	Freeboard Remaining	Gust Heel Angle 150% Avg Wind	Freeboard Remaining
Force 3: 9-10 knots	23.48 kW	4.85 knots	4.00 knots	0.76°	1.70 m	1.70°	1.63 m
Force 4: 3-15 knots	32.04 kW	5.40 knots	4.45 knots	1.70°	1.63 m	3.89°	1.49 m
Force 5:19-21 knots	31.2 kW	5.35 knots	4.40 knots	1.65°	1.64 m	3.68°	1.50 m
Force 6:25-27 knots	55.9 kW	6.37 knots	5.35 knots	2.57°	1.57 m	5.71°	1.37 m

Table 8 Grågås Codex freeboard Resultant Sailing Parameters

The vessel in the Grågås Codex displacement configuration still does not satisfy the '*modern'* stability criteria, for the righting moment at 30° angle of heel, but this does not imply that the vessel was unable to function in this loading configuration.

A problem exists when attempting to examine the stability and performance of an archaeological reconstruction, what "rules" should be used as a reference. It is unlikely that any "stability rules" were in force during the original construction of the vessel, other than common sense and possibly to some extent "trial and error". As can be seen in the preceding section the hypothetical reconstruction "fails" for many of the floatation configurations when using modern stability criteria.
However, the two criteria which fail are;

1. the area under the Gz curve between 30° heel and the downflooding angle.
2. the area of positive stability being less than the area of negative stability when rolling due to wave action is taken into consideration.

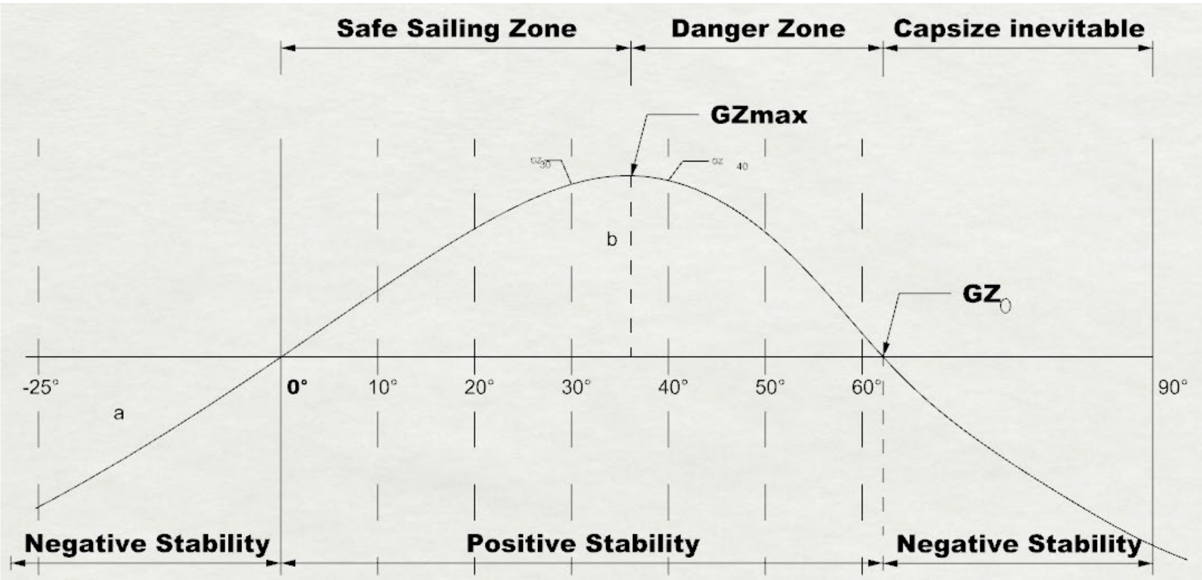


Figure 19 Generic Stability Curve

Taking the fictitious stability curve (Figure 19) for a generic sailing vessel, once the sails are set the vessel will begin to heel, due to the wind heeling moment, until a state of equilibrium is reached, whereby the righting arm moment balances the wind heeling moment. As long as this state of equilibrium occurs between 0° and the angle of GZ_{max}, which differs for every vessel, the vessel is sailing in the "safe sailing zone" where the heeling moment will be opposed by an increasing righting moment, and all is good in the world.

The problems begin when the vessel heels beyond the angle of GZ_{max} where the amount of righting moment is decreasing. In this "danger zone" a small increase in heeling moment caused by a slight wind speed increase, or even, a seemingly insignificant crew movement causing a centre of gravity shift, will result in a large heel angle increase which could overwhelm the decreasing righting moment, and in this zone between GZ_{max} and GZ_0 the sails should be eased or reduced to decrease the Wind heeling arm. Failure to reduce the heeling moment within this "danger zone" will quickly result in the vessel heeling beyond the angle of GZ_0 which will result in an inevitable capsize.

The real danger for a sailing vessel, is one where the vessel can still sail in apparent comfort, such as the deck edge not yet underwater, but beyond the angle of GZ_{max} whereby a slight increase in healing moment could lead to undesirable consequences. Attempts to reduce these dangers have led to the introduction of "general rules" such as GZ_{30}, GZ_{40} and GZ_{30-40} and generic wave roll loading such as equilibrium -25°.

Many of the modern criteria have been developed and refined in an effort to "force" stability and safety into the design of a vessel so as to reduce the potential for catastrophic failure due to "pilot" error, a need which has arisen in part due to the increase in "amateur" or inexperienced sailors having relatively easy access to sailing or boating in general. Criteria such as GZ_{30} and GZ_{40}, while working for smaller vessels are more difficult to achieve with a larger sailing vessel. In addition, not many large (25 m plus) sailing vessels would even consider operating at these angles of heel.

A proposed set of criteria to assess the hypothetical reconstruction could be simplified to examine the vessel using a common-sense approach while still ensuring a reasonable margin of safety. These rules should ensure the vessel sails within the "safe sailing zone" with a clear visual indicator of when the vessel heels beyond the angle of GZ_{max} and enters the "danger zone".

This would have the effect of ensuring the resultant heel angle, due to wind loading, is not in the negative stability zone where capsize is inevitable (Rule 1).

The caprail atop the bulwark will remain above water at the resultant heel angle (Rule 2).

The heel angle will be within the safe sailing zone (Rule 3).

The caprail atop the bulwark reaching the water being a clear visual indication of the vessel heeling to the GZ_{max} angle and as such a warning to reduce sail area (Rule 4).

The caprail is still above the water with the vessel heeled by the wind and wave roll (Rule 5).

1. Steady Equilibrium less than GZ_0.
2. Steady Equilibrium less than Downflooding angle.
3. Steady Equilibrium less than GZ_{max}.
4. GZ_{max} greater than Downflooding angle.
5. Steady Equilibrium + 9.58° less than Downflooding angle.

The hypothetical reconstruction comfortably passes all of these criteria in all three loading conditions and in any wind strength up to and including force 6 (25kts or 12.9 m/sec) with gusting up to 150%.

I.10 Sailing Performance

The physical position and geometry of the shrouds supporting the mast, is dictated by the fixing points located on the channel whales and the overall mast height. The location of these shrouds prevents the yard from being rotated much farther than 40° from the transverse centreline of the vessel. As the vessels alters course to sail closer to the wind, the effective sail area reduces due to the inability to rotate the yard more than 40°.

199m² from 180° to 140° wind angle.
105m² at 90° wind angle.
81m² at 80° wind angle.
55m² at 70° wind angle.

Force 3: 9-10 knots: $_{Power}$ 0.118 kW/m² x $_{Sail\ Area}$ 199 m² = 23.48 kW
23.48kW at 120° wind angle
12.39kW at 90° wind angle
6.49kW at 70° wind angle

Force 4: 13-15 knots: $_{Power}$ 0.161 kW/m² x $_{Sail\ Area}$ 199 m² = 32.04 kW
32.04kW at 120° wind angle
16.95kW at 90° wind angle
8.85kW at 70° wind angle

Force 5: 19-21 knots: $_{Power}$ 0.312 kW/m² x $_{Sail\ Area}$ 100 m² (^{reefed}) = 31.2 kW
62kW at 120° wind angle (31.2kW reefed)
32.76kW at 90° wind angle (16.22kW reefed)
17.16kW at 70° wind angle (8.44kW reefed)

Force 6: 25-27 knots: $_{Power}$ 0.559 kW/m² x $_{Sail\ Area}$ 100 m² (^{reefed}) = 55.9 kW
55.9kW at 120° wind angle (reefed, 111.14kW full sail)
29.07kW at 90° wind angle (reefed, 58.7kW full sail)
15.09kW at 70° wind angle (reefed, unable to carry full sail)

With an 80° arc of downwind or ideal wind angle of 140° or higher, 80° arc of reaching with wind angles of 90°, 40° of 'upwind' sailing with wind angles of 70° or higher and the remaining 160° arc a "no go" area, Table 9 gives the potential achievable speed for varying wind direction and speeds.

	Force 3			Force 4			Force 5			Force 6		
Wind Angle	140	90	70	140	90	70	140	90	70	140	90	70
LightShip	7.0	6.1	5.1	7.4	6.5	5.6	8.4	7.3	6.6	--	--	--
Displacement	--	--	--	--	--	--	7.4	6.5	5.5	8.2	7.3	6.4
Beam End	4.8	3.9	3.1	5.4	4.4	3.5	6.6	5.4	4.4	8.4	7.5	5.9
Displacement	--	--	--	--	--	--	5.4	4.3	3.4	6.4	5.2	4.2
Grågås Codex	4	3.2	2.5	4.5	3.6	2.9	5.5	4.5	3.6	8.1	7.1	--
Displacement	--	--	--	--	--	--	4.4	3.5	2.8	5.3	4.3	3.4

Table 9 Estimated Potential Speeds

Weather and Sea Conditions

Departing the north-west coast of Germany would take the vessel out into the southern half of the North Sea. Figure 20 (after Sandwell and Agreen, 1984, pp. 2047–50) indicates an average wind speed of 5 to 7m/sec (force 4) during the summer and 9 to 11 m/sec (force 5-6) during the winter months, with average (1/3 height) wave heights of 2m and 4m respectively.

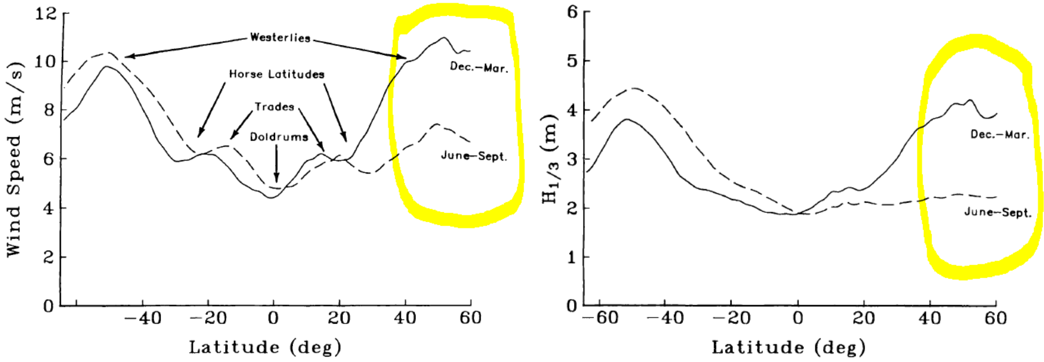


Figure 20 North Atlantic average wind and waves

The authors (Bouws and Pöttgens, 1983) suggest that for the northern part of the North Sea, mean wind speeds may reach 38-40 m/sec, with averages about 20% greater than the southern North Sea, and maximum wave heights are likely to exceed the 30m level, which is twice that found in the south.

Modern pilotage charts for the North Atlantic give a more comprehensive overview of the weather and sea conditions which may be encountered on a potential voyage.

April (Figure 21 top) has an average wind strength of force 4, with the prevailing direction being variable in the North Sea, this would result in a 50% chance of favourable wind directions. Gales of force 8 and above would be encountered on average 10% of the time. Wave heights greater than 3.6m would be encountered less than 10% in the North Sea, increasing to 25% between Shetland and Iceland.

August (Figure 21 middle) has an average wind strength of force 4, with gales of force 8 and above less than 3% of the time. Wave height will be less than 3.6m on average, with a 10% increase between the Faroe Islands and Iceland.

December (Figure 21 bottom) has an average wind strength of force 5 to 6, with the prevailing wind direction being south-westerly for the North Sea as far as Shetland and then backing easterly to north-easterly between the Faroe Islands and Iceland. Gales of Force 8 and above will be encountered on average 18% of the time, and calm conditions less than 1% of the time. Wave heights greater than 3.6m will be encountered 15 – 20% of the time in the North Sea, increasing to over 50% between the Faroe Islands and Iceland. Dawson (Dawson et al., 2010) notes an average of 23 winter (October to March) gale days out of a total 182 days, recorded at North Unst, Shetland over a 40 year period.

April to September would more than likely be the most suitable months to undertake a long voyage to Iceland. Once leaving the German coast, a direct route to Iceland would entail 1,036 nautical miles across completely open and exposed seas.

An alternative route would be to follow the Danish coastline north until making landfall after 270nm in Norway, a second leg 270nm to the Shetland Islands, followed by the options are a direct 520 nautical mile leg to the Shetland Islands, followed by a 'short' 200 nautical mile leg to the Faroe Islands, and a final 340 nautical mile leg to Iceland.

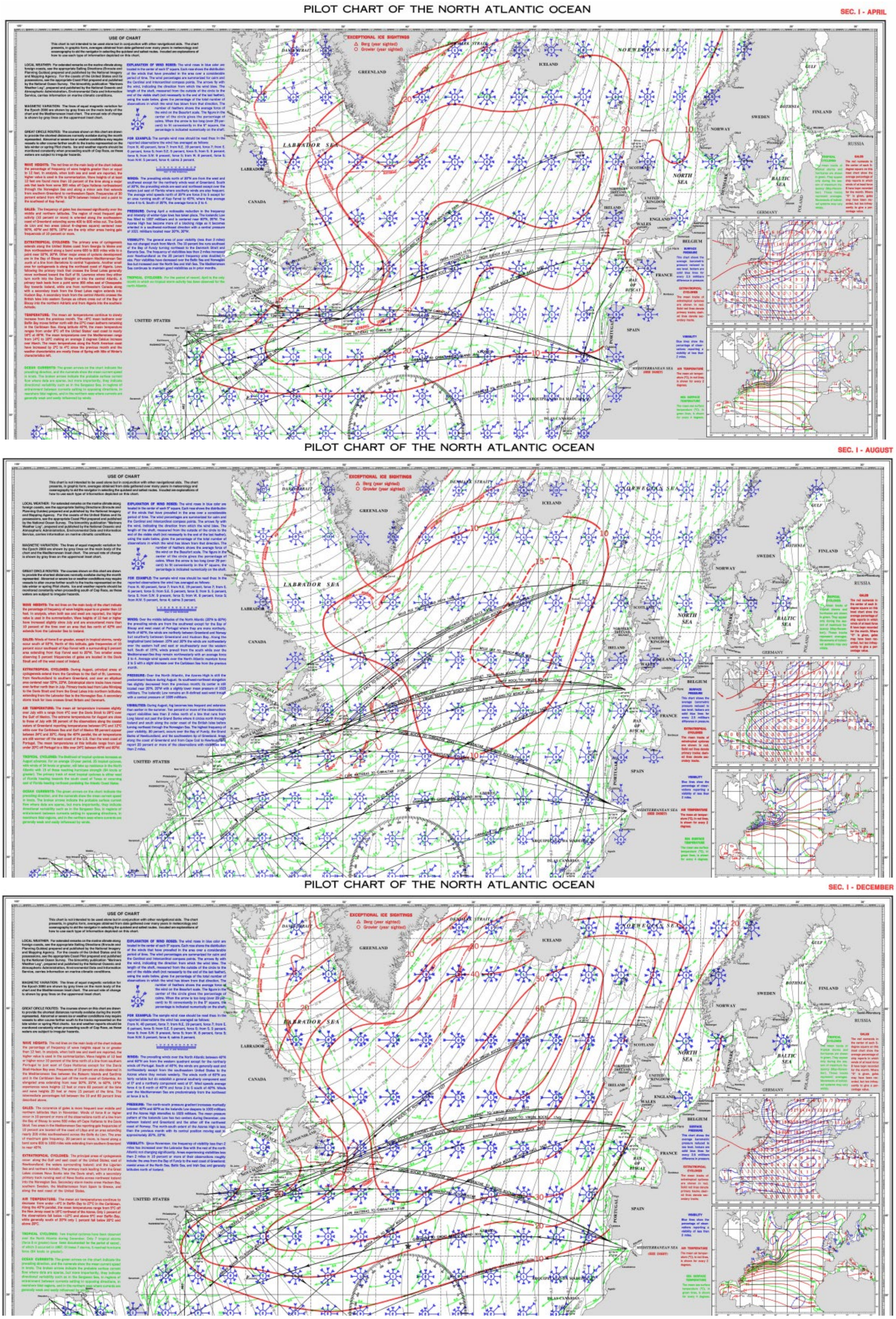


Figure 21 Pilotage Charts North Atlantic Ocean

Cargo Capacity

- *The merchants from Bremen and Hamburg were sailing to the North Atlantic, and Iceland, where they were not allowed to stay during the winter. They usually left the ports mid-March to early April and arrived at their destination about a month later. Most likely they called in harbors on the English and Scottish east coast before leaving the North Sea and sailing across the open Atlantic. The earliest mentioned departure date is March 11th. They were not allowed any trading activity in Iceland before May 1st. They usually came back from this trip in the period July to August.*

- *The main cargo was dried cod (or other species converted to stockfish). Wool-products and sulfur is also mentioned, and a very rare commodity were live falcons. In one reported case more than 50 falcons were brought to the European mainland to be sold to the nobility. Typically, only find the cargo capacity of the ships travelling North is recorded. This was about 60 Last but as these measurements in the Medieval and early modern periods were far from being standard, we do not know a reliable conversion into metric (or imperial)* (M. Belasus, pers.comm., December 29, 2017).

Medieval and early modern measurements are at best vague, and at worst utterly confusing and unreliable, often substituting and intermingling volume as well as weight. In addition, these weights and measures vary widely between regions.

Morken (1988, pp. 399–400) describes a last as a net register ton, and the formula for establishing it is based on the Mathew Brown equation of 1582, with amendments from the Dutch formula of 1669 and an eighteenth century Swedish set of figures. The working of the formula is $\frac{\text{Length x Beam x Depth in English feet}}{168}$ or $\frac{\text{Length x Beam x Depth in meters}}{4.8}$. This formula is meant to state a ship's deadweight and volume in lasts. The definition of one last being:

1 last = 1.3 ton deadweight of rye (or wheat) in barrels if the ship is open
= 1.9 ton total deadweight if completely decked
= 100 English cubic feet
= 1 net register ton

Examples from The Stowage of Ships and Their Cargoes (Stevens, 1863) quotes feathers as "*a bale weighs 1cwt and a Last 17cwt, in some places 1,700lbs forms a last.*" For Germany, Bremen and Hanover, "*1 Last = 11⅛ quarts of wheat or 11 quarts of barley*" Lubeck "*1 Last = 11.04 quarts*", Hamburg "*1 Last = 11⅛ quarts of wheat, peas or beans, barley = 10⅞ quarts, oats = 10½ quarts*", Rostock "*1 Last = 10 quarts*". For Herring Stevens quotes "*180 barrels of red herring weigh 11tons, or 144 barrels of white herring weighs 21½ tons.18 barrels of unpacked herring make a last*".

From this a Last of red herring would weigh 1.63tons (1,656kg) and white herring would weigh 2.68tons (2,728kg).

Cod fish (Stevens, 1863, p. 56) 16cwt dried cod in bulk, or 12cwt in casks of any size go to a ton for freight, and a last of Cod equates to 12 barrels (flour barrels of 196lbs). Therefore 1 Last = 2,352lbs or 1,066kg.

Cargo lists of the vessels impounded in the north-east ports (Clarke, 1979) note '33 lasts of white herring', '22 lasts of grease and oil', and '2800 hardfish' which were stored in barrel casks (36 gallons / 163ltrs)
1cwt = 112lbs = 50.8kg
1ton = 20cwt = 2,240lbs = 1,016kg

As shown, the physical weight of a Last varies significantly depending on the actual cargo object, demonstrating the Last is more of a volume measurement than a weight. Ellmers (1985) estimated a cargo capacity of 40 lasts for the Bremen cog, originally estimated at 130 deadweight tons or about 65 lasts of grain (Frühmittelalterliche Handelsschiffahrt, 257).

Hocker (2004:89) notes the last varied from town to town, and from grain to grain, but generally ranged either side of 3m³, the rye last of Lübeck in 1400 was 3.024 m³, while the ship last of Danzig was 3.105 m³, and a figure of two metric tons per last is an approximation commonly used by ship scholars.

However, as Stevens quotes a precise weight for a Last of cod (12 barrels at 196lbs), equating to 2352lbs or 1,066kg, and a stowage rate of 12cwt or 609kg per ton, if the Builders Old Measurement: $\text{tonnage} = \frac{\left(L - \frac{3}{5}B\right) \text{x B x} \frac{1}{2}B}{94}$ = 199.5 tons is used, this would give a total cargo weight of 121,615kg. Far above the calculated total maximum capacity of the vessel which is 108,003kg.

A total of 60 Last, as documented in the historical records could weigh circa 64,010kg for cod fish. This would submerge the vessel below the point where the through hull crossbeams are immersed, but not as deep as the maximum calculated capacity in accordance with the medieval Grågås Codex freeboard rules.

With such variation and potential confusion, specifying a cargo capacity in lasts, is akin to saying the ship could carry 40, or 60 boxes.

From the previous section, the vessel has a calculated cargo capacity or deadweight tonnage of 43,345kg in Beam End displacement condition, and floating as per the Grågås Codex Freeboard law, the cargo capacity or deadweight tonnage is 108,003kg.

Provisions and Stores

Bremen to Iceland is 1,920 km = 1036 nautical miles. A 5kt average would take 200 hours or 8.4 days, while a 2kt average would take 500 hours or 20.8 days.

As shown in the preceding pages the average wind strengths which would be encountered are force 4, and the prevailing wind directions are either south west or variable, resulting in a favourable direction not more than 75% of the time.

A close-hauled course of 70° to the wind will result in having to sail or tack a total of 2.9 miles for every mile distance gained to windward. This represents a 190% increase in the actual distance sailed. If the vessel encountered unfavorable winds for 50% of their time this would result in a net increase of 95% for both distance and duration at sea. Even an unfavorable wind for 25% of the time would result in a net increase of 47.5% for both distance and duration at sea. Therefore, the actual distance sailed could be between 1,528 and 2,020 nautical miles.

As already calculated, the vessel in a fully loaded capacity, could expect to achieve speeds of circa 2.9 knots while sailing close hauled, and 4.5 knots while sailing downwind in a force 4 wind. A total voyage of say 1,700 nautical miles at an average of 3.6 knots could take approximately 472 hours or 19½ days. Again, it must be noted that these are hypothetical speeds, in 'best case' or ideal condition scenarios, unlikely to have been higher, and could in reality be a lot lower than estimated.

Modern day recommended allowances for water are 5 litres per person per day, therefore a 20-day total for a crew of 12 would be 1,200 litres. The additional weight of vessels or containers could bring the combine weight closer to 2,000 kg.

Lacking written records, weights for the crew and their effects are difficult to estimate, The Stowage of Ships and Their Cargoes (Stevens, 1863) lists the weight for a man and his effects at 100 to 127kg. This would give a figure of between 1,200 and 1,524 kg for crew and effects. Likewise, provisions for the period are difficult to estimate, a ships manifest for provisioning the 74-gun Bellona in 1760, with a crew of 650 for a four-month voyage, totals 386,847kg equating to circa 4.9kg per person per day. This would result in 1,175kg provisions for the 20-day voyage. It is unclear if the medieval mariner was as well fed and found as his modern contemporary, but these figures result in a total of circa 4,695kg for crew and provisions.

This has the nett result of reducing the cargo capacity to 38,650kg or 103,305kg depending on whether the beam end displacement or the Grågås Codex displacement is used.

I.11 An Ocean-Going Cog

The Hanseatic League, a confederation of trading cities, extending from Cologne in the west to Riga and Reval on the Baltic in the east, emerged as an informal cooperative in the early thirteenth century. A surviving example of this trade is the account book of Johannes Wittenburg. Wittenburg from an old-established Lubeck family, with extensive landed property, involvement in League politics, and burgermeister of Lubeck in 1356 traded with Flanders, England, Scania, Prussia, Livonia and Russia. From the west he imported cloth from Valenciennes and Louvain. From the east he imported furs and wax to sell in Bruges, and also traded in bulk goods such as barley, malt and beer (Rose, 2007, p. 75).

The ships of the League, which were known as cogs dominated trade in the Baltic, and became increasingly important in the North Sea, ports on the east coast of England and the Netherlands. Rose (2007, p. 76) notes the suggestion that prior to the fourteenth century most goods coming from the Baltic were trans-shipped through Lubeck to Hamburg and then onto Flanders and the North Sea, however the ships were making what was called the *ummelandfart* (the voyage round Jutland via the Sound) much earlier than this. The cog as a ship type was well suited to these journeys which was a natural extension of the voyages to Skania (southern Sweden) for herrings which had been the root of the Wendish ports prosperity.

The total number of towns and cities in the League varies over time, with about seventy considered full time members, the most important being Cologne, Bremen, Hamburg, Lubeck, Rostock, Straslund, Visby (Gotland) and Danzig. All these conducted a major part of their trade by sea or navigable rivers. Other major trading centers included Novgorod, Bruges, Bergen, London. Bruges for example had over 600 Hanseatic merchants, their assistants and apprentices living in the town in 1457. Smaller trading centers spread throughout the northern regions such as that at Kings Lynn in England. The cogs which landed at the wharves in London and Bruge were laden with a variety of goods. Some high value such as wax and furs, fox, squirrel and sable from Novgorod and eastern Europe, armour and weapons from Cologne, as well as essential bulk goods such as timber and its byproduct pitch, salt herrings, Osmund or Swedish iron and hemp for rope making. Return cargoes consisted mainly of cloth and small quantities of wine. By the late 1450's over ten thousand cloths a year were exported by the Hanse from England. The Hanse kontor at Bergen controlled almost all the seaborne exports of Norway by the fifteenth century, with Hanseatic vessels dominating the seaways through the Sound to the Baltic and across the North Sea to King's Lynn (Rose, 2007, pp. 76–77).

Rose (2007, pp. 77–79) notes the 'quasi monopoly' of the Hanseatic cities in the most important northern trade routes as being due to their harmony in maritime and business practices and the superiority of their ships.

> '*Their characteristic vessel, the cog, was larger and handled better than vessels of other designs, an advantage particularly noticeable from the mid-fourteenth to the mid fifteenth centuries. Their fleets were also larger and better coordinated than those of possible rivals. League members could command around one thousand ships at the end of the fifteenth century.'*

Rose also suggests one third of the fleet traded via the Sound with Denmark and Sweden, *en route* to England and Flanders for cloth and to Gascony for wine and salt; one third were employed in the Baltic trade; and the remainder would sail to Iceland or within the North Sea.

Iceland, first ruled by Norway since 1262, and then Denmark following the union of Kalmar in 1397, traded stockfish, air-dried cod, which was a popular 'fast day' and Lenten fare throughout most of western Europe, in return for all manner of cloth, ironwork and hardware, timber and personal items or household items difficult to come by locally. The Danish king tried to insist that all trade with Iceland went via Bergan as this entailed the payment of high tolls to himself (Rose, 2007, p. 74). However, one reason for the welcome given to English traders in Iceland was that the Norwegians seemed unable to send the six annual ships with supplies to Iceland which had been specified in the treaty of 1262. That same year the Icelandic annals noting no news from Norway to Iceland, also recorded a strange vessel crewed by 'fishermen out from England' seen off Dyrholm Island (ibid. p. 76-77).

The Icelandic annals mention the voyage, not without its dangers, nearly eight hundred miles across the stormy North Atlantic, as a formidable undertaking by boats from Lynn, Hull and other east coast ports beginning in about 1412. Ships from Bristol would have sailed for Iceland from ports such as Galway on the west coast of Ireland. The course would have been slightly west of north, making it an easier heading to follow by compass, and easily made good with the prevailing southwesterly winds (ibid. p. 74).

Morken (1988) states environments shape ships, and the North Sea coast of present-day Denmark, Germany and Holland consists chiefly of sandy, low shores with a tidal range of circa 3m. This means any harbor which dries out will have at most 3m depth of water at high tide, and Morken says ships using these waters and harbors should not draw more than about five feet (1.5m), and when built in wood this tends to restrict tonnage. He also notes a keel should be avoided and a flat bottom is preferable to aid loading and unloading while aground between tides. Morken suggests the ancestor of the cog appears to be the so-called Bruge Ship which had dimensions of 14.5m x 3.5m x 1.35m equating to 14.2 lasts. He says the Bremen cog, the best-known surviving example is flat bottomed, with steep sides and no keel is not a ship but a barge, and the box like shape of the cog precludes it as an ocean-going ship. Other factors which he quotes as adding to this belief are the fact they (cogs) were small, Lubeck customs lists for 1227 show that *all* ships using the port were between five and twelve lasts. These ships he says were, at the time, merely coasters.

For the 'Ocean Going' vessels which made the American discovery, traded with Iceland and Greenland, carried the Holy Land voyagers and bore King Magnus Barelegs and King Sigur Jorsalfar on their tremendous journeys, Morken prefers instead the Norse *'Knarr'* (Figure 22) as an example of an ocean-going cargo vessel. He notes the knarr of Torarin Nevjulfson which in 1024 made the round trip to Iceland from Norway, and on the emigration voyage of Erik the Red, where some 25 ships left north-west Iceland in 985 or 986 carrying about five hundred people, with cattle, sheep, horses, tools, seeds and provisions. Table 10 recreates the dimensions and cargo capacity of four Knarrs, the first two based on documentary evidence from the sagas, the other two from excavations at Bergen during the 1950's.

Vessel	Date	Length	Beam	Depth	Tonnage
Knarr One	800	28m	7m	3.5m	143 Lasts
Knarr Two	1000	32.8m	8.2m	4.1m	230 Lasts
Knarr Three	1000-1100	24.9m	6.2m	3.1m	100 Lasts
Knarr Four	1200	34m	8.5m	4.25m	256 Lasts

Table 10 Knarr sizes after Morken 1988

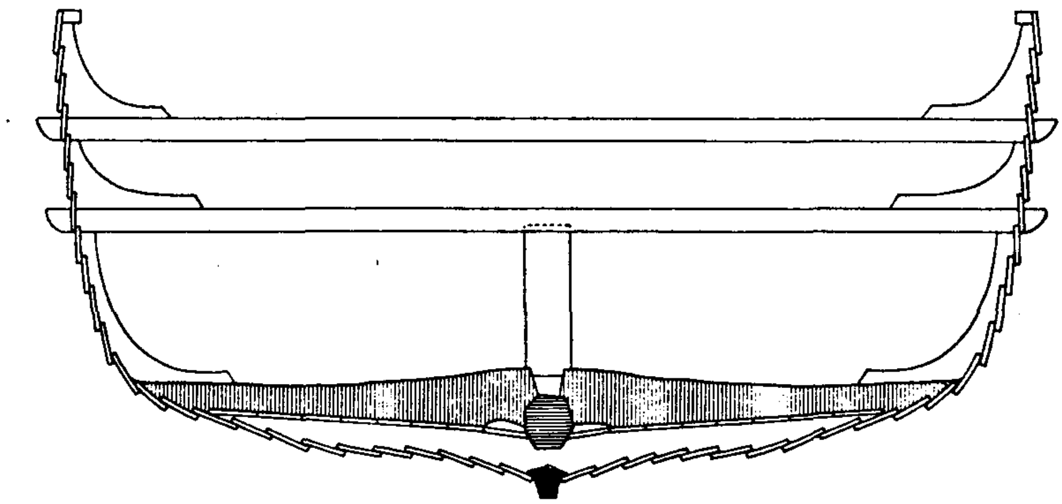


Figure 22 Reconstructed midship section of a knarr based on finds excavated at Bergen after Morken 1988

Elmers (Gardiner and Unger, 1994, pp. 29–46), suggests the earliest cog like vessels dates back to Roman times, and these inland boats seem to have been the regional boat from the Rhine valley to the Wesser valley, and as all the rivers in that area flow into the North Sea, cog shaped boats may well have been used along the southern coast of that arm of the ocean. He notes that these were not used in long term trade, during the Roman Iron Age, as there is strong evidence of Roman merchants in Roman sailing vessels of Mediterranean construction, from the Rhine as far as Scandinavia and the Baltic. Elmers notes the *hulk* as depicted on a Charlemagne coin from circa 800 AD represents the outstanding vessel type for traffic between the Continent and England.

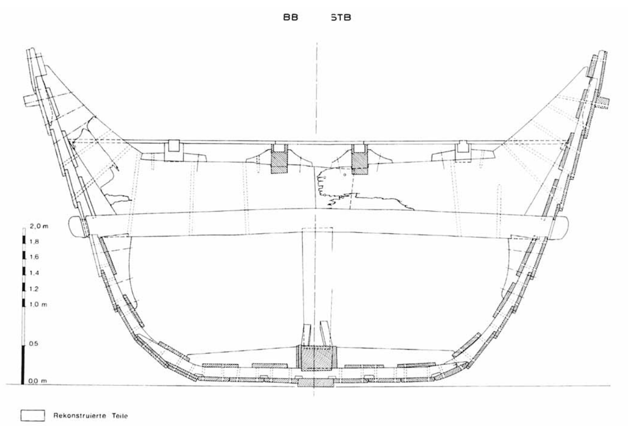
He states the Frisians at Hedeby copied and modified this coin to represent the flat bottom and upward turned ends typical of the coastal vessels on the shallow flats of the Wadden Zee. This he claims to represent an early version of the cog. Elemers states the crossbeam, positioned above the fourth of eight strakes on the Bremen cog, is a new construction element, which was to become typical for the late Middle Ages, and is positioned on the fourth or top strake of the earlier cogs. According to Elmers, there is no record of cogs in England or along the French coast prior to 1200, but there is evidence in the ninth and tenth century for cogs in the Netherlands. As such he believes the early seagoing cog was a ship of the Wadden Zee, sailing the relatively calm waters behind the islands and dunes.

Elmers also notes the cog had one further quality, which would be considered unpleasant by modern standards. The deck planks which were laid at right angles to the sides, rather than fore and aft, did not for a watertight seal with the sides of the ship. This meant that rainwater and sea spray falling on the deck did not collect on the surface, but flowed directly into the bilges, where it acted as additional ballast and provided a counterbalance. This meant the risk of capsizing was substantially reduced in bad weather, and as a result the vessel was much more stable at sea.

Nothing could be further from the truth, and this demonstrates a complete misunderstanding of the consequences of free surface effect. This is the mechanism whereby liquids, or any unbound aggregates of small particles such as grain, moves in response to changes in a vessels attitude or velocity. In a normally loaded vessel any rolling from perpendicular is countered by a righting moment. This assumes the center of gravity is relatively constant. As the liquid inside the vessel moves towards the roll, due to gravity or momentum, this counters the effect by moving the center of gravity towards the low side. In addition to the new position for the center of gravity, the added weight moved towards the low side will have the effect of increasing the angle of roll.

The momentum of large volumes of moving liquids cause significant dynamic forces, which act against the righting effect. When or if the vessel returns to the vertical, the roll continues, and the effect is repeated on the opposite side. In a heavy sea state, this can result in a 'positive feedback loop', causing each successive roll to become more extreme, eventually overcoming the righting effect and leading to a capsize. As such, any uncontrolled water inside a vessel is the anathema of the seafarer, and explains the primacy of the bilge pump(s).

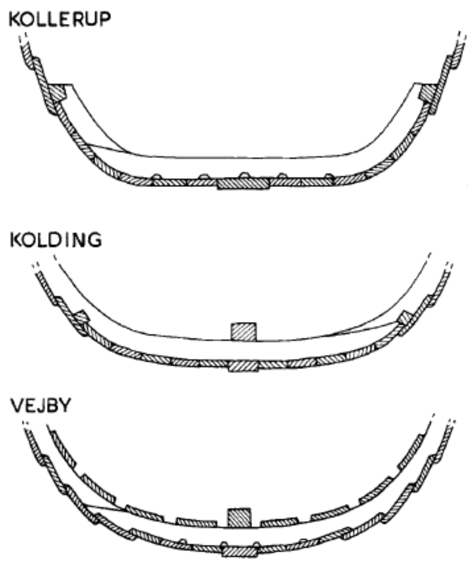
Ole Crumlin-Pedersen (2000, pp. 230–246) describes certain features to define archaeological criteria for the cog as a ship type. These refer primarily to the bottom structure: a flat keel; continued fore and aft with large angular transition pieces; straight stem and stern posts; a flat external floor of flush-laid (carvel) planking amidships, changing to overlapped planks in the sharp fore and aft underwater body; alternating floor timbers covering the bottom and part of the sides; fastenings of chisel tipped hooked nails rather than nails and roves or treenails; moss forced into grooves in the plank seams and secured with laths and sintels.



In addition, strong cross beams protruding through the overlapping hull strakes, combined with huge standing knees are described as particularly characteristic features of this ship type. Crumlin-Pedersen notes the Bremen find, enabled for the first time, archaeologists and historians to match the medieval written and iconographic evidence of cogs with a concrete archaeological find.

Figure 23 Cross-section amidships of the Bremen Cog. (After Lahn, 1992)

Crumlin-Pedersen notes the Bremen find triggered a series of efforts to build up a universal model for the origin of and development of the 'cog-type' from prehistory to modern times. He also notes the three wrecks from Kollerup, Kolding and Vejby (Figure 24), as a chronological series of cogs ranging from c. 1200 to c. 1375



Discussing these three vessels, Crumlin-Pedersen states while all three display the same set of characteristics, there are marked differences in other respects. The youngest, Vejby, discovered with traces of cargo, is contemporary with, and very similar to, yet smaller than the Bremen cog. The oldest of the three, the Kollerup cog, initially dated to c. 1200, but later revised using dendrochronology as having been built of timbers felled c. 1150, is longer but much narrower than the Bremen cog. The keel length and width of the ship were 18.6m and 4.8m for Kollerup, versus 15.6m and 7.8m for Bremen. Giving a L_{keel} / B_{ship} coefficient of 3.9 and 2.0 respectively.

Figure 24 Cross-sections of the Kollerup, Kolding and Vejby cogs. Not to scale. After (Crumlin-Pedersen, 1979)

Crumlin-Pedersen (2000, p. 235) also notes the older Kollerup cog was built to a higher standard, using higher quality tangentially split planks, compared to the sawn planks used in the Bremen cog.

Hocker (2004:73–75) notes that while the Bremen ship was not the first excavated vessel to be identified as a cog, it was the first to be widely known, and quickly resulted in the complete rethinking of cog development. Numerous examples built in a similar manner have been excavated or identified from older excavations, and by his count, a minimum of twenty-two share the essential characteristics. Of these nine from the reclaimed Zuiderzee, five from Denmark, five from Sweden, one from Belgium, and two from Germany. Ranging in dates from ca 1150 to ca 1425, he suggests two noticeable chronological groups, one clustered in the 1150-1250 period and the other 1350-1420.

The five earliest finds (Kollerup, Kolding, Skagen Kuggmaren, and Bossholmen) are from Scandinavia and all but Bossholmen show evidence of having been built in southern Jutland (Denmark). While this does not prove ultimate origins of the type, Hocker notes it does strongly suggest the neck of the Danish peninsula played an important role in the development of this type of craft into seagoing merchant craft.

Hocker slightly refines Crumlin-Pedersen's criteria into a list of characteristics, shared by all or nearly all of the major finds:

1. A keelplank rather than a beam keel (Bossholmen may be an exception)
2. Straight stem and stern posts, connected to the keelplank by intermediate knees, usually called hooks (Bossholmen has two long hooks without a central timber)
3. Bottom (and sometimes bilge) planking that is laid edge-to-edge in the middle part of the ship, but usually becoming lapstrake at the ends
4. Lapstrake side planking fastened together with double-clenched nails rather than rivets
5. Caulking of moss (occasionally hair) held into seams by wooden laths fastened down and protected by broad iron staples, usually called sintels
6. A strernpost rudder
7. A single mast stepped in the forward half of the ship

Other characteristics such as the through beams, false stems or sternposts and the heavy standing knees are excluded as "typical" by Hocker as they are either not present, or relatively few finds are sufficiently well preserved to reveal details of how the upper-works were constructed.

Interestingly Hocker does not include the prerequisite of flat floors in the characteristics of a cog, but does mention that the Bremen cog, as well as several others identified as deepwater vessels, have flat floors a little over half the total breadth of the hull, straight, high, outward sloping sides, and moderately hard bilges. He notes the IJsselmeerpolders find M107 and NZ43 have more rounded bottoms, low sides and no discernable bilges, while M107 and the Kolding vessel actually have a small amount of deadrise amidships, and comments these are almost too fine and graceful to be "true" cogs.

Significantly, Hocker identifies the fact that all excavated cogs have hollow sections at the ends, as well as a slight to moderate hollow in the lower waterlines (Figure 25). Which he states has sometimes been interpreted as a conscious choice by the shipbuilders to give them more speed and ease in a seaway. There have been many descriptions of the cog as a flat bottomed, wide vessel with fine ends. Hollow end sections and hollow lower waterlines do not create a vessel with fine ends, rather they create a bluff or full bow with a sharp forefoot.

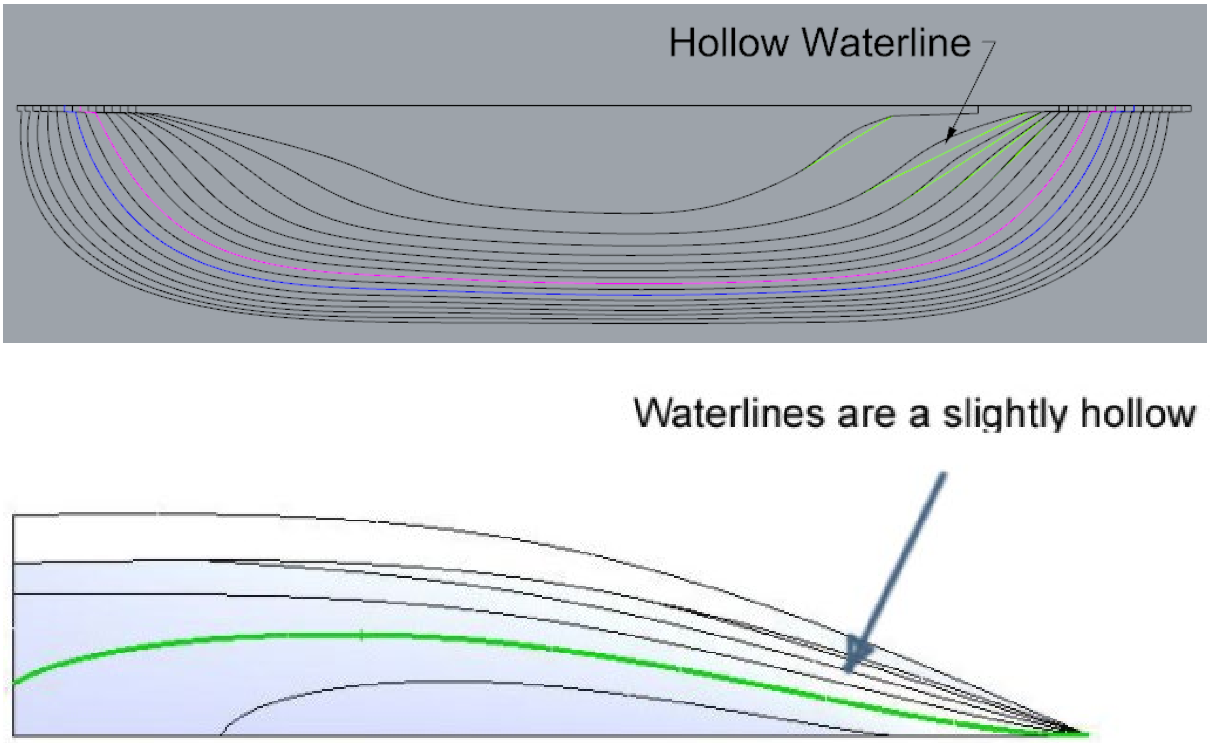


Figure 25 Water Lines

The early cog finds (Kollerup, Skagen, and Kuggmaren) show some differences from the other finds. They tend to have more of the hull flush planked, planks tend to be converted by splitting rather than sawn, the hooks tend to be longer, and the join between hook and post occurs higher up (Hocker and Ward 2004:75–76). With such variations in size and form Hocker asks if it is possible to characterize all these vessels as cogs, or are only the larger, deepwater examples such as the Bremen ship, true cogs. While a distinct building tradition does exist, described by Hocker as bottom-based, he raises the question, is this what identified a ship type to thirteenth and fourteenth century seafarers, or is the cog just one example of a vessel built in this manner. Did cog refer to function (deepwater merchantman) as well as construction or general configuration?

The separation of the planking into two distinct groups, flush and lapstrake, is perhaps the most direct indicator of the bottom based concept behind these ships according to Hocker. As the bottom planks are overlapped and fastened to each other at the ends, he suggests the flush arrangement amidships was chosen for functional reasons, as a deliberate adaptation of an all-lapstrake ancestor. The flush planking being more suited to the shallow waters where occasional grounding was fact of life, or where vessels took the ground to unload. Such abuse rapidly eroding the edges and fastenings of a lapstrake bottom.

The apparent evolutionary trend from many flush strakes, including the central keel plank, Kollerup and Kolding had thirteen and eleven respectively, while Vejby and Bremen had seven and nine, leads Hocker to postulate the gradual “clinkerization” of an all-flush ancestor. The earliest cogs having the lowest two strakes completely flush all the way to the hood ends he cites as another indication that the type was developed from a flush planked prototype.

Whichever reason is nowadays the preferred explanation, for the seemingly strange mix of both flush laid and clinker planking in the same vessel, the fact that this was not done as a one-off trial or on a whim is apparent.

- Kollerup has 6 flush laid strakes per side well beyond the turn of the bilge.
- Kolding has 5 flush laid strakes per side almost to the turn of the bilge.
- Bremen has 4 flush laid strakes per side almost to the turn of the bilge.
- Vejby has 3 flush laid strakes per side almost to the turn of the bilge.

As Hocker (2004:85) points out, the bottom-based approach to building, has the advantage of simplicity of structure and shape, allowing quite large vessels to be built with a minimum of complex shaping. The resulting vessels, often with all the beauty and grace of a packing crate, are cheap per ton of capacity to build and simple to repair.

Many theories and suppositions have been postulated regarding the transition between clinker and carvel planking.

- more timber used by clinker planking due to strake overlaps
- Less iron used in carvel with no nail and rove fastenings
- Cheaper to build carvel due to reduced labor costs

There are many other reasons cited for the pros and cons, of each method. However, in my own experience of building and repairing, and the simplest answer, given by practically most shipwrights is that, clinker is easier to build but more difficult to repair, while carvel is more difficult to build, but much easier to repair. One of the major differences is the shaping and fitting of the hull strakes. For carvel, every plank needs to be carefully worked and shaped on both bottom and top edges to create a tight seam, suitable for caulking. A badly formed seam, with incorrect caulking bevels, can make caulking difficult or completely impossible to caulk. Clinker planking on the other hand, tends to be more forgiving of minor errors, and generally quicker to complete.

Is the flush planked bottom of the cog a solution to the problems associated with the vessel grounding and drying out while unloading, a solution engineered to protect the strake edges and fastening from erosion? A simpler but less elegant solution would be the fitting of small battens or sacrificial rubbing strakes along each of the lower strake edges.

Is it evidence of a bottom based design as Hocker suggests, a method of laying several planks side by side to form a panel, before either cutting a boat shape, or twisting the strake ends to form the underwater profile, before adding clinker strakes to extend and raise the sides?

To transition from flush laid to overlapping clinker along the same strake require significant additional work to shape and adjust the lands, and rebates, which form that transition. Perhaps the reduction in number of flush laid strakes is simply a time, labor and hence cost reducing evolution. Or the realization that the strakes at and above the turn of the bilge, rarely took the ground and could be left clinker.

One thing that is very clear from the waterlines (Figure 25 top), the intention, or primary concern with this vessel was the width. This suggests a cargo carrying emphasis. The exaggerated hollow in the lower waterlines is caused, by maintaining that ‘extreme’ width too far forward before transitioning to vertical at the posts, rather than beginning the transition earlier at the expense of bottom width.

How Big is She Really?

With trade expanding throughout the Baltic, and along the southern portion of the North Sea, Elmers (1994, p. 38) mentions the need for increased cargo capacity, and refers to a cog mentioned in 1241 which had a capacity of 240 tons. He states, '*the Bremen cog from 1380 with a cargo capacity of 80 tons is just a small version of this type*'.
Hocker (2004:75) says of the Bremen cog: *'As deep-water cogs go, it is of medium size, at 24m long, with a capacity of 40 lasts (about 120m³, which is about 80 metric tons of rye). In fact, it is smaller than nearly all contemporary accounts would suggest was typical. Medieval documents show that some Hanseatic cogs exceeded 100 lasts by the 1240's and cogs of 150 lasts were known in the fifteenth century.'*

While a vessel of 100 or 150 lasts at first, sounds like it is 2½ to 4 times larger than the small or medium sized Bremen cog at 40 lasts, the laws of relativity and similitude state if you double the size of a vessel (or anything else) you will increase its surface area by four times and its volume by eight times.

Of the more than twenty wrecks recovered which fit the archaeological definition of a cog, the longest recorded keel lengths have been 18.6m for Kollerup and 18.7m for Skanör. If a vessel of the same proportions, length to width ratio as Bremen, which Crumlin-Pedersen already noted is shorter but wider in comparison to Kollerup, were constructed on these longest recovered keel lengths, the resulting vessel would have a capacity of somewhere in the region of 75 lasts.

To increase the capacity of the Bremen cog to what might be considered a 'typical' large cog of say 150 lasts (Figure 26), would require a little over 50% or circa 8m added to the keel length, resulting in a vessel of circa 35m overall length, with a beam of 11.6m a loaded draft of 4.1m and a waterline length of 27.75m. If the same proportions are applied to sail, this 'large' cog would have a sail area of almost 800 m². As Hoffman (2009, p. 289) pointed out, the replica cog required a minimum of five crew to operate the barrel winch and handle the 300kg yard. How many crew would be required to manage this sail plan?

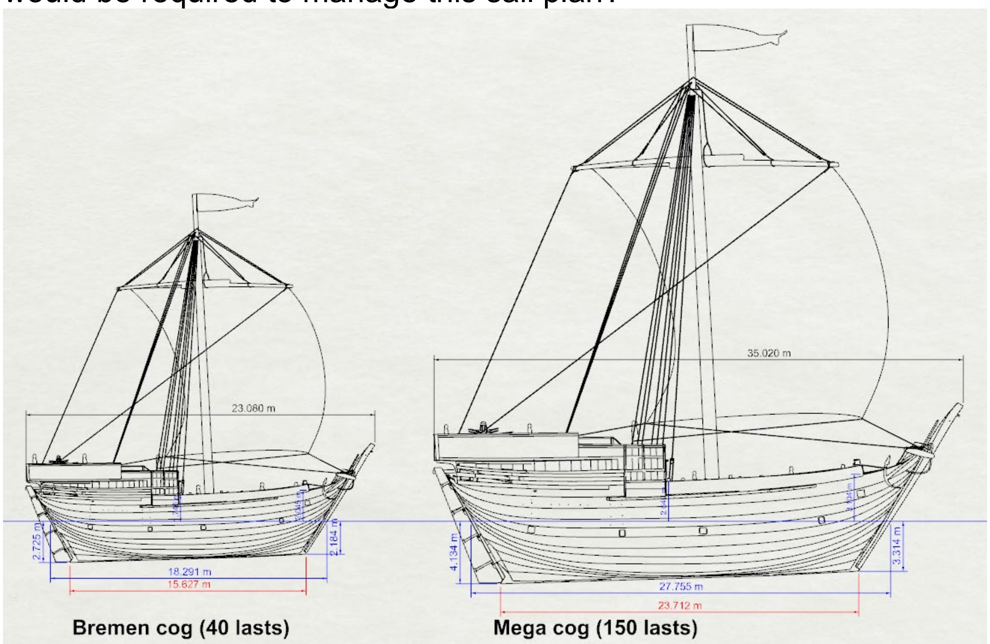


Figure 26 Relative Cog Sizes

I.12 Discussion

The superiority of the cog cannot be denied, as evidenced by the sheer quantity of references throughout the historical record, archives, town seals and coins. What is this superiority based on? Is it the actual characteristics of the vessel type? It if were the preeminent or unrivalled example of maritime transportation, it would have continued for beyond the fifteenth century. Is the cog the best vessel for a specific purpose? Without doubt it is, or it simply would not have flourished to such an extent. The question then arises, which characteristic, or combination of, makes the cog so superior. Or is that superiority simple a superiority in numbers.

Hoffmann (2009, pp. 292–93) states a cog skipper would have reckoned on a voyage from Hamburg to Bruges and back, a return voyage of 610 nautical miles (1,130km) taking an average of seven weeks. Allowing for two weeks in port at Bruges to unload and load a return cargo, or wait on weather, this averages at 0.73 knots if sailing non-stop, or an average of 2.2 knots if day sailing only. If the turn-around time were reduced to a few days, the average speeds would be 0.5 knots or 1.1 knots for non-stop and day sailing respectively. Hoffmann also mentions 12 weeks, for a return voyage to Norway. Hamburg to Bergen is 863 nautical miles (1,600km). Again, seemingly low average speeds of 0.45 knots or 1.1 knots for non-stop and day sailing respectively.

If these average speeds were applied to an Icelandic voyage, the journey could be 58 days each way. Hoffmann (ibid. pp. 289-90) states the replica *Hansekogge* went on her “shakedown cruise” in 1992. Sea-trials with a crew of 15, led by a team from the Institute of Ship and Sea Technology, Berlin took place that summer but never in a wind greater than Force 7 (15m/sec). Easily steered by one man in most conditions the cog required two at the helm only in fresh winds, and the helmsman needed to be vigilant as she would turn quickly. Her heel remained good for a freighter, up to 15°. Hoffmann continues by saying the average speed over all courses and wind conditions was 5 knots. She sailed well when the wind was dead astern, or on either quarter, and like most sailing craft, sailed best at about 150° to the wind, up to 8-9 knots in a fresh wind.

This heel angle appears to agree with the calculations carried out earlier for the vessel in Beam-End displacement, where result give a 14.2° heel in a Force 6. The same wind strength would heel the empty (Lightship displacement) vessel to 32.4°, and the fully loaded Grågås Codex displacement version to a mere 5.7°. Speed figures from Hoffmann of 8-9 knots in a fresh wind, if Hoffmann’s fresh wind equates to the standard definition of “fresh” as a Force 6, again agree with the performance calculations for the Beam-End displacement at 8.4 knots.

These two descriptions by Hoffmann, vessels voyaging to Brugge or Norway averaging 0.5 – 1 knots, and the replica ‘*averaging 5 knots on all course and all wind conditions’,* cannot be easily reconciled. Perhaps these shakedown and sea-trials were akin to a modern-day test drive, find a nice area, open her up and let’s “see what she can do".

A second replica, the *Ubena* first set sail in 1991, captained by Joachim Möller, a time-served master mariner, from ship’s boy to captain, who has sailed freighters on every ocean, as well as experienced in sailing “square riggers” aboard traditional sailing ships. Möller sails the *Ubena* with a crew of 12, saying shortening sail in heavy weather requires two men at the braces, two on the clew lines, six for the buntlines one or two for the tiller and the captain to give orders. The 18m yard, weighing three tons with the sail attached, is too unmanageable and dangerous to be lowered on deck in a seaway. This number of crew cannot be reduced through training, their physical strength is required (Hoffmann and Hoffmann, 2009, p. 292).

Of *Ubena 's* characteristics, Möller says she can take a Force 8 under full sail, but not downwind when the loss of stability on the crest of a wave becomes too dangerous. She has survived a Force 11-12, with the sail taken in and the engine working (not particularly relevant to medieval seafaring), listing up to 40°, but without shipping green seas (meaning solid walls of sea water). He says the cog is a dry ship, but she rolls awfully, causing seasickness for all aboard, himself included. Winds of Force 3-4 or less result in *Ubena* merely drifting sideways, in a Force 5-6 she carries weather helm, and is able to make about 5 knots in smooth water at about 80° to a strong wind. However, a drift of 10-15° means she cannot make good any height over the ground. As a result, with an inshore wind *Ubena* can keep an offing from the coast, but she cannot sail clear of the coast. Drifting before the wind without sail the castle and high sides can generate as much as 3-4 knots, and Möller says the *Ubena* is unwilling to tack through the wind, going about is more a chance happening, he prefers instead to jibe, even if the cog will lose all that ground to windward.

Again, these figures as quoted by Möller, would appear to agree with the calculated performance results generated by the Orca 3D software for a vessel in the Beam-End flotation condition. Perhaps also the comments on the “upwind” characteristics of the cog reflect the description by Ellmers (1994, p. 40) where he states:

> *While sailing against the wind was possible in theory, few seamen did so as they were unwilling to let the coast slip out of sight. If there was fog, an unfavourable wind or a storm… …… there was nothing for it but to drop anchor and wait for better conditions. Sailing along the Hanseatic routes in the reconstruction of the Bremen cog has generated first-hand knowledge of how important it is to know all sheltered bays along the coast which could be havens in emergencies. The worst situation of all occurred if a storm changed direction and the wind began to blow into the open mouth of a bay which had hitherto afforded protection. Most of the cog wrecks which have been discovered in Scandinavia and the Netherlands were driven onto the shore during storms.*

Elmers also discusses the navigation methods of cog sailors, stating from around 1225, harbour markers of the type used in Scandinavia were introduced into the Hanseatic area as a further aid to navigation. These were tower shaped wooden structures enabling those sailing along the coast to spot the entrance to harbour towns or estuaries from a long way off.

As all harbours used by cogs were not reached solely by coastal sailing, it was necessary to cross the open sea out of sight of the coast. This Ellmers states was achieved by waiting for a clear night in order to navigate by means of the pole star. The helmsman simply steering the vessel while keeping the pole star visible above the same part of the ship. He further states it was essential that the crossing be to a coastline which could be at least dimly discerned on the horizon when the view of the pole star faded as morning broke. Islands with high elevations therefore became important navigational aids. According to Elmers this method of navigation was called *Nachtsprung* (leaping in the night) by the historian Adam von Bremen, who wrote in the eleventh century.

There appears to be a lot of individual elements, all requiring suitable alignment for this to be the only approach to sea crossings. How many times will the wind be in the correct direction, of suitable strength, sea state not too rough, and the sky sufficiently clear to view the pole star. Adding a few superstitions, never set sail on a Friday (Thursday or Thor's day was also considered unlucky in many cultures), 13th day, red-haired women, black cats, and it is unlikely the medieval mariner would have ever left port.

It would appear form the remarks by Hoffman, and the many available images of each replica afloat, that all three vessels are always sailed in a "half loaded" flotation condition, with the through hull beam ends at or slightly above water level. The Beam Ends flotation condition hydrostatic data, and potential performance calculated earlier would appear to be in agreement with the recorded results and comments of the replica captains above. It is doubtful if any of these replicas has ever sailed in a fully loaded or Grågås Codex displacement.

Archaeological evidence such as Doel 1 (Figure 27), and iconographic representations depicting cogs, many of which clearly show triangular or wedge-shaped blocks of timber attached to the exterior of the hull, adjacent to the through hull beam ends. As discussed by (Vermeersch and Haneca, 2015, pp. 123–24) these blocks have often been referred to as fenders, but should rather be designated fairing blocks. This author agrees with conclusion that these blocks not in fact designed and fitted as simple fenders to protect the protruding beam ends from impact with a pier for example, but rather their tapered or curved shaping would indicate an intentional shaping to enhance the flow of water or other debris around the protrusions. In addition, the complex arrangement of rebates to accommodate the hull planking indicates a desire by the builder to achieve a watertight connection between the beams and exterior hull, thereby allowing the vessel to float with these protruding beams either partially or wholly submerged.

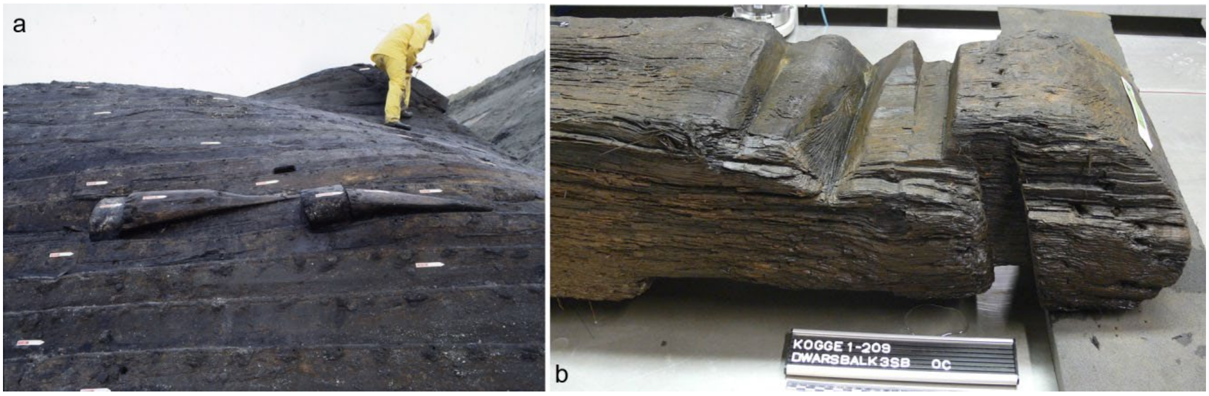


Figure 27 Beam End fairing blocks on the Doel cog after (Vermeersch and Haneca, 2015)

Loading the vessel to the Grågås Codex displacement would have the effect of submerging the through hull beam ends by circa 0.5m, and thereby increasing the cargo carrying capacity by a factor of 2.5, from a meagre 38 tons to 108 tons. In addition, as demonstrated in the hydrostatic calculations, the vessels stability is greatly increased.

The roll time for a vessel, the time taken to return to upright has a direct bearing on the comfort of the crew as well as the safety of the vessel. A long slow roll period can result in a wallowing drunken roll, uncomfortable for the crew and potentially causing the vessel to roll beyond the point of no return. By contrast a very short roll time results in a snappy or violent response and is uncomfortable or dangerous for the crew. Ideal roll time for stability and comfort should be equal to the waterline beam of the vessel, that is B_{WL} / $Roll_{SEC}$ = 1. Results between 1 and 1.1 will have sufficient stability and have a comfortable motion in rough seas.

The Bremen cog, in Beam End displacement has a roll period of circa 4.8 seconds, and a waterline beam of 5.96m giving a $B_{WL}/Roll_{SEC}$ ratio of 1.242. In the deeper draft, Grågås Codex displacement, her roll period is circa 5.8 seconds with a waterline beam of 6.5m giving a $B_{WL}/Roll_{SEC}$ ratio of 1.12 which is much closer to the ideal range of 1-1.1.

It would appear from these calculations that the vessel loaded to the Grågås Codex displacement has an additional 150% cargo carrying capacity, is more stable and possible reacts in a more sea-kindly fashion than when loaded just to the beam end displacement condition. The 3 replicas, in their current configuration, with inboard engines, watertight decks, and internal furnishings do not accurately represent an original medieval cog. Likewise, their flotation condition with the through hull beams above the water would not appear to represent a “fully loaded” vessel.

I.13 Conclusion

From the outset, one significant question was raised. Throughout the Hanseatic records, the cog appears as the predominant vessel for seaborne transport. The majority of trade ranged from Russia in the East, across the Baltic Sea, to England in the west across the North Sea. Records also show trade with ‘outlying’ regions such Iceland in the north west Atlantic Ocean, as well as south into the Mediterranean.

Is the Bremen cog a typical example of the vessels which traded with Iceland as documented in historic records? Or put more simply, Is the cog the ocean-going vessel of the Hanseatic League?

Evidence both archaeological and historic has shown that the cog as a vessel type, traded extensively throughout the Scandinavian region. It is obviously a vessel well suited to this activity, for if it were not, it simply would not have flourished to such an extent.

The Skagerrak, Kategat, Baltic Sea, and southern half of the North Sea are largely similar in both wind and wave conditions.

Mean wave heights tend to be 1m or less throughout the year, only increasing to 1.5m during November to February. Maximum heights tend to be in the 2m to 3m range, and extremes such as 4.7m recorded during a 22m/s wind (42 knots or F9 severe gale) in January.

The Kattegatt is a 30,000 km² (12,000sq m) sea area bounded by Jutland (Denmark) to the west, the islands of the Danish strait to the south, and Scania or Sweden to the east. This sea is a little over 50 nautical miles (92km) wide, east-west, and north-south transits not much more than double that. The northern Baltic Sea tend to be little over 160 nautical miles in an East – West direction, and 320 nautical miles North to South. The southern Baltic is circa 300 nautical miles East to West, and little over 100 nautical miles North to South. Similarly, the southern half of the North Sea is a little over 280 nautical miles from Denmark westwards towards England.

A vessel capable of carrying between 50 and 100 tons of cargo and sailing at average speeds of circa 5 knots (given the right conditions), would be ideally suited to these coastal journeys, or “sea crossings” of up to 300 nautical miles. Typical duration for these voyages (in the right conditions) would be somewhere in the region of 60 hours or two to three days. This would result in a total weight of 1,750kg for crew and provisions.

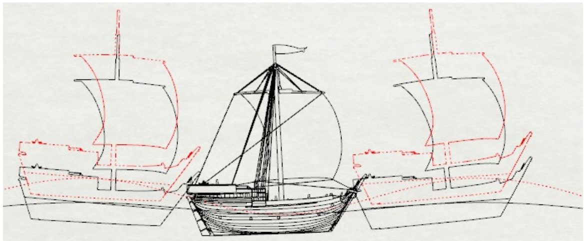
Other than the weather, the other major influencing factor on any sea voyage is the sea state. The state of the sea is primarily influenced by waves. The three main factors which make up waves are wind speed, duration of wind, and fetch.

Fetch is the distance of open water that the wind blows over. All of these factors work together to create waves, and the greater each of the variables in the equation, the greater the wave. Waves are measured by height H_W from trough to crest, length L_W from crest to crest, period T the length of time between crests, and steepness the ratio of height to width.

It is a well-known fact that storm waves (force 8 wind) in the North Atlantic can reach heights of 35ft (10.6m) with a length of 1,000ft (304m), while those in the Baltic seldom exceed 8ft (2.4m) in height and 100ft (30m) in length. The longest wave ever observed was about 2,800ft (853m) long and traveled at speeds of 74kts (Marchaj, 1964, pp. 400–401).

There are theoretical limits for each variable in the equation. If there is a limited fetch of say 10nm to land, then a wind blowing at 36kts (Force 8) will create a significant wave height of 2.1m no matter how long the wind blows. Whereas the same 36kts wind blowing for two or three days with an unlimited fetch can generate a significant wave height of 10m. Waves are never created in one uniform height. Instead creating a systemic pattern of varying sizes. Significant wave height is used, which is the average of the highest 1/3 of the waves in a system. To translate significant wave heights to actual heights, the average height will be 0.64 times the value, with the highest 10% being 1.29 times the value and the largest wave will be 1.87 times the significant wave height value.

A storm (force 8) wind in the Baltic, creating a significant wave height of 2.4m will have an average height of 1.5m while the largest individual wave could be 4.5m, wave length in unlikely to exceed 45m (Figure 28 top). The same storm in the North Atlantic will create an average wave of 6.8m, with an individual maximum height of 19.8m. This maximum height can take as little as 12 to 15 hours to form and can be more than 200m in length (Figure 28 bottom). The speed at which the two waves travel is calculated by multiplying the square root of the wave length in feet by 1.34. The 1.5m Baltic wave will travel at 16.25kts while the 6.8m North Atlantic wave travels at up to 34kts. This means that the crest of a Baltic wave will pass a fixed location every 5.3 seconds, while the crest of the North Atlantic wave passes every 11.3 seconds.



Red lines indicate maximum heights.

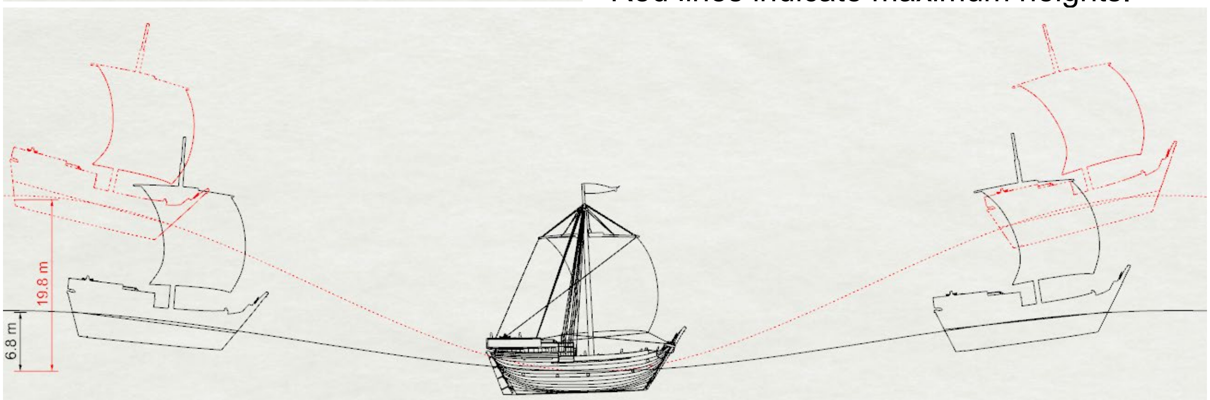


Figure 28 Typical wave heights in the Baltic Sea versus the North Atlantic

The resulting sea states would be best described as violently choppy for the Baltic, whereas the North Sea equivalent is more akin to riding a rollercoaster at speeds approaching formula one racing levels. Of significant importance is how the vessel behaves during these almost vertical changes in position. As the vessel reaches the top of a crest, it pitches forward over that crest to begin accelerating down the face of the wave. In extreme cases, such as the red cog ship in the bottom left position of Figure 28, this forward pitching, and associated dropping of the bow, can lift the stern area almost clear of the water resulting in a temporary loss of steerage as the rudder has nothing but air to grip.

This is followed by a short, very rapid speed increase as the vessel “surfs” down the face of the wave into the trough, followed by a rapid, and often violent deceleration as the bow hits the back of the wave ahead, followed by a further deceleration as the vessel combats gravity while climbing the face of the next wave. In extreme, and surprisingly regular cases, this sudden and violent deceleration can cause the bow of the vessel to “dig-in” to the back face of the wave ahead.

The wave speeds and heights as calculated, are a passage of motion only, and not the water. The actual movement of the water particles which compose the wave is formed by orbital movement centered on the mean height of their at rest position. The actual motion of the vessel due to the passage of a wave, is primarily a vertical movement as the vessel rises and falls on each successive crest and trough. An indication of this vertical movement can be seen in the case of the Baltic wave where the vessel rises and falls by an average 1.5m up to a maximum of 4.5m every 5 or 6 seconds. By contrast the North Atlantic wave results in a 6.8m average, up to a maximum 19.8m rise and fall every 11 or 12 seconds.

All the motion of the vessel in this case, is purely a result of gravity. The vessel will accelerate as it travels “downhill” on the face of a wave and decelerate as it travels “uphill” on the back of the next wave. In the case of the smaller Baltic wave this will result primarily in a pitching motion as the wave crest passes along the length of the ship, lifting firstly the stern and then the bow. By contrast the deeper and longer swell of the North Atlantic wave will result in the vessel being bodily lifted, up to a maximum of 19m, when the vessel then finds herself sailing “downhill” for some 5 or 6 seconds into the trough, followed by an “uphill” sail to reach the next crest.

The orbital rotation of the water particles within the wave creates an orbital velocity at the surface of each wave. The higher the wave the faster the orbital rotation of its water particles. The direction and velocity of this orbital flow varies, depending on which part of the wave surface is involved, and while this orbital velocity can be rather small compared with wave velocity, its effect on vessel behavior far from negligible.

The formula for orbital flow calculation is $U_{orb} = \frac{\pi H_w}{T}$. For the two waves previously calculated, the Baltic wave has a height H_w of 1.4m average and 4.5m maximum with a period T of 5.3 seconds, while the North Atlantic wave has a height H_w of 6.8m average and 19.8m maximum with a period T of 11.3 seconds. From this the Baltic wave will have an orbital flow velocity of between 0.8kts and 2.7kts, while the North Atlantic wave has an orbital flow velocity of between 1.9kts and 5.5kts.

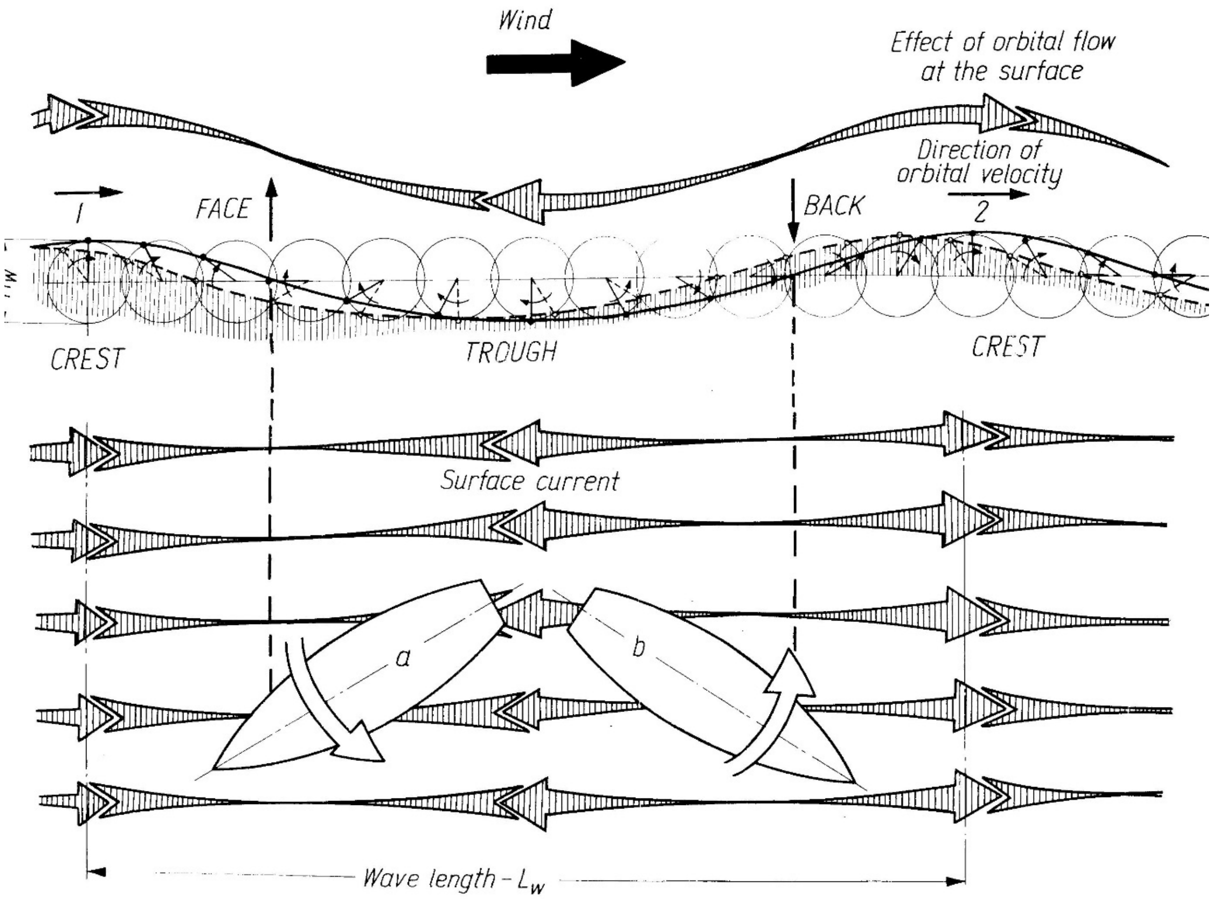


Figure 29 Effect of Orbital Surface Flow after (Marchaj, 1964, p. 398)

Figure 29 clearly shows the influence of the orbital flow surface current on a vessel will depend on:

1. The ratio of the wave length L_w to length of the hull waterline LWL, L_w/LWL
2. The position of the boat in relation to the wave.

Boat a in Figure 29 travelling upwind and crossing the wave at an oblique angle will be affected by the orbital velocity which will tend to push the boat off course. Boat b, which is more relevant to our cog example, is a vessel running before the wind in heavy seas. This vessel will, if left uncorrected by the helmsman, find herself turning more into the wind and perpendicular to the waves back.

A vessel running before the wind in a heavy sea will, out of necessity be obliged to sail obliquely across the wave system. This is required to avoid running directly perpendicular into the back of the next wave, which will bring the vessel to an abrupt stop and bury the bow into the back of that wave. The oblique angle of attack also has the effect of reducing the steepness of the waves back, giving the vessel a better chance to climb the next crest. However, the orbital flow in the crests and troughs will cause a marked tendency for the vessel to broach, where the bow passes through the wind, the sail(s) can fill from the wrong side and a knockdown (mast in the water) or capsize and complete rollover are inevitable. Constant corrections on the rudder are required by the helmsman to counteract this yawing moment if such a scenario is to be avoided.

By analyzing Figure 29 it can be seen that this effect is maximized when the wave length L_W is twice that of the hull waterline length LWL. In this case, when the forepart of the hull reaches the trough, the afterpart will be on the crest. In this position, as well as the unstable yawing effects caused by surface flow, rudder effectiveness is considerably reduced due to the orbital flow significantly reducing the surface flow around the rudder upon which it depends to operate effectively.

In the case of the Bremen cog, this worst-case wave length would be LWL (18.3m) x 2 = 36.6m. A wave of this length would only develop in the Baltic with winds exceeding 15m/sec (Force 7) and lasting for more than 12 hours. In the North Atlantic a wave of this length will develop more frequently as shown in Table 11. And with the typical or most frequent winds being 10m/sec (Force 5) in North Atlantic, it could take as little as 12 hours for this wave system to develop.

Wind Strength	Hours	Avg. Height	Max. Height	Height after 24 hrs
Force 3	55	0.8m	1.4m	1.4m
Force 4	30	1.2m	2.2m	3.2m
Force 5	13	2.4m	4.5m	5.0m
Force 6	10	3.1m	5.8m	7.6m
Force 7	6	3.7m	6.9m	10.8m
Force 8	3	4.6	8.6m	19.5m

Table 11 Wind strength and wave height

As noted by Marchaj (1964, p. 399), the deep forefoot of the earlier ships had a tendency to dig into the back of the wave ahead when the vessel was running before a heavy sea. This can be dangerous as the CLR (center of lateral resistance) temporarily moves a long way forward, leading to a loss of directional control by the rudder. In this event the vessel can broach to, slewing around broadside on, and going over on her beam ends. Marchaj states that it may be that the real, if only partially understood, reason why the very blunt bows persisted for so long on square rigged vessels is that they had less of a tendency to dig in and would therefore provide some safeguard against broaching. The yacht's hull with its cut-away forefoot is much less susceptible to broaching to according to Marchaj. He also notes that running before a high wind and sea demands the full attention of the helmsman in anticipation of the possible consequences.

Indeed, I well remember an incident while sailing aboard a custom built offshore racing yacht, when a simple sneeze at a very inopportune moment by the helmsman, causing just such a broach, resulted in very wet crew, and the much-anticipated hot meal needing to be scraped off the underside of the deck.

Depending on how severely the bow buries into the wave ahead, loading the foredeck with many tons of water, the vessel will in the best-case scenario come to a complete and abrupt stop, and in the worst-case scenario, will pitch-pole, whereby the stern passes vertically over the stem (Figure 30).

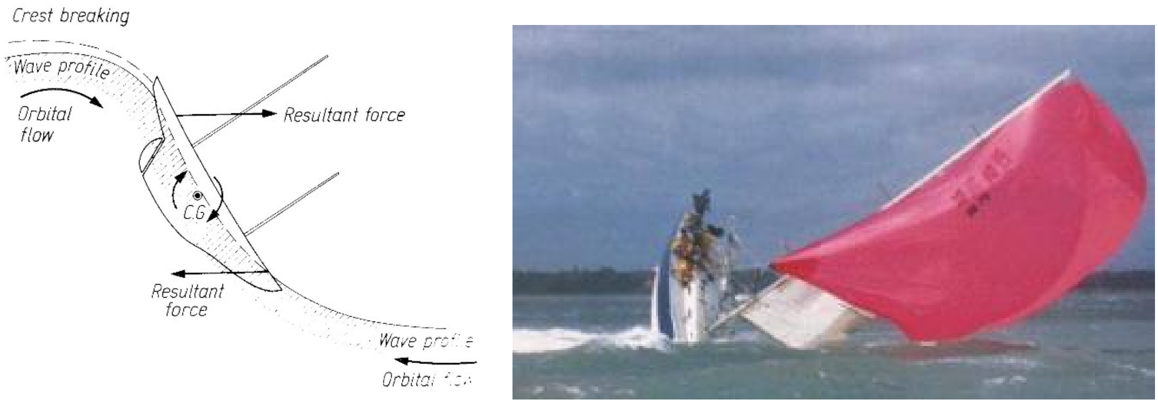


Figure 30 Vessel in Steep Waves

Figure 30 left after (Marchaj, 1964) illustrates the forces at play while on the face of a steep wave, and Figure 30 right (photo: Beken of Cowes) illustrates a more recent example of a boat "*Silk 2"* pitchpoling, which I witnessed while sailing during Cowes race week 1996. In this case the vessel was not sailing in particularly steep waves, and the crew can be clearly seen positioned well aft in an attempt to lighten the forepart of the vessel. The bow did however bury into the wave ahead resulting in a dramatic pitchpole.

The Bremen cog, it could be argued has a relatively full or blunt bow, which should create additional buoyancy forward to counteract the broaching and reduce risk of the bows burying into the face of a wave. However the hollow sections forward, and hollow lower waterlines as earlier identified by Hocker (2004:75), and illustrated in Figure 25 create an almost vertical or fin like shape in the lower forefoot of the vessel. This sharp forefoot will in fact dig in to the back of a wave long before the blunt forward hull shape lifts the vessel. This creates a large surface area buried deep into the orbital surface flow of the wave system and greatly increases the possibility of broaching to.

As illustrated, the sea state and immediate situational awareness of the helmsman is the preeminent concern for any vessel in these conditions, far outweighing factors such as wind direction or desired course towards destination. For the vessel to not only function, but also to survive in this type of wave system, the helmsman needs to be constantly aware of both his current position within the overall wave system, and his updated position in as little as 10 seconds ahead. He is at any one point in time correcting the vessels course in reaction to the immediate change whilst also planning his next imminent course correction. To achieve this, he is watching the evolving wave ahead, as well as monitoring the upcoming wave from behind, while at the same time watching for the rogue beam wave trying to catch him unawares. All split-second calculations processed to arrive at the decision to either push or pull the tiller, turning the bows into or away from the crest or trough arriving in 5 seconds time.

The position of the helmsman at the tiller, in an almost cave-like enclosure, prevents any possibility of a clear view of the surrounding sea state. This is absolutely critical if the helmsman is to react in time to the continually and rapidly changing environment. Any suggestion of a captain standing on the raised stern castle, or a lookout at the bow relaying instructions to the almost completely blind helmsman simple could not work.

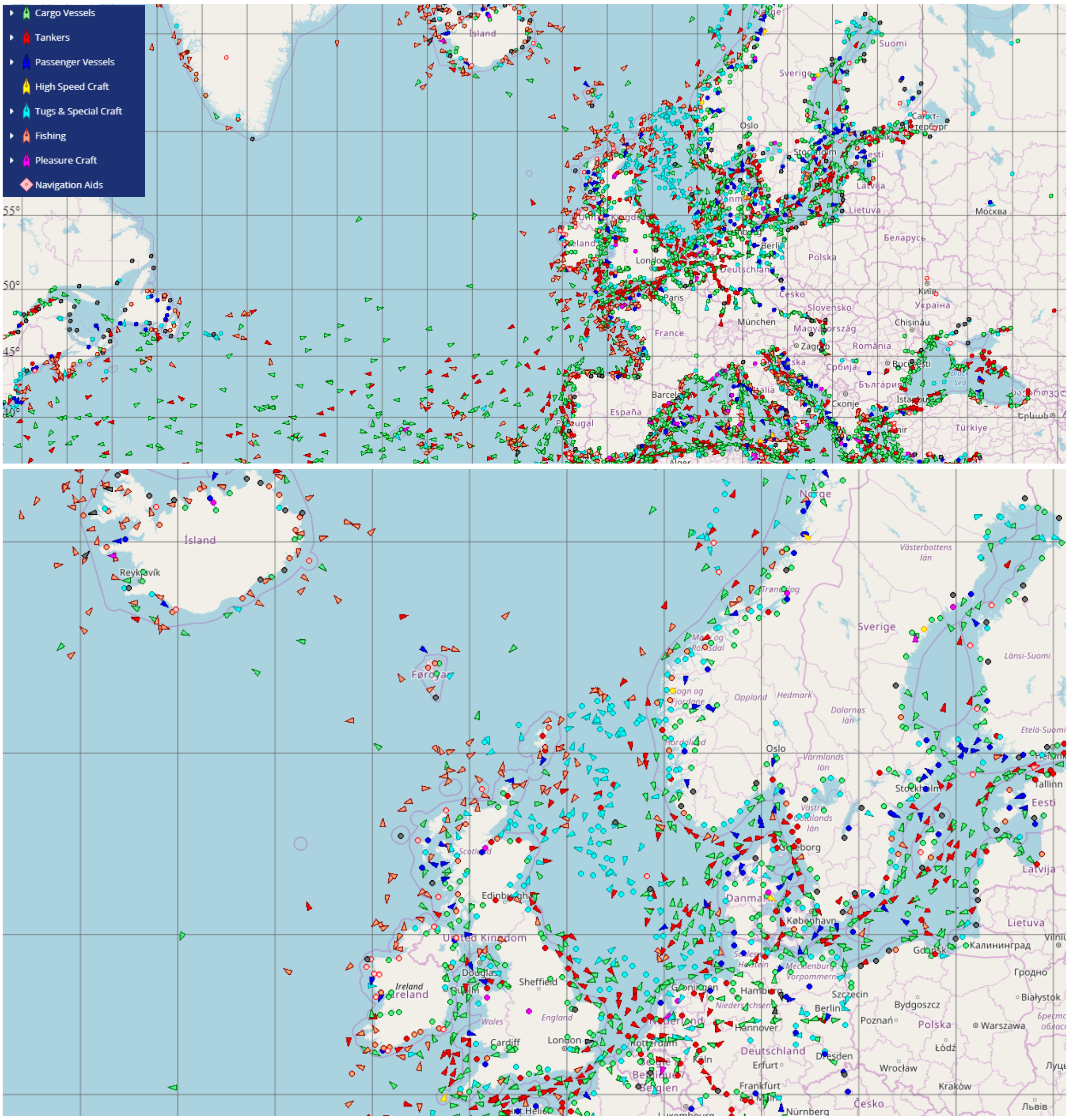


Figure 31 Maritime Traffic snapshot 2017

Figure 31 is a "snapshot" of the positions of maritime vessels on a particular date and time. Even in modern times (2017) clear patterns for each route can be seen. The majority of traffic is routed along or close to a coastline. The same applies throughout the Baltic, Scandinavia, the North Sea, and the Mediterranean. Practically all of the trans-Atlantic traffic is crossing below 45° North, even though "great circle navigation" clearly shows the shortest route is an arc with its apex as far north as you dare, resulting in the shortest distance travelled. The decision to remain below the 45^{th} parallel results in smoother seas and more favorable wind conditions. Yes, even modern high sided ships are susceptible to winds. There is a concentration of vessels in the central part of the North Sea, but the color coding shows these are all either tugs or specialist craft, with a need to be there (oil and gas exploration or wind farms). Several fishing vess

els can be seen dotted around the coast line of each land mass, but other than four cargo vessels and one tanker (on this day), the entire North Atlantic, west of Ireland and above the 50^{th} parallel is completely devoid of vessels.

I, as a boatbuilder, and probably every boatbuilder before me has been asked for the same thing, what might be called the ultimate boat. This fictitious vessel should be the same length, thereby costing the same as boat X, but it must carry more cargo (be it people or goods), at a faster speed than the original. These three factors are mutually exclusive. More cargo on the same length requires additional beam, which adversely impacts speed. More speed on the same length requires less beam, which adversely impacts cargo capacity. Consequently, the only solution to additional cargo capacity, with increased speed is, as a well know movie actor said, *"We're going to need a bigger boat"* which subsequently increases cost.

There is no such thing as the ideal boat, it is not physically possible to design a vessel which is perfect for every task, sea state or weather condition. Whatever the criteria used for designing such a vessel, there will always be a limiting factor. Whether that limit is overall size dictated mainly by cost or availability of raw materials, the draft dictated by available depth of water, or any other factors, the goal of the boat builder or naval architect is to create a vessel best suited to its environment. That environment is a complicated recipe, made up in part of: materials, cost, intended function, local conditions both sea and weather and the myriad of "secret extras".

If cargo capacity is the sole requirement, ample evidence exists of contemporary vessels, some which predate the Hanseatic period, descended from the Nordic tradition (clinker built), and easily equal or surpass the cargo capacities of the cog (Englert, 2000). One such example could be the so-called 'Bergen Big Ship' which is estimated to have been ca 30m long, with a beam of 9-10m and a draught of 2.4m. Cargo capacity for this vessel is estimated at ca 120-150 tons, but it is unclear to this author how this has been calculated. If this is an accurate estimate, using the approximation of two metric tons per last (the 'academic' last) gives a capacity of 60-75 lasts. The last as defined by Morken, $\frac{\text{Length x Beam x Depth in meters}}{4.8}$ would result in 230-250 lasts capacity.

The Bremen cog as a vessel, based on its hull shape, can carry a cargo of circa 100 tons, at a draft of 2.7m. The vessel with a waterline length of 18.3m has a theoretical maximum speed of 10.4kts and could achieve speeds of between six to eight knots in a Force 5 or 6 wind speed with ideal sea conditions. As such it is well suited to transporting cargo along the coastal routes and relatively short sea crossing on the sheltered waters of northern Europe.

The flat bottom, which would result in severe slamming in a large sea, combined with the overall hull shape and performance characteristics, would not indicate a vessel ideally suited to operation on the large seas of the exposed North Atlantic.

It is not possible to state whether a vessel like the Bremen cog ever successfully completed a voyage to Iceland, or crossed the exposed Bay of Biscay, en-route to the Mediterranean. Certainly, the historic record suggests that cogs were known, at least in the Mediterranean, but is this a misuse of the name cog as a label. It is the opinion of this author, if alternatives existed, this vessel would not be the primary choice for such an adventure.

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Appendix J 3D Documentation of the Marsala Punic Ship

3D Documentation of the Marsala Punic Ship: Digital Conservation and Archiving

by Mateusz Polakowski and Pat Tanner

The Honor Frost Foundation
LONDON - MARSALA - ROME - BOSTON - HFF 2020

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J.1 Details

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2.2 Lead Person
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2.3 Team Members
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Mateusz Polakowski (University of Southampton)

Ship Science and Laser Scanning
Pierre Poveda (AMU/CNRS/CCJ)
Pat Tanner (3D Scanning Ireland Ltd/University of Southampton)

Photogrammetry and Spatial Reference
Lionel Roux (AMU/CNRS/CCJ)
Vincent Dumas (AMU/CNRS/CCJ)

2.4 Project Website(s)
VR Exhibit

- https://www.thinglink.com/video/1258758888233107457

Traditional Boats of Ireland SketchFab

- Marsala Punic Ship: https://skfb.ly/6KIqB
- Marsala Punic Ship Cantine Pelligrino Moulds: https://skfb.ly/6Ktp6

J.3 Web Summary of completed project

Authors: Mateusz Polakowski and Pat Tanner

3.1 Introduction of Project

The Marsala ship is one of the few examples of Punic ships surviving in the archaeological record and serves as the best example of Punic ship construction. The Punic ship, dated using pottery found on the wreck site to the 3rd century BC, is one of the only excavated shipwrecks that provides information on building techniques used by Punic shipbuilders at that time (Figure 1) (Johnstone:1977, 1978, 1983). It is housed at the Regional Archaeological Museum Baglio Anselmi in Marsala, Sicily which has in 2019 been reorganized under the new Parco Archaeolgico Lilbeo-Marsala. Following a reexamination of archival data by the Trinacria Sounding Project (TSP) (Berlinghieri and Calcagno 2013) and a new effort in 2018 to reexamine the ship's conservation by a team of nautical archaeologists and conservators from the Arc-Nucléart restoration laboratory and the Centre Camille Jullian (Aix Marseille University, CNRS), the Marsala Punic Ship was found to be in a dangerous state requiring intervention and conservation.

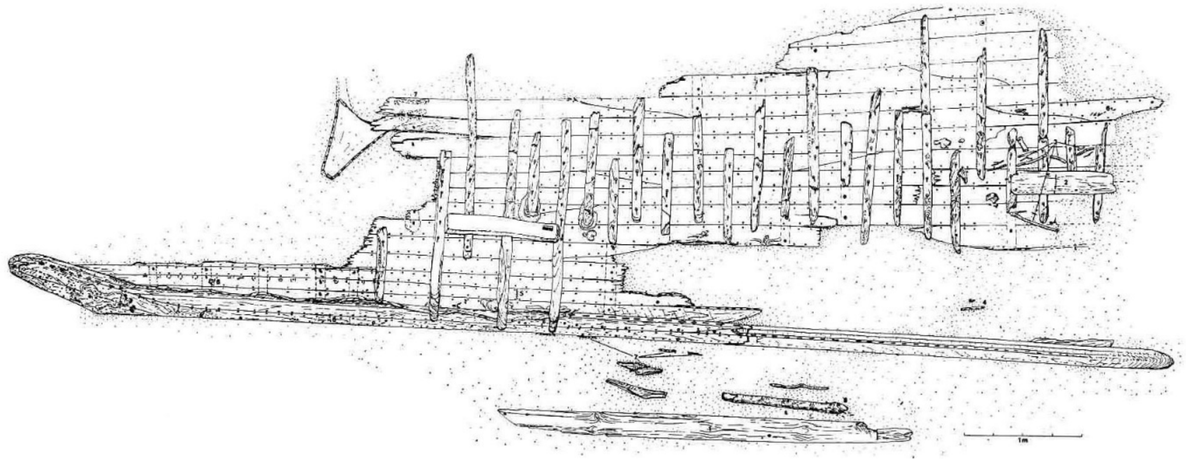

Figure 1 Plan of the Punic Ship (Frost 1981a, fig. 9)

3.2 The Aim of Project

This project documented the Marsala Punic ship with a high-resolution three-dimensional scan using the Faro Focus (S-series). The primary goals of this project were to produce a high-resolution archive of the Marsala Punic Ship and its associated remains to inform conservators and archaeologists about the ship's current integrity and future conservation efforts. The project goals were to achieve:

1. A digital survey by 3D laser scanning coupled with improved photogrammetric survey and the topographic survey of permanent target network within the building.
2. A digital survey of the timbers not on display in the museum such as keel models and stanchion support(s).
3. A laser scan of the original plaster casts taken by Honor Frost of the timbers during initial excavation (currently housed at the Cantine Pellegrino, Marsala).
4. Process a high accuracy three-dimensional model of the archaeological remains
5. Produce a first stress-model of the archaeological remains and examine it against historical datasets to determine the percentage of deformity and degradation.
6. Use this preliminary dataset to aid in conservation efforts to stabilize the shipwreck.

The digital documentation of the ship in its current display will help to formulate a conservation strategy and document the ship before any intervention begins. The resulting models will allow archaeologists and conservators in interact with objects without causing further damage.

3.3 Background

In 1970 Honor Frost (1972, 1973, 1974a, 1981a; Basch 1974) gathered an international team of archaeologists, engineers, and divers to excavate two ancient wooden ships near Marsala, off the western coast of Sicily. Between 1971 and 1974 the Marsala Punic Ship and the Sister Ship were excavated. The Punic ship was raised and eventually put on display in the Regional Archaeological Museum Lilibeo in Marsala. The Sister Ship was recorded by Frost's team but was reburied and left on the seafloor (Frost 1974b, 1975).

3.4 Conservation

Before conservation treatment, essential parts of the hull were replicated by means of plaster casts. These parts were the maple sternpost rise of the keel, a section of the keel, four of the aftermost floor-timbers and a short timber intended to carry a stanchion (Frost 1981a:44) and were subsequently displayed in the 'Cantine Pelligrinno'.

The Marsala ship timbers were conserved in tanks from 1975 to 1978 following the same procedure used for the treatment of the Kyrenia ship in Cyprus. Trials indicated that timber of maple required a combination of PEG 1200 and 4000. The ship's timbers responded well to a procedure with a prolonged bath in circulated PEG 4000, dissolved in water and kept at a controlled temperature of 60° centigrade with a maximum increase of the percentage of PEG 4000 to 80% over a period of 250 days (Clarke 1985). At the completion of the treatment the extra PEG on the surface of the wood was removed and the timber was left to dry out.

The condition of most of the pine timbers of the ship after the treatment was satisfying with a good stabilizing effect of the PEG on both surface character and dimensions. However, the timbers of maple and some of the oak pieces behaved differently and developed cracks and area of collapse (Clarke 1985). As a side effect of the treatment, the specific weight of the timber had increased (around 1.2 g/cm3), and the light yellow surface of the planking turned dark. The letters painted on the planking, which were carefully recorded during the excavation, were not visible and had to be indicated in different ways in the exhibition.

3.5 Restoration

Based on the records of the ship's timbers, a preliminary set of lines and sections was lofted by Adam (1977, 1978) in 1977 and used as a basis for the reassembly of the planks. The conserved wood was mounted in the Baglio Anselmi on a steel cradle by the local shipbuilder Vito Bonanno and his brothers, under the supervision of Honor Frost. The keel was placed on an inverted U-beam of steel mounted on top of a series of concrete blocks, 1m high. Slender steel bands (50 x 6mm) bent to the external shape of the ship were positioned at 1m intervals with adjustable oblique supports and a few longitudinal steel bands, thus forming a slender cradle for the assembly of the planking.

Fractures in the planking required reinforcing the cradle (Clarke 1985). Extra longitudinal and diagonal bands were inserted to carry the weight of the hull. Broken pieces of the planks were fixed to the main lengths of planking with stainless steel pins, pressed or hammered into the wood. Finally, additional planking and keel of new wood were added to indicate the general character of the ship structure. The shipwright Bonanno, also built a wooden replica of the ram structure of the "Sister Ship" during the re-assembly phase (Frost 1981b), which is now on display in the museum.

3.6 The 1990 Danish project

In 1990, the Soprintendenza per i Beni Culturali ed Ambientali di Trapani entrusted Crumlin-Pedersen (1990) with the task of preparing a detailed project regarding a new metal support for the hull torso. Honor Frost with Kirsten Jespersen, John Nørlem Søresen and Ole Crumlin-Pedersen joined Dr.'s Antonio Bartolotta and Cosimo di Stefano on a study visit in Marsala in preparation for a revision of the presentation of the Punic ship (Crumlin-Pedersen 1990).

3.7 The 1997 Danish project

In February 1997, a team from the National Museum in Denmark was entrusted by the Soprintendenza per i Beni Culturali ed Ambientali di Trapani to produce a detailed report on the state of conservation of the ship, a detailed plan for its restoration, and a general proposal for the exhibition. The final report was delivered in two parts. The first presents the state of conservation of the ship and a plan for its restoration including the material needed, the detailed schedule and cost of each task (Boetto et al. 1997). The second provided a general proposal for the exhibition following the ideas elaborated by Crumlin-Pedersen seven years before in the wake of the Frost's general concept of presentation of the Punic Ship (Figure 2) (Christiansen et al. 1997; Giglio and Boetto 1999).

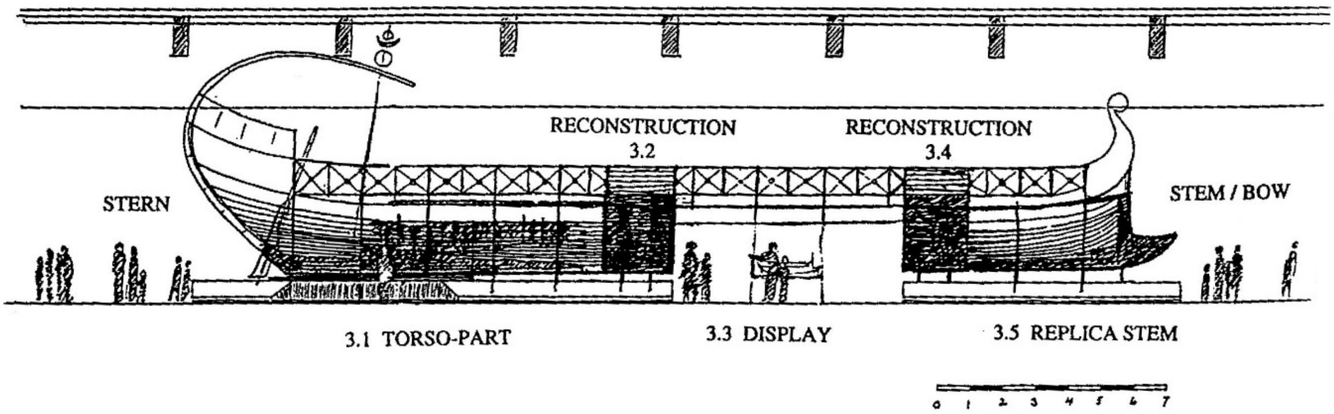

Figure 2 Plans of the Marsala Punic ship exhibit (Christiansen et al. 1997, fig. 5)

3.8 2018-2019 Survey

In early April 2018, a team from the Arc-Nucléart, the Center Camille Julian (Aix Marseille University), and the University of Southampton composed of maritime archaeologists, conservators, and photographers spent four days conducting an initial survey of the Punic ship. This team collected samples of timber from various parts of the ship to test for levels of degradation and conducted a photogrammetry survey of the ship. The team concluded that the remains have undergone heavy remodeling due to the use of modern screws, plates, and rods to support the wooden structure. The assessment also noted that the current support structure of iron bands was providing insufficient support to the timbers causing them to deform and warp.

This initial survey prompted the proposal of creating a high accuracy 3D digital model of the ship. In 2019 Pat Tanner and Mateusz Polakowski (University of Southampton) joined the project team to conduct a three-dimensional digital survey of the Marsala Punic Ship.

3.9 Methodology

From 24th April to 1st May 2019 the Marsala Punic ship and associated artefacts were recorded using a combination of 3D laser scanning and photogrammetry by the combined project team. Access was granted to scan associated timbers and ship elements not on current display in the museum as well as the original plaster moulds taken by Frost and her team during the ship's excavation.

A total of 98 individual laser scans were recorded for the vessel remains, as well as over 3,500 digital photographs. The 98 individual laser scans (Figure 3) recorded with a Faro Focus S70 scanner were registered into a unified project point cloud with an accuracy of 2.4 mm using Faro scene software.

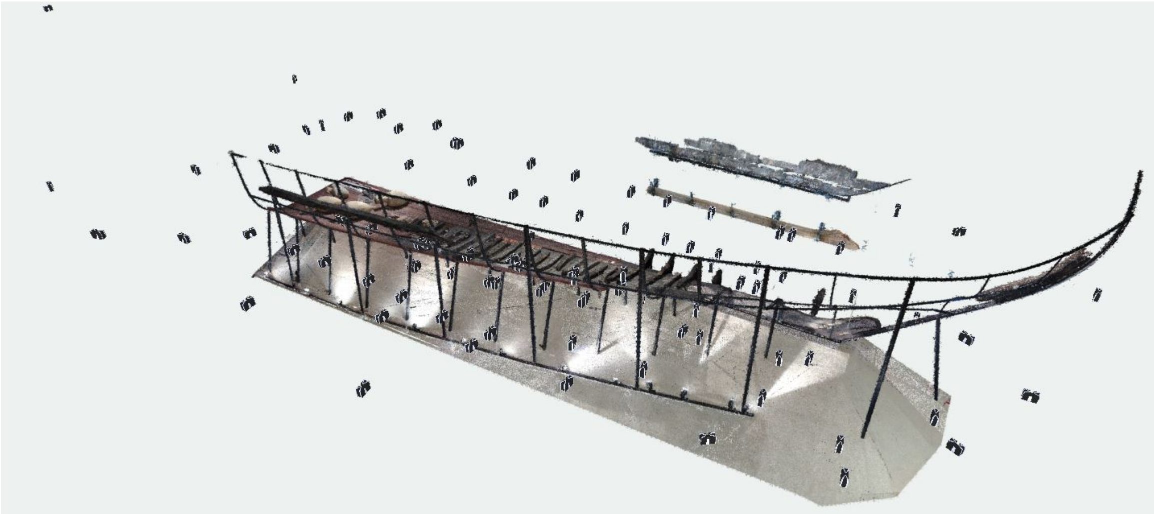

Figure 3 Individual scan positions around the ship

The laser scan point cloud was imported into Reality Capture software and combined with the digital photographs in order to supplement the scan data with photogrammetry data. This had the result of generating a super high-resolution 3D polygon mesh model of the vessel (Figure *4*)consisting of 261 million triangles and textured using more than 2,500 high resolution photographs.

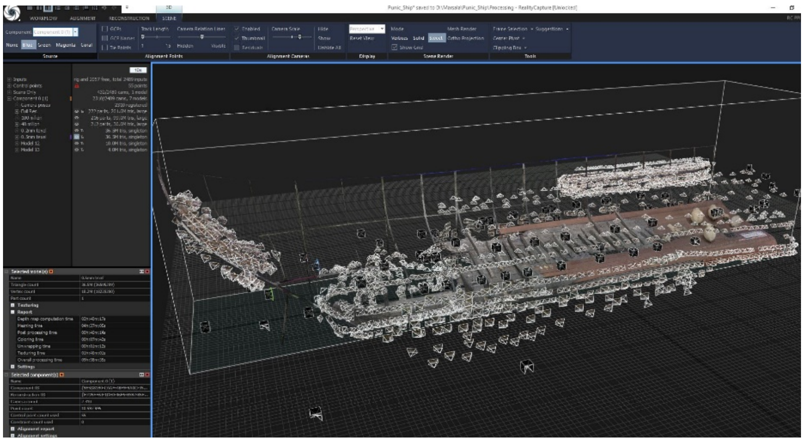

Figure 4 Reality Capture screen grab

This mesh file would be too large to work with and is decimated in order to reduce file size. The decimated high-resolution mesh was then exported to Rhino for further analysis (Figure 5 and Figure 6).

Figure 5 High resolution decimated mesh model (interior view) imported into Rhino

Figure 6 High resolution decimated mesh model (exterior view) imported into Rhino

The same process was also used to record the keel and frame moulds housed in the Cantine Pelligrino' (Figure *8*), as well as the museum model of the keel (Figure 8), the disarticulated starboard side planking (Figure 9) and the replica stem section from the so-called 'Sister Ship' (Figure 10).

Figure 7 High resolution 'Cantine Pelligrino' moulds imported into Rhino

Figure 8 High resolution museum keel model imported into Rhino

Figure 9 High resolution disarticulated starboard planking model imported into Rhino

Figure 10 High resolution 'Sister ship' stem model imported into Rhino

3.10 Combining the digital data

With each of the documented components rendered as a 3D mesh model at full scale, each model was imported into a master Rhino file and correctly orientated and aligned to each other (Figure 11), allowing for the first time a three-dimensional digital reassembly of all the available constituent components of the Marsala Punic Ship.

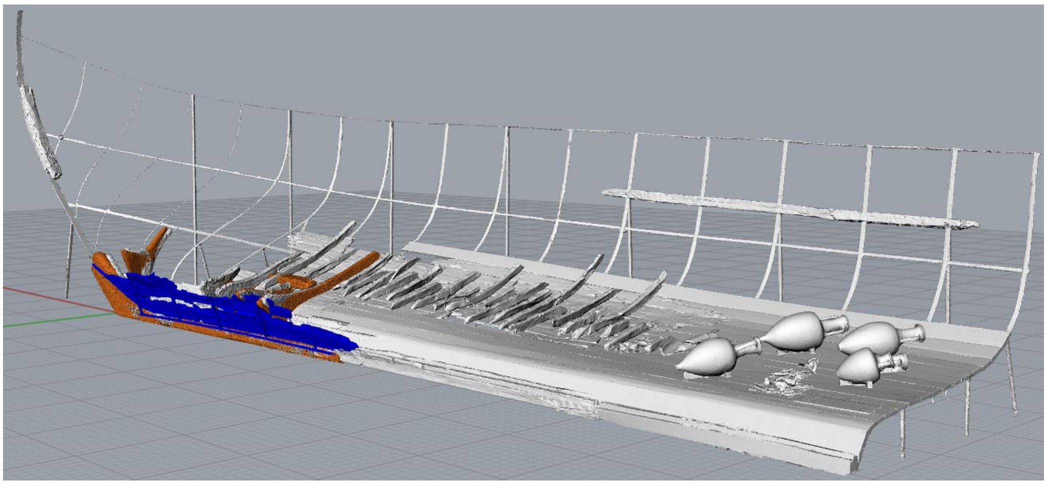

Figure 11 Individual 3D models correctly orientated and aligned to each other

J.4 Account of research carried out

4.1 Initial Assessment and Results

Once the 3D models were correctly orientated within 3D world space, it became immediately apparent that there was significant movement and sagging of the support cradle for the vessel. The sternpost visibly leaned towards the port side of the vessel, and once a central vertical reference plane was inserted it was possible to measure the angle of the sternpost position. It can be clearly seen (Figure 12) that the sternpost has leaned to port by 2.3°, resulting in a horizontal movement of 176mm towards the port side at the upper extremity.

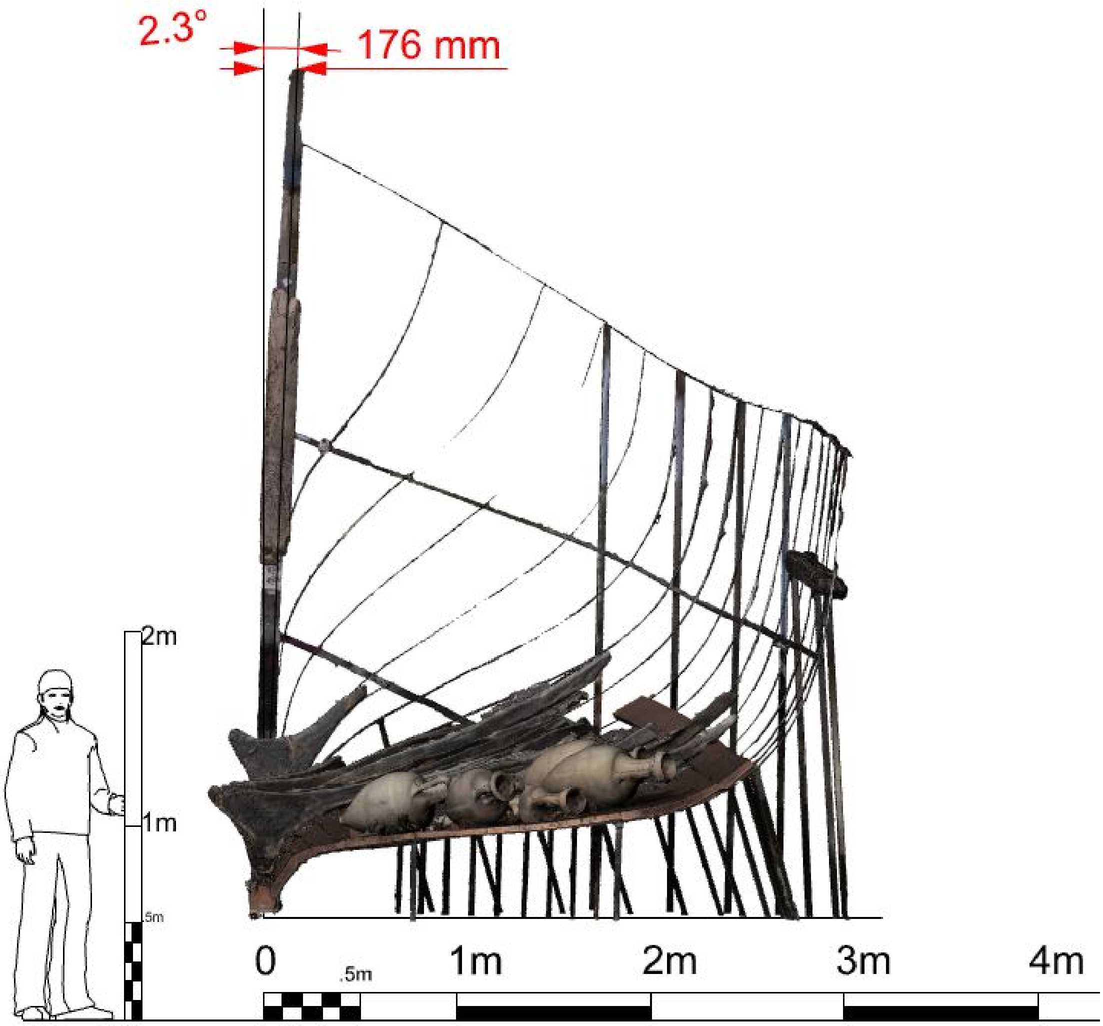

Figure 12 Showing sternpost displaced towards port side

It seems that the asymmetric loading caused by the weight of the port side of the vessel, is inadequately supported by the cradle structure and is causing a torsional moment within the whole structure. Viewed from the midship area looking towards the stern, the keel is visibly twisted towards the port side by 13.4° (Figure 13).

In addition, a section taken through the 'as-displayed' vessel, 4m forward of the aft end of the keel shows that the frame and planking appears to be canted towards the port side (Figure 14). With the missing starboard side mirrored through the vessel's centre line, it is clear that the hypothetical frame shape creates an open V form (Figure 15) in contradiction with the surviving starboard side fragment at the base of the frame. If the surviving port side is mirrored through the extant frame's centre line, shown in red hatched lines in Figure 16, it clearly illustrates the port hand list in the 'as-displayed' vessel shape. With the port side rotated by 4.4° and mirrored through the vessel centre line the resultant frame shape forms a more natural continuous curve on the inboard face (Figure 17).

Figure 13 Keel twist towards midship extremity

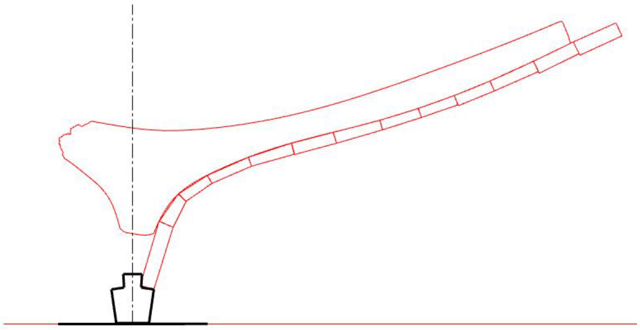

Figure 14 Section through frame and planking 4m forward of stern

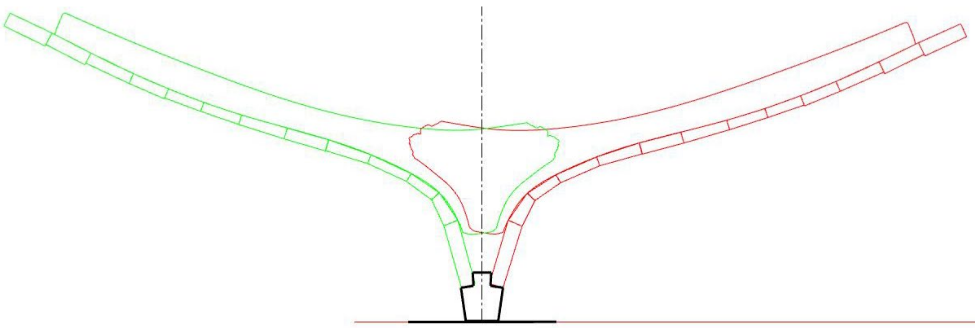

Figure 15 Port side mirrored through the vessel's centre line

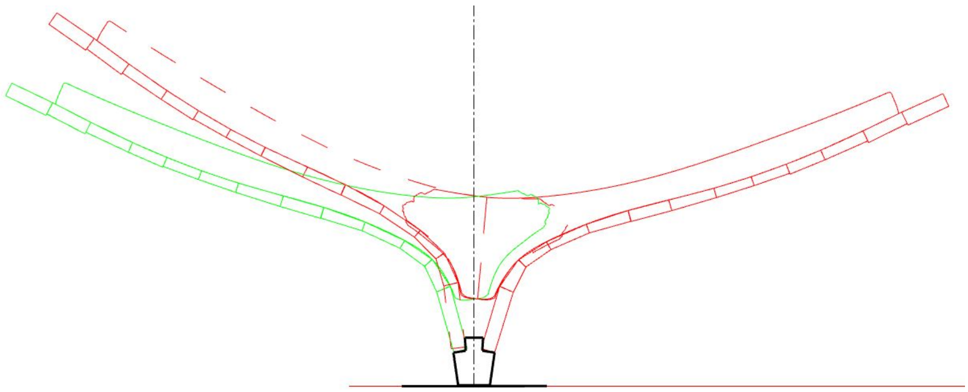

Figure 16 Port side mirrored through the frame's centre line

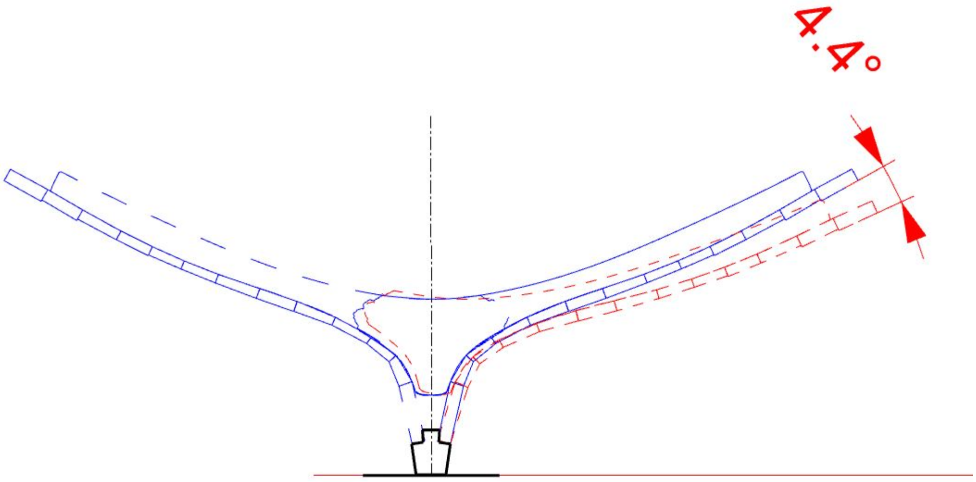

Figure 17 Port side levelled and mirrored

4.2 Shapes of the Punic ship

Lines drawing are a standard form of architectural plans, used by ship builders, to present a three-dimensional shape of a ship on a two-dimensional surface. Programs like Rhinoceros and Orca3D provide software platforms allowing for experimentation with interactive models that can be quickly modified and retested. The great advantage of using this software over hand-based drawing is the ability to quickly change and alter hull shapes while producing highly accurate hydrostatic tests.

The four published interpretations of the Punic Ship represent four different ships (Figure 18). In order to study the lines relative to one another a 3D surface was created for each of the separate lines-plan drawings. On initial analysis of the 3D surfaces of the Marsala Punic ship, none use a "standard" section or station spacing. This made any comparison of the various shapes extremely difficult. In order to compare the shapes, a fair surface was generated from each individual set of lines-plan drawings, and a standard 1m station spacing generated from each of the four resultant hull forms.

Analysis of the four aligned 3D plans showed substantial differences in hull shape, hull form, and overall size. Once a technical analysis of the hull shapes was conducted, background information was collected to provide context to understand the wide variety of shapes. A technical discussion and research context of the varying hull shapes is provided in *Appendix 1: Technical Report of Marsala Punic Ship Shape*. The next section presents initial research into the Marsala Ship's shape and its possible interpretation.

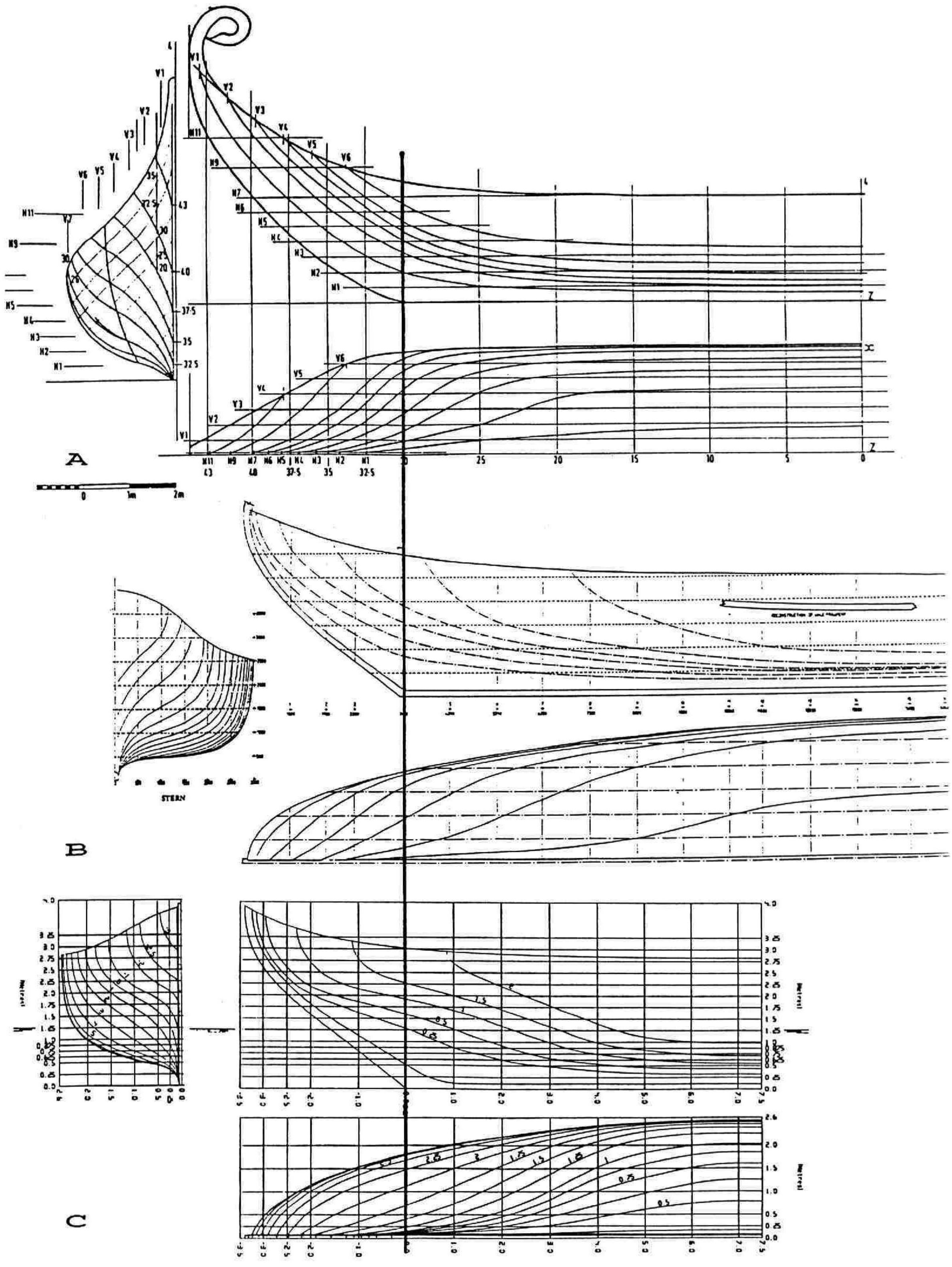

Figure 18 Line drawings of the Punic Ship. A: Paul Adam 1977; B: Carol Green 1981; Austin P. Farrar 1989 (Crumlin-Pedersen 1990).

4.3 Hull lines and overall dimensions

Based on the records made during and after the excavation, scholars provide different reconstructions of the original shape of the hull (Adam 1977, 1978; Greene in Frost 1981b, fig. 10; Farrar 1989; Ole Crumlin Pedersen 1990). During the initial study of the Punic ship, Frost (1981b:65–75) stated the discovery of a contemporary prow structure from the nearby wreck of the 'Sister Ship' enabled naval architects to deduce the shape of the whole vessel. Proof that their calculations were correct was supported when the dismembered remains did in fact fit nail-to-nail into the metal framework built in accordance with the lines they projected. A reconstructed portion of the parallel midship section and life-sized replica of the prow based on the structure of the 'Sister ship' were constructed providing a visual statement to the public visiting the museum. However, spaces of 1m between the three sections means an overall length of 31m which was less than the ship's calculated length of 35m (Figure 2)

In 1972, combining archaeological data both from the Punic Ship and the "Sister Ship" for the stem, iconographic evidence and research on ship models, Adam reconstructed a ship of 35 m in length with a beam of 4.80 m and a length to breadth ratio of 7.29. The waterline was placed at 1.20 m and Frost (1978:143–144) noted that according to Adam the displacement of the Marsala Punic ship was estimated at 120 metric tons, with a midship underwater sectional area of 3.94m² (Frost 1981a) (Figure 19). Adam (1977:35–37) stated that it cannot be claimed the drawings for an attempted reconstruction of the Marsala Punic ship are an accurate reconstruction of the Punic ship excavated. His interpretation was meant to represent a ship of the same general class. While these lines provide a basic impression of the ship, they were deemed not to provide the original shape of the ship or the original cradle shape. Consequently, the first set of lines plans are of little value when assessing the original shape and form of the Marsala Punic.

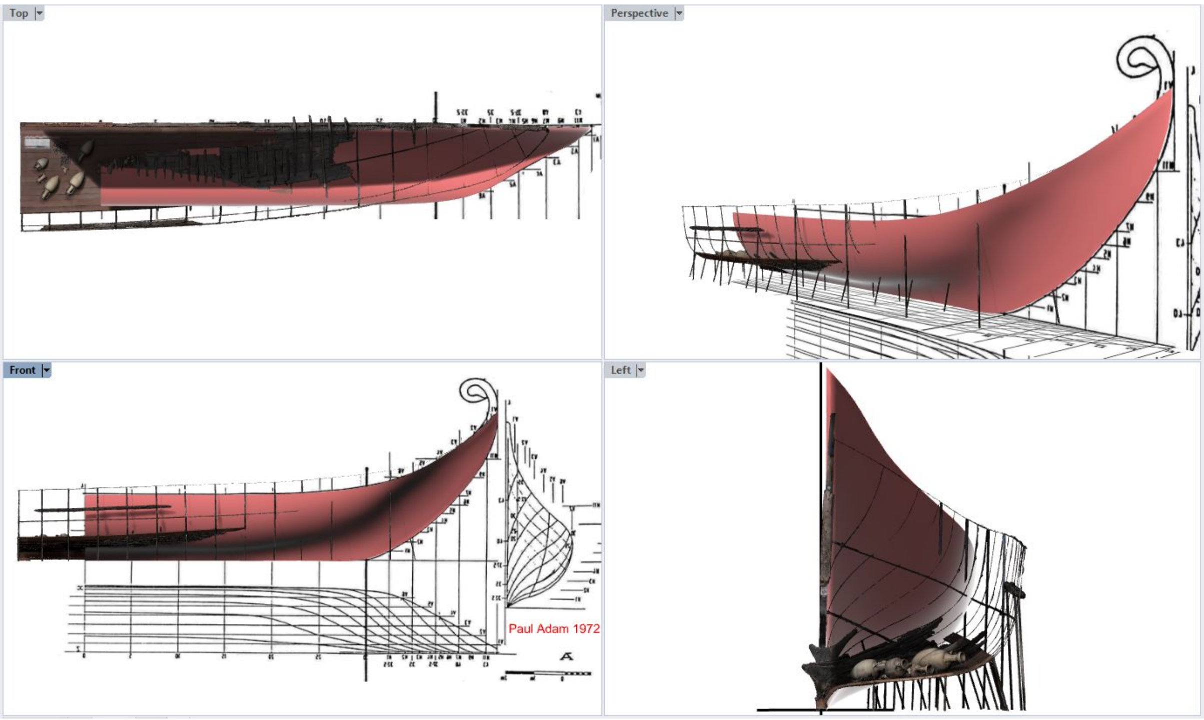

Figure 19 3D surface generated from the Adam 1972 lines plan drawing

Between 1979 and 1981 Carol Green took measurements of the reconstructed ship and developed an interpretation of the ship when it was in its first phase of display at the Marsala Museum. Frost (1981b) noted the importance of the lines of the reconstructed ship and that shape published by Green was the sum of the joint research. Farrar (1989:368–370) later discovered by the time Green was recording the ship timbers that, "sadly after several years in the damp Anselmi building, the frame sagged, and the reconstructed ship distorted, so that the lines taken off by Carol Green and published in the Mariner's Mirror February 1981, were not in fact accurate"(Figure 20).

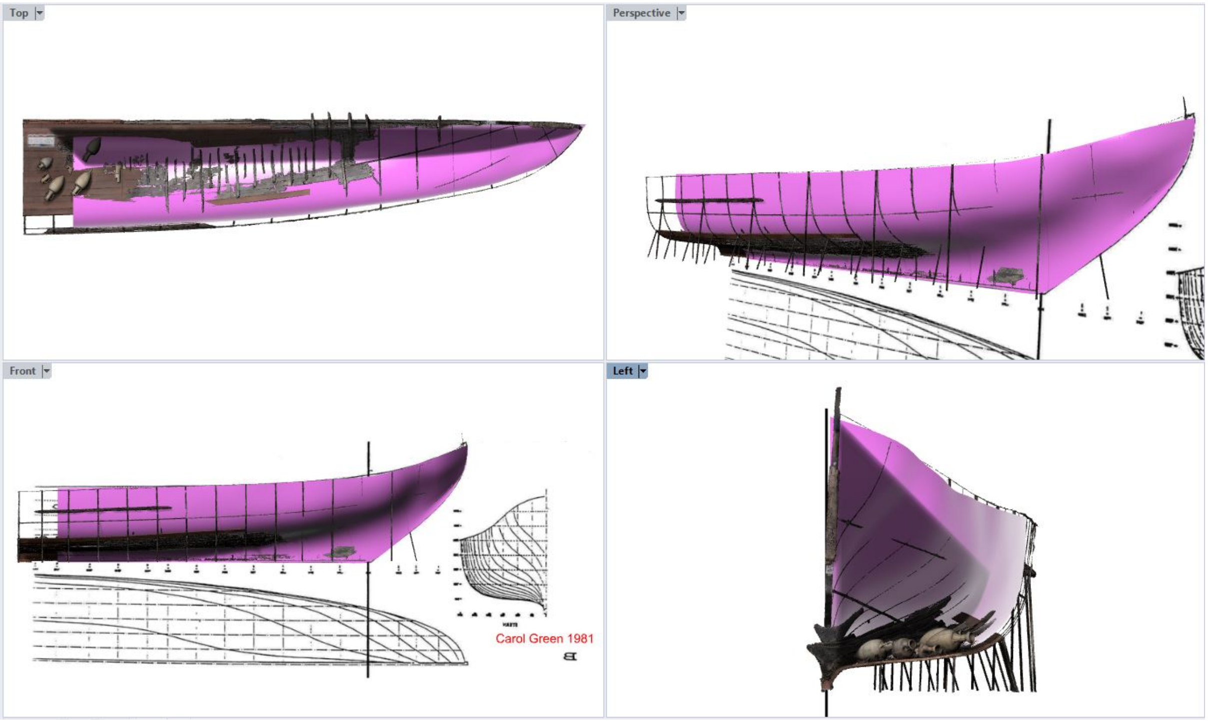

Figure 20 3D surface generated from the Green 1982 Lines Plan drawing

Farrar's (1989:368–370) lines for the estimated shape of the Punic ship were produced in co-operation with Paul Adam and Frank Howard culminating in 1989 with Farrar lofting full size section drawings (from a table of offsets produced by him) on the museum floor in Marsala. The Bonanno brothers then used these drawings to construct the steel frame into which the timbers were fitted. A subsequent revised set of Farrar's lines were faired using computers by BMT Cortec ltd. working to accuracies of half a millimeter. This removed any of the bumps or hollows not visible in the scale drawings, as well as mathematically removing any irregularities by drafting the lines full-size, and subsequently publishing revised scale drawings (Figure 21).

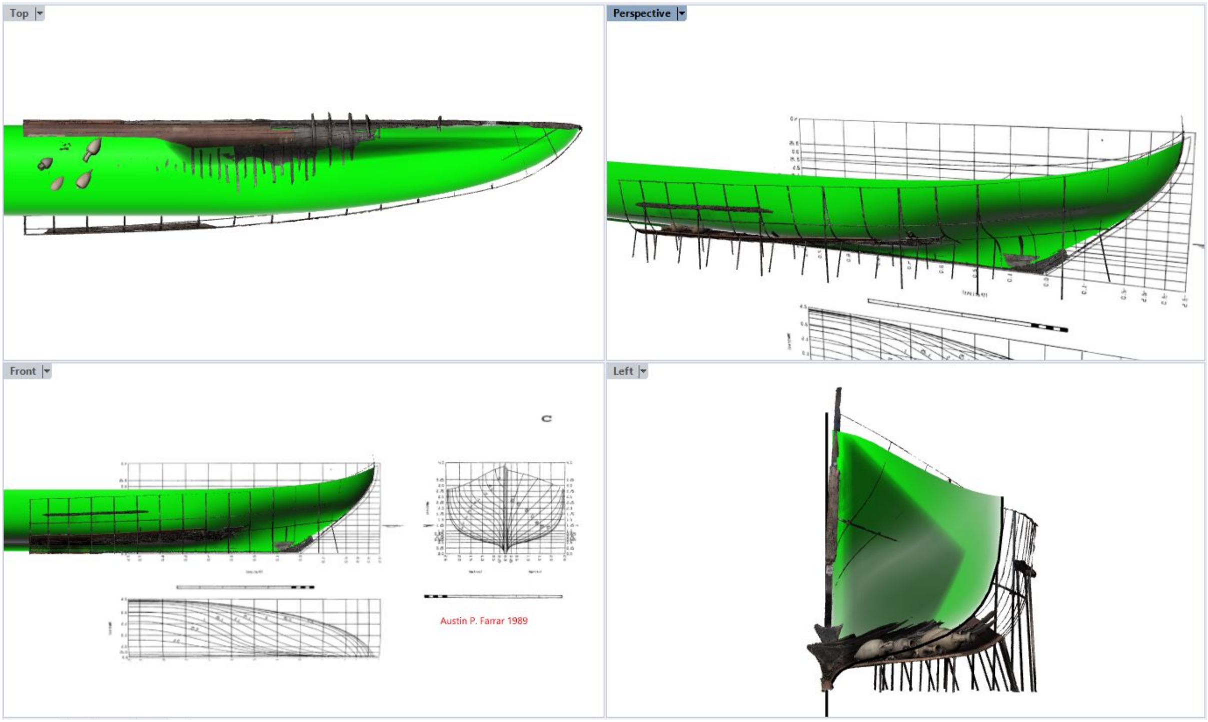

Figure 21 3D surface generated from the Farrar 1989 Lines Plan drawing

In 1990 Crumlin-Pedersen created another interpretation of the hull to aid in the ship's renewed conservation efforts. He stressed it would be necessary to use the actual preserved parts as the main guideline to establish the original shape of the hull. This would also indicate the position of some other original elements from the ship (the upper part of the stern and a wale). During the project Crumlin-Pedersen measured a series of sections of the hull with details of the angle and width of the outside of each plank. After careful observation of the ship, in particular near the rise of the keel where the planks were opening up at their end, it was determined that the latest set of revised lines produced by Farrar in 1989 required further revision before they could be used as a basis for determining the precise shape of the supporting system (Crumlin-Pedersen 1990) (Figure 22).

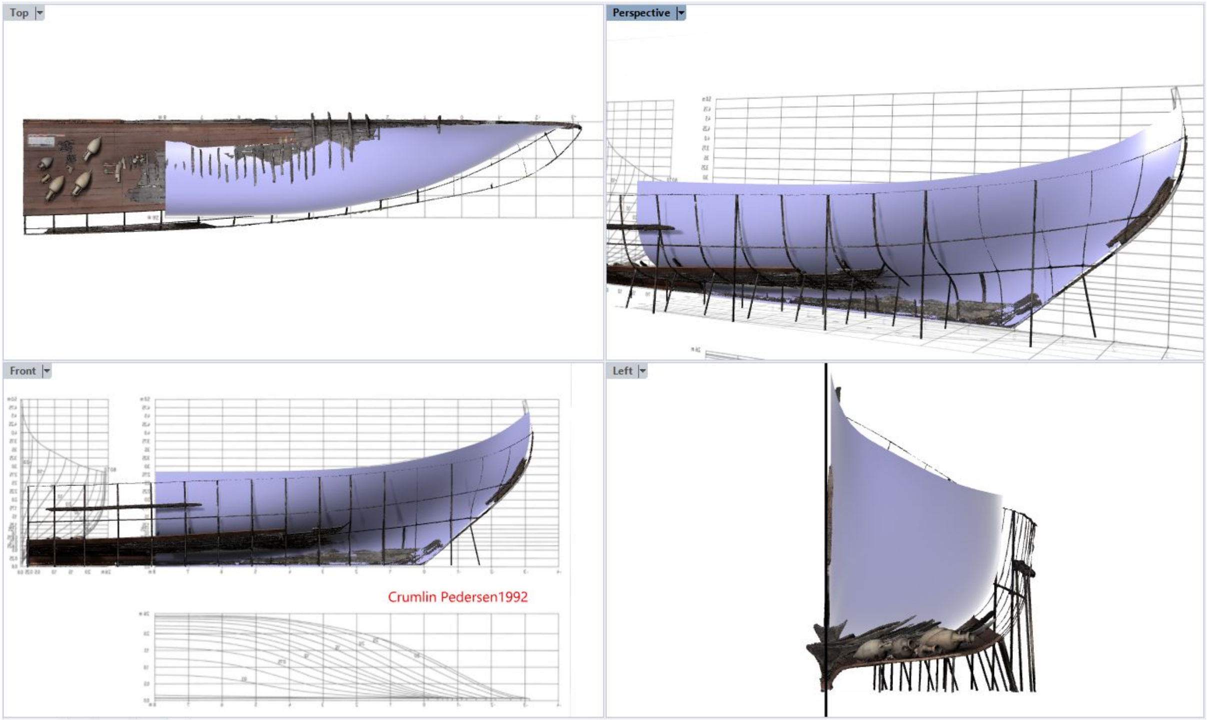

Figure 22 3D surface generated from the Crumlin Pedersen 1992 Lines Plan drawing

J.5 Summary of results

5.1 The Lines Plans

The four published interpretations present four vastly different hull shapes. Adam's 1977 plans were drafted to give a general sense of the ship and could not be used to determine the shape of the actual hull remains. Green's lines plan drawing from 1981 introduce a significant amount of distortion already present from 10 years of the ship on display (Figure 23). Green's plans could be of benefit as a point-in-time survey recording the amount of sag and distortion in the vessel as displayed in the museum hall compared to its current shape state. Frost (1981b:65–75) also found that while the drawings by Green in 1981 show a 'family' resemblance to the drawings published by Adam in 1977, there were a vast amount of differences between the two.

After analysis and modeling it was determined that of the four only Farrar's 1989 and Crumlin-Pedersen's 1992 reconstructions seem to agree on a general hull shape. However, comparisons of the two sets of lines show there are many irregularities in the interpretations. It is clear from Figure 24 that the remains as displayed do not conform to either of the two remaining lines plan drawings, and there are some outstanding issues with the two proposed hull forms which require further examination and analysis in order to arrive at a defined hypothetical reconstruction of the Marsala Punic ship.

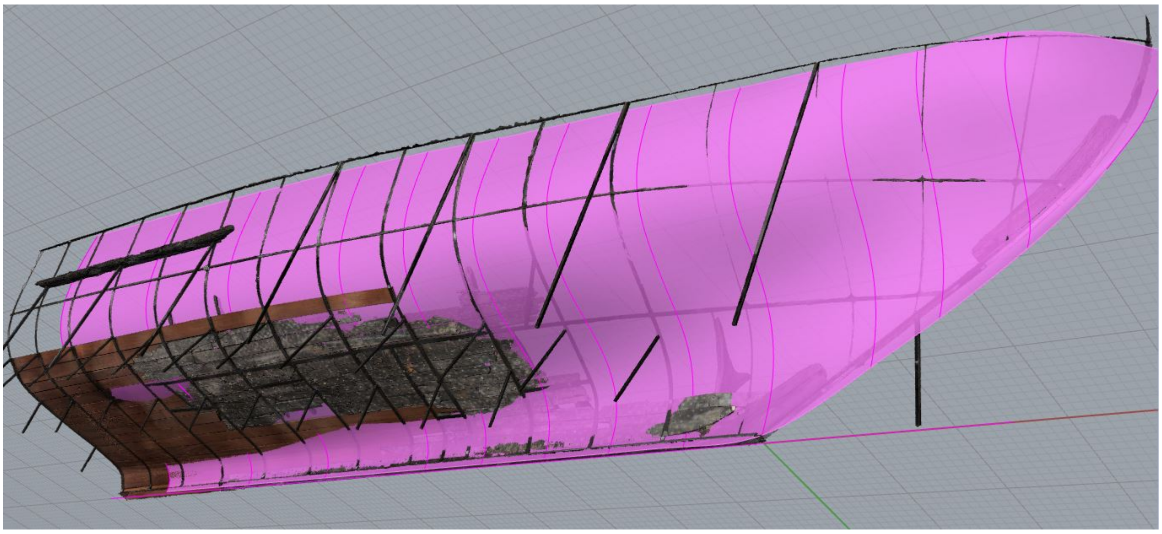

Figure 23 2019 3D laser scan compared to Green's 1981 survey lines plan

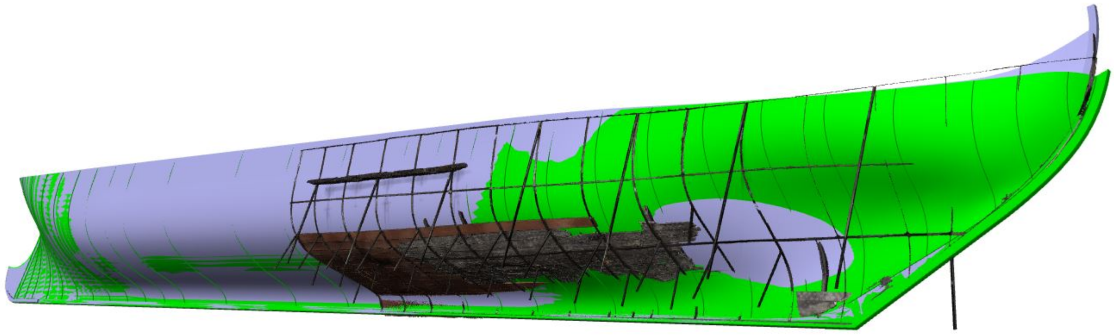

Figure 24 Comparison of the Farrar and Crumlin Pedersen hull forms

5.2 The Supporting Cradle

In the 1990 Crumlin-Pedersen reported the cradle fabricated in 1978 was providing inadequate support. The planking was sagging between the cradle struts (Figure 25) and even with a considerable number of extra supports, it would be impossible to prevent sagging. To avoid this problem, he determined it would be necessary to provide the planking with additional internal strength to carry its own weight between supports, preferably spaced a wider distance than the support fabricated in 1978 (1 m or less). Crumlin-Pedersen suggested the use of stainless steel and to substitute the original tenons with new oak tenons fastened with small pegs as in the ancient system (Figure *28*).

Figure 25 Existing cradle support structure at circa 1m intervals

In order to quantify the sagging between cradle supports, a faired surface representing the inboard or support face of the cradle was created using the digital data. Any part of the planking strakes protruding through this grey surface denotes an amount of sagging between the supporting struts (Figure 26). It can be clearly seen that the original timber planking is sagging between every one of the supporting struts, and the preserved 'timber' has inadequate structural stiffness to span the 1m distance between struts.

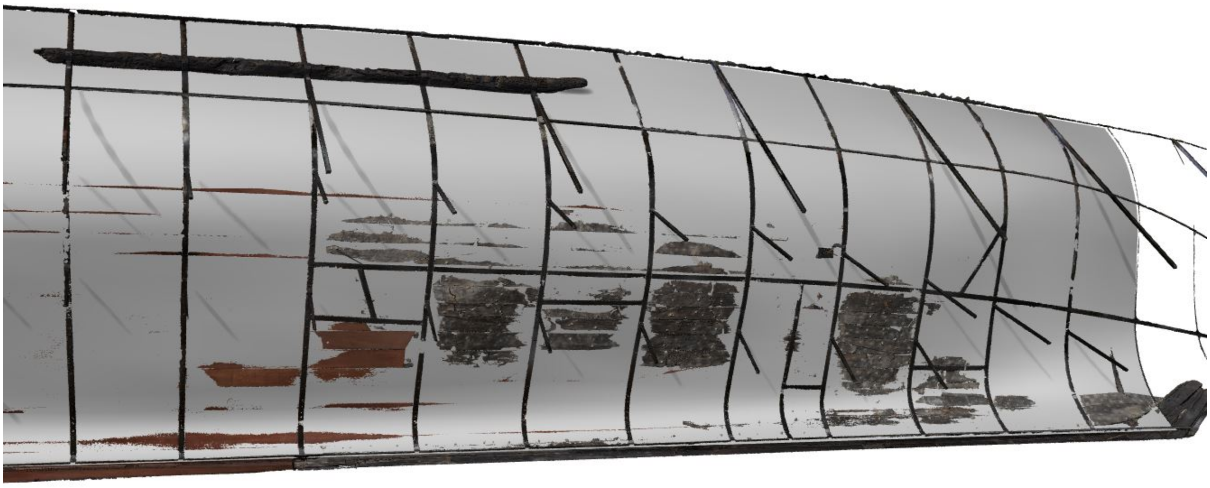

Figure 26 Surface representing the support face of the cradle to illustrate plank sagging

A section through this faired supporting surface taken 4m forward of the keel's aft end illustrates the amount of sagging in the planking strakes is between 19–22 mm (Figure 27).

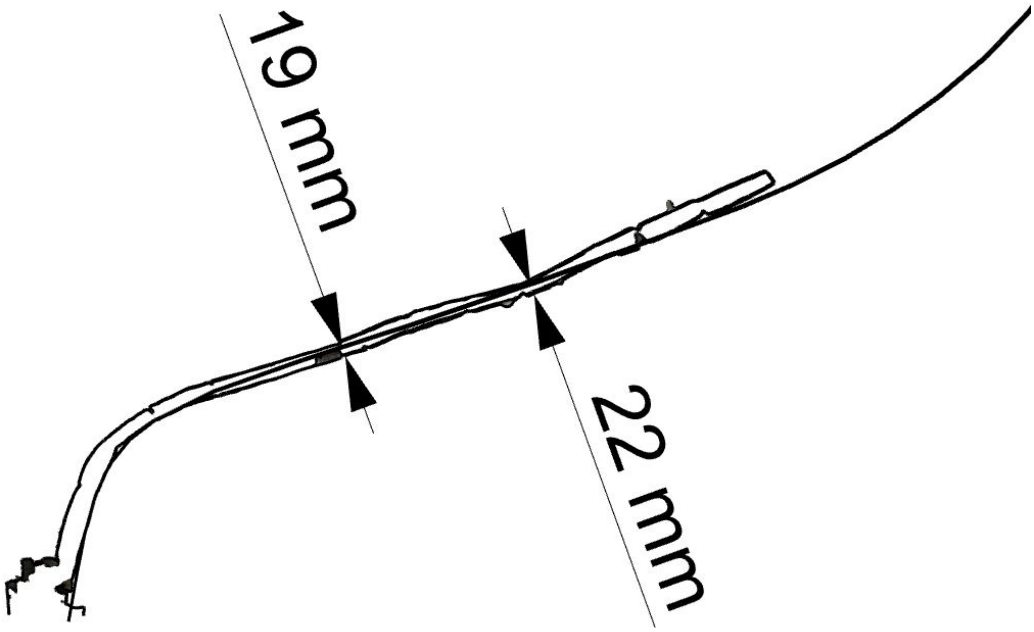

Figure 27 Section illustrating plank sagging

Sagging or deflection is caused by excessive weight or load being supported by the material, or the material itself having insufficient strength to support its own weight between supports. The human eye will notice a deflection of 2.5 mm per running meter. If the span between struts is halved, then the deflection or sag is eight times less. If the number of struts were doubled, creating a span of 500 mm the sag would be reduced to 2.75 mm which is still above the limit of detection with the naked eye. This would suggest the planking material would require support struts at ca. 400 mm intervals. This would mean increasing the number of struts supports from 15 to at least 32. This excessive number of struts would obscure the archaeological remains and would not resolve the sagging issue. The solution proposed by Crumlin-Pedersen, of an integral support to carry the weight of each strake would appear the best solution (Figure 26).

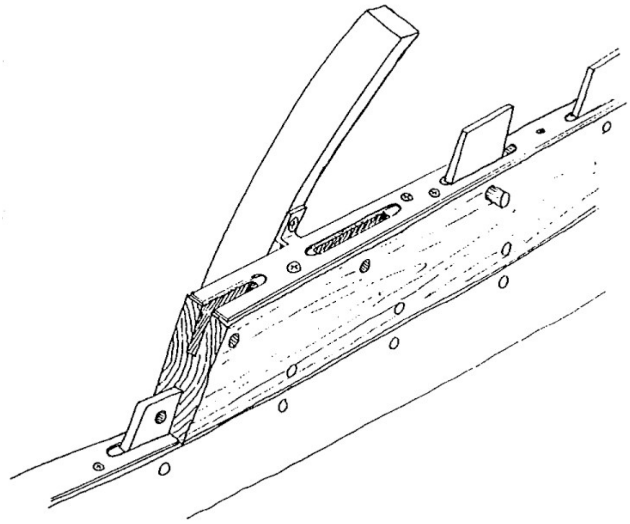

Figure 28 Sketch by Crumlin-Pedersen showing the use of new tenons and steel bands fastened to the upper edge of each plank as internal strength members for the planking (Crumlin-Pedersen 1990, fig. 17).

These issues are not isolated to the Marsala Punic ship. Many other museum ships are under threat of deformation and destruction due to inadequate support structures (Jones et al. 2013; Tanner 2013, 2018). In order to determine an effective conservation strategy and to ensure the ship's timbers have adequate support, the shape of the ship and cradle structure need to be determined. The shape will help determine structural integrity, stress points, augment the current cradle, or help develop a new cradle system. This approach will provide the most cost-effective strategy and help minimize further damage to the ship. In order to achieve this goal a new hypothesis must be developed, and an acceptable hull shape must be determined.

5.3 Modeling

The results of the laser modeling process were compared with the Arc-Nucléart-CCJ team's 2018 photogrammetric results in order to evaluate archaeological recording methods for applications to future projects. Initial results would suggest that in order to determine structural integrity of the archaeological remains on display in the museum, laser scanning is a preferable methodology due to its speed and accuracy. Photogrammetric survey of the remains is preferable to capture the texture of the ship's timbers which is a preferable methodology to analyze any discoloration along the surface of the timbers and for museum quality or publicly accessible models.

5.4 Comparison of plaster moulds made during the excavation

While the plaster moulds taken by Frost's team during excavation were scanned, modeled, and aligned they were ultimately unable to provide a cloud comparison to help determine the ship's degradation. The high level of variability between the moulds and the ship's timbers resulting from various interpretations and modifications to the ship's display made any quantitative analysis impractical. Any stress analysis comparing the moulds to the ship's current state was determined to produce misleading data on the percentage of deformity and therefore of little value to the ship's ongoing conservation efforts.

The plaster moulds do provide valuable information into the thought process of Honor Frost and her team. Constructing replicas that could be easily studied by ship builders and archaeologists, allowed for a means to study individual ship components without direct contact of the archaeological timbers. This foresight ensured the preservation of the Marsala Punic Ship and will allow the next phases of the conservation efforts to develop comprehensive strategies.

5.5 A Second Phase

The project's results also confirm that a second phase is necessary. The second phase will require a research-based approach to reconstruct the ship in order to conduct hydrostatic tests to determine the ships potential cargo and seafaring abilities. These reconstructions are critical to identifying the best support system for the ship's timbers and will serve as the basis of future conservation efforts.

J.6 Summary of how your aims & objectives were met

The objectives of this project were to produce a highly accurate model of a mortise-and-tenon Punic ship. The project set out to:

1. Conduct a laser scan of the Marsala Punic Ship timbers on display at the Regional Archaeological Museum Baglio Anselmi
2. Process a high accuracy three-dimensional model of the vessel and compare with the model obtained by the CCJ team through photogrammetry
3. Generate a stress point analysis of the vessel in its current display
4. If requested permission is granted, conduct a laser scan of the original plaster casts taken by Honor Frost of the timbers during initial excavation (currently housed at the Cantine Pellegrino, Marsala)
5. Process a high accuracy three-dimensional model of the timbers
6. Generate a point cloud analysis of the timbers from the ship and the plaster casts to determine the percentage of deformity and degradation

The 2019 project successfully completed high resolution digital records the Marsala Punic Ship, its cradle, the surrounding building, its associated timbers (not on display), and the original moulds taken during the ship's excavation. The high accuracy three-dimensional laser scans were successfully aligned with the photogrammetry created by the CCJ team using a common datum. The resulting models provided quantifiable levels of distortion and indicated stress points in the current display cradle. While the plaster moulds taken by Frost's team during excavation were scanned, modeled, and aligned they were ultimately unable to provide a cloud comparison to help determine the ship's degradation. The digital reconstructions can also be developed through a virtual reality engine to create immersive models that would allow visitors to take virtual tours of the ship. A preliminary virtual tour of the ship currently in development and available to view and share to the public. These models can assist as a capacity building tool for the museum's educational outreach and public engagement programs.

J.7 Summary of advances in knowledge or understanding provided by your project

Conservation of shipwrecks is a difficult, extensive, and expensive task. Even after timbers have been conserved there are many factors that will affect their degradation and deformation (Clarke 1985). The main objective of three-dimensional recording is to capture sites and objects in as much detail as possible. Since archaeology is inherently a destructive process these methods are valuable ways to help preserve and extend the accessibility to artifacts and sites. Three-dimensional models of the archaeological remains of a shipwreck constitute the basis of reconstructing the vessel's structure, shape, and insight into the ship's characteristics.

The three-dimensional models of the Punic ship will allow for greater study and preservation of the shipwreck. The models will serve as a baseline for future study and will allow conservators and archaeologists to engage with the ship without causing further damage. This in turn will create a more informed and comprehensive conservation program. It will allow for a more efficient and effective support structure to enable better preservation of the remains and better viewing within the museum. The 2018 and 2019 datasets of the Marsala Punic Ship offer an invaluable tool for the study of ancient ship construction and the continued engagement and education of the public.

J.8 Future Research Plans?

Frost (1989b) noted that more than 10 years in adverse conditions damaged the bronze nails, treated wood of the ship, and the modern steel support cradle was being eaten away by rust. Fortunately, the dilapidated state of the Anselmi building has since been rectified, the unique vessel still survives, and chemical analysis of the ship's timber by the CNRS indicated they were in good condition (Boetto 2018:30–39).

This initial assessment concludes that re-treatment is necessary as well as feasible, and reconstruction can start for the second time, providing the excessive humidity is treated and normal conditions established in the room housing the ship. Proposals to continue the conservation of the Marsala Punic ship include re-treatment of the timber and a redesign of the cradle system to replace the rusted sagging metal framework. At the very least the current cradle requires immediate stabilization and additional support. Since the cradle framework functions to reproduce the vessel's original shape, it must be built by the naval architects after careful calculation of the shape of the Punic ship.

Short term solutions would benefit from biannual structural assessments utilizing a laser scanner to monitor the rate of deformation and change in the ship's timbers. This would provide critical data on the dynamic state of the ship remains and the scans would be automatically aligned used the pre-established datum points from the 2018 and 2019 surveys which would ensure accuracy and minimize scanning time.

In the longer term, further examination and study of the ship is needed to develop a hypothetical reconstruction of the ship's shape. It was determined that a new hull shape hypothesis will be needed to help direct the current conservation efforts. Once a more definitive hypothetical reconstruction shape has been developed, then the remaining outstanding issues such as the shape of the support cradle and reconfiguration of the distorted remains can be resolved. It is necessary to carry out detailed 3D modelling for weight and structure analysis on the hypothetical reconstruction in order to determine factors such as overall weight, center of gravity and cargo carrying capacity before any subsequent work should proceed. These hypotheses are critical for any future revisions to the ship's support structure and cradle system.

J.9 Appendix 1: Technical Report of Marsala Punic Ship Shape

A 3D surface was created for each of the separate lines-plan drawings in order to study their variations. Of the four available sets of lines plan drawings for the Marsala Punic ship, none use a "standard" section or station spacing, making any comparison of the various shapes extremely difficult. In order to compare like for like, a fair surface was generated from each individual set of lines-plan drawings, and a standard 1m station spacing generated from each of the four resultant hull forms. Each of the subsequent section drawings is reproduced here on 100x100mm gridded paper for ease of comparison.

The section at 8m forward of the aft keel face (Figure 29), which is close to the forward extremity of the surviving remains clearly shows some significant differences between the data sets. The blue curve-Crumlin Pedersen 1992 and green curve-Farrar 1989 shapes are practically identical. The magenta-Green 1982 shape has clearly spread (between 250 and 300mm at half height) and sagged (300mm at sheer height) by comparison, which Farrar (1989) attributed to the rusted and sagging frame. It can be also seen that the 3D scanned hull shape has moved up to a further 50mm in places. The red-Adam1972 shape appears to be a clear first draft version as noted by Frost (1981b), the shape at the keel area is obviously inaccurate, while the width is over 200mm narrower than Farrar or Crumlin Pedersen, resulting in an overall beam difference of up to 0.5m. Likewise the sheer height proposed by Adam is almost 600mm lower than that of Farrar or Crumlin Pedersen.

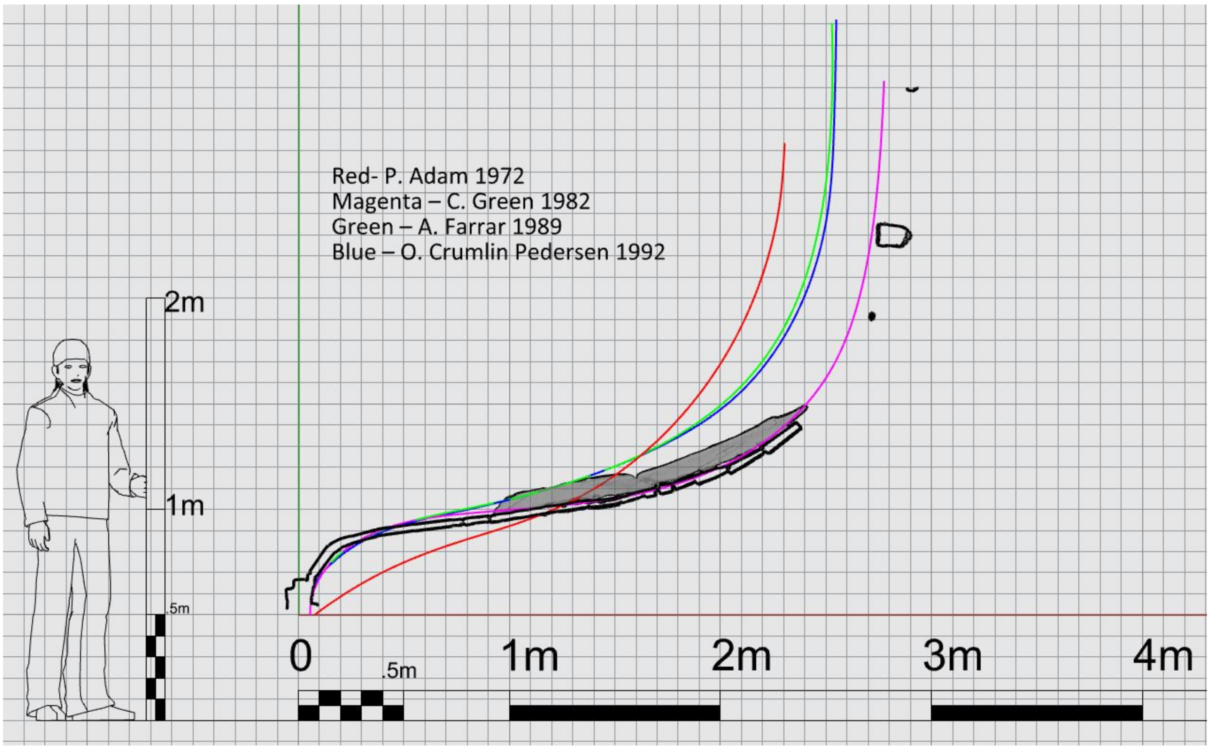

Figure 29 Section 8m forward of Aft Keel face

The section at 6m forward of the aft keel face (Figure 30), also shows some significant differences between the data sets. The blue curve-Crumlin Pedersen 1992 and green curve-Farrar 1989 shapes are again practically identical, although the Crumlin Pedersen's hull changes from very slightly wider and fuller, to being narrower and tighter from keel to bilge area. The magenta-Green 1982 shape has clearly spread (between 150 and 250mm at half height) and sagged (250mm at sheer height) by comparison. It can be also seen that the 3D scanned hull shape has moved by 50mm or more in places. The red-Adam1972 shape again a clear first draft version as noted by Frost (1981b), with obvious differences in the keel area and both the width, and sheer height proposed by Adam clearly different from that proposed by Farrar or Crumlin Pedersen.

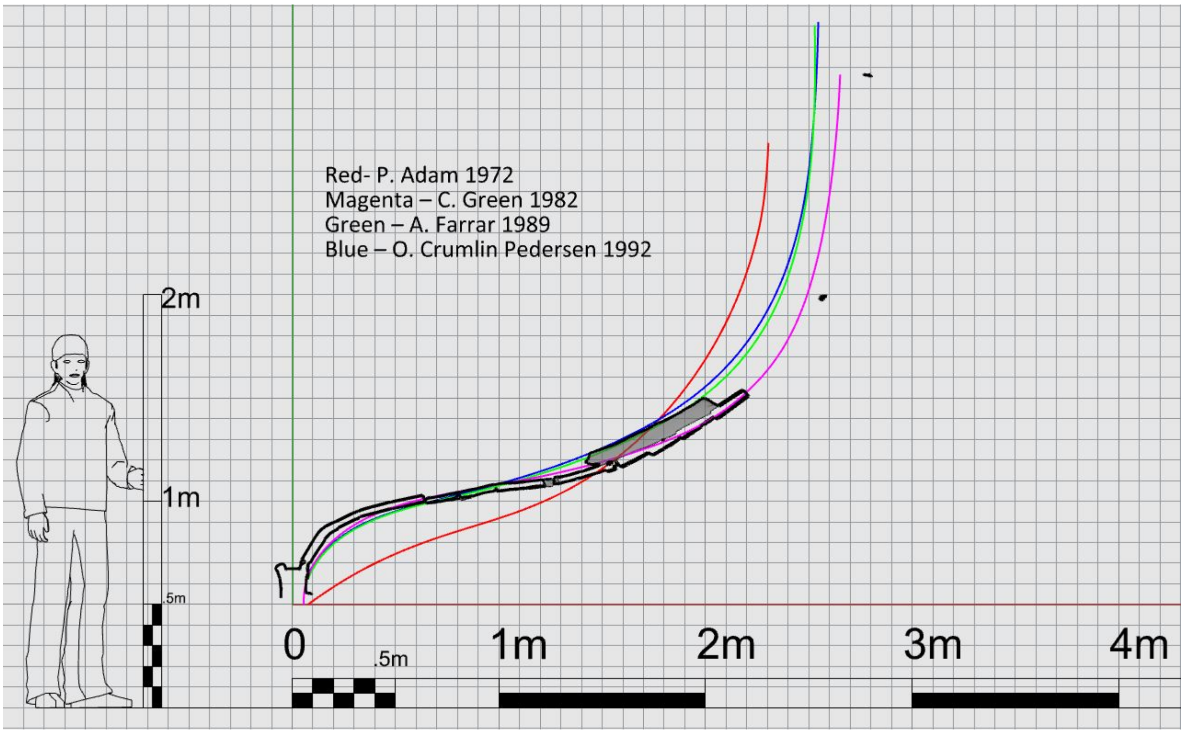

Figure 30 Section 6m forward of Aft Keel face

The section at 4m forward of the aft keel face (Figure 31) showing the red-Adam1972 shape again a clear first draft version as noted by Frost (1981b). The magenta-Green 1982 shape has clearly spread (200mm at half height) and sagged (200mm at sheer height) by comparison. The blue curve-Crumlin Pedersen 1992 and green curve-Farrar 1989 shapes remain similar, with the Crumlin Pedersen's hull being narrower and tighter from keel to bilge area.

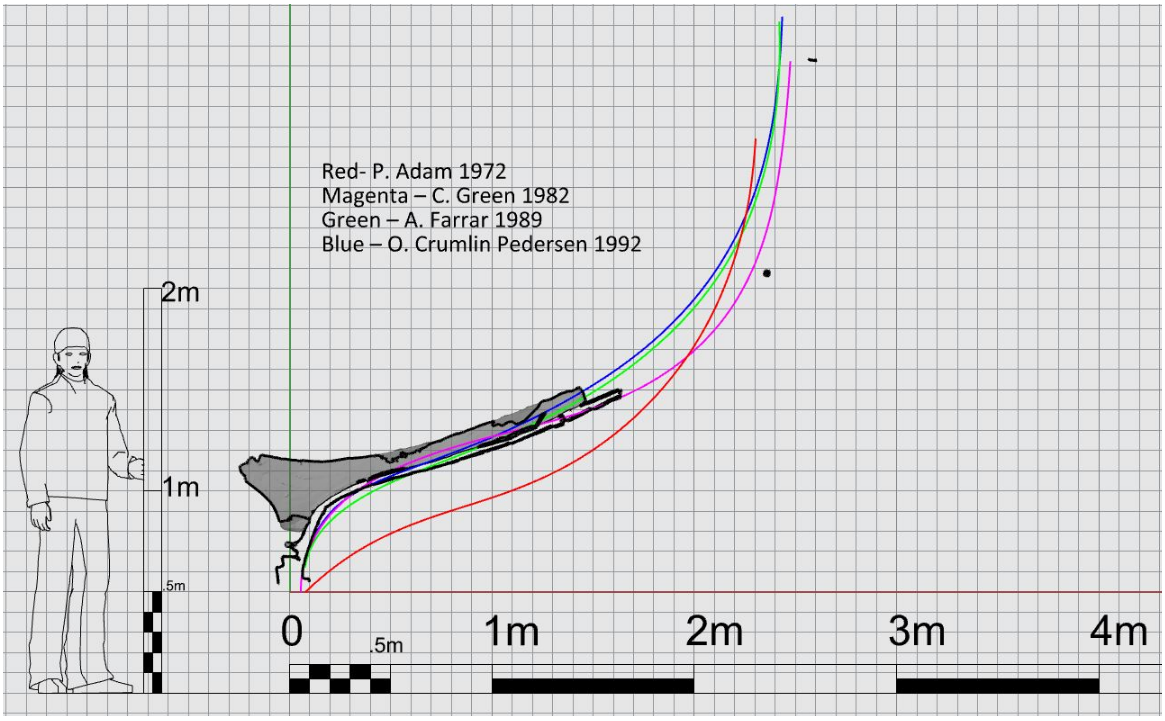

Figure 31 Section 4m forward of Aft Keel face

The section at 2m forward of the aft keel face (Figure 32) showing the red-Adam1972 shape again a clear first draft version as noted by Frost (1981b). The magenta-Green 1982 curve has changed in shape and form significantly compared to the green-Farrar 1989 curve shape. As shown in Figure *12*, the sternpost has been displaced by up to 176mm towards the port side, while a similar or even greater spread would be expected at the sheer height recorded by Green, the actual point plotted is some 100mm narrower, resulting in a form something akin to a "beer-belly" at this station. This would suggest either a recording or drafting error by Green, or a redesigned hull shape in this area by Farrar. Additionally, at this point a significant difference in hull form is developing between the 1989 Farrar hull and the 1992 Crumlin Pedersen hull. While the Farrar hull appears to follow a similar transition from the preceding sections, Crumlin-Pedersen's hull is becoming wider and flatter from keel to bilge, then changing to narrower and higher from bilge to sheer. The 1992 hull has become 256mm narrower in the beam, with a 71mm sheer height increase.

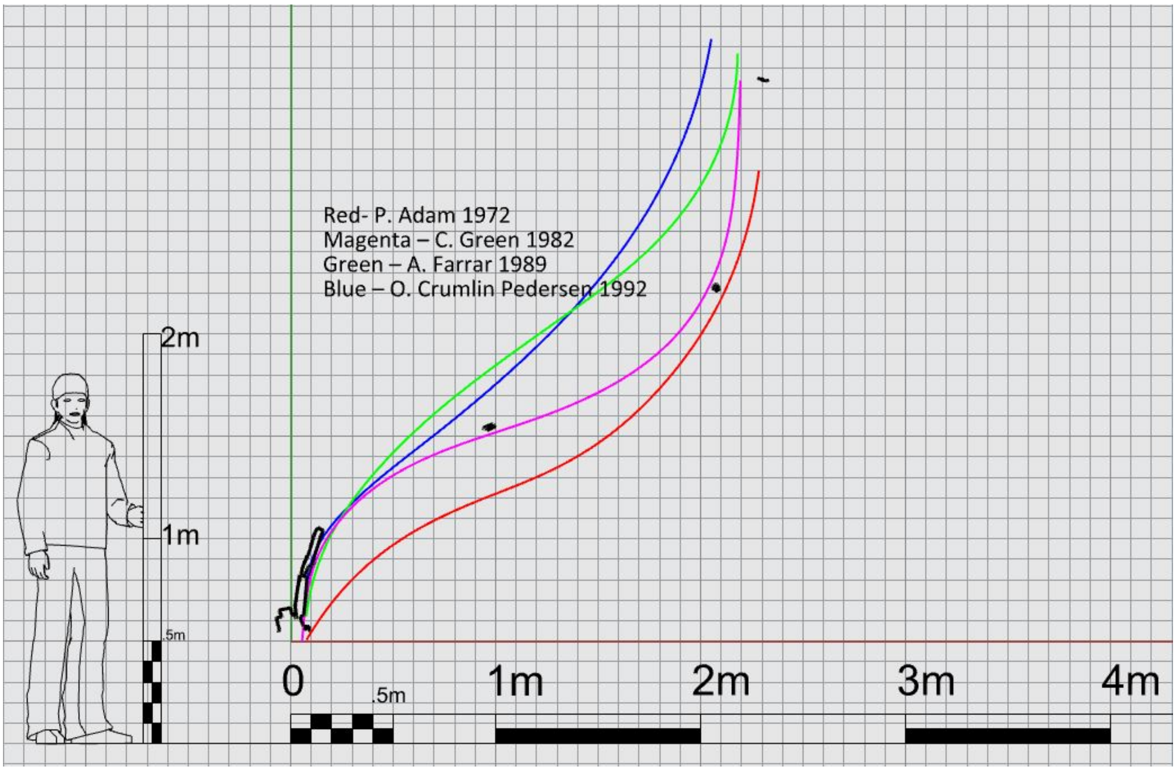

Figure 32 Section 2m forward of Aft Keel face

The section at the aft keel face (Figure 33) showing the red-Adam 1972 shape again a clear first draft version as noted by Frost (1981b). The magenta-Green 1982 curve again changed in shape and form significantly compared to the green-Farrar 1989 curve shape. Suggesting either a second recording or drafting error by Green, or more likely a redesigned hull shape in this area by Farrar.

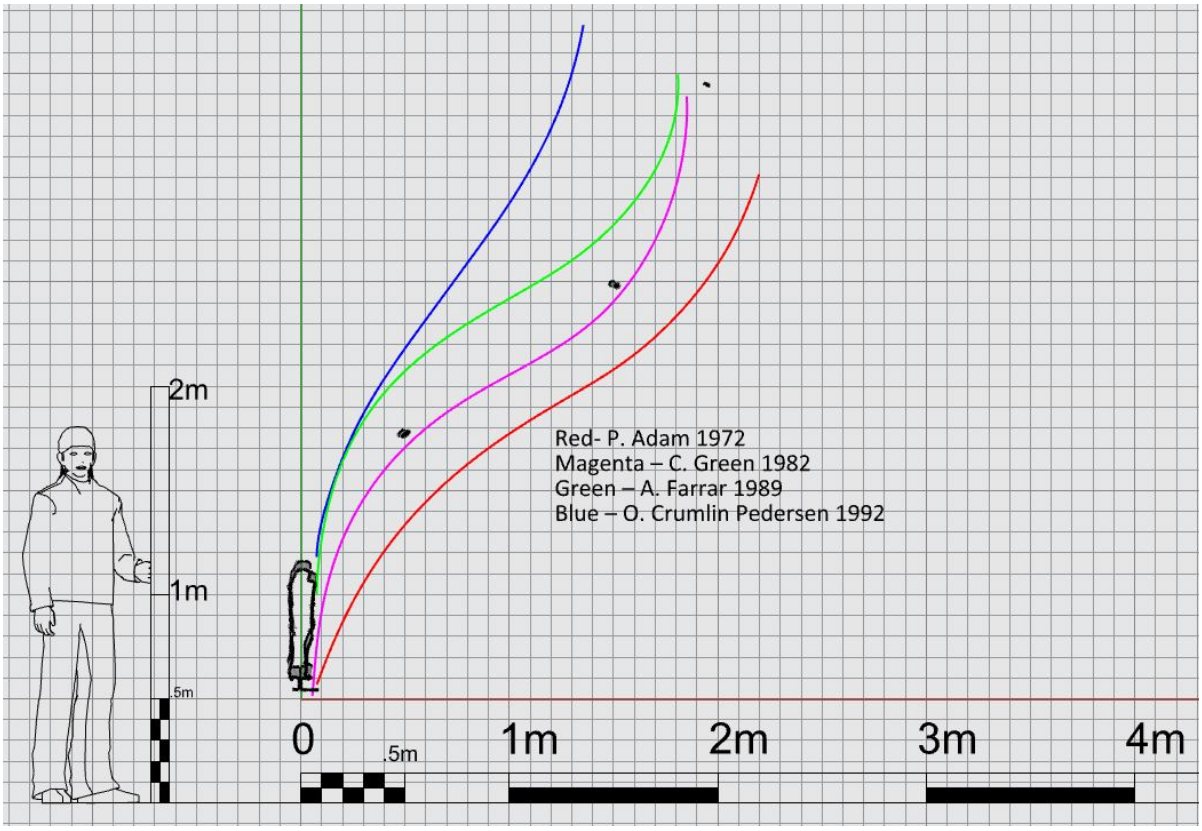

Figure 33 Section at Aft Keel face

The significant difference in hull form between the 1989 Farrar hull and the 1992 Crumlin-Pedersen hull increases with Crumlin Pedersen's hull much flatter from keel to sheer. The 1992 hull has become 0.9m narrower in the beam, with a 236mm sheer height increase.

The section at 2m aft of the aft keel face (Figure 34) showing the red-Adam1972 shape again a clear first draft version as noted by Frost (1981b). The magenta-Green 1982 curve again changed in shape and form significantly compared to the green-Farrar 1989 curve shape. Suggesting either a third and very significant recording or drafting error by Green, or even more likely a redesigned hull shape in this area by Farrar, which has even become wider in places than the original shape suggested by Adam 1972. Another noteworthy point is the sheer height of the green-Farrar 1989 hull has at this point dropped lower than the recorded steel cradle height.

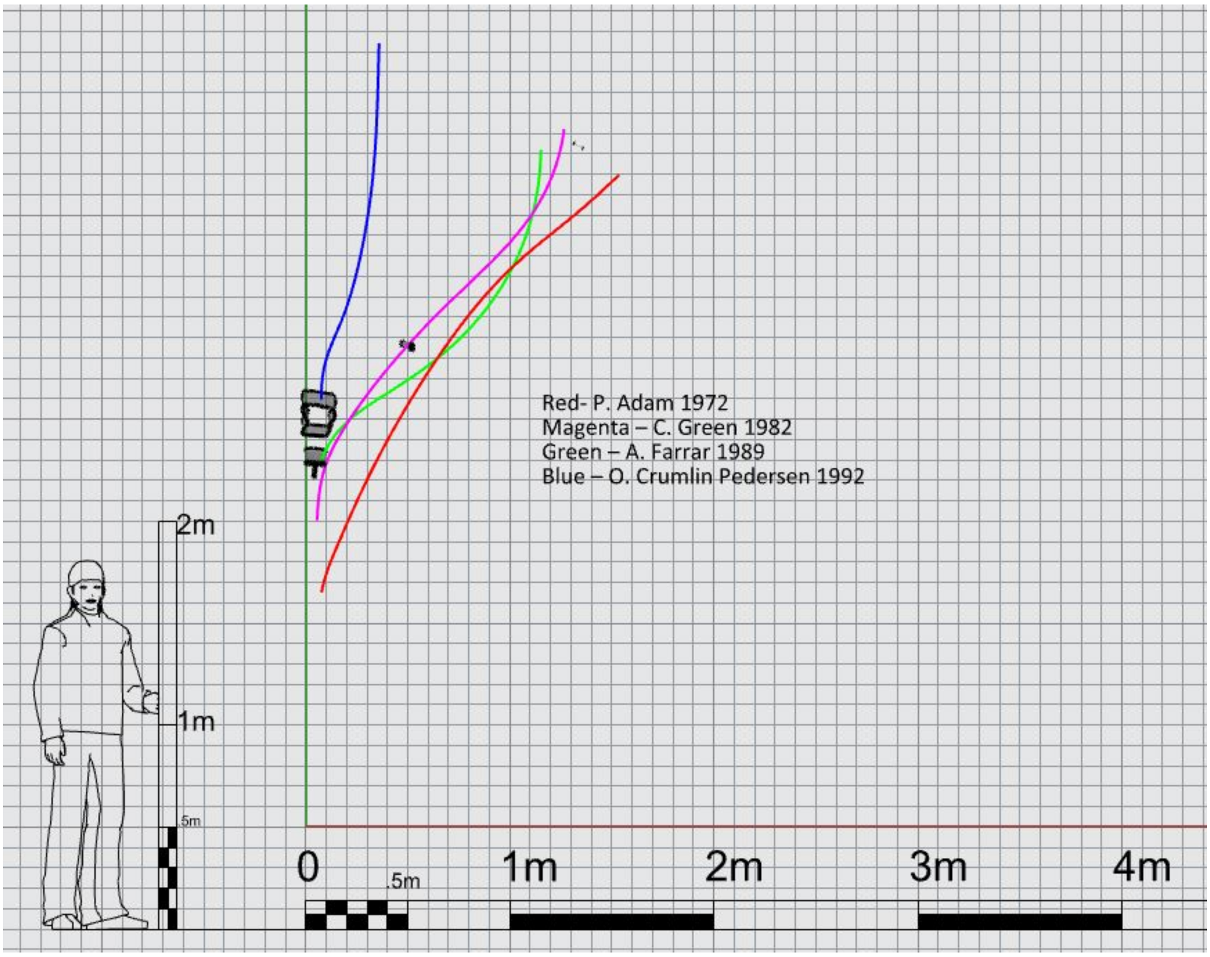

Figure 34 Section at 2m aft of Aft Keel face

The significant difference in hull form between the 1989 Farrar hull and the 1992 Crumlin-Pedersen hull increases still further with Crumlin-Pedersen's hull much flatter from keel to sheer. The 1992 hull has become 1.5m narrower in the beam, with a 0.5m sheer height increase. With the Crumlin-Pedersen 1992 sections (body plan) overlaid on the Farrar 1989 sections (Figure 35) the similar midship area but very disparate stern forms are immediately apparent.

The difference between the two forms could be explained by the fact that in the 1990 Danish report, Crumlin-Pedersen (1990) noted after careful observation of the ship, in particular near the rise of the keel where the planks were opening up at their end (Figure 36), that even the latest set of revised lines produced by Farrar required further revision. Crumlin-Pedersen stressed that it would be necessary to use the actual preserved parts as the main guideline to establish the original shape of the hull. The aft-most recovered frame is not in its correct position in the assembled vessel due to the distorted run of the port strakes (Figure 37).

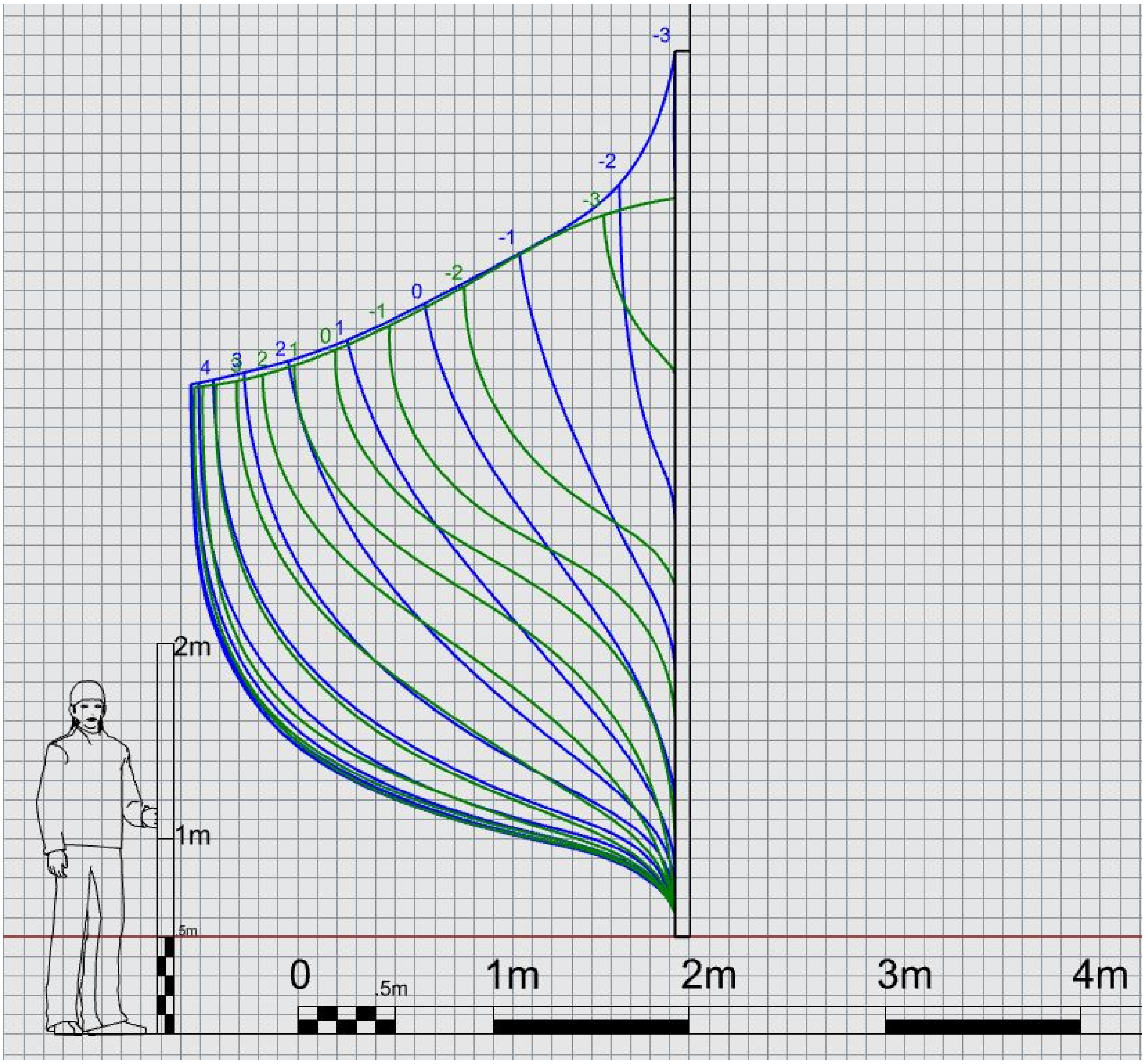

Figure 35 Crumlin Pedersen 1992 body plan overlaid on Farrar 1989 body plan

Figure 36 Port side view of the keel/stern post and strakes

Figure 37 View of the displaced aft-most recovered frame and distorted port strakes

Crumlin Pedersen's solution to this issue appears to be the introduction of an angled keel (Figure *38*) commencing 3.3m ahead of the aft face of the keel and rising circa 141mm towards the aft end. In addition, the furthest aft recovered frame, located circa 600mm forward of the aft face of the keel, requires to be displace vertically by 262mm for both the Farrar and Crumlin Pedersen hull shapes (Figure 38).

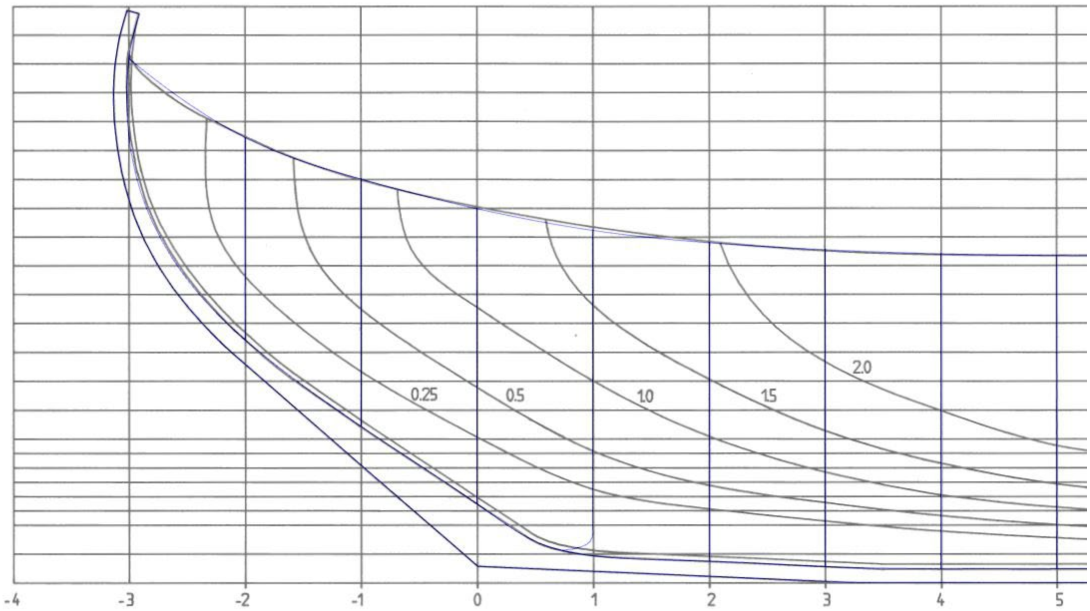

Figure 38 Crumlin Pedersen lines plan with angled keel

There are at least four published sets of lines plans based on the Marsala Punic ship: Paul Adam 1972; Carol Green 1981; Austin Farrar 1989; and Ole Crumlin-Pedersen 1992. As noted by Frost (1981b:65–75), while the drawings by Green in 1981 show a family resemblance to the drawings published by Adam in 1977, a vast amount of detailed modifications lay between the two. Adam himself (1977:35–37) states that it cannot be claimed the drawings for an attempted reconstruction of the Marsala Punic ship are an accurate reconstruction of the Punic ship excavated by Honor Frost and are at best a representation of a ship of the same general class.

As noted by Farrar (1989:368–370) the frame sagged, and the reconstructed ship distorted, so that the lines taken off by Carol Green and published in the Mariner's Mirror February 1981, were not in fact accurate. Consequently, both these sets of lines plans are of little value when assessing the original shape and form of the Marsala Punic ship. Green's lines plan drawing from 1981 could be of benefit as a point-in-time survey recording the amount of sag and distortion in the vessel as displayed in the museum hall compared to its current shape state (Figure 23).

This leaves the revised Farrar lines plan drawings from 1989, and the Crumlin Pedersen lines plan drawings dated 1992. For the surviving portion of the ship, both Farrar and Crumlin Pedersen are in agreement for the shape, but as shown in Figure 33, Figure 34 and Figure 35 from the aft face of the keel to the stern post both have significantly different proposed hull form shapes.

A closer examination of the aft-most recovered frame shape would appear to suggest the presence of reverse or double curvature in the hull form at this station as per the Farrar lines plan, rather than the predominantly convex curvature suggested by the Crumlin-Pedersen hull form (Figure 39). Has the Crumlin Pedersen lines plan introduced an alien influence such as the predominantly convex forms found in the ends of the Danish (Viking) vessels (Crumlin-Pedersen et al. p123, 172, 228, 268 and 295), or is the surviving portion of the aft-most recovered frame distorted on its upper extremity and falsely suggesting a reverse or double curvature to the hull shape in this area?

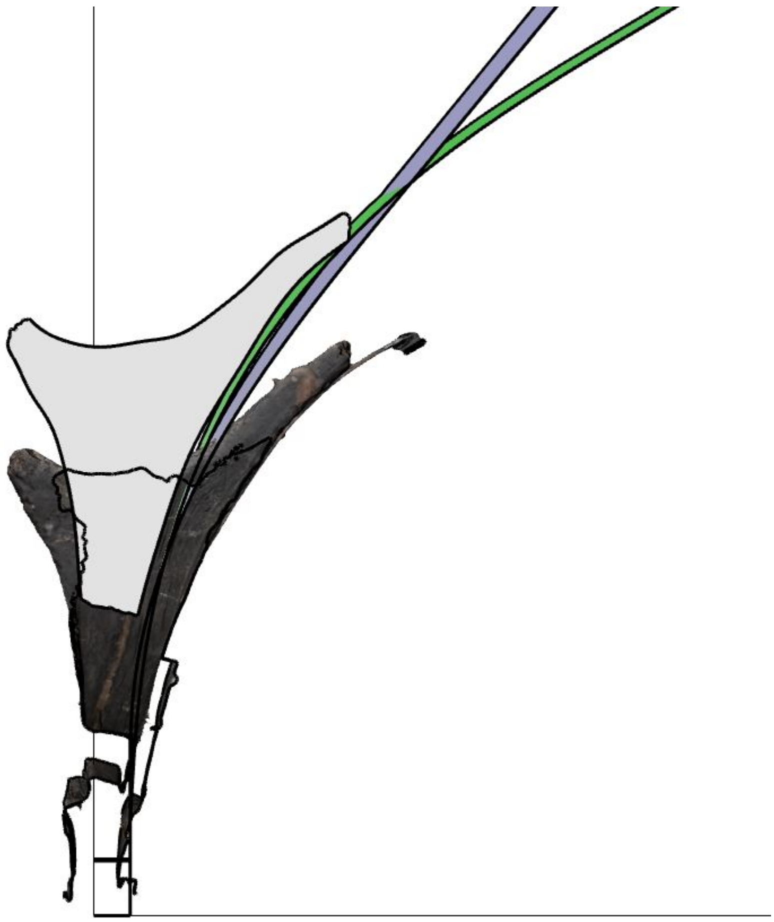

Figure 39 Close-up of the aft-most recovered frame

It is clear from Figure 25 that the remains as displayed do not conform to either of the two remaining lines plan drawings, and there are some outstanding issues with the two proposed hull forms which require further examination and analysis in order to arrive at a more definitive hypothetical reconstruction of the Marsala Punic ship. It will be necessary to carry out a detailed 3D modelling for weight and structure analysis on the hypothetical reconstruction in order to determine factors such as overall weight, center of gravity and cargo carrying capacity before any subsequent work should proceed.

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Glossary of Terms

Artemon	(Greek for foresail), a sail set well forward, often on an inclined mast, whose main function was largely as an aid to steering
Downflooding	Means the entry of seawater through any opening into the hull or superstructure of an undamaged vessel due to heel, trim, or submergence of the vessel. Downflooding Angle means the static angle from the intersection of the vessel's centreline and the waterline in calm water, to the first opening that cannot be closed weathertight and through which downflooding can occur.
FP	Forward Perpendicular, the point where the design water line (DWL) intersects with the stem
LCG	Longitudinal centre of gravity
Reconstruction	A thing that has been rebuilt after being damaged or destroyed. An impression, model, or re-enactment of an object or past event formed from the available evidence
Replica	An exact or accurate copy or reproduction of an object.
Sheer clamp	A long board that runs along the inside of the boat along the sheer line. The sheer strake attaches to the outside face of the frames and the sheer clamp attaches to the inside face of the frames. Sometimes also called the Inwale.
Shim	a thin slip or wedge of material, for driving into crevices or gaps, as between machine parts to compensate for wear, or beneath bedplates, large stones, etc. to level them
Shimmed	or shimming, to fill out or bring to a level by inserting a shim or shims
TCG	Transverse Centre of Gravity
Thwart	A thwart is a strut placed crosswise (left/right) in a ship or boat, to brace it crosswise. In sailing vessel often added to support the mast, in rowboats it can also serve as a seat for a rower.

Tumblehome	the term describing the narrowing of a ship's hull as it rises above the waterline
VCG	Vertical Centre of Gravity