Stability Characteristics of an Early XVII Century Portuguese *Nau*

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ABSTRACT

During the XVI and XVII centuries the India Route was the longest regular commercial route of its time and connected Lisbon, Portugal, with Goa or Cochin in the Indian subcontinent. However, there is presently very little technical knowledge about the technical characteristics of the different ship types employed in this trade. This paper starts by describing briefly the shipbuilding treatises, techniques and shipyard organization at this time. Then, a shipwreck discovered at the mouth of the Tagus River, which was identified as the Portuguese ship *Nossa Senhora dos Mártires*, of the *Nau* type, lost in this place in 1606, is described. Taking in consideration shipbuilding treatises and archaeological remains, a reconstruction of the ship's lines plan, structure and rigging is then presented. This information is used to investigate the floatability and stability of the ship in a number of different loading conditions, including overloading of the ship, which was a usual condition when these ships returned from India. Accidental conditions such as those arising from flooding are also discussed. The results are compared with modern stability criteria for large sailing vessels.

Keywords: *Intact stability, Damage stability, Nau, History, Archeology*

1. INTRODUCTION

The Portuguese ship *Nossa Senhora dos Mártires*, known to be of the *Nau* type, sunk at the entrance of river Tagus in Lisbon, on the 14th September 1606, therefore almost exactly 400 years ago. The ship was returning from India, after having travelled across the India Route (*Carreira da India*). This was the longest regular commercial route of its time and linked Lisbon, in Portugal, to Goa or Cochin in the Indian subcontinent. The route was sailed by Portuguese ships yearly between 1498, the year Vasco da Gama returned from his exploratory voyage, and the XVIII century.

It is known that *Nossa Senhora dos Mártires*, probably an almost new ship at the time, had left Lisbon on the 21st of March 1605 and arrived in Goa on the 28th September 1605.

After loading in Cochim, the ship departed from that harbour on 16th January 1606. The ship made a smooth voyage and scaled the Azores Islands in June, before arriving near Lisbon in the middle of a severe storm on the 13th September. The ship dropped anchors, but two days later the mooring cables broke and the ship's captain decided to attempt entering the river. On the morning of 15th September, the ship grounded on the coast at the entrance of river Tagus in very heavy following or stern quartering seas and, possibly, against a strong tidal current. The ship's hull was broken against the rocks in a matter of hours. On 19th September, about 200 bodies had already been washed ashore together with a large peppercorn black tide.

Although a substantial number of details relating to ship losses, life aboard, navigation techniques and events in India have been studied extensively by historians, very little is known about the technical characteristics of the ships engaged in this trade. These ships were built in a pre-industrial era when technical design and documentation procedures almost did not exist and, in fact, their construction relied mostly on practical knowledge and tradition. For these reasons, modern investigators are left with little more than contemporary drawings such as those shown in Figure 1.

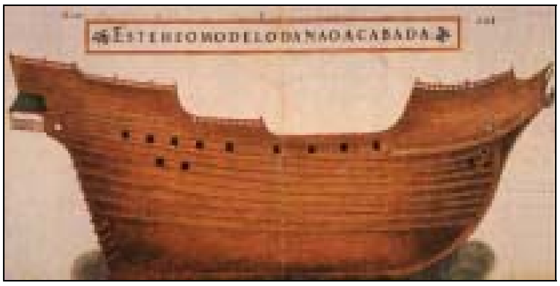

Figure 1 The India Nau from the *Livro de Traças de Carpintaria*, Manoel Fernandez (1616)

The current study is considered as the first stage of a larger and more comprehensive naval architecture investigation of the nautical characteristics of an early XVII century Portuguese *Nau*. The current paper attempts a step forward in the same line of classic studies in this field, such as those of Barata (1989), Branco (1994), Blot *et al.* (1994) and Domingues (2004). However, most works are still insufficiently integrated with naval architecture expertise and fail to explore many technical aspects of XVII century ship design and shipbuilding.

The methodology to investigate the technical characteristics of these ancient ships must be based on the analysis of archaeological remains and ancient shipbuilding treatises, which was in this case carried out by Castro (2001, 2003). Based on this work, Fonseca *et al.* (2005) present the analysis of the ship's stability at the departure from India and a comparison with modern stability criteria for large sailing vessels.

Compared to the former publication by the authors, this paper adds: a review of the ancient Portuguese shipbuilding treatises, a description of the procedure to reconstruct the hull geometry, stability results for additional loading conditions including overloading, and stability results for various damage conditions. Additionally, the calculation of the weight distribution and position of the centre of gravity is slightly improved.

2 RECONSTRUCTION OF THE GEOMETRY OF *NOSSA SENHORA DOS MÁRTIRES*

2.1 Portuguese Documents on Shipbuilding

The Portuguese shipbuilding practices of the late XVI and yearly XVII centuries are relatively well known because of a number of texts comprising shipbuilding treatises and other documents. These documents are of fundamental value for the reconstruction of the characteristics of ships used in the India Route.

The first important text is Fernando Oliveira's *Livro da Fábrica das Naus* (Book on the Fabrication of Naus), dating from circa 1580. Oliveira was born around 1507 and published extensively on grammatics, navigation, naval warfare and shipbuilding. He travelled to Spain, Genoa, France and England, where he visited the shipyards. The *Livro da Fábrica das Naus* is one of the first European treatises on shipbuilding, the theoretical work of a scholar and not the practical work of a shipwright. It is comprised of a clear text, divided into nine chapters with few illustrations, covering timber characteristics and seasons; ship types; hull shape and structural details; hull erection sequence; rudder details. Oliveira illustrates his methods and practices with a 600 toneis India *Nau* but never completed his work.

The second important text to be considered is an anonymous list of the timbers necessary to build a three-decked, 600 toneis *Nau* for the India route included in the *Livro Nautico* (Nautical Book), a codex of Lisbon's National Library, dating from the 1590s, reproduced by Domingues (2004). This text is clear and detailed, explaining the hull erection sequence and providing detailed lists of the timbers necessary for building each part of a ship. The building sequence is covered from keel laying up to rigging outfit, with examples given for the *Nau*, galleon and caravel types of ships.

The third important text is the manuscript entitled *Livro Primeiro da Arquitectura Naval* (First Book of Naval Architecture), by João Baptista Lavanha, written sometime around 1600. Lavanha was born in Lisbon in the middle of the XVI century, became cosmographer and published extensively on navigation matters but also on shipbuilding. The book contains general information on the nature of naval architecture, on timbers and on the dimensions and shapes of the hull structure up to the first deck. The book is incomplete and is clearly the work of a scholar, with a clear text which makes extensive use of geometry.

The fourth important text was Manoel Fernandez *Livro de Traças de Carpintaria* (Book of Shipwright Drawings) dated to 1616. Nothing is known for sure on the author, but certain documents refer Fernandez as a master shipwright at the Crown's Shipyard. The book comprises a large number of fine drawings, one of which is shown in Figure 2, illustrating a substantial number of ship types of this epoch, including a three-decked *Nau*. The drawings illustrate texts dedicated to individual ship types of different sizes, both sailing ships and rowing ships. The texts are frequently obscure and are clearly the work of a practical man, but most probably reflect contemporary practice in the shipyards. The book also contains details on the cranes, cradle and procedures used to launch the ships.

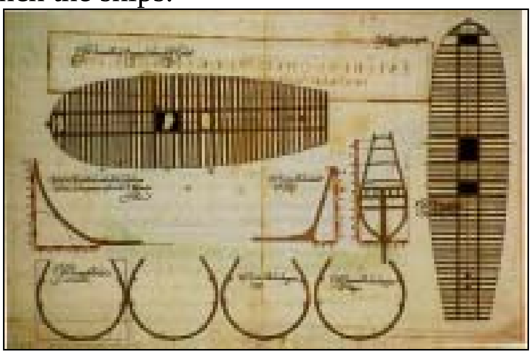

Figure 2 Plate from the *Livro de Traças de Carpintaria*, Fernandez (1616)

2.2 Lines and Rigging Plans

This section describes the method used to reconstruct the hull form, which is based on information included in contemporary documents and the archaeological remains recovered at the Pepper Wreck site. Written records show that Portuguese n*au* was conceived in the sixteenth and seventeenth centuries as a central box with two ends (Lowen, 1994). The frames that composed the central portion of the hull – the so-called box – were designed and built according to an old non-graphic system, developed in the Mediterranean sometime after the 11th century, probably for the building of galleys.

After mounting, leveling, and shoring the keel, stem and sternposts on the stocks, shipwrights would erect the stern panel, consisting on two fashion pieces and a number of transversal reinforcements of which the widest was placed at main deck level, and called *gio* (Figure 3).

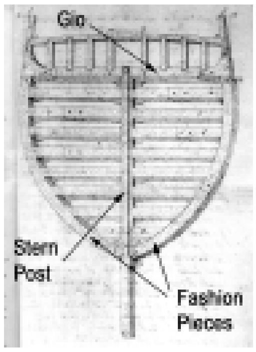

Figure 3 The stern panel

Traditionally the *gio* was half as wide as the ship's maximum breath, which was measured, not necessarily at main deck, on the master frame.

With the keel and posts in place, including the stern panel arrangement, the next step was to erect the master frame, or midship frame. The master frame, or frames, for there were one, two, or three master frames in an India *nau*, depending on the keel length, was fully designed on the floor, somewhere in the shipyard. The master floor timber was assembled to the first futtocks with scarves and iron spikes, making sure that these connections were solid on both sides, and would not move once erected on the keel.

The most important thing in the design of the master frame was the position of the turn of the bilge points. These symmetrical points marked the division between the ship's bottom and sides and were the control points for the design of all the frames that composed the central box. The last frames of this pre-designed and pre-assembled central box were appropriately called tail frames. The other two control points were located on the upper portion of the futtocks and marked the ship's width at main deck level, as shown in Figure 4.

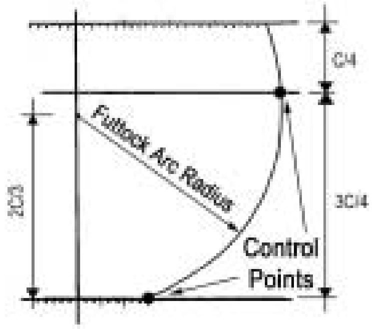

Figure 4 Position of control points

The section of the ship would change therefore incrementally, from the master frame's shape, to the tail frames, by narrowing and rising the positions of the turn of the bilge points, and by rising and widening the points of the deck breadth, as shown in Figure 5.

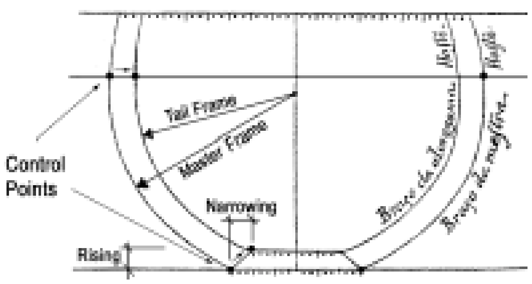

Figure 5 Narrowing and rising of the frames

A smooth rising and narrowing of the bottom was obtained with the help of one of a number of geometrical algorithms available to the shipwright at the time. One interesting particularity of this method is the fact that it is non-graphic. In other words, shipwrights did not need to make any drawings to obtain the shape of each one of the pre-designed frames. All tasks were achieved with the help of two moulds and a variable number of gauges, as shown in Figure 6.

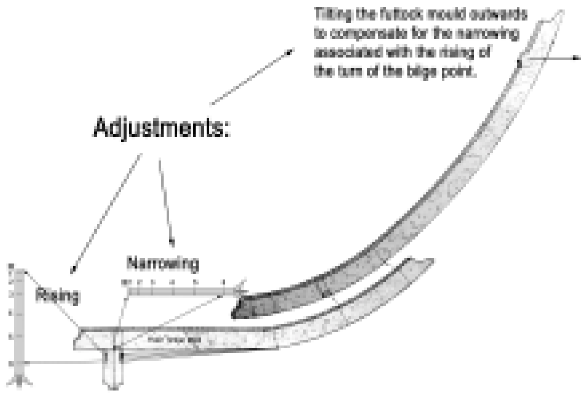

Figure 6 Adjustment of the mould

From the shape of the midship frame the shipwrights would deduce the shape of the tail frames by adding the total rising and subtracting the total narrowing of the turn of the bilge points. The length of the total rising or narrowing to be distributed along the pre-designed frames was called *compartida* in Portuguese. The gauge with the incremental values, to be added to or subtracted from each of the frames, was called *graminho*. The word *graminho* may lend itself to confusion because it designated both the gauge and the method, or algorithm, utilized to obtain the incremental values or coordinates of the curves.

Some of these geometric algorithms were described in sixteenth- and seventeenth-century Portuguese treatises and texts on shipbuilding, under designations like *meia lua, besta*, *saltarelha*, *brusca*, and *rabo de espada* (Barata 1989). These algorithms are very simple and well-understood. The one that seems to have been used in the design of the Pepper Wreck frames is the method known as *meia lua*.

The *meia lua* method, or *besta*, as Fernando Oliveira calls it, is referred in Italian texts from the fifteenth century onwards and consists of a quarter of a circle with a radius equal to the *compartida*. The quarter of a circle is divided into as many equal parts as the number of offsets required or, in other words, as many equal parts as the number of pre-designed frames to be placed from the midship frame to the tail frame in any particular vessel.

The offsets can be obtained by the expression: $x_i = 1 - \sin\alpha_i$ where α_i is the angle of the radius that touches point *i* on the quarter of the circle. However, the traditional way to obtain these values is graphic and quite simpler, consisting on adding another quarter of a circle, mirroring the first one, and on passing lines horizontally across, connecting the correspondent points. The resulting scale was directly engraved on a wooden gauge from the 1/1 scale drawing (see figure 7).

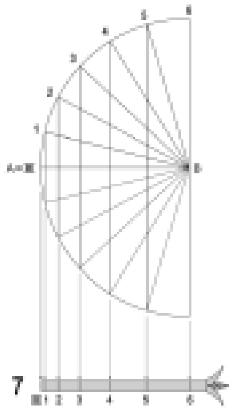

Figure 7 The *graminho*

Once the Nautical Archeologists started recording the remains of the ship's frames a number of turn of the bilge point's marks became apparent. These carpenter marks were used to reconstruct the ship's hull form. The method used in the ship's reconstruction was fairly simple: the sets of values obtained from the archaeological remains were tested against the sets of theoretical values generated by all available algorithms (Castro 2005a). Several contemporary texts on shipbuilding offer a number of recipes to build an India *nau* and the sets of values generated with the algorithms above mentioned were adapted to the recipes.

As a result, the Pepper Wreck timbers seem to have been cut using *a meia lua* to distribute the incremental values of the bottom's rising and narrowing over 18 frames before the three central, master frames. According to the model of Fernando Oliveira (1580), another 18 pre-designed and pre-assembled frames were erected abaft the central frames, totaling 39 the number of pre-designed frames in this ship (Castro 2005a). Once the shape of the bottom was found, the remaining parts of the ship's hull were easy to reconstruct based on Oliveira's treatise. As in other shipbuilding texts and treatises of this time, most dimensions are simple fractions of the value of the keel length. Figure 8 presents the reconstructed lines plan and Table 1 the main particulars of the ship.

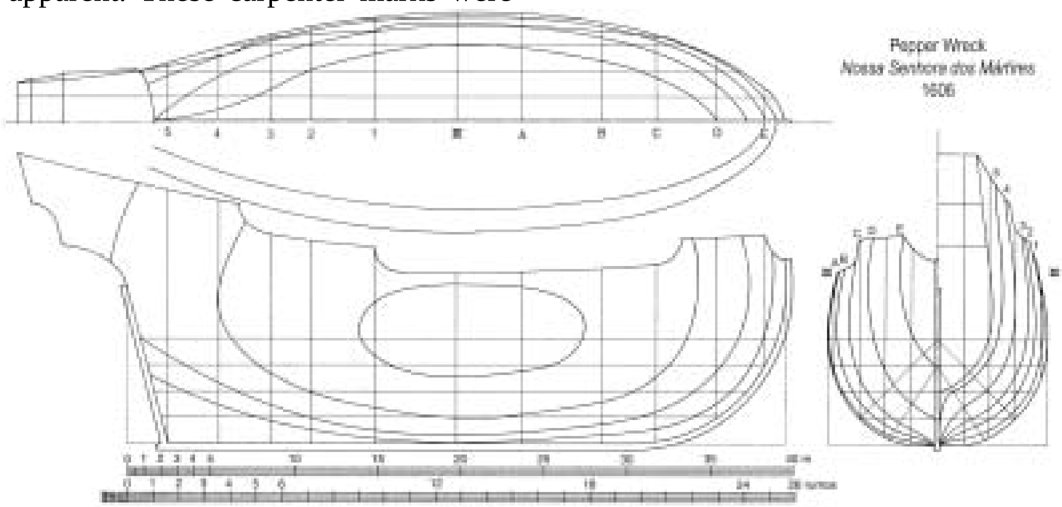

Figure 8 Lines plan of Nossa Senhora dos Mártires

Table 1 Main particulars of the ship

Length over all (m)	50.4
Length betw. perp. (m)	38.0
Breadth, extreme (m)	13.2
Depth to main deck (m)	8.21

Regarding the reconstruction of the internal space arrangement of an India *nau* is not a simple affair: firstly because contemporary data on this subject is scarce and fragmentary; secondly because these arrangements seem to have been changed by the ship's captains prior to every trip; and thirdly because the descriptions of cargoes, crews, passengers and victuals frequently pose more questions than they provide answers. Based on contemporary shipbuilding treatises Castro (2001), proposed a general arrangement with three decks, a poop deck at the stern and a forecastle (figure 9).

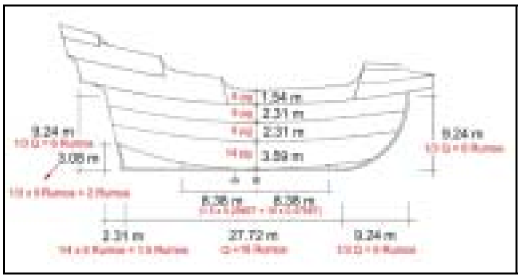

Figure 9 Reconstruction of the general arrangement of the *Pepper Wreck Nau*, Castro (2001)

The reconstruction of the ship's rigging arrangement was based upon the documents indicated above, that describe masts and spars for this type of ships, and give their dimensions as proportions of the keel length and maximum beam (Castro 2005b). According to these sources, which are fairly consistent, the lengths and diameters of the ship's masts and yards can be obtained from the ship's keel length and are simple fractions of the main mast. The sizes of the sails were easy to determine once the lengths of the masts and yards were known, with the exception of the spritsail, which in some documents seems to be much higher than the one designed for this study. Figure 10 show the reconstruction of the masts and yards and corresponding sail plan.

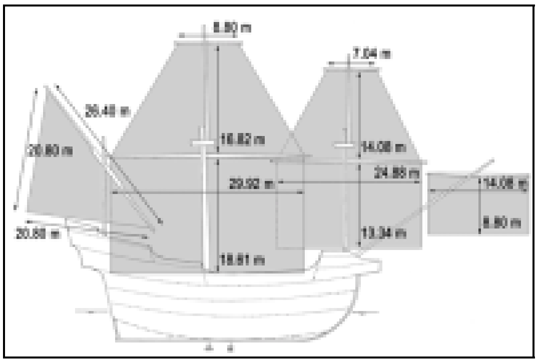

Figure 10 Reconstruction of the sail plan of the *Pepper Wreck Nau,* Castro (2005b)

Figures 11 and 12 show two three dimensional views of the ship, allowing an approximate understanding of how an India *Nau* might have looked like.

Figure 11 Three-dimensional view of the ship seen from the bow (courtesy of José Varela)

Figure 12 Three dimensional view of the ship seen from the stern (courtesy of José Varela)

3 RECONSTRUCTION OF THE LOADING CONDITIONS OF *NOSSA SENHORA DOS MÁRTIRES*

The analysis of the floatability and stability of any ship requires knowledge both on the ship's geometry and the ship's mass and centre of gravity. The estimation of these properties for an early XVII century ship, whose geometry and constructive details are not known accurately, represents a major task and one bound to yield a result with some uncertainty.

The loading condition at the departure from India for the return voyage was investigated in Fonseca et al. (2005). It is known that these ships tended to be severely overloaded and this appears to have caused a considerable number of losses around the turn of the 16th to the 17th centuries, especially in the area of the Cape of Good Hope. The former results are compared here with additional calculations for the arrival at Lisbon condition, since it is of interest to evaluate the ship's stability at the moment of the accident.

The weight of the ship has been subdivided in a number of components: hull, masts and yards, sails, rigging (shrouds, etc), anchors and ship's boats, artillery, ballast, cargo, crew, soldiers, passengers and supplies. Fonseca *et al.* (2005) describe the methodology to estimate all these weights and their positions onboard, as well as the related sources of information.

Figure 13 presents the weight distribution for the loading condition at the departure from India. For the arrival at Lisbon condition, it is assumed that weight of the water and wine, biscuit and other supplies is 10% of the corresponding weights when departing from India.

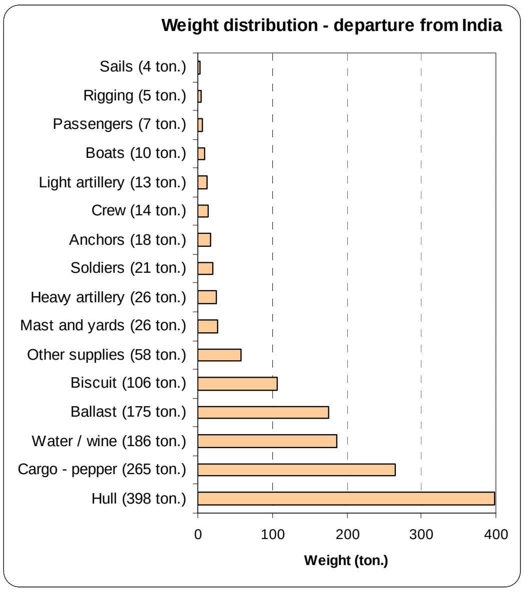

Figure 13 Weight distribution for the loading condition at the departure from India

When the ship is severely overloaded, as was common in those days, and the available literature clearly documents, the floatation characteristics of the ship change. On this subject, it is worth reading D'Intino (1998) or Malheiro do Vale (1988). In this case, it was assumed that the crew, soldiers and passengers were carrying in the return voyage twice the load they were legally allowed, apart from their personal belongings, which were included in the previous loading conditions. This load consisted of a number of boxes (called *liberdades* or *favores*) with spices or other items which the crew and soldiers were allowed by the Crown to carry from India and which they could then sell in Lisbon. Taking into account the estimate on the number of people on board and the different number of boxes which people of different categories were allowed to carry, it can be estimated that the ship could be carrying 1630 of these large boxes. If one assumes a standard weight of 59kg per box, the total extra weight is of over 96t. From contemporary texts, it is known that these boxes were mainly carried in the superstructures or in the main deck, therefore raising the centre of gravity to 5.36m at the departure from India and 5.25m at the arrival in Lisbon.

Table 2 presents the estimated total weight of the ship and position of the centre of gravity for these four conditions. Longitudinal position of the centre of gravity (Lcg) is with respect to the aft perpendicular and the vertical position (Vcg) is with respect to the baseline.

Table 2 Weight of the ship and position of the centre of gravity

	Weight (t)	Lcg (m)	Vcg (m)
Departure from India	1331.4	19.75	5.13
Arrival at Lisbon	1016.4	19.50	4.94
Depart from India (overloaded)	1427.6	19.77	5.36
Arrival at Lisbon (overloaded)	1112.6	19.55	5.25

4 ANALYSIS OF THE FLOATABILITY AND STABILITY OF AN INDIA NAU

4.1 Intact Floatability

Figure 14 shows the ship's hydrostatic properties. In these hydrostatic calculations the planking thickness (11cm) was taken into consideration when defining the hull sections and the forecastle and aft superstructure were not considered watertight. Table 3 shows the drafts, freeboard and metacentric height in the different conditions.

Regarding the issue of determining if these drafts are correct, it is worth mentioning that Oliveira (1580) points out that the first wale of the hull was layed at approximately the height of the beam shelves of the first deck amidships. He also indicates that below this level the hull had no wales because these would perturbate the flow of the water past the hull. So, it is possible to assume that this first wale was not too far below the waterline. Taking in consideration the drafts above and that the depth to the first deck was around 3.84m, the first wale would be between 0.37m and 1.41m below the waterline, depending on the loading condition. The second wale would be, for all the estimated loading conditions, above the waterline.

Table 3 Drafts of the ship in different loading conditions

	Draft Aft(m)	Draft Forw(m)	Trim (m)	Free-Boar d(m)	GM (m)
Departure from India	5.25	4.75	0.50	3.21	1.00
Arrival at Lisbon	4.68	3.74	0.94	4.0	1.13
Depart from India (overloaded)	5.48	5.03	0.45	2.96	0.77
Arrival at Lisbon (overloaded)	4.90	4.03	0.87	3.75	0.84

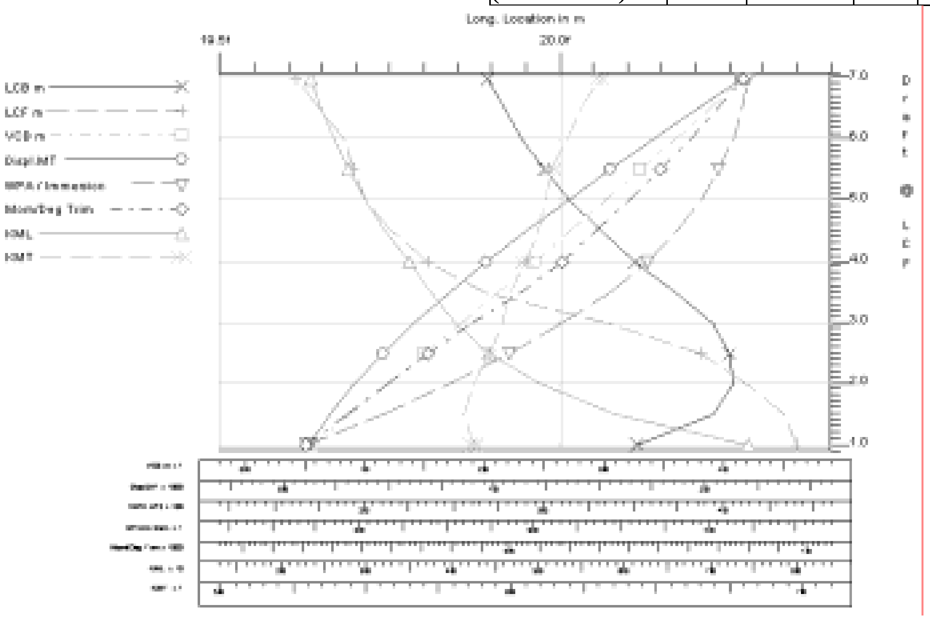

Figure 14 Hydrostatic properties of the *Pepper Wreck Nau*.

4.2 Intact Stability

The Portuguese shipbuilders of the late XVI century knew very little about ship stability, except that, for example, locating large weights high in the ship would degrade the ship's stability and that increasing the beam had good effects in the behavior and cargo carrying capacity of the ship, as mentioned by Oliveira (1580).

In what concerns the intact stability of this ship, Figure 15 shows the righting levers of the ship in the standard loading conditions. It is possible to see that the ranges of stability are 104º and 112º and the righting energies are 0.84m.rad and 1.19m.rad.

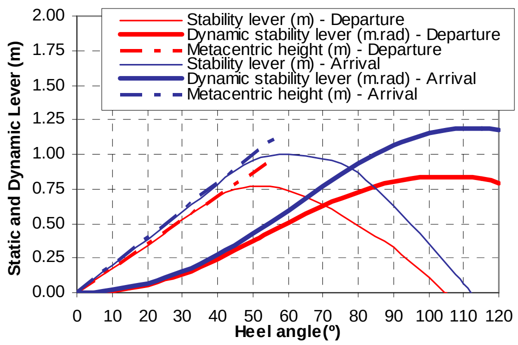

Figure 15 Righting lever curves for Pepper Wreck Nau (ship properly loaded).

Figure 16 shows the righting levers in the overloaded loading conditions. It may be seen that the ranges of stability have decreased to 93º and 100º, respectively. The maximum righting energies have also decreased to 0.55m.rad and 0.76m.rad.

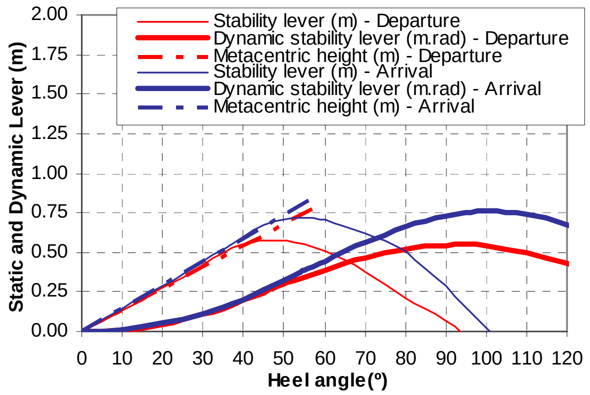

Figure 16 Righting lever curves for Pepper Wreck Nau (overloaded ship).

4.3 Evaluation of Intact Stability using a Large Sailing Vessel Criterion

It is interesting to investigate if a Portuguese *Nau* would comply with modern intact ship stability criteria. There are a number of such criteria available, some of which can be used in the stability evaluation of large sailing vessels. The International Maritime Organization generally advises the use of the classic cargo ship stability criterion and the weather criterion, both contained in IMO-Assembly (1990). However, it recognizes that both criteria are not suitable for ships fitted with extensive sail areas. For this purpose, the US Coast Guard (1983) established a criterion, contained in the Code of Federal Regulations which will be used in the present study.

According with this criterion, the ship shall have numerals *X*, *Y* and *Z* larger than given values. The *X* numeral expresses a measure of protection against water on deck. Numeral *Y* expresses the resistance against downflooding the interior of the ship and numeral Z indicates the capacity of the ship to resist a knockdown (leading to capsize). The numerals are given by:

$$\frac{1000.\Delta.HZ_a}{A.h} > X \quad \frac{1000.\Delta.HZ_b}{A.h} > Y \quad \frac{1000.\Delta.HZ_c}{A.h} > Z$$

where:

Δ = displacement (*t*),

A = projected lateral area of the hull and sails (m^2),

h = vertical distance between centre of pressure of the projected lateral area and center of the underwater lateral area (*m*).

HZ_a, HZ_b and HZ_c are calculated using:

$$HZ_a = \frac{GZ_c}{\cos^2 \theta_c}$$

$$HZ_b (or \quad HZ_c) = \frac{I}{((\theta_v / 2) + 14{,}3.\sin 2\theta_v)}$$

where:

θ_c = angle of deck immersion (º),

GZ_c = righting arm (m) at the angle of deck immersion,

θ_v = angle of downflooding (º) or 60º, whichever smaller, when calculating HZ_b; 90º when calculating HZ_c,

I = righting energy ($m.rad$) up to downflooding angle or 60º, whichever smaller, when calculating HZ_b; righting energy up to 90º or the angle of extinction, whichever larger, but not more than 120º, when calculating HZ_c.

For a ship intended for navigation in exposed areas, the angle of extinction must be larger than 90º and the numerals must exceed the following values:

$$X = 16.4\ t/m^2 \quad Y = 18.6\ t/m^2 \quad Z = 20.8\ t/m^2$$

The calculations were made for the full sail plan and assuming that all sails act on the fore-and-aft plane and have the areas shown in Table 4. The ship has been assumed watertight up to the main deck level, that is, the gun holes could be secured watertight. Downflooding can occur only through the main deck hatches, located at the centreplane, near the mainmast, originating that the angle of downflooding is larger than 60º. The angles of deck edge immersion are approximately 28.3º and 39.9º. The angles of extinction are 104º and 112º, clearly above the minimum required angle of extinction of 90º.

The ship numerals can now be calculated and are given in Table 4. It may be concluded that the ship complies with the stability criterion in both loading conditions. It is worth noting that numeral X increases substantially from the departure condition to the arrival condition because of the large difference of the freeboards. This conclusion is valid in conjunction with the assumptions regarding watertightness and for the loading condition indicated above. In practice, watertightness was generally far from satisfactory and the overloading and overcrowding common practice. In fact, for instance, D'Intino (1998) indicates that the real distribution of cargo, supplies and people onboard seldom followed the theoretical scheme of Falcão (1607).

If the criterion is applied to the loading conditions, which take in consideration the overloading, the results are as shown in Table 5. It may be concluded that the ship does not comply with the criterion in what concerns the X and Y numerals.

For numeral X the overloaded ship complies in the arrival condition but not in the departure condition. This is caused by the substantial increase in freeboard (0.8m) as the large amounts of provisions and water supplies are consumed. Regarding numeral Y, the ship does not comply in both conditions, especially in the arrival condition, because the ship is lighter and has an increased exposed area to the wind. Finally, for numeral Z, the ship still complies with the criterion, both the values have decreased substantially in relation to the previous conditions.

Table 4 Numerals and angles of extinction for standard loading conditions.

Parameter	**Minimum value (criterion)**	**Departure**	**Arrival**
X	16.4	19.4	31.1
Y	18.6	21.5	18.9
Z	20.8	31.9	31.7
Angle of extinction	90º	104º	112º

Table 5 Numerals and angles of extinction for overload loading conditions.

Parameter	**Minimum value (criterion)**	**Departure**	**Arrival**
X	16.4	14.7	23.1
Y	18.6	17.9	15.6
Z	20.8	23.5	24.0
Angle of	90º	93.4º	100.9º

4.4 Damage Stability

The India Route was sailed yearly by Portuguese ships between the beginning of the XVI century and the middle of the XVIII. The circumstances of some of the shipwrecks that occurred during this period were registered by Gomes de Brito (1735) in his *História Trágico-Marítima* (Maritime and Tragic History).

Among the most frequent problems that beset the voyage of these ships when returning from India was the poor condition of ships regarding watertightness. This caused a steady inflow of water to the lower deck of ships, which had to be pumped out night and day while underway. There were pumps aboard for this purpose, linked by a pipe to the bottom of the lower hold. Aft of the main mast step was located a cofferdam (*arca da bomba*) where water collected and from where it was pumped.

As the ship continued voyage, often subject to heavy weather, especially while going round the Cape of Good Hope, the structure of the ship could gradually gave way and the inflow of water increased. This had another negative consequence because it further reduced the freeboard and stability of the ship, a critical situation when sailing in the tempestuous seas of what is today South Africa.

An assessment of the effects of flooding of the lower hold will now be carried out. For this purpose account has to be taken that the lower hold is filled, first, by a layer of ballast with a height of 1.46m. On top of the ballast, the cargo of pepper is carried. Therefore, the lower hold is filled, with an estimated probable permeability of 0.1. For the analysis, the departure condition with overloading shall be considered. Table 6 shows the effects of various degrees of flooding in the lower hold. It may be seen that the metacentric height remains almost constant, the draft amidships increases by less than 0.15m and the trim by the stern remains largely constant.

Table 6 Effects of flooding the lower hold

Flooding	Water(t)	GM(m)	Draft(m)	Trim(m)
Intact	0.0	0.77	5.25	0.45
10%	7.3	0.76	5.26	0.43
30%	14.8	0.76	5.28	0.42
50%	36.9	0.75	5.33	0.41
70%	51.6	0.75	5.37	0.40
90%	66.4	0.82	5.41	0.40

5 CONCLUSIONS

This paper presents a study of the reconstruction of the hull form, weight distribution, loading conditions and floatation and stability characteristics of an early XVII century Portuguese *Nau*, the *Nossa Senhora dos Mártires*, which wrecked at the mouth of river Tagus in September 1606.

The ship’s drafts in two standard loading conditions (departure and arrival) and two overloaded loading conditions (departure and arrival) were calculated and found to be in accordance with contemporary texts. The overloading was found to increase the draft by 0.25m.

The ship’s stability in the two standard and two loading conditions was also calculated. The US Coast Guard intact stability criterion for large sailing vessels was then applied to the ship in these loading conditions. It was found that the ship complies with the criterion when not overloaded but fails to comply in case of overloading.

Finally, the effects of flooding of the lower hold when the ship was departing from India were also studied. It was found that, as the lower hold would probably be filled by ballast and cargo, the effects of flooding were a 0.15m increase of the draft, but almost no change in the metacentric height and trim by the stern.

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