SEVEN BOATS

Assessing the performance of ancient boats

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Esbjerg 2012

Bo Ejstrud, Alexander Cattrysse, Massimiliano Ditta, Dan Nicolescu, Dimitra Perissiou, Stephanie Said & Moriah Sherman:
Seven Boats. *Assessing the performance of ancient boats.*

Maritime Archaeology Programme
University of Southern Denmark
www.sdu.dk/maritimearchaeology

Edited by Bo Ejstrud
Print: Print & Sign, University of Southern Denmark

ISBN: 978-87-992214-7-9

Published by:
Maritime Archaeology Programme
University of Southern Denmark
Niels Bohrs Vej 9-10
DK-6700 Esbjerg
Denmark

Printed in Denmark 2012

FOREWORD

The following is the product of one of the two ‘Special Topics’ classes taught during the spring of 2012 in Maritime Archaeology at the University of Southern Denmark. The theme of the work is the application of techniques from naval architecture on ancient boats. We originally had entirely different plans for the topic of this class. But plans can change, and sometimes fast, and due to circumstances outside our control, this topic had to be developed with a few days’ notice just before semester start.

The title of the topic became “Understanding boats”. In fact the broad ideas were already there, as this years’ work follows on our previous work on the Vaaler Moor logboat (Ejstrud & Maarleveld (eds.) 2012). Still some improvisation was necessary, and the students of this class must generally be commended for having made a real effort in realising the project, contributing much to its realization. This was new ground to everyone, and with a rather comprehensive programme for the project, the students did the work with only limited training in the software - or in model building. In the light of this, much was actually accomplished in understanding these boats.

With seven authors and seven boats, the setup has naturally been that each author was responsible for describing and analysing one boat. Even so, it is an editorial choice not to put author names on the individual chapters. Firstly because there are common chapters to which all have contributed, and this will be the situation in most of the projects we do with the students. Secondly because it is a deliberate part of the brief of the Special Topics classes that the product is a collective effort and that all authors are responsible for the entire project. The idea of the lone archaeologist researching the finds is still prevalent; in fact it is common across the humanities. But a collective effort may be a more effective way of advancing research, especially in the work functions that most of our students will enter after studying. Few ivory towers are left standing anywhere.

The seven authors of this book also represent seven countries, and almost as many different traditions of archaeological practice. Even after running this programme for several years it is still an eye-opener and a challenge to your every professional preconception to work in an environment like ours. The chronological and spatial diversity of the boats presented here may also be a reflection of the wide scope of our student’s interests.

Esbjerg, 21 November 2012

Bo Ejstrud

CONTENT

1. INTRODUCTION

Boats and archaeology

Ships and boats form a core part of the academic study of maritime archaeology. While other maritime aspects of past human lives form key facets of the discipline, the vessels themselves are all-important, being the main instrument by which human societies made themselves maritime. As maritime archaeologists we should certainly understand boats.

However, there are many ways of 'understanding' boats. In archaeology we are mainly confronted with them as wrecks. Much of our professional training and experience is therefore aimed at handling shipwrecks from the sea bed. We know about surveying, diving and documentation techniques; we can aim to reconstruct our fragmented finds, and will almost invariably focus on cultural aspects of our discoveries, as human culture is what archaeology is all about. One could argue that the work of maritime archaeologists is much defined by the archaeological context of our data, and rightfully so. Nevertheless, as phrased by Schiffer (1972), our finds also had a 'systemic context'. The original context of ancient vessels was to function as sailing machines. With experimental archaeology there is already a long tradition for approaching this aspect in maritime archaeology, but outside these often expensive and time-consuming trials, one could question to what extent maritime archaeologists have the tools to understand boats as working devices in the water.

The following project is much inspired by a previous work on the Vaaler Moor logboat (Ejstrud & Maarleveld (eds.) 2012). This Roman Period boat from NW Germany was a 12 m long expanded logboat, which we analysed and reconstructed. We put the boat in its spatial and cultural context, and could compare it to a large database of other logboats from Europe. One question was difficult to answer, though: How well did it perform? The Vaaler Moor boat belongs to a group of large logboats which has been found along the northern Wadden Sea coast. They would most likely have sailed the tidal waters of the area. This means shifting seas with strong currents and occasionally choppy conditions, it is generally an area that is not easy to navigate for smaller vessels. This boat, and the research we did on it, still left us wondering how this boat would fare on the water.

The questions related to the seaworthiness and stability of the Vaaler Moor boat then gained a new tragic perspective when in February 2011 a boating accident happened in the sheltered waters of Præstø Fjord, Denmark. A dragon boat belonging to a local boarding school went out in fair weather with 11 pupils and two teachers on board. As they went out, the weather worsened and the skipper ordered the boat to turn around and go back. During this turn the boat capsized in a beam sea. With the very cold water, with -unavoidable- delays in alerting rescue services, and with the crew being improperly dressed and equipped for boating in February, the skipper of the boat tragically lost his life while helping his crew. Being in the cold water for very long, several of the pupils suffered severe and lasting injuries, and none of them escaped unscathed. The Vaaler Moor boat is not exactly a dragon boat. But being a long and slender vessel with a low freeboard and a large crew for its size, it shares the same general features. The accident happened in a sheltered location, while the boats of the Vaaler Moor type would generally have encountered much more difficult conditions in the Wadden Sea. This tragic event made a strong impression on everyone, and was very thought provoking for those of us who take students out to sea. It also stressed that there was something essential we as maritime archaeologists needed to understand about ancient boats. The seaworthiness of our primary research objects and the practical conditions under which they could be used is simply too vital an aspect not to be familiar with.

The project

Other professions work more directly with the aspect of sailing in their understanding of boats. The main idea and aim behind the following project is therefore to make an assessment of the performance of ancient boats by applying techniques of naval architecture to them.

The project is in a sense also an attempt to understand the methods of naval architecture. Calculating a prismatic coefficient or a moment of inertia seems more meaningful when we can apply those values to boats which are within the normal realms of maritime archaeology, rather than the modern ships for which such measures are routinely calculated and explained in textbooks and academic papers. Although well published and under continuous study, the behaviour of modern container ships, Ro-Ro ferries and navy destroyers is of little immediate value to maritime archaeology. However, the methods used in these studies seem very relevant.

Naval architecture is an entire profession with many approaches to sailing vessels. The project was from the start envisioned to work along two main strands. The properties of the boats would be calculated theoretically, using mainly computer based modelling, but also the boats would be built as physical models, so that we could see them in practice on the water. In lieu of making full scale replicas, these two strands will allow us to compare and combine the theoretical results with actual boat behaviour on the water.

The boats

Only little would come from analysing one boat, so the research setup is a comparative analysis of several boats, trying to understand their performance on the water, and the differences between them. Seven boats have been chosen for closer study (Table 1). They are all either archaeologically known boats or, at least, 'traditional' boats. The focus is on smaller open boats. Larger ships are certainly also interesting, but for our purpose the small boats are better used, because stability and hull form is more critical to the behaviour of the boat. A smaller boat generally needs to be more stable than a larger one, and any differences between the boats are easier to measure and describe.

Boat	Type	Length	Area	Age
Vaaler Moor	Logboat, expanded	12.3 m	Germany	2nd-4th century CE
North Ferriby 1	Plank boat, sewn	15.8 m	England	19th-17th century BCE
Sampan	Plank boat	6.0 m	Singapore	Traditional
Gokstad Faering	Plank boat, clinker	6.5 m	Norway	9th century CE
Wa Mikael	Outrigger canoe	7.9 m	Micronesia	Traditional
Kinneret	Plank boat, mortise and tenon	8.8 m	Israel	1st century CE
Dashur	Plank boat, mortise and tenon	9.8 m	Egypt	19th century BCE

Table 1. The boats analysed in this workbook.

Focussing on small open boats, we have otherwise tried to maximize differences between the boats. This is terms of geography, age, building materials and -not least- hull shape. Most of the boats can be considered 'inshore' vessels, working just off a sea coast, but for comparative reasons we have also included two inland vessels. Coincidently, or possibly due to the material generally available, all boats are from the Old World (Figure 1). There is a concentration in North-western Europe, but the boats cover a wide range in both time and space.

For the purpose of this project the boats selected had to have been preserved to an extent where they could be reliably reconstructed. This is not a simple proposition. The same wreck may be open for several different interpretations, as we shall discuss in the following chapters. To get the widest possible coverage in terms of types and geography we have in some instances used ‘traditional’ boats, from the 19th or early 20th centuries.

Figure 1. Geographical and chronological distribution of the boats.

While the boats are chosen to be different, they also form groups to some extent. Vaaler Moor and North Ferriby are both larger boats presumably carrying a large crew, although they are otherwise very different. The Gokstad faering, the Singapore Sampan and the Pacific outrigger canoe are smaller vessels which were probably used mainly for coastal transport. While being different types of boats, the faering and the sampan share the same general dimensions. Finally, the Dashur and Kinneret boats are inland vessels, making the conditions of waterborne transport different again. Dashur differs from the others by being fully decked.

Previous research

With a stated goal of assessing the performance of selected boats, it has evidently been important to define what we mean by ‘performance’. This is based on a review of the literature, and we have looked into three types of sources, namely maritime archaeology, naval architecture and modern safety rules. In this section we will necessarily introduce technical terms (e.g. ‘metacentric height’ and ‘righting arm’) which will only be defined more precisely in chapter 2.

Maritime archaeology

Other archaeologists have looked into the aspects of performance. Sean McGrail has been a lead figure in attempts to learn the rest of the profession how boats actually work, possibly as a result of having practical experience at sea (Adams 2006).

In 1977 McGrail and Corlett did a short paper on the speed potential of ancient boats. This was based on Corlett’s observation that boats with a volumetric coefficient of less than 0.002 can semi-plane when at speed. Based on this observation they list seven ancient boats, which may have had a very high speed potential. These are the Gokstad Faering, the Gokstad ship, a (most likely conjectural) trireme and four logboat (Brigg, Clifton 1, Clifton 2, Poole).

In his work on the logboats of England and Wales, McGrail developed his studies much further (McGrail 1978). Apart from being a seminal work on logboats, this work contains a wealth of information on how to formally assess small boats. According to this work, there are five aspects to consider for logboat performance and safety:

"*Performance*	*(i)*	*speed (minimize resistance and maximize propulsive forces)*
	(ii)	*payload (maximize displacement and minimize hull weight)*
	(iii)	*manoeuvrability*
Safety	*(iv)*	*structural strength and durability, and watertightness*
	(v)	*stability*" (McGrail 1978: 95).

Theoretical calculations are made on three ideal shapes (semi-circular, rectangular and square), but actual logboats are also analysed using a range of coefficients and measurements (McGrail 1978: 131ff). Some of the measurements are only relevant to logboats, but most are general coefficients, which can be used on any boat. Stability is measured through the metacentric height. McGrail states that although there are other ways of measuring stability, calculating the initial metacentric height is a '*sine qua non'* in such work (McGrail 1978: 97). Using Simpson's First Rule the displacement at various load lines was calculated for the 24 logboats where sufficient information was available. This is a very comprehensive work, especially considering that this is done before the PC revolution made such calculations a matter of routine.

In a later paper on the performance of the Hasholme logboat, McGrail defined 'performance' more briefly as the boat's *stability and trim*, *cargo capacity* and *speed*. Focussing only on performance, this paper is indeed more focussed, and seems to summarize McGrail's work regarding these aspects well. McGrail lists six different ways of assessing boats (McGrail 1988: 35):

a. By eye.
b. Using simple coefficients.
c. Using hydrostatic curves.
d. Small-scale models.
e. Computer work.
f. Building full-scale replicas and undertaking trials.

The first option is mostly available to the trained eye, and although a goal of this project has certainly been to begin honing our skills in that respect, this is both difficult to learn and the results difficult to reproduce. Building full-scale replicas has also been out of question for this project, as it would be in most projects of archaeological boats. This leaves five options (b.-e.) for a 'normal' -or 'cost-effective' (McGrail 1988: 35)- evaluation of an archaeological boat. Options we have all used in the following.

Armed with these definitions, McGrail investigates the Hasholme boat. Hydrostatic curves are calculated for continuous load lines up to a draught of 1.25 m - the entire depth of the hull. Such curves are considered the most cost efficient method of assessing a boat, and the metacentric height is considered fundamental to understand stability (McGrail 1988: 35f). While trim is discussed theoretically, it does not seem to be applied to the actual boat. The speed potential is assessed through the maximum hull speed, and through relevant coefficients. It is found unlikely that this boat could achieve its maximum theoretical hull speed. Assessing the load capacity, McGrail defines five standard loading conditions for which displacement, and thereby cargo capacity, can be calculated. These are the 'light' condition with only the unloaded hull, a maximum with full load, and then four different displacements at 50%, 60%, 67% and 75% of draught to the height of the sides. McGrail finds the "Grågås" ratio of 60% draught the most promising method for comparing boats.

Following up on his work on the performance of logboats, McGrail (1990) published an assessment of the Ravensbourne, which was a replica of the Clapton logboat. This was based on lines drawings for the replica, for which a naval architects made hydrostatic curves. It was found that although the boat could theoretically carry a crew of four, a crew of one would be both the most effective and the safest. With a full form, the boat was assessed to have a speed potential of *c*. 2.5 kts, about half its theoretical maximum hull speed.

The work with application of techniques and methods from naval architecture has been continued in e.g. *Ancient Boats of North-West Europe* (McGrail 1987). As much as an overview and cultural interpretation of maritime finds before 1500 CE, this book is also a comprehensive overview of various methods by which one can assess a boat from the past.

Steffy

In W*ooden Shipbuilding and the Interpretation of Shipwrecks (1994)* J.R. Steffy wrote a couple of comprehensive chapters on basic ship hydrostatics which gives the novice ship enthusiast an understanding of the various concepts. He gives a good explanation of stability and the basic ideas behind the construction of a ship, during which he stresses the importance of the ship's function for the design. Furthermore the meaning of a lines plan is explained in clear language; a crucial tool in studying ships' hydrostatics and their designs. The former function of lines plans is explained in more detail in an appendix in which the method for calculating displacement from a lines plan is explained. In a second appendix the basic proportions and hydrodynamic properties, namely the length, breadth, and depth dimensions, the length-beam ratio, the waterplane area and the waterplane, midship, block and prismatic coefficients, are listed together with a short summary defining and explaining them. These are considered to be the most useful proportions and properties for archaeologists, according to Steffy (Steffy 1994: 253).

Other works

An important inspiration for doing formal assessments of boats has apparently been the experience of constructing actual boats. At least we see a tendency for these calculations being made primarily by people with boat building experience. One example could be the North Ferriby boat (Wright 1985: ch. 4), where the collaboration between Wright and boat builder John Coates lead to an extensive analysis of the boat, and even plate developments, although the boat was not then built in full scale.

Practical building considerations were also behind the work on the *Min of the Desert*. The aim of this project was to build a full size construction of a pharaonic ship. ‘The design is based on details from 22 ancient Egyptian full-sized craft, sea-going ship timbers, ship models and images of seagoing ships, especially those from Hatshepsut’s mortuary temple at Deir el Bahri’ (Ward, Couser & Vosmer, 2007: 123). The boat was designed and analysed using a software called Maxsurf Naval Architecture design suite from Formation Design Systems (Ward et al. 2007: 124). Basing the design on the Dashur boat, modifications were made to improve its stability, as this was a river-going vessel and needed to be compatible for sailing on open waters on the Red Sea. This experimental craft was built with the intention of testing its performance, manoeuvrability and response to different sailing conditions, but above all water tightness and strength of the hull (Ward et al. 2007: 128).

When the Gokstad Faering was built in replica (McGrail 1974; McKee 1974), this also led to calculations of the properties of the boat. Based on the plans made by Christensen in 1958 the Faering was reconstructed, after which the hydrostatics of the ship were studied in various load conditions. Furthermore the sailing qualities of the boat were tested in open-water use. These tests allowed for further study of the functioning and use of the Faering.

On a somewhat similar note, hydrostatic calculations were done as part of the project of building the *Tilia Alsie*, the full scale replica of the Hjortspring boat (Hocker & Fenger 2003). The replica was thoroughly documented using digital technologies, and the calculations were therefore made on the actual boat, not on a set of plans. It was noted that due to the flexibility of the hull and the way it changes form with different types of support, several different solutions could be correct. The relation between draught and displacement was calculated, giving a draught of 13 cm for the empty hull, increasing to 35 cm with 2000 kg of cargo on board. The boat was compared to the original reconstruction by F. Johannesen. The new reconstruction has more rocker and sheer and is somewhat fuller in hull form, and this has an influence on the calculated draughts and coefficients of the boat.

The metacentric height was also found to be higher for the new reconstruction. Practical tests looked especially on drag and dynamic movements of the boat.

The Slusegård boats were expanded logboats found in graves in the Danish island of Bornholm. They were initially studied by Ole Klindt-Jensen, however further studies were carried out with regards to grave customs and the boat-graves themselves. The function of these boat-graves has been discussed by Ole Crumlin-Pedersen: whether they have a practical purpose, a secular significance or a religious significance (Crumlin-Pedersen 1995). The hydrostatic results produced from the reconstructions of the 3 and 5 meter logboats where carried out in order to see how they perform in water, therefore their seaworthiness. The results also gave an approximation of the number of people and goods that the logboats could carry. (Andersen, Lind & Crumlin-Pedersen 1991)

Technically more advanced than most of these studies, a PhD thesis by Kenn Jensen (1999) was written as the naval architect's analysis of ancient boats. This work was done in cooperation between the former Centre for Maritime Archaeology in Roskilde and the Department of Naval Architecture and Offshore Engineering at the Technical University of Denmark (DTU). The analysis was based on the software *I-ship*, which has been developed at DTU. The thesis covers a number of aspects, including basic hydrostatics. A main effort was put into structural analysis using the replica Helge Ask as basis. This is very valuable and in many respects a unique analysis for the field of maritime archaeology.

In an appendix the basic hydrostatic properties of 34 ships and boats is listed. It has the form of a table with a long list of measures and coefficients, of which a large proportion is never used in the research, but possibly just reflects a standard reporting format by naval architects. They may be much information hidden in these numbers, but they are not readily available to the reader as they are presented without any comment or analysis.

In the publication of the *Haithabu/Hedeby* ships, Jensen also did hydrostatic calculations of two of the ships (Jensen 1997). The results are again presented summarily and without much discussion.

Certainly with much more discussion on the cultural aspects, Fonseca *et al*. published a study of the 16th century so called *Pepper Wreck* in 2005. A reconstruction allowed for the calculation of the hydrostatic properties of the ship, and the stability of the vessel was compared to modern criteria. This was followed up by further methodological and specific studies of the cargo capacity and stability of the vessel (Castro & Fonseca 2006; Castro *et al*. 2008).

The small *Årby boat* from Viking Age Sweden was reconstructed by Roberts (1993). Based on trials, the boat was considered versatile and easy to handle, if only for one person:

> "*Indeed for a lake-side dweller this little boat may have represented the same convenience and capability as one would today expect of a bicycle*." (Roberts 1993: 97)

Calculations were made for Årby in three successive states: Light (54,5 kg), with one person (+60 kg), and with his dog (+15 kg). Inclining tests lead to the calculation of the righting moment, which was further used to calculate a tenderness ratio by the method also used on the Gokstad fearing (McKee 1974).

Flat-bottom boats

Most of the works mentioned above follow the same general pattern, applying established techniques from naval architecture to ancient crafts. An entirely different approach was proposed by Roberts (1983). The aim was a characterization of flat bottomed boats, based on their dimensions. The relation between the maximum beam (mb) and the beam at the bottom (bb) together with the flare angle (ϕ) was worked into an index of the boat's basic form (Figure 2):

$$Index = \sin\phi\left(\frac{bb}{mb}\right)$$

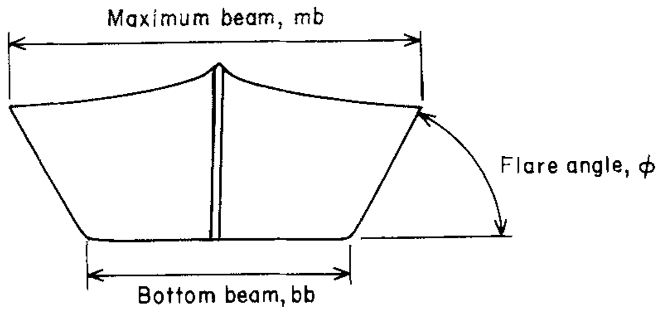

Figure 2. The dimensions used for Robert's boat index (from Roberts 1983: 327).

This index was then considered indicative of the use of the boat, as different values would indicate different environments, for which the boat was suited:

> *"(a) Above 0·9 are boats suited to calm rivers or lakes and intended for carrying people, beasts or small dense cargoes, depending on the beam dimension.*
> *(b) Between 0·9 and 0·65 are boats from big rivers and lakes and expected to carry relatively large loads of any cargo available. Slight flare is beginning to appear.*
> *(c) From 0·65 to 0·43 are boats used on lagoons and estuaries and perhaps managing short coatline* [sic] *voyages in settled weather. These would be used in fishing, ferrying and cargo carrying.*
> *(d) From 0·43 to 0·39 would seem to be the index range of boats intended for serious sea work in all forms of business or livelihood.*
> *(e) Below 0·39 come those shallow, very widely flared boats used on shallow, quiet, inland waters for moving comparatively large bulky cargoes." (Roberts 1983: 329)*

The basic idea of this work is very appealing. By defining environments in which these boats could be used ("calm rivers", "lagoons and estuaries"), this index gives a measure of the seaworthiness of the boats, not in terms of metacentric heights any other –more or less theoretical- values, but terms of what we may be interested in as archaeologists. The index does even seem have some merit for smaller boats, but especially for the larger vessels, it does not seem to capture the right dimensions. The cogs from Bremen and Kolding were both classified in group c) above, described as "*perhaps managing short coastline voyages in settled waters*". The medieval cogs may not be the best sea boats ever built, but surely they should categorize in category d) above. There must also be an absolute value to all of this; the differences between the Bremen cog and the Egernsund barge are difficult to capture in one single coefficient, without consideration for e.g. dimensions, displacement and freeboard.

Also there seems to be a rather simple relation between the flare angle and the *bb/mb* ratio, at least for straight walled vessels. A simple check of the 31 boats mentioned by Roberts confirms this (Roberts 1983: tables 1-3).

While it is worth acknowledging this effort for being developed precisely to the needs of maritime archaeologists, it may also serve to illustrate just how difficult it is to make simple measures for the somewhat complicated matter of seaworthiness.

Modern works on naval architecture

Modern work of naval architects has naturally focussed on larger vessels. As an introductory textbook we initially used the classic book on *Basic Ship Theory* by Rawson & Tupper (2001). According to this authors, "*naval architecture is concerned with ship safety, ship performance and ship geometry*" (Rawson and Tupper 2001: 2), and they carry on to cover the basics of ship design techniques. A slightly shorter version is written by Tupper (2004: 2), in which he initially defines that, "*Naval architecture is the science of making a ship 'fit for purpose'*". Such a brief definition is naturally expanded and explained later, but one may well be advised to keep this '*fit for purpose'* clause in mind when assessing waterborne craft: A float or raft may well be 'simple', but if it fits its purpose, it may equally well be a 'good' craft (Figure 3).

Figure 3.Floats used while fleeing Assyrian archers across a river. Bas-relief from Nimrud. (Hornell 1942: Pl. II).

Other basic textbooks could have been used equally well, and in fact by comparison to older literature, the basics of naval architecture have long been established; a textbook on the topic written by E.L. Attwood was originally published in 1899 and became a standard work to English speaking naval architects through the first half of the 20th century. Reading through the 1922 (19th) edition of this book, the main difference to modern textbooks seems to be the introduction of SI units. In practice computers have obviously made a huge difference to the practical work with ship design, though.

Apart from the basics of naval architecture, on which there is a vast literature, it was natural in this project to focus on the construction on smaller vessels. A few books on yacht design have become classics, and were also to some extent useful to this project.

Skeene

The first of these, and apparently still in use in its revised versions, N.L. Skeene wrote a book on the *Elements of yacht design*, which was first published in 1904. Written at a time where traditional building methods were still used to some extent the book does reflect both tradition and modernity in its approach to boat building. Some of the theories behind the design process, which Skeene proposed in his original work, are now obsolete even where the practical solutions he derived from these theories are sound. In reality theories are probably derived from practical experience; he knew what worked but did not have the correct theoretical explanation. The book came in several editions, the latest being from 1938. This book had a renaissance when F.S. Kinney completely revised the book in 1962, and again several reprints and revised versions have been published.

As introduction to the first version, Skeene established that there are four characteristics to be sought after in yacht design: *Seaworthiness*, *large cabin accommodation*, *beauty* and *high speed* (Skeene 1904: 1). These characteristics set the agenda for his approach to yacht design, although other design considerations are also covered. Being no longer than 87 pages including nine plates at the end of the book, it is a brief and direct introduction to the basics of yacht design. It may owe some of its popularity to the brief straightforwardness with which it is written.

Larsson & Eliassen

Finding that there were no recent and available books on yacht design, Larsson and Eliasson (2000) wrote a complete design manual for yachts, explicitly aiming for producing a modern replacement for Skeene's work, which could be used by amateurs and professionals alike. The result has been influential and must be considered the current standard work of small craft design work. Throughout the book, the authors use a specific yacht -YD-40- as their example, and this makes the book coherent as a textbook.

Being a designer's manual for modern yacht design, the book is very systematic and specific in its description of the working process. It is a useful book to be acquainted with, but being deliberately aimed at modern designs and modern materials, and with an approach that is the direct opposite of that of the archaeologist, it is of somewhat limited use to this project. Through the description of the design process however, there is important discussions on the design of small vessels.

Describing the initial stages of a new design, they describe how four considerations are made before any actual design work is done (Larsson & Eliassen 2000: 10ff):

- *Type of boat*
- *Intended use*
- *Main dimensions*
- *Cost*

Out of these points, the first is interesting, in that a client would often have a particular boat in mind before ordering a new one. This preconceived image can apparently be difficult to change:

> "*Personal opinion often governs the choice of type to such an extent that the more logic and scientific arguments may become of secondary concern, if not set aside entirely."* (Larsson & Eliassen 2000: 10)

There is an interesting claim in this, demonstrating the strength of cultural perceptions even in a modern, and allegedly knowledge-driven society. Any archaeologist will know that form does not follow function in any stringent or uni-linear way. The form of a boat can hardly defy its function, but generally studying artefacts from vast time spans and large geographical areas, this profession should be first to realize that there are many forms to fulfil the same function. The point of this is of course that in assessing boats we have to factor in tradition. The eyes of the beholder and the specific training of the builders would have had an influence –possibly even a strong one- on the forms of the boats. On the other hand such perceptions are developed together with practical experience. Sailing a craft on open water is inherently a dangerous undertaking, and one does not a priori expect to see boats which are unacceptably dangerous when sailing the waters they are built to navigate.

Marchaj

It does happen, though. Aimed specifically on the seaworthiness of yachts, *C.A. Marchaj* wrote a comprehensive and well-illustrated book published in 1986. His point of departure was a concern for the development of racing yachts where the consideration for speed and the efforts to surpass various rating rules has produced boats that are indeed outright dangerous to sail; In the cultural environment of racing, high risk has been accepted in the pursuit for better speed margins. This concern led to a book presenting a both hearty and comprehensive analysis of the problem of seaworthiness. Focussing on the sailing yachts and modern rating rules not all discussions in the book are directly relevant to maritime archaeology, although the calculations and mechanics behind them certainly have been relevant to this project. As a treatise on nomological effects on the development of boat forms over time it is still interesting reading to any archaeologist with an interest in the sea.

According to Marchaj there are three requirements of importance to a non-racing boat:

- **"*Seaworthiness* -** *Strong, durable and watertight construction, structurally sound rig, good survival characteristics in extreme weather.*

- ***Seakindliness*** - *... Slow, small and easy motion in spite of rough seas and weather.*
- ***Habitability*** - *... providing the crew with an environment that permits them to function effectively without degrading their mental or physical performance ..."* (Marchaj 1986: 6f).

While the habitability of a pleasure boat generally refers to qualities such as standing headroom in the cabin or the general comfort, the term may be expanded to cover even the working space of a smaller, non-cruising boat. Strangely Marchaj seems to equate habitability with seakindliness to some extent, as he especially talks about the effects of motion on the crew in his definition.

Other works

As a general comment for the modern books, they do of course focus on modern conditions and materials, which limit their use to an archaeological project. Kenn Jensen's dissertation (1999), as mentioned in the previous section, is the work by a naval architect which is probably most directly aligned with the work we present here.

Apart from these classical books there is a vast array of scientific and technical papers on the issue of boat performance. In our search for literature we have focussed especially on the aspects of stability and safety as seaworthiness is naturally of paramount importance.

Modern safety standards

A potentially important source to the understanding of the safety of boats may be modern standards. Although they are indeed modern and ancient crafts cannot be expected to comply with them, they demonstrate which criteria today is considered vital to boat safety, and how to evaluate these criteria. A survey of some of these standards is therefore presented here.

IMO

The *International Maritime organization* (IMO) has traditionally focussed on standards for large commercial vessels above 24 m in length, which are generally beyond the scope of this study (IMO 2008). Recognizing the importance of the commercial fishing fleet and the generally limited size of most of the world's fishing boats, voluntary recommendations have been developed over the last two decades.

In a set of *model regulations* covering small crafts in Africa, IMO (2002) defines a number of criteria for safety and stability. The minimum freeboard is set to the greater value of 250 mm or 300+44×(L_{OA}-4.5) mm. The fixed minimum value of 0.25 m is exceeded by the equation with a boat length of 1.37 m, and would rarely be used.

Stability is otherwise established by a heeling test where the boat fully loaded has its load shifted athwartships equivalent to a heeling moment of the greater of either a passenger heeling moment (M_P) or a wind heeling moment (M_W):

- $M_P = W \times B_P / 6$, Nm

, where W = weight of passengers (75 kg), and B_P = the maximum breadth of decks available to passengers (in m).

- $M_W = P \times A \times H$, Nm

, where P = wind pressure (36.6 kg/m^2 in sheltered and 73.3 kg/m^2 in open waters), A = Projected lateral area of the boat above the water in m^2 and H = height of the centre of the area above the waterline in m.

In an open boat the freeboard can be reduced by no more than 25% by this test. Open boats are also required to have reserve buoyancy so that even if fully flooded, the boat will remain floating and stable.

Following the work which was initiated in 1995, IMO invited FAO and ILO to work jointly on standards for small fishing vessels in 1999. This work first lead to the *Voluntary Guidelines for the Design, Construction and Equipment for Small Fishing Vessels*, which was presented in 2004, and covered vessels between 12 and 24 m length. The same year it was decided that the safety of small fishing vessels was a priority area, and again together with FAO and ILO, work was begun on what became the *Safety recommendations for decked fishing vessels of less than 12 metres in length and undecked fishing vessels*, which were presented at the 2010 annual meeting of the Maritime Safety Committee under IMO. In these recommendations the design categories (A-D) developed by the ISO and European Union have been adopted. These categories are presented below. Unlike the European rules, the IMO recommendations allow open boats to be classified in category A and B.

Under these recommendations, all boats are required to have a GM of no less than 0.35 m, and decked boats must have a righting lever of no less than 0.20 m at 30° heel. There are also criteria for the minimum area under the righting lever curve at 30° and 40°, and it is specified that the maximum righting lever should preferably occur at an angle of heel of 30°, but no less than 25°. If the necessary information for the calculations of metacentric height or righting lever is not available, a number of alternative methods are proposed, including numerical approximations to GM and definitions of a maximum roll period. For European boats the rolling period in seconds must be less than the breadth of the boat in m, while for traditional Asian craft the maximum roll period is defined by the relation between breadth and depth of hull. The alternative methods are applicable to both decked and open boats. Only an offset load test to determine stability is not recommended for smaller open boats.

These criteria, which are relatively recent, reflect developments in the national or regional rules, which precede them. It is important to notice the words *model*, *voluntary*, *guidelines* and *recommendations* in these IMO papers. They are not compulsory as those of the larger ships. Small ships and boats are assumed to be regulated nationally.

Nordic Boat Standard

Nordic Boat Standard was a set of rules worked out by the Nordic maritime authorities, setting up a common construction standard for small craft less than 15 m in length. First worked out in 1969, the standard was implemented in the early 1980s, and more than 1,000,000 boats have been certified under these standards. The rules set minimum requirements for construction, stability and equipment of smaller boats.

According to this standard, the safety of open boats is determined by a minimum freeboard, which is defined by the overall dimensions of the boat, though never less than 0.5 m, and by setting that the GM should not be less than 0.35 m. If the boat can heel to 30° without downflooding, then a GM of 0.20 m is allowed, similar to the requirements for closed boats. Maximum load limits are also defined.

European Union, Recreational Crafts Directive

The Nordic Boat Standard, as well as other national rules in Europe, has now been phased out, and replaced with a European CE standard, which is described in the *Recreational Crafts Directive* 94/25/EC and required for any new boat sold within the European Union. The individual details of this system are described in a number of ISO documents. The stability is described in *ISO 12217*, parts 1-3. Under this scheme there are four design categories of vessels (Table 2):

Design category	**Wind force (Beaufort)**	**Significant wave height ($h_{1/3}$, m)**
A – Ocean	> 8	> 4
B – Offshore	≤ 8	≤ 4
C - Inshore	≤ 6	≤ 2
D - Sheltered waters	≤ 4	≤ 0.5

Table 2. Design categories in the European CE approval system. Source: European Commission (2004).

Being formulated in ISO documents, these standards have become internationally recognized. As such they are implemented in several countries outside Europe - if for no other reason, then because they are a requirement for boat builders to enter the European market.

The design categories are assigned in different ways based on length and whether the vessel carries sails or not. For our purposes, design categories C and D are most interesting, as none of the boats we work with can be considered for 'offshore' or 'ocean' use. We also focus on hull forms, and do not consider sails. This is a natural choice for maritime archaeologists, as details of the rigging are rarely known for archaeologically known boats. The criteria for non-sailing boats (ISO 12217-1) are therefore possibly more interesting to look at. In terms of stability and buoyancy, rules are specified for openings, freeboard, offset loads and heel due to wind.

The *freeboard* is measured with a load like the entire crew and all gear is in the boat, assuming a weight of 75 kg per person. The freeboard should generally not be less than 0.75 m for category C and 0.40 m for category D, if the boats are larger than 6 m. Boats shorter than 6 m are allowed a freeboard of 0.3 (C) and 0.2 m (D), although rising towards the 6 m limit. For sailing crafts the freeboard is given as a downflooding angle, being minimum 35° for category C and 30° for category D. For boats smaller than 6 m, downflooding angle is not an issue, instead they have to demonstrate that the crew can right the boat in case of capsize, and/or that they have enough reserve buoyancy build in to keep afloat.

The *offset load test* is a test of the heeling angle, when the crew sits as close as possible to one gunwale. According to the standard, this angle, ϕ_O, should not exceed:

$$\phi_O = 11.5 + \frac{(24 - L_{OA})^3}{520}$$

For a 10 m long boat this gives a maximum heeling angle of 16.8°, while an 18 m long boat is allowed to heel up to 11.9°. Minimum freeboard during this heeling test is set to $0.110\times\sqrt{L_{OA}}$ for category C and $0.07\times\sqrt{L_{OA}}$ for category D. These equations are for boats without extra buoyancy chambers. If buoyancy is added, then category D may have a heeling freeboard as low as 1 cm.

The *heel due to wind* is only calculated for open vessels where the exposed windage area (A_{LV}) of the hull is larger than $L_{OA}\times B_{OA}$; so only if the vertical projected profile of the boat above water is larger than the horizontal rectangle circumscribing the boat on the water. If this is the case then the heeling moment due to wind is compared to the righting moment, assuming constant wind speeds of 17 m/s for category C and 13 m/s for category D (the corresponding values for categories A and B are 28 and 21 m/s respectively). As an alternative the heeling moment may be compared to the heeling moment due to the offset position of the crew. The heeling moment is calculated as:

$$M_W = 0.3 A_{LV}\left(\frac{A_{LV}}{L_{WL}} + T_M\right) v_W^{\,2}\text{, Nm}$$

, where M_W is the heeling moment in Nm, A_{LV} is the windage area in m^2, L_{WL} is the water line length of the boat, T_M is the draught amidships and v_W is the wind speed in m/s.

Russia

In Russia the *Rules for the Classification, designing, construction and equipment of small-scale vessels of the Fishing Fleet* has developed a detailed system for boats between 4.5 and 10 m length. This system makes a distinction between open and decked vessels. The decked vessels are divided in three classes; M (sea going), O (lake) and P (river), while the open boats are classified according to their maximum permissible wave height. The wave heights are defined as $h_{0.95}$ for coastal waters and $h_{0.99}$ for inland waters. The significant wave heights are therefore considerably less. The stability of open boats given certain wave heights is generally considered adequate if they fulfil the criteria summarized in a table (III-2), here shown as Table 3.

Standardized value	Permissible wave height, m			
	0,25	0,5	0,75	1,0
Residual freeboard height $f_{ост}$, m	0,17	0,22	0,3	0,37
Beam of vessel B, m	1,2 – 3,0	1,2 – 3,0	1,2 – 3,0	1,2 – 3,0
Roll period of vessel T_{θ}, sec	1,4 – 1,8	1,4 – 1,8	1,4 – 3,0	1,4 –3,0
Minimum bow height of freeboard $f_{н}$, m	0,28	0,45	0,7	1,0
Permissible distance of vessel from shore, km	0,5	2,0	6,0	10,0
Minimum permissible speed of vessel, km/h	5,0	5,0	8,0	12,0

Table 3. Permissible wave heights for open boats in Russia.

The minimum residual freeboard is measured or calculated with the design loads including crew being shifted halfway from the centre of the boat to the gunwale. As the IMO rules, these rules also work with the maximum roll period of the vessel, and also set up rules for maximum distances from shore and minimum speeds.

Under the Russian rules the maximum service life is envisaged to be 12 years. If this is actually upheld, then there is work to do for the heritage agencies of Russia to preserve examples of these boats, which otherwise disappear very fast.

Screening values

Apart from these formal rules, simplified screening values for stability have also been developed, typically supplementing the rating rules developed for racing. For this reason many of them are designed for sailboats, and therefore are of limited interest here: We do not know the sail areas for most of these boats, and therefore calculating for instance a Dellenbaugh angle (calculating the angle of heel at 8 m/s) Larsson & Eliassen 2000) is of limited interest. The same would go for the ISO Stability Index or STIX which is implemented in law throughout the European Union. Several other stability indices, generally more simple than STIX, have also been developed over the years.

Another type of screening values is developed for small commercial motor vessels, especially fishing boats. They are there to function as simple tools for skippers and crews, as well as local builders, to assess the seaworthiness of a boat without having the full technical information. With the development of easily accessible ship design software, such screening values are of less importance, as even the most difficult hydrostatic calculations are done automatically and instantly. For the skipper at sea, quick screening values may still be more important, especially because a fishing vessel will change its properties while at sea with weather changes, nets going out and catch coming in. Even rules of thumb may be used for this purpose. IMO (1973) recommends that the fishing skipper is alert to increases in roll period during periods of ice formation, as this indicates a lowering of metacentric height.

Summary

The general picture from these rules is that the main concerns for open boat stability is initial freeboard, loss of freeboard due to shift of weights (hauling in equipment along the side of the boat) and heeling due to weather. Initial metacentric height is an important and recurrent defining stability criterion, while a maximum roll period (related inversely to metacentric height) is also defined in some rules.

The rules generally apply weather criteria for the classification of boats, so that they are approved for a certain sea state, and different types of water are often defined, for instance in the form of a distance from the coast, but also as specific stretches of water, or types of water (surf zones, channel bars etc.).

For decked boats, the stability criteria are mainly based on minimum metacentric height and calculations of the righting arm. A heeling angle of 30° is recurrent as a defining point across several definitions. The Russian rules and IMO require the maximum righting arm to be at least at 30°, if possible, and otherwise no less than 25°. In the Nordic Boat Standard, the righting arm at 30° must be at least 0.20 m, while the angle of maximum stability cannot be less than 25°.

The assumptions behind these modern standards are of course based on modern boats, and they do not always apply well to the older crafts we are working with. Under modern European standards the Vaaler Moor boat is not considered sufficiently seaworthy even for a sheltered lake, as it fails the requirements of category D in the European system. In fact it would fail every one of the rules described above. Building a full scale replica of this boat would be an interesting project, but it would surely require experienced seamen to operate the boat, and most probably much wrangling with the competent maritime authorities to get it approved for use on the water.

Defining performance

Armed with this literature we have endeavoured to work our way into the field of naval architecture. It is interesting to see, that while archaeologists (in practice mainly McGrail) have focussed on very specific characteristic of the boats (speed, stability, cargo capacity), the naval architects seem to formulate their profession in much more general terms (seaworthiness, habitability, intended use). For obvious reasons the rules and regulations have an entirely different character again, giving very specific criteria to evaluate a -rather narrow- set of criteria, which vessels must comply to.

In this project one main concern has been that of seaworthiness and seakindliness. The interest has been in examining how different hull forms behave on the water. The aim is to get a better general understanding of various hull forms. The technical analyses are written against the background of each boat and its cultural and environmental context. Drawing mainly on the writings by McGrail, we have investigated the *cargo capacity, speed* and *stability* of the vessels.

The basic dimensions of the boats determine all these calculations, and are therefore important. Cargo capacity may not be the same as what was actually loaded on the boat, and this means that a combination of definition and interpretation is needed.

Stability is the ability of the boat to keep safe in bad weather. As seen above, stability is only one part of the seaworthiness of a vessel, but only few assessments have been done on the sturdiness of the constructions: Unless there are indications to the contrary we have assumed that the boats are built to last their intended purpose.

As speed is also a function of crew actions, relatively little weight has been given to this aspect, although we have looked into the question of semi-planing hulls. Otherwise only general indications are given.

The question of *seakindliness*, as described by Marchaj is also interesting: A certain hull may not necessarily capsize during bad weather, but it may move in such an unpleasant way, that crew efficiency is severely hampered, thereby creating potentially dangerous situations.

The analyses may then finally lead to a better understanding of the *type of boat* and its *intended use* (Larsson & Eliasson 2000). While using techniques of naval architecture, the work of maritime archaeology with these techniques will always be done in opposite order, from the designed boat towards its specifications.

2. METHODS

Introduction

In choosing the seven boats to examine, it was important that they were preserved and documented to a state where we could plausibly analyse them. That meant in general that we had to rely on good lines plans. Boats available to study were therefore limited by this requirement of documentation.

A comparative analysis of the boats necessitate that they are analysed in a relatively uniform way. In this chapter we therefore present the general methods used to describe and examine the boats. These methods will be used throughout the following seven chapters (ch. 3-9), each describing one of the boats. It is also clear that the chapters will not be entirely uniform in structure, due to the differences in cultural contexts of these boats.

It is nonetheless important not to confuse the specific local context and use with the requirements of a comparative analysis. Discussions during class proved how difficult this distinction can sometimes be. For instance, we submitted the inland boats to wave conditions that they would never have encountered. It is hardly realistic that the Dashur boats would have encountered very rough seas on the lower reaches of the Nile. But to understand why this is a river boat, it is important to see its performance under similar conditions to the other boats. The same goes for all the boats; we have not analysed them in the conditions of their home waters, but have made an attempt at analysing them under similar conditions.

There are many methods that can be applied in analysing boats. In this chapter we present and define those methods we used, and occasionally discuss some that we did not use.

A number of *basic measurements and calculations* are present in all work of this type. A first section of this chapter is therefore devoted to the technical definitions of these values. We must add that although relatively standardised the nomenclature is not entirely consistent across the literature, and therefore this section is also used to describe the set of definitions used in our work. The issue of *stability* is dealt with in the next section. Here we deal with both the theory behind boat stability, and how we have chosen to measure it in practice for our boats. Finally in this chapter we will describe the *model experiments* we did with boat models in scale 1:20.

Software

We have used DelftShip to model the boats (Figure 4). This software is available in a free version, which is adequate for doing all hull modelling and basic hydrostatic calculations. All software must be learned, but DelftShip is generally easy to use. Coincidently a series of updates were launched during the period when this research was done, changing the user interface while the mechanisms of the programme seemingly remained unchanged. It was all cosmetics.

DelftShip has a proprietary file system, meaning that the hulls had to be modelled within the program. It is also possible to import from various formats, but in the main the boats had to be modelled from scratch. There are several ways of doing this. One options is to use the default hull generated by DelftShip (a standard yacht hull with transom), and then modify it to the specific drawings. Another option is to import a keel line and stations in a text file, based on measurements of the hull or the lines plan. With some work, sometimes much work, in fairing the control points, both methods would produce a reasonably close approximation to the hull.

When we work with archaeological finds, it is important to acknowledge that a ‘reasonably close’ approximation is often the closest we can get. As will be discussed in later chapters, the boats often have several possible reconstructions. In one case we have pursued this aspect, producing two substantially different versions of the same boat find (North Ferriby 1, ch. 4), but otherwise we have chosen one plausible reconstruction of the boat, based on the published lines plans.

Especially when working with imported coordinates DelftShip has a peculiar tendency to ‘auto fair’ the points in an uneven way. Every imported point must subsequently be corrected manually. This may happen because we import hulls of unexpected forms, but seems somewhat unnecessary, given that the coordinates that are entered are relatively precise.

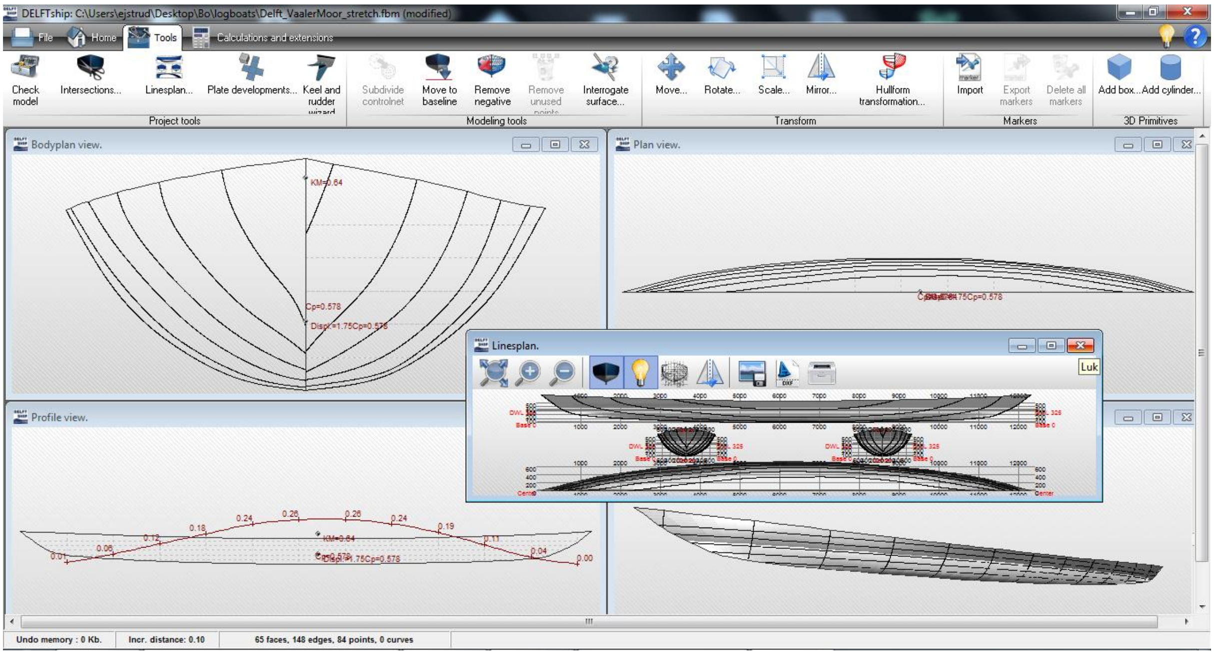

Figure 4. Screenshot from DelftShip. The boat is shown in four views, and a lines plan is shown, here in a small window.

On the basis of the corrected hull form and a set water line, all important hydrostatic values are calculated automatically by the programme. The effort of making a good representation of the hull therefore pays off in terms of reduced – or in practice non-existing- calculation times. These would otherwise be complicated and time consuming.

Apart from the hydrostatic calculations, DelftShip will also produce plank developments from which the boat models could be built; or a full scale boat for that matter. We chose to do so in some instances, but not all, depending on the type of hull.

Further calculations were done in a normal spreadsheet. To standardize the processing and reporting, we developed a standard template, which was used for all boats.

For the calculations of righting arms in chapter 10, we also used Orca3D, which is a marine extension to the CAD system Rhinoceros. This combination was also used for calculations of the outrigger Wa Mikael (ch. 7), as DelftShip is not well suited for multihulls.

Basic measurements and calculations

Dimensions

Length

There are two measurements for length employed here (Figure 5). First the length overall (L_{oa}), which is the distance between the extreme ends of the vessel, excluding any projectiles, for example decorative elements. Second the waterline length (L_{wl}), the distance between the extreme ends of the vessel along the waterline when the vessel is at rest (Tupper 2004: 31).

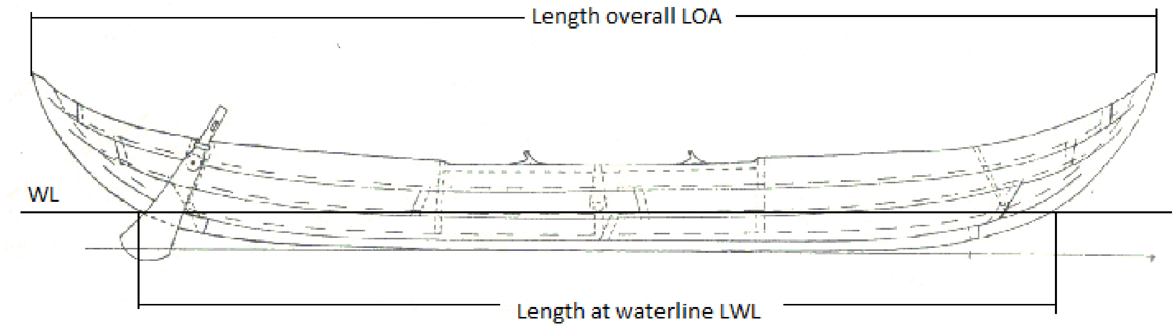

Figure 5. The length overall and length at waterline, here shown on the Gokstad Faering. (From Christensen 1958).

Beam

There are also two measurements for beam. First the beam overall (B_{oa}), the distance across the widest part of the vessel. Second the beam at the waterline (B_{wl}), the distance across the widest part of the vessel at the waterline when the ship is at rest (Tupper, 2004, p. 31).

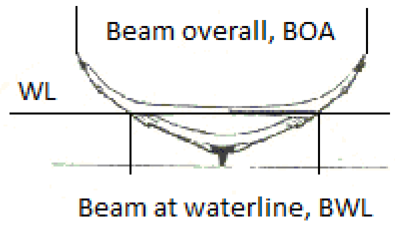

Figure 6. The beam overall and at waterline (from Christensen 1958).

Depth

The depth (D) is the distance between the bottom of the hull at the midship location, in the case of a keeled vessel the measurement is taken from the top of the keel, and the deck line at the midship location (Tupper, 2004, p. 32).

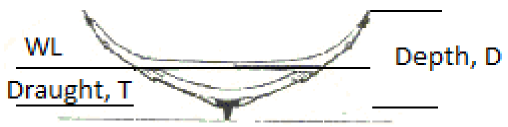

Figure 7. The depth and draught (from Christensen 1958.)

Draught

Draught (T) is the distance between the bottom of the vessel's hull to the waterline. The draught and the freeboard together make up the depth of the hull.

A boat does not have one single draught. It varies with the load of the vessel. In some reconstructions the draught has proven to be faulty, as some vessels cannot float at the arbitrary levels set or require ballasting to do so (McGrail 1988: 38). As already described in the previous chapter, a fixed set of draughts are tried. McGrail finds that the “Grågås ratio”, where 60% of the depth of the hull is submerged, and 40% is above the waterline is the best option for comparing boats (McGrail 1988: 38). We will generally follow this suggestion, as use a draught of 60% as our standard in this work. This ratio is also used by e.g. Jensen (1999).

Exceptions must be made however for some of the boats. Some of these vessels are highly unlikely to have had a draught of 60%. This is because it would result in an unrealistically high load, or with the Pacific boat because such a draught on the main hull would completely submerge the outrigger. We have therefore tried to make a guess at the highest realistic load, and in these cases other ratios of draught seemed to work better.

Before discussing any extra loads, the minimum draught would be that of the ‘light’ condition, that is the draught at which the hull carries its own weight. To determine this we have to estimate the weight of the hull. DelftShip can do this, but allowance must be made for the extra weight of frames, decks and other structural parts of the boat, which we have not modelled. The weight of the hull, and the corresponding minimum draught is therefore an estimate.

The maximum draught is normally the draught measurement allowed to operate safely within certain areas, it basically limits the draught to a certain maximum limit; for example the maximum draught of ships allowed in the Panama Canal is 12.04 m (Tupper 2004: 21). In our case however, we define the maximum draught as the draught at ‘full load’. Following McGrail (1978), full load is here defined by safety, so that the maximum draught is that allowing for a freeboard where the boat can still heel 10° without letting water in over the gunwale.

Displacement

Draught and displacement is therefore directly linked. The displacement is the submerged volume of the hull represented by the weight of water which is equal to the weight of the boat. This can be expressed in different ways. Due to the differences in density between salt and freshwater it may be practical to simply measure the volume of the submerged body of the hull in m^3. But accounting for saltwater, the displacement is typically given as $\Delta = \rho\nabla$, in which Δ is the displacement, ρ is the density of the water and ∇ the submerged volume of the hull. The density of the water varies with salinity, but 1.025 is a generally accepted standard value, and the result is measured in metric tons. Calculating in m^3 is in practice the same as setting ρ to 1.000, but is mostly an attempt to avoid the problem of incorporating the specific properties of the water.

Rather than a volume or weight, the displacement can also be calculated as a force, measured in Newton (N), by the following formula: $\Delta = \rho g\nabla$ with the same symbols as above and g being the acceleration due to gravity (9.81 m/s^2) (Tupper 2004: 35).

The effect of saltwater is that a hull will sit higher in the water for the same load when moving from freshwater to saltwater. Oppositely the boat will sink slightly when moving from the sea and into for instance a river. Where river harbours tend to silt up, this may eventually add to a natural problem.

Waterplane area

The waterplane area A_w is the measurement of the area outlined by the lines created by the length at the waterline and the beam at the waterline (Tupper 2004: 422).

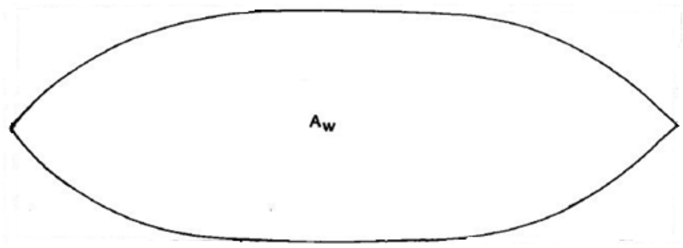

Figure 8. Waterplane area (from Steffy 1994: 255).

Wetted Surface Area

The wetted surface area is the measured surface area of the submerged potion of a vessels hull (Tupper 2004: 159). This value is related to the resistance of the hull.

Coefficients

Every boat in our research has its own unique properties. As the absolute dimensions may vary even if boats are otherwise similar, the general properties are usually described with the help of several coefficients. These coefficients are dimensionless ratios which can help us compare the different hull proportions (Steffy 1994: 254). In this section we will be defining the different applied coefficients, to help the reader comprehend the hydrostatic data that we will provide in the following chapters.

Length-Beam-Draught ratios

$$L{:}B = \frac{Lwl}{Bwl}$$

$$L{:}T = \frac{Lwl}{T}$$

$$B{:}T = \frac{Bwl}{T}$$

The length, beam and draught can all be paired and converted into ratios. The length-beam ratio is a simple measure of the fineness of the boat. A slim boat will have a high L:B ratio, while a plump bulk carrier will have a much lower number. A high number indicates a boat with large directional stability, hence being more difficult to manoeuvre. A high length-draught ratio will oppositely show good manoeuvrability, as the draft is relatively shallow (McGrail 1978: 97).

Waterplane coefficient

$$C_{WP} = \frac{A_W}{L_{WL} \times B_{WL}}$$

The waterplane coefficient (C_{WP}) is the ratio between the waterplane area and the product of the length (L_{WL}) and beam (B_{WL}) at the waterline. The waterplane area is defined as the contour of the waterline. The length between perpendiculars is the distance from the stem to sternpost measured at the waterline. The value obtained from the equation reflects upon the displacement. Beamier hulls like cargo vessels (Kyreneia shipwreck) give a higher C_{WP} result, while boats with narrower beam such as warships (trireme) will tend to give a lower C_{WP}.

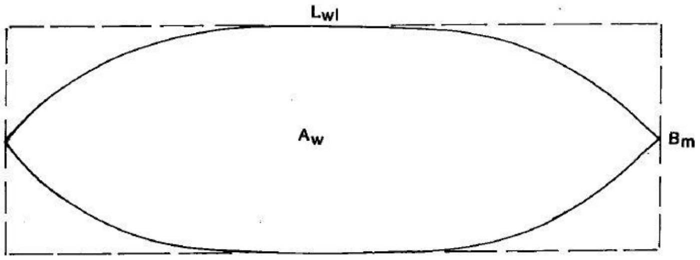

Figure 9. Waterplane area, enclosed within a rectangle (from Steffy 1994: 255).

Block coefficient

$$C_B = \frac{\nabla}{L_{WL} \times B_{WL} \times T}$$

The block coefficient (C_B) is the displacement volume (∇) divided by the product of the length at waterline (L_{WL}), beam (B_{WL}) and draft (T). Steffy defines this as the "*relationship between the displacement volume of a hull and that of a block whose volume is the product of the draft*" (1994: 254). Once again it gives us results related to displacement.

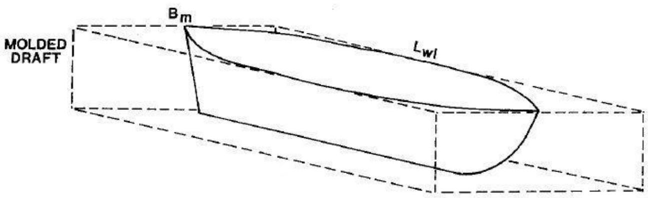

Figure 10. Block coefficient (from Steffy 1994: 255).

Midship coefficient

$$C_M = \frac{A_M}{B \times T}$$

The midship coefficient (C_M) divides the crossectional area (A_M) of the hull by the product of the beam (B) and the draft (T). Similarly it is related to displacement; a boxy cargo vessel will give a higher C_M compared to a sailing vessel.

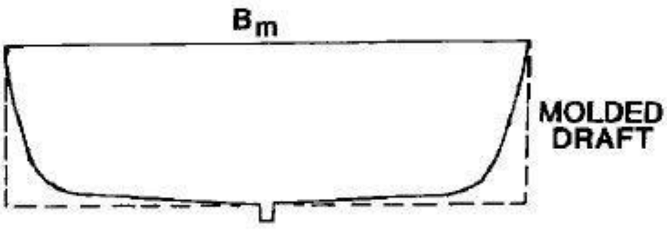

Figure 11. Midship coefficient (from Steffy 1994: 255).

Prismatic coefficient

$$C_P = \frac{\nabla}{L_{WL} \times A_M}$$

Prismatic coefficient is the displacement volume (∇) divided by the product of the waterline length (L_{WL}) and the crossectional area (A_M). In this case instead of using a block to visualise the result of the coefficient, we use a prism shape. This result also provides us with a displacement value but can also be related to the speed capabilities of the boat. If the prismatic value is high, our boat is less hydrodynamic thus its speed capability is limited (Roberts 1997: 78).

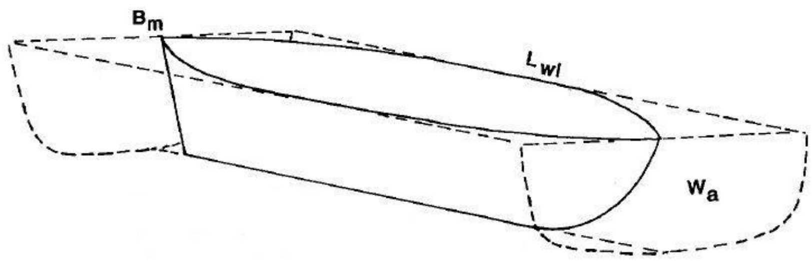

Figure 12. Prismatic coefficient (from Steffy 1994: 255).

Hull speed

A theoretical maximum speed can be calculated for a displacement hull. This is based on the fact that the boat will create waves around the bow and stern while moving, creating a trough at the middle. At the maximum speed, it will drag itself down into the trough it is creating thereby increasing resistance. In fact this speed is not an exact value. Traditionally the formula is given with lengths measured in feet. In metric units it converts to:

$$S_{MAX} = 2.42\sqrt{L_{WL}}$$

Displacement/Length ratio

Unlike the other coefficients, the Displacement/length ratio is not dimensionless: It cannot be calculated by any coherent set of units, and then give the same result if calculated by another. Traditionally, the ratio is calculated as:

$$\Delta / L = \frac{\Delta}{(0.01 L_{WL})^3},$$

with the displacement, Δ, measured in long tons (lb/2240) and the length in feet.

For comparability it could be practical to use this definition. However using SI units throughout in this work it also seems most practical to stick to these. An alternative is therefore to calculate the same relation, although in SI units. This is the method used by e.g. McGrail & Corlett (1977), where they define this as the volumetric coefficient, C_V:

$$C_V = \frac{\nabla}{L_{WL}{}^3}$$

In both cases the displacement, as or approximated to a volume, is compared to the volume of a cube formed by the length of the boat. The numbers for the volumetric coefficient comes out small, which is possibly why the reciprocal value is also calculated. It is described in e.g. Larsson & Eliassen, who calls this a more modern version of the coefficient measured in feet (2000: 73):

$$L / \nabla = \frac{L_{WL}}{\nabla^{1/3}}$$

Jensen (1999), also calls this the '*volumetric coefficient'* and the '*coefficient of fineness'*. The first term is also used above, while McGrail (1978) uses the latter expression for the L:B ratio.

These three values convert in a predictable manner, but the actual numbers are not immediately comparable. We have chosen to use the volumetric coefficient here, but it is not of much consequence.

No matter how it is calculated, the ratio is mainly related to resistance, which is proportional to the displacement. The ratio is therefore used to estimate speed potentials of boats. A heavier boat will push more water in front of it, thus creating higher waves and increasing wave resistance (Roberts 1997: 76-77). Larsson & Eliassen (2000: 78) explains how a L/∇ ratio of at least 5.7 is often described as the planing limit for a hull. This would require a light hull, with plenty of power.

They also explain how it is difficult to build standard yacht to values higher than 5.2, as it will cause structural problems. Another use of this ratio is therefore to evaluate the scantlings of the boat. Brewer (1994) made a classification of the type of boat, based on the displacement-length ratio (Table 4).

Boat type	**Δ/L**	**C_V**	**L/∇**
Light racing multihull	40-50	0.0014 - 0.0017	9.0-8.4
Ultra-light ocean racing boat	60-100	0.0020 - 0.0034	7.9-6.7
Very light ocean racing boat	100-150	0.0034 - 0.0051	6.7-5.8
Light ocean racing boat	150-200	0.0051 - 0.0068	5.8-5.3
Light cruising auxiliary boat	200-250	0.0068 - 0.0085	5.3-4.9
Average cruising auxiliary boat	250-300	0.0085 - 0.0102	4.9-4.6
Moderately heavy cruising auxiliary boat	300-350	0.0102 - 0.0119	4.6-4.4
Heavy cruising auxiliary boat	350-400+	0.0119 - 0.0136+	4.4-4.2-

Table 4. Modern boat types classified by the displacement-length ratio as expressed in three different versions of the ratio. Classification by Brewer (1994).

Traditional boats are generally heavier than modern yachts, and this classification may not be very helpful, because it has its specific context; the problem of designing planing racing hulls is generally a modern one.

To add to the confusion there is even a fourth and slightly different version of the Displacement-length ratio. Following the calculation of maximum hull speed, in which the square root of the length is part, it can make sense to express the displacement-length ratio as:

$$\Delta / L = \frac{\Delta}{\sqrt{L_{WL}}}$$

This displacement/length ratio is calculated by dividing the displacement in tons (△) by the square root of the length at waterline (L_{wl}). We have not used this ratio.

According to McGrail (1987: 196ff) other indicators of high speed of a vessel are:

Block coefficient (C_B) < 0.65

Midship coefficient (C_M) < 0.85

Prismatic coefficient (C_P) < 0.75

These values may present a more direct way of assessing the speed potential of the boat.

Roll motion

Radius of gyration

Beyond the simple calculations, the radius of gyration can be considered as the average distance by which weights are distributed around the boat. It is quite literally a weighted average. The radial location of mass matters more to the movements of a boat than mass itself. If one imagines hanging a heavy weight from the top of a mast, it seems obvious that it matters more to roll than if the same weight was placed inside the hull (Marchaj 1986: 129).

The radius of gyration, or gyradius, is normally abbreviated with the letter k or as R_G. We will use the latter term here.

Moment of inertia

The moment of inertia is the measurement of a vessel's resistance to rolling motion. A high number indicates that the boat reacts more slowly to external forces. A ship with a high moment of inertia may not react much to fast moving waves, because the moment this moment induces a time delay of the roll, by which small fast waves may already have passed. (Marchaj 1986: 129).

The moment of inertia is calculated by DelftShip. It is related to the mass (m) and the radius of gyration of the boat:

$$I = m \times R_G{}^2$$

This means that the radius of gyration can also be calculated from data available in DelftShip:

$$R_G = \sqrt{I / m}$$

In practice m is given by $\triangle$, while otherwise the displacement is considered a force in these dynamic calculations, and measured in tonnef or kgf.

Roll period

All boats will have a natural roll period, which is also of importance to the behaviour of the boat in waves. The roll period can be established by experiment on a full scale boat, but we found it unrealistic to get reliable results with our 1:20 scale models. Fortunately, the roll period can also be established by calculation:

$$R_N = 2\pi\sqrt{\frac{I}{GM\Delta}}$$

The roll period is therefore also linked to the mass and moment of inertia, together with the metacentric height, (GM -explained below). This also means that the roll period is linked to the radius of gyration:

$$R_N = 2\pi\sqrt{\frac{R_G{}^2}{gGM}} ,$$

with g again being the acceleration due to gravity (9.81 m/s^2). (Marchaj 1986: 127ff).

Stability

With the introduction of some of the basic variables in roll motion, we have already moved into the question of stability. The movements of a boat in the water can happen *along* or *around* three axes (x, y, z), and is therefore a system with six degrees of freedom (Figure 13).

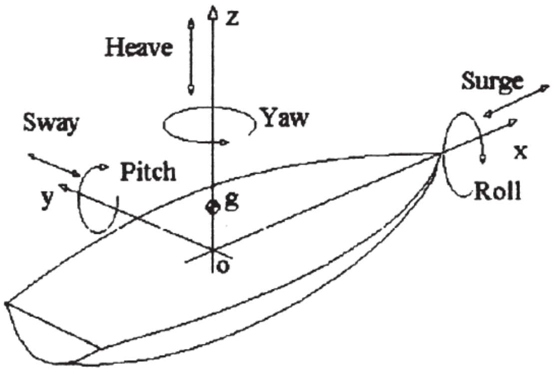

Figure 13. The boat axes and modes of motion (from Neves et al. 1999: 1392)

Around the x-axis the boat can *roll* (or heel), while movements along the axis, other than the steady forward motion, is called *surge*. Around the y-axis the boat will *pitch*, while it will *sway* along it. Finally the boat can *yaw* around the z-axis, and *heave* along it. Movements are normally assumed to take place around the centre of gravity, G, of the boat.

Six different simultaneous movements are complicated to simulate, and in estimations of stability it is normal to isolate one or a few components, making the calculations much simpler. The three movements most important to the stability of the vessel, as well as the comfort of the crew are roll, pitch and heave. (Marchaj 1986: 66ff).

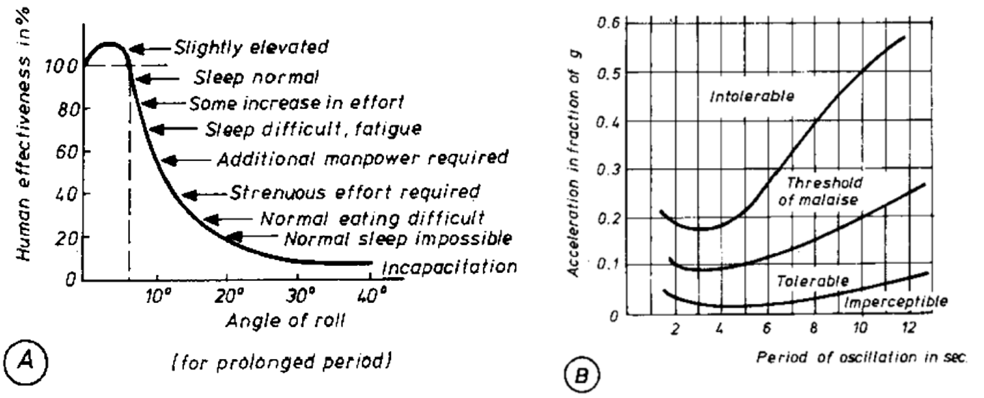

Figure 14. The effect of rolling and accelaration on crew performance and comfort (from Marchaj 1986: 75).

Looking at the effect of roll on the crew (Figure 14A), it seems that a slight motion is actually pleasant and beneficial to crew performance. But at roll angles above 6°, there is a rapid decrease in crew efficiency, and beyond 10°, the crew will have difficulties in performing normal functions including sleeping and eating.

In a small boat, where one sits in the centre, the acceleration forces of roll will normally be relatively limited, ever depending on the wave pattern, but heaving and pitching can become very bad. Motion sickness is individual, but in general heavy motion with a short period of 2-5 seconds can quickly become intolerable (Figure 14B)

Pitching acceleration, a_P, can be estimated by (Marchaj 1986; 77):

$$a_P = \left(\frac{2\pi}{T_P}\right)^2 r\phi \text{, m/s}^2$$

, where:

T_P is the period of pitching in seconds,

r is the distance from the pitching axis, and

ϕ is the angle of pitch in radians ($^\circ \times \pi/180$), measured from the horizontal.

The acceleration can be expressed relative to the gravity acceleration, g = 9.81 m/s^2, as is done on Figure 14B. This means that from our model tests we can relate the measured pitch to this graph. This is best done at a predefined place in the boat, for instance at the bow.

Stability is the ability of the vessel to return to its upright position from these movements around the three axes. The movements are normally induced by wind and waves, but in fact the initial calculation of stability presupposes a calm sea. These initial calculations form the core, and mostly the only part of stability calculations for boats and ships. As may be realized from the above, the actual stability of the vessel is a much more complicated affair, both in reality and in the computational approximations hereof. What we aim to do in this section is to give a basic description of the forces involved, and then find valid criteria to describe the stability of our boats.

Initial Stability

The stability of a vessel in rest in based on a balance of forces. Gravity pulls the boat downwards, while buoyancy pushes it up in accordance with *Archimedes' Principle*. This means that the upward push is equal to the weight of the water which the underwater part of the hull displaces. At a given waterline, the mass of the boat (or its 'weight' in everyday language) will equal the mass of the water that is displaced by the hull. Archimedes' Principle is why a 32 pdr cannon ball cannot float on the water, while a 30,000 tons heavy battleship can.

While these forces work all over the hull, they can conveniently be described as working through their geometrical centres, called the *centre of gravity* for the boat, and the *centre of buoyancy* for the hole it has created in the water. These centres are normally characterized by the letters G and B. Measured as a distance from top of the keel they may also be called KG and KB.

When the boat is at rest in the water the centres of gravity and buoyancy are placed directly over each other, creating a state of equilibrium. When the boat is inclined, the geometry of the underwater part of the hull changes, and centre of buoyancy is shifted in the direction of the heel (Figure 15). This means that the upward push of buoyancy is no longer vertically aligned with the centre of gravity. The difference creates a moment which tends to push the boat back into the upright position.

The strength of this moment can be described by the horizontal distance between the two centres. This is called the *righting arm*, normally abbreviated GZ. Multiplying GZ by the displacement of the vessel, we get the entire *righting moment*. As can be seen from the figure the righting moment will increase with larger angles of heel, but only at small angles of heel. When the vessels heels strongly the geometry changes substantially, and the boat's ability to right itself will decrease and eventually be lost, so that the boat capsize.

Another way of describing the righting moment is to measure the height at which the upright and inclined buoyancy force meet. This is called the metacentre, or M. It is easy to see (Figure 15), that a higher position of M compared to G would produce a longer righting arm, and therefore a stronger righting moment. The distance between G and M is called the metacentric height, or GM.

This is why modern rules define a minimum GM, typically of 0.35 m. The metacentre must be placed above the centre of gravity; otherwise the boat will be unstable and capsize. If M is placed directly on G, then the stability will be neutral, and the boat will not react to an outside force by further movements (Rawson & Tupper 2001: 93ff).

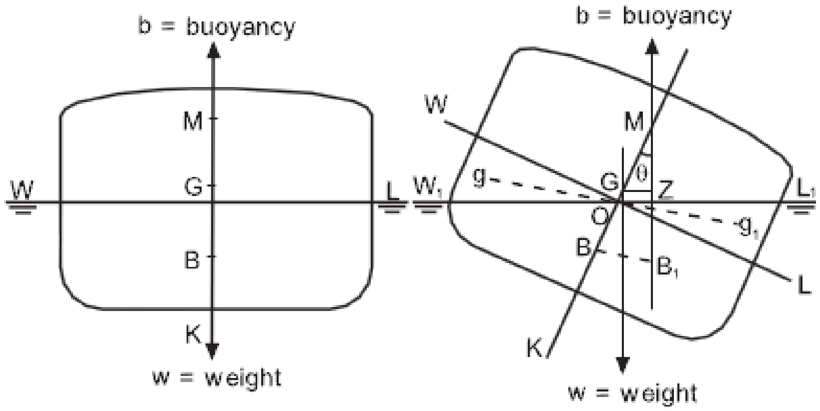

Figure 15. Stable equilibrium (from Derrett & Barrass 2001: 44).

Since the angle of heel (θ) is the same as the angle at M, the righting arm can be calculated by:

$GZ = GM \times \sin(\theta)$

For small angles of heel, up to 10 or 15º, the metacentre can be considered fixed for all practical purposes. Given more heel, the metacentre changes its position too much for this to be true.

The initial position of the metacentre is obviously an important factor in stability, and we will use it in our analysis of the boats.

Complete stability

If the vessel heels more than a small amount, then the geometry changes too much for the initial metacentric height to be useful. Calculating the righting moment at large angles of heel is much more complicated, and several methods have been devised for calculating the geometric properties of a hull to calculate the righting moment through all degrees of heel (Rawson & Tupper 2001: 104ff). In the age of computers these problems are lessened much.

The importance of calculating the righting moments for a broad range of heeling angles was first illustrated with the capsize of the HMS Captain in 1870. The methods to calculate so were only just being developed by this time.

The HMS Captain was the brainchild of Captain Coles, who had developed a rotating turret for heavy guns. At this time warships still had their main armament along the broadsides. With the introduction of armour in a decade earlier, heavier guns were needed, but the position of the guns restricted their weight. Coles came up with the solution of housing the guns in rotating turrets, placed along the centreline of the ships.

After experiments, and after the experience with the American USS Monitor, the Admiralty decided to build the HMS Monarch with turrets. The ship was given a moderate freeboard and good sea keeping qualities. It was completed in 1869. Coles however wanted a lower freeboard, and launched a political campaign to get the Admiralty to make a ship after his ideas. It was only through a political decision that in 1866, Coles was finally allowed to design the ship. The ship was commissioned in 1870. A few months later it capsized and sank in a gale off the Spanish coast, taking with it almost its entire crew, including Captain Coles himself, who was on board to observe the ship. (Brown 2006: 55f).

The MHS Monarch continues to serve a long career, only being broken up in 1905. These two contemporary ships had roughly the same dimensions and displacement, they were both turreted armoured warships. The visible difference was in the lower freeboard of Coles' design. But how could it be explained that the one ship capsized during its first storm, while the other served on for years, and through several gales?

The answer was found in the righting moment (Figure 16). By drawing curves of static stability of the two ships, it became clear just how insufficient the stability of the HMS Captain was (Attwood 1922: 176ff). It had its maximum righting moment -the *angle of maximum stability* (AMS) – at a heel of only 21º, while the Monarch would continue to increase her righting moment to 42º.

The *angle of vanishing stability* (AVS), where the ship is no longer able to right itself, was a mere 54½º for the Captain, while the Monarch would continue to 69½º.

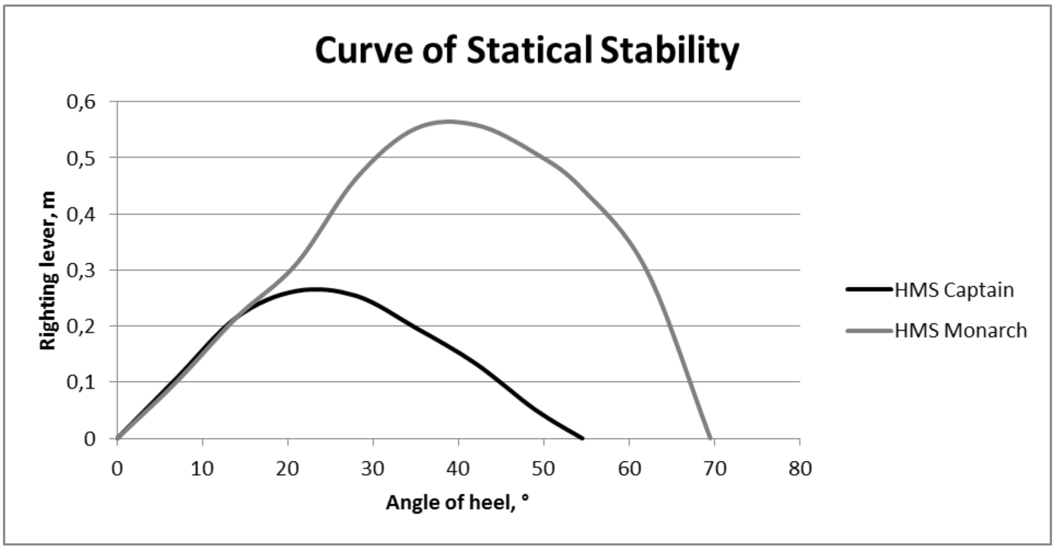

Figure 16. Curves of static stability for the HMS Captain and the HMS Monarch. (Data from Attwood 1922).

When these calculations were done for the Captain, it was only ever the second time they had been done at all (Brown 2006: 57). But the comparison between the two warships defined the importance of calculating stability curves, and methods were gradually developed to facilitate such calculations.

They are still an important part of the assessment of the stability of boats and ships. If the boat does not have the ability to right itself across a range of stability conditions, it should not be allowed at sea. HMS Captain was the tragic event to trigger this understanding, and in that sense has the same importance as the Titanic to the modern development of safety rules for ships.

Unfortunately these curves are not very meaningful for open boats. If the boat heels beyond the *downflooding angle*, where water can enter over the gunwale, the conditions of stability changes altogether, therefore these curves of static stability are quite theoretical for these boats. One will also notice how such curves are never required for open boats under modern rules. We will actually show then anyway as part of the discussion in chapter 10, as they do illustrate some important points about different hull forms.

Dynamic stability

The ocean is not exactly a calm place. So while the calculations of stability are normally done assuming a still surface, with focus on the transverse stability, this has actually got very little to do with the dynamics of an actual boat as it moves through the water. Calculating the movements of the ship in actual circumstances of the sea is very complicated and by necessity the problem had to be ignored. With increasing power and availability of computers this is less of a problem today, although the calculations are still very complicated. Even so there will always be simplifications and the outcome of such an analysis depends largely on the assumptions behind the dynamic model (McTaggert 1999).

These calculations are done in a time-domain, recalculating the position of the ship in short time steps. This means that unlike the static calculations, these systems have memory, registering where the ship was just before. A wave may therefore affect the boat at a time when it is already heeled over, adding to an existing heel rather than the upright. Broaching and slamming may also be modelled with these techniques (e.g. Bassler et al. 2007).

As this is all very complicated, we have not pursued the calculations of dynamic stability any further, but have preferred to do actual tests on the water with our boat models.

Other stability criteria

There are other ways of expressing stability than through calculations of moments and angles, of which a few examples may be illustrative.

Dynamic analysis involved a time domain, and would mostly entail stochastic modelling of dynamic wave spectra. As such there is not one result, but instead a range of outcomes, resulting from several model runs. Capsize is therefore expressed as a probability rather than a discrete event. Probabilities can then also be expressed as a function of longer time periods, for instance a year or the duration of a journey. In an analysis of power boats used for passenger transport in the Bunny River estuary in Nigeria, K.D.H. Bob-Manuel (2002) used this approach to evaluate the risk of capsize. Following logically from the setup, where capsize risk was evaluated on a yearly basis, one recommendation to reduce the capsize risk was to reduce the number of travels during a year.

It makes sense, though, to look at the use life of the boat. Some of them would not necessarily have sailed during 'winter' conditions – winter here used as a term for the part of year with adverse weather, even in parts of the earth where winter as such does not occur.

In an entirely different approach, we have already mentioned the Dellenbaugh angle, which is a simple method for assessing the stability of a sail boat. The Dellenbaugh angle is the approximate angle that a sailboat will heel in a breeze of 8 m/s (Larsson & Eliasson 2001: 52). The angle is calculated for a triangular sail as:

$$Dellenbaugh = 279\frac{A_S HA}{\Delta GM}$$

, where:

- A_S is the sail area in m^2
- HA is the heeling arm, defined as the distance between the CE of the sail and the CE of underwater part of the hull (normally just half draught)
- Δ is displacement in kg
- GM is the metacentric height.

Later derivates from this equation substitute the sail area and CE with the exposed area of the ship itself and its centre. In our case, these areas are mostly so small that the calculation will come out with very small values. It is not wind heel that is the largest problem for these vessels.

In modern times simplified criteria have also been developed, apart from those already formulated into rules, as presented above. In an attempt to find an alternative to the increasingly complex dynamic models, a project was formulated to find simple stability criteria for the assessment of small fishing vessels of Britain (Deakin 2010). Based on empirical and theoretical considerations, a critical wave height was based on the range on stability and the beam of the vessel:

$$h_{critical} = \frac{Range\sqrt{M_{MAX}}}{10B}$$

, where:

Range is the Range of stability (between 0 and AVS)

M_{MAX} is the maximum righting arm

B is the Beam of the vessel

As part of the same study, a simple critical significant wave height was developed on the basis of the IMO rules:

$$h_{s,critical} = \sqrt{1+0.4LOA}-1$$

While such criteria may apply to a fleet of modern vessels, we cannot use them in our situation where the boats differ from modern building traditions. Otherwise they make a tempting shortcut to something that is otherwise quite complicated to derive. It would be useful to have something similar for ancient boats, but the variation in forms generally defies simplification.

Stability criteria used

Centres

From all of this, how do we assess the stability of our seven boats? The estimation of initial stability gives information to understand the reliability of the boat in motionless water and the results could be used as parameter of comparison with other boats.

This means that we have to estimate the initial height of the centers of buoyancy (KB), gravity (KG), the metacenter (KM), and the metacentric height (GM). While DelftShip will provide this data, there is the challenge that we have not modeled the entire vessel nor the crew in DelftShip. This will change the centre of gravity and therefore also GM, and therefore adjustments have to be made to the numbers given by the software.

The weight of the hull, crew and cargo must all add up to the displacement at the chosen draught. A reasonable guesstimate for a crew weight is 60 kg. This is based on a ‘normal’ Body Mass Index, BMI, as recommended by WHO, and an average height of 1.70 m (*cf*. Ejstrud & Maarleveld (eds.) 2012). McGrail (1978) used the same weight in his calculations on British logboats, although estimating slightly lower heights of 1.65 m. The difference in height for the same weight covers, that while McGrail assumes that this is the total weight of the person including an oar or paddle, the Vaaler Moor project assumed this to be the naked body weight. For Vaaler Moor data for the Northern European Iron Age population was used. Covering a wider geographical and chronological frame in the current project we will go with the weight assumptions of McGrail.

Crews sitting are assumed to have their centre of gravity 30 cm above the thwart, and 110 cm above deck when standing (*cf*. Hocker & Fenger 2003; McGrail 1978). Any cargo is assumed to be stowed low, so that the centre of gravity is set to ¼ the depth of the vessel. This does not go for the Dashur boat which most likely carried a coffin on deck, but then the centres are adjusted. The centre of gravity of the hull itself is given by DelftShip.

Armed with these numbers, and some assumptions about the weight and distribution of cargo and crew, it is possible to estimate the actual position of the centre of buoyancy when the boat was in use. On boats of this size, the crew is such an important factor, that it will always be an estimate.

Downflooding angle

The downflooding angle (θ_f) is defined as the maximum inclination of the vessel until the gunwale reaches the waterline at given draught. The downflooding angle gives the maximum rolling angle of the vessel before starting to take on water, a situation which inevitably leads to a state of danger. To compute the downflooding angle, the following formula is used:

$\theta_f = ARCTAN(F / (B/2))$

, where F is the available freeboard at the given draught and B the maximum beam.

Minimum freeboard

Another parameter of seaworthiness in naval architecture is the minimum freeboard. The minimum freeboard of a vessel is the vertical distance from the gunwale/ flooding entrance to the maximum permissible draught, measured at the middle of the ship's length. The minimum freeboard, as defined by McGrail (1978), is the freeboard which allows the boat to heel 10º without downflooding. Modern rules have other definitions, as seen in the previous chapter.

In McGrail's definition, the minimum freeboard can be found by :

$F_{min} = B/2 \times TAN(10°)$

, where B again is the maximum beam. It is possible to simplify this calculation by dividing maximum beam by 11.34.

Rolling period

The rolling period is inversely connected to GM. However it has a meaning of its own, as the rolling period affects the seakindliness of the vessel, and hence crew comfort. We therefore consider the roll period, as described above, as part of the stability criteria.

When measured against the maximum beam, this will give us an idea of the tenderness of the vessel. A stiff vessel will have a short rolling period, while a tender, but more pleasantly moving, vessel will have a higher rolling period. Although we have not managed to find a proper reference for it, a '*stability index'* is coming up regularly on several internet forums and yacht designer's webpages, which we have chosen to use:

Stability index = T_R/B

In this index a boat with a value below 1 is considered stiff, while a value above 1.5 is considered tender. Boat designer Richard Gerr (2007) recommends that this value should be between 1.0 and 1.1 for powerboats, so for him a stiff boat is recommendable.

As some modern rules recommend that GM should be more than 10% of the maximum beam, we have also chosen to report the GM-Beam ratio, although this is more or less the reciprocal of the above index.

A weather criteria

The criteria above are all based on initial stability considerations. The values are somewhat theoretical, although based on well-established empiric and theoretical considerations. We also needed a criterion which more directly defined the sea state in which these boats could safely sail. This will give a background for evaluating and understanding the model tests, where we move actual model boats in waves.

As indicated above there are many approaches to modelling the complexities of ship's movements in the water. A simple weather criterion, as the one developed by IMO (2008), or the Dellenbaugh angle from which it traces its history, did not seem satisfactory as they are based on other types of vessels. The IMO rules are for large ships, and when we tested it the values came out wrong for our boats; as the rollling period is estimated in the IMO method, while the Dellenbaugh angle is developed for sail boats. In our case we focus on small boats, and have chosen to focus on hulls and ignore the rig.

With this focus, excitation from waves is possibly more interesting than that of wind. Ignoring rigging, these boats have relatively limited areas exposed to windage. Instead it is the waves which seem most interesting in our case.

Waves

Waves can be described by their length, *λ*, and their height, *h*. The ratio between the two is called the *steepness*. It is the steepness which defines the danger of the wave. Most work has been done on deep water waves, as they are computational simpler, while shallow water waves behave somewhat differently.

Since the ocean is highly irregular, there is not one wave height. Instead the *significant wave height* (h_s) is generally used. That is the height corresponding to the average of the top 1/3 of all wave heights (Rawson & Tupper 2001: 314). With this definition and with a standard assumption on the probability distribution of waves, other heights can be determined (Bretschneider 1964):

- Average wave height, h_μ: 0.64 h_s
- Highest 10% of waves, $h_{0.1}$: 1.27 h_s
- Highest 1% of waves, $h_{0.01}$: 1.64 h_s
- Maximum wave height, h_{max}: 2 h_s

Assuming a simple wave pattern, other parameters of the waves can be calculated from wave length (Table 5).

Wavelength	λ	
Angular velocity	ω	$2\pi g / \lambda$
Wave period	T_W	$2\pi / \omega$
Speed of wave	υ	λ / T_W

Table 5. Wave parametres calculated from wave length (from Rawson & Tupper 2001: 306ff).

The relation between wind and waves was established by Beaufort's well-known scale of sea states, which again assumes an open sea, and time for the waves to build up.

Excitation moment from waves

The next problem was to find the height of the wave that would be dangerous to the boats. Based on Long *et al*. (2010, p. 532), the wave induced excitation moment in regular waves can be approximated by the following equation:

$$M_{Wave} = a_0 \omega_n^2 \pi (h/\lambda) \sin \chi \cos \omega_e \Delta$$

, where:

a_0 is the effective wave slope coefficient, and set to 0.729

ω_n is the initial natural rolling period, which reduces to:

$$\omega_n = \sqrt{\frac{g}{(T_R / 2\pi)^2}} \text{ , } g = 9{,}81 \text{ m/s}^2.$$

h is the wave height

λ is the wave length

χ is the encounter angle between wave and boat (stern is 0°), and

ω_e is the encounter frequency of waves

We have followed this work relatively closely, applying the equation to our boats. In their dynamic analysis, Long *et al.* (2010) used a wave spectrum based on North Atlantic data, and otherwise set the sea conditions to those of the Adriatic Sea. We will not do the dynamic analysis, but simply use this equation to find a marginal dangerous wave height for our boats.

The expression (h/λ) demonstrates that danger cannot be defined by wave height alone. What is important is the steepness of the wave. A 3 m high swell may not affect a boat very much, as the length of swell is normally quite long. But 3 m high waves of much shorter length would spell immediate danger to small boat.

Setting the encounter angle to 90°, with the seas beam on, we can ignore χ (since sin(90°) = 1).

What we have done is to set the wave length, λ, so that wave period T_W matches the rolling period T_R of each boat. Then we found the wave height where the M_{Wave} just exceeded the righting moment of the boat at the downflooding angle.

The critical wave length can be found by:

$$\lambda_{critical} = \frac{T_R^2 g}{2\pi} \qquad , g = 9{,}81 \text{ m/s}^2.$$

When the wave period matches the natural rolling period of the boat, parametric resonance rolling occurs, and the rolling becomes very severe. In practice this does not happen often, as the seas are rarely regular enough to induce this type of rolling, and because it can be mitigated by the vessel changing course. But it is the most dangerous situation to the boat, and therefore worth investigating to define safety conditions.

The righting moment at the downflooding angle can be calculated as: $M = \Delta GM\sin(\theta_f)$. For some of the boats the downflooding angles are slightly higher than the 15° which is normally the limit for using this simple method. But our calculations of the full curves of static stability (chapter 10) showed that there were no practical differences between the two values. As the full curves were not calculated exactly for the downflooding angle value, we therefore found it easier to calculate the moment by the simpler metacentric method.

What we do with this value is to find the critical wave height which will capsize the boat – or at least immerse one gunwale- in a beam sea, and with the worst possible wave length. This is the same assumption that lies behind the IMO weather criterion, although the approach is different. As indicated above it is not a very realistic scenario, because parametric rolling is rare and because the crew can change course to avoid it. What we get from this calculation is then a theoretical value, indicating the most dangerous wave conditions. We can use this value for comparison between the boats.

Since the seas are irregular, not every wave will have to be of the critical height for the sea to be dangerous. The significant wave height is lower than the critical value. Using standard wave height distributions and assuming that only every tenth wave is of the critical height, the significant wave height h_S can be found by:

$h_S = h_{critical}/1.64$

This is set somewhat generously: this safety margin assumes that one wave out of every ten can potentially capsize the boat. But since the scenario is somewhat hypothetical, and would rarely occur in a real world situation, it is a question of the approaching reasonably realistic values for the wave height.

Knowing the significant wave height, one can work back through Beaufort's tables to find a corresponding wind speed and sea state. These numbers are of course only valid in the open sea; in deep water with a relatively free fetch and time for the wind-wave relation to develop. Shallow waters add unnecessary complication, as local conditions of depth, tide and fetch would have to be factored in.

With this method we can therefore find a maximum wave height if the boats were to sail off the immediate beach area.

Model experiments

An alternative to the theoretical calculations of stability and seaworthiness is to sail the ships in practice. For apparent reasons it is not possible to build full-scale replicas of our seven boats, or even one boat, in a project like this. As an alternative we have built the boats in model and then sailed them in waves to see their performance on the water. The models have been scaled at 1:20. Although small, it was chosen as a convenient and realistic format to work with, and is also within the range of modern tank-testing scales.

Working with ships in model is a well-established technique in naval architecture. Although there were previous attempt at towing models, the tank developed by William Froude at Torquay was novel in every respect, and his work laid the theoretical and practical foundations for modern work with ship models (Brown 2006).

We have not had access to advanced test facilities, and so our tests will be less extensive that those performed in a modern tank test facility. The purpose of the model tests is mainly to see the performance of the boats in ‘real’ conditions, leading to a better understanding of the seas they could navigate. By simply seeing the boats on the water we already gain valuable experience. Even among professional maritime archaeologists few will ever have the opportunity to sail actual replicas of all the different boats we work with here. The experience will therefore put the theoretical calculations of naval architecture into a practical context. We aim to understand how such measures can be used in understanding boats, and therefore have to see those boats on the water.

Furthermore, we have developed more formal experiments with the boats. The aim of these experiments, which we describe below, is to get measurable expressions of the sea keeping qualities of the boats.

Similitude

One concern of the model tests is to maintain similitude between the model and the original boat. The relations were developed by Froude in 1874, and this work made tank testing possible. Dimensional similitude is relatively straight forward to achieve, as that is a question of building the model to the correct scaled dimensions, maintaining all angles, while scaling lengths down by a factor of 20. It is important to remember that the scale, 1:L, is measured in one dimension. With two dimensions, as in areas, the scaling effect is $1{:}L^2$. With three dimensions, as in volumes and weights, the scaling effect is $1{:}L^3$.

A half-scale model of a boat with an original crew of eight will therefore not carry four people, but only one. When the length is scaled to 1:2, the volumetric scaling factor is $1{:}2^3$. This has come as a surprise to some: Reporting from a backyard project building a half scale replica of the Hjortspring boat, Bodensteiner mentions that the builders only discovered this effect when sitting in the boat on the first day of launch (Bodensteiner 2000). Reconsidering the matter they still overestimated the capacity, assuming a scaling factor of 4, rather than the actual 8, and put 6 people in the boat where 3 would have been more appropriate. In our case, with a scale of 1:20, the scaling factor for volumes and weights is 1:8000. One gram in the model equals 8 kg in the original.

Variable	Factor	Original/Model
Length	L	20
Area	L^2	400
Volume, weight	L^3	8000
Time, Speed	$\sqrt{L}$	~4.47

Table 6. Scaling factors for similitude at 1:20.

For time and speed measures, the scaling factor is √L. The mechanism behind this relation is why it makes mathematical sense to express the Displacement-length ratio as Δ/√L, as discussed above.

Where we cannot achieve similitude in scale is in the viscosity of the water and air that the boats will be moving in. As traditional is such tests we will just have to assume that that this effect is very limited.

So while our models will be 1/20 in length of the original, their displacement will be 1/8000. They will be sailed at a speed of 1/√20, but since the distances covered are still 1/20, the model boats will sail relatively faster than the original. In other words, obtaining similitude means that the scales change depending on what we measure. Scaling factors for other aspects of the boats vary in other proportions, but will not be used here.

Building the models

The first challenge of doing practical experiments with these boats is to build them as accurately as possible in model. Accuracy could mean many things, though. In this case we are not building display models. Any minor details which could make the model look good on the mantelpiece would not only be superfluous, but would also make the models less sturdy to handle in practice without adding anything to the experiment. We have not built these models to look good. Accuracy in this particular context must focus especially on recreating the outer lines of the hull as closely as possible to the original. With the way we set up our experiments, it is also practical that inside of the hull is done fairly accurately, because hull thickness together with frames and other structures inside the boat will affect the trim and the centre of gravity of the boat. But it is the outer form which is crucial to the experiments.

The other main consideration, apart from form, is weight. If the model is built accurately, both inside and out, and in the correct materials, then we will get an approximation to the original hull weight. The result is never more than an approximation, though. Mainly because the density of wood can vary considerably even within a species, but also because at this scale one would not add for instance iron rivets or bolts. The final weight of the boat in the water is also higher than that of the hull itself, so it is not important to hit an exact value, as weight will be added anyway. In modern tank testing the hull would often be carved out of a large block of laminated wood, with the inside cavity only shaped enough to hold the necessary equipment for the test. The “displacement” is then controlled by the towing rig. Our test setup is somewhat simpler, and our models will therefore have to be built so that they can function on the water on their own device.

How the models were built in practice varied according to the boats and their construction, as well as the information available to us. In some instances the planks were already developed and published, and could be used directly to build from, after scaling to 1:20. In other cases the planks were developed in DelftShip. Any overlap of strakes was not modelled in DelftShip and had to be added. Where it was not possible to use DelftShip other methods had to be used. Fortunately there is a large body of literature for model builders, and otherwise it was all a question of employing general craftsmanship to the problem.

To test the setup, all models were built in cardboard before any wood was cut. This proved to be a good investment, as many smaller adjustments were often necessary to put the boats together.

Crew and cargo

Unlike those building half-scale models, we will -at least- not have to worry about the effect of putting full-scale people in our model boats. But with boats of the size we are dealing with in this project, the crew is an important part of the sailing properties of the vessel, and a ‘crew’ must be added.

The crew influence the centre of gravity strongly on a small boat, and their weights must be added at the correct height. But there is also an important effect of the crew’s movements in the boat. When a boat heels, the crew will almost invariable lean in the opposite direction to counteract this movement.

This ensures that the centre of gravity stays closer to the centre of the boat, thereby maintaining the righting moment.

We found a simple solution to mimic this effect. Large washers with a weight of 7 g (equal to 56 kg) were suspended on pieces of copper wire placed as thwarts. Being secured in place by a notch in the insulation around the cobber wire, the washers were free to pivot around a horizontal axis, leaving gravity to keep them upright, even when the boat model heeled. This system seemed to work well. It did not allow for correction of the crew position with pitching, but this movement is much less critical to the stability of the boat than heeling. The weight of the washers was enough to keep them upright in a heel. The total weight of the system would obviously depend on the beam of the boat, as the lengths of wire were suspended across the boat, but in general we approached values close to an actual crew weight.

The hull and the crew make the basic weight of the model. To this comes the weight of any gear or cargo. As discussed above there is no simple or single solution to the question of loads and 'design' waterlines. Generally we have decided on a draught of 60% of the depth of the hull. Common sense dictates that any extra weight should be put as low as possible in the boat. The material used is of limited consequence to the experiment, although it is important to place it so that a good trim of the boat is maintained.

Indoor tests

Apart from towing the boats in waves, we also did two simple stability tests of the boats. Inspired by modern safety rules we did a heeling test, where the assumed crew and load of the vessel was shifted towards one gunwale, in a distance of 1 cm from it (20 cm in real scale, half the width of a seat). After heeling the boat we could measure the remaining freeboard.

To get an impression of the relative impact of any water shipped into the boats during the towing tests, we also filled them gradually with weight until they sank. This gave the maximum (or marginal) carrying capacity of the boat. This number is normally smaller than the maximum displacement calculated just below the gunwale. Without any flotation devises added, swamping would be a problem for these boats.

A poor man's tank test

While tank testing is a well-established practice in naval engineering, such facilities operate in a large commercial market, and therefore rarely accessible within the normal budgets of maritime archaeology. Models of the Oseberg ship were tested in such facilities, yielding important results (Bischoff 2010). Actual tank testing has not been possible here, and we therefore had to develop a set of tests which were more within the realms of the realistic.

Test area and setup

The models were tested in a lake in a nearby public park. While there are several such lakes in the vicinity of Campus, this particular one was chosen for being on a sheltered location where interference from wind-generated waved was limited. In the initial design it was considered to let the waves be generated naturally, varying the wave height by choosing lakes with varying degrees of shelter, and days with different wind conditions. Reconsidering the matter we felt it best to generate the waves ourselves, as this would make for more comparable conditions between the tests.

For laboratory wave studies, two main types of wave makers are generally used. The first type is a horizontal generator, including piston and paddle-type wave-makers, which produce waves by a simple oscillatory motion in the direction of the wave propagation. The second is the plunger–type wave maker, which consists of a solid that generates waves by an oscillating vertical movement in the surface of water, displacing fluid which forces the wave motion.

For the aim of the model tests, a plunger-type wave-maker with a cylindrical section was put together. The reasons for this choice are mainly of practical nature, like the simplicity of building, the minimum effort required for the oscillating vertical movement and a better control in the waves frequency/height.

Furthermore, the plunger-type has the advantage of giving regularity and uniformity in the shape of the generated waves, at distance from the generator and it results more efficient for deep water (Hughes 1993: 365) even if the theoretical calculations for its configuration are difficult and often executed empirically (Hughes 1993: 364).

Having also considered and tried varying the direction of the wave, we decided on keeping the wave maker in a fixed position, letting the waves meet the boat on the starboard bow. The variation of heel and pitch with other directions is a simple sinusoidal function, and would not add much to the project. That is when we ignore the effects of following waves and possible broaching. We consider the situation where the waves come in at some angle from the direction of the boat.

To document the boat's movement across the water, a vertical frame with a 10 cm grid marked on it was put in the water parallel to the sailing direction. To minimize the interference with the waves, the grid was made using nylon string in bright colours. The motion of the boat was captured with two video cameras. The first was placed perpendicular to the frame to capture pitch. The second camera was placed aiming along the towing line, and could capture heel. Due to the risk of capsize it was not feasible to place cameras or any other sensors inside these relatively small model boats.

After some trial runs the setup was standardized with fixed positions for each member of the team. This allowed for relatively standardized tests.

Figure 17. The test setup. The boat was towed between the two persons at the start point and camera 2 (Photo: Bo Ejstrud).

Speed and towing

The boats were towed across the water so propulsion itself is not a variable. Towed speed should not exceed the hull speed of the vessel. The risk of capsizing in waves generally increase with the speed of the vessel. Speed is therefore a variable in assessing seaworthiness although it is obviously linked to crew actions more than to hull form. To facilitate the comparison between the different boats, we aimed for maintaining a relatively regular speed.

Coming across the term of semi-planing hulls, we also made one very fast run with each boat. This was done to check how it reacted to speeds above the nominal hull speed. A normal 'displacement' type would dip the stern into the water letting water in by the rear, while a semi-planing vessel is able to generate some lift at speeds of 1.5-2 times the hull speed. This may happen with even in a traditional sail boat, or at least the purpose was to check for it. Planing hulls as such is a more recent invention.

Several setups for the towing rig were considered. A remotely controlled speed boat model could tow the vessels, but earlier tests showed that it was difficult to control in terms of speed and turning radius. The towing gear was therefore a fishing rod with a wheel with a gear ratio of 5:1. With the models connected to a line on land, we also minimized the risk of losing them, in spite of any capsize. Relatively regular speeds could be maintained with this rig, when worked together with a metronome and control of the reel diameter, although we did not achieve absolute uniformity and in general moved the boats slightly faster than planned.

Formal experiments

While towing the boats would give an immediate visual impression of their behaviour on the water, we also devised more formal tests. Each boat was towed three times across the water in different waves. For each test run we analysed the resulting videos frame by frame to deduct towed speed, wave height, wave period, and angles of heel and pitch of the boat. The measurements are given as averages, ideally of at least five waves, but in practice sometimes fewer. The recorded videos did not always show sufficiently parts of the run to yield more than a few measurements.

Another measure is to look at how wet the boat will be. An open boat may take in some water without actually capsizing. Any water shipped was therefore weighed after each run. This gave an indication of the sea keeping qualities of the boat. The result is best given in % of the maximum carrying capacity of the boat, as established above, where capsize is then 100%.

Simulated weather conditions

There is obviously no way to control the weather in an outdoor test environment, especially with the time frame of one semester given for the project. But choosing a sheltered location we minimized the impact of natural weather conditions, and instead were free to simulate our own.

The purpose of these tests was to see and compare the boats on the water. This means they are not necessarily subjected to 'realistic' waves according to the waters where they originally sailed. What was important for the comparison was that the different boats were subjected to identical, or at least similar, wave patterns.

Although it would generally be preferable to sail out in fair weather, our tests would aim for the marginal conditions of rough seas. All boats can sail straight on a flat surface. The interesting thing to examine is the performance of the boat in high and steep waves.

Although we used a mechanical wave maker, the natural environment therefore had to be considered, at least in general terms. A boat working just off the coast should be at least able to work in a moderate breeze (Beaufort 4) with 1 meter high waves. As described above, the modern C-classification of an "inshore boat" allows them to sail in a fresh breeze (Beaufort 5) with 2 m high waves at the open sea. Not all boats with a C-classification would in practice agree well with waves this high. During the sea trials of the Hjortspring replica *Tilia Alise* the crew found their maximum wave height around 1 m (Vinner 2003). This height is obviously also negotiated by wave length, which in the inner Danish waters, where *Tilia Alsie* sails, generally means relatively short, steep waves.

It would be reasonable to assume that any vessel going out to sea, even if always a 'safe' distance to shore, should be able to navigate 1 m high waves.

At Beaufort 4-5, breaking waves is not normally a problem at the open seas. But since these are mainly inshore vessels, breaking seas is an issue when the boats get near the coastline or in conditions with strong current, like tides or estuaries. Especially when approaching a beach the size of the breaking waves are easy to underestimate from the water. With the chosen setup this effect was difficult to simulate in a controlled fashion, though.

Sails

Although some of these boats would carry sails and it formed an important systemic part, we have not made any tests of them. This may be a natural choice for archaeologist, as we rarely have access to information on the rig. Our interest in this project therefore lay in the hulls.

Final remarks

The following seven chapters will use the methods and calculations presented in this chapter. In many respects it is an extensive programme we have laid out for a short project such as this. But much is done more or less automatically once the boats have been modelled in 3D in DelftShip or Rhino. Therefore it is not an impossible task to do a thorough analysis of a boat within a limited timeframe. The set of parameters will be examined for each individual boat in the following seven chapters. Chapter 10 is then written as a comparative analysis of the boats, where we can summarize the work across different hull forms and sizes.

3. VAALER MOOR

Introduction

The logboat from Vaaler Moor has been reanalysed and published recently (Ejstrud & Maarleveld (eds.) 2012). It is as more than 12 m long expanded logboat, which is today on display at the *Landesmuseum Schloss Gottorf* in Schleswig, North Germany. The boat has already been mentioned several times in the previous sections of this book, as it was the basis of previous work and in many ways inspired the current project.

The boat is exceptional, but what makes it even more interesting is that it is not unique. In the same area another three contemporary and large logboats have been found. Unfortunately none of these are preserved today. The most notable is the boat from Lecker Au, which -apart from being slightly longer- is an almost direct parallel to the Vaaler Moor boat. When found it was very well preserved, but is almost gone today. Other likely parallels include finds at Ritsch and Gotteskoog, and possibly the damaged Egernsund boat (Crumlin-Pedersen 1981) on the opposite site of the Jutland peninsula. A boat from Haale is much smaller, but technically similar. (Hirte 1989).

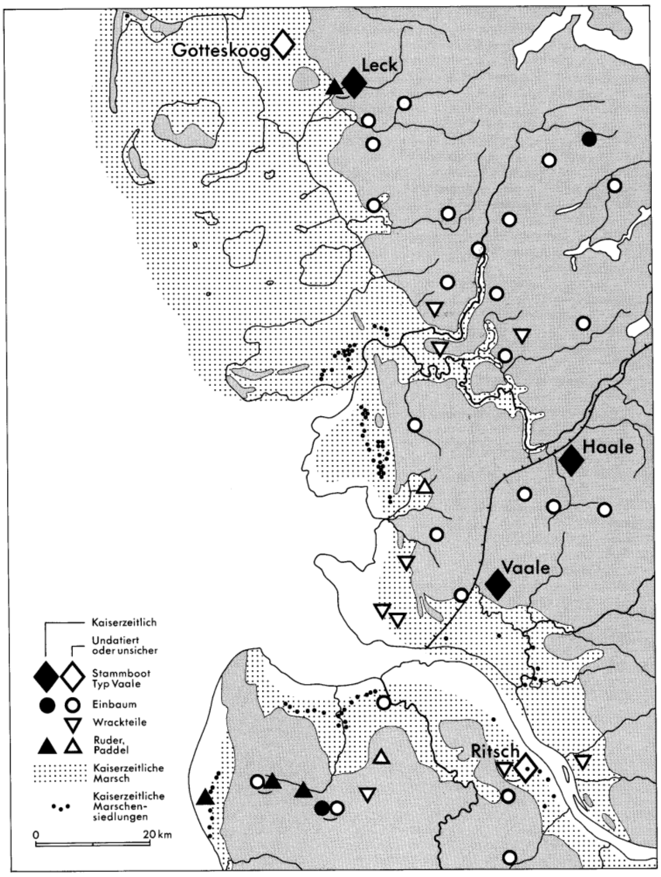

Figure 18. Logboats finds on the Wadden Sea coast of Schleswig-Holstein, North Germany. The finds mentioned in the text are those marked with a large signature (from Hirte 1989: 126).

Where the boats are scientifically dated, they belong to the Roman Iron Age. It seems that for some reason a group of very large logboats (10+ meters) were built and used in the northern Wadden Sea during the first centuries CE. The Wadden Sea is otherwise not an easy place to navigate with a strong tidal current, relatively constant wind, low water levels, and the choppy seas that result from these conditions. As already explained in the introduction to this work, this group of boats is something of an enigma. The Maritime Archaeology Programme in Esbjerg is situated along the same Wadden Sea coast, and save some sheltered locations or unusually fair weather, it does not seem very appealing to venture out on these waters in boats of this type. The boats of the Vaaler Moor group make an interesting problem.

Discovery and excavation

The boat was discovered in 1878 in the Vaaler Moor bog, in Holstein, North Germany. This bog is located in the marshes just north of the river Elbe, some 15-20 km from the mouth of the river. Having been informed about the find by the local dean, archaeologists took the gruelling 5 hour train trip from the museum in Kiel to investigate (Hirte 1989), an 80 km trip by modern roads. During recovery the boat broke in two and it was taken up in pieces, a first attempt to take it up as a whole being abandoned. In situ the boat was measured to a length of 12.29 m, while the sides had collapsed with a width of only 0.8 m. Nine frames were preserved in the boat, with traces of two more. Today the boat has twelve frames, but most likely it is the small frame XII in the stern of the boat has been added during restoration.

Brought to the Museum in Kiel, it was restored using practices we would not consider today, but which were probably state of the art back then. It is inherently difficult to conserve a 12 m long log even today, but where the boat was badly preserved, pieces were sawn off, and new wood was inserted, coloured and textured to resemble the original as closely as possible. It is far from apparent today which parts are original and which are reconstructed.

Description of the boat

Today the boat is preserved to dimensions of 11.87×1.30 m. Correcting for shrinkage by comparing *i.a.* to the shrinkage of the Nydam ship with which the boat is displayed (Gøtche 2000), the original dimensions are estimated to *c.* 12.30 × 1.44 m (Ejstrud & Maarleveld (eds.) 2012).

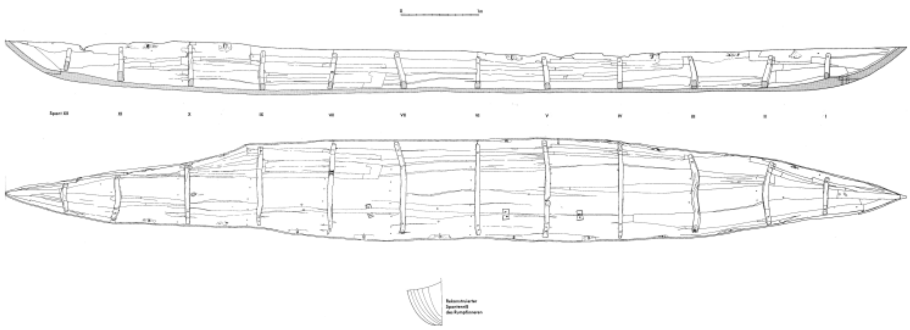

Figure 19. The Vaaler Moor boat in plan and profile (from Hirte 1989: Pl. 1). 1:100.

The eleven frames indicate that this is an expanded logboat. They span over such a width, that even when correcting for distortions of the wood, this can hardly have been the original width of the tree trunk. Expansion would mean that the boat had a rockered bottom, and a pronounced sheer. A sheer of *c.* 10 cm was already built into the shape of the boat (Hirte 1989). A large crack in the bottom of the wood is repaired with two cleats and pairs of holes, in which withies or similar probably tied the crack together. Cracking happens regularly in expanded logboats during the process of expansion.

The boat is double ended, but based on the shape of the frames one end is slightly fuller than the other. The damaging reconstruction that this boat was subject to must be taken into account when assessing the form, but in plan view, the boat seems to have had a slightly lanceolate shape, with the widest part shifted just forward of the middle. We interpret the fuller part as the forward of the boat.

As natural for an expanded logboat, the boat is rounded in section. But towards each end the shape approaches the triangular, and a fin-like protrusion is carved out of the wood in each end, making a rudimentary keel structure, although probably working like the skegs of a sculling boat. While it is impossible to determine the amount of rocker that originally resulted from the expansion, these two skegs turned out to be a help, as it must be assumed that they must have been in the water at normal waterlines. A cardboard model was initially made slightly too narrow and when it was expanded with the frames it therefore almost lifted the ends of the boat to the level of the gunwale amidships (Ejstrud & Maarleveld (eds.) 2012). The reconstruction we propose here is therefore based on a guesstimate of a 'reasonable' amount of lift of the ends, together with the shape of the frames.

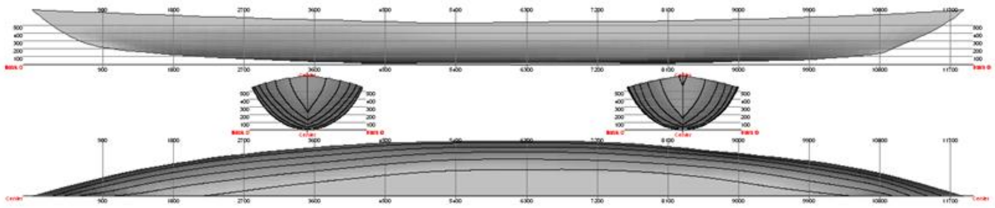

Figure 20. The Vaaler Moor boat reconstructed in DelftShip. 1:100.

Along the gunwales there are opposing pairs of horizontal cleats. They are all pierced with a vertical hole, about 5 cm in diameter. Åkerlund (1963) suggested that these cleats supported thwarts, on which the crew would be seated. We, and others before us (Timmermann 1956; McGrail 1978), find it much more plausible that the thwarts have been supported on the frames, while the cleats would have held a kabe or a thole pin. This means that while Åkerlund saw this as a paddled vessel, we find it more likely that oars were uses. Given that it is correct that the boat has its bow in the fuller end, there is a relatively regular distance between frames and cleats of about 30 cm. This distance is generally recommended today as the optimal distance between seat and oarlock.

Although not entirely preserved, ten pairs of cleats and eleven frames would provide seats, footholds and tholepins for a complement of ten rowers. In the aft end of the boat there are indications of some structure along at least one of the gunwales. What kind of structure is not clear, as only traces of *something* carved is seen along the upper side of the boat. A helmsman could sit here, manning a steering oar or a rudder. This brings the crew up to 11 men.

Environment and cultural background

The boats of the Vaaler Moor group are found along the northern Wadden Sea coast, in Schleswig-Holstein, Germany. A possibly similar boat is found at Egernsund, just north of the Danish-German border, but on the other (eastern) side of the Jutland peninsula, and therefore in very different waters. This boat was cut to pieces by dredging, and all than can be said about it is that it was roughly the same size and time as the Vaaler Moor boats. But other than that no details can be given (Crumlin-Pedersen 1981).

The other boats (Gotteskoog, Lecker Au, Vaaler Moor and Ritsch) are found in the marshlands bordering the North Sea coast. Two (Vaaler Moor and Ritch) are found some 15-20 km up the river Elbe, while the other two are found relatively close together further north in the Wadden Sea marshes, near the Danish-German border. Had it not been for these two boats, and possibly the Egernsund boat, it would have been easy to regard Vaaler Moor boat as a river boat, designed to go up and down the Elbe. The northern boats may have done so too, but it would have required them to cross the Wadden Sea to get to the Elbe. This makes the question of seaworthiness more pressing.

Vaaler Moor is radiocarbon dated to 1790 BP ± 44 (KI-2249; Hirte 1989: 124). Calibrated C^{14} date is 75-320 CE. The boat from Lecker Au has a very similar dating to 1820 ± 55 BP (KI – 2342; Hirte 1989: 120), which calibrates to 125-255 CE. The strongly fragmented boat from Egernsund is dated to 1920 ± 70 BP, calibrated date 1-210 ce (K – 2513; Crumlin-Pedersen 1981: 36). The much smaller but technically similar boat from Haale is dated to 1720 ± 55 BP, calibrated to CE 244-406 (KI-2250, Hirte 1989: 125). There are obvious problems in dating large logboats, because the tree trunk has to be very tall, but for the three German boats at least, the sample was taken from the top of a gunwale.

The dates place these boats firmly into the Roman Iron Age of this area. While the German boats all belong to the marshes on the West coast, and what is later 'North Frisian' territory, the Danish boat from Egernsund illustrates that such large logboats are not just a Wadden Sea phenomena. Although we do not know the exact character of the Egernsund its location is not far from the find spots of either the earlier Hjortspring or the later Nydam boats. This is an area with plenty of indications of boat-faring during the Iron Age. From the Wadden Sea coast the best known larger Iron Age boat is probably the elusive boat from Gredstedbro, which is somewhat later (Crumlin-Pedersen 1968; Ejstrud & Maarleveld (eds.) 2008; Ejstrud 2008).

If the interpretation of the cleats as fasteners for thole pins is correct, then this is among the earliest evidence of rowing in Northern Europe. Westerdahl has discussed the significance of rowing, suggesting that "*the rowing ship as an embodiment and symbol of the smaller units of society"* (Westerdahl 1995). This idea help explain the continuing importance of rowing and the apparently late introduction of sails into Northern European societies.

The interpretation also puts these boats into a certain social and political context, in which areas with a limited political stability would require the following of armed men when engaging in external contacts. In row boats, or paddled boats, the rowers are also warriors, and boats are not made as bulk carriers. Given political instability, the most important -and probably also the most possible- form of trade is the exchange of prestige goods between polities and their leaders.

In such an interpretation, these boats are important tools in the political and social development and interaction of the entire area. Whether used as raiding vessels or in diplomacy they provide the means through which relations across Iron Age societies were established. The larger political units and kingdoms which later grew out of this process could hardly have happened without boats of this kind, although the larger types from Nydam and Gredstedbro may have been even more instrumental in that, somewhat larger, process.

From this theory what we expect are boats with large crews and limited cargo capacity, and that is exactly what we see with all boats known so far from the North European Iron Age, be it Hjortspring, Vaaler Moor or Gredstedbro.

Hydrostatics and performance

The reconstructed dimensions with a length of 12.30 m and a beam of 1.44 m make this is a very slender and in many respects elegant boat.

The original weight of the boat was most likely 1050-1100 kg. With a standard draught of 60% of the depth we have here estimated it to 1096 kg. This means that the boat would carry its own weight at a draught of 24 cm, slightly under half the depth of the hull. Manned with a crew of 11 (each 60 kg), this brings the draught close to the 60% mark which we use here, on a displacement of 1756 kg (Figure 21). The good correspondence between the weight at our estimated crew size and the Grågås ratio seems to confirm the estimate, but also seems to demonstrate the wider applicability of the ratio, which is otherwise from medieval Iceland.

This boat was built to carry a crew and nothing else. The cleats along the side show that a full boat of rowers was envisioned and this leaves room for no cargo. This again corresponds well to the theories presented above.

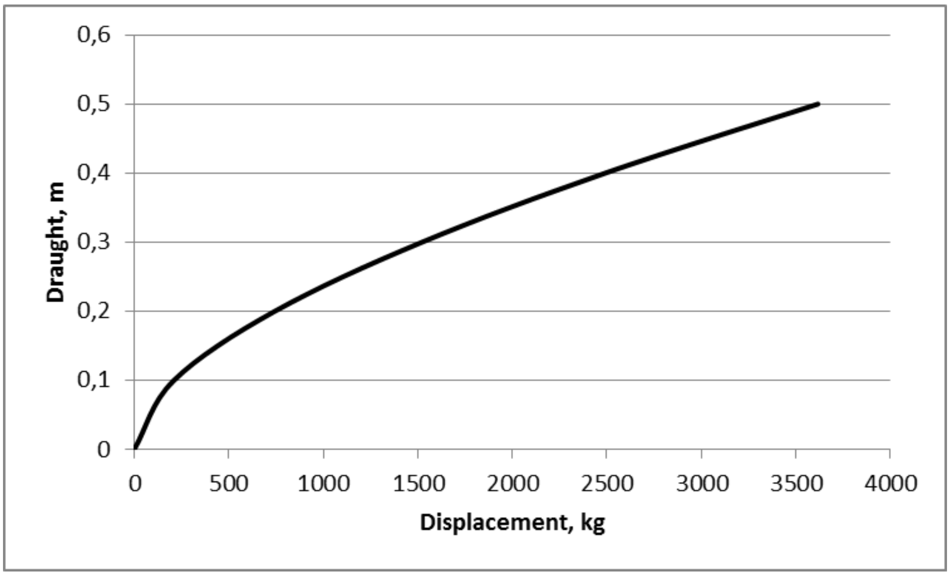

Figure 21. Vaaler Moor, displacement curve. The minimum draught is 24 cm.

With a waterline length of 11.7 m, the maximum hull speed works out at slightly over 8 kts. It seems that this boat should not have difficulties achieving this speed, given a sufficient crew of rowers. According to the criteria given by McGrail & Corlett (1977), the boat would semi-plane at speeds above 2-3 knots. The coefficients of the boat also suggest a very fast boat. Manned with a crew of 11 rowers it should be able to reach high speeds fast.

The lack of a proper keel will possibly make up for the limited manoeuvrability that such a long and slender boat will suffer from, or at least not worsen the matter. On the other hand the limited draught to this length at least improves manoeuvrability. The two fin-like protrusions at each end still indicate that directional stability was desirable, and with them it was probably not a problem. Acting as the skegs on a sculling boat these fins probably give sufficient traction, and without a sail no actual keel is needed.

Stability

With a downflooding angle of 15.2° the Vaaler Moor boat lies within a normal range for an open boat. The minimum freeboard should be 0.13 m at 10° heel, meaning that the maximum safe loss of freeboard is only 6 cm, adding a little over 200 kg to the displacement, increasing the capacity by 11%. The boat has a rolling period of 2.4 seconds, resulting in a Roll period-Beam ratio of 1.6; it is actually not surprising that this is a tender boat.

Centres

The centre of buoyancy was calculated to 0.28 m. With a crew of 11 on board, seated 25 cm above the bottom, the centre of gravity is at 0.38 m. The height of the metacentre is 0.64 m, leaving a metacentric height (GM) of 0.26 m. Although the metacentric height is not large, the metacentre is placed well above the gunwale, and this number is within the realms of modern stability standards. If the crew were to stand in the boat, the GM would drop to 4.9 cm.

In his reconstruction of the boat, Timmermann (1956: 220) arrived at exactly the same height of the centre of buoyancy as we have (0.28 m), although his reconstruction differs from ours.

Vaaler Moor								
Dimensions								
Length overall	L_{OA}	12.30	m		Depth of hull	D	0.52	m
Length at waterline	L_{WL}	11.07	m		'Standard' draught	T	0.33	m
Maximum beam	B	1.44	m		Minimum draught	T_{MIN}	0.24	m
Waterline beam	B_{WL}	1.19	m		Maximum draught	T_{MAX}	0.39	m
Maximum hull speed	S_{MAX}	8.05	kts		Draught-Depth ratio	100 D/T	62.5	%
Volumes, areas and weights								
Displacement, volume	∇	1.713	m^3		Moment of inertia	I	34.478	m^4
Displacement, weight	Δ	1756	kg		Estimated weight of boat		1096	kg
Wetted surface area	A_{WS}	11.15	m^2		Deadweight		660	kg
Waterplane Area	A_{WP}	9.06	m^2		Maximum Deadweight		854	kg
Midship Area	A_M	0.26	m^2		Deadweight to sink		3400	kg
Coefficients and ratios								
Length-beam ratio	L:B	9.3			Block Coefficient	C_B	0.411	
Length-draught ratio	L:T	34.1			Prismatic Coefficient	C_P	0.475	
Beam-draught ratio	B:T	3.7			Waterplane Coefficient	C_{WP}	0.573	
Displacement-length ratio	$L_{WL}/\Delta^{1/3}$	9.3			Midship Coefficient	C_M	0.683	
Stability								
Centres					**Stability Criteria**			
Centre of Bouyancy	KB	0.21	m		Downflooding Angle	θ_f	15.2	°
Centre of Gravity	KG	0.38	m		Minimum Freeboard	F_{MIN}	0.13	m
Metacentre	KM	0.64	m		Freeboard, heeling test		*Capsize*	m
Metacentric height	GM	0.26	m		Rolling period	T_R	2.4	sec
Heeling calculations					**Other criteria**			
Critical wave height	h_{CRIT}	0.51	m		GM-beam ratio	GM/B_{WL}	0.22	
Significant wave height	h_s	0.40	m		Roll Period-Beam ratio	T_R/B_{wl}	1.6	
Approximate wind speed		3.5	m/s		Angle of max. stability	AMS	23	°
Beaufort		3			Angle of vanishing stability	AVS	36	°

Table 7. Summary table for the Vaaler Moor boat.

The metacentric height was calculated to 0.55 m, which is lower than in our reconstruction. This also means that in Timmermann's reconstruction a GM of 5 cm is reached already if the crew sits on thwarts across the gunwale, as proposed by Åkerlund (1963). Placing the thwarts 15 cm down below the gunwale increased the GM to 11.2 cm. A standing crew would create a negative GM of -4.8 cm, i.e. the boat would capsize.

Timmermann’s results are not exactly like ours, as the calculations are made on two different reconstructions. In our calculation, the crew can stand in the boat, if they stand very still, while this would surely lead to capsize in Timmermann’s reconstruction. He used slightly smaller crew sizes from us (10 and 8 compared to our 11), and a weight per crew member of 75 kg to our 60 kg. But assuming a beamier boat (1.44 m compared to 1.30 m), our calculations of GM are consistently about 10 cm higher than those calculated by Timmermann.

Critical wave height

The tenderness of the boat was further illustrated by the theoretical calculations of significant wave height to capsize the boat. Hit beam on the boat would dip its gunwale at a wave height of 0.51 m, in our model equivalent to a significant wave height of 0.40 m. This occurs in the very low end of Beaufort force 3. Although these are theoretical calculations, they still give an indication that this is not a boat that one would bring far out to sea.

Model tests

The Vaaler Moor boat was the first of the eight boats to be tested, and the test setup was not quite in place. Therefore this boat is tested is a different setup than the rest. This boat served as a model to develop the tests, and we subsequently changed the arrangement to improve data capture. The descriptions in chapter 2 are therefore of the final setup, which was used on the following boats.

Building the model

The model of this boat was already made as part of a previous project (Ejstrud & Maarleveld (eds.) 2012). The model was based on a CAD reconstruction of the frames and keel line, which were developed into a solid hull model. Several horizontal sections were cut through this model at regular intervals, and the outline at each section transferred to thin planks of oak, which were cut out and laminated together with epoxy. The model was then sanded down to correct dimensions before frames and cleats were finally installed. As the epoxy tended to shatter under power tools -in spite of the manufacturer’s assurances of the opposite- and in order to get a precise surface, much of the sanding was done by hand. To protect the model it was finally varnished.

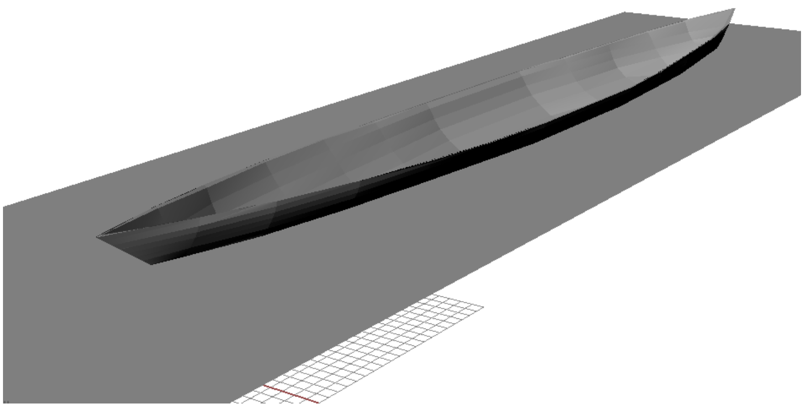

Figure 22. The CAD reconstruction of the Vaaler Moor boat. Screenshot from Rhino3D.

The final model weighed 126 g, equivalent to 1008 kg in full scale. The oak used was well stored and very dry, however, and therefore too light for a boat in the water which would have a higher moisture content. Also some -very small- allowance should also be made for the epoxy glue which typically has a density around 1.5, and therefore weigh twice as much as the oak for the volume. The volume of glue is very small, but not entirely negligible. Both these factors would add to the projected weight of the boat. A reasonable estimate of the boat's original weight would therefore be around 1050-1100 kg. Timmermann (1956) made a 1:10 scale model of the boat, which weighed 1064 g, equivalent to 1064 kg in full scale. To make the weights add up with a crew of 11 and no cargo, the boat is here set to 1096 kg.

Heeling test

The heeling test proved interesting in that the physical model capsized with the entire crew placed along one side. It required three crew members to sit in the centre position for the boat to keep the gunwale just at the water level. The helmsman was placed in the narrow aft of the boat, and could therefore not be moved to either side. This means that a total of four crew members have to stay in the centre line to keep the gunwale just clear of calm water. This is not a very seaworthy boat. Even embarking and disembarking this boat would require an experienced and shipshape crew.

The tests

Six test runs were made, with varying wave heights and periods and with the waves in various directions to the boat. Of these one was without waves, three were with "low" waves and the last two were with "high" waves (about 5 cm).

We did not achieve the planned test speed of 0.58 m/s (5 kts) in any of these tests, but moved the boat slightly too fast. In the last tests we did approach the speed quite well, and nowhere did we exceed the hull speed of the boat.

Test run	Wave height, h_S, m	Wave length, λ, m	Wave direction	Speed of boat, kts
1	-	-	stb. quarter	6.0
2	0.28	9.06	stb. quarter	6.5
3	0.00	0.00	n/a	6.5
4	0.27	16.76	bow	5.7
5	1.09	8.34	bow	5.5
6	1.05	5.93	stb. bow	5.5

Table 8. Overview of the five test runs. All values are converted to full scale from 1:20, using the rules of similitude.

Test run 1

Unfortunately no results came from test run 1. The waves were very low during this first run, the wave maker too far away, and the camera set at too low a zoom level. In combination these factors made any movements of the boat almost indiscernible in the videos. In fact the boat moved steadily across the water, and the bow wave almost seemed higher than our induced waves in this test (Figure 23). These waves had no measurable effect on the boat.

Test run 2

With test run 2 we then proceeded to producing somewhat higher waves (h_s = 1.42 cm) with a relatively short wave length of λ = 45 cm (full scale: h_s = 0.28 m and λ = 9.06 m in). The boat did not keep a straight course towards the grid, but once there it passed close to parallel to the grid.

The boat was towed at 0.75 m/s, or 6.5 knots in full scale, and the waves were on the starboard bow. When passing the grid, the position of the wave maker gave different wave patterns, where the first half of the pass yielded a visible roll, while the boat then settled in the second half of the pass.

The average heel of 7.3° is measured at the first part of the grid, where the boat rolled the most. The maximum pitch was 2° upwards and 1.5° downwards.

Figure 23. Snapshot of video from test run 1. The bow wave seems to be higher than the water waves.

Test run 3

This test run was made as a control with no waves at all. Therefore no pitch or heel is measured, the boat running smoothly across the water. As we did not measure drag or other properties of the hull itself is this project, this test was not informative beyond seeing the boat in calm waters.

Test run 4

This test was made with relatively low and long waves with a significant height of 1.36 cm and a length of 84 cm (0.27 and 16.76 m in full scale). The boat drifted during the start of the run, so that it met the waves at somewhat changing angles, leading to various degrees of pitch and heel. When it passed the grid, the waves were on the bow. Towards the end of the run, the wave pattern changed, also changing the movement of the boat significantly.

The boat was towed at a speed of 0.65 m/s (5.7 kts in real scale). During the main part of the run, the boat moved relatively gently across the waves. Towards the end a shorter, steeper, but not higher wave pattern was encountered, resulting in a short, sharp pitch, which seemed uncomfortable, even when adjusting for scale speeds. We did not register the length and height of the latter wave pattern, which seemed to be a secondary product of the position of the wave maker.

The maximum pitch angle was 1.4° upwards, while the average total movement was 2.3°. The average maximum heel was 6.2°. The heeling angles were measured while the boat was turning into course as it got near the grid and the towing line straightened. This turn gave a good angle for the camera, but the heel is measured slightly earlier than the pitch.

Test run 5

This test was made with high and steep waves coming in from the bow. The waves had a height (h_S) of 5.5 cm and a length of 42 cm (1.09 and 8.34 m in full scale) with some tendency to break.

The boat was towed at a speed of 0.63 m/s (5.5 kts in full scale). While there was visible pitch of the boat, the general impression was that of a relatively gentle movement across the waves, with no serious loss of freeboard. Roll was therefore limited.

The maximum pitch angle was 5.1° upwards, while the average total movement of the stem was 7.7° , equivalent to 17.9°/s from stern to stem (4°/s in full scale). As the waves were met almost bow on, heeling was very limited, and could not be measured on the videos. The wave period in this test was very close to the natural rolling period of the boat, and had we let it meet the waves beam on another result could probably have been expected.

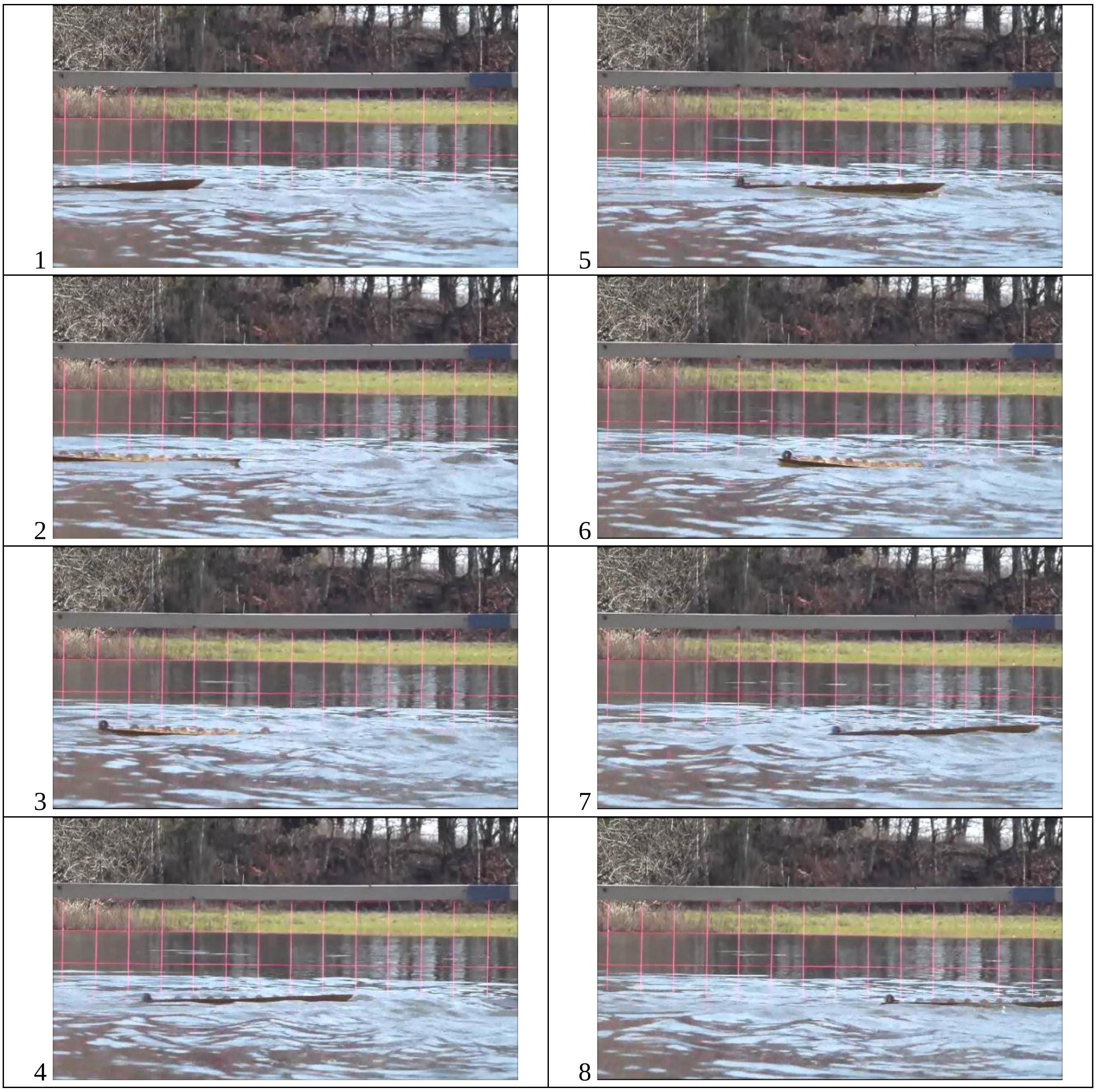

Figure 24. The Vaaler Moor boat in high and steep waves (h_s= 5.3 cm, λ = 30 cm). Snapshots from video of test 6 taken at 1/√20 seconds interval, equivalent to 1 second in full scale.

Test run 6

This test was made with high and steep waves coming in from starboard bow. Although to some extent a repeat of run 5, the waves in this run were even steeper, with a stronger tendency to break, and they met the boat at a different angle. The significant wave height (h_S) is calculated to 5.26 cm with a wave length of 30 cm (1.05 and 5.93 m full scale). The result was a highly dynamic sea, with an uneven wave pattern.

The boat was towed across this surface at a speed of 0.63 m/s (5.5 kts in full scale); same speed as in test run 5. The result was what can possibly be described as a “cork screw” movement with strong heel and pitch as the boat encountered the waves at an oblique angle (Figure 24).

Maximum pitch angle measured was 5.8° upwards, and the average maximum movement of the stem was 7.9° from top to bottom. This is equivalent to a change from stern to stem of 20.0°/second (or 4.5°/s in full scale). Unfortunately the heel could not be measured, but it was surely in the range of

14-16 degrees°. The reason why we can determine the maximum angle of heel without precise measurements is that the gunwale is seen to occasionally dip into the water in the videos, with 15.2° being the downflooding angle of the boat. Even during the relatively short run the boat did therefore ship water, with spray around the bow also being visible on the video together with the -slightly- submerged gunwales. Towards the end of the run the boat filled with water and it began to sink. This may also have been a result of the model coming too close to the wave maker. But there is no doubt that with this test we brought the boat to the limit of its sea keeping capabilities. In real conditions this would have been a rough and very dangerous ride.

Discussion

Omitting the unsuccessful test run 1 and the wave-less test run 3, we did manage to record four data producing runs for the Vaaler Moor boat. The lack of heel in completely calm waters is naturally also a result, but run 3 did not require much of an effort to measure. The lack of measurements of the heel angle for two of these tests is unfortunate, and all part of the learning experience, but as the degree of heel was in fact close to the gunwale, letting water into the boat, we can estimate it to about 15° in the worst case, which was test run 6. The maximum heeling angles in test run 5 were much less as the waves were met almost bow on.

The results are summarized in Table 9 and shown in Figure 25. The pitch and heeling angles are here correlated to the wave steepness. We have also shown the speed of the boat in the table as this is important to the boat's response to waves. One will notice that as the wave steepness increased, the speed of the boat fell slightly. This was not planned, but more a question of gradual adaptation during the tests. Keeping the speed uniform would have yielded more comparable results.

With this being a tender boat, it does heel noticeably at relatively low steepness of the waves. However it seems to stiffen, as the relationship between wave steepness and heel is not linear.

Test run	Wave steepness, °	Speed, kts	Pitch, °	Heel, °
2	1,8	6,5	3,5	7,3
3	0,0	6,5	0	0
4	0,9	5,7	2,3	6,2
5	7,5	5,5	7,7	-
6	10,1	5,5	7,9	-

Table 9. Summary table of the model tests. Speed is converted to full scale.

It is noteworthy that while test runs 5 and 6 are seemingly comparable in numbers, the visual impressions of the boats on the water were very different in the two runs. The increase in wave steepness (by the shortening of wave length) had a visible impact on the boat. While the boat seemed to glide relatively gently across the water in test run 5, this was certainly not the case in test run 6. In the latter the wave length was exactly half the length of the boat. This may explain some of the difference, although the waves in this test were generally more irregular than in the other tests. While pitch was easier to measure than heel, it must be remembered that the boat met the waves at different angles. So although it seems that there is a simple relation between pitch angle and wave steepness, as indicated by the trend line, this relation is somewhat more complicated. The angle of the wave to the boat is naturally an important factor in determining degrees of pitch and roll.

Although the theoretical calculations in a previous section showed that in the worst case, the Vaaler Moor boat would capsize in a wave of 0.51 m, or a h_S of 0.40 m, one main result of these tests is possibly, that we have seen the boat sail in waves of up to 1 m (h_S). We have also seen that with increasing steepness and at a less convenient angle, a wave height of 1 m can result in highly dangerous and certainly unpleasant situations even when the waves are nowhere close to beam on. In a swell, and in other non-breaking conditions, this boat may be useful up to wave heights to 1 metre, but based on these tests, a realistic safe limit in waves would be somewhere between 0.5 and 0.75 m. It must be remembered that these tests were done with a 'crew' which were designed to counteract the heel, and therefore helped to stabilize the boat by constantly moving its centre of gravity. This may explain some of the difference between the theoretical and the practical numbers

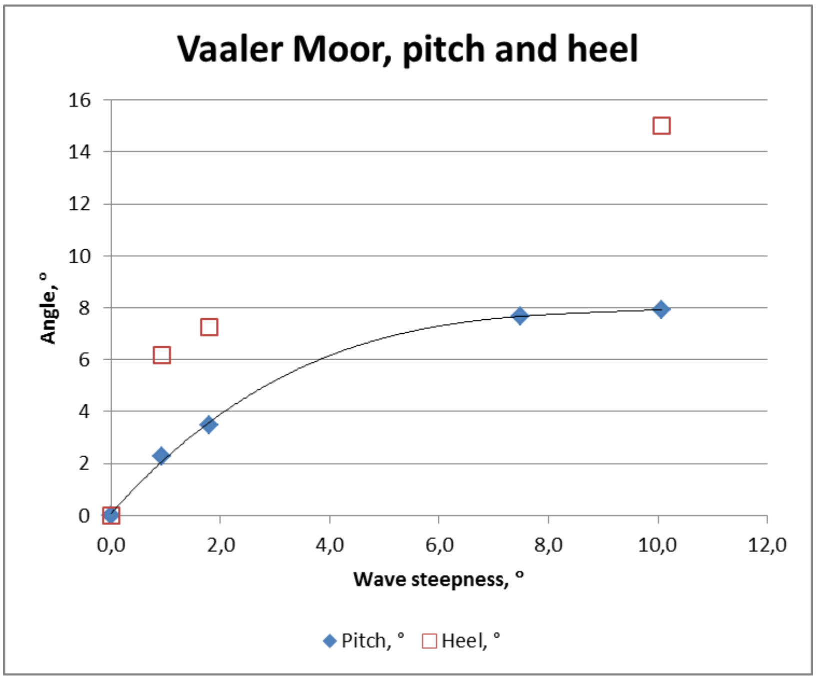

Figure 25. Vaaler Moor. Summary of pitch and heel with varying wave steepness. The heel angle of 15 ° is an estimate for the worst sea state (test run 6), and marks the downflooding angle. A trend line is fitted for the pitch angles.

Discussion

The Vaaler Moor boat is an extremely long and slender boat. Although widened by the expansion, it still comes out very slim and elegant. It was rowed by a crew of ten with a helmsman bringing the crew up to eleven. Crewed thus there is room for no cargo. In fact the estimated weight of the boat and crew gives a freeboard that cannot be anything but close to the old Grågås ratio of 60% draught. This seems to substantiate the reconstruction and the interpretation of the boat.

As it is slender, the analyses above have indicated that it is also a tender boat. We did not manage to capsize it during the formal tests (although at the end of one run it accidently came too close to the wave maker and shipped a substantial amount of water). While theoretically this could have happened, the crew is obviously a stabilizing factor, as long as they do stay in the lateral centre of the boat. The fact that we capsized the boat in still water simply by letting the crew lean against a gunwale was something of a surprise, and does not inspire much confidence in this as a seaworthy boat.

But maybe it was not. These results inspired us to take another look at the distribution map on Figure 18. As the boats are found along the Wadden Sea coast, we have assumed that they sailed the Wadden Sea. But in fact they are all found in inland waters. Vaaler Moor and Ritsch in the marshes along the river Elbe, and Lecker Au and Gotteskoog in the system around the stream Lecker Au. While this is certainly not a major river, it is still a large stream, useable for boats of this kind. It is not entirely impossible that these were river boats, rather than inshore vessels.

Although we stated in the introduction to this work that the Vaaler Moor boat was not a dragon boat there are indeed some similarities. Developing from war canoes, dragon boats are racing vessels for ritualized competition on rivers or similarly sheltered waters. The dragon boats have probably still functioned as war canoes, at least in unstable political circumstances. Racing may seem a very modern purpose for a boat, but if it could develop in the rivers and estuaries of South East Asia, why then not in the streams of Schleswig-Holstein? There is in fact no way of determining whether similar ritualized competition developed in the Wadden Sea region.

But that is an important argument against such speculations. We cannot determine the use by speculation, and few other options are in fact given. We do have Pliny describing the use of logboats as vessels of war, although in mentioning crew of up to 30 men he probably exaggerates the matter somewhat (Pliny, *Hist. nat*. XVI, 76).

One could also argue that although the Lecker Au drainage system is not small, it is a limited system for such large boats, and that they would make more sense as war boats, if they could move outside the immediate catchment of that drainage system. The contemporary logboat from Egernsund was too badly preserved to reconstruct, but of similar dimensions. It was found in only semi-sheltered waters, so there is some evidence that boats like these were meant to navigate at least the littoral zone.

Other uses similar to that of the later 'church boats', which are known from at Northern Europe, is also an option. These are communal boats meant to transport villagers to and from church every Sunday. Hirte (1989) indicated similar uses for the Vaaler Moor boats. In that case they make sense as large river boats. The explanation would presuppose that communities were required to move together regularly – like the villagers going to church every Sunday. Given its stability characteristics, this is certainly also an option; but do church boats have to be fast? There are several places in Scandinavia where traditional church boats are raced today, but apparently that is a recent development, aimed to maintain these boats which are otherwise going out of use, and is fast becoming cultural heritage instead.

Interpreting the logboats of the Vaaler Moor group used for war parties seems the most immediate explanation, partly also substantiated by Pliny's remark. But war waged at any distance needed to take place in fair weather, otherwise the crews would be in mortal danger long before combat commenced. There is no evidence for or against any of the other explanations. They are some obvious preconceptions of Germanic tribe societies that would make it difficult for us to imagine a dragon boat festival taking place in Schleswig-Holstein some 1700-1900 years ago, while a war party of fierce warriors comes much easier to mind. Preconceptions, which may even be substantiated in valid theory. It still stands that the logboats of the Vaaler Moor group are interesting and exceptional boats, and that their presence in Iron Age societies must have a bearing on our perception of these societies.

4. NORTH FERRIBY 1

Introduction

The North Ferriby 1 boat is possibly one of the most debated archaeological finds in maritime archaeology. Ever since it was discovered questions about its use, its environment, its shape and its performance on the water have been a subject of debate from various researchers (e.g. McGrail 2007, Coates 2005a, 2005b, Gifford & Gifford 2004, Wright 1985). Most of these issues remain unresolved to this day.

The most recurrent subject of debate regarding the North Ferriby 1 is the reconstruction of the boat that reflects its properties and whether or not it was seaworthy. When the National Maritime Museum in Greenwich opened a new gallery in 1977 and decided to include a diorama of the North Ferriby finds, four of Ted Wright's proposed reconstructions were built into small scale models. Three of them had a flat bottom and two side strakes while one of them, the last one to be added in the diorama, had a rockered bottom and three side strakes. Two of these reconstructions with very different values and capabilities have been widely published and discussed. The minimalistic reconstruction No.1 (Figure 26) which has a flat bottom, two side strakes and a fairly shallow draught, and reconstruction No.4 (Figure 27) which has a rockered keel and three side strakes. (McGrail 2007; Coates 2005a).

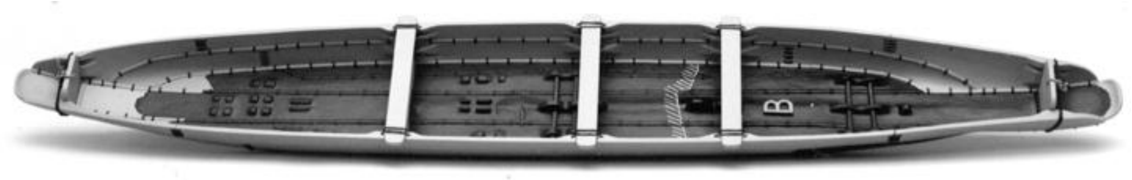

Figure 26. North Ferriby, Reconstruction No.1 (Photo courtesy of Hull and East Riding Museum, Hull Museums).

In this chapter we do not intend to solve the dispute that has been going on for so long, but as it is stated on the introduction of this book, the purpose of this study is to conduct a comparative analysis of different hull forms. Since we decided to include in our project such a controversial archaeological find, we decided that it would be useful to build in model and test both of the proposed reconstructions. That way we could have a more complete conception of the capabilities and the environment in which the North Ferriby 1 boat was originally sailed in. But before we discuss the results of the experiment we conducted, we will discuss the find itself, as well as its environment, possible construction, its properties and its use.

Description of the find

North Ferriby 1 was first found by Edward Wright on the north bank of the Humber estuary in September 1937. Within a distance of c. 400 m the remains of three more boats of the "Ferriby type" were found in later excavations. Those boats, known as Ferriby 2, 3 and 4 have been dated from 2000 BCE to 600 BCE. The North Ferriby 1 (F1), which was the most complete of the boat finds, dates back to c. 2000 – 1700BCE (Coates 2005b: 38).

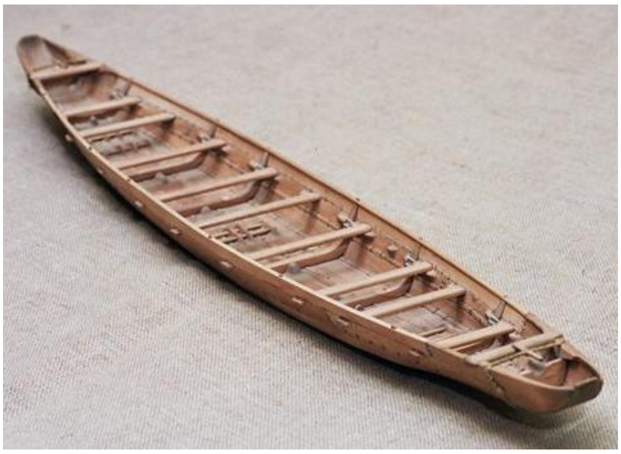

Figure 27. Reconstruction No.4 (*Photo courtesy of Hull and East Riding Museum, Hull Museums).*

The find consisted of a bottom structure of total breadth 1.67 meters, with a central keel-plank of 13.32 meters length as measured on site, two “outer bottom planks” on each side of the keel-plank and a part of the “lowest side strake” in the western side of the boat (Figure 28) (Wright 1990: 62). As the boat was theoretically equally ended, Ted Wright in his reports prefers to refer to east and west end of the boat, using the orientation of the boat as found *in situ*, although in some cases the west, most complete, part of the boat is referred to as “the bow” (1976: 16).

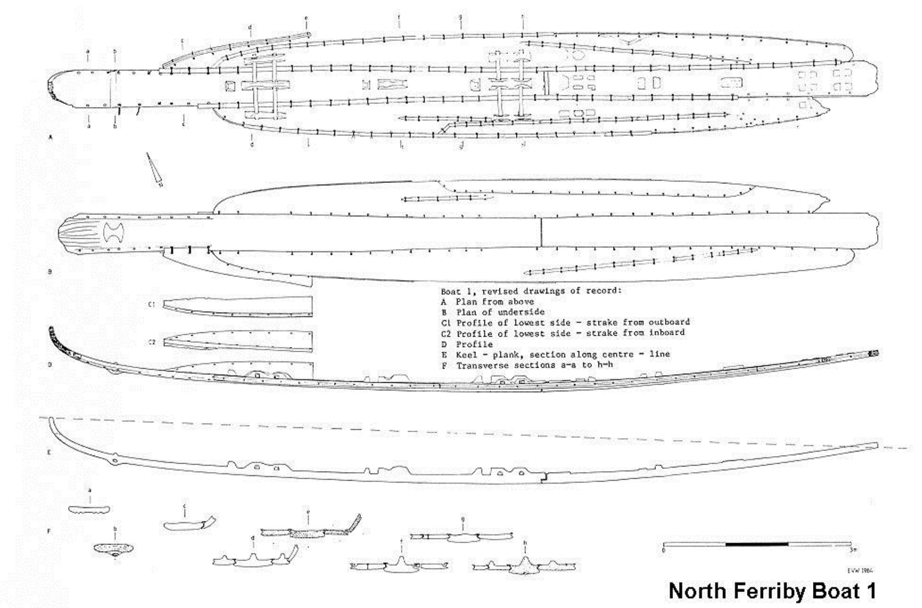

Figure 28. The North Ferriby 1 as found in situ (from Wright 1990).

The keel-plank consisted of two planks joined with a box-scarf amidships (Figure 29). The overlap of that joint was 8 cm. Both planks were getting thicker and narrower towards the scarf (Wright 1976: 58-71) while the average thickness of the keel-plank is c.14 cm (Steffy 1994: 37). On the western end of the boat, the keel was curved and was protruding at height of at least 25 cm (Wright 1976: 58-71), which according to Wright was the maximum height that could be worked out of the original half-log. On the west end of the keel-plank, 87 cm east of the extreme tip, was a transverse ridge. The underside of the so called “bow” was carved with a pattern of horizontal grooves and just east of them was a cleat carved out of the parent log and penetrated by an oval transverse hole (Figure 30). The edges of the keel-plank were cut with V-shaped groves (Figure 28) in order to receive the outer bottom-planks (1990: 58-71; 1976: 17-22).

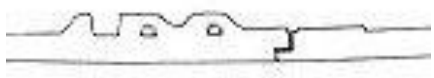

Figure 29. The box scarf connecting the two planks of the keel (from Wright 1990).

Figure 30. Underside of the "bow" (from Wright 1990).

The outer bottom planks were 10.6 metres long, 60 cm wide in breadth (Wright 1990: 100) and had about half the width of the keel-plank (Steffy 1994: 37). They were fitted to it with the help of seams made from withies of yew (*Taxus*), and the rabbet that was carved on the sides of the keel-plank. The outer bottom plank of the north, 'starboard', side of the boat had a crack 3.7 metre long which was repaired in antiquity. Its counterpart in the 'port' side had also a repaired crack and a replacement of a part of the plank (Figure 30). The outer edges of these planks, similarly with the keel-plank, were cut with V-grooves to facilitate the fitting of the strakes. The lower side of the V shaped groove was extending further than the upper one, possibly in order to protect the seams connecting the two planks (Figure 31d) (Wright 1990: 64-65).

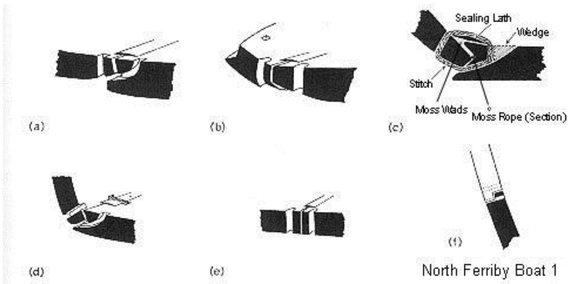

Figure 31. Seams between different strakes (from Wright 1990).

The seams connecting the planks with each other, as well as the seams used for repairs in F1 were all made of yew, had moss luting and were capped by laths of oak (Figure 31) (Wright 1990: 65).

The lowest side strake that was found on the western part of the boat was fitted to the bottom structure as described above, but in order to achieve the required angle to create the chine and have a sturdy connection with the bottom structure, the strake was hollowed and given a double curvature at the point where it meets the keel-plank (Wright 1990: 66).

Distributed on the top side of the bottom-structure, there were several cleats carved out of the parent logs, some of which were penetrated by transverse timbers. Wright names those features “cleat systems” (Figure 28, Figure 32). Two pairs of those “cleat systems” were preserved in the western part of the boat. The transverse timbers were connecting the keel-plank with the outer bottom planks, and in some cases they were secured in their position with the aid of wooden wedges fitted in the cleats. In the eastern side of the boat there were remains for two more pairs of “cleat systems”, but the transverse elements did not survive and most of the cleats were severely worn out. While the whole boat was made out of oak, the transverse timbers of the “cleat systems” were made of ash (*Fraxinus*) Apart from those systems, on the top side of the keel-plank; there were several blocks of different dimensions carved out of the parent log. Those blocks were of uncertain use (1990: 68-71).

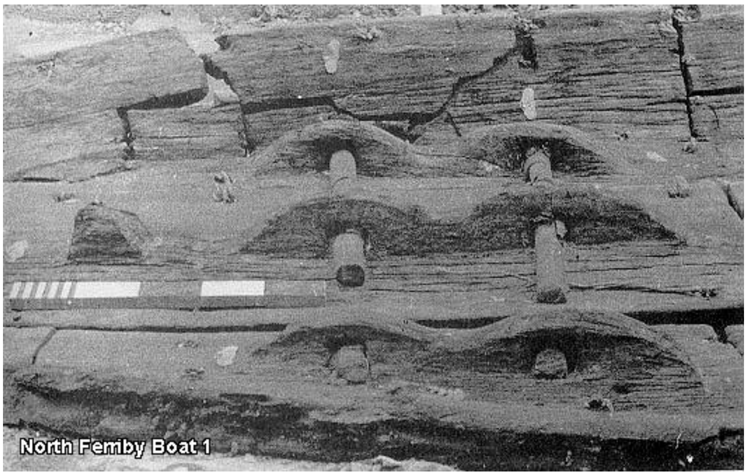

Figure 32. “Cleat systems” (from Wright 1990).

State of preservation

There is a big discussion regarding the state of these remains and how reliable a re-examination of that material would be. The discussion is directed mostly to the reconstructed interpretation of the remains and especially to the “rockered or not” issue, referring of course to whether the boat was flat bottomed or rockered.

The fact is that some of the remains of the Ferriby boats were unfortunately destroyed during the hostilities of the Second World War when the site was left unprotected from the weather conditions (Wright 1990: 23-43; Coates 2004: 21). Another part of the remains, together with Ted Wright’s archive, are currently placed in the Kingston upon Hull Museum (McGrail 2007: 257). Apart from that, Wright claimed that part of the material was heavily distorted because of the treatment it received by Dr R.M. Organ of the British Museum Research Laboratory. Dr Organ initially treated the remains with polyethylene glycol (PEG), but according to Wright,

> *“The programme of impregnation was monitored by Organ and in its latter days, acting on his advice, additional heating was applied to accelerate the driving off of the remaining moisture. This experiment was in the event unsuccessful since the timbers so treated became severely distorted*;”

Although he continues,

> *“The remaining pieces of the main planks were in due processed at the original slower pace and emerged several years later stabilized without serious distortion.”* (Wright 1990: 51).

John Coates almost 15 years after the latter publication by Wright also claims that a lot of the material “dried and disintegrated” due to absence of experience on the conservation of waterlogged wood back at the time of discovery of the Ferriby boats (Coates 2004: 21; 2005a: 38). McGrail states that up until the early 1980s a lot of material survived in a state that was sufficient for analysis but he agrees that by now, the Ferriby remains are “a shadow of their former self”. McGrail although insists that “*an impartial and informed team*” should examine the archives of Wright and the elements that “*probably still exist*” in the Hull Museum (McGrail 2007: 257).

Environment, use of site and cultural background

The Ferriby boats were found on the northern bank of the Humber Estuary and specifically near North Ferriby, which is situated in the southernmost part of the Yorkshire Wolds (Van de Noort 2004: 93), 2 kilometres east of the Melton foreshore. The river Humber starts at the point where the rivers Ouse and Trent meet at the Trent Falls, and flows into the North Sea between Spurn Point and Donna Nook (Figure 33) (Van de Noort 2000: 167). The distance a Ferriby boat would have to cover in order to reach the North Sea is just c. 55 kilometres (34 miles), and the distance from Ferriby to present day Rotterdam is only c. 370 km (230 miles).

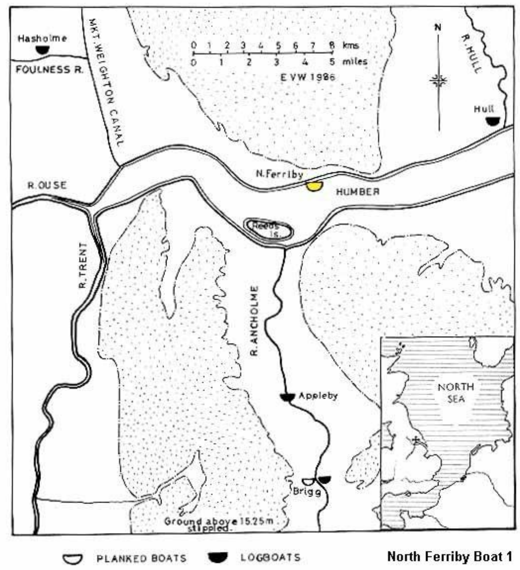

Figure 33. Locations of logboats and planked boats found in the area of Humber (from Wright 1990).

Two projects about the reconstruction of the past landscape of the area have been conducted so far. One of them was conducted by The Land Ocean Interaction Study (LOIS) programme while the other was completed by the Humber Wetlands Project that started in 1992. According to those reconstructions, during the Holocene there was a development of ‘eutrophic’ wetlands alongside the Humber, including salt marshes and intertidal mudflats (Van de Noort 2000: 167; 2004: 91). The Humber became a tidal inlet around 6000 BCE; subsequently in the Early Bronze Age there was a significant rise in the sea level that led to “*further marine transgression during the first millennium BC, thus burying the old ‘eutrofic’ wetlands*” (Van de Noort 2004: 91) .The reconstructions depict the Humber during the Bronze Age as “*a wide channel, fringed by mudflats and salt marsh, intersected by tidal creeks. In the foreground is higher ground, dominated by grasses*” (Van de Noort 2000: 171).

Regarding the Ferriby boats and the conditions of their submergence during the Bronze Age, Van de Noort taking into account the sea-level of the period, reports that they were submerged by tidal water and the sediments it contained during spring or high tides. Putting it in simpler words he says that “*the boats did not sink, but were overwhelmed by the water whilst resting at their natural landing places*” (Van de Noort 2004: 91).

The soil in the area and especially the salt marsh sediments that cover the peat deposits (Wright 1990: 4) are favourable for preservation of organic material. Apart from the Ferriby Boats, several prehistoric sites have been recorded in the area during the Humber Wetlands Project that started in 1992 and wooden features are fairly common among the remains. (Van de Noort 2000: 164f). Some of the most important finds from the general Humber area are the prehistoric logboats from Brigg, Appleby Scotter and Hasholme (Figure 33); the Late Bronze Age sewn plank boat from Brigg, known as the Brigg raft (Van de Noort 2004: 90-1); and the two Middle Bronze Age Hurdle trackways that were found in the salt marsh sediments. (Van de Noort 2000: 165).

Those trackways which are positioned parallel to the estuary have been depicted in two different ways in landscape reconstructions. John Craig in Wright's report in 1990 depicts the trackways as a semi-permanent landing place for the boats (Figure 9). This representation implies that the North Ferriby site was used as a marine route from North to South Ferriby. Another element that supports this reconstruction of the site is the nomenclature of the area. The name Ferriby indicates the use of ferries for cross-estuarine action. As we know, the area that forms a natural harbour was indeed used for this reason during the Middle Ages (Van de Noort 2004: 90-1) as the bridges were few and inadequate in the area (Barley as quoted by Wright 1990: 1), and there is no reason to believe that the site was not used as such since the prehistoric period. The possible use of the Ferriby 1 as a cross-estuarine ferry does not mean that the boats were used only for this reason. To return to the use of the site though, we have to mention that Wright interprets it as a boatyard (1990: 167-95). This interpretation is supported by several finds in the area, such as oak chips with bronze axe marks, cut-offs of yew withies, and some finds interpreted as shipwright's tools, such as a 'tingle' used for repairing holes and cracks on boats and a pistol-shaped tool used for the yew stitches (Van de Noort 2009: 161-2). Robert Van de Noort, even though he also supports that the North Ferriby site is an ancient estuarine harbour and the oldest known shipyard, criticises the landscape reconstruction by Craig regarding the hurdle trackways. Van de Noort's counterproposal about the trackways is that they were used to provide an effective way to evacuate cattle from the salt marshes to a higher ground during the spring floods (2004: 94).

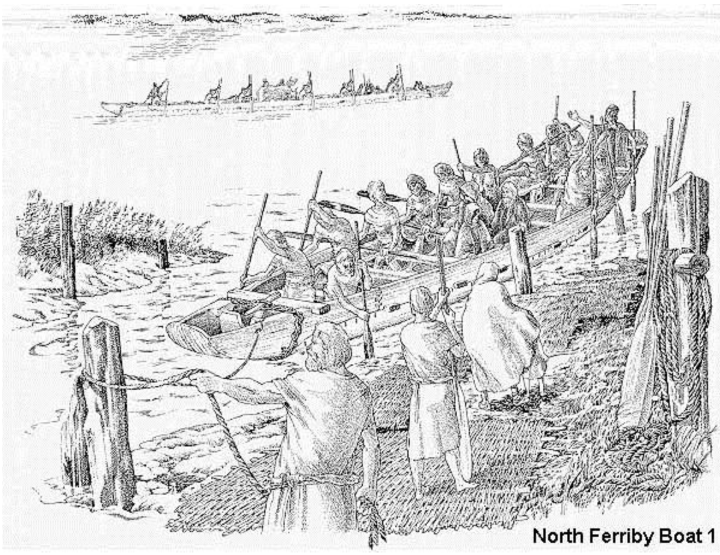

Figure 34. Reconstruction of the North Ferriby site (from Wright 1990).

Regarding the cultural background of the area, the emergence of the Beaker culture and its parallel development both in Britain and Continental Europe, give us solid evidence that ever since the Late Neolithic and the Early Bronze Age there is trade and exchange of ideas across the North Sea. The trade includes prestige items such as Beakers, elaborate flint, daggers, jewellery made of gold and amber that were found mostly in burial sites. Those 'rich burials' suggest the rise of elite groups. During the Early Bronze Age when in Britain we have the emergence of the 'Wessex culture', those burials get even richer and amongst the finds we frequently have amber from the Baltic Sea and early bronzes of continental origin. (Van de Noort 2004: 93).

North Ferriby is located just north of the Yorkshire Wolds that are considered an 'elite region' of the Early Bronze Age, as we encounter Great Barrows and several 'rich burials' with prestigious items

(Van de Noort 2004: 92; Smith 1994: 11). However the foreshore of North Ferriby itself is surprisingly bare in terms of finds. We do not encounter any monuments, Barrows or valuable goods and neither have we encountered any ‘votive’ deposition of metal artefacts as we see it happening elsewhere in Britain during that period. Some indicative finds from the site that are not related to the boats or boatbuilding, are a clay sinker, a bronze knife blade, fragments of pottery and the hurdle trackways mentioned above. Those finds suggest that the area was mainly used for farming, and we have no evidence that the boatbuilding or the marine activities were linked to anything religious or ritual. That image can be contradicted by the Kilnsea boat that was found a few kilometres east, on the shore of the North Sea, close to several ‘rich’ burial mounds. (Van de Noort 2004: 95-6). The two sites are certainly different but if we could come to a conclusion about the perception of the Early Bronze Age people of Ferriby regarding the boat activities, we would probably say that those activities were considered simply as a part of the everyday life.

Reconstruction

The reconstruction of North Ferriby 1, as it is already mentioned on the introduction of this chapter is a controversial issue. In this part of the chapter we will describe the constructional features and the properties of reconstructions No.1 and No.4.

When Wright first attempted to reconstruct the Ferriby 1, he supported his reconstruction on a very specific logic that was based on his interpretation of several features of the boat. From 1946 until 1978 that logic remained the same but produced various results. Reconstruction No.1 was a product of that logic, which was presented in Wright’s reports of 1976, and 1990. In the report of 1976 he explains his reconstruction based on the idea that the keel plank must not have been much longer than it was found; the bottom structure was designed to be flat; the ends of the keel-plank were most possibly curved and not bended; the ends of the strakes must have curved downwards; a ‘stop ridge’ playing the role of a fitted transom, as it is common in dugouts, was inserted at the point of the lateral ridge on the keel-plank (1976: 43-49). In the report of 1990, Wright refers to some different elements, on which he based these early reconstructions. In particular he mentions that,

> *“there were fastenings for two more side strakes in addition to the only piece found that time, making three on each side; that the boat was equal ended; that it was strengthened by three ribs located on the slots on the keel-plank and combined with thwarts lashed to the top edges of the third strakes so as to form frames; further strengthened by girth-lashings at each end passing through winged cleats on the underside of the keel-plank”* (Wright 1990: 85-86).

Although the reasoning between the two reports is not completely coherent the elements are not contradictory. In the case of reconstruction No.1 (Figure 26), the result of the logic as presented above was a minimalistic representation of an equally ended boat, with a flat bottom structure; two side strakes made by three planks each and stitched together; three ribs tied together with thwarts; two fitted transoms, about a meter in from the bow and stern; and lashings supporting the structure, passed through a cleat on the underside of the keel-plank. The dimensions of reconstruction No.1 are 15.4 meters length, 2.6m beam and 0.7m depth amidships (McGrail 2001: 187).

Coates claims that this reconstruction is only 0.5m deep at its ends (Coates 2005a: 40), something that creates an image of an inverted boat. Unfortunately the only criteria we had to judge those contradictory descriptions while writing this chapter were pictures of the reconstruction No.1, as there are no published lines plans of that model in the relevant literature. Coates’ allegation about the depth at the ends does not make much sense, and when he comes to calculate the hydrostatics of such a boat he concludes that “*its likely total load-carrying capacity, including crew, if the transoms are not relied upon, would not have been much more than the bare weight of the hull*” (Coates 2005a: 41). A boat with such properties has extremely limited potential and it is highly unlikely that it was even capable of crossing the Humber. It is thus possible either that the transoms in reconstruction No.1 are watertight and elevate the ends at 0.70 m, either that the ends of the model are not as shallow as

Coates estimates them. In the same article, he calculates the Hydrostatics of the same model, as if the transoms were watertight. That gives a load of up to 7 tonnes at a 0.2 m freeboard. Such a small freeboard suggests that the boat could only operate in sheltered waters (2005a: 41).

McGrail suggests that the primary use of the Ferriby 1 boat was that of a ferry crossing the Humber from north to south and vice-versa, while it was also operating in the smaller rivers that flow into it (McGrail 2001: 187; 2007: 263). Specifically he claims that,

> *"by eye and by simple calculation … seagoing was not their usual role. These boats did not have the shape or the structure to match the stability, the freeboard or the sea-kindliness required by a boat regularly used at sea. The Ferriby boat's primary role was probably as a cross-estuary ferry on the stretch of the Humber where there have been ferries since at least Roman times … In medieval and earlier times such cross-Humber passages connected south-north routes along the Lincolnshire Wolds and the Lincoln Edge to similar routes on the Yorkshire Wolds"* (McGrail 2001: 186-7 as quoted in Coates 2005a).

He also believes that the boat's L/B ratio would have given the necessary 6 knots speed required to cross the fast flowing Humber (McGrail 2007: 264) so, the two-strake, flat bottomed Ferriby fits his description for the use of the boat. A last thing that needs to be mentioned about reconstruction No1 is that the model maker of the Hull museum had great difficulties in shaping the hood-ends of the side-strakes to mate with the extensions of the keel-plank (Wright 1990: 87) which raises questions about the accuracy of a reconstruction with only two strakes and the possibility of being able to carve a plank so big (c. 0.70 cm wide) (Coates 2005a: 41) and with such a curvature from a single log, as the one that would be needed for the hood-end of the second strake from that model.

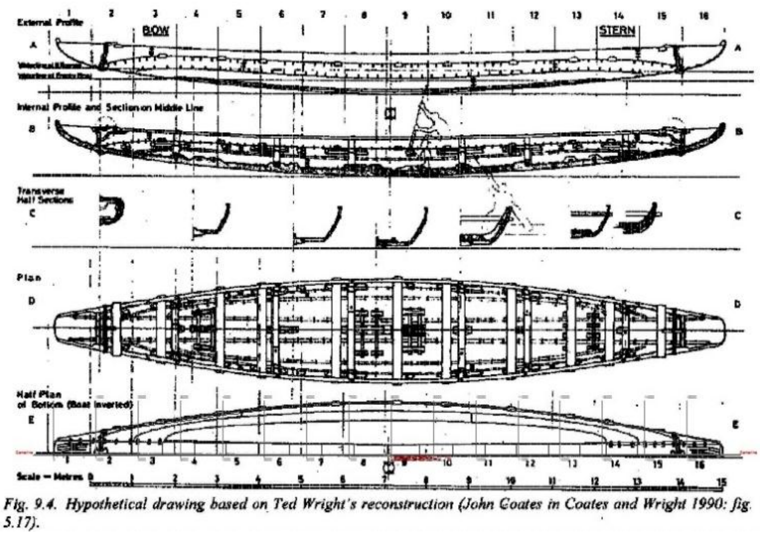

Figure 35. Plans of reconstruction No.4 (from Wright 1990).

Reconstruction No.4 (Figure 27, Figure 35) was proposed by Ted Wright in 1978 and published by him in 1990. This reconstruction proposes an equally ended three strake boat, with a rockered bottom, six ribs positioned on the slots of the bottom structure, eleven thwarts positioned independently form the ribs, and dimensions 15.9 m length, 2.52 m maximum beam, 1.32 m height on the ends and 0.98 m amidships (Wright 1990: 100).

This reconstruction is the only one with a rockered bottom which changes the properties and the capabilities of the boat by making it sea going (Wright 1990, Coates 2004, 2005a, 2005b, Gifford & Gifford 2004). Wright changed his opinion about the reconstruction of the boat while a replica of the find *in situ* was made for the purposes of the Hull Museum Exhibition (Wright 1990: 86-7). He then realized that the boat as first observed must have had a curved bottom and he supported this argument by pulling up his own records by 1937 where he quoted "*Probing with a walking stick indicated an obstruction up to six feet (1.8m) wide which became steadily deeper in the clay for some twenty feet (6m) and then rose to the surface over 40 feet (12 m) from the eastern end*" (Wright 1985: 107-12). Another indication about the original curvature of the boat is a preliminary sketch that Ted Wright's brother had made in 1937 depicting the stratigraphical setting of Boat 1 (Figure 36) (Wright 1985: 105-7).

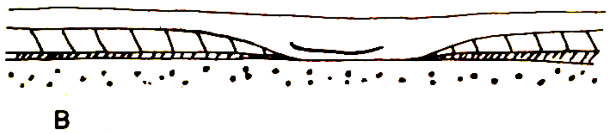

Figure 36. Stratigraphical setting of Boat 1 (from Wright & Wright 1939).

Reconstruction No.4 according to Coates depicts a vessel that would have been of significant seagoing capability because a rockered bottom of increased hull depth would have coped better with waves. "Rocker, like round bottoms, also prevents the large losses of stability which occur in any flat-bottomed boat or ship if quite small amounts of bilge water whether from leakage or from waves slopping over the gunwale in a seaway, are allowed to swill about freely" (2005a: 41). If reconstruction No.4 is correct, the theory about the use of the boat changes a lot. The rockered version of Ferriby 1 could have carried 7 tonnes with a seaworthy freeboard of 0.4metres (Coates 2005a: 41). The boat could still be used as a ferry operating in Humber and the nearby rivers but it could certainly operate also as a cargo vessel navigating on the inshore waters of the west coast of England, if not across the North Sea all the way to continental Europe. According to Van de Noort reconstruction No.4, with a speed of 6 knots and good weather conditions could reach the Dutch coast in just over 24 hours from Spurn Point, carrying a cargo of seed corn for crops, or even domesticated animals (Van de Noort 2004: 92)

Apart from the shape of the hull, another controversial issue regarding the reconstruction of the Ferriby 1 is the use of a sail. In north-west Europe the first iconographic evidence for a mast, is the gold boat model from Broighter, Ireland which dates back to the 1st century BCE (Wright 1990). The first literary evidence comes from the same period with Strabo's *Geographicus* (4. 195) and Caesar's *Bellum Gallicum*, while the first artefactual evidence comes on 800 CE with the Oseberg ship (Wright 1990: 109-10). Ted Wright and John Coates however, suggest that the presence of a saddle shaped feature on the bottom structure of the boat could be interpreted as a mast step (2004: 27-8) and thus they suggest that the Ferriby boat could have been sailed. Gifford and Gifford (2004: 80) interpret the saddle features in the same way and when they were testing their half scale model of reconstruction No.4, they placed a very small sail amidships in one of the runs. Even though the wind was not strong, the ship reached a speed of 2.2 knots and took no water on board.

The addition of a sail in the Ferriby boat has been strongly criticised by McGrail who points out that Coates' justification for the addition of a sail is inadequate. Specifically Coates claims that "it must be virtually certain on grounds of the overwhelming advantages of sail over oar and paddle on sea passages of any reasonable length that boats would have been sailed from their inception" (Coates 2005b: 521-2). McGrail quite logically adds that "*although conjecture is an understandable, probably desirable, reaction to the absence of evidence, it is hardly a conclusive argument*" (2007: 262). Indeed the use of a sail in north-west Europe almost two millennia before the emergence of any relevant evidence is highly unlikely. Additionally, the fact that the sail was known and widely used in the Mediterranean Sea in that same period does not constitute evidence for a sailed Ferriby boat.

The Ferriby boat was probably not sailed but the question still lies whether it was propelled by oars or paddles. In 1937, fifteen meters north from the Ferriby 1 find, a timber probably made of ash

(*Fraxinus)* was found. The dimensions of that blade shaped timber were 1 meter length, 0.15m width and 0.023m thickness (Figure 37) (Wright 1990: 151-5). That blade could be interpreted either as paddle, oar or a steering paddle. The earliest north-west European evidence for oars is the gold boat model from Durrnberg, Germany which dates to c.500 BCE (Wright 1990: 110) thus many researchers prefer the interpretation of the blade as a paddle, while others including Wright, Coates and Gifford prefer the oar interpretation based on the fact that in Ferriby 4 the spacing between a thwart and a rib is ideal for a rower sitting on the thwart and pulling an oar against a fulcrum provided by the rib (Wright 1990: 113).

Figure 37. The paddle blade as photographed the day of the excavation (from Wright 1990)

Regarding the possible crew that could be on the Ferriby boat, Wright and Coates suggest that it would be twenty men, eighteen paddlers plus two (1990: 114). Such a crew would weigh 1.5 tonnes if every man weighs 75kg including gear, while the equipment for the boat, like paddles, poles, ropes, stone anchors etcetera would weigh around 0.2 tonnes (Wright 1990: 113-4). Wright and Coates estimate that with 18 paddlers the boat (reconstruction No.4) would keep up to 6 knots for about half an hour, while with a more modest assessment of twelve paddlers, the boat would achieve only 5.2 knots (1990, p. 114). The tide stream of the Humber is estimated at 5 knots, thus manoeuvring would have been really difficult with only 12 paddlers.

The question of the cost of building such a boat was answered by the building of a half scale model of the rockered reconstruction by Gifford and Gifford. The 8 meter long model, cost 30,000 British pounds which can be translated to up to two man-years of work. The cost of a full scale boat would be according to Coates about six to eight times that amount, i.e. 12 to 15 years of labour for one man. (Coates 2005b: 527-8). If 15 to 20 men would be needed to complete the endeavour of building that boat (2005b: 527-8), then about 220 to 300 hours would be required. Coates estimates that the building of such a boat would need "*a settled agriculturally supported community of about 250 to 300 people occupying and living off about 50 square kilometers of arable, pasture and woodland*". If that is correct the question that automatically arises is: would such a small community make such an investment for a boat that would be used only as an estuarine ferry? Even if the boats were serving a wider area and a much larger population the cost and the expertise needed to build them probably still exceed the cost that they would invest for an estuarine ferry. If we also take under consideration the life expectancy of these boats, which was 20 to 50 years (Coates 2005b: 527-8), we can assume that such a long term investment was not only expensive but also significant for the population related to it and we would expect them to take a full advantage out of it.

Material and methods of construction

The materials used for the building of Ferriby 1 as well as the methods of its construction have been studied by several researchers including Coates (2005b), McGrail (1987: 98-162) and Ted Wright who has published a very detailed study of these aspects in his report of 1990 (1990: 117-43). Trying to avoid repetition we will briefly refer to the main materials and the basic construction method in order to give a rough image of how the boat was constructed. The basic purpose of that is so that the reader can observe the differences in construction between the original Ferriby 1 and the 1:20 scaled models that we constructed for the purposes of this project.

Starting with the material, as we have already mentioned the planks of the Ferriby 1 were made of oak, while the transverse elements of the bottom structure were made of ash and the stitches were made from withies of yew.

The dendro analysis from samples of the keel-plank suggests that the two keel planks of the Ferriby 1 were cut from one tree log (Hillam 1985: 153) split longitudinally. The ends of the boat have been given an upward curve by hollowing out the end of the keel-plank while the side strake was hewn to give curves in two planes (McGrail 1987: 105). The planks of the bottom structure were bent to shape (Wright 1990: 142). The first step in the sequence of construction would be the extraction of the planks from the logs and the bending as described above. The keel-plank, which is the basic element of construction, would be lying with the right curvature and the cleats and slots in place, when the V-shaped grooves were carved to receive the outer bottom planks and the side strakes. The next step would be the fitting of the transverse timbers in the cleat systems, something that would help with the assembly of the bottom structure (Wright 1990: 138). Once the outer bottom planks were fitted in the bottom structure they would be stitched with the withies, luted with moss and capped with laths of oak at the joint with the keel-plank. The side strakes, which were joined to the keel-plank and bottom structure in the same way, would most probably be stitched plank by plank and not as whole strakes. The ribs would then be shaped and added to the inside of the hull to make the whole structure sturdier.

In reconstruction No.4 the thwarts which were penetrating the hull, were added before the third strake was placed, in which case the second and third side strakes were cut out to facilitate the placement of the thwarts. In reconstruction No.1, the thwarts were simply placed on top of the second strake and kept in place with a rope passing through cleats carved on the upper part of that strake.

Hydrostatics and performance

Table 10 and Table 11 present the hydrostatic calculations for the two different reconstructions. Most of the values are from the models we developed on *DelftShip* and some have been calculated in *Excel*. The draught has been set to 60%.

According to the ship database (Jensen 1999: 51) the Length- Beam ratio (L/B) of both models indicates that the boats are neither typical long boats nor the typical seagoing cargo boats but are placed in between. The block, prismatic and waterplane coefficient values however, indicate that the boats are closer to the cargo vessel category.

The displacement curves (figure 38) show that we are dealing with boats with high cargo capacity for the group of boats we have analysed. With its rockered bottom, model 1 has a higher draught for a given load, while the higher freeboard means that it can carry more. The rocker is seen as a curve, while model 2 displays the straight line of a box shaped cross-section.

The fact that reconstruction No 1 has a slightly higher GM value than reconstruction No 4 is rather surprising. If we take a look at the rest of the stability values however, reconstruction No 4 (R4), seems to be much more stable than reconstruction No1 (R1). The downflooding angle of R4 is 32.6 degrees while for R1 is only 12.2 degrees which means that R1 will take water in a much lower degree of heeling and consecutively in a lower wave. This is supported by the fact that the critical wave height of R4 is 1.24 m while for R1 is just 0.91 m, and also by the fact that R4 can sail up to Beaufort wind force 5, while R1 can take only up to Beaufort force 3.

The rolling period is quite low and identical for both models. This rolling period suggests that the boat is rather uncomfortable to sail in and could be related to the seaworthiness of the boat. Jensen claims that better seaworthiness, even though is difficult to quantify, it is mostly based on how pleasant or not is the sailing experience on a boat (1999: 57). According to the same author, a tender boat is a more “dry” experience than a rigid one (Jensen 1999: 57). Both reconstructions are stiff with an index stability value of 0.8, which theoretically makes them less seaworthy, but the question of seaworthiness could be better answered by the observation of the models’ performance in open water.

North Ferriby Model 1 (reconstruction No 4)

Dimensions

Length overall	L_{OA}	15.80	m		Depth of hull	D	0.98	m
Length at waterline	L_{WL}	13.84	m		'Standard' draught	T	0.59	m
Maximum beam	B	2.56	m		Minimum draught	T_{MIN}	0.31	m
Waterline beam	B_{WL}	2.33	m		Maximum draught	T_{MAX}	0.75	m
Maximum hull speed	S_{MAX}	9.00	kts		Draught-Depth ratio	100 D/T	60.0	%

Volumes, areas and weights

Displacement, volume	∇	8.775	m^3		Moment of inertia	I	281.53	m^4
Displacement, weight	Δ	8994	kg		Estimated weight of boat		3131	Kg
Wetted surface area	A_{WS}	29.77	m^2		Deadweight		5863	Kg
Waterplane Area	A_{WP}	23.9	m^2		Maximum Deadweight		10048	Kg
Midship Area	A_M	1.174	m^2		Deadweight to sink		24560	Kg

Coefficients and ratios

Length-beam ratio	L:B	5.9			Block Coefficient	C_B	0.473	
Length-draught ratio	L:T	23.5			Prismatic Coefficient	C_P	0.540	
Beam-draught ratio	B:T	4.0			Waterplane Coefficient	C_{WP}	0.740	
Displacement-length ratio	$L_{WL}/\Delta^{1/3}$	6.7			Midship Coefficient	C_M	0.855	

Stability

Centres					Stability Criteria			
Centre of Bouyancy	KB	0.37	m		Downflooding Angle	θ_f	32.6	°
Centre of Gravity	KG	0.38	m		Minimum Freeboard	F_{MIN}	0.23	m
Metacentre	KM	1.21	m		Freeboard, heeling test		0.40	m
Metacentric height	GM	0.83	m		Rolling period	T_R	2.0	sec
Heeling calculations					**Other standards**			
Critical wave height	h_{CRIT}	1.24	m		GM-beam ratio	GM/B_{WL}	0.36	
Significant wave height	h_s	0.98	m		Roll Period-Beam ratio	T_R/B_{wl}	0.86	
Approximate wind speed		6.5	m/s		Angle of max. stability	AMS	24	°
Beaufort		4			Angle of vanishing stability	AVS	34	°

Table 10. Hydrostatic calculations of Ferriby 1, reconstruction No.4.

North Ferriby Model 2 (reconstruction No 1)

Dimensions

Length overall	L_{OA}	15.40	m		Depth of hull	D	0.70	m
Length at waterline	L_{WL}	13.82	m		'Standard' draught	T	0.42	m
Maximum beam	B	2.60	m		Minimum draught	T_{MIN}	0.18	m
Waterline beam	B_{WL}	2.30	m		Maximum draught	T_{MAX}	0.47	m
Maximum hull speed	S_{MAX}	9.00	kts		Draught-Depth ratio	100 D/T	60.0	%

Volumes, areas and weights

Displacement, volume	∇	7.371	m^3		Moment of inertia	I	256.68	m^4
Displacement, weight	Δ	7555	kg		Estimated weight of boat		2643	kg
Wetted surface area	A_{WS}	27.97	m^2		Deadweight		4912	kg
Waterplane Area	A_{WP}	16.48	m^2		Maximum Deadweight		6095	kg
Midship Area	A_M	0.85	m^2		Deadweight to sink		14920	kg

Coefficients and ratios

Length-beam ratio	L:B	6.0			Block Coefficient	C_B	0.566	
Length-draught ratio	L:T	32.9			Prismatic Coefficient	C_P	0.629	
Beam-draught ratio	B:T	5.5			Waterplane Coefficient	C_{WP}	0.712	
Length-Displacement- ratio	$L_{WL}/\Delta^{1/3}$	7.0			Midship Coefficient	C_M	0.878	

Stability

Centres					Stability Criteria			
Centre of Bouyancy	KB	0.23	m		Downflooding Angle	θ_f	12.2	°
Centre of Gravity	KG	0.28	m		Minimum Freeboard	F_{MIN}	0.23	m
Metacentre	KM	1.12	m		Freeboard, heeling test		0.2	m
Metacentric height	GM	0.85	m		Rolling period	T_R	2.0	Sec
Heeling calculations					**Other standards**			
Critical wave height	h_{CRIT}	0.91	m		GM-beam ratio	GM/B_{WL}	0.37	
Significant wave height	h_S	0.72	m		Roll Period-Beam ratio	T_R/B_{wl}	0.87	
Approximate wind speed		5.4	m/s		Angle of max. stability	AMS	14	°
Beaufort		3			Angle of vanishing stability	AVS	30	°

Table 11. Hydrostatic calculations of Ferriby 1, reconstruction No.1.

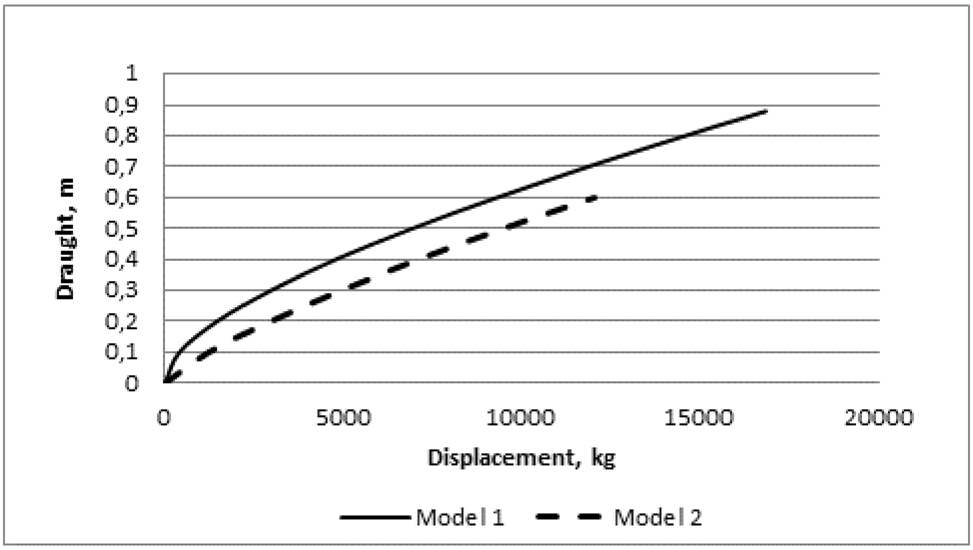

Figure 38. North Ferriby 1. Displacement curves for the two models.

Model tests

Constructing the models

As it is stated in the introduction of this chapter, we attempted to build two models of the Ferriby 1 boat during this project, one for each proposed reconstructions discussed above. Both models were built in scale 1:20, using the same materials and the same methods, but with a slightly different start. All these issues will be briefly discussed on this part of the chapter.

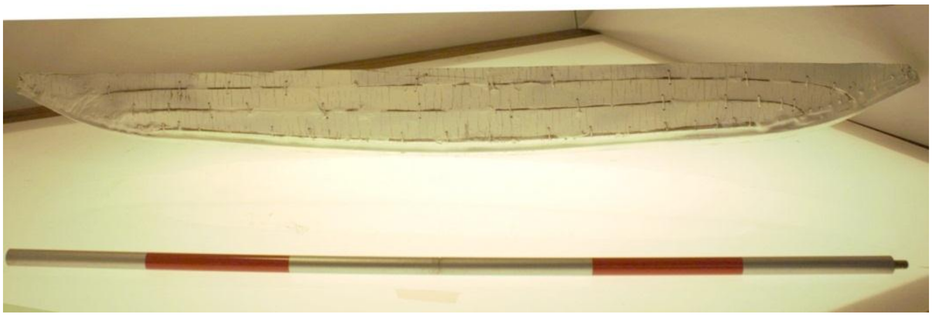

Figure 39. Scaled model of reconstruction No.4.

Figure 40. Scaled model of reconstruction No.4 (painted).

Before we started to build a 1:20 wooden model of reconstruction No.4 (Figure 39, Figure 40) we attempted to reconstruct the model in cardboard by using the planks plan that Coates and Wright have published in the report of 1990 (Wright 1990: 100). We encountered problems when we tried to connect the ends of the side strakes to the keel-plank as they did not seem to match. Our next approach was to use a software that could solve the problem of the planks plan. Having already a model of reconstruction No.4 in DelftShip, which we created by using the lines plan of the reconstruction published by Wright (1990: 106-7), we simply generated a new planks plan by the click of a button and had a satisfactory result. That planks development was then printed out in scale and used as a guide for the cutting of the wood. The wood we used was a 3.5mm thick plywood. The bottom structure was cut out as a whole and an extra keel-plank was added in order to give the right thickness. The side strakes were not cut into three planks, but they were sawn as solid pieces to avoid extra stitching. The assemblage started by sewing the first side strake (S1) to the bottom structure with metal wire. When the two lower side strakes (S1a+b) were connected to the bottom structure, a slight rocker appeared on the bottom of the hull. Consequently the second strakes (S2a+b) were added and the effect became even more evident. Because the purpose of the models is to duplicate the outside shape of the hull, we did not place the thwarts on top of the S2 strakes and we advanced directly to the placement of the third strakes (S3a+b). Once S3a and S3b were put in place, the model almost automatically took the required shape and there was no need to add any type of internal framing. The model was then treated with epoxy glue in order to cover the wholes from the stitches and be made watertight. Finally the model was painted and varnished for aesthetic reasons and to protect it.

Figure 41. Scaled model of reconstruction No.1.

The model of reconstruction No.1 (Figure 41) was built in the exact same way as reconstruction No.4. The difference is that we did not have a lines plan for this model and the only directive information we had was the dimensions that McGrail (2001: 186) and Coates (2005a: 40) give for this reconstruction. The way we proceeded in order to make the replica was to modify the DelftShip model we already had for reconstruction No.4. What we did was to remove a strake from the previous model and drag the control lines to a shape that seemed to be close to what was described in the bibliography. Consequently we printed in scale the new planks development and started building the model as described above.

The lines plan produced in DelftShip for the two models are given in figures 42-43.

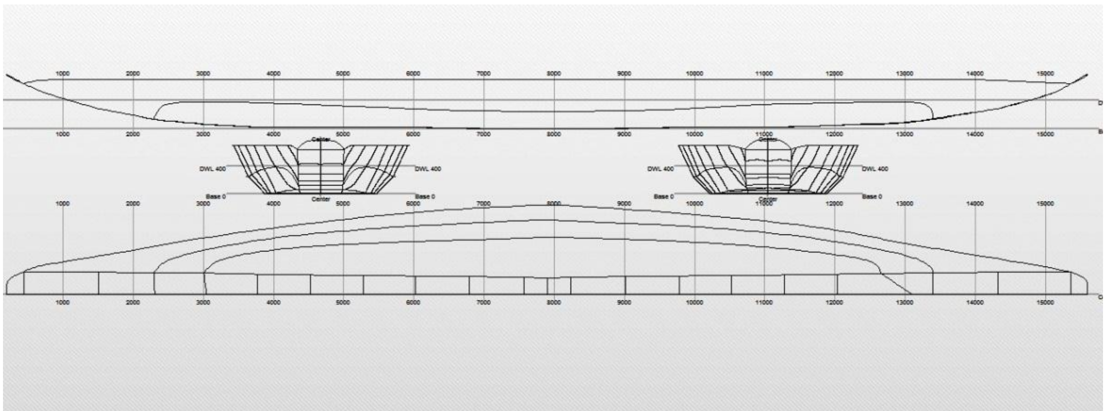

Figure 42. Lines plan of reconstruction No.1 as developed in DelftShip.1:100.

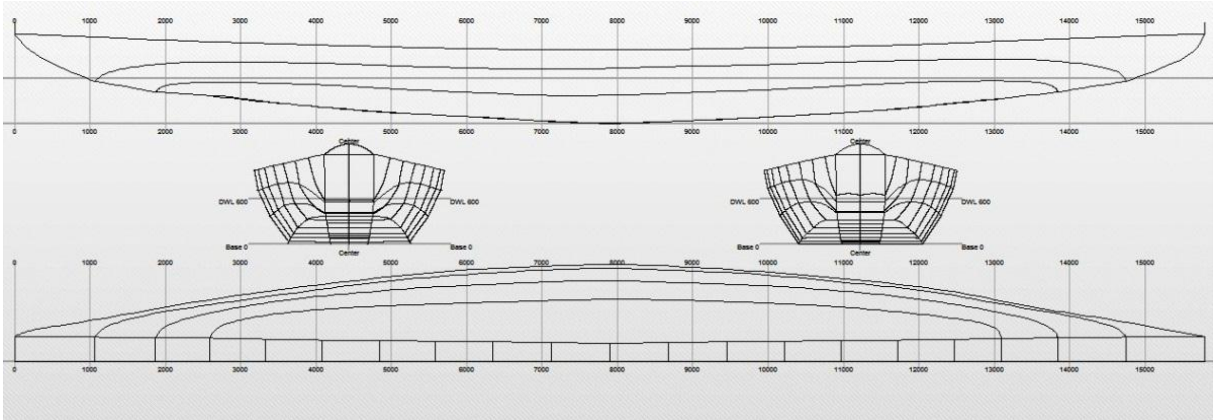

Figure 43. Lines plan of reconstruction No.4 as developed in DelftShip.1:100.

The tests

First of all we have to state that the equipment we used for the test, the models themselves and the software we used for the analysis, were not the optimal neither the most accurate, hence the results should be attentively interpreted.

The experiment itself is extensively described in chapter 2 but in brief, we conducted four different runs to observe the two Ferriby boats' behaviour in open water. One of the runs was a speed test in calm water, while the other three were testing the reaction of the models in waves. All the waves were coming on the starboard bow. The specific conditions of these tests are presented on the tables below (Table 12, Table 13)

In order to achieve the pre-set draught of 60% we added extra weight on the two models. A first observation that could be made is that model 2 (reconstruction No.1) was way overloaded on that draught since the T_{MAX} is 47cm and the draught we set was 42cm. This setting minimized the freeboard and made the model more unstable in its performance.

Speed tests

The purpose of the speed test was to see whether the hull is a planning or a displacement hull. To achieve this we made the model exceed the maximum hull speed which in the case of both models is 9 knots. The speed we achieved for model 1 (R4) was 13.5knots, while for model 2 (R1) it was 12.2 knots. The -unsurprising- observation is that both hulls are displacement hulls, as they dipped the stern deeply into the water at these speeds.

Model 1 (R4)

Test run 1

During the first test the model was towed at a maximum speed of 6.6 knots. We measured the wave height of 5 waves and found an average height of 1.76 cm, a significant wave height of 2.75 cm, a period of 0.39 s and a length of 0.24 cm. When scaled, this would be equal to waves with an average height of 0.55 m, a period of 1.7 sec and a length of 4.87 m. The average wave height is still well below the boats critical wave height of 2.46 m.

In these waves the model had an average pitch of 17.2° which was the highest pitch angle we encountered in the tests. The heel was 28.1° on average which is still below the boat's downflooding angle of 32.6°. During this test the model had a water intake of 34g, which scaled corresponds to 272kg.

Test run 2

During the second test the model was towed at a maximum speed of 6.6 knots. The scaled average wave height of 5 waves was 0.64m. The wave period was 1.1sec and the length 2.04m. The average wave height is well below the boats critical wave height of 2.46 m.

In these waves the model had an average pitch of 11.3°. The heel was 28.4° on average which is still below the boat's downflooding angle of 32.6°. During this test the model had a water intake of 150g, which scaled corresponds to 1200kg. This was the highest water intake observed during the tests. The addition of 1200 kg in the displacement of the boat however, was not critical and did not result in the sinking of the model.

Test run 3

During the third test the model was towed at a maximum speed of 6.6 knots. The scaled average wave height of 5 waves was 0.83m. The wave period was 1.6sec and the length 3.98m. The average wave height is still well below the boats critical wave height of 2.46 m.

In these waves the model had an average pitch of 13.7°. The heel was 28.4° on average which is still below the boat's downflooding angle of 32.6°. During this test the model had a water intake of 110g, which scaled corresponds to 880kg.

Discussion

The three test runs are summarized in Table 12.

Test run	Height of wave (h_S, m)	Length of wave (λ, m)	Angle, °	Boat speed, kts	Pitch, °	Heel, °	Water in kg
1	0,55	4,87	6,4	6,6	17,2	28,1	272
2	0,64	2,04	17,5	6,6	11,3	28,4	1200
3	0,83	3,98	11,8	6,1	13,7	28,4	880

Table 12. Test results for model 1 (reconstruction No.4).

If we take an overall view of the tests we observe that the shipping of water varied regularly with the steepness of the waves (Figure 44). The highest wave angle in test two resulted to the highest water intake, but this could also be a result of the shortest wave length, which would hit the boat at least 7-8 times over its length.

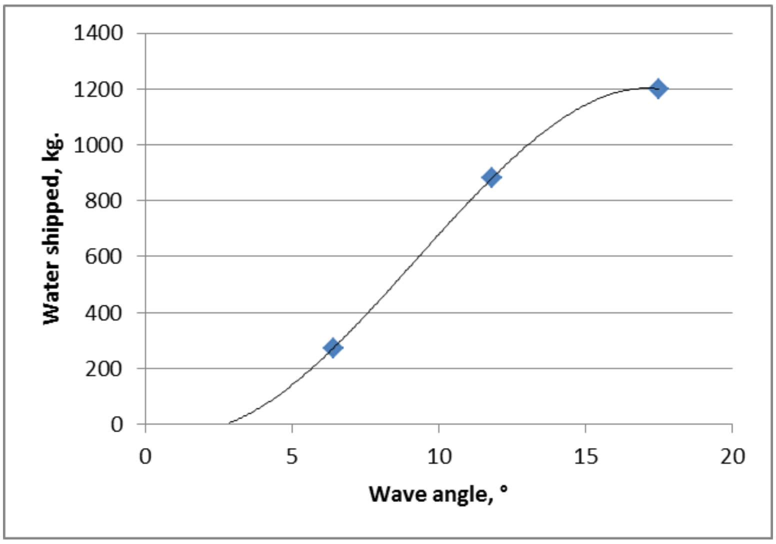

Figure 44. North Ferriby 1, model 1. Amount of water shipped during tests. A trend line is fitted.

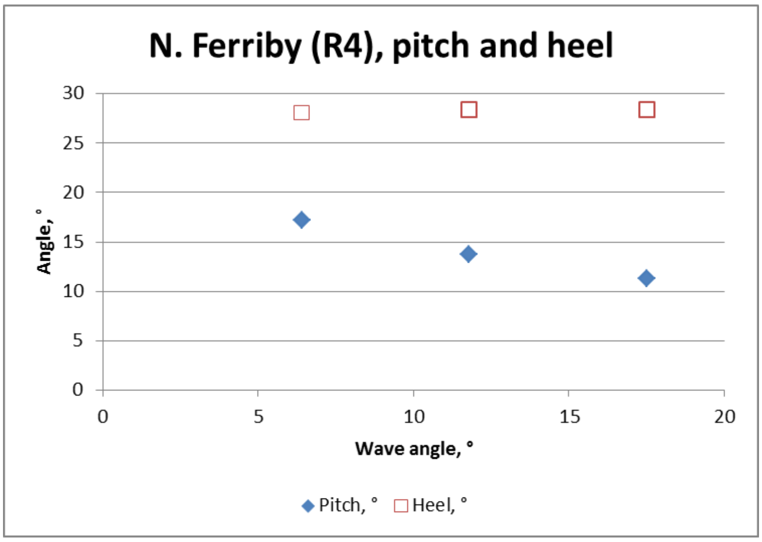

Figure 45. North Ferriby 1. Pitch and heel.

The relation between wave angle and pitch/ heel was somewhat surprising at first. The maximum heel remained constant throughout the three runs, while pitch decreased with steeper waves (Figure 45). Again this may be related to the short length of these waves compared to the length of the boat. The steepest waves had the shortest wave length, and the hull would therefore be carried over several wave crests at any given time, reducing pitch. The specific direction of the waves as they spread from the wave maker may also influence this result.

Model 2 (R1)

Test run 1

During the first test, model 2 was towed at a maximum speed of 5.5 knots. The scaled average wave height of 5 waves was 0.76 m. The wave period was 1.4 sec and the length 3.12 m. The average wave height is still a bit below the boats critical wave height of 0.91 m.

In these waves the model had an average pitch of 4.7°. The wave's angle for this test was 13.6° which is a bit over the boat's downflooding angle of 12.2°. During this test the model had some water intake, which we did not measure but it seemed to be a relatively low value.

Test run 2

During the second test, model 2 was towed at a maximum speed of 4.8 knots. The scaled average wave height of 5 waves was 0.77 m. The wave period was 1.4 sec and the length 3.25 m. The average wave height is still a bit below the boats critical wave height of 0.91 m.

In these waves the model had an average pitch of 14.5°. The wave's angle for this test was 13.4° which is a bit over the boat's downflooding angle of 12.2°. During this test the model passed successfully in front of the grid, but had such a water intake that sank shortly after.

The fact that such a small difference between wave no. 1 and wave no. 2 resulted to such different behaviour, probably means that 0.76 was the critical wave height for the constructed model and led to the boat pitching and heeling dramatically more. This result also means that the model was not accurately reconstructed from the given lines plan.

Test run 3

During the third test, model 2 sank before arriving to the grid. We could thus measure only the waves. The scaled average wave height of 5 waves was 1.09 m. The wave period was 1.6 sec and the length

3.87 m. As we can see the average wave height is over the boats theoretical critical wave height of 0.91 m.

Test run	Height of wave (h_S, m)	Length of wave (λ, m)	Angle, °	Boat speed, kts	Pitch, °	Heel, °	Water in kg
1	0,76	3,12	13,6	5,5	4,7	25,6	Some (not measured)
2	0,77	3,25	13,4	4,8	14,5	30,6	sank
3	1,09	3,87	15,7				sank

Table 13. Test results for model 2 (reconstruction No.1).

Discussion

The tests we conducted and the models we created for this experiment are certainly not the most accurate ones and the results we have are not enough to give us a safe answer to the question of the use of Ferriby 1. Some simple observations however, can be made from the way the models behaved in the water.

Model No.2 (R1) seems to be extremely unstable and uncomfortable to sail in. We believe that it could only be suitable for the cross-estuarine transfers in Humber. In difficult weather conditions though, if the boat would carry heavy cargo, it would be really difficult to manoeuvre and even to cross the Humber safely.

Model No.1 (R4) is much more stable than model 2. This model is seaworthy as it seems to be relatively safe even with a big amount of water on board. The model could be characterised an inshore boat and would have no problem sailing along the east coast of England. Whether similar boats would regularly cross the Channel is a more open question, as the flat bottom in combination with the occasionally very choppy waters would make for an unpleasant ride. The boat is perfectly capable of making the journey, though.

If we had to come up with one conclusion regarding the use of Ferriby 1, we would say that most probably it would be used as an inshore or coastal cargo boat. The high cargo capacity of such a longboat as Ferriby 1 makes it look like it would be an extreme waste of possibilities and resources for it to be used strictly as an estuarine ferry.

5. SINGAPORE SAMPAN

Introduction

The rich and lively waters around Singapore have seen for at least the last two centuries this small pram-style boat (also known as Sampan Kotak), a perfect example of "*melting pot"* in boatbuilding. The almost total absence of sources regarding the history and characteristics of this vessel could be explained by its nature of a working vessel and by the fact that, as it will be explained later, this Sampan is not built by a specific guild as happens for other traditional vessels of the area.

One of the earliest accounts of the presence of this boat in Singaporean waters is a painting done by General Charles Dun in 1854. In the painting, several typical boats of the area are depicted on the Singapore river and in the foreground are clearly visible the curves of a Singapore Sampan with its "o*culus*". Gibson-Hill (1952: 96) refers to sampans being visible in the painting as Chinese shoe-boats as early reported by Cameron (1865: 55) describing a plate in his text about the English possession in Malay.

Although Singaporean sampans have appeared often in paintings and memories of western visitors in Singapore, only in 1906 in the "*Mast and Sail in Europe and Asia"* by Warington Smyth (1906: 335), is it possible to find a brief account on this boat. Smyth refers to the Singapore Sampan as "high-sided Chinese junk" which was only able to sail along the coast between October and February, when the weather otherwise does not allow local navigation. Furthermore Smyth classified these small craft as a member of the Chinese Sampans family, describing them as:

> *"[…] gaily painted, two-tailed boats […] great beam, flat bottom, and deep rudder, they are good carriers and rapid sailors, but their best point of sailing is undoubtedly a 'soldier's wind"* (1906:418).

Even though Smyth reports about the sailing properties of this sampan, often the most used source of propelling is human force, as clearly visible in several illustrations of the Singapore harbour, with a crew of maximum three (Gibson-Hill 1950: 163).

The only available lines plan and detailed drawings of the Singapore Sampan were made by William Maxwell Blake during his stay in Singapore. These drawings are the only direct documentation on this scarcely considered traditional craft and actually are part of "*The William Maxwell Blake Collection of Drawings of Far East Watercraft*" in the Smithsonian's collection of watercraft plans, maintained by the History of Technology Division of the National Museum of American History. Between 1906 and 1920, William Maxwell Blake (1874-1939) worked as naval architect (Classic Yachts) and on his return to England, published several short articles on watercrafts he found in Singapore and in the surrounding areas. The lines plan and the detailed drawing of the Singapore Sampan is a pure piece of art, making possible this study thanks to the precision and richness of details.

Gibson-Hill in his article *The fishing Boats operated from Singapore Islands* (1950: 160-165) outlines better the occurrence, placing them in the *"Chinese Keelless Boats"* family, and outlining the distribution area of the Sampans Kotak which is limited to the Singapore Islands. Although the general design lines are followed, there is a considerable local variation in the form and size from sampan to sampan, and the largest reach a maximum length of about 10 meters and a maximum beam of 3 meters. Furthermore, Gibson-Hill (1950: 163) claims that generally the larger models, despite the wide beam and gently flat bottom, are too heavy to be beached and are left in the water, while the smaller specimens are beached or moored where the receding tide could leave them grounded.

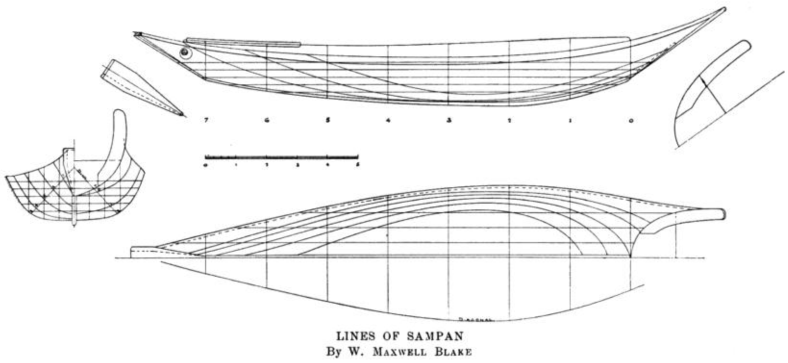

Figure 46: Lines plan of the Singapore Sampan by W. Maxwell Blake (Drawing courtesy of History of Technology Division, National Museum of American History).

In addition, regardless of the limited homogeneity within the Kotak, two families could be distinguished: the Singapore Kotak and the Penang Kotak. The only palpable difference lies in the dimension of the bow; in the Singapore it is wide and relatively short while in the Penang type the bow is narrow and high (Gibson-Hill 1950: 161).

Figure 47. An undated picture from Singapore Quays. Several Sampan and bumboats are visible. Notice the overloaded sampan Kotak in the front (from Missing the Past, Singapore River, accessed on 24.04.12).

The main role of this vessel is to transport goods or passengers, as suggested by its Malaysian name “Kotak” that means “container”, around the Singapore harbour from the large ships stationed off the port and the harbour warehouse or quays (Jayapal 1992: 31). This procedure was, and still is, caused by the condition of the seabed, as it will be explained later, that does not allow the access of the harbour to large vessel. The small examples are also used for fishing off Singapore Island (Gibson-Hill 1950: 165).

After the "Clean-up Rivers Campaign" in the 1980s, few examples of these Sampans still remain in Singapore, but just moving around the coastal areas of mainland Singapore and the surrounding islands it is possible to notice the continuation of the tradition.

Using Maxwell Blake's drawing as base, an analysis of the boat was attempted while also analysing its socio-cultural-geographic context trying to identify those features that make the Singapore Sampan a perfect example of "melting pot" in boat building.

Description of the boat

Focusing on the size and design of the bow, the Sampan Kotak here analysed is clearly of the Singapore type, with dimensions of 6 m overall, a beam of 1.53 m and a depth amidships of 0.7 m, is probably one of the smallest examples.

The Singaporean Sampan is of flush-strake construction with a wide round beam and transom raked both bow and stern. Examining the shape of this traditional craft the first noticeable characteristics, in contrast with the other Sampan-like constructions, are the slender breadth lines and the triangular short bow. As in line with the "Chinese Keel-less Boat" tradition, the Singapore Sampan has a rockered bottom provided with a false keel of 5 cm sided, attached at the centreline from the bow to the stern end section.

From the body plan is visible that the boat starts in a V-section at the bow, the lines evolving in a gentle rounded shape at mid-section with a flattish bottom, a usual shape for small-crafts that are frequently hauled up on the beach. The waterlines show a modern design, since the bow is fine and the widest section is aft the amidships ending with a full stern. This design is actually used by modern day cruisers, characterizing displacement and semi-displacement hull (Brewer 1994: 22).

The elegant rocked shape of the sheer plan ends at the stern with a high double tail, a similar feature is visible on Shanghai Sampans, while the prominent prow is ornamented on both sides by the typical "oculi".

The flush-laid planking of 2 cm of thickness develops till the gunwale delimited by a semi-circular wale, with a height at amidships of about 50 cm. The freeboard of this sampan is increased thanks to an internal extension; a 10 cm high coaming connected to the gunwale by side-decks of 10 cm in width. This extended coaming is kept in place by a sort of hanging knee fixed on the bulkheads and the futtocks.

The frame system and other features

The Singapore Sampan is built with a frame system clearly attributable to the Chinese tradition, since the presence of bulkheads and ribs. Analysing the vessel from the bow, it is possible to synthesize the frame system as follows:

Bow Stern

Transom	Bulkhead	Floor Timber	Floor Timber	Bulkhead	Floor Timber + Futtock	Floor Timber + Futtock	Floor Timber	Bulkhead	Floor Timber	Floor Timber	Transom

The internal framing (but also the lines of the vessel) reminds the *Chao-T'ou* (*T'ai-Wan Sampan*) with the difference that, in the Singapore Sampan, there are only two floor timbers connected with futtocks. The bulkheads divide the boat in three watertight compartments and the first one, near to the bow, has a specific function. According to Worcester (Worcester 1956: 312) that described the same device on the *Chao-T'ou* and that is still a common practice in the South-East Asia sampans, the foremost compartment is free flooding. The empirical explanation given by the junkmen to this feature, is that it helps to decrease the stress of the vessel in case of head resistance of the sea. The flooded compartments should balance the difference of pressure between the outside and the inside and consequently reduce the pounding and the related "painting" phenomenon.

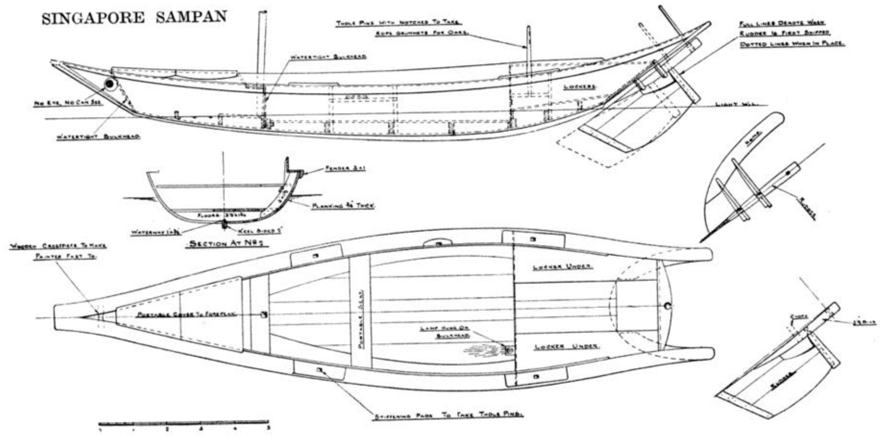

Figure 48. Details plan of the Singapore Sampan by W. Maxwell Blake (Drawing courtesy of History of Technology Division, National Museum of American History).

From the drawing, only two of the seven floor timbers are fitted out with a futtock, particularity not seen in other traditional sampans, which are simply laterally joined. The floor timbers do not seem connected to the false-keel since, precisely on the false-keel line, are present holes with a function of waterways. From the head bulkhead and the last one, a series of strakes create a steady ceiling planks system supported by the floor timbers.

Two lockers along each side between the third bulkhead and the transom, delimit the area used for steering the sampan or rowing it with two long oars and keeping personal possession. Forward of amidships a moveable seat makes a seat for the crew, while a fixed thwart at the second bulkhead also has the function as mast-partner. Furthermore, between the fixed thwart and the first bulkhead, a portable cover to the foreship is fitted out, creating a sort of compartment that could be filled with goods or, in case of fishing vessels, the planks are pierced allowing the flooding of the compartment to keep fish alive (Gibson-Hill 1950: 164).

On the gunwale, two stiffening pads on each side are fixed to support the thole-pins, for two pairs of long-shafted oars, while a lamp holder is placed on the third bulkhead just forward of one of the lockers.

An element, which is always present in the South-East Asia tradition, is the characteristic *oculus* on the external side at the bow. The *oculi* are rounded in shape and looking at the water since, as also noted on the drawing by Blake, the junkmen believe that without them the vessel would be "blind" and could not see the fish (Worcester 1956).

At the bow, at the level of the *oculi*, a wooden crosspiece is used to tie a painter. From the drawing, but not found mentioned in any sources, this crosspiece seems to be in relation with the *oculi*, as though the *oculi* are the top head of the crosspiece creating a sort of cross-beam. This could be the origin of the widely spread phenomenon of the oculi.

The Singapore Sampan, although a small inshore vessel, can be fitted with a mast (which is why it has a thwart mast-partner) and rigged for sailing, generally with a battened Chinese lug sail. The mast and sail comes together with the attachment of an axial rudder. The rudder is drawn in two different line types to show the two different positions that can be assumed one when not used and one when fitted out. This feature probably allows to haul up the boat more easily or to sail in shallow water, where the raised rudder is advantageous.

Construction techniques and materials

In Malaysia, as well as in all the South East Asia, two traditions in shipbuilding coexist: the Malay modification of the European technique and the Chinese Tradition. Although there are no direct source about the building technique used for the Sampan Kotak, it is possible to theorize since it is linked to the Chinese background that the Kotak is built according the Chinese Tradition.

The well documented method (Waters 1946; Gibson-Hill 1950; Bucknell 1955; Worcester 1971) is essentially the shell-first technique, where the hull of the vessel is built first then the frames are fitted later. The planks are first pegged with iron or wood dowels and after, being bent with the aid of slow fires, set butted to each other. Subsequently, frames are inserted and nailed to the planks. The bulkheads, some floor timbers, the transom and the bow pieces are set as soon as the garboard and the first two or three bottom planks have been laid (Gibson-Hill 1950: 159), helping the shaping of the hull, such as in the case of the Chinese cargo boat *"Twaqo"* built in Singapore (Waters 1946: 158-168).The seams are caulked with a species of oakum or discarded fishnet and covered with a caulking compound, a cement-like filling of lime and wood oil.

Regarding the wood used for the construction of the Kotak, it is probable that shipbuilder have adapted to the local available specimens trees. Three woods in Malaysian shipbuilding are mainly used, the Chengal, the Giam as reported by Waters (1946) and the Maranti, preferred by Chinese shipwrights (Gibson-Hill 1950).

The Chengal is a slow-growing hardwood (the density range is between 915 to 980 kg/m^3) and very durable (FRIM 2011a). With a breaking strength superior that of oak, both radially and horizontally, this wood is highly flexible, making it perfect for bending planks and, like teak, it contains protective compounds that defend the heartwood giving an high durability over the years also in exposed conditions (Bever 1986: 5036).

The Giam is another autochthonous hardwood (the density range is between 865 and 1220 kg/m^3) tree characterized by a pale yellow wood, close-grains, elasticity and very high durability (FRIM 2011b). Suitable for all general light construction, the Maranti is light red-brown wood (the density range is between 595 and 755 kg/m^3) which lightness is offset by its low durability (FRIM 2011c).

The context: Singapore and its community

The Singapore harbour

The maritime vocation and the commercial spirit of Singapore are unmistakable since its foundation. Although its history started under the name *Mahasin* nearly 950 years ago (Colless 1969: 1), Singapore as known today began its transformation in 1819 with the foundation of the harbour by Sir Thomas Stamford Raffles (Marres 1941: 226). As the same Raffles confessed the 22 February 1819, "*It has been my good fortune to establish this station in a position combining every possible advantage geographical and local*" (after Dobby 1940: 84), Singapore is located in a vital strategic point at the end of the Malacca strait and at midway between the Indian Ocean and the South China Sea.

Built on Island composed by a network of marshy contiguous islands and waterways, the town became a free-port in which trade and commerce developed rapidly. The Island was under the control of British India and in 1832, Singapore, became the centre of government of the Malaysian possessions. Due to the exponential growth of the town and the increasing importance of the harbour, Singapore became a Crown Colony on 1 April 1867 and was ruled by a governor under the jurisdiction of the Colonial Office in London (Abshire 2011: 37-59).

The dynamic harbour area has been developed on the estuary of the 3.2 km long Singapore Strait known also as the "River". The riverine calm waters were ideal for trading activities, and served as the waterfront for the growing British Settlement. In 1823, the first quay called "Boat's Quay" was built, where warehouses and docking facilities were established (Ryan 1976: 123), and became a focal point from where several companies set-up in Singapore. Among the first European trading house was that founded by Alexander Laurie Johnston, who was considered as one of the Singapore's pioneer businessmen (Cornelius-Takahama 2001). In the 1860s, the river's scarce and unsuitable berthing facilities and the increase of shipping led to the development of the New Harbour (later called Keppel) that was already in use around 1852 (Dobbs 2003: 11).

Figure 49. View of Singapore's Harbour in the 1930's. Noteworthy the small sampan Kotak in the middle used as ferryboat (from Postcards of the Past Singapore, accessed on 24.04.12).

On the one hand, the presence of the river has allowed the development of both Harbours, on the other hand it has been and still is dangerous to navigation due to the silt transported and the formation of sandy or muddy bars. Looking at one British pilot book dated to 1867 (Admiralty hydrogr. dept.: 263-270), it was quite easy to approach the Singapore Strait from different direction, having a depth ranging from 30 to 10 fathoms (a British fathoms is 1.85 m). However, the situation changes profoundly in proximity of the harbour, where a shallow and "intricate" mud seabed (1867: 277) with a depth of 3 fathoms limited the access to vessels with a deep draught. This factor with the combination of strong tides (1867: 286) probably have contributed to the development of light crafts as best adaptation to these conditions, since shallow draught and knowledge of the seabed by the local sailor allowed the moving of goods between the anchored ships and the quays through the treacherous shallow waters .

The Climate

Although often described as "monsoon" climate, a relic of the colonial domination of the British India (Dobby 1940: 91), Singapore is an example of insular equatorial climate with a constant average of rainfall during the year. The monotonous weather, with constant winds and rare storms, slightly changes between April to May and October to November where winds are less constant and thunderstorms are usual (Dobby 1940; 92).

Thus the general favourable weather and the calm waters have always ensured a safe navigation, probably influencing the seaworthiness requirements for boats that with these conditions could be minimized.

Sampans and migrations

The Chinese origins of the Sampan Kotak are supported by several anthropological and linguistic evidences. Browning any handbook or dictionary of the Malay language, it is possible to encounter statements such as:

"*Sampan Kotak : a chinese Sampan"* (Hamilton 1944: 108)

Although the term “Sampan” gave rise to heated debates between scholars to locate the provenance, either localized in Cambodia, China or Malaysia, the Chinese origin is commonly accepted (Péri 1919: 13-19). The literal meaning in Chinese of the word “sampan” is three planks and is applied to any Chinese open or half-decked small boat (Worcester 1948: 505). While in Malaysian, it has no meaning but only used to label small boats or skiffs (Péri 1919: 13-14).

Comparing the sampans from the Chinese mainland with the ones in Singapore, the framing systems are identical; the similarities are notable thus pointing to the clear origin of these pram-style boats.

> *“[…] There are three bulkheads, forming four compartments […] the free-flooding foremost compartment, the standard pattern of gaudy design, and, sometimes, the oculus”* (Worcester 1971: 215).

This short description of a Shanghai Harbour sampan could be mistaken for a superficial description of a sampan Kotak, since the internal division and the decoration are the same. The similarity in shape and constructional pattern are the common points of the Chinese sampan in the South China Sea, as is the case of the Shanghai Harbour Sampan (Worcester 1971: 215) and the Kotak, which owe somewhat to Amoy influence in design.

The 19th century was the era of large-scale international migration. The movement of labour-force and capital from countries where they were relative abundant to countries where they were relative scarce was a necessary condition of the expansion of the international economy. The phenomenon interested also China, where factors such as demographic pressure, poverty, political instability and bands of armed bandits encouraged a mass migration of Chinese, especially from coastal areas (Pan 1998: 56).

Although the earliest recorded Chinese settlement in Malaya was a small community in Malacca around 1400’s, made up of *Hokkien* Traders, they were relatively insignificant. This changed when the Singapore British colonization of mass immigration was prompted by the new economic opportunities (Pan 1998: 172-173).

Stable connections were established between China and Singapore, through the *Fujian* province with base in Amoy (Xiamen). Amoy seaman, thanks to their sea-going experience, permitted regular and safe crossing of the South China Sea giving to the city of Amoy the role of emigration hub of *Fujian* (Pan 1998: 57).

Hence, these movements created an inevitable *melting pot* of traditions and cultural features around the South China Sea. The *Twaqo* or *Twa-kow*, for instance, is a perfect example of the direct consequence of the migration flow and can be used as a benchmark for comparison. This local bumboat coaster is still in use today, and was introduced in Singapore by Fujian people. Its construction is held by *Hokkien* speaking guilds, where Chinese tradition met Malaysian materials and requirements (Waters 1946: 158-159). It must be borne in mind that the organisation of workers in guilds was a typical feature of Chinese overseas communities. Guilds were characterized by one dialect community, which held also a slice of a specific market, such as trading or fishing in the case of the *Hokkien* (Neville 1966: 245-246). Although its role is of a heavy and slow cargo boat, it shares with the Kotak some constructional features such as the framing system and the *oculus*. The absence of a specific guild for the Kotak which holds its construction could be explained by its wide spreading diffusion and versatility that allowed its adoption by others communities.

A deeper study of the origin of the Sampan Kotak, under the social and anthropological point of view, could reveal precious information on maritime culture about the technological influence and cultural contaminations of the first Chinese overseas communities. Albeit an interesting aspect, it would have gone beyond the aim of this study.

Constructing the model

A fundamental step of this project was the construction of both virtual and real models of the boats. The availability of a precise lines plan, although the only existent, for the Singapore sampan allowed this without great difficulties.

The virtual hull model shaped in Delftship has been used to perform the hydrostatics analysis and building the in-scale from its planks development table. The virtual reconstruction of the Singapore sampan was limited only to the external hull, the only element that actually is important to the hydrostatics analysis.

Although the Blake lines plan is drawn without referring to a scale, a metric reference in the drawing itself permitted to build a 3D model and, due to the lack of information, it was decided to define a total of six planks as well as the two transom pieces.

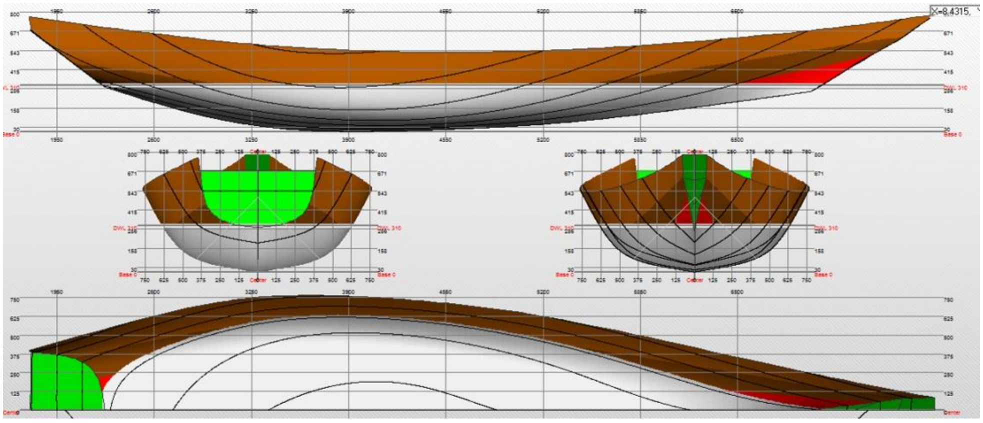

Figure 50. Plan Lines from Delftship.1:50.

The physical model in scale 1:20 was built according to the plank developments extracted from DelftShip. As material for the planks plywood of 1 mm was used with 2 mm plywood for the transom pieces. To assemble the model it was tried to simulate the same technique used by the Chinese shipwrights: the bow and stern pieces were secured in position and the bottom planks bent by the use of a source of heat. Subsequently, with the assistance of guiding frames corresponding to the bulkheads, the remaining planks were placed, bent and glued forming a strong shell.

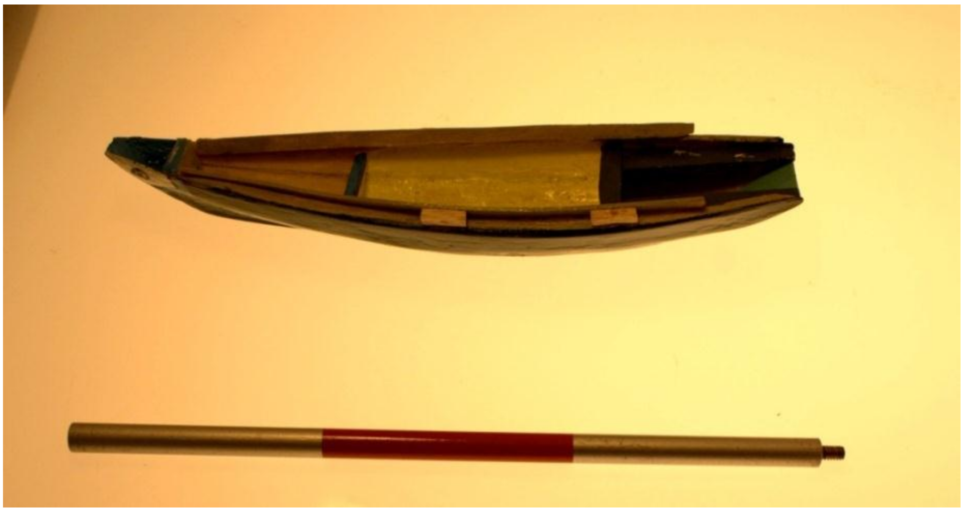

Figure 51. The model of the Kotak.

Additionally a false keel, made of balsa, was added as well as the extra wash-strakes, the lockers and the bulkheads. The resulting model correspond well to the original, showing that the curves of the planks naturally develop without the use of further frames and the bulkheads are guiding elements in the construction process.

Made waterproof by the use of epoxy glue, the small sampan has been painted and decorated with the distinctive *oculi* according to the tradition. The final total weight of the empty model is 42 grams, although greater than the supposed “empty” weight in the full scale exemplar, it does not reach the established displacement therefore leaving space for additional ballast.

*Figure 52. 3D reconstruction in Rhinoceros 4.0 and rendering in Blender 2.52 of the Singapore Kotak (*Ditta *del.).*

Hydrostatics and performance

Table 14 show the result of the hydrostatic and stability analysis performed with DelftShip, Orca3D on the 3D model and other values calculated with Excel. All the calculations were made with a fixed draught estimated at the 60% of the depth of the hull.

Observing at the Length-Beam ratio value of 3.8 is possible to assert that the examined Singapore Sampan is a stable and manoeuvrable vessel with a good compromise between stability and speed efficiency, an assessment supported also by the Prismatic Coefficient value of 0,5 that describes the fineness of the design. A low C_P value is index of better performance and less resistance on the water, a value that for small boats reaches its efficiency optimum between 0.52 and 0.54 (Phillips Burt 1957: 262) while a value 0.7 is usually considered a good compromise between adequate buoyancy and sufficient fineness in modern medium speed fishing vessels (Fyson 1975: 34). The Block coefficient of this sampan is very low, an important value especially for cargo vessels since a greater number means more load capacity but also C_B considerably affects resistance (Schneekluth & Bertram 1998: 24). The medium value of the L/B ratio combined with the low block coefficient, for the design theory, gave like result a boat with good course stability (Watson 1998: 257).

Considering another value such as the Displacement-Length ratio with a value of 5.1, the sampan could be labelled as a medium speed cruising boat, thus confirming the good compromise of the sampan hull design between speed efficiency and cargo/fishing needing.

An estimated GM value of 0.50 m can be compared to the rule of thumbs that a value greater than 0.15 m is needed for a small boat to be considered seaworthy (Philips Burt 1957: 262). This gives an idea of the reliability and the empirical experience in the design of the Sampan Kotak, confirmed also by the stability criteria GM-Beam ratio with a value of 0.38 that exceeds the minimum value of 0.1 by a broad margin. Both centre of Buoyancy and Gravity are well located deep in the hull, with a difference of only 3 centimetres between them.

Singapore Sampan

Dimensions								
Length overall	L_{OA}	6.00	m		Depth of hull	D	0.55	m
Length at waterline	L_{WL}	4.86	m		'Standard' draught	T	0.33	m
Maximum beam	B	1.53	m		Minimum draught	T_{MIN}	0.12	m
Waterline beam	B_{WL}	1.29	m		Maximum draught	T_{MAX}	0.42	m
Maximum hull speed	S_{MAX}	5.33	kts		Draught-Depth ratio	100 D/T	60.0	%
Volumes, areas and weights								
Displacement, volume	∇	0.859	m^3		Moment of inertia	I	5.103	m^4
Displacement, weight	Δ	880	kg		Estimated weight of boat		160	kg
Wetted surface area	A_{WS}	4.976	m^2		Deadweight		720	kg
Waterplane Area	A_{WP}	4.391	m^2		Maximum Deadweight		1165	kg
Midship Area	A_M	0.263	m^2		Deadweight to sink		2816	kg
Coefficients and ratios								
Length-beam ratio	L:B	3.8			Block Coefficient	C_B	0.360	
Length-draught ratio	L:T	14.7			Prismatic Coefficient	C_P	0.500	
Beam-draught ratio	B:T	3.9			Waterplane Coefficient	C_W	0.480	
Displacement-length ratio	$L_{WL}/\Delta^{1/3}$	5.1			Midship Coefficient	C_M	0.401	
Stability								
Centres					**Stability Criteria**			
Centre of Bouyancy	KB	0.21	m		Downflooding Angle	θ_f	16	°
Centre of Gravity	KG	0.24	m		Minimum Freeboard	F_{MIN}	0.13	m
Metacentre	KM	0.74	m		Freeboard. heeling test		0.1	m
Metacentric height	GM	0.50	m		Rolling period	T_R	1.9	sec
Heeling calculations					**Other criteria**			
Critical wave height	h_{CRIT}	0.69	m		GM-beam ratio	GM/B_{WL}	0.38	
Significant wave height	h_s	0.54	m		Roll Period-Beam ratio	T_R/B_{wl}	1.5	
Approximate wind speed		4.4	m/s		Angle of max. Stability	AMS	18	°
Beaufort		3			Angle of vanishing stability	AVS	31	°

Table 14. Singapore Sampan. Summary table.

Noteworthy is the relative low draught at several increasing displacement conditions, as shown on Figure 53, fundamental features in marshy waters and for an easy beaching. The shallow draught affects also the wetted surface area, only the 54% of the total external hull area at the fixed draught, which is an important variable in the resistance of the hull trough the water.

Figure 53. Singapore Sampan, displacement curve.

The freeboard and the downflooding angle are important values which inform about the reserve of buoyancy and the maximum heeling the vessels can afford without taking water. The values in the table are estimated without taking in consideration the additional 10 cm coamings that extends the available freeboard. Thus the downflooding angle that is at 16° at the gunwale, assuming watertightness of the extended structure, stretches to 22°. Same sort for the maximum freeboard that at the maximum safe load condition is at 0.13 m, with the additional strakes stretches to 0.23 m consequently allowing more manoeuvring freedom and a good degree of seaworthiness. Even if the coamings are not connected to the hull creating a wholly watertight structure, they still keep the interior hull dry, protecting from possibly sprays, as it has been visible in the model tests.

Since there is no information about the waterproofness of the coamings, the stability analysis was done without considering those elements. The angle of maximum stability is 2° more than the downflooding angle, so the two values are very close. The coamings would provide some extra degrees of safe heeling, as discussed below.

Moreover, according to the Roll Period-Beam ratio the Sampan Kotak could be considered a fairly comfortable and seaworthy boat since showing a value between stiff (1.0) and tender (1.5), with a rolling period of 1.9 sec.

To conclude, the hypothetical weather condition that could imperil the boat is estimated at Beaufort 3 with a critical wave height of 0.69 m, a wave that in case of hitting the beam could bring to a capsize since higher than the available freeboard. The sea under Beaufort 3 is usually characterized by a gentle breeze of about 12–19 km/h, a usually low danger condition that as it will be seen in the in-water tests is well faced by the boat thanks to its ability to ride the waves.

Model tests

As with the other boats, the model was towed for a total of four runs, with different types of waves hitting always the starboard side of the boat with an angle of 45°, using as reference the grid. In order to simulate the condition at the given draught of 60%, extra weight on the model was added as cargo, distributed in the several bulkhead compartments, and as crew, consisting of two in-scale weight positioned one at the lockers level while the second in the central compartment.

Preliminary Observation

A crude experimental test was carried out to superficially explore the hull speed properties, allowing to define whether is a semi-planning or displacement hull. The sampan was towed to exceed its maximum hull speed of 5.33 knots and reaching a speed of 14.7 knots, an obvious lift of the bow showed that it can be possibly labelled as semi-displacement hull.

Test run	h_S, m	λ, m	Angle, °	Boat speed, kts	Pitch, °	Heel, °
1	0.59	9.79	3.4	5.4	10.7	16.5
2	1.01	13.60	4.3	4.8	12.3	22.3
3	1.60	17.63	5.2	5.3	18.4	13.5

Table 15. Results of the sailing tests.

Test Run 1

This test was performed under waves with an average height converted in real scale of 0.58 m and a length of 1.26 m. The model, towed at a speed of about 5.4 knots, literally rode the waves with a pitch angle of 9.4° and a heel angle of 16.5°, corresponding to the downflooding angle without wash-strakes.

Figure 54. A snapshot of the pitching of the sampan during the run 1.

Test Run 2

In the second run, the waves were probably the most dangerous for this boat with a height of 1.04 m and a length of 0.50 m. The bow of the boat in theory should have been overwhelmed by the crest of the wave, since it has a height of 77 cm. The model, under a speed of 4,8 knots, instead reacted simply riding without difficulties the waves, with a pitch of only 5.9° and an heel angle of 22.7°. Such a wide angle of heeling it could be explained thanks to the additional coamings that give a further protection against flooding and an extension of the heeling ability and, for a certain degree, also for the physical phenomenon called superficial tension of the water that could affect small models.

Test Run 3

The last test simulates what could be called long-waves, typical of rough open sea, with a height of 1.54 m and a length of 13.09 m. Also in this case the model, towed at 5.3 knots, has dealt admirably with the water conditions. Although the sampan reached a pitch angle of 18.7°, it overwhelmed in complete dryness the crest of the waves, while the heeling angle was only of 13.5° thus under the minimum downflooding angle(without coamings).

Indoor Tests

A static heeling test and maximum load capacity test were performed in an indoor water basin. The former was achieved moving all the ballast and the weight simulating the crew on one side. It has been seen that the model well answered to this test, with a result of an available freeboard on the heeled side of 10 cm (scaled). Maximum load capacity test was run to estimate the weight needed to sink the boat. The result was of 2816 kg, almost 2 tons more the load capacity at the draft at 60 % of the hull's depth.

Discussion

Although a good dose of caution have to be used when looking at those results, especially with respect to the difficult estimation of the pitch and heel angles, some general considerations can be stated. In the three run tests, despite the theoretical critical wave height was exceeded already in the second test, the boat did not take in water during the tests showing a high seaworthiness of the design, at least for those tested conditions. The high bow, compared to the midsection, allowed it to literally surf the waves keeping the vessel dry, while the additional coamings have demonstrated their value in the event of excessive heeling.

Furthermore, a direct relation exists between the wave steepness and the heel angle, while an inverse proportional relation marks the wave steepness against the pitch angle. With the tendency of the sampan to sail on the waves, with steeper waves the pitch angle is higher because of the rising of the bow on the wave crest. The maximum deadweight estimated to achieve the sinking, as it was seen in the indoor test, shows that probably in good weather/sea condition the boat could be overloaded since two more tons give a high range of load capacity for the size of this boat.

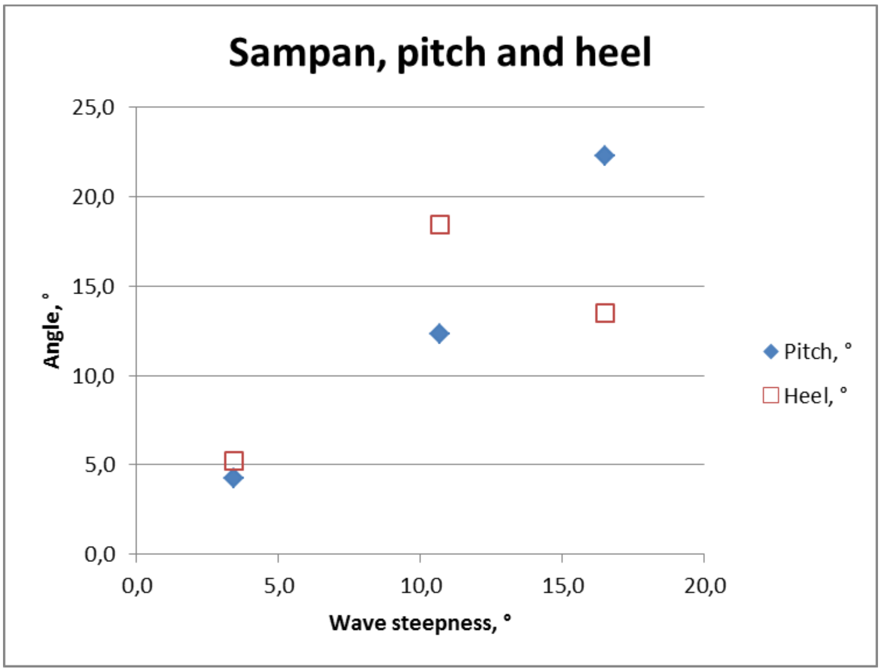

Figure 55. Sampan Kotak. Pitch and heel.

Conclusion

Notwithstanding the difficulties encountered during this study, especially regarding the real model tests, which made the work possibly more interesting and challenging, it is possible to draw some conclusions.

Both the hydrostatic analysis and the model tests points to an impressive stability of this vessel. Although of small size, all the analysed values seem to point on a high degree of seaworthiness. These results fit well with the multifunctional use of the vessel not only as carrier between moored vessels, or banks of the river, but also as a coastal fishing vessel. As well known, for a stable boat or ship to gain stability it has to sacrifice slenderness of lines and consequently speed. In spite of the fact that no data are available about the speed range of the Sampan, which could depends on several factor like rigging and crew ability, only observing at the lines and the hydrostatics values such as Block and Prismatic coefficients, this boat seems to be a fast sailor as well as stable.

The combination of desirable properties could be seen on the shape of the hull, typical of Chinese vessels, which has a fine entrance with a transom, probably to gain extra buoyancy at the bow, and a fuller end with the maximum beam at 18% aft the amidships section. This shape, like a reverse drop or better remembering the body of a duck on water, is considered the most suitable and less resistance shape for low speed vessel. It has inspired western boat builders to such an extent that it was adopted at the end of the 19th century for racing yachts (Ronan 1986: 86) and is still in use in modern medium size sailing cruisers.

Chinese shipbuilders used the model of aquatic birds as justification to the hull lines for their boats, in contrast with the European colleagues which adopted the mackerel head and cod tail design, because

> "*les oiseaux aquatiques sont le plus souvent plongés, comme les vaisseaux, dans deux milieux différents, l'air et l'eau, tandis que les poisons ne le sont que dans un seul*" (Paris 1840: 3).

The design rationale, the technical choices behind and the development of this vessel are wrapped in a fog of indifference towards them, that further historical/anthropological studies could unveil and thereby provide a more complete frame for comprehending the Sampan Kotak. It would for instance be interesting to know if this vessel played a role in the phenomenon of opium smuggling committed by Chinese secret societies in Singapore during the 19th century, a really lucrative traffic between the Singaporean coasts and the European ships moored off the harbour, since the quality of this boat well fit very well with the requirements needed in a such duty.

6. THE GOKSTAD FAERING

Introduction

The Gokstad Faering is the smallest of three boats found inside the Gokstad ship, dated 880 CE (McGrail 1974: 1; Seal 2003: 238). The three boats and the ship were excavated from a burial mound to the west of Oslo fjord in 1880 by Nicolay Nicolaysen, at the Gokstad farm in Vestfold (McGrail 1974: 1; Delgado (ed.) 1997: 172).

Discovery and excavation

The grave mound is locally known as the King's Mound; it was built on the low-lands close to the Viking Age shore line. The ship was probably navigated over water to the burial site and then carried over the small distance between the old shoreline and the burial site (Delgado (ed.) 1997: 172).

Recently an interesting discovery was made by a research team of the *Gokstad Revitalised* project (2012). During a geophysical survey of the area surrounding the grave mound, a possible Viking settlement was found. A large number of houses or plot boundaries were discovered using ground penetrating radar; most of them were concentrated along a street. This was about 500 meters to the south of the Gokstad mouth, at the Viking shoreline. The structures are part of a Viking workshop settlement that was indicated during observations in the past. Furthermore, a Viking-age harbour has been discovered at the Viking-age shoreline. Research into crop marks of the 1970's shows that there are four more burial mounds located around the Gokstad ship mound—this has been confirmed by a geophysical survey which shows that the density of mounds in the area is higher than originally expected. The researchers expect the presence of more burial mounds to the east of the Gokstad ship mound (Figure 56) (Gokstad Revitalised, 2012).

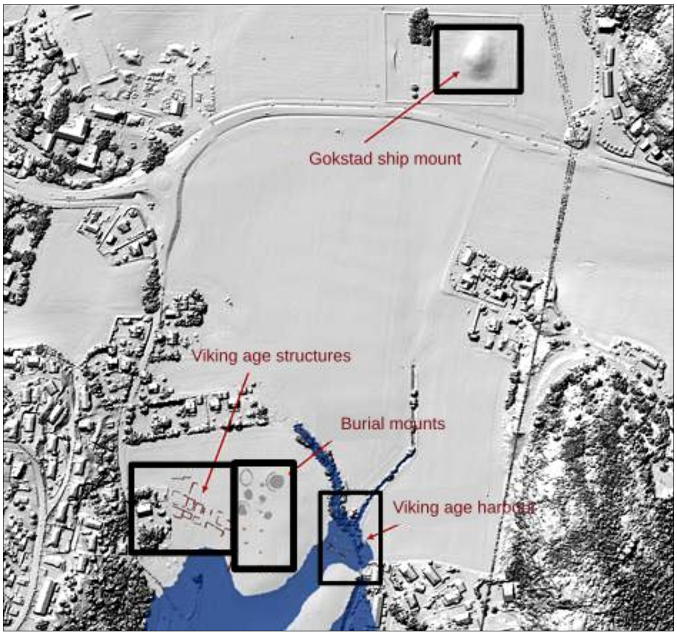

Figure 56. Geophysical data of the area surrounding the Gokstad ship mount (from Gokstad Revitalised, 2012).

The Gokstad ship mound holds the grave of a male together with the ship itself, the small boats, and other grave goods such as a sled, a copper cauldron, the wooden parts of a tent, beds, buckets in wood, a board game, a horse harness,... Next to the grave goods the dead is also honoured by animal sacrifices of a peacock, horses, and dogs. The finds in the grave suggested that the dead was a member of the highest strata of Viking society. There is a possibility that this person is one of the Yngling kings (Delgado (ed.) 1997: 172; Brøgger& Shetelig 1971: 55-56).

Description of the boat

There are multiple theories on the method by which Viking age boats and ships were built. One theory talks about a process of copying which could be done in two ways: one by having the original at hand and directly copying from such; or by copying the ship out of recorded measurements. The recording of a ship happened by the use of the boat ell which is the recording of certain measurements of a base line located between the two end-posts and by use of the boat level, which shows the angle of each strake and the breadth of each of these. Even though these techniques certainly have a long history in Scandinavia, it is uncertain whether they were available to the Viking shipwright. Another possibility was building the boat by eye. According to this theory, the shipwright would have worked the same way as a sculptor does, adjusting the shape of the boat as it is being built in order to create the optimal shape. Boatbuilding according to this tradition still happens to this day in Scandinavia, but again there is no proof of such a technique being used during Viking ages. Two more possibilities are that the boats were modelled according to traditional rules of thumb, or by the use of moulds used for the creation of every frame or for the creation of the mid-ship frame (McGrail 1974: 44-45). It is generally thought that Viking ships are built out of memory or by eye; the author *Seal J.* however believes that the Viking shipwrights constructed a ship by copying other ships and altering them where needed (Seal 2003: 238).

The Gokstad Faering is a four-oared, clinker-built vessel with a T-shaped keel (McGrail 1974: 2). This keel is slightly rockered and has a length of 4.26 meters, 21.6 centimetres in height, and 12.7 centimetres in width (Seal 2003: 238; McGrail 1974: 9-10). To this keel, high stem- and stern-posts are attached using vertical scarfs. It is steered using a side rudder and is completely built out of oak, except for the sheerstrakes, which are made out of pine (McGrail 1974: 2).

The boat has an overall length of 6.51 meters, and a beam amidships of 1.38 meters. This suggests that it was designed to save as much weight as possible (McGrail 1974: 2).

Each side of the boat consists of three strakes. These strakes are 10 to 12 millimetres in thickness and up to 55.9 centimetres in breadth. The pine sheer strakes have a length of 6,705 meters. At the bottom of the outer face of each of these strakes, a small groove was made which holds traces of tarred wool and cows' hair. This is used as luting in the overlap between the frames (McGrail 1974: 2).

The boat counts a total of 5 frames; two inclined 'bulkhead' frames and three proper frames. The midship frames consist of floortimbers that extend to the edges of the garboard; from here two naturally curved pieces extend the frame up to the sheerline. The other two frames consist of grown pieces that go from the port sheerline to the starboard sheerline. The three frames were attached to the frames using one treenail per strake; the inclined frames are nailed to the strakes. All the treenails were wedged from the inside. The treenails of the frame amidships go through a small cleat at the garboard. This in order to secure the treenail better (McGrail 1974: 2 & 7; Christensen 1976: 276).

There are two remarkable features about the vessel's construction. First of all the strakes were not attached to the frames by lashing, as was customary at the time of construction, but were attached using treenails and secondly the end-posts were open and V-shaped. They were also fitted with steps to which the strakes were attached. These features would repeat themselves in younger ships such as the Skuldelev ships from the tenth and eleventh centuries (McGrail 1974: 2).

There is a lot of discussion about the presence of a sail on the faering. Only two mast steps were found to the three small boats in the find, and these are probably to be associated with the two bigger accompanying boats. The faering has two holes near the upper edge of the second strake almost amidships of the boat. These could have been holes meant to fit a mast (McGrail 1974: 2). J. Seal suggests that the Faering was fitted with a four-meter high mast that carried a square, woollen cloth sail. Although the open water trials with his model seemed to suggest that if a sail was used, it was only used when this seemed profitable since the vessel seemed to function best as a rowing boat (Seal 2003: 243). As a conclusion to the sea trials conducted with the 1:1 replica of the Faering, built by the National Maritime Museum in Greenwich, McKee writes that because of directional properties of the Faering, no sail could be better to go upwind than the hull itself, furthermore he writes that it would be difficult to tack with the boat since a sail would make it hard to turn upwind and it would need the help of an oar to turn her back downwind (McKee 1974; 26). The excavator of the Gokstad ship mound, Nicolas Nicolaysen, writes that the boats of the *Bâtr* class, to which the Faering belonged, were fitted with a mast and a sail (Nicolaysen 1882: 24-25). The modern counterparts of the Faering, the Oselver, are sometimes built purely for the purpose of rowing them, but there are also examples of Oselver built for sailing (McGrail 1974; 8). The presence of a rudder mounted on the boat seems to suggest however that the boat was sailed. Due to the boat's characteristics it could be however that the sail was only used when the conditions would allow the effective use of a sail.

The oars of the ship were held on a so-called kabe (Figure 57), which is a block of wood fitted onto the sheer strake. To this block a rope was attached, with which the oar was fixed (Nicolaysen 1882: 24).

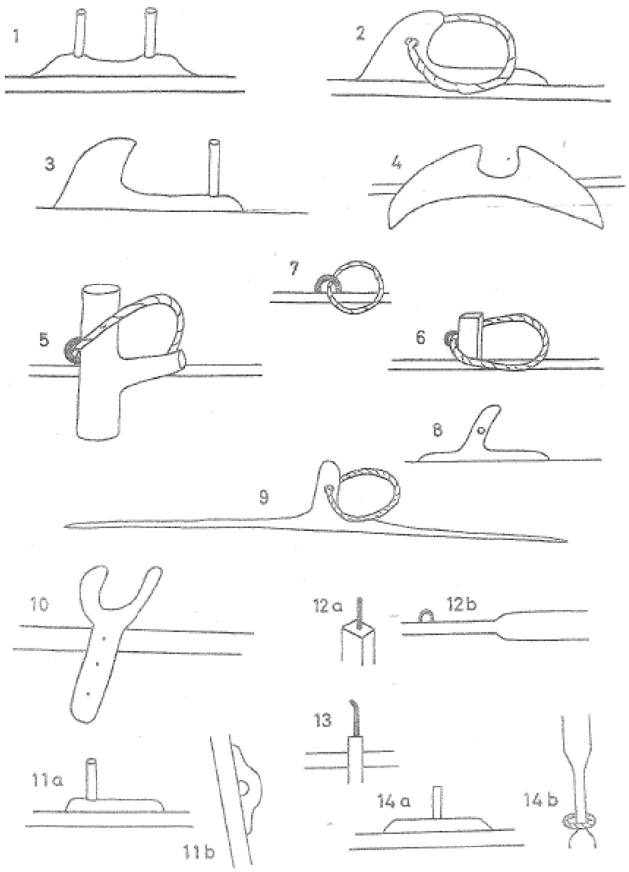

Figure 57. Various types of traditional Norwegian kabes and other oarlocks (from Høeg 1978).

It is remarkable that the Gokstad Faering has a lot of similarities with boats still in use in Western Norway (Delgado (ed.) 1997: 173): the Oselver boats. These boats, which are mainly used in South West Norway, show strong similarities in both their appearance and lines plan. They are symmetrical in plan, are built clinker, the frames are connected by treenails, they have a shallow draught, the sheer line has a similar shape, the central rib and beam assembly is similar and the sides are still made up of three broad strakes (McGrail 1974: 8-9).

Other modern day boats with close similarities are the Shetland boats. Shetland belonged to Norway between the ninth century and 1469, and strong relations between the Shetlands and Norway were maintained until the nineteenth century. A type of Shetland boat is called the Fourens, which shows clear similarities with the Norwegian term Faering. Just like with the Norwegians Oselver boats, the Shetland Fourens show similarities to the Faering in appearance, linesplan, and constructional elements such as the luting, the wedged treenails, keel-endpost scarfs, keel shape, and the clinker nails used. These ships are modelled using both the rule of thumb and the by-eye technique, although there is no direct evidence that these were remnants of Viking age techniques (McGrail 1974: 7 & 45).

Environmental Context

The Gokstad ship and its three accompanying smaller boats were found in a burial mound on a flat treeless plain to the west of Oslo fjord, near Sandefjerd and less than 1.5 kilometres of Lahelle Bay (McGrail 1974: 1; Brøgger & Shetelig 1971: 56).

Norway is surrounded by the North Sea, the Norwegian Sea and the Skagerrak. The first two seas can be considered shallow due to them being part of the continental shelf with the drop of point to the oceanic plate being at 180 meters deep, while along the Norwegian coast these are deeper due to the presence of the Norwegian Trench, which results in a depth of 300 to 400 meters (McGrail 2004: 166; Grabbe et al. 2009: 1901). The Skagerrak then again can be considered as a deep sea due to the Norwegian Trench which goes down to 700 meters (Grabbe et al. 2009: 1901).

The Norwegian coast is made up out of rock, formed through time by weather to form headlands, promontories, peninsulas, capes, bays, and inlets. These inlets can contain deep water and thus form fjords which make for good natural harbours. The same kind of rocky coast with deep water running close to land can be found in Spain, Portugal, and parts of France, Ireland and Britain. Along the whole of these coastlines small islands can be found of the coast (McGrail 2004: 166).

Due to an absence of specific information on currents, tides and winds before the twentieth century, twentieth century data is used for the discussion of the environment of the Norwegian coast (McGrail 2004: 169).

The current along the Norwegian coast is called the North Atlantic Current. This current originates in the Gulf Stream current which starts its flow in the Gulf of Mexico, goes up along the American coast and then crosses the Atlantic between the south of Nova Scotia to the bay of Biscay and the British and Irish archipelago. This North Atlantic current creates north-east currents along the Norwegian west-coast and weak currents flowing out of the Baltic along the Norwegian southern coast (Figure 58) (McGrail 2004: 169).

Next to the general current, there is of course the influence of the tides. The tides are semi-diurnal, which means there is an ebb twice a day and a flood twice a day. These tides were especially important for inshore boats like the Gokstad Faering. One cycle means that during flood there is a current that flows first with increasing and later with diminishing, strength towards one direction for about 6 hours and 15 minutes and then in the opposite direction during ebb for approximately the same time (McGrail 2004: 169-170). The main part of the tidal current comes from the north of Great-Britain and flows northward along the Norwegian coast (Grabbe et al. 2009: 1902). The tidal streams coming from the Baltic Sea can be neglected since they are limited in strength (McGrail 2004: 170).

Another factor that has influence on the currents of the sea is the wind. On the Norwegian coast these come from the north in the summer; in the Skagerrak however it is mainly western and south-western winds that prevail. For the rest of the year winds from the north-west to the south-west prevail (McGrail 2004, p.170).

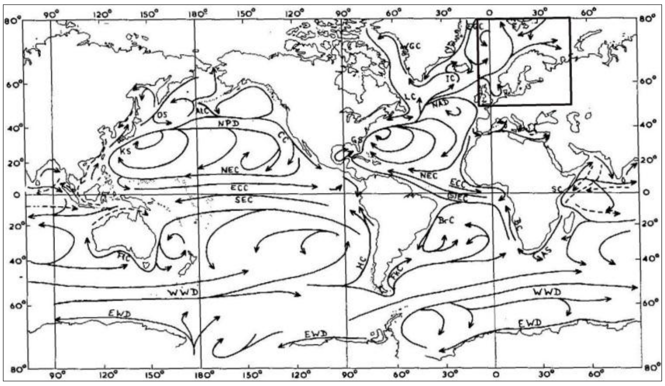

Figure 58. Main ocean currents (from Lamb 1972: 321).

As said, fjords are wide inlets which can create suitable locations for harbours that give some protection from the weather on the open sea. These fjords are however still under the influence of the tides. Furthermore fjords create special conditions for both wind and general currents. The wind will always follow the shape of the fjord and create currents out of or into the fjord, depending on the direction. When the North Atlantic current passes the mouth of a fjord it will flow in on the south side of the fjord and keep to the south side until the end of the ford where it will turn and flow back out of the fjord along the north side (Sognjefjord swim festival).

The estuaries of the rivers are also under the influence of the tides. Just as for fjords, the tides can determine the periods in which ships can navigate inland or seawards.

Use

The ship had a crew of three to two oarsmen and a person at the rudder (Seal 2003: 238). The boat belonged to the class of 'boats', in that time called '*bâtr*' (Nicolaysen 1882: 24).

J. Seal believes that we have to look at the Faering as a pleasure ship more than a practical boat. This is due to its elegant lines, low freeboard, shallow draught, low cargo space, high construction complexity and high speed. He makes the comparison between the Faering and a modern day sports car, which is used more as a status symbol than for its practicality (Seal 2003: 244). This is furthermore represented by sea trials that have been conducted with previous replicas of the Gokstad Faering. Reports say that the replicas have a tendency to plane (Christensen 1976: 277).

Another interpretation is that the Gokstad Faering was the Gokstad ships' dinghy, as is common for Viking ships. It is however very unlikely that all three of the boats found with the Gokstad ship were used to this end: Brøgger and Shetelig (1971: 97) state that "*Only the smallest of them can have been the regular dinghy, the two others being a part of the superabundant grave furnishings.*" If their assumption is correct, then the Gokstad Faering, which was the smallest, would have been the Gokstad ships' dinghy (Greenhill (ed.) 1976: 227).

Another possible use for the Faering boats comes from the use of the Shetland Fourens boats. These boats were used for inter-island communication (McGrail 1974, p. 6). The rough Norwegian inland made sea-based transport the main method for communication and travel up until recently and there is a possibility that the Viking-age Faering boats had the same functions as the modern Fourens: quick communication and fishing (Stylegard 2005: 256; McGrail 1974: 6).

Seals' interpretation seems a bit far-fetched: it could have been a boat that represents a certain social status but that does not necessarily mean it was used just as a pleasure craft. The most likely theory to us is that the Faering was used to allow for fast communication between the Gokstad ship and the coast. Since the Gokstad ship was used as a burial ship for a person of high social standing, it could well be that the Faering was also associated with the higher social strata.

DelftShip reconstruction

Using the 1958 drawing by Christensen A.E. Jr. (Figure 59), a digital model in DelftShip (Figure 60; Figure 61) was created. In order to mimic the three clinker strakes, we creased two control lines thus creating three strakes. When the model was completed, a test was conducted to discover any leak points, and the three discovered leak points were all located along the sheer line, as is to be expected. Using this model a lines plan was created and a hydrostatic test conducted.

The results of the hydrostatics test were then collected in a standard spreadsheet in order to facilitate an easy comparing of the various boats. The data in the spreadsheet is compiled using the software programs Orca3D and DelftShip.

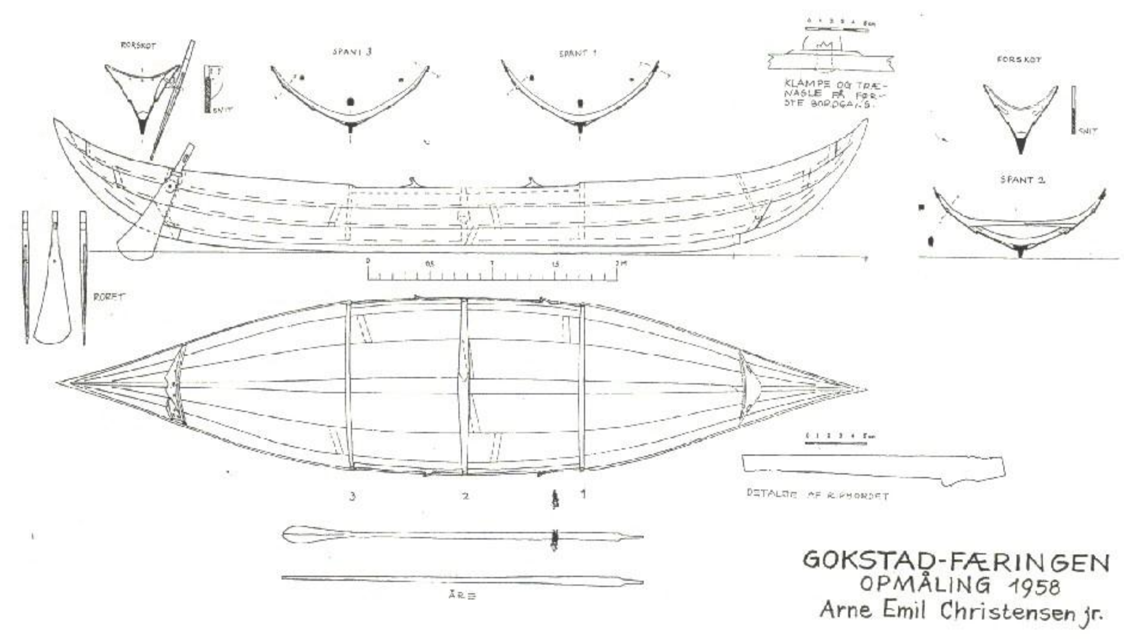

Figure 59. The Gokstad Faering drawing by Christensen A.E. Jr. (from Christensen 1958).

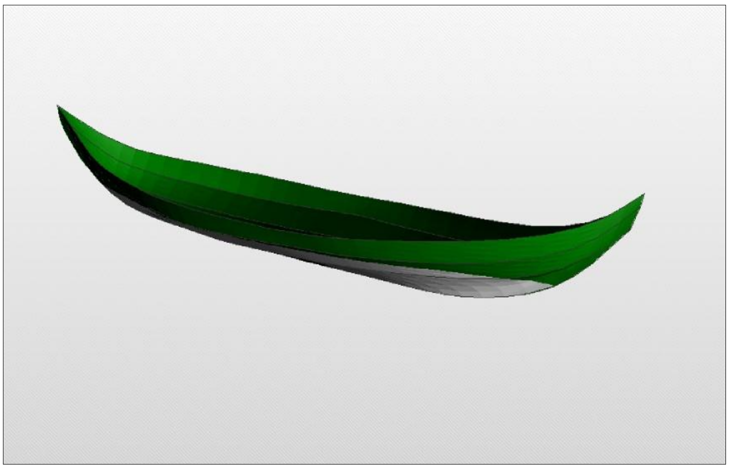

Figure 60. DelftShip reconstruction of the Gokstad Faering

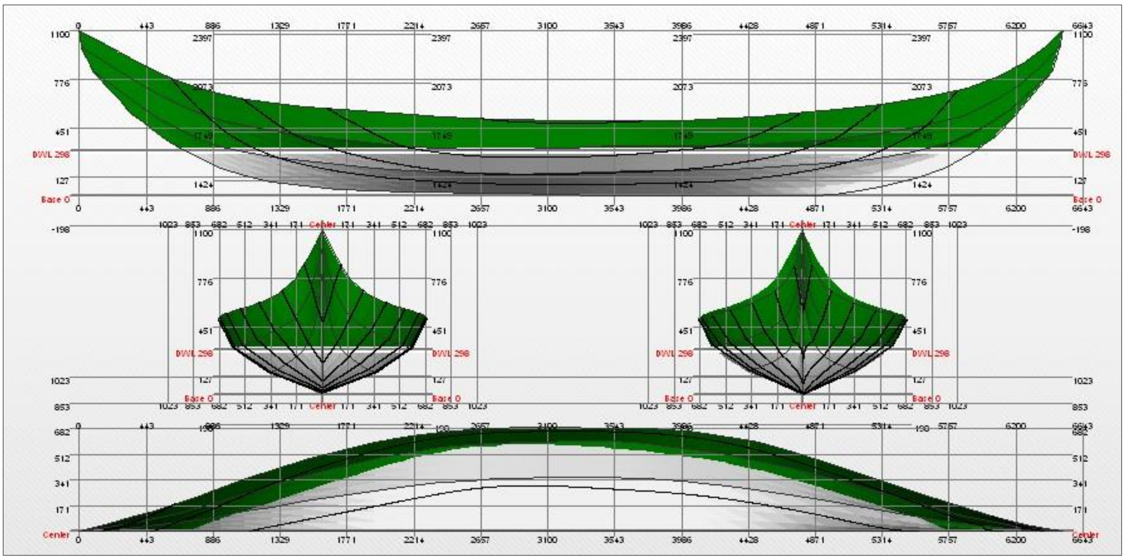

Figure 61. Lines plan of the Gokstad Faering, created using DelftShip.

Hydrostatics and performance

The waterplane coefficient of the Gokstad Faering has a result of 0.43, its midship coefficient is 0.49, and its block coefficient is 0.40. These three values illustrate a lean hull. This means that there is less resistance from the water facilitating the vessel's speed.

The length:beam ratio is 4.5. This means that the beams fit 4.5 times in the ship's length. This places its value in between the fast longship and the slower seagoing cargo ship (Jensen 1999: 50).

Its displacement-length ratio is 6.3. Compared to a modern boat this value would fall in the range of a very light ocean racing boat, suggesting that the Faering was built for speed (Sponberg 2010: 17).

The boat's hydrostatic results seem to describe a boat capable of high speed. The boat has a hull speed of 5.5 knots, however, tests with full scale models have shown that the Faering is capable of breaking this barrier and begins to plane. The ability of the Faering to plane will be tested in the open water test.

If we look at the stability it can be said that the Gokstad Faering is not the safest ship to sail in. Beaufort 3, or a gentle breeze, is the safe limit to go out with the Faering (Rowlett 2001). The downflooding angle is 16.1° which means it does not need a lot of heel in order for the boat to take on water. Furthermore it is not the most comfortable boat, with a rolling period of only 2.8 seconds. This however is in the range of the other boats in this investigation.

One of the problems encountered during the hydrostatic test had to do with the weight. Supposing the ship had three crewmen on board, as Seal supposes (Seal 2003: 238), then the loaded weight of the ship goes over the supposed displacement when counting on a draught of 60%. There are two possible explanations for this.

For rowing there is only a need for two people, but it is possible that the ship just had a higher draught while being sailed due to the addition of an extra crew member to sail and the weight of the sail itself. Another possibility however is that the ship always went out with just two crewmen. Two could row the boat and when the conditions were positive they could sail by putting the oars in the boat and setting up the sail. One crew member could then operate the sail while the other actually steered the boat using the rudder. According to the calculations used for this book the use of only two crewmen combined with a draught set at 60% would leave room for 285 kg of extra weight for sails, mast, oars, and maybe cargo.

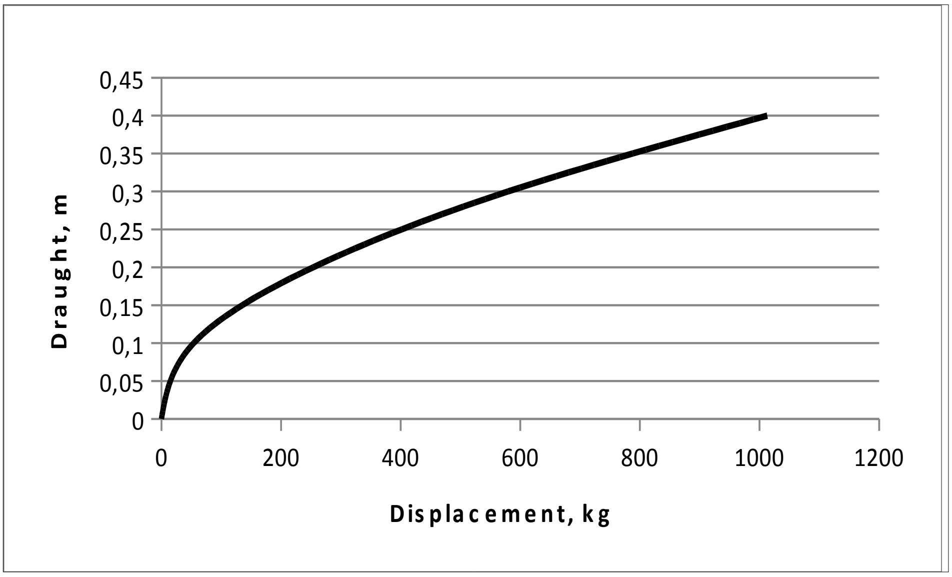

Figure 62. Graph showing the relationship between displacement and draught.

Comparison with the replica from Greenwich

The model built by the National Maritime Museum in Greenwich differs slightly from the model reconstructed using DelftShip in this paper. While the DelftShip model was created using the dimensions of the drawing by Christensen A.E., the museum's model is slightly longer (0.051 m) and slightly broader (0.04 m). These differences however can be considered negligible. The height dimensions are the same (McKee 1974: 6).

There is however a considerable difference in the weight between the DelftShip model and the museum's model. The museum's boat has a weight of 108 kg, while according to DelftShip the boat weighed only 66 kg. Since DelftShip does not take into account the weight of the frames and the clinker nails, the weight of 107.96 kg of the 1:1 replica has been used for the hydrostatics in this chapter. Furthermore there is also considerable difference between the museum's and the model's block, prismatic, and midship section coefficient (McKee 1974: 6 & 8).

	Replica by the National Maritime Museum	*DelftShip model of the Faering*
Block Coefficient	0.260	0.320
Prismatic Coefficient	0.594	0.457
Midship Section Coefficient	0.514	0.456

Table 16. Data on the coefficients of the National Maritime museum's replica compared to the DelftShip model (from McKee 1974: 8).

The differences in the coefficients can be explained by another draught being used for the calculations by McKee instead of the 60% draught considered by the authors of this book.

This would result in a different supposed displacement. The differences in the draught, displacement, beam and length result in different results for the various coefficients.

Gokstad faering								
Dimensions								
Length overall	L_{OA}	6.51	m		Depth of hull	D	0.497	m
Length at waterline	L_{WL}	5.23	m		'Standard' draught	T	0.298	m
Maximum beam	B	1.38	m		Minimum draught	T_{MIN}	0.169	m
Waterline beam	B_{WL}	1.15	m		Maximum draught	T_{MAX}	0.376	m
Maximum hull speed	S_{MAX}	5.5	kts		Draught-Depth ratio	100 D/T	59.9	%
Volumes, areas and weights								
Displacement, volume	v	0.559	m^3		Moment of inertia	I	4.596	m^4
Displacement, weight	D	573	kg		Estimated weight of boat		108	kg
Wetted surface area	AWS	4.653	m^2		Deadweight		465	kg
Waterplane Area	AWP	3.747	m^2		Maximum Deadweight		812	kg
Midship Area	AM	0.188	m^2		Deadweight to sink		1188	kg
Coefficients and ratios								
Length-beam ratio	L:B	4.5			Block Coefficient	C_B	0.320	
Length-draught ratio	L:T	17.5			Prismatic Coefficient	C_P	0.457	
Beam-draught ratio	B:T	3.9			Waterplane Coefficient	C_{WP}	0.417	
Displacement-length ratio	$L_{WL}/\Delta^{1/3}$	6.3			Midship Coefficient	C_M	0.456	
Stability								
Centres					**Stability Criteria**			
Centre of Bouyancy	KB	0.20	m		Downflooding Angle	θ_f	16.1	°
Centre of Gravity	KG	0.32	m		Minimum Freeboard	F_{MIN}	0.12	m
Metacentre	KM	0.70	m		Freeboard, heeling test		0.06	m
Metacentric height	GM	0.38	m		Rolling period	T_R	2.1	sec
Heeling calculations					**Other standards**			
Critical wave height	h_{CRIT}	0.94	m		GM-Beam ratio	GM/B_{WL}	0.22	
Significant wave height	h_S	0.74	m		Stability Index	T_R/GM	2.4	
Approximate wind speed		5.5	m/s		Angle of max. stability	AMS	20	°
Beaufort		4			Angle of vanishing stability	AVS	34	°

Table 17. Gokstad faering. Summary table using a crew of two.

	1:1 replica	DelftShip model
Draught, m	0.286	0.298
Displacement, kg	385	573
Freeboard, m	0.21	0.20

Table 18. Comparison of the displacement at a similar draught (from McKee 1974: 11).

The draught set in the DelftShip hydrostatics conforms best with the afloat test at the 'Passenger' condition in McKee's tests: this condition replicates a state in which there is a man each on the fore and aft thwarts together with four oars, and a helmsman manning the rudder, and the trial equipment (McKee 1974: 9; 11). The draught and the freeboard seem to conform to each other with only a limited deviation of one to two centimetres; the displacement however shows a considerable difference. The difference of 188 kg made us go back and recheck the dimensions of the DelftShip model against Christensen (1958) drawings, but they seem to match well. A difference in draught of 1 cm explains an additional (*c.*) 37 kg difference in displacement, but the dissimilarity between the two boats is still marked. We cannot explain the difference, but one could possibly infer that the Greenwich replica came out a leaner machine than our DelfShip model. As they are based on the same frames and the same find, it is difficult to see how this came about.

Draught of Greenwich replica	0.238	m
Angle to bring the replica to 5% of the maximum beam as freeboard above the waterline	22	°
Draught of DelftShip model	0.238	m
Downflooding angle	20.6	°

Table 19. Comparison of the downflooding angle (from McKee 1974: 11).

A test using the 1:1 replica from the museum shows that the sheerline is just not submerged under the waterline at an angle of 22°. According to the calculations used in this book however the downflooding angle at the same draught should be 20.6°. The differences here are however negligible (McKee 1974: 13).

Model tests

Building the Model

Before the wooden model was built, a cardboard model was constructed. During the construction of this, using modelling cardboard and glue, it became immediately clear that the tensions on the construction would be a problem during the building process. The cardboard frames proved unable to keep the hull construction open, and collapsed. It was however possible to attach the strakes without the frames: the frames proved very adequate to create a clinker model with the particular shapes of the Gokstad Faering.

In a next phase, the wooden modelling followed. At first the strakes were attached to the keel using tape in a similar manner as the cardboard model: the idea was to add the frames to the keel in a second phase and then glue the various parts of the model together. With the wooden one-millimetre plywood strakes this turned out to be a more problematic approach. So it was decided to attach the two millimetre plywood frames to the two millimetre plywood keel and endposts first, using super glue, and then use the frames to guide the strakes into the right shape. Already with the attachment of the first garboard strake it proved harder to bridge the gap between the garboard strake and the keel. The first problem with the tension arose with trying to attach the stern part of the first middle strake. It took several tries and a lot of pressure for the glue to secure the strake in place. The real problem arose with the sheer strakes. The installation of the sheer strakes proved no problem in building the cardboard model, but due to the lesser flexibility of the keel and the strakes, which were overlapped by the sheerstrakes, these strakes, although cut according to the plans' length, proved just one millimetre too short on both sides. After several tries it was decided to cut two new longer strakes and attach these over the frames instead. The model thus created shows a sturdy structure, nicely keeping the forms of the boat. The only problem is that the stern's inclined frames were lifted off the keel by the force of the strakes on it during the hours after construction. Although several attempts were undertaken to press the frame back in place, none were successful. The gap between the frame and the keel does however only consist of two millimetres and is thus negligible. After the completion of the wooden model, the boat was made watertight with a resin consisting of a mixture of epoxy and hardener. This resin was applied to the inside of the model along the keel line and in overlap of the strakes. The model was then sanded to get rid of irregularities and excess resin. Finally the boat was painted and covered with a layer of varnish in order to protect the paint and to contribute to the water resistance of the hull.

The model was given its scaled weight by dividing its displacement weight by eight. This resulted in a model weight of 71.6 grams. Three 'crew members' were inserted using copper wire and round washers. The washers would heel on the wire thus representing the crew's movement in the boat. A real crew would counteract the movement of the boat due to the waves, by suspending the weights on this copper wire an equal reaction would be given by the weights to the crew's movement. The boat was supplemented with extra weights representing its equipment until it reached the desired weight.

Performance in open water

The Test Conditions

In order to test the Faering's behaviour in open water, four tests were conducted. The first test was a high speed test with no waves in order to observe the boat's reaction when it broke its hull speed barrier of 5.5 knots. The next three tests were all conducted in waves coming at an angle of 45° from the starboard side of the bow.

Test run	Height of wave (h_S, m)	Length of wave (λ, m)	Angle, (°)	Boat speed, (kts)	Pitch, (°)	Heel, (°)	Water intake (kg)
1	0.64	9.27	3.9	7.1	17.2	13.1	0
2	0.70	9.52	4.2	6.6	9.2	16.0	72
3	0.75	6.24	6.8	5.1	16.2	12.7	56

Table 20. Results of the towing tests.

After the open water test a heeling test and a sinking test were also conducted in an indoor water basin.

First observations

While conducting the open water test a number of observations could be made. During the high speed run it became very clear that the Gokstad Faering has a semi-planing hull.

The Faering seemed to ride the wave without being influenced by pitch. It has to be taken into account however that due to the limited size of the model the results of the observations made during the tests are influenced by superficial tension as a result of the cohesive force of the water.

Figure 63. Snapshot of the Gokstad faering during speed trials.

Test one

During the first test the Faering was towed at a speed of 0.81 m/s, when scaled this is equal to a speed of 3.6 m/s or 7.1 knots. This means the model went well above its hull speed during this test.

Using the grid, the heights of 5 waves were measured, which averaged a height of 2.04 cm, a period of 0.51 s and a length of 0.46 cm. The significant wave height during this test was 3.19 cm. When scaled this would be equal to waves with an average height of 0.41 m, a period of 2.3 s and a length of 9.27 m with a significant wave height of 0.64 m. Both the significant wave height and the average wave height are still well below the boat's critical wave height of 0.94 m. The same can be said about the wave length and the wave period. The critical wave length is 14.06 m. and the critical wave period is 3 s. Both are still well below the waves reached during this test. There was no water intake during this test.

In these waves the model had an average downward pitch of 1.2° and upward of 5° which results in a total pitch of 6.1° on average while passing one wave. The model had an average of 13.1° of heel while riding the waves created during the first test. This is still well below the boat's maximum heeling angle of 16.0°.

Test two

During the second test the model reached a speed of 0.76 m/s which scales into a speed of 3.4 m/s or 6.6 knots, thus breaking its hull speed by a full knot, scaled.

The five measured waves of test two had an average height of 2.24 m, a period of 0.50 s and a length of 0.48 m, which translates to a scaled height of 0.45 m, a period of 2.3 s and a length of 9.52 m. The test's significant wave height was 3.50 cm or 0.7 m. All of these values are still well below the boat's critical wave values.

The model took these waves with an average downward pitch of 1.7° and upward 7.5° which results in a total pitch of 9.2°, showing a considerably stronger movement than in test 1. Also the average heel of this test reached 16°, which is very close to the boat's downflooding angle of 16.01°. This might explain why the boat took on 9 grams, or a scaled 72 kg of water during test two.

Test three

The third test was conducted at a speed of 0.58 m/s or a scaled 2.6 m/s which equals to 5.0 knots. This means that during the third test the boat's hull speed was not surpassed.

The average values of the waves generated during this test were a height of 2.39 cm, a period of 0.42 s. and a length of 0.31m. Scaled this is respectively 0.48 m., 1.9s, and 6.24m, with the significant wave height being 3.74 cm. or 0.75 m. Again the critical wave values have not been reached.

The average downward pitch during this test was 6.3° and upward 9.9° which resulted in a total pitch of 16.2°. The heel reached was only 12.7°. The boat did take on some water: 7 grams, which equals to 56 kg of water.

Indoor test

After the wave tests, two more tests were conducted in an indoor water basin. The first was the heel test during which the boats scaled ballast and crew were all brought to one side in order to make the model heel. This resulted in a freeboard of only 3mm or 6 cm in full scale.

After the heeling test, the model was tested to see how much weight was needed to make it sink. The resulted total weight was 162 grams or 1296 kg. The weight of the cargo and crew placed into the model to sink it was 126 grams or 1008 kg.

Discussion of the open water tests

Caution should be used when taking these values into account. Particularly during tests two and three, the measurement of the heel and pitch was problematic. The height waves prevented a clear view of the Faering's model while it was passing the grid.

The critical wave value for this boat was never reached but the second wave test was the most dangerous for the model. During this test both the wave period and the wave length came closest to the Faering's critical values. The wave height was higher during the last test but is to be considered safer due to the shorter wave length. The pitch does however increase strongly from test one to three (Figure 64).

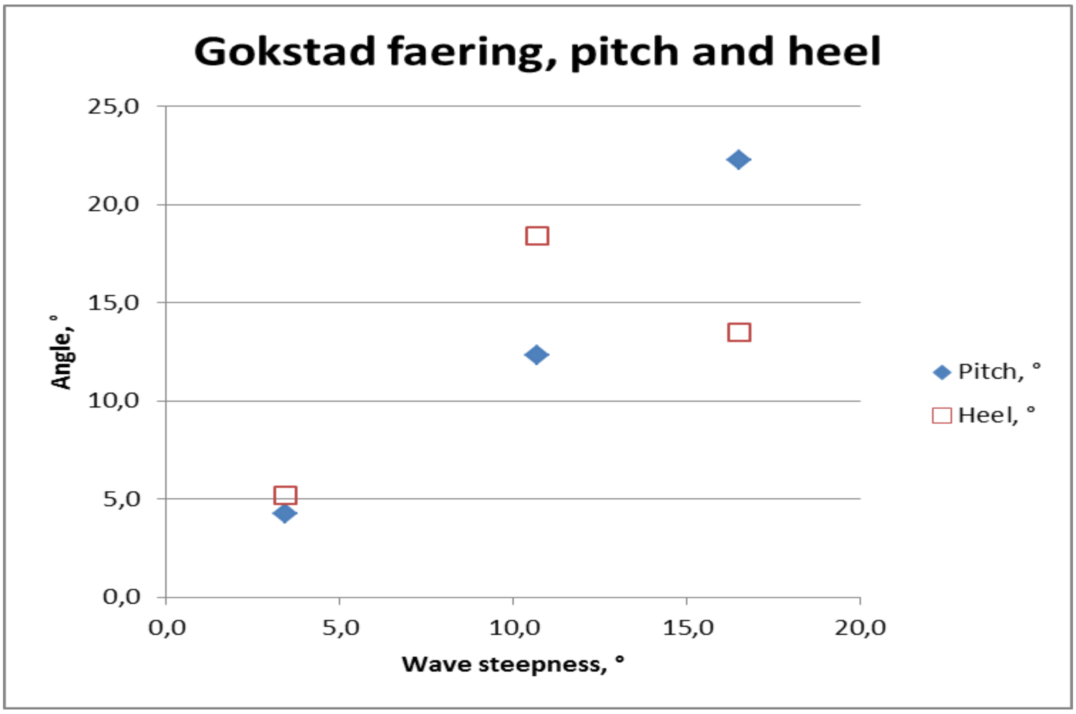

Figure 64: Gokstad Faering: Pitch and heel.

It was also during test two that the boat took on an extra 72 kg. of water above the weight of 573 kg it already had. The resulting weight of 645 kg was however still well below the 1296 kg needed to sink the faering.

Discussion

The Gokstad Faering was a boat that could be rowed, or sailed in the right conditions, with a crew of two on relatively calm seas. Being a small boat it cannot be considered the safest of vessels, which means it is unwise to use the boat in bad weather conditions.

Due to its long and narrow shape combined with its light weight, however, it was able to ride the waves with a lot of success and if speeds over 5.5 knots were reached it would even start to plane. This said, however it must be taken into account that during the waves test using the critical wave height calculated by the authors was never reached and thus we were unable to research its reaction to the waves in the worst of conditions.

This boat type could have been used in order to communicate along the Norwegian coast or as a ship's dinghy. Similar modern boat types however suggest that it also could have been used for coastal fishing.

The Gokstad Faering is an example of the high standards of Viking-age ship construction, built for speed on calm waters.

7. WA MIKAEL OUTRIGGER

Introduction

The Caroline Islands' area (part of the Federated State of Micronesia) spreads – from east to west – over an impressive approximate 1,500 nautical miles area, comprising of islands and atolls. In spite of the size of this area and the distances involved, the main means of island and interisland transportation has been the *single outrigger canoe*, being used across the islands, with similar types being used across vast stretches of the Pacific. The similarities in these boats across such vast areas indicate that this type of watercraft must have had attractive properties. This was confirmed in western observations, tests and narratives, where they were dubbed the "*flying proas*" (Alden 1877).

The "*flying proa*" of the Caroline Islands archipelago ought to be looked at as a self-integrated body. This view is generated by the unique fashion in developing and evolving the design of the single outrigger canoe. Lacking any substantial contact with either Polynesia or Indonesia – inasmuch as cultural human relations are concerned – a long period of comparative isolation has been the backbone for shaping the Caroline Islands – and possibly the entire Micronesian – flying proa development process.

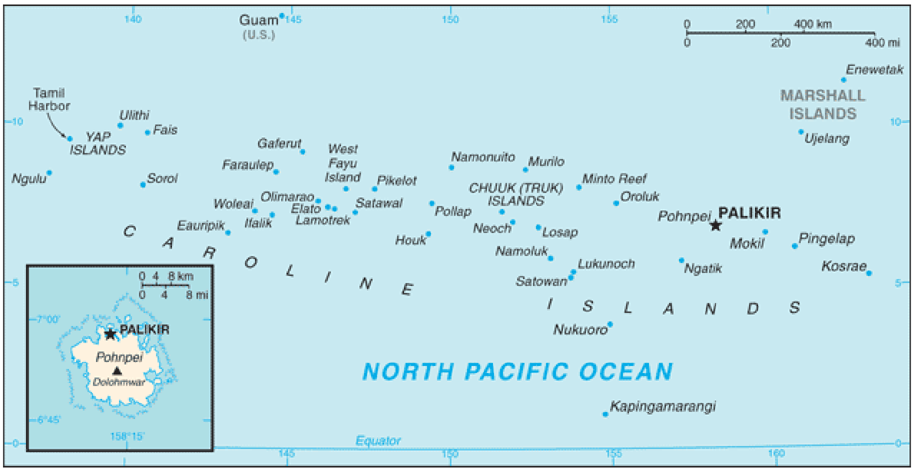

Figure 65. Political Map of the Federated State of Micronesia (from CIA Maps, The World Factbook, accessed 12.04.2012).

In order to zero in on the area which is to form the cradle of the single outrigger canoe, one must by differentiate between the western, central and eastern sub-bodies of islands and atolls. Only the western and central areas share the same approximate ideals on canoe construction. Nevertheless, it is within the central group where the flying proa with both a lee platform and booms attaching a float, forming the outrigger structure, are present. As such it is in this region where our focus lies.

The single outrigger "wa" type of the Puluwat Atoll

The entire Pacific represents a vast area where canoes for fishing, interisland communication and voyaging are indispensable. As such they have spread within this enormous watery part of the world among all peoples of *Austranesian* characteristics. Doran (1981) describes the term *Austranesian* as having replaced older ones, e.g., *Malayo-Polynesian*, to permit the identification of the language phylum characteristic to an array of peoples which inhabit the islands between the Easter Island and Indonesia reaching westward towards Madagascar. The names used by Austranesians when referring to their canoes range between titles of similar pronounciation: Wa'a (Hawaii), va'a (Tahiti), vaka (Tonga), wangga (Fiji), oanga (New Britain and New Ireland), waga (New Guinea), haka (Banda), banka (Philippines), laka (Madagascar), etc. In the Puluwat Atoll, situated in the centre of the Carolines, the modern name *proa,* is still being referred to as the *wa* (Doran 1981: 19).

It is the aim of the following sections to analyse, examine and describe the Micronesian single outrigger canoe of the central part of the Carolines, namely the flying proa of the Puluwat Atoll. It was here where the most pregnant and obvious development of the single outrigger canoe was reached (Doran 1981: 21). Canoes on Puluwat are individually owned, but when not in use by the owner – this being sheltered either near or inside a canoe house – the canoes are considered to be a common asset. This practice generally applies to the smaller fishing canoes (paddling canoes) on Puluwat; as for the foundations of the Puluwatan maritime network, it is the interisland sailing canoe which act as principal (the actual *wa*). This study is based upon this one example of a *flying proa* which as a type is part of the *wa* family and was "christened" *Mikael*: hence the name of our study subject is the *wa* (type) *Mikael* (name).

The builders

'*A select group*' is how Gladwin (1970) refers to those united by the common goal of keeping alive the traditional methods of flying proa construction. As one would expect it is the older among them which hold the precious information and tutor those still novice in the art of canoe building, which generally are in their thirties. Back when Gladwin wrote his reports on the Puluwat Atoll, no more than thirteen builders were present (counting only those who have to that point in time built a interisland voyage capable canoe). As also expected, the older of the builders also act in the capacity of navigators – given their comprehensive knowledge of the navigational routes and prerequisites. This additional set of skills adduces increased prestige and respect.

The method of passing on the techniques of building the proas is probably as old as times and involves – generally – the father teaching their sons who become their apprentices; Sometimes knowledge is also transferred without a direct parental relation, yet the apprentice still must bear some extent of relatedness to the older master builders. The apprenticeship is established by a young aspirant who approaches and asks for permission to be taught an active builder; the latter – if willing – upon assessing the wannabe apprentice' suitability accepts to work alongside the young aspirant (until the latter becomes knowledgeable enough to build on his own, a process which takes several years) (Gladwin 1970: 70-1).

Figure 66. A sailing canoe, showing the outrigger (left) and lee platform (right) on opposite sides (from Gladwin 1970: 73).

Construction

What defines the flying proa is the presence of the single outrigger – which is encountered likewise in the Marianas but the complexity of its attachments has attained an increased level on Puluwat, in the Carolines. As the outrigger is fitted always on is weather side, the lee side is fitted with a platform which serves as counter balance applying the cantilever principle against the weight of the outrigger and its decking.

The hull of the Carolinian *wa* is axially asymmetrical. Due to the presence of the single outrigger, the type is inherently asymmetrical, with the outrigger on the weather side (Doran 1981: 30). But even the main hull itself is – as a general rule of thumb- not symmetrical, as the outrigger side is fuller than the opposing lee platform side. The difference can be more or less marked in different parts of the Pacific, and sometimes the lee side is almost completely flat. The Carolingian Proas are somewhat fuller, but still noticeably asymmetrical (Haddon & Hornell 1991: 377).

The boats are, however, symmetrical on an athwartships axis, and there is no fixed bow or stern as the two ends are identical. This allows the boat to *shunt*; rather than tacking or wearing, this boat will turn by simply reversing direction. Shunting keeps the outrigger on the weather side.

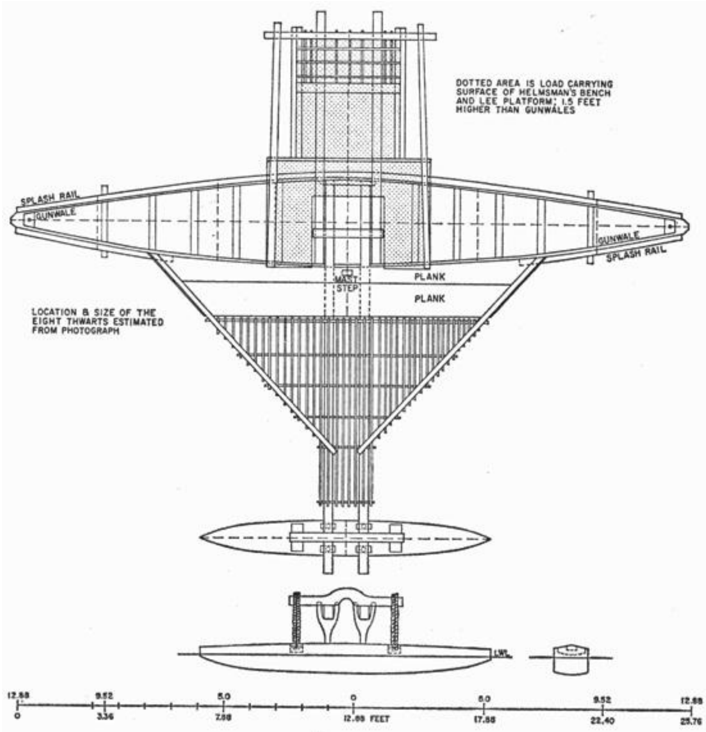

Figure 67. Deck plan and float elevations of the wa Mikael (Doran 1981: 31).1:100.

The hull

A Puluwatan sailing canoe comprises four essential elements: the hull, the outrigger, the lee platform, and the rigging and the sail. As the drawings show (Figure 67; Figure 68), the hull is narrow and deep forming (a cross-sectional) V at the bottom. As noted above, the end-to-end symmetry is preferred. The weather side is designed to be a bit higher in order to conform with the upward slope of the heavy outrigger booms where they manage to intersect the hull. The dimensions of the boats are described by Gladwin (1970). Hulls around Puluwat average 7.92 m (26') in length. The *wa Mikael* is 7.85 m in length when measured from the base of the V-shaped ornament at each end. The waterline length measurements will generally be 0.76 m (:2.5') shorter. There is some variation in width. The average will be found somewhere in the region of shortly over 0.9 m at the top of the hull. What is more interesting is the variation in L:B ratios of the Pusuluwatan canoes – with some being broader and other showing increased levels of narrowness. Basically the builder may either opt for speed –

narrowness – sacrificing cargo room, or *vice versa*, while he is also limited by the breadfruit tree trunk's availability. Consequently this ratio varies from nine to as high as twenty; while beam-to-depth can go as low as 0.5 (Gladwin 1970: 76). According to Gladwin, the *wa Mikael* has a L:B ratio of twelve. Our calculation however yields a number of less than eight. In both cases this can be interpreted as a cargo oriented canoe.

A system of proportional measurements determines the size of the elements which are to constitute the hull. Pursuant to all considerations on the design of the boat, the builder starts by defining the keel piece which constitutes the backbone of the hull. The keel piece is a single piece of wood which is shaped and hollowed to form the lower half of the hull running the full length. The breadfruit of choice for this operation will determine the size of the canoe – which is why choosing a proper trunk is a hallmark operation. From this logboat base the hull is built up from planks – of the same wood, or some other type, if breadfruit is scarce – which are to match the contours of the keel piece. As all voyaging canoes have freeboards greater than 0.76 metres (2.5') this makes them safe to face most sea conditions. (Gladwin 1970: 76).

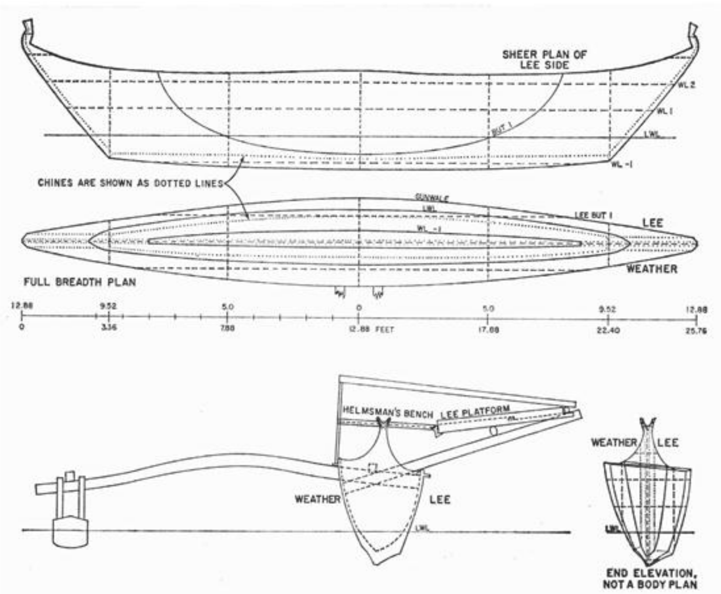

Figure 68. Midship cross-section and lines of the wa Mikael (Doran 1981: 32).1:100.

Next holes are bored at regular distances on each side of the joint, and the two pieces of wood (the keel piece and the upper planks) are lashed together – but just temporary at first. To finalise the lashing process, grooves are cut to allow for the coir cords to be countersunk into the surface of the hull.

After the hull's completion, the remaining elements are sized by applying proportionality relative to the length. Thus the mast as well as the boom will be measured to the full length of the hull. The sizes of the outrigger and its corresponding platform and the lee platform will be established in a similar manner. Applying traditional ratios in a system of proportional measurements allows the builder to harmoniously construct a flying proa.

This is by no means an easy process, and takes experience. As the construction process does not make use of jigs or additional measuring devices and contraptions, the measurements must be determined on the initial roughly hewn trunk, adzed away (before the European brought iron tools to the islanders the adzing as well as all the finishing works were done using simple shellfish implements), redrawn, and once again re-worked by the use of sharp tools till reaching the final form. At any point, a slight miscalculation or error in working the adze can mean that the breadfruit log can no longer be used in the process. In addition to respecting the measurements as part of the labour process, the master builder is also to know the manner whereby the water is to flow along the surface of sailing canoe. He must appreciate where the waves are to form, where pressure is to push against the hull and where pounding from the waves is prone to materialise. Only with all this in the back of his mind can a fair attempt be made at successfully creating the least resistance; because what has to happen is that on the lee side the water must run smoothly along the hull, whilst on the windward side the hull is required to resist the pressure as exercised by wind (Gladwin 1970: 80-1).

Quite common is that the finished hull is painted in varying patterns of red, black and white: black colour will usually cover the lower parts of the sides; white will then be applied as part of bands running along the upper part of the sides. In the end, a large triangular panel of red paint will cover each side of the bow (at both symmetrical ends), leaving the gunwale to be painted black (Haddon & Hornell 1991: 379).

The outrigger, the lee platform and the rigging

There are some common features shared between the steps of constructing each of these three complementing structures. Each will consist of two or three heavy timbers, all lashed together using coir (made of coconut fibres).

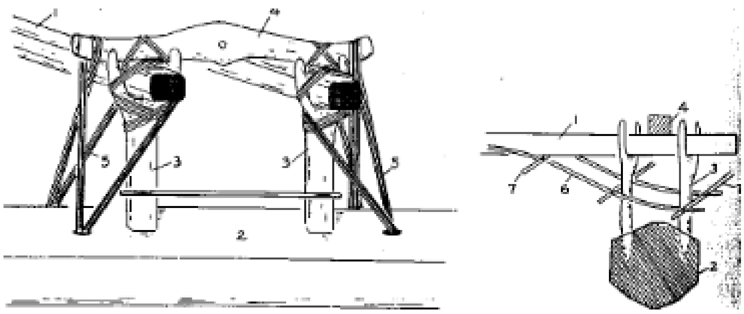

Figure 69. Outrigger structure: the Y stanchions shaped as forks and placed in tandem followed by coir lashing to the float (from Haddon & Hornell 1991: 380).

Construction of the outrigger structure will begin by having two heavy timbers serving as booms as they arch up out of the hull and consequently curve in a downward fashion towards the float. The booms are attached to the float by the use of two Y-shaped stanchions arranged in a tandem fashion requiring the using of a cord made up of a multitude of lashings (of the same coconut fibre coir).

The float structure will mirror the shape of a canoe. It is a heavy piece of solid breadfruit wood. The lashings holding the float tied to the booms is of utmost importance given that such a complex structure is difficult to repair whilst at sea; not least considering that at rough weather conditions the small solid of breadfruit endures extreme pounding and exertion. Lastly, the outrigger structure is also equipped with a platform on top of the two arching booms. It is intended to increase the canoe area for passenger occupation, cargo and gear carrying, and serving the structural purpose of holding the outrigger booms at a right angle to the hull therefore stiffening the narrow hull (Gladwin 1970: 86).

It is worth noting how the whole structure of the outrigger performs whilst at sea, as this is essential to understand a flying proa. As already noted the outrigger will always be on the windward side. The force of the wind pushing on the sail lifts the outrigger float out of the water, which in turn will induce a gravity force on the outrigger. Therefore the stabilising effect of the float results out of its considerable weight and not from its buoyancy. Should the whole structural arrangement be placed in the opposite, a big wave or powerful gust of wind would drive the float underwater. This would cause the canoe to swing downwind and turn sail still more broadside to the wind (Gladwin 1970: 92-3).

The lee platform is also devised to rest upon two heavy timbers (of almost matching scantlings to the outrigger ones but shorter). The two lee platform booms head outwards and in an upward fashion from the lee side point of connection to and insertion into the gunwale. With the outrigger providing a downward force to the weather side, the purpose of this platform is to counterbalance the outrigger.

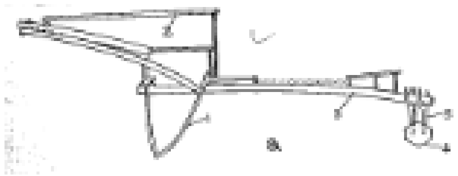

Figure 70. Cross Section through hull, outrigger, and lee platform (from Haddon & Hornell 1991: 381).

Securing the two heavy timbers is done by lashing a heavy bar across the two timbers immediately inboard of the weather side. Moreover, these two are further secured on the outboard side by bracing them together with crossbars, the latter elements serving as supports the flooring of a platform which resembles that present on the outrigger. Both these platforms are intended for holding provisions and light cargo. In addition to these two, Haddon and Hornell describe the present of a third platform placed over the centre of the hull, in continuation of the lee platform which is meant as additional passenger space (Haddon & Hornell 1991: 381).

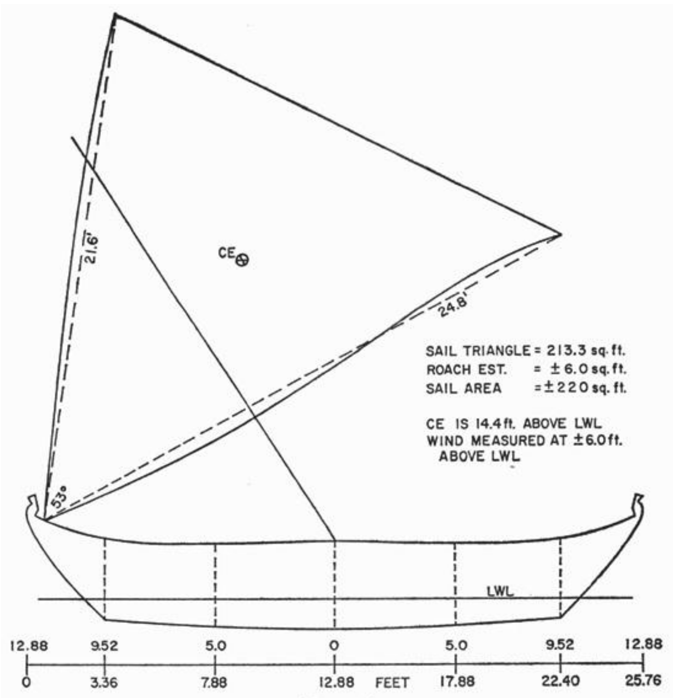

Figure 71. Sail plan of the wa Mikael (Doran 1981:30).

The four main components of the rigging are the *sail* itself, which has to be tied securely to a *yard* at its upper front edge and to a *boom* at its lower one, and the *mast*, the latter component serving to suspend the entire rigging structure above the hull of the canoe (Figure 66; Figure 71).

The sail is an Oceanic lateen sail (also "crane sprit" or "crab claw" sail). This means that it stands lashed to the yard which in turn comes suspended from the mast as opposed to being fastened to the mast itself. The mast may well be considered another spar as will pivot depending on the direction of sailing. Traditionally pandanus was used as material for the sail, but as a post-World War II development white cotton cloth became common. The latter fabric is lighter and not so heavily affected by pouring rain, meaning it does not need to be lowered every time threats of rain linger on the horizon. Pandanus woven sails on the other hand, are heavier, less flexible, and less durable and proved deficient in holding the wind. Also, it had to be lowered each time there were signs of rain which could soak the pandanus making its weight unmanageable. In a later development, Dacron is also used (Doran 1972).

The sail is triangular, the yard taking an almost vertical stance when the sail is raised, almost giving the impression that the yard is the mast; a false impression which is further sustained by the yard resting in a socket near the forward end of the hull. It is the pivoting mast which holds the sail in an upward position, resting in another socket in the middle of the canoe, at the border between the gunwale and the outrigger platform (Gladwin 1971: 96-97).

Hydrostatics and performance

Following Doran (1972), the displacement is here given as 1315 kg (2900 lbs). This is an estimate, including a crew of five. With our assumption of 60 kg per person, this leaves a weight of 1015 kg for the boat. The value includes the hull and outrigger, and probably also the rig. This is a light boat for its size. No cargo is added, and keeping with Doran's numbers we have a draught of this vessel of only 34% of the depth of the hull. This however does not match the drawing published by Doran, and his given LWL must be too low. If we allow the draught to go up to 40% this leaves room for additional cargo. With this particular type of boat, however, there is a tight upper limit to the possible cargo carried, as too much weight would submerge the outrigger. Cargo could be loaded as considered appropriate by the vernacular users of the canoe, which will indeed lead to an increase of the draught within some margins the indigenous builders and users have come to apply as safe for their seafaring.

The very high downflooding angle (55.4°) only applies to the lee side of the canoe opposite the outrigger. If applied to the outrigger side, this value becomes meaningless.

The calculation of stability values for this outrigger boat proved very complicated. DelftShip cannot handle asymmetrical hulls, nor does Orca3D seem able to handle an outrigger. More over the calculation of the stability of outrigger hulls is not incorporated in standard works of naval architecture, so even calculating the values manually provided too much of a task within the given time frame. This is apparently not part of the standard basic curriculum of naval architecture, nor does standard software cater for these hulls. They are of limited commercial interest, which is probably the reason why such calculations are not standard.

One can also note that even the rules by IMO for the stability of smaller vessels (IMO 2002; 2004) dismiss outriggers. These calculations are apparently much more complicated that we had foreseen when selecting our boats. Regrettably, we therefore had to give up on these calculations within the time frame we had for our project.

Running the hull itself through Orca3D without the outrigger gave the rather interesting result, though, that it was close to neutral equilibrium. That is, the metacentre was only a few centimetres above the centre of gravity at most angles of heel until downflooding was achieved. If this is correct, then these hulls were designed at the verge of stability, and only a slight increase in KG would capsize them. They are so narrow that they cannot sail safely by themselves. They were also never meant to, and the outrigger is an integral part of this structure, but it is interesting to see a hull deliberately constructed this close to the border condition. Neutral equilibrium can otherwise seem a somewhat theoretical option in practical ship building.

While the outrigger is therefore a necessary part of the entire boat, it also makes sense to describe it as a separate entity. For the Wa Mikael, the design ratios (L:B) given for the hull itself (Doran 1972), excluding the outrigger. We have followed this practice in Table 21, but this means that the outrigger is considered an additional element, rather than an integral one.

Wa Mikael Outrigger Canoe								
Dimensions								
Length overall	L_{OA}	7.99	m		Depth of hull	D	1.15	m
Length at waterline	L_{WL}	6.33	m		'Standard' draught	T	0.39	m
Maximum beam	B	1.05	m		Minimum draught	T_{MIN}	-	m
Waterline beam	B_{WL}	0.62	m		Maximum draught	T_{MAX}	-	m
Maximum hull speed	S_{MAX}	6.5	kts		Draught-Depth ratio	100 D/T	33.7	%
Volumes, areas and weights								
Displacement, volume	∇	1.283	m^3		Moment of inertia	I	-	m^4
Displacement, weight	Δ	1315	kg		Estimated weight of boat		1015	kg
Wetted surface area	A_{WS}	-	m^2		Deadweight		300	kg
Waterplane Area	A_{WP}	3.00	m^2		Maximum Deadweight		-	kg
Midship Area	AM	0.15	m^2		Deadweight to sink		3497	kg
Coefficients and ratios								
Length-beam ratio	L:B	7.8			Block Coefficient	C_B	-	
Length-draught ratio	L:T	18.6			Prismatic Coefficient	C_P	-	
Beam-draught ratio	B:T	2.4			Waterplane Coefficient	C_W	-	
Displacement-length ratio	D/L	6.66			Midship Coefficient	C_M	-	
Stability								
Centres					**Stability Criteria**			
Centre of Bouyancy	KB	-	m		Downflooding Angle	θ_f	55.4	°
Centre of Gravity	KG	-	m		Minimum Freeboard	F_{MIN}	-	m
Metacentre	KM	-	m		Freeboard, heeling test			m
Metacentric height	GM	-	m		Rolling period	T_R	-	sec
Heeling calculations					**Other standards**			
Critical wave height	h_{CRIT}	-	m		GM-Beam ratio	GM/B_{WL}	-	m
Significant wave height	$h_{1/3}$	-	m		Stability Index	T_R/GM	-	m
Approximate wind speed		-	m/s		Angle of max. stability	AMS	-	°
Beauford		-			Angle of vanishing stability	AVS	-	°

Table 21. The Wa Mikael. Summary table.

This view is reinforced by Abramovitch (2003). According to that article the *wa*’s outrigger is to function as a general feedback control system that is: “*to carry out commands; the system maintains the controlled variable equal to the command signal in spite of external disturbances*” (definition by Mayr 1970 cited in Abramovitch 2003: 58). The outrigger is therefore an additional mechanism that “*senses and resists angular disturbances*” (Abramovitch 2003: 59).

Model tests

During our practical work in the water, the Wa Mikael outrigger canoe stood out as a unique design, due to the presence of both the outrigger and the lee platform which makes the maximum width 7.19 m. Consequently, the guiding pole – used as standing pole for Camera B and through which the fishing line was pulled – had to be distanced slightly farther away from the grid to avoid any case of the outrigger getting entangled into the strings of the grid. As such, the distancing of the guiding pole, and with it of Camera B, albeit provided for good unaltered testing runs, it made difficult to make proper use of Camera B when determining the waves (height, length and period) and for calculating the heel of the canoe during all three runs.

Building the model

As a main purpose of the project was to test and compare the scale models of the boats, the *Wa Mikael*, was, like all the other ones, rebuilt at a 1:20 scale. Since it cannot handle asymmetrical hulls and outriggers, DelftShip could not be employed to create a 3D reconstruction. Instead we opted to use Rhinoceros 4.0 software to make the 3D model (to enable stability calculations using Orca3D). Also those plans were scaled to 1:20 and used to build a scale model which was to be tested on the water.

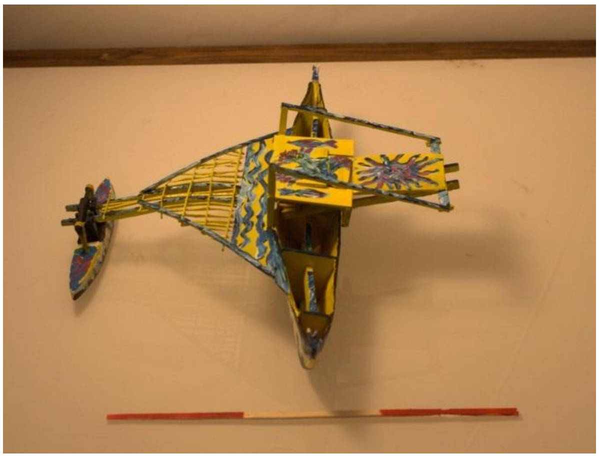

Figure 72. 1:20 scale model of the wa Mikael as reconstructed using the Doran (1981) lines plans; scale bar is 30 cm.

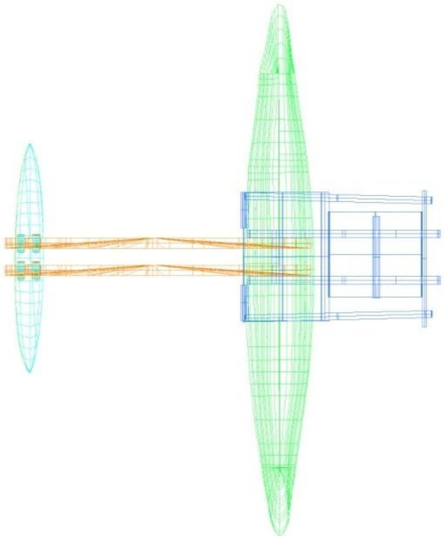

*Figure 73***.** *Top view of the 3D model as designed in Rhinoceros 4.0.*

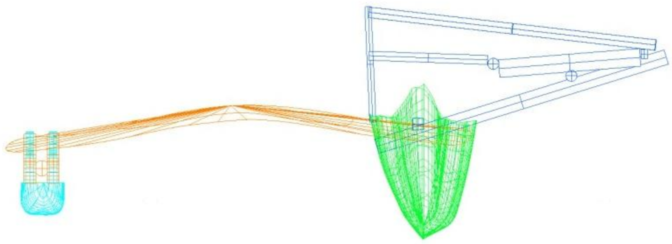

Figure 74. Front view of the wa Mikael.

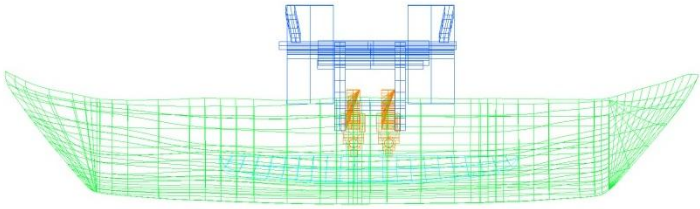

Figure 75. Side view (lee side) of the wa Mikael.

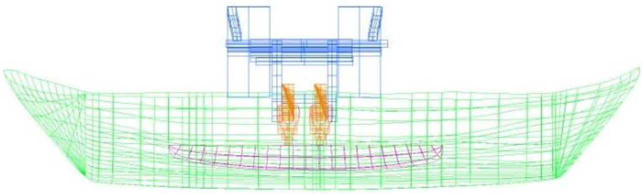

Figure 76. Side view (weather side) of the wa Mikael.

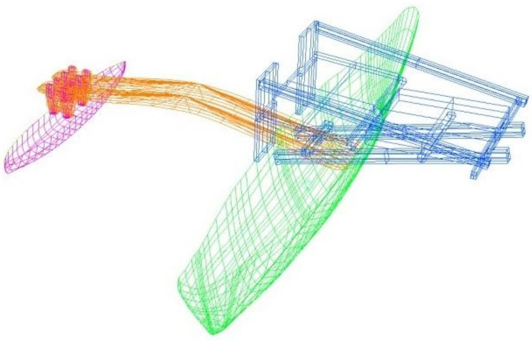

Figure 77. Isometric view of the wa Mikael.

In addition to providing another perspective of the boat, Rhino 3D helped this project by allowing a set of scale frames to be designed. These in turn was printed on paper in 1:20 used as reference for cutting a set of 5 frames which could then be mounted on a building jig to act as support for gluing balsa planks to mimic the light nature of the breadfruit tree dug-out keel piece and added upper planks. The construction of the scale model entailed the following steps: (i) building a jig on which a traditional keel piece was fitted (after being cut to required length from balsawood), (ii) then, within the keel cuts were made to allow the insertion of the frames, (iii) the frames were inserted at regular

1:20 intervals and accordingly aligned to fit the profile of the canoe, (iv) balsawood planks were cut and attached to the frames furthering the forming of a dug-out canoe shape, giving priority to attaining the asymmetrical hull shape, (v) the entire hull was sanded to create smoothness and fair the lines (with super glue used to put everything in position), (vi) a layer of epoxy putty was applied to the outside of the boat, so that the different pieces would stick together and have a solid, waterproof surface, (vii) the dried up epoxy was sanded to create a smooth hull surface resembling an actual hull dug out from the trunk of a breadfruit tree, (viii) the outrigger and the lee platform structures were designed and subsequently attached (ix) as the *wa Mikael* actually materialised it was sprayed with a ground layer of protective lacquer, followed by another layer of yellow spray paint (to make it more visible during the lake testing runs), and lastly (x) the entire structure was decorated as seen above (*Figure 72*).

The tests

As with all the boats four tests were conducted. Out of these four the first one was not made using any degree of wave making and high velocity was used. The three tests that will form the analysing resources of this section were described by consequentially increased wave heights, lengths and periods (from low to medium, to high). The analysis shall consider the calculated average of each of the three runs wave height, length and period.

Given that a Beaufort force 2 (4-6 knots), such a canoe would sail at speeds between 5-6 knots (Gladwin 1970, p.109), a proper speed for the tests was achieved (0.72 m/s or 6.3 knots, 0.73 m/s or 6.4 knots, and 0.84 m/s or 7.3 knots). The speeds reached during the testing would therefore be at Beaufort 3 or 4.

Before describing the tests it must be said, that through an error the sailing direction of the canoe on the lake was unfortunately the one used in real life. The canoe should have had its outrigger on the side facing the oncoming waves. This is due to the fact that as the weather side (windward side) of the canoe is that of the outrigger, by such construction the float is intended to be pulled up, outside of the water by the wind blowing into the sail from lateral, at an angle. However, since during our testing neither wind conditions nor sails were tested, it does not affect the results.

Test run	Wave height, h_S, m	Wave length, λ, m	Speed of boat, kts
0 (preliminary)	n/a	n/a	13.7
1	0.36	6.30	6.3
2	0.80	2.39	6.4
3	0.56	4.14	7.3

Table 22. Overview of the 4 (3+1) test runs. All values are converted to full scale from 1:20, using the rules of similitude.

Test run 1

The first test run was made using waves of low intensity but long waves. The average height was 1.78 cm and the length was 32 cm (0.36 m and 6.30 m in full scale). The canoe started slicing through the waves smoothly, initially drifting slightly to the port side as the waves hit the main hull whilst passing along the grid. At the start of the run the waves hit the boat mildly (at a 45 degree angle) on its starboard bow. As it continued its course into the actual waves, the movement of the canoe also changed regaining a straight course, but increasing the pitch angles, with the heel slightly decreasing.

The boat was towed at a speed of 0.72 m/s (7.2 knots in real scale). The outrigger proved very useful in stabilising the canoe thus allowing for it to tackle each incoming wave without heeling to any dangerous level.

The maximum pitch angle was 10.5° upwards and 9.2° downwards from vertical, whilst the total average maximum pitch was 20.0 degrees. The average maximum heel was 18.9°. The heeling angles were measured while the boat was turning into course as it got near the grid.

Figure 78. Snapshot of video from test run 1. It can be seen how the canoe stands in an almost perfect horizontal position as the wave (reduced intensity at pre-grid position) passes the main hull and reaches the outrigger float, thus raising the float by the wave height.

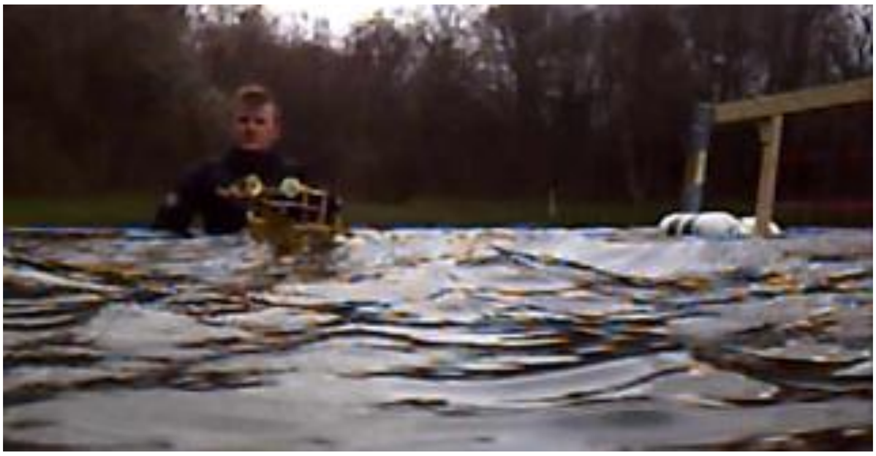

Figure 79. Snapshot of video from test run 1. It shows how the boat starts curling by the waves as it begins passing by the grid and facing the full force of the 1st run waves.

Test run 2

This test was made with high and steep waves coming in and pounding the bow at starboard from a 45 degree angle. The waves had an average height (h_S) of 4 cm and an average length of 12 cm (0.80 m and 2.39 m in full scale). As this time the waves concentrated more on steepness and were not as sinuous as before (and long as well) the canoe, in these conditions, did no longer tend to turn port side as guided by the wave as they came from the starboard side.

Figure 80 Snapshots of video from test run 2; pictures (left – downward pitch; right – upward pitch) show how the bow (or more correctly: forward heading end) visibly plunges and then climbs as the waves hit its lee side.

The boat was towed at a speed of 0.73 m/s (6.4 knots in full scale). The evidenced pitch of the boat was – to the naked eye – close to impressive; there was substantial movement across the waves as they hit at a 45 degree angle – which did not alter as above where the canoe amended its straight going direction). There was no report-worthy sign of loss of freeboard as the hull consistently rose with the waves riding on top of them.

Figure 81 Snapshot of video from test run 2. The canoe shows signs of heeling whilst managing to maintain its freeboard as it progresses with riding almost on top of waves; the float of the outrigger is the part suffering most water immersing thus fully performing its purposes of maintaining the canoe's stable course – without dangerously heeling.

The maximum pitch angle was 10.1° upwards and 12.0° below horizontal. Insofar as heeling is concerned this was 18.3° (average maximum heeling).

Test run 3

This last test run was made with high and steep waves coming in from starboard bow. It was designed to increase the wave strength. Despite the wave-maker's concentrated efforts, the run did not add substantial difference, thus this run resembles the previous one with just minor alterations. The waves in this run were (even steeper, with a stronger tendency to break, meeting the canoe at the same 45 degree angle. The significant wave height (h_S) is calculated to 4.34 cm with a wave length of 21 cm (0.87 m and 4.14 m in full scale). The result was a highly dynamic sea, with an uneven wave pattern.

Figure 82. Snapshots of video from test run 3 showing consecutive stances of pitching downwards (bottom) and then upwards (top).

The boat was towed across this surface at a speed of 0.84 m/s (7.3 kts in full scale); both speed and waves were designed to stretch the limits of the canoe at rough sea sailing. The result as seen on the was a rather gentle gliding on top of the waves with observable pitch and heel as the 45 degree angle hit the main hull (Figure 83).

Figure 83 Snapshots of video from test run 3 showing two consecutive stances of heeling at portside (outrigger side) (up) and then at star board side (down)

Maximum pitch angle measured was 9.1° upwards, and the average maximum movement of the stem was 15.1° from top to bottom. The maximum heel was 17.5º on average (although more difficult to measure given the bad video positioning of the canoe in relation to the grid (Figure 17)). Even at this increase in roughness conditions the boat did not come close to sinking; the amount of water it took in only changed by 5 grams from 16 grams at test run 2 to 21 grams in this instance. The outrigger canoe proved to work well for such conditions that in real life would have been translated into a very rough and very dangerous sea exposure.

Discussion

These tests illustrated the seaworthiness of the outrigger canoe. The preliminary high-speed test was conducted in calm waters, although not considered very relevant for the outrigger canoe. All three actual test runs have produced results with regards to the heel and pitch angles. What was tried by attempting the three consecutive test runs was an increase in steepness and intensity in the same directional wave pattern. Rather unsurprisingly the Wa Mikael coped quite well with even the worst of the test runs wave conditions. The only recorded downside is the fact that as the waves increased more water went into the canoe, but not anywhere close to affecting its floating capacity.

The results are summarized in Table 23. The pitch and heeling angles are also correlated to the wave steepness (Figure 84). We have also shown the speed of the boat in the table, as this is important to the boat's response to waves. It is important to remember that small variations could be the mere result of poorly analysable videos given the equipment at hand.

The Caroline Islands outrigger canoe does behave as a water craft with a tendency to stiffen at hi. It rides each wave, and it maintains a rather unaltered line in relation to heeling – in respect of which it designs an almost linear heel.

Test run	h_S, m	λ, m	Angle, °	Boat speed, kts	Pitch, °	Heel, °
1	0.56	6.30	5.0	6.3	20.0	18.9
2	1.25	2.39	27.6	6.4	19.0	18.3
3	0.87	4.14	11.8	7.3	15.1	17.5

Table 23. Summary table of the model tests. Speed and distances are converted to full scale,

Although the video measurements and subsequent results show that it is test number 2 that generated the highest wave they were nonetheless shorter in length whilst test number 3 produced lower waves yet with a longer length and slightly more periodical. As such the worst conditions attainable were registered in the final run where the boat behaved laudably taking in only 5 grams of water more that in test number 2.

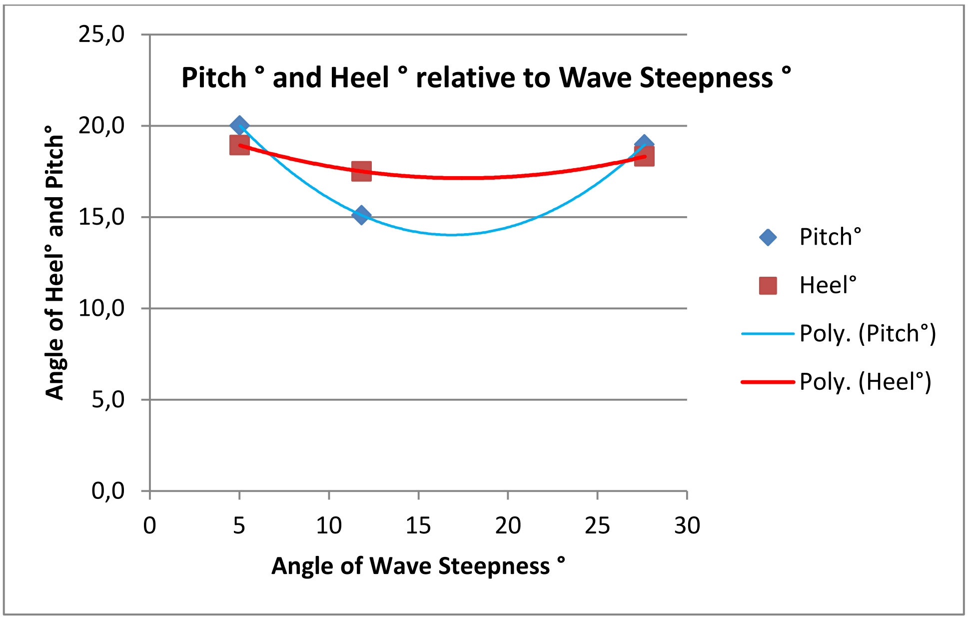

Figure 84. Wa Mikael. Summary of pitch and heel with varying wave steepness. Two trend lines are fitted for the pitch and heel angles. None of the angles attained while testing marked the downflooding angle.

Discussion

Micronesian/Carolinian single outrigger canoes – of which the wa Mikael proa is an example - are notorious for being fast sailors. The freeboard is suitable for open sea and the proa's overall body narrowness assists in this respect, considering its length to beam ratio which is appreciably high. This creates fine entrances and runs and leads to minimum drag. Modern evaluation (and comparison with one other vernacular type of canoe, the vinta – a double-outrigger canoe from the Philippines, and one modern type – the trimaran) by Doran (Doran 1972: 157) goes to ascertain that the indigenous wa and vinta in some respects are superior to modern variants with regards to their sailing abilities.

It is commonplace that voyages of 150 miles took place across open by watercraft similar to the Puluwat Atoll wa, and this goes to attest (in an applied fashion) that proas are good sea boats.

8. KINNERET

Introduction

The ים כנרת or in English the Kinneret Sea, is located in the northern part of the African Syrian Rift Valley in present day Israel (ILCE, 2009). Also referred to as the Sea of Galilee by some, it is a site of religious importance for many. The climate of the area, which has remained stable for the last 2,000 years, is generally hot in the summer with an average temperature of 25 degrees Celsius, and temperate in the winter at an average of 15 degrees Celsius (ILCE, 2009).

The Kinneret Sea, which is actually a lake as it is fully landlocked, is the largest freshwater lake in Israel and the second most low lying lake in the world. The Kinneret has a surface area of 170 square kilometres, and a maximum depth of 43 meters (ILCE, 2009).

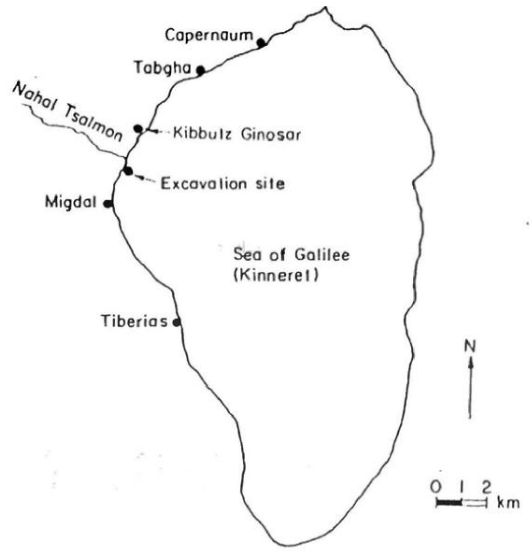

Figure 85. The Kinneret Boat's excavation site on the lake (from Wachsmann 1990: 376).

Discovery and Excavation

During a drought in January of 1986 Yuval and Moshe Lufan found a partially exposed boat on the beach some hundred meters south of Kibbutz Ginosar (Wachsmann et al. 1987: 233). The discovery was reported to the Israel Department of Antiquities, whose assessment of the wreck concluded that it was 'antique', as shown by its mortise-and-tenon joints (Wachsmann et al. 1987: 233).

A probe to determine the extent of the boats preservation was conducted over the course of two days, and showed that a good portion of the hull was intact as well as in a good state of preservation (Wachsmann et al. 1987: 233). Several artefacts were found at this time, all terracotta, one a cooking pot and an oil lamp, both of which date to the mid-first century CE through the 2nd century CE and several pottery sherds (Wachsmann 1989: 472). A group of coins were also found at this time, but without any archaeological context (Wachsmann 1995: 249).

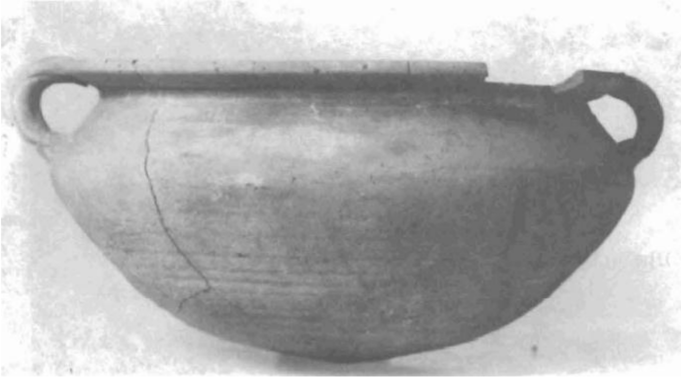

Figure 86. The cooking pot (from Wachsmann 1990: 377).

The decision was made to rebury the boat until a more appropriate time for excavation, but an article in the news appeared calling it the 'Boat of Jesus,' and rumours spread quickly, including the idea that the boat was filled with gold coins (Wachsmann et al. 1987: 233). This meant that the boat was now unsafe in its current unexcavated state, so the Israel Department of Antiquities began a salvage excavation of the boat (Wachsmann et al. 1987: 233).

The Kinneret Authority dammed the lake partially to prevent the site from flooding (Wachsmann et al. 1987: 233). The interior was excavated, recorded and drawn first, and the mud was kept for checking later (Wachsmann et al. 1987: 234). Three assemblages of wood were found, two of which were determined to be the remains of other boats (Wachsmann et al. 1987: 234). When all *in situ* work was completed the boat was prepared for removal (Wachsmann et al. 1987: 237).

Fiberglass supports reinforced the frames, and the boat was sprayed with polyurethane foam (Wachsmann et al. 1987; 237). The area was flooded and the boat was floated to the coast (Wachsmann et al. 1987: 237). The entire excavation and removal took only 11 days (Wachsmann et al. 1987: 237).

Figure 87. Floating the boat out of the lake (from Wachsmann 1990: 382).

Description of the boat

The preserved dimensions of the boat are 8.2 m. in length overall, a 2.3 m. maximum breadth, and 1.2 m. deep at the stern (Steffy 1987: 325). The boat is estimated to have actually been 8.8 m in length overall, a 2.5 maximum breadth, and 1.25 m. at the midship sheer (Steffy 1987: 329).

The entirety of the rockered keel was preserved, at a length of 8.27 m., a moulded (vertical) dimension of 11.5 cm, and a sided (horizontal) dimension of 9.5 cm (Steffy 1987: 325). The keel is rectangular in shape, and was not rabbeted (Steffy 1987: 325). It consisted of two parts, wedge hook scarfed at amidships, the four of which was cedar (*Cedrus*) and the aft of which is jujube (*Ziziphus* *spinachristii*) (Steffy 1987: 325). Neither the stern or stem post was recovered, as they were removed, most likely for reuse in another vessels construction (Wachsmann 1995: 367).

The planks were made from true cedar (*Cedrus libani*), except one plank of pine, which was most likely a replacement (Steffy, 1987, p. 325). The planks were all edge joined pegged mortise-and-tenon, including the garboard strakes which were not rabbeted to the keel (Wachsmann 1995: 138).

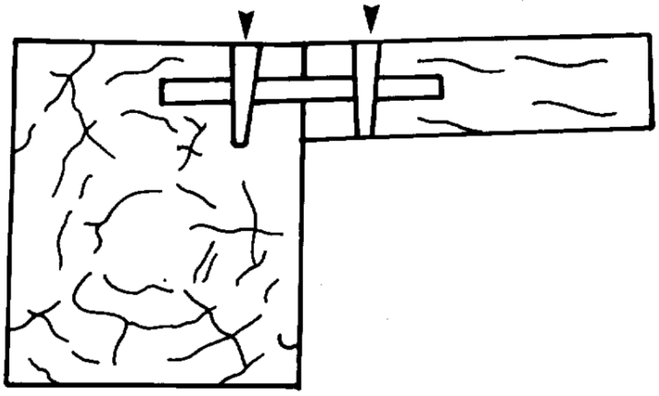

Figure 88. A drawing showing how the garboard strakes are attached to the keel (from Wachsmann 1990: 140).

The mortises were each around 5 cm. wide, 6 cm. deep, 5 mm. thick, and the tenons, made of oak (*Quercus*) were each around 1 cm. shorter than the combined length of the mortises in which they were placed (Steffy 1987: 325). Twelve rows of strakes were preserved on the starboard side, and twelve to fourteen rows of strake fragments were found from the port side (Steffy 1987: 325). The strakes were narrow overall, with the exception of those found at the turn of the bilge, some of which measured more than 25 cm. in width (Steffy 1987: 325). The average thickness of the strakes overall, measured at 30 separate locations, was just 3.1 cm. Of the preserved strakes all were diagonally scarfed together with iron nails (Steffy 1987; 325).

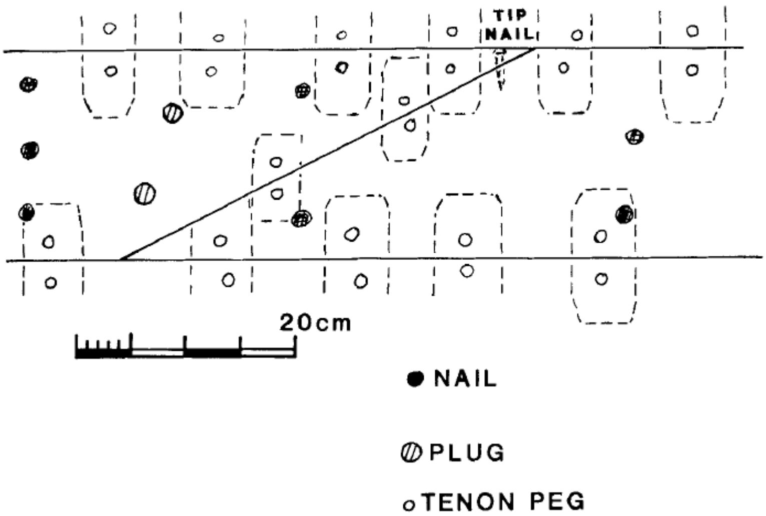

Figure 89 .The strakes were diagonally scarfed together with iron nails (from Steffy 1987: 326).

The frames were attached to the strakes with iron nails, none of which passed all the way through to the interior surface of the frames (Steffy 1987: 327). The majority of the frames were oak (*Quercus*), but there are also single examples of willow (*Salix*), hawthorn (*Crataegus*), and redbud (*Cercis*) all of which are most likely replacement frames (Steffy 1987: 327). A portion of the frames are very twisted and still contain their bark, they were almost entirely unworked (Steffy 1987: 327). The average sided dimension of the frames is 6 cm. and the average molded dimension of the frames is 7 cm. (Steffy 1987: 327). Thirty-two frames remain of the original thirty-four, the two fore most frames having been removed (Steffy 1987: 327).

There is no indication of a keelson being used here, nor any permanent ceilings (Steffy 1987: 327). Discoloration on the upper part of the keel and four nail holes indicate a possible mast step (Steffy, 1987, p. 327). Removable ceilings were most likely placed at both the fore and aft of the vessel (Wachsmann 1995: 361).

The vessel was well used and repaired many times over (Wachsmann 1995: 152). Several staple shaped iron fastenings were found, most likely placed there to strengthen loose mortise-and-tenon joints (Wachsmann 1995: 152). Staple repairs are unusual in the Mediterranean area, but this may have been due to the fresh water the boat was sailed in, which is harsher on wood then salt water (Wachsmann 1995: 152). Where wood types other the oak and cedar have been used, they were most likely replacements (Wachsmann 1995: 366).

The hull was covered on both the interior and exterior with pitch or bitumen, most likely from the Dead Sea (Wachsmann 1995: 361). The hull would have them been submerged in the water, allowing water to flood into the seams, which swelled the wood and sealed the seams (Wachsmann 1995: 361).

Dating the Boat

The boat can be dated using three different methods, analysis of the boats construction, analysis of the pottery found with the boat, the coins and C14 dating (Wachsmann 1989: 471). Being that this was an inland freshwater lake, it is possible that construction fashions here lasted much longer then the in the comparatively culturally fast paced Mediterranean (Wachsmann 1989: 234). There is also a distinct lack of boats to compare construction techniques with in the area, so it is ill-advised to base the date of the construction in the Kinneret's case (Wachsmann 1989: 234). Though it may be ill-advised, when compared to vessels of the Mediterranean, date the boat to between 1st century BCE and 2nd century CE (Wachsmann 1989: 472).

The oil lamp found with the boat is of a rare type (Wachsmann 1995: 236). The lamp was made on a wheel, as opposed to the popular Roman style molded lamps (Wachsmann 1995: 242). A lamp expert, Varda Sussman, dates this lamp to between 50 BCE and 50 CE (Wachsmann 1995: 242). The cooking pot, was also dated to between 50 BCE and 50 CE (Wachsmann 1995: 244). The sherds date to between 50 BCE and 70 CE (Wachsmann 1989: 472). The pottery could not be connected to the boat with any certainty, and is therefore a less the desirable method to rely on for a date (Wachsmann 1995: 234).

The coins, which had no archaeological context to connect them to the boat, were also dated (Wachsmann 1995: 249). Of the 57 coins found, only 43 could be identified, the oldest of which dated to the 3rd century BCE and the youngest of which was an American penny from 1808 (Wachsmann 1995: 250). Ten samples were taken for C14 testing, after calibration the samples varied from between 130 BCE and 80 CE (Wachsmann 1995: 249). The average date of the samples is 40 BCE +/- 80 (Wachsmann 1995: 249). All of this evidence combined suggests that the boat was not built before 100 BCE and was not dispossessed until 67 CE (Wachsmann 1995: 349).

Theoretical Reconstructions

Neither the stern nor the stem of the boat was preserved completely. While the stern size and shape was determined by the seine net, there are two plausible theoretical reconstructions of stem, visible in the sheer view of the preliminary lines plan (Steffy 1987: 328). Both reconstructions can be seen in contemporary art of the area, so either is compatible with the reality of the boat (Steffy 1987: 328).

The shape of the stem could have been pointed outward, almost in a ram shape, which can be seen as a dotted line in the plan (Steffy 1987: 328). Also just as likely was a simple curved stem, also shown with a dotted line (Steffy 1987: 328). Though both are plausible, the reused nature of a vast majority of the wood used in the construction of this boat, indicates that any element considered superfluous would have been left off, whether or not a ram would have been considered so at this time however is unknown.

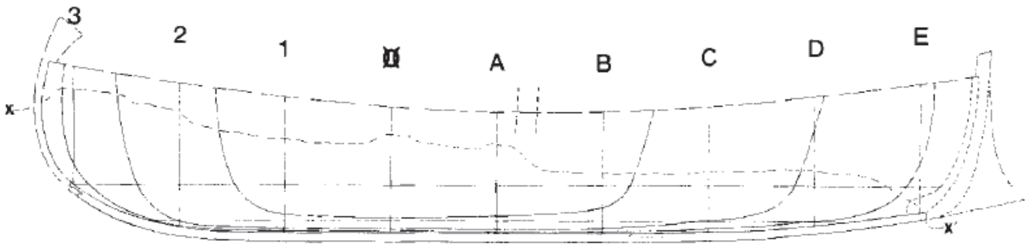

Figure 90. The sheer view of the lines plan, demonstrating the two possible stem shapes (from Steffy 1987: 328).

Interpretation and Historical Background of the Boat

The large box like structure of the boat was convenient for its main purpose, fishing (Wachsmann 1995: 324). The removable ceiling was most likely used to store the nets used for fishing, and sheltering the crew in particularly bad weather (Wachsmann 1995: 326). The boat would have most likely been rowed by four men, when the sail was not in use (if there was in fact a sail as indicated by the discoloration on the keel), and helmed by a fifth man (Wachsmann 1995: 362).

As discussed previously many of the timbers used in the construction of this boat were previously used (Wachsmann 1995: 357). They were of such a poor quality, that they most likely would not have been used in Mediterranean shipbuilding usually (Wachsmann 1995: 357). The quality might have been due to a wood shortage, but there is no evidence for such an occurrence, and in fact Vespasian was apparently able to find enough wood near here to aid in the construction of his fleet before the Battle of Migdal (Wachsmann 1995: 357). The reused planks had to be prepared properly before they were added to the boat (Wachsmann 1995: 359). Holes were plugged with wooden pegs and planks were narrowed to rid the boat of the mortise-and-tenon-joint scars, resulting in some very narrow planks (Wachsmann 1995: 359).

When the boat had finished it service, many sections were detached for reuse (Wachsmann 1995: 367). The stem and stern posts were removed, the two most for frames were pulled out, the mast step was removed, and the wooden wedge in the scarf of the stempost was knocked out (Wachsmann 1995: 367). What was left was unusable to the dismantlers, as it could not even be used for firewood in its pitch covered state (Wachsmann 1995: 367). The remaining hull remains were floated out onto the lake and sunk off shore (Wachsmann 1995: 368).

Iconographic and Literary Evidence

Ten years before this excavation an excavation at Midgal revealed a 1st century mosaic that closely resembles what the Kinneret boat is projected to have looked like (Wachsmann 1989: 473). The mosaic shows the boat being propelled by four rowers, as projected earlier (Wachsmann 1989: 473).

Josephus wrote in his history that when he was the magistrate of the area, he ordered all the boats of the lake to be sailed for Tiberias, where captives were taken to fight with Josephuses men at Migdal (Wachsmann 1989: 474). He describes that each boat was oared by no more than four men, which fits with both the interpretation and the mosaic found at Migdal (Wachsmann 1989: 474). Without cargo and loaded with the captive men, a boat of this type could have held up to 15 men (Wachsmann 1989: 475). Josephus also makes it clear that the primary use for these boats was fishing, and not war, as he was using them for (Wachsmann 1989: 475).

Figure 91. The mosaic (CD Israel, 2008).

Seine Fishing

The Kinneret boat's main use was for fishing, particularly seine fishing (Wachsmann 1988: 31). Boats of the Kinneret, which maintained a similar construction technique before the introduction of the motorized boat, continued to employ this method of fishing well into the 19th century (Wachsmann 1988: 33). Seine fishing nets vary in size from 150 to 300 m long ropes of about 70 m long at both ends, around 2 m in height at the sides and 5 to 6 m high in the centre (Wachsmann 1989: 476). The net is usually carried in the stern, hence the removable ceilings in the Kinneret boat (Wachsmann 1989: 476). To employ a seine net, means that half the crew stays on land with one rope, while the other half keeps the second rope, the boat is rowed first perpendicular then parallel to the shore, when the boat lands on shore, the net is pulled up with it and captures the fish within (Wachsmann 1989: 476). The fish are then sorted on the shore (Wachsmann 1989: 477).

The use of a seine net required a large boat, somewhere in the range of 7 to 9 m. long, and this held true both in the 1st century BCE and up through the 19th century on the lake (Wachsmann 1989: 477). Though the Kinneret Boat's stern was not preserved, it is likely that this area would have been the largest part of the boat and contained a removable deck under which the seine net was stored (Wachsmann 1989: 477). Though fishing was the main purpose of this boat, the shallow draft of the boat made it a swift military craft as well during times of need, which were frequent in this period of Roman control over ancient Israel (Wachsmann 1989: 478).

Hydrostatics and performance

The Kinneret boat was modelled in DelftShip from the preliminary lines plans in order to obtain hydrostatic data (Steffy 1987: 328). Only the shape of the hull, the average thickness of the strakes, and the density of the wood were considered for this model. DelftShip has features to calculate the hydrostatic properties of any hull shape that is modelled within it or imported from similar programs, such as Rhino3D. The Kinneret boat was modelled entirely within DelftShip, without the use of any third party modelling software.

Determining a realistic displacement for a fishing vessel is especially difficult, because it will change during the trip. Outgoing displacement has got to have a reserve for the successful catch. The first analysis was generated using the Grågås ratio (60 % of the hull submerged, or 0.68 meters), but this resulted in more than 4.5 tonnes of cargo needed on top of a four man crew in order to sink the boat to that percentage. Lake Kinneret may be rich in fish, but this seemed unrealistically high. The second analysis, which was calculated in the reverse of the Grågås ratio (40 % or 0.46 meters), resulted in a more realistic cargo of about 1850 kg on top of a five man crew. This number still amounts to a lot of fish, even taking the weight of fishing gear and sail rig into account. A comparison with modern data can illustrate this. Having considered a total ban for two years (Friedman, 2010), the Israeli government instituted a four month annual break in fishing in Lake Kinneret from 2011 (Ashkenazi, 2011). This was due to dramatically decreasing landings over a decade, where catches fell from 2144 tons in 1999 to 157 tons in 2009. With these modern numbers in mind, 1.85 tons of fish and fishing gear seems a lot.

Josephus also gives an account of the boats capacity, claiming that a boat of this type transported 15 people including himself to Tiberias where they anchored. This group included 5 crew, 7 soldiers, Josephus, and two of his friends (Wachsmann 1995: 315). We have previously established a reasonable weight per man at this time to be 60 kg, and this is fair for the 5 crew members, Josephus, and his two friends, but it is reasonable to assume the 7 soldiers would have been expected to be carrying heavy gear, and cargo. The weight of these 15 men without gear or cargo comes out to 900 kg. Much work has been done on the gear and armour of the Roman soldiers of this time, Junklemann's “*The legions of Augustus: the Roman soldier in an archaeological experiment*,” actually traces the journey of 9 men carrying the complete 1st century BCE Roman soldier's gear weighing 45 kg on a four week journey across the Alps. We cannot say that a soldier under Josephus would have carried the exact same gear, in fact they most likely would not have given the completely different geographical setting, however it is fair to guesstimate at least that on a journey such as this each person, soldiers included would have carried with them somewhere around a maximum of 45 kg of gear and cargo. This brings the total weight up to 1575 kg, which still leaves 575 kg free if the crew does not want the boat to be loaded past the 40% draught. It is not necessary to fill this extra space however, as a lighter draught would have given the vessel even more speed, and important commodity in a sometimes war vessel.

Based on the digital model and allowing for frames and other structures, the hull weight is here estimated to 1750 kg, although this is a guesstimate. At this weight the boat will carry itself at a draught of 0.27 m. The maximum draught which still allows for a 10° heel is 0.94 m, with a displacement of 9920 kg. If our estimation of the hull weight is correct, then this means that in calm water the boat could safely carry more than 8 tonnes. This safety criteria was originally developed for logboats (McGrail 1978), and this boat may illustrate the borders of its applicability.

The hydrostatic report generated showed that the craft was, in general, seaworthy. With a GM of 0.68 m the initial stability should be more than ample, and even at the unrealistically deep 60% draught, GM is still more than half a metre.

Forming an almost straight line beyond the first c. 10 cm draught, the displacement sheet illustrates the wall-sided construction of the Kinneret boat very well.

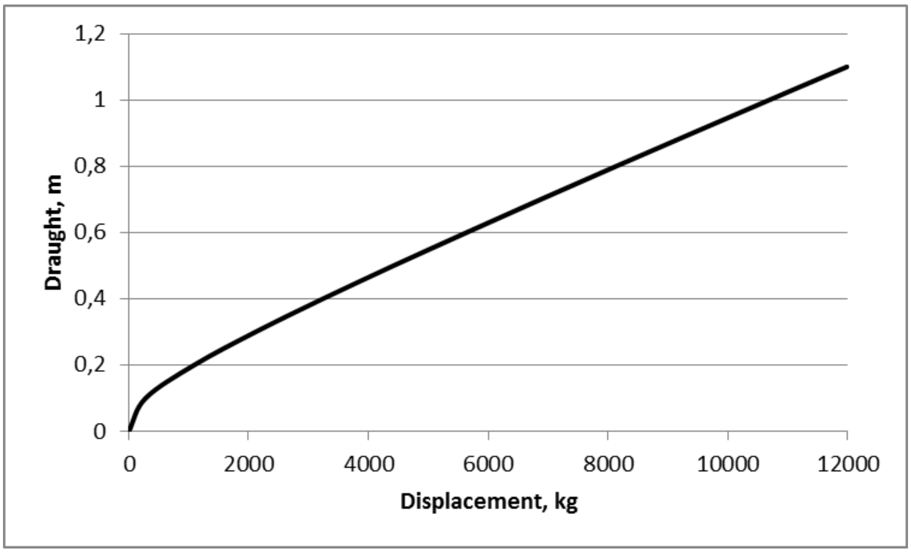

Figure 92. Displacement sheet for Kinneret. The minimum draught is 27 cm.

Kinneret, 40% draught

Dimensions								
Length overall	L_{OA}	8.80	m		Depth of hull	D	1.14	m
Length at waterline	L_{WL}	8.58	m		'Standard' draught	T	0.46	m
Maximum beam	B	2.24	m		Minimum draught	T_{MIN}	0.19	m
Waterline beam	B_{WL}	2.18	m		Maximum draught	T_{MAX}	0.94	m
Maximum hull speed	S_{MAX}	7.09	kts		Draught-Depth ratio	100 D/T	40.0	%
Volumes, areas and weights								
Displacement, volume	∇	3.799	m^3		Moment of inertia	I	39.699	m^4
Displacement, weight	Δ	3894	kg		Estimated weight of boat		1750	kg
Wetted surface area	A_{WS}	14.77	m^2		Deadweight		2144	kg
Waterplane Area	A_{WP}	11.593	m^2		Maximum Deadweight		8170	kg
Midship Area	A_M	0.745	m^2		Deadweight to sink		8990	kg
Coefficients and ratios								
Length-beam ratio	L:B	3.9			Block Coefficient	C_B	0.457	
Length-draught ratio	L:T	18.8			Prismatic Coefficient	C_P	0.580	
Beam-draught ratio	B:T	4.8			Waterplane Coefficient	C_{WP}	0.572	
Displacement-length ratio	$L_{WL}/\Delta^{1/3}$	5.5			Midship Coefficient	C_M	0.653	

Stability

Centres					**Stability Criteria**			
Centre of Bouyancy	KB	0.28	m		Downflooding Angle	θ_f	31.5	°
Centre of Gravity	KG	0.37	m		Minimum Freeboard	F_{MIN}	0.20	m
Metacentre	KM	1.05	m		Freeboard, heeling test		0.4	m
Metacentric height	GM	0.68	m		Rolling period	T_R	2.1	sec
Heeling calculations					**Other standards**			
Critical wave height	h_{CRIT}	1.96	m		GM-beam ratio	GM/B_{WL}	0.31	
Significant wave height	h_S	1.54	m		Stability Index	T_R/B_{WL}	1.0	
Approximate wind speed		8.1	m/s		Angle of max. stability	AMS	29	°
Beaufort		5			Angle of vanishing stability	AVS	45	°

Table 24. Summary table for the Kinneret boat at 40% draught.

Kinneret, 60% draught

Dimensions								
Length overall	L_{OA}	8.80	m		Depth of hull	D	1.14	m
Length at waterline	L_{WL}	8.58	m		'Standard' draught	T	0.68	m
Maximum beam	B	2.24	m		Minimum draught	T_{MIN}	0.31	m
Waterline beam	B_{WL}	2.18	m		Maximum draught	T_{MAX}	0.94	m
Maximum hull speed	S_{MAX}	7.09	kts		Draught-Depth ratio	100 D/T	59.6	%
Volumes, areas and weights								
Displacement, volume	∇	6.465	m^3		Moment of inertia	I	43.969	m^4
Displacement, weight	Δ	6627	kg		Estimated weight of boat		1750	kg
Wetted surface area	A_{WS}	18.78	m^2		Deadweight		4877	kg
Waterplane Area	A_{WP}	12.191	m^2		Maximum Deadweight		8170	kg
Midship Area	A_M	1.221	m^2		Deadweight to sink		8990	kg
Coefficients and ratios								
Length-beam ratio	L:B	3.9			Block Coefficient	C_B	0.522	
Length-draught ratio	L:T	12.6			Prismatic Coefficient	C_P	0.617	
Beam-draught ratio	B:T	3.2			Waterplane Coefficient	C_{WP}	0.571	
Displacement-length ratio	$L_{WL}/\Delta^{1/3}$	4.6			Midship Coefficient	C_M	0.759	

Stability

Centres					**Stability Criteria**			
Centre of Bouyancy	KB	0.53	m		Downflooding Angle	θ_f	22.4	°
Centre of Gravity	KG	0.34	m		Minimum Freeboard	F_{MIN}	0.20	m
Metacentre	KM	0.89	m		Freeboard, heeling test		-	m
Metacentric height	GM	0.55	m		Rolling period	T_R	1.9	sec
Heeling calculations					**Other standards**			
Critical wave height	h_{CRIT}	1.07	m		GM-beam ratio	GM/B_{WL}	0.25	
Significant wave height	h_s	0.84	m		Stability Index	T_R/B_{WL}	0.9	
Approximate wind speed		5.9	m/s		Angle of max. stability	AMS	40	°
Beaufort		4			Angle of vanishing stability	AVS	84	°

Table 25. Summary table for the Kinneret boat at 60% draught. No heeling test was made for this draught.

Model tests

Building the model

The model boat of the Kinneret was constructed in several steps, based on the DelftShip model and the original reconstruction drawing. First a balsa wood jig was cut and the shape of the hull was drawn on both sides. Second plywood sections were placed within cuts made into the balsa to give the model its shape. Third thin strips of plywood were wetted with hot water and bent around the sections while being glued into place by the lines drawn on the balsa. Fourth the balsa was cut away to form the keel and the outside of the model was faired with an epoxy based fairing putty. Finally the epoxy was sanded to smoothness, the outside painted and to finish off the entire model was varnished.

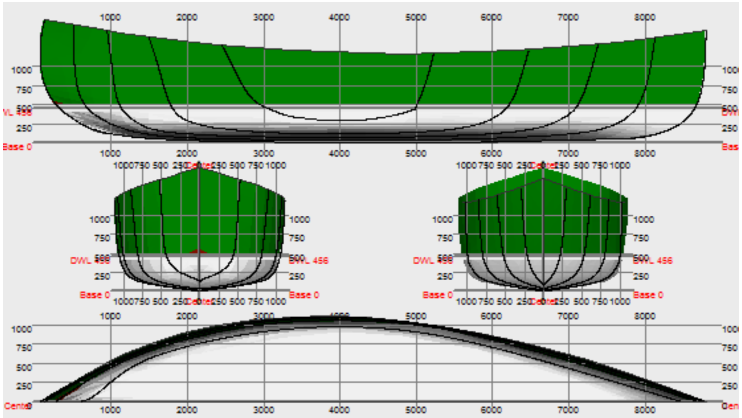

Figure 93. Lines plan from DelftShip.1:100.

The tests

Three tests runs were performed on each wooden model on a small sheltered lake, with little to no wind with the following results.

Test run	h_s, m	λ, m	Angle, °	Boat speed, kts	Pitch, °	Heel, °
1	0.37	5.31	3.9736492	5.5	10.0	25.3
2	0.79	5.85	7.7294745	6.0	11.0	17.8
3	0.94	3.59	14.626671	6.6	14.2	20.5

Table 26. The results of the wooden models test runs.

Test Run 1

The model was towed at a maximum speed of 5.5 knots (converted from the smaller scale), with a maximum wave height of .37 meters. The hydrostatic results show that this is well below the critical wave height for both the 60% and 40% draught models, which is 1.96 and 1.07 meters respectively.

The average pitch of the model was 10°, while the average heel was 25.3°. In this case the average heel of the model is less than the downflooding angle of the 40% draught model at 31.5°, but overwhelms the 60% draught model's downflooding angle of 22.4°. The model took on no water in this test run.

Test Run 2

The model was towed at a maximum speed of 6 knots, with a maximum wave height of .79 meters. Once again the average wave height was well beneath the critical wave height of both the 60% and 40% draught models.

The average pitch of the model was 11°, while the average heel was 17.8°. While the first test run showed the 60% draught model would be overwhelmed by its heel, this run shows that both the 40% and the 60% draught model’s downflooding angles are within tolerance and would not have been overwhelmed on this run.

Test Run 3

The model was towed with a maximum speed of 6.6 knots, with a maximum wave height of .94 meters. The average wave height is still beneath the critical wave height of both the 60% and 40% draught models.

The average pitch of the model was 14.2°, while the average heel was 20.5°. The average heel of this run was within tolerance of both the 60% and the 40% model's downflooding angles. This was the only run in which the model took on water, 13 grams in total and 104 kg in scale.

Sink and Heeling Tests

The model was also subjected to both a sink test and heeling test. The sink test, a test just like it sounds, consisted of loading the empty model down while it floated in a container until it began to take on water and sink. In this case the model was able to take on 1053 grams before it sank, which in scale is an impressive 8.4 tonnes.

The heeling test, which involved moving the crew (the weighted washers in this case) to one side of the boat one by one to see if the whole crew could heel the boat safely to one side showed in this case that model could handle all of the crew heeling the boat to one side, though with only 2 cm to spare, or 16 cm in scale.

Discussion

The wooden model was not overly 'pitchy', as it did not slam against the waves to harshly in any of the runs. The model also heeled very well considering the height and veracity of the waves, though we are unable to account for why in the first test run, the 60% draught was overwhelmed by its dramatic heeling, but not in any other test run. The wooden model also showed very clearly the seaworthiness of such a vessel in scale as it only took on water in the in the third and most treacherous run, 13 grams in scale and 104 kilograms in full scale.

Discussion

The main point of this experiment is to understand the seaworthiness of the Kinneret boat. The hydrostatic report generated showed that the craft is, in general, seaworthy. The lake on which it was originally sailed could be almost as dangerous as the sea at times, with for example sudden storms. So the seaworthiness of such a craft was never really in question; even here boats needed to be able to handle themselves in a seaway. It's comparability to other similar vessels, such as its Mediterranean cousins, is however in question. The vessel's excavator and main reporter, Shelly Wachsmann, has stated several times that such comparisons would be ill-advised, but the hydrostatic report shows that it could most likely handle the Mediterranean Sea (Wachsmann 1989: 234). Though the context in which it was found, the lake, limits the comparison somewhat, the hydrostatics opens up a new avenue for comparison to these Mediterranean vessels. An avenue which we believe will lead to a better understanding of the influences of Roman vessel building techniques in Roman occupied and influenced areas, such as 100 BCE-100CE ancient Palestine, despite the original geographical context.

9. DASHUR

Introduction

The Dashur boats were discovered in 1894 by Jean-Jacques de Morgan, buried near the brick pyramid of Sesostris/Senusret III (c. 1878-1843 B.C.) at Dashur (Jones 1995: 78). According to de Morgan's reports, six boats were discovered dating to the Middle Kingdom, c. 1850 B.C., however today only four are known to still exist. Two are currently exhibited in Cairo's Egyptian Museum, another in the Chicago Field Museum of Natural History, and the fourth in the Carnegie Museum of Natural History in Pittsburgh. (Ward 2000; 83)

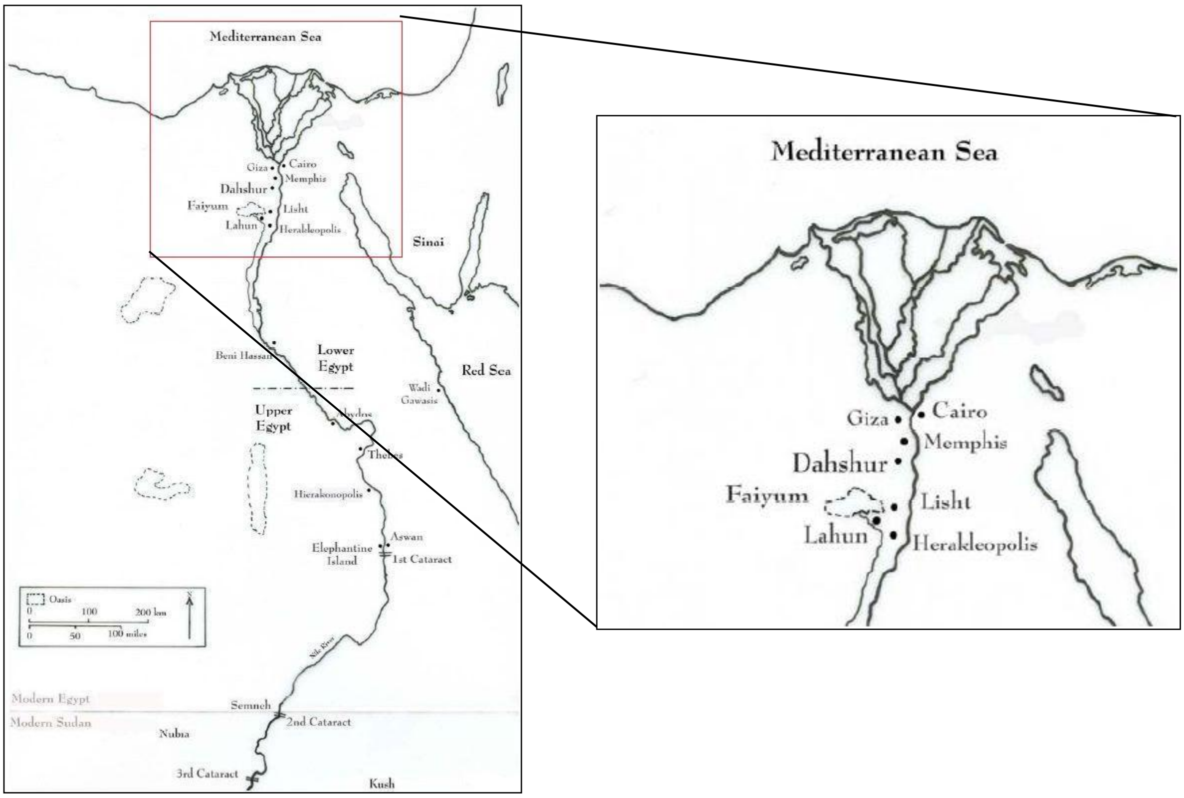

Figure 94. Map of Ancient Egypt (from Creasman 2005: 2).

Cheryl Ward Haldane conducted the first examination of these hulls in 1984. Her studies impinged upon previous misinterpretations, and revealed their importance with regards to boatbuilding techniques. Halden believes that these boats functioned as royal funerary boats, transporting Senusret III and the royal family to their final resting place - the pyramid at Dashur (Haldane 1984: 89). Further research by P.P. Creasman in 2005 was conducted on the two boats held at the Egyptian Museum in Cairo. These two major studies give a holistic view of the Dashur boats.

Funerary Boats

The Ancient Egyptians believed that the dead had to cross a stretch of water, before they could resurrect in the afterlife. In Egyptian texts, this was called 'the Winding-Waterway' and was often described as being travelled by boat. Boats were therefore considered an essential necessity both for this world and the next (Jones 1995: 12). They were deemed to be the "*only way to reach the gods, and were equated with power, knowledge, and freedom from daily cares when referred to in a funerary context*" (Ward 2000: 12).

Literary texts such as the *Pyramid Texts* and *Coffin Texts* provide us with evidence for Egyptian watercraft. 'The Old Kingdom spells allude to thirty-two different types of boats, including celestial vessels sailed by the gods and the stars, earthly boats for the king, boats of divine justice and taxation, transport boats to bring food to the king in the other world, and funerary boats' (Ward 2000: 12). Water transport played an important role in the lives of ancient Egyptians as can be gleamed by the thousands of models, representations, and references to watercrafts in Egyptian tombs and living sites (Ward 2000; 2). Middle Kingdom reliefs provide us with some evidence for the actual funerary journey (Figure 95).

Figure 95. Men carrying a mummy to his tomb on a boat-shaped bier (from Jones 1995: 19).

There were two types of journeys depicted: one to the sacred site of Abydos, and another crossing the Nile on the day of burial. The latter journey consisted of the mummy being carried over the Nile to the west bank in a full-sized funerary boat. The coffin was then placed either on a papyriform boat or boat-shaped bier and dragged on a sledge by men or oxen across the desert to its final resting place. (Jones 1995: 19) The canopy covering the coffin had a curved roof and was lavishly decorated. Very often the goddesses Isis and Nephthys were represented either as statues or actual female mourners, protecting the coffin with outstretched arms. A priest was also present to recite magical spells that would ensure the survival of the deceased in the next life (Jones 1995: 48).

"*Papyriform boats were used for ceremonial and religious purposes and as means of transporting the deceased and the grave goods across the river to the necropolis*" (Jones 1995: 43). These boats were characterised by a rounded bottom and broad beams, and often ended in stylised papyrus umbels. The boat was steered by means of oars on each quarter and the blades were generally decorated with stylised lotus flowers and wadjet eyes. Sometimes the top ends of the oars were decorated with a carved jackal or falcon heads. The colour green, representing resurrection, was used for the hull. The sides were also designed with narrow sheer lines or a pattern running parallel to the gunwale. The prow was decorated with wadjet eyes in order to protect the vessel and its occupants from harm. (Jones 1995: 19-20).

During the New Kingdom, papyriform (funerary) boats retain their previous characteristics (Jones 1995: 57). They were broad and had a shallow draught and kept the decorative finals at the bow and stern. The canopy was also retained, supported by four light columns underneath which the deceased was placed. Small steering-oars on the quarters were supported on posts. However these 'boats were never rowed or sailed but always towed either by another vessel or by a company of men from the bank' (Jones 1995: 58). This navigation method might also have been used in Middle Kingdom funerary boats.

No evidence for the use of ballast has yet been recovered; however it is very likely that Egyptian boats, including funerary crafts, applied ballast under the deck. This was applied to reduce the risk of capsizing. Stone has been suggested as being a possible ballast material (Jones 1995: 69).

The Chicago Boat

Ward stresses the fact that "*one of the most technologically advanced and economically powerful cultures of the ancient world evolved along the banks of the Nile River and drew its strength from the vessels that plied its waters*" (2000: 142). Today, the Chicago boat is one of the four boats that can still be admired by the general public. The boat was found buried along with the other Dashur boats, beyond the south wall of Senusret III's pyramid. It was buried beneath diluvium gravels and had unbaked bricks support the sides of the hull (Haldane 1984: 4).

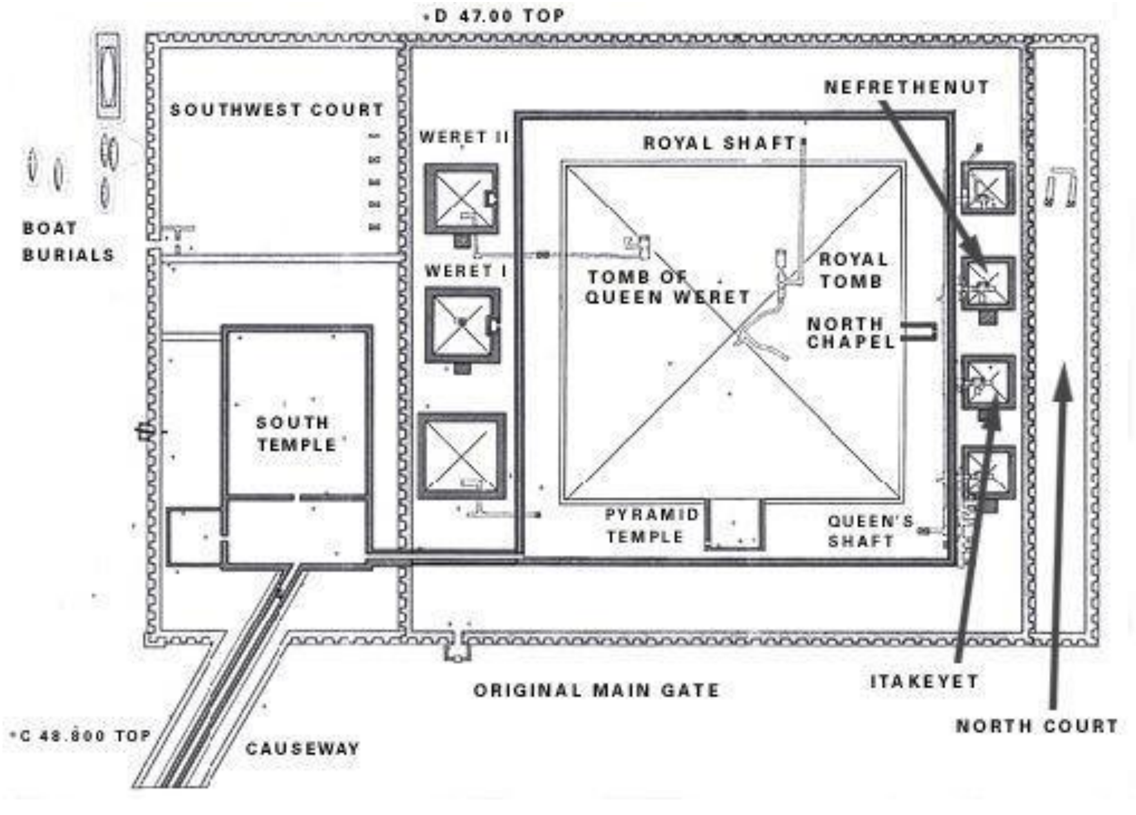

Figure 96. Plan (detail) of the Pyramid of Senusret III (from Arnold, 2004, accessed 18.03.12).

The proximity of the boats to the pyramid led archaeologists to conclude that they functioned as funerary boats for Senusret III. This is further attested by the shape and decoration which is typical for papyriform (funerary) boats. However, the material that was discovered amongst the boats does not concur with the above idea. A possible alternative proposed by Haldane, is that they might have been used in funerals for non-royal persons buried near the pyramid (1984: 6).

Haldane describes the boats as "*well-constructed examples of the boat builder's craft*" and the pieces that form the boats "*produce a shallow, beamy vessel*" (1984: 6). The Chicago boat has a round bottom, with a broad beam and curving sheers. It was built shell-first and according to Haldane (1984: 8) measures 9.8 meters in length, 2.37 m in beam and 0.72 m deep amidships. The latter number is the inside depth; the lines plan shows a hull which is 0.82 m high. It was built around a thicker central strake, which serves as a structural foundation; like a keel. The strakes which form the side of the boat are made up of short pieces of wood, attached together by lashing mortises and mortise-and-tenon joints (Jones 1995: 79). There are three strakes on either side of the central plank and the uppermost strake has a gunwale/bulwark attached to it.

The boat is constructed out of carved elements and made out of thick cedar planks (Haldane 1984: 8), possibly coming over from Lebanon or Syria (Lucas 2003: 488) . This importation of wood is attested in ancient Egyptian documents, but also from identified wooden artefacts found within the archaeological record (Lucas 2003: 489). "*Cedar from Lebanon is a fairly light material (560kg/cubic meters), durable, easily worked and is said to resist marine biological attack*" (Steffy 1994: 257).

"*Imported cedar of Lebanon was preferred for ceremonial and seagoing vessels, but abundant supplies of locally available tamarisk and acacia woods were used to build the more numerous and economically significant frieghters. Ceremonial boats had long timbers sculpted and carved to precise curvatures*" (Ward 2001: 281-284).

Throughbeams resting on the upper edge of the third strake act as strengthening features, but also as the base for the deck to rest upon. With regards to navigation, the boat still retains a single-steering oar and two steering oar stanchions (Haldane 1984: 8). These latter features supported the steering oars.

The current boat has the bow and stern cut off square, however these may have ended in decorative finals since mortises are found at the bow (Jones 1995: 79). When discovered a majority of the decoration had already vanished, but the blue-winged falcon heads which originally decorated the tops of the post survived. Some traces of paint can still be seen on the gunwale. In its original state, the latter, consisted of "*thin blue or black sheer-lines enclosed within one or two thicker red lines which once decorated it – a design particular to funerary boats*" (Jones 1995: 80).

Overall the Chicago boat is in good condition, although surface erosion of the lower strakes is present (Haldane 1984: 8).

Central Strake

This is composed of three parts: a central wide plank and two tapering planks, one towards the bow and the other to the stern. The total length of the stake is 10.21 meters, whilst its maximum width is 0.38 meters. The three parts were attached together by means of butt-joints. Towards the centreline, shallow rectangular sockets were chiselled probably keeping hold of the stanchions. As previously mentioned the bow and stern were probably decorated like other typical funerary vessels, with decorative finals. This is attested by the fact that 'the stern rises about 50 centimetres above the bow and is slightly fuller' (Ward 2000: 87). These three planks are the largest and thickest in the hull

Throughbeams

In total thirteen throughbeams support the sides of the boat and bear the deck planks. Notches were cut into the upper strake so that eleven of these throughbeams can rest on it. The other two beams lie across the hull at either end of the boat. (Haldane 1984: 16) The throughbeams were placed about 0.75

meters apart, however only two are original. These measure about 0.12 meters in width and 0.06 meters in thickness. They also had grooves as seen in Figure 98, where the deck planking could fit in.

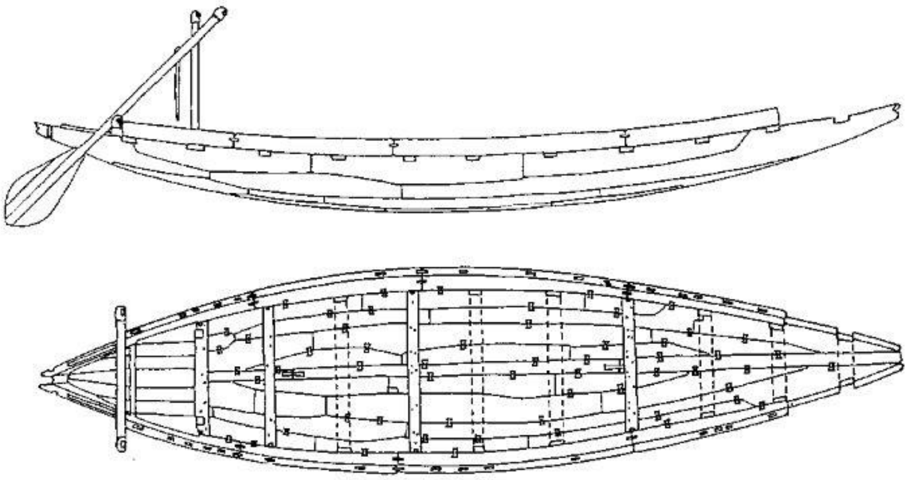

Figure 97. Plan and elevation of Dashur boat in the Egyptian Museum, Cairo (from McGrail 2001: 38).

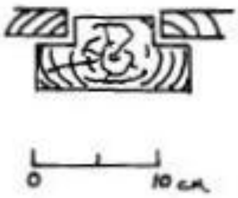

Figure 98. Throughbeam grooves and deck planks (from Haldane 1984: 18).

Rectangularly sectioned treenails attached the throughbeams to the upper strake, however none of these have remained intact. The treenails passed through the wood and probably were flush with the outside of the hull (Haldane 1984: 18). The thickness of the planking and the cross-beams is sufficient enough not to require further frames and still have a stable hull (Jones 1995: 79). According to Haldane, v-shaped lashing holes found on the cross-beams may have been used to attach deck furnishings (Jones 1995: 79).

Planking

In total 27 pieces of wood were used in order to create the hull. These were attached in such a manner to create seven strakes; a central strake and three strakes on either side of this. These were all made of cedar wood, having dimensions ranging from 1 meter to 4.5 meters in length. The inside of the boat was smoothly finished and most probably so was the outside, although this cannot be confirmed from the current conditions of the planks. Looking at the boat from on top, one notices the symmetrical layout of the boat. The planks were fashioned following the grain of the wood and seem to have been cut from the central part of the tree. They were also bevelled in two different ways, so that adjacent planks fit together tightly. (Haldane 1984: 22) As seen in Figure 99, the strakes were attached together by means of mortise-and-tenon joints on the upper and lower edges of the planks.

Washstrakes/Bulwarks

The bulwarks enclose most of the deck area. Each is made up of three planks, lashed together by means of double holes at the ends. These are further attached by means of mortise-and-tenons to the upper strake. (Haldane 1984: 26). The deck area originally covered the whole top, from the forward most to the aftermost throughbeams. The planks forming the deck lay flush against the side of the hull and might also have been attached to the throughbeams by means of treenails (Haldane 1984: 35).

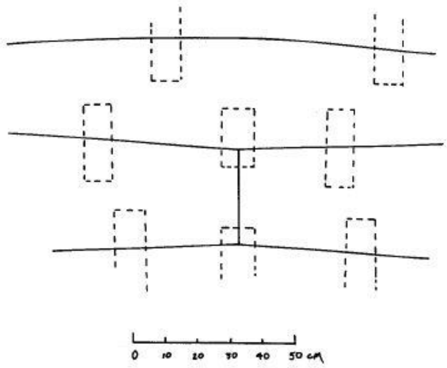

Figure 99. Mortise-and-Tenon joints found along the edges of planks to fasten them together (from Haldane 1984: 24).

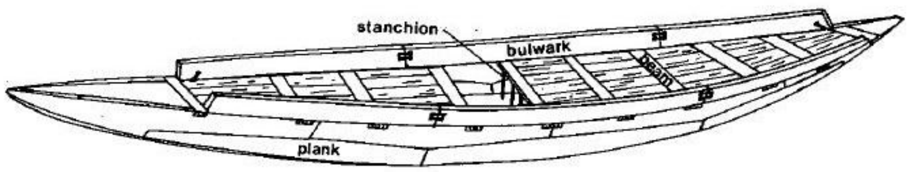

Figure 100. A ceremonial boat, with labelled components (from Ward 2000: 148).

Steering Oar and Stanchions

As mentioned earlier in the text, steering-oars and stanchions were buried along with the boat. This set of navigation tools is typical of Egyptian funerary vessels. As seen in Figure 101, each oar was placed on either side of the stern and supported by means of stanchions which were connected by a crossbeam.

The stanchions passed through a square hole and rested on the hull surface. These measured 2.02 meters and 1.62 meters in length. The top end is round in section, but this gradually flattens to become square (Haldane 1984: 33). The stanchions, although decorative also added support to the boat. The steering oar had a round-tipped blade and measured 3.98 meters in length and a blade width of 1.42 meters (Haldane 1984: 30). The blade is formed out of two halves which are attached by means of tenons and mortises to a slightly curved loom. Within the top end of the loom a slot runs diagonally, which might have held a tiller (Haldane 1984: 30).

Haldane also observed several tool marks still visible on the hull. Plank ends show saw marks, whilst adze marks feature on the outer surface of the upper strakes (Haldane 1984: 36).

When Reisner (1913) described the Cairo 4925 boat, he mentioned a fair amount of decoration. This included traces of plaster and paint: the hull was of a yellowish/ochre colour and the upper surfaces of the deck boards were white. The gunwale was decorated with strips of blue, red and black. The port stanchion was painted red, whilst the starboard stanchion was yellow. The steering oars were elaborately painted with lotus leaves, rosettes and wadjet eyes. This had all vanished by the 1970's, however Reisner's description reflects a very colourful boat, colours which were possibly also applied to the other Dashur boats. (Haldane 1984: 80)

Figure 101. Wooden model funerary boat, 12th Dynasty (c. 1900 BCE), British Museum (from The History Place, accessed on 21.03.12).

Figure 102. Quarter rudder, (after De Morgan 1895, pl. XXXI), showing the decoration which includes the wadjet eyes, lotus flowers and papyrus leaves (from Creasman 2005: 114).

Lines plan

From Figure 103 we can notice that the Dashur boat has a smooth outer hull, a relatively wide beam and a round cross-section. This latter has been compared to an inverted arch (Haldane 1984: 90). The arch shaped cross-section and the wide midship provided most of the stability of the boat and made it possible to carry cargo on the deck, such as the coffin. Both material used and method of construction reflect a durable and steady boat which although it might have only been used once, on the funerary journey, further usage would have been possible (Creasman 2005: 117). The shallow draught was ideal to travel over the Nile, which experienced seasonal fluctuating depths and sand bars.

The central strake is the back-bone of the whole structure. It is thicker than the other strakes and a majority of mortises-and-tenons are found along it, reinforcing the boats' design. The planks which were attached by means of regularly spaced deep mortise-and-tenon joints, added considerable longitudinal strength to the boat (Creasman 2005: 120). It was initially thought that dovetail fastenings were found in the upper strake (Haldane 1984: 100), however these may have been the 'remains of shallow lashing mortises, significantly eroded at the time of discovery and subjected to substantial alterations along with the rest of the hull' (Ward 2000: 93).

Most probably, the construction of the boat began by the selection of sturdy timbers. These were shaped with traditional means and tools and further trimming was done by axes and adzes. The first to be laid were the central elements and following that, each strake was then fitted to that below it. As mentioned previously the edges were bevelled in order to create a tight seam. Prior to attachment mortises were cut and tenons placed. Notches on the upper strake were cut before placing the bulwarks, in order to fit the throughbeams. The latter were fastened to the hull and made to be flush with the hull. (Haldane 1984: 95) "*Decking, steering gear, finals, super-structure, and decoration were the last elements of the hull to be completed*" (Ward 2000: 97).

Building the model

When it came to constructing the model, a clear and precise lines plan was essential (Figure 103). This was the basis for the 3D reconstruction on DelftShip (Figure 104). The lines plan was available and so was a flattened plan of the boat. Therefore, the planks were initially taken directly from the flattened plan and scaled to 1:20. However, this did not turn out to be as hoped. The flattened plank plan is a distorted view of the boat and as such of little value in the reconstruction of the boat. The result was not satisfactory and therefore the planks were developed with DelftShip, as close as possible to the ones found on the boat, in number and shape. A trial model, made out of cardboard proved this approach successful.

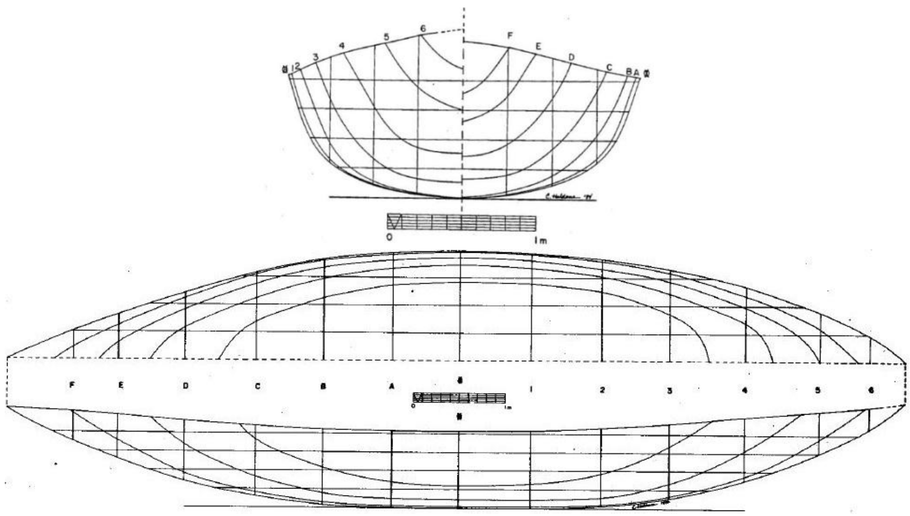

Figure 103. Lines plan for the Chicago hull (from Haldane 1984: 91-2).

These planks were then transferred onto wood, 3.5 mm thick and cut out with saws and other cutting devices. A layer of epoxy glue was applied to the inside of the boat, so that the different pieces would stick together and have a solid, waterproof surface. Another layer of thickened epoxy was applied to the outer surface, this also acted as a filler to the gaps and to smoothen the surface. The next step was to sand the outside down and get a round, u-shaped outer hull as shown in the lines plan. The last pieces were then added, such as the throughbeams, the deck and the coffin.

When cutting the planks for the box coffin the stature of the person buried within it had to be taken into consideration. If we consider these funerary boats to be part of Senusret's funerary journey, then the coffin being carried should belong to him. Manetho describes Senusret III as being a great warrior '*of great height at 4 cubits, 3 palms and 2 fingers'*, that is over 1.80 meters (Dunn, 2011, accessed 30.03.12). Looking at other dimensions of coffins dating to the Middle Kingdom, a final conclusion was made to make the box coffin measure 2.20 meters in length, 0.56 meters wide and 0.60

meters in height. Since this was Senusret's burial he was probably also buried within an anthropoid coffin which was placed within a box coffin. An important feature in the Middle Kingdom is the development of the anthropoid coffin. This identified the deceased as Osiris, whilst the box coffin represented a range of protective characters. (Snape 2011: 144-5). "*The ideal set was, of course, an anthropoid coffin contained within a box coffin*" (Snape 2011: 145).

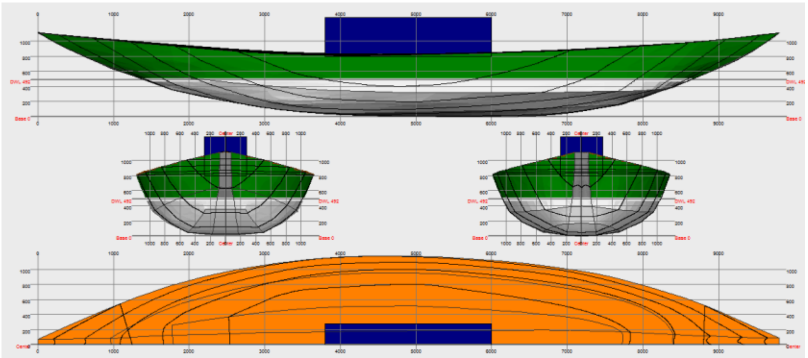

Figure 104. DelftShip lines plan.1:100.

The final touches included sanding and painting. A smooth round hull was created by sanding the wood down. It was tested in a tank full of water to see if there were any leaks. These were sealed and a layer of brown paint was sprayed to give the hull a uniform colour. Acrylic paints were then applied, following the available iconographic and literary information. Green was applied to the hull, and blue to the stem and sternpost. The bulwarks were decorated with stripes of red and blue with a black outline. A final layer of varnish was sprayed to protect the paint (Figure 105).

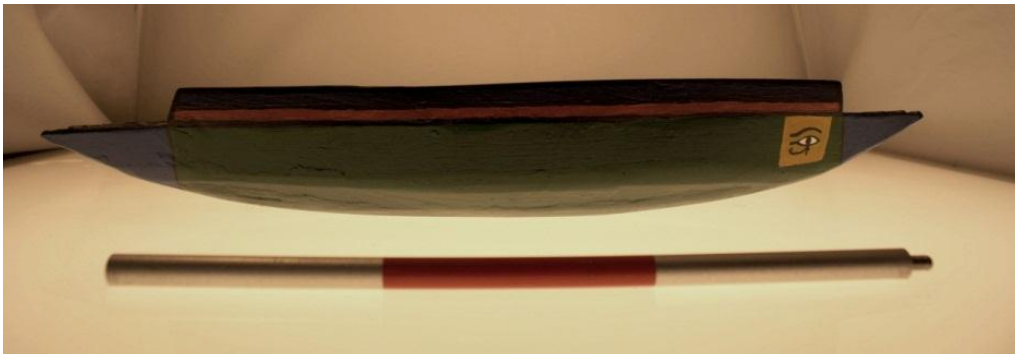

Figure 105. Scaled model.

Hydrostatics and performance

Table 27 shows the basic measurements for the Dashur boat, following the results created by DelftShip. Two of the measurements were calculated from the boat model, not DelftShip; deadweight to sink (kg) and the heeling test (m). The draught was set to 40% of the total depth of hull. This was done due to the exceedingly large displacement of almost 3.7 tonnes, if it was set to 60% (Table 28). The displacement of 1881 kg is still quite large for a funerary boat, especially when taking into consideration what might have been carried aboard.

As previously mentioned, the number of people aboard often included two mourners, a priest, an oarsman and the deceased. This makes up a total of about 300 kg, if we apply the normal weight of 60kg per person as deduced from the WHO recommendation on BMI. From the boat models we also see that the corpse either lay on a bed, or within a coffin. The coffins used during the funerary processions were probably quite light, made out of wood, weighing between 20-100 kg (information acquired from the *Ny Carlsberg Glyptotek*, 17.09.12). However, coffins were also lavishly decorated, which would have made them heavier. Taking this into account a decision was taken to apply a 40% draught, seeing that this provided a displacement that was sufficient enough for the cargo being carried. But also considering the fact that the waters being navigated had fluctuating depths, depending on the season. Nevertheless, a 60% draught could also be considered if the cargo weighed more – ever depending on how lavishly the coffin was decorated.

The heeling test gave a result of 2.6 cm (0.52 m in full scale) exceeding the standard freeboard of 0.5 m. Such a high freeboard gives ample room for more weight, however if the gunwale is excluded this gives a result of 1.1 cm (0.22 m in full scale). The latter was attached in order to extend the hull sides, and facilitated it keeping the deck planks in place. The model does not feature the two stanchions on either end or the canopy, which stood over the coffin. These were also made of wood and would not have weighed much. The passengers and cargo carried on board, as discussed above left ample spare displacement. Whether this weight was there to accommodate larger or more lavishly decorated coffins or other cargo, we cannot really infer from the data we have.

The coefficients all indicate towards a cargo hull, rather than a fast sailing boat. As previously mentioned the round shape of the hull makes the boat more stable, this is reflected in the metacentric height (GM) of 0.63 meters. The higher this value is the more stable the boat tends to be. This is supported by the *stability index* of 1.1, making it a rather stiff hull. This latter factor is further accentuated by the rather low rolling period of 2.7 seconds. This boat was made to navigate down the river Nile, with few waves, and the above results reflect this, however further observations were made from the test runs.

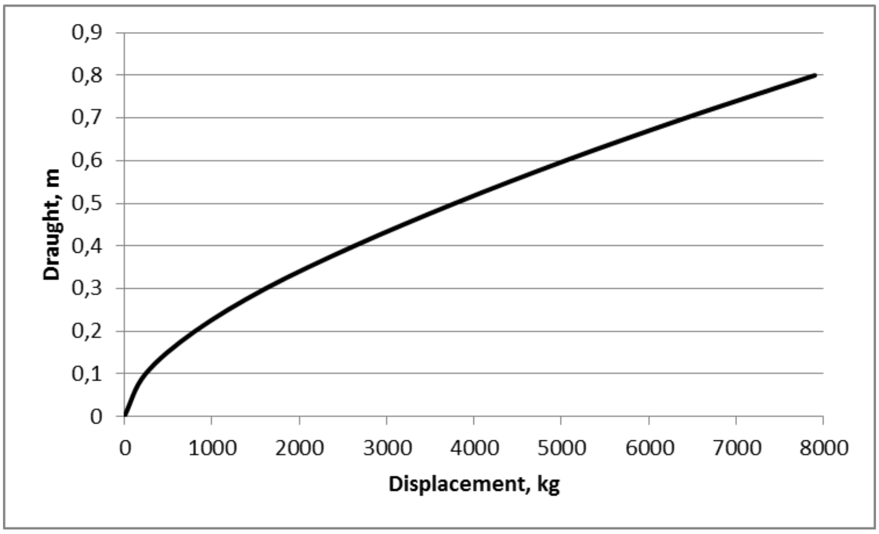

Figure 106. Diagram showing displacement (kg) against draught (m)

Model tests

From the theoretical analysis, the model seemed to be very stable, with an angle of maximum stability of about 40 degrees. When it was placed in the water and towed in different wave conditions, we were shocked at how much it rocked from side to side, on the verge of capsizing.

A total of three test runs were made, with varying wave types. We kept the same direction of waves, at an angle of 45 degrees to the starboard on the bow. Table 29 gives a general overview of the results achieved. These results should be interpreted with care, as the software used to analyse the movie clips did not provide us with optimal visual results.

Dashur, 40% draught

Dimensions								
Length overall	L_{OA}	9.80	m		Depth of hull	D	0.82	m
Length at waterline	L_{WL}	6.32	m		'Standard' draught	T	0.33	m
Maximum beam	B	2.37	m		Minimum draught	T_{MIN}	0.29	m
Waterline beam	B_{WL}	1.92	m		Maximum draught	T_{MAX}	0.61	m
Maximum hull speed	S_{MAX}	6.08	kts		Draught-Depth ratio	100 D/T	40.0	%
Volumes, areas and weights								
Displacement, volume	∇	1.835	m^3		Moment of inertia	I	24.942	m^4
Displacement, weight	Δ	1881	kg		Estimated weight of boat		1418	kg
Wetted surface area	A_{WS}	10.49	m^2		Deadweight		463	kg
Waterplane Area	A_{WP}	9.629	m^2		Maximum Deadweight		3759	kg
Midship Area	A_M	0.448	m^2		Deadweight to sink		8990	kg
Coefficients and ratios								
Length-beam ratio	L:B	3.3			Block Coefficient	C_B	0.473	
Length-draught ratio	L:T	19.3			Prismatic Coefficient	C_P	0.418	
Beam-draught ratio	B:T	5.9			Waterplane Coefficient	C_W	0.415	
Displacement-length ratio	$\Delta/L_{WL}^{1/3}$	5.2			Midship Coefficient	C_M	0.576	

Stability

Centres					**Stability Criteria**			
Centre of Bouyancy	KB	0.21	m		Downflooding Angle	θ_f	22.5	°
Centre of Gravity	KG	0.77	m		Minimum Freeboard	F_{MIN}	0.21	m
Metacentre	KM	1.40	m		Freeboard, heeling test		0.52	m
Metacentric height	GM	0.63	m		Rolling period	T_R	2.7	sec
Heeling calculations					**Other criteria**			
Critical wave height	h_{CRIT}	2.66	m		GM-beam ratio	GM/B_{WL}	0.33	
Significant wave height	h_s	2.09	m		Roll Period-Beam reatio	T_R/B_{wl}	1.1	
Approximate wind speed		9.7	m/s		Angle of max. stability	AMS	40	°
Beauford		5			Angle of vanishing stability	AVS	84	°

Table 27. Summary table for the Dashur boat at 40% draught.

Dashur, 60% draught

Dimensions								
Length overall	L_{OA}	9.80	m		Depth of hull	D	0.82	m
Length at waterline	L_{WL}	7.25	m		'Standard' draught	T	0.49	m
Maximum beam	B	2.37	m		Minimum draught	T_{MIN}	0.31	m
Waterline beam	B_{WL}	2.09	m		Maximum draught	T_{MAX}	0.61	m
Maximum hull speed	S_{MAX}	6.52	kts		Draught-Depth ratio	100 D/T	60.0	%
Volumes, areas and weights								
Displacement, volume	∇	3.593	m^3		Moment of inertia	I	38.188	m^4
Displacement, weight	Δ	3683	kg		Estimated weight of boat		1418	kg
Wetted surface area	A_{WS}	13.849	m^2		Deadweight		2265	kg
Waterplane Area	A_{WP}	11.719	m^2		Maximum Deadweight		3759	kg
Midship Area	A_M	0.777	m^2		Deadweight to sink		8990	kg
Coefficients and ratios								
Length-beam ratio	L:B	3.5			Block Coefficient	C_B	0.494	
Length-draught ratio	L:T	14.7			Prismatic Coefficient	C_P	0.472	
Beam-draught ratio	B:T	4.2			Waterplane Coefficient	C_W	0.505	
Displacement-length ratio	$\Delta/L_{WL}^{1/3}$	4.7			Midship Coefficient	C_M	0.666	

Stability

Centres					**Stability Criteria**			
Centre of Bouyancy	KB	0.31	m		Downflooding Angle	θ_f	15.5	°
Centre of Gravity	KG	0.90	m		Minimum Freeboard	F_{MIN}	0.21	m
Metacentre	KM	1.18	m		Freeboard. heeling test		-	m
Metacentric height	GM	0.27	m		Rolling period	T_R	3.5	sec
Heeling calculations					**Other criteria**			
Critical wave height	h_{CRIT}	2.06	m		GM-beam ratio	GM/B_{WL}	0.13	
Significant wave height	h_s	1.62	m		Roll Period-Beam reatio	T_R/B_{wl}	1.5	
Approximate wind speed		8.3	m/s		Angle of max. stability	AMS	-	°
Beaufort		5			Angle of vanishing stability	AVS	-	°

Table 28. Summary table for the Dashur boat at 60% draught.

A preliminary test was done, called the speed test. The model was made to exceed its maximum hull speed of 6.2 knots. A speed of 14.7 knots was achieved and as expected the result reflected a displacement hull, rather than a planning hull. The boat dipped the stern deeply into the water.

Test run	h_S, m	λ, m	Angle, °	Boat speed, kts	Pitch, °	Heel, °	Water Intake, Kg
1	0.56	12.31	2.6	4.7	20.1	24.1	64
2	0.48	5.44	5.1	6.3	15.0	18.4	128
3	0.94	14.23	3.8	5.9	10.2	24.8	32

Table 29. Overview of the three test runs, converted to full scale from 1:20.

Test 1

The first test (Figure 107) was carried out with relatively low waves and a long wavelength. The wave height achieved was 0.56 meters, which is below the critical wave height of 0.72 meters. The speed achieved was 4.7 knots. The boat moved along with the waves, resulting in a high heeling and pitch angle, both of which exceed the downflooding angle of 17.7 degrees.

Test 2

In test run 2, larger waves were created with a shorter wavelength. The speed reached was that of 6.3 knots. The pitch angle is below the downflooding angle, however the heeling angle is 18.4 degrees. As can be seen from Figure 108, the boat was climbing the waves and rocking quite a bit. Some water did come in the boat (16 g or 128 kg in full scale), but the boat remained afloat.

Test 3

The last test (Figure 109) was done with stronger waves, a shorter wavelength and higher wave height. The model looked very stiff as it rocked from side to side. However, barely any water got in the boat (4 g or 32 kg in full scale). The boat was going at 5.9 knots, less than the second test run, however the heeling angle achieved was the same as the first test run, that of 24.8 degrees.

From the results shown in Table 29, we can notice a very high heeling angle throughout the three test runs. On the other hand, the pitch seems to have decreased as wave heights grew in size. When looking at the movie clips taken of the Dashur model, one can notice that the boat follows the wave patterns and unlike the other boats does not seem to ride over the waves.

The models' reaction to rough waters can be compared to those experienced by the replica of the *Min of the Desert*. This floating hypothesis was based upon five reliefs of sailing ships (*c*. 1482 BCE) found in Queen Hatshepsut's funerary monument at Deir el Bahari, which are shown arriving and departing from a location called Punt (Ward et al. 2007: 122). The Dashur boat was used as the basis for the hull form, however some adjustments made to improve its stability, as the Min was made to operate in open water on the Red Sea. When the replica was tested, it was very stiff in the water and uncomfortable for the crew, but as soon as the sail was unfurled, the boat became very stable and sailed smoothly.

Discussion

The tests conducted on the scaled model provided us with further information on the hydrostatics of the funerary boat, above all its stability. DelftShip provided us with a perfectly curved stability graph, however as we saw in the tests the model was very stiff with a high heeling angle, resulting in a rocking boat.

Figure 107. Snapshot from test run 1.

Figure 108. Snapshot from test run 2.

Figure 109. Snapshot from test run 3.

The above observations indicate that if the Dashur boat were to have a mast and sail, it would be seaworthy enough to sail in seawaters with conditions similar to those of the Red Sea. The tests conducted in the lake proved the boats' strength and stability in the water, even though these were made using the available equipment at the time.

Studying this boat design in detail makes one more aware of the knowledge these ancient Egyptians had acquired over time. This includes skills in woodworking, methods of attaching wooden elements together and knowing how different boat types will behave in different kinds of environments.

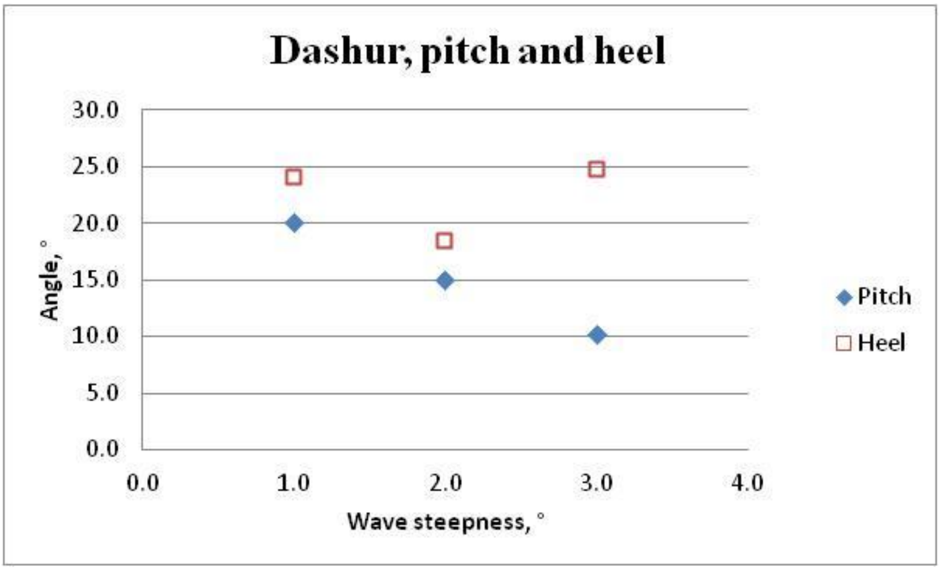

Figure 110. Pitch and Heel for the Dashur Boat.

As we shall see in the following chapter, further comparisons between different boat types can lead to a better understanding of the characteristics required of a boat used for a specific function within a certain environment.

10. DISCUSSION

Seven boats have been described and studied in the previous chapters. In fact we ended up working with eight boats, as two possible reconstructions of the North Ferriby boat were tested against each other. Unfortunately, the theoretical calculations for the outrigger canoe proved to be too much of a challenge even for the specialized software we used, and therefore it is the seven other boats which are in focus in this chapter, which will discuss and summarize the results.

Modern ships and ancient boats

Working with techniques from naval architecture we have worked with methods from a field which is normally occupied with modern ships. One important question when using new techniques on old things is of course how similar the items are. The *U.S. Navy Salvage Engineer's Handbook* lists typical form coefficients for 24 modern ship types, seven naval and seventeen civilian. The coefficients used are block coefficient, C_B, midship coefficient, C_M and waterplane coefficient, C_{WP} (Bartholomew et al. 1992).

To examine just how different our boats are from modern vessels, apart from the size, a Principal Component Analysis was made of these three coefficients for our boats together with the 24 modern ships. The result is shown on Figure 111. This analysis illuminates that the differences between our traditional boats and the modern ships are indeed strong. Only the two reconstructions of the North Ferriby 1 boat is close to the modern ships, in terms of these form coefficients, but the rest are widely separated from them, forming a group in the lower left side of the diagram. In the lower right side is found what could be classified as the modern 'workboats', like cargo carriers, tugs and tankers. These are relatively slow, box-like vessels. In the top are the faster and leaner vessels, including all warships and passenger ships.

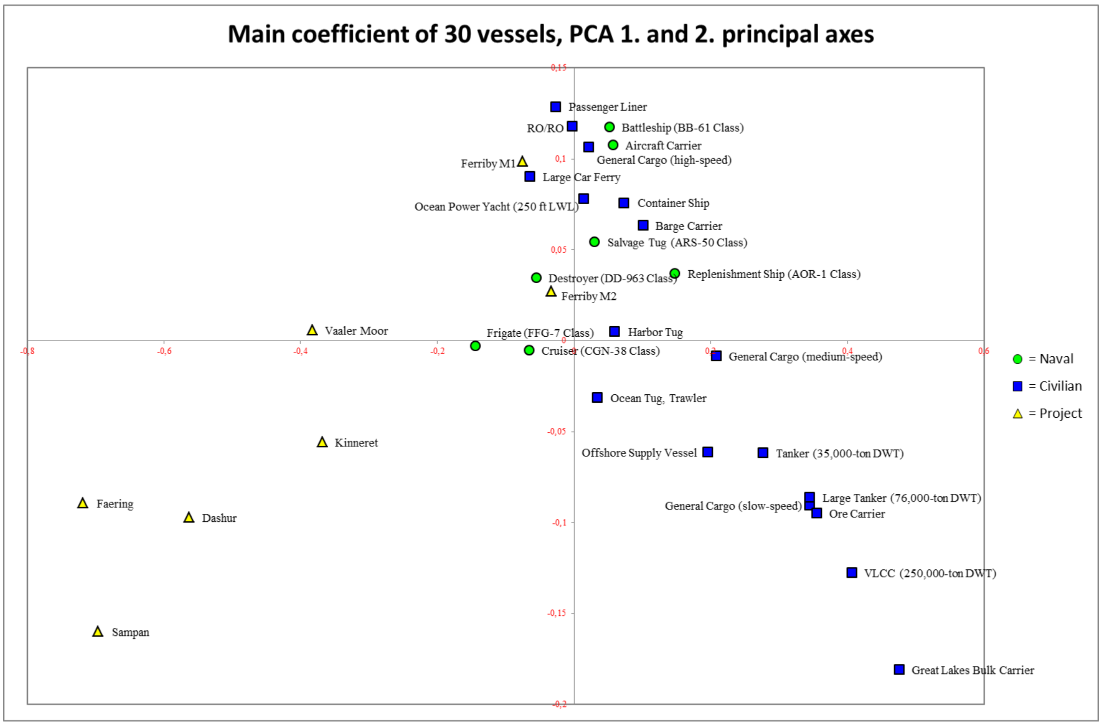

Figure 111. Principal Component Analysis of 24 modern ships, and seven of the boats analysed here.

The comparison is obviously not entirely just, as these vessels are from each their end of the size (and time) range, but the 24 modern vessels are probably representative for the type of vessels that the majority of naval architects work with today. Working with form coefficients only, size is not directly a component in the analysis, but obviously big ships are different from small boats. What we illustrate with this comparison is not the difference between the vessels; multivariate statistics is not required to see that they are dissimilar. Instead we illustrate that the design concepts used by modern naval architects are fundamentally different from those of ancient boat builders.

Modern ships reflect traditions of form, as much as the ancient boats do. The suggestion by McGrail (1988: 35) that one could assess an ancient boat by eye would require that it is possible to see beyond the tradition within which one is building. Surely naval architects are also trained in the design of small craft, but the vast majority of professional literature is on the large vessels.

Dimensions

The boats vary in length between the 6 m long Singapore Sampan to the almost 16 m long North Ferriby 1. They vary greatly in construction and appearance, as well as in age, geographic origin, environment and use.

As such there are few general relations between the dimensions and coefficients of the boats, and they are difficult to compare directly. One correlation was found, though, and although it is hardly surprising in itself, the regularity of it is. Length and displacement varies almost perfectly linearly for the planked boats in our study (Figure 112). The only boat that falls outside this line is the Vaaler Moor boat, which has very limited capacity for its length, compared to the plank boats.

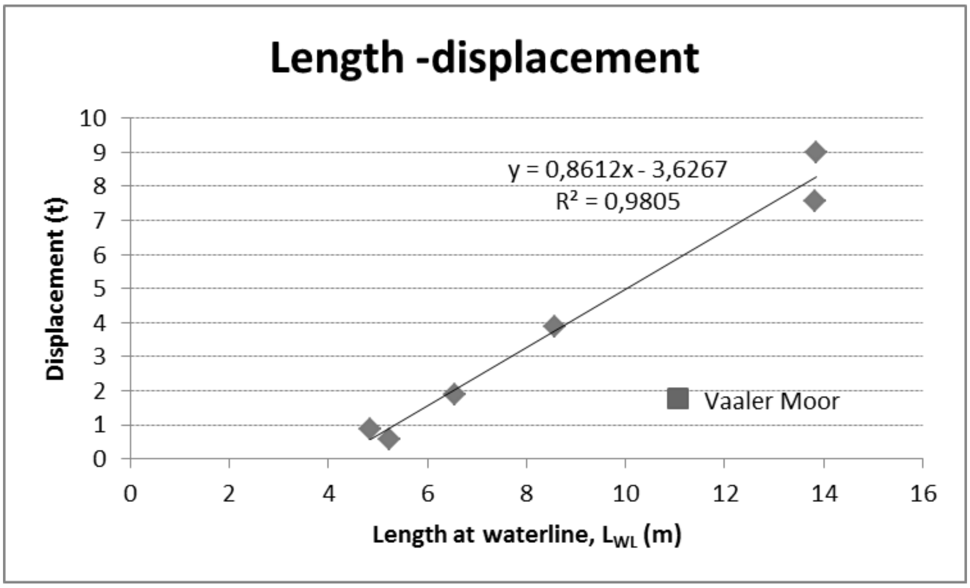

Figure 112. Relation between waterline length and displacement.

Adding data from more boats would unquestionably make the relation less clear. Nonetheless, this is already based on boats that are very different, and therefore should not inherently relate in any way, other than the obvious of being boats. On the basis of these data, one could suggest that for traditional planked boats between 6 and 16 meters, the heuristic relation between waterline length and displacement would be about $0.86 \times L_{WL} - 3.63$. Such relations can be practical to use in a preliminary assessment of a new archaeological finds. We will refrain from such a suggestion, though, as the data are too few for generalization. Besides, the trend line cannot be used outside this range: the displacement would reach zero at a length of 4.21 m, and therefore the curve should more likely be polynomial across a wider range of sizes. The very clear relation was a surprise to us, though, and the graph also demonstrates one of the fundamental differences between logboats and plank boats.

There is also a correlation between the sizes of the boats, measured as length, and their form coefficients (Figure 113). These correlations look more as expected, not perfectly linear, but there is a positive correlation between LWL and the three form coefficients shown here. In other words: a longer boat is generally fuller in form. The simple explanation is probably that when one makes a larger boat, it is mostly because of a need to carry more on board. A fuller form would therefore complement the increased length.

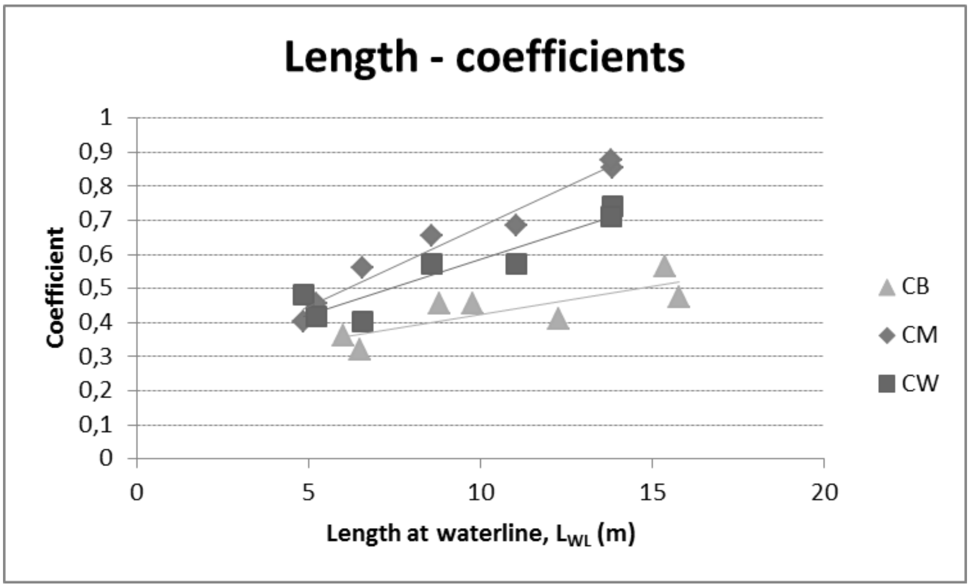

Figure 113. The relation between the length of the boat and the three main form coefficients. Linear trend lines are fitted.

Cargo capacity

With varying sizes of the boats, their carrying capacities obviously also varies (Figure 114).

The deadweight is calculated as the displacement minus the weight of the boat, and accounts for the weight of crew, cargo, provisions and ballast. The values are slightly exaggerated as we have disregarded rigging in this study, and generally the numbers are dependent on the precision of our estimated hull weight, but still give an idea of the absolute carrying capacity of these hulls. As could be expected, the small boats like the Gokstad Faering and the Singapore Sampan, as well as the lean Vaaler Moor boat can only carry little compared to the other boats. But even the boat from Dashur can carry very little cargo, given the assumed draught of 40%. Given the overall size of the boat this is remarkable, but it leaves only a small footprint in the water and even at 60% draught, the carrying capacity is not overwhelming. Being of intermediate size, the Kinneret boat also stands in the middle of the distribution, with a deadweight of more than 2 tons at 40% draught. Finally, the two versions of the North Ferriby boat have high capacities for this group of boats.

Bigger boats generally carry more cargo. It may be more interesting to look at the deadweight relative to the displacement of the boat (Figure 115). Surprisingly, it is the small boats which have the highest relative cargo capacity. Again we have to correct for the weight of the rig, and obviously the smaller boats are more sensitive to any miscalculations in hull weight: being 10 or 20 kg off means more for these than for the larger boats. But at least in the case of Gokstad, the weight comes from an actual 1:1 replica, and can hardly be entirely wrong. These boats seem to be effective for their size.

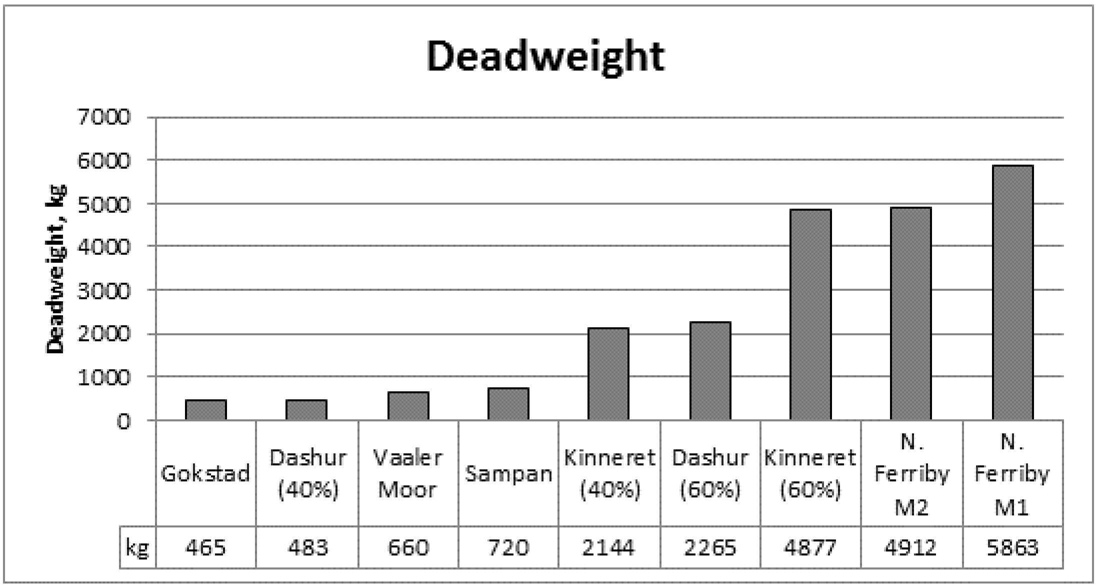

Figure 114. Deadweight of the boats.

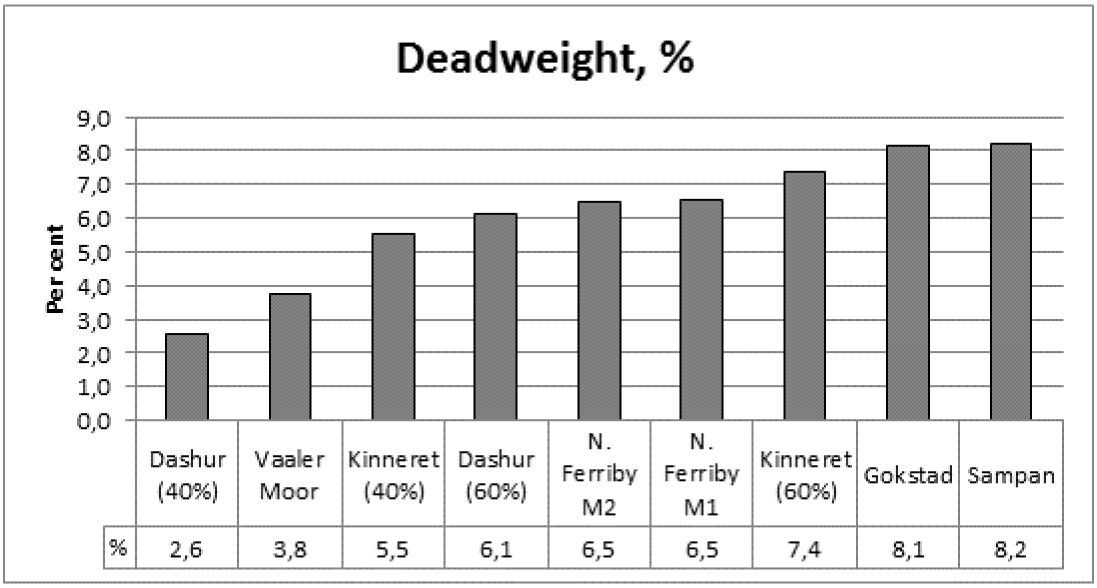

Figure 115. Deadweight in per cent of displacement.

At 60% draught, the Vaaler Moor boat is the only boat with less than 6% carrying capacity, while both Kinneret and Dashur at their assumed 40% draught would generally carry relatively less than the boats which are calculated at 60%. The numbers for 60% draught for these two boats is therefore also shown in the graphs.

These numbers do not seem high. Even at a draught of 60%, only 6.5% of weight can be added in addition to the weight of the North Ferriby boat(s). The average for all the boats is just around 6%. In comparison, the values for modern ships should lie in the range of 60% for a container ship, 80% for a tanker and 35% for a passenger liner (Watson 1998: 59; Charles et al. 2001: 261). Small boats are comparatively heavy for their capacity.

Before it is concluded from Figure 115 that it is the smallest boats (the Sampan and the Faering), which are the most efficient, it must be remembered that the crew would take up a relatively larger part of the capacity of small boats.

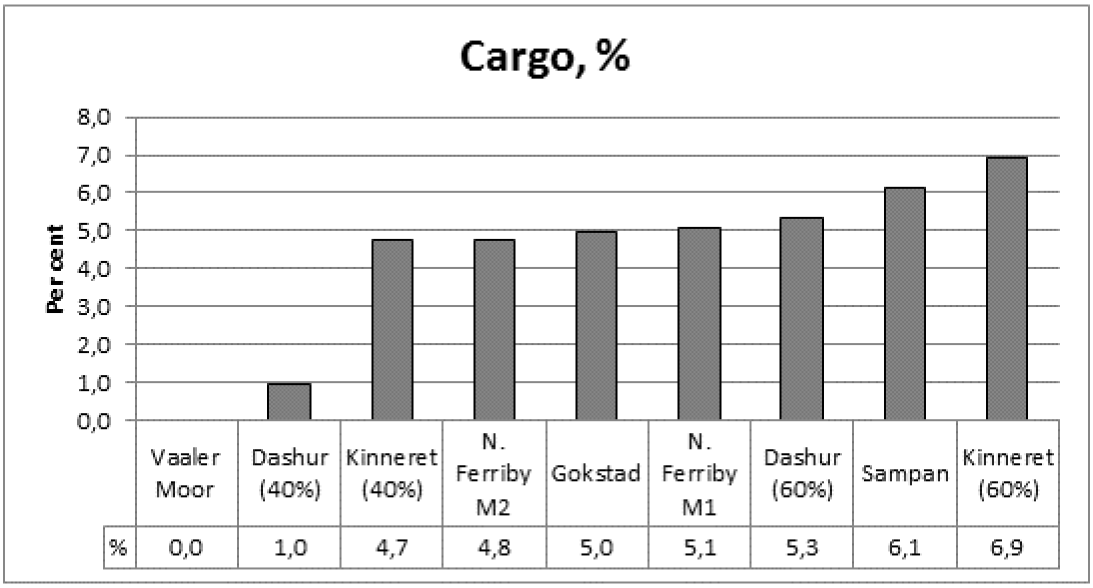

Figure 116. Cargo capacity (total deadweight minus crew) in % of displacement.

In Figure 116 we have calculated the cargo capacity, deducting the weight of the assumed crew for each boat. With this we see that the Sampan is still efficient, while the Gokstad faering is moved to the level of the North Ferriby and Kinneret boats. This is assuming a crew of three for both the small boats. At least the Gokstad Faering can be both rowed and sailed by only two persons, in which case the percentage would go up to 6.0%, almost exactly matching that of the Singapore Sampan. Generally the carrying capacity of these boats is around 5% of their total displacement. Vaaler Moor is assumed to carry no cargo while the Dashur boat still stands out with a very low carrying capacity at 40% draught.

Speed

We have only touched briefly on speed in the previous chapters. In the model tests we did do a very fast run for each of the boats, to test whether it could be semi-planing. A displacement hull which is towed at high speed will dip its stern into the water while a semi-planing hull will produce enough lift to keep out of the water; not exactly planing but appearing to do so. We found that some of the boats may have been able to semi-plane, while others certainly had not.

The importance of this does not lie in a discussion of whether these boats actually semi-planed when used, but is an experimental way to assess the general speed potential of the boats.

The outrigger canoes are renowned for their very high speed potential, outperforming western sailboats and yachts when the design was brought to Europe during the second half of the 19th century. Hence the name of '*flying proas*'. We can safely assume that this was also the case for the Wa Mikael, which was even known locally to be a fast boat. These boats lead to the development of the modern catamarans and trimarans.

The speed potential of the other boats cannot be assessed similarly through a contemporary tradition. McGrail and Corlett (1977) saw the Gokstad Faering as a very fast boat. With a volumetric coefficient of 0.0012, the Vaaler Moor boat would also be very fast. Strangely the highest volumetric coefficient is found with the Singapore Sampan, which otherwise looks somewhat similar to the Faering. Using the criteria for fast boats described by McGrail (1987: *cf*. ch. 2), all the boats seem to have C_B, C_M and C_P coefficients below the threshold values defined. Only the North Ferriby boat, in both reconstructions, has too high a midship coefficient to be considered fast (Table 30).

	Displ., t.	L_{WL}, m	L:B	C_B (<0.65)	C_M (<0.85)	C_P (<0.75)	C_V (<0.002)
Gokstad	0.573	5.23	4.5	0.32	0.46	0.46	0.0039
Sampan	0.880	4.86	3.8	0.36	0.40	0.50	0.0075
Vaaler Moor	1.756	11.07	9.0	0.41	0.68	0.48	0.0013
Dashur (40%)	1.894	6.56	3.5	0.46	0.56	0.42	0.0065
Kinneret (40%)	3.894	8.58	3.9	0.46	0.65	0.62	0.0060
N. Ferriby M2	7.555	13.82	6.0	0.57	0.88	0.63	0.0028
N. Ferriby M1	8.994	13.84	5.9	0.47	0.86	0.54	0.0033

Table 30. Summary of form coefficients for the boats. In brackets are McGrail's and Corbett's criteria for fast boats. Note that Gokstad does not meet C_V in our calculations.

Stability

Most of the hydrostatic calculations that has been done in the previous chapters could be done by the free version of DelftShip. One thing that this version cannot do is to calculate the righting arms and moments at different degrees of heel. We therefore exported our DelftShip models to the CAD system Rhino, to which Orca3D is a marine extension, which will do these calculations. The result is shown on Figure 117 with the calculated righting arm for all boats. In fact several of the curves started to fluctuate with very high angles of heel. We have chosen to remove these fluctuations in the graph, and simply let the curves continue down towards 0 m using regression analysis.

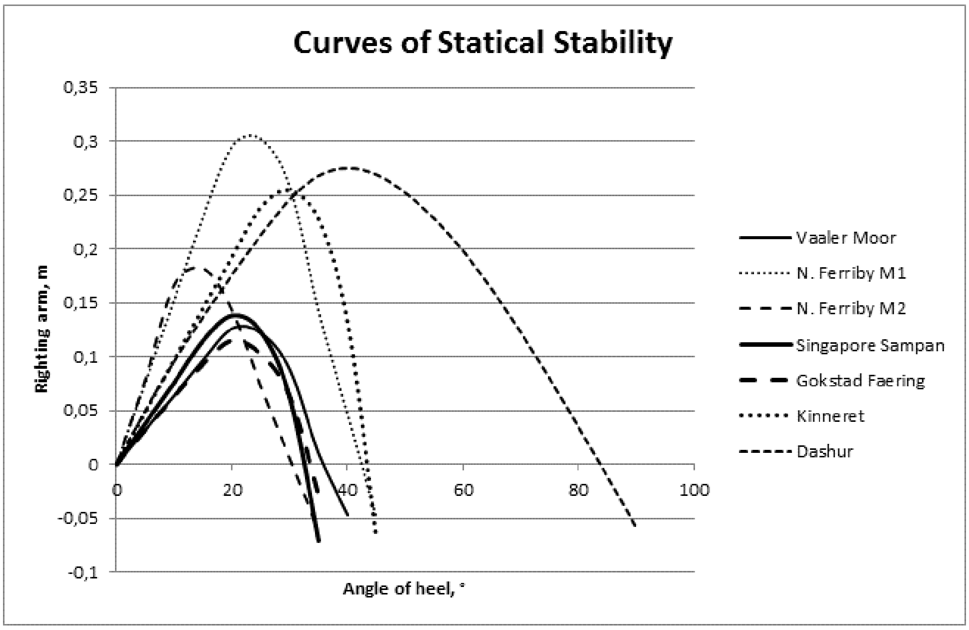

Figure 117. The righting arm of the seven boats, as calculated by Orca3D.

This graph borders the nonsensical for at least two reasons. First because we are working primarily with open boats, and any heel beyond the downflooding angle is theoretical, at best. This was-probably- why Orca3D gave erratic results on high angles of heel. Secondly because in putting these boats in the same graph we suggest that we can compare them. Righting arms can obviously be compared, but it makes most sense to do so with boats of the same displacement. The righting moment will differ considerably for boats with different displacements, even if the length of the righting arm is the same. Nonetheless the absolute value of the righting arm is the only comparable number available, and because of that it is also used in e.g. modern safety rules. Righting arms are compared in practice among naval architects, even though the righting moment is a more accurate measurement.

Although we cannot compare too directly the absolute values of the righting arms, there is a noteworthy pattern in the relative values, which this graph does show: it seems that it is the inland boats which have the "best" stability. The highest values for Angle of Maximum Stability and Angle of Vanishing Stability are found for the Dashur and the Kinneret boats, while those boats which actually sailed on the sea seems to have lower values. Especially the Dashur boat stands out, although it was a river vessel. The Kinneret boat could still encounter storm waves across the lake.

So in an immediate interpretation, the most seaworthy boats are those that were never intended to go to sea. Marchaj (1986: 112ff) offers a possible explanation to this apparent paradox. While stressing the importance of a large stability range, he labels the belief that a stability curve is an objective measurement of a boat's stability as a "*fallacy of misplaced concreteness*" (1986: 113). The reason why this curve may be misleading is that it is exactly static. Static stability is calculated on a flat sea surface and no input of input of energy is assumed. This is hardly a realistic description of a boat moving on the sea.

In a dynamic sea, the boat moves in a system with both a constant and constantly changing influx of energy and with 'memory': the heeling at any given time is dependent on the heeling just before. This means that heeling can build up successively under the wrong circumstances. The problem is especially in resonance rolling.

When the wave period, or rather the period of encounter, matches the natural rolling period of the boat, resonance rolling occurs as an incremental increase of the heel with every encounter. Theoretically the rate of magnification can grow indefinitely at this point, although in practice damping will counter this, together with the natural irregularity of open sea waves.

If the boat's rolling period, T_R, therefore is kept high, then resonance rolling is will occur at longer wave lengths, which are more likely to be less steep. Therefore it can be advantageous to keep T_R high. It will be remembered from chapter 2 that there is an inverse relationship between metacentric height, GM, and natural rolling period, T_R. Reducing the risk of excessive rolling in dynamic conditions therefore means that GM must be kept low.

Normally one would consider a high metacentre good for stability. Naval architect Kenn Jensen even stated this directly in his work on ancient boats: "*GM(T) is a way to describe the initial stability of a ship. GM(T) has to be positive, and the higher GM(T), the more stable the ship*" (1999: 55), (the (T) indicates that this is the transverse metacentric height).

But it is also well known that tender boats with a low GM rolls less in waves than stiff ones with a high GM. So a boat with a high GM will feel more stable when it is boarded, but less so when it starts sailing. This effect is not reflected in the calculation of GM or a stability curve. The GM can therefore be misleading as a safety guide, because too high a GM can lead to excessive and abrupt rolling, thereby making the boat less seaworthy or at least less seakindly to the crew.

This could be the reason for the stability curves that we see in Figure 117. Paradoxically safety dictates that the seagoing boats should be "less stable", as defined by the curves, than the inland ones.

On the other hand this interpretation should not be overextended. It was quite clear that model 2 of the North Ferriby boat is a bad sea boat, and that model 1 is much better. Since these two reconstructions are of comparable dimensions, this can be read relatively directly from the graph of static stability, and surely model 2 should not venture outside the Humber estuary, but would probably make a fine ferry when conditions were not too choppy.

GM is not a straight forward measurement of seaworthiness. On the other hand, few of the other modern screening values for stability that we calculated seem to give good indications of the behaviour of the boats in the water.

Maximum wave heights

One of the exceptions to this is the theoretical calculation of the critical wave height to capsize the boat. Although a theoretical value, it does give a uniform and comparable indication of the seaworthiness of the boats.

When summarizing the significant wave height to capsize the boats, most of the boats are found at values between 0.5 and 1 m (Figure 118). For the Singapore Sampan, the calculations were only done to the gunwale, while for technical reasons the side decks and coamings are not considered. We have indicated an additional 15 cm to allow for these features in the graph, although the exact value is not calculated here. The only boat which fell below 0.5 m is the Vaaler Moor boat, which seems particularly vulnerable in comparison with the other boats.

At the other end of the spectrum, it is no surprise that a higher wave is needed to capsize the boats from Kinneret and Dashur, when they are given a draught of only 40%, compared to the 60% of the other boats. But even at a draught of 60% the Dashur boat have a very high value.

This is due to the way that the centre of gravity has been calculated for this boat. The Dashur boat is the only of these boats which is decked, and following contemporary models and depictions, we have placed the coffin on the deck, and let the crew stand up. For the other boats the crews sit, and cargos are stowed low in the boat. The high position of the weights means that this boat has a low metacentric height (GM), and consequently a high rolling period. This is in fact an illustration of the points made by Marchaj, as discussed above. With a high rolling period, longer waves are needed to reach the resonance conditions, and they in turn need to be higher to achieve a dangerous steepness. A relatively low GM can therefore be safe, although there is a lower limit.

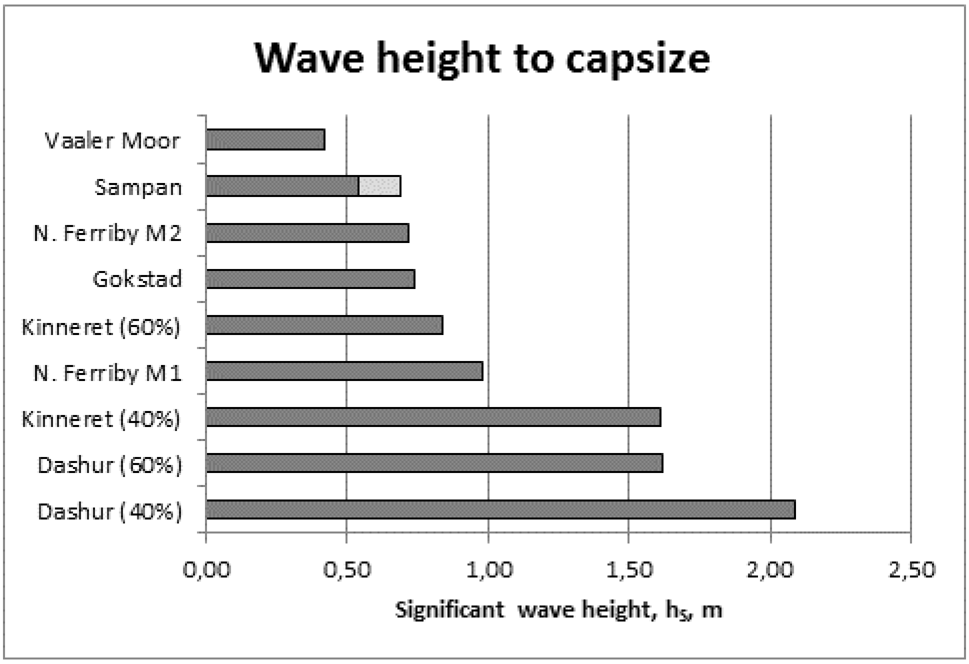

Figure 118. Theoretical wave heights to capsize the boats with waves beam on. Additional height is indicated for the Singapore Sampan to allow for the side deck and coamings. Kinneret and Dashur are calculated for both 40% and 60% draught.

It would naturally be a mistake on the basis of this to consider heavy weights stored high in a boat to add to safety. The equation used to calculate the critical wave height simply assumes a standard distribution of weights in the boat, and cannot account for the higher heeling moment of a cargo which is placed too high up in the boat. If we recalculate the Dashur boat under the similar assumptions as the other boats, with the cargo (and coffin) stowed in the bottom of the boat and the crew sitting on thwarts 30 cm below the gunwale, then the critical wave height decreases to 0.91 m for the boat at

60% draught. This value has nothing to do with the boat as it was used, but increases comparability and place the hull form neatly in between Kinneret (60% draught) and North Ferriby Model 1.

The lack of ability to take into account the internal weight distributions of the boat is obviously a shortcoming of the equation, but it still produces comparable numbers when comparable conditions are applied to the hulls.

Quoting Marchaj one should still be vary of the "*fallacy of misplaced concreteness*". The significant wave height of 0.42 m which we calculated for the Vaaler Moor boat does not in fact mean 0.42 m: In the model tests we saw it cope with much higher waves, and it must be remembered that the calculation examines the worth possible situation with beam seas and resonance conditions. But it means that the boat is less seaworthy than the other boats that we have examined. In this way it may be a good indicator of seaworthiness.

Downflooding angle

A simpler and possibly better indicator of seaworthiness is the downflooding angle. In our model tests we saw that model 2 of North Ferriby sank. This boat also has the lowest downflooding angle of the boats, while model 1 of the same boat has the highest (Figure 119). It makes immediate sense that boats with higher freeboards are safer. This number is also not affected by any particular arrangements of cargo and crew, just the hull shape and the freeboard. Only the Singapore Sampan should again have added some value due to the coamings and half deck. This is a much simpler calculation than above, and would add 3.4° to the 16° calculated from at the gunwale.

Evaluated thus, Ferriby Model 2 comes out significantly worse than any other. The lack of rocker to the bottom even detracts further from the stability of this vessel. At the other end of the scale Kinneret (40% draught) and North Ferriby model 1 both have high freeboards with very high downflooding angles. Dashur at 40% draught also has a high downflooding angle, although more in the range of the other boats. Being a decked vessel, the downflooding angle is less critical to the Dashur boat, although with the intended use and environment, a heel of more than 20° would not exactly mark a pleasant situation.

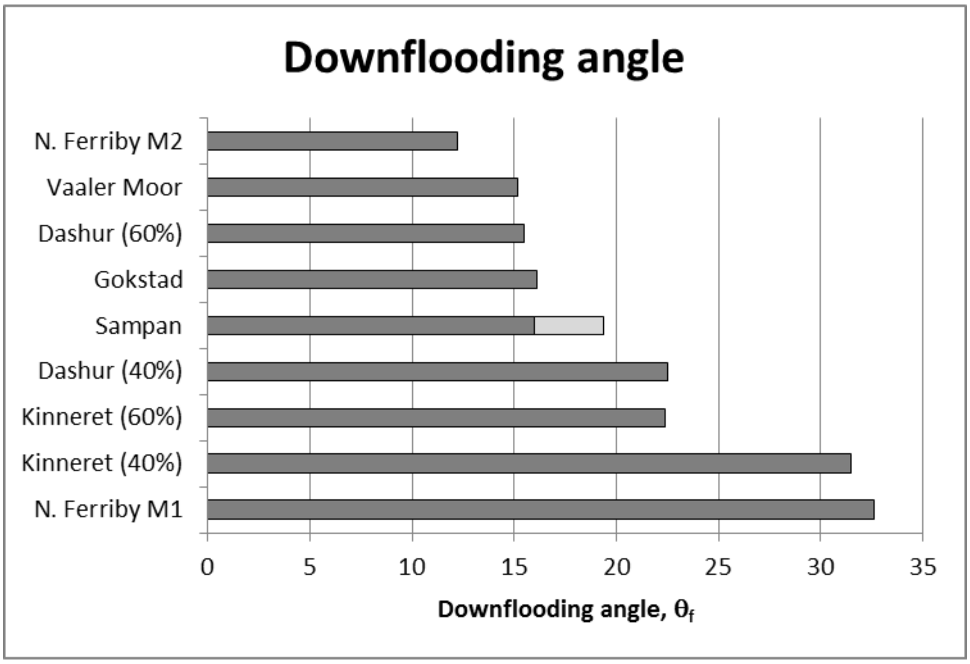

Figure 119. Downflooding angle of the boats. 3.4° are added to the Sampan to allow for the half deck and coamings. Kinneret and Dashur are calculated for both 40% and 60% draught.

The downflooding angles are essentially a measurement of freeboard. The advantage of this measure is that it does not give an absolute height, but measures relative to the beam of the boat. This angle is what makes the freeboard interesting.

Model tests

The model tests were much more direct demonstrations of the limited seaworthiness of North Ferriby model 2. Two out of three test runs led to its sinking in the waves we exposed it to. This was the only one of the boats which got into real trouble and sank. This reconstruction is outright unseaworthy.

In spite of the shortcomings and simplicity, the test setup did work in giving an impression of the boats' behaviour on the water. We did them acknowledging that for several good reasons we could not have access to fully equipped tank facilities, and that extensive improvisation was necessary. It was useful to see the boats in the water, and as such these model tests belong more to the sphere of experiential than experimental archaeology (Reynolds 1999; Cunningham *et al*. (eds.) 2008). We gained valuable experience through these tests, and this is probably the most important outcome.

Towed speeds

The boats were towed at an average speed of 5.9 kts in full scale. Half the runs were in the range of 5.5 to 6.5 kts, and the total range was from 4.7 to 7.3 knots (
Figure 120). Considering the nature of the towing rig, these numbers must be considered fairly consistent.

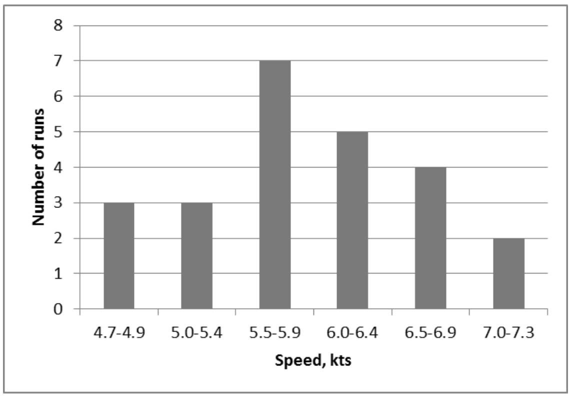

Figure 120. The speeds measured during the tests.

The waves

The aim of the model tests was to expose the boats to waves large enough to approach the border conditions of their seaworthiness. After the initial tests with the Vaaler Moor boat, we settled on making there runs with each boat, subjecting them to three different wave patterns. On average we had a significant wave height equivalent to 0.77 m in our tests (Table 31). The wave height were increased during each of the three tests, but as the second set of runs were made with generally shorter waves, the resulting average wave angles ended up being relatively identical in the two last runs.

Test run	h_s, m	λ, m	Angle, °
1	0.57	6.06	5.9
2	0.77	4.03	8.4
3	0.99	7.02	9.0
Average	0.77	6.66	7.3

Table 31. The waves produced in the tests. Average values converted to full scale.

These are average values, however, and in practice the waves varied much; the tests were made and recorded with simple equipment, but for each boat we did manage to get three distinctly different wave patterns. Comparing the actual wave slopes to the graph of storm waves in different environments published by Marchaj (Figure 121), we see that the waves generally have a short period compared to the possible. This is in good accordance with the fact that we have tested relatively small boats, for which shorter period waves are the most dangerous. The range of slopes varies from relatively calm to open sea storm, although most of the values fall below the average line for sheltered waters and estuaries (line C on the graph). In general we have imitated the sheltered inshore conditions, where boats of the size range of ours would normally be operating.

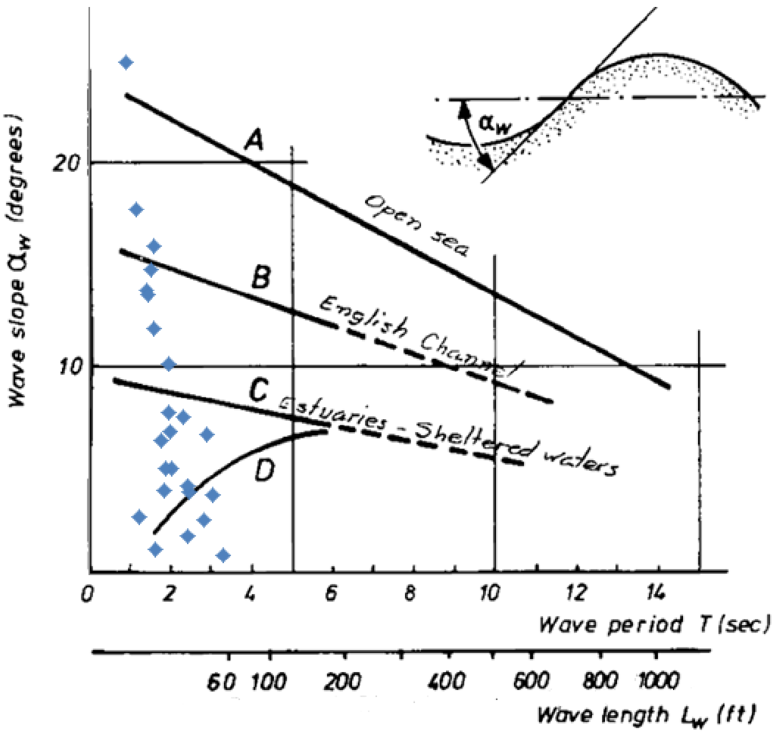

Figure 121. Wave periods and wave slopes of the experiments, superimposed on the diagram of storm waves shown by Marchaj (1986: 140).

Pitch

Although not all waves reached storm level, or were intended to, the waves seemed to cover well our criteria of letting the boats sail in 'bad' conditions. This became obvious when the pitch acceleration of the boats were calculated for each test run. We did the calculation at a position of 10% of the length behind the bow of each boat.

The result of this calculation shows that although the waves did only rarely capsize the boats, we put them into situations which would have been very unpleasant to the crew, had this been full scale experiments on an actual sea (Figure 122). The snapshots from the videos shown in the previous chapters also illustrate this well. Only a single test run was on the threshold of the tolerable, otherwise a person standing in the bows of these boats would most likely have been perceptibly weakened, or downright seasick.

While the boats generally seemed seaworthy in relatively bad conditions, their seakindliness was certainly tested. Figure 122 proves an important point about the assessment of boats, in that seakindliness may be just as important as seaworthiness. As shown here, the boats were subjected to conditions which would have been intolerable to a normal crew.

Modern boats are sometimes sold on a phrase that the crew will give up before the boat. Without boating experience it can be difficult to envision what is meant by this. But it is in fact exactly what has been going on in most of our experiments.

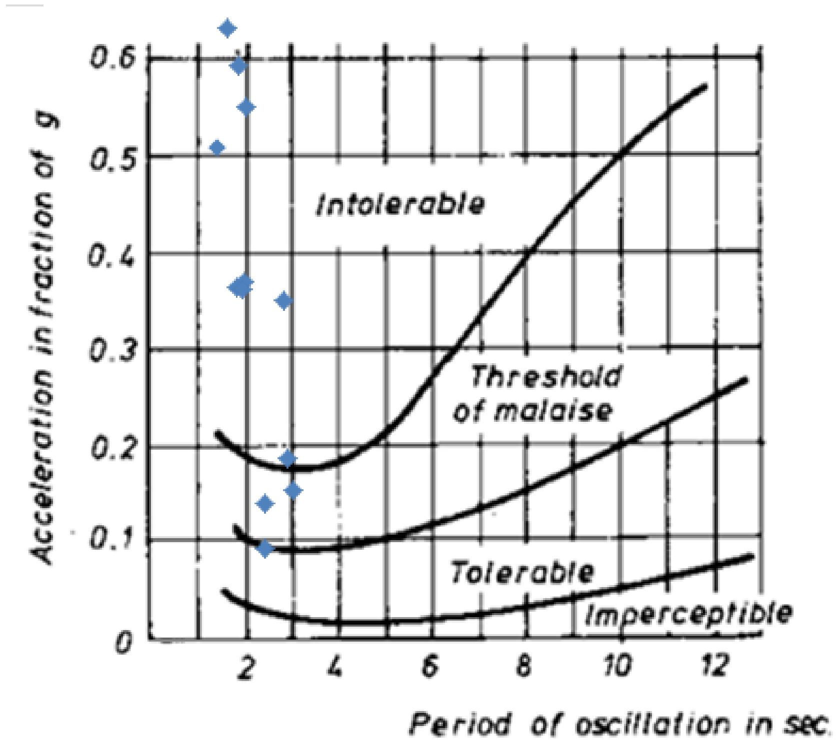

Figure 122. Acceleration at the bows of the boats superimposed on the diagram of sea sickness shown by Marchaj (1986: 75). Another eight values were positioned above this graph.

Heel

The heeling angles are more difficult to assess. The analysis was not made easier by the fact that the programme's underwater video equipment broke during just before project start. As a substitute we chose to buy the cheapest camera we could find for position 2 (measuring heel, cf. Figure 17). This was to avoid the risk of bringing more expensive equipment out on the water, but gave us a resolution on this camera of only 640×480 pixels. Camera 1 (pitch and speed) was HD quality, and posed less difficulties in the analysis.

The measured heel must therefore be read with considerable care. Indeed the results can be difficult to interpret, as there are no obvious trends in the data. This may be the result of low quality data, but for e.g. the large North Ferriby boat we have also suggested that this is a function of the boat's size compared to the length of the waves. Due to the uncertainties of the measurements we will not go further into this discussion here.

We can say that the heeling angles were generally no less unpleasant than what was shown for the pitch above.

Fitness for use

As already discussed in the introductory chapter, there is *a priori* no such thing as a 'bad' boat. A boat may be bad for a particular use, but it must be evaluated against its intended use and environment.

Being contemporary, but otherwise separated widely in space, both the North Ferriby 1 and Dashur are made on a central strake, or keel plank. Both boats are also held together using elaborate carving, with bevelled planks making tight fits. Otherwise they look nothing like each other. They also did not perform like each other. The North Ferriby 1 boat was a combined personnel and cargo carrier with a good carrying capacity and some seagoing capability (at least in the more plausible of the two reconstructions). Made to sail the Nile, and possibly for one specific journey, Dashur had a limited cargo capacity, but surprisingly good stability. The shape of the vessel, and the doctrine by with it was loaded and used, was entirely different from that of North Ferriby. The English North Sea coast and the Nile are very different waters indeed.

The Gokstad Faering and the Singapore Sampan are comparable in size, but not in construction. In fact they could easily be seen as different building traditions' expression of the same type of boat. The context has stood in the way of such an interpretation. The Sampan is known as a common working boat from Asia, while the Gokstad find is a royal tomb. We therefore see interpretations of this boat as a kind of yacht or even racing boat. If we look historically at the faerings, though, they were small inshore working boats, simply smaller versions of the seagoing boats (Diriks 1863). The royal context may in fact be deceiving in this case, and the boat better interpreted more commonly as a convenient and well sailing small boat, just as the Sampan.

The fitness of the proas, exemplified by the wa Mikael, cannot be questioned. These were the main instruments of interisland communication across vast areas of the Pacific, and gained a reputation in the Western world for being very fast seagoing boats. With the outriggers they also represent a building tradition which apparently never developed in Europe or the Americas, but is particular to The Pacific and the Indian Ocean.

The Kinneret boat has a high freeboard, good stability and if necessary a very high cargo capacity. These are properties which are good for a fishing boat, although we decided that loading it to 60% of the draught would give unrealistically high loads. As with the other inland boat, we therefore decided for a 40% draught, which still gave plenty of room for a good catch.

Finally the limited seaworthiness of the personnel carrier Vaaler Moor again illustrated that it is an enigmatic boat, the purpose of which is still difficult to understand. Capsizing the boat by simply leaning the crew to one side was a thought-provoking and somewhat unsettling exercise.

11. CONCLUSION

In a review of previous reconstructions of the Vaaler Moor boat, Hirte described how Timmermann (1942) in his work was aiming for a lines plan and "*in no way aimed for a detailed reconstruction of the find*" (Hirte 1989: 123, our translation). This is the archaeologist assessing the work of the naval architect. A lines plan is not an artefact drawing, and Hirte is right in that result does not directly look like the actual boat. But Timmermann certainly produced a detailed reconstruction of the Vaaler Moor boat with his plan. In fact it is in many respects a more precise reconstruction than traditional archaeological artefact drawings. The work presented in this project had been impossible without good lines plans. We have noticed that such drawings are mainly published by professionals with actual boat building experience. Whether building full scale replicas or scale models, it probably takes that practical experience to realize that when it comes to boats, the traditional archaeological artefact drawing is next to useless when it comes to transforming the two-dimensional drawing to a three-dimensional object. Even when published, many archaeological boats are not accessible in a format where it is possible to understand them as the three dimensional objects they are.

The purpose of this project has been to assess the performance of ancient and traditional boats, using mainly techniques developed by naval architects. In the introductory chapters the Vaaler Moor logboat was used as a recurring example, because the work was inspired from an earlier project on that boat (Ejstrud & Maarleveld (eds.) 2012). During the course of this project, however, it became increasingly clear that these are all very interesting boats in their own right, each one of them opening similar research problems.

There is no way of becoming naval architects during a three months project, and there is obviously still much to learn. However, developments in modern software technology means that all the basic calculations, once very complicated and time consuming to make, is now within reach of anyone with an interest in ships, even with free or low cost software. The implication of this to maritime archaeology is that these calculations can be incorporated with relative ease whenever a boat is sufficiently well preserved for its main dimensions to be reconstructed. As a profession we will therefore have to foresee that the approaches of naval architecture will be more standard, and that we will have to develop a better understanding of them in our work with ancient boats and ships. As the calculation of displacements, centres and moments of inertia is no longer specialist knowledge, the informed interpretation of these numbers can also no longer lie within a limited group of specialists.

The main theme and result of this project is therefore perhaps mainly methodological. In calculating the basic measures of these boats there is much to learn about them as sailing machines. This must necessarily have a bearing on their archaeological interpretation. For this reason the methods section of this work is relatively long, even discussing methods which we considered, but ended up not using; much of this could still be useful and developed into.

The seven boats which have been analysed and discussed here were deliberately chosen to be as dissimilar as possible. The premise for a comparison of the boats is therefore that there would be very few similarities between them, apart from being boats. Seven boats do not make the basis for an overarching synthesis of boat construction, but some general traits may be inferred from this study.

Tradition is a strong factor in a study with this setup. As quoted in chapter 2 even modern naval architects -and their clients- are strongly influenced by their preconceptions of what a 'proper' boat should look like. This is no less the case for the boats we have studied, which have clearly been built in very different traditions. There are elements of boat building which cannot be determined in a purely rational analysis, although in human societies tradition-based behaviour also has its purpose and rationale.

The calculation of cargo capacities is a very useful tool in understanding the boats archaeologically. This should be a standard operation for any reasonably well preserved boat, as the ability to carry something or someone across water is the *raison d´être* of any waterborne craft. Knowing how much it could carry is a good starting point in trying to guess what was carried. These calculations are made acknowledging that we will never know how hard each individual vessel was loaded, and that a range of different displacements are possible. It is still a defined range, as there is both a lower and an upper limit, defined by the weight of the boat (and mostly one person) and the height to the gunwale. The standard draught of 60% is generally practical for comparison, but for three of the seven boats examined here, it was considered too much. Kinneret and Dashur could theoretically have been loaded to 60%, but would carry unbelievably large cargoes, while the Carolingian proa could not have been loaded to 60% as it would completely submerge the outrigger.

One aspect of assessing the possible ranges of draughts is to look at the seaworthiness of the vessel. This is validated through understanding the environment in which the boat was supposed to work. The seemingly inverse relation between metacentric height and environment was a surprise to us, but with Marchaj found an explanation in the avoidance of resonance conditions.

With inspiration from modern developments in naval architecture, we tested a method to assess the maximum permissible wave height for the boats. Applying this equation to Dashur revealed a problem with it. Being decked, Dashur is loaded differently than the other boats, and this was not reflected in the numbers. The approach is still worth pursuing, especially if a standard model could be developed, with a general applicability to ancient boats. The calculations were done in a spreadsheet, and do not require special software.

The physical tests at least showed that unless in resonance conditions and beam on, the boats could negotiate much higher waves than calculated theoretically. Although much effort was put into the building and testing of the physical models, and although it was an interesting and useful exercise, these tests could clearly have been done with more rigour. The current project was made as a one semester course with a practical timeframe of three months. The results must necessarily be assessed in the light of this, and the fact that this project was done as part of educational activities. Perhaps the main result is that we have a better idea of how we would design such tests in a further series of tests.

The video analysis was very crude, and not overtly precise. Still, a substantial amount of tedious work lies behind the pixel-level analysis of individual frames from several videos. It was elucidating to see the boats in the water, and it is always a learning experience to build them in model. Tank testing is still beyond the reach of most archaeological projects, but developing a more formalized approach which can cater for both archaeological questions and archaeological budgets could be an interesting next step. The commercial tank testing facilities may not be needed in an experiential approach to ancient boats. An even in full scale most of the work that has been done is more experiential than experimental.

This project has analysed seven specific boats. Hopefully it can also point forward to the development of new projects and methods, and thereby to a better general understanding of the ships and boats that we focus so much energy on in maritime archaeology.

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