Naval Architecture Applied to the Reconstruction of an Early XVII Century Portuguese *Nau*

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Abstract: The Portuguese sailed yearly on the India Route during over two centuries, between the early XVI century and the XVIII century. Most ships employed in this route belonged to the *Nau* type and were among the largest and strongest ships of their time. Although extremely interesting, there is presently very little knowledge about the technical characteristics of these ships. The reason is that they were built in a pre-industrial era when technical design and documentation procedures almost did not exist. The method that is presently being applied by the authors to investigate the technical characteristics of these ancient ships combines the analysis of archaeological remains, the interpretation of contemporary texts on shipbuilding and modern Naval Architecture techniques.

The paper starts by describing the ship wreck discovered recently at the mouth of the Tagus River, known as the *Pepper Wreck*, which was identified as the Portuguese ship *Nossa Senhora dos Mártires*, lost in this place on its return voyage from Cochim, in India, on September 14, 1606. This is the first significant ship wreck of a Portuguese *Nau* comprehensively excavated and analyzed by Nautical Archeologists and in fact the resulting data made possible the study presented here. Based on the analysis of the archaeological remains and on contemporary texts, including Portuguese shipbuilding treatises, a reconstruction of the lines plan and rigging is proposed, as well as the lightweight and cargo distribution on board. The cargo spaces resulting from the reconstruction of the hull are evaluated using ancient tonnage measurement techniques and modern Naval Architecture techniques to evaluate the cargo capacity of the ship. The intact floatability and stability of the ship are also investigated and compared with a modern stability criterion appropriate for large sailing vessels.

1 *INTRODUCTION*

The Portuguese Discoveries and Expansion, from the XV to the XVII centuries, changed dramatically the world by promoting the worldwide exchange of, not only goods (initiating the global market), but also of people, knowledge, culture and ideas. The Discoveries contributed strongly to the development of the modern European values, the humanism and basically promoted the fall of the medieval principle of authority in science and philosophy.

The India Route (known in Portuguese as *Carreira da India*) was the longest commercial route of its time and the vessels that sailed it from Lisbon, Portugal, to Goa or Cochin in the Indian subcontinent, were the largest and strongest of their time. This route was sailed by Portuguese ships yearly between 1498 and the XVIII century, as recorded in the *Memoria das Armadas que de Portugal passaram a India* and *Recopilação das famosas Armadas que para a India foram(…)*, both reproduced by Reis (1990). Surprisingly, little is known of the details of the different types of ships employed in this trade and of the technical causes for the large number of ship losses reported over this long period of time. Bernardo Gomes de Brito (1735) describes many of these tragic events in his famous compilation *Historia Tragico-Marítima*, which has even become a significant text in the Portuguese literature.

Figure 1 presents a sketch of the India Route, which was opened by Vasco da Gama in 1497-1498 and during the following centuries the Portuguese ships sailed around the African continent and into the Indian Ocean, loaded with as many as eight hundred passengers and crew, and enormous quantities of precious and exotic merchandises.

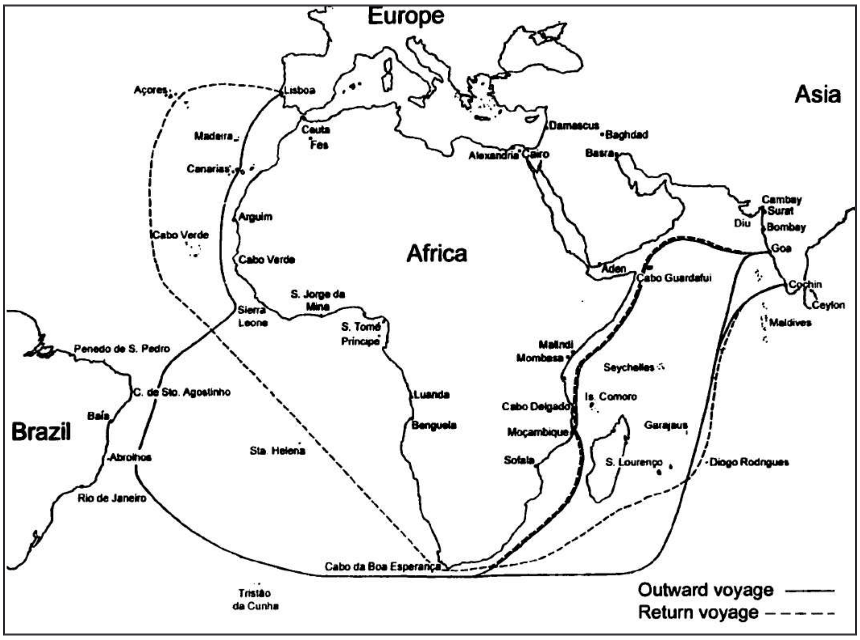

Figure 1. The India Route, Castro (2001)

Historians have studied extensively the period of the Portuguese expansion, but mainly from the humanistic point of view. In fact, there is nowadays a good knowledge of the intellectual environment in which these voyages were carried out, the artistic and architectural trends, the fashions in the dressing, etc. More technical issues have also been addressed, such as the difficulties encountered by sailors, the instruments and calculations available to estimate the ship's position at sea, and the skills of fifteenth century map makers.

However there is presently very little knowledge about the technical characteristics of the vehicles of the Portuguese expansion, meaning the ships of the Age of Discoveries. 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, detailed technical descriptions of the ships are not available and modern investigators are left with little more than contemporary drawings such as those shown in Figure 2.

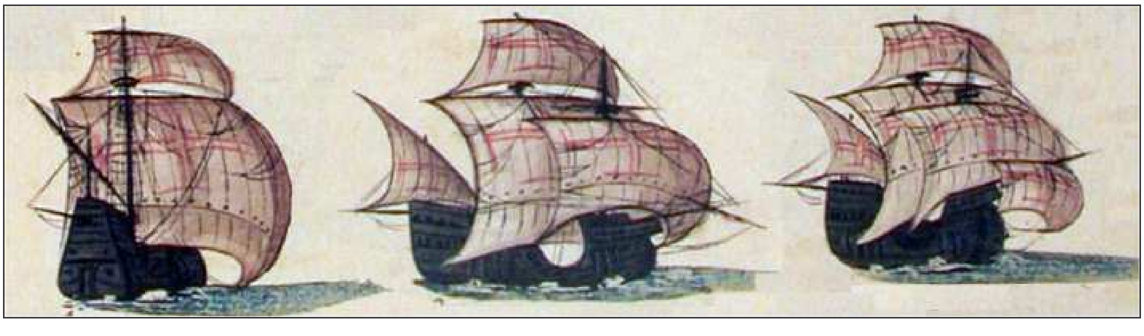

Figure 2. Contemporary drawings of *Naus*, Livro das Armadas (Reis, 1990).

The methodology which can be applied to investigate the technical characteristics of these ancient ships must be based on the analysis of archaeological remains and ancient shipbuilding treatises.

This initial investigation work has been carried out by Castro (2003, 2005b) for a shipwreck discovered in 1993 at the mouth of the river Tagus, Portugal. The shipwreck was tentatively identified as the Portuguese ship *Nossa Senhora dos Mártires*, known to be of the *Nau* type, and wrecked at this site on 1606. Its archaeological excavation between 1996 and 2000 led to a tentative reconstruction of the ship's hull form and rigging by Castro (2001). The information derived from this study is used in the present paper to analyze, from the naval architect's point of view, the floatation and stability of the *Nossa Senhora dos Mártires.* The stability results are compared with modern stability criterion applicable to large sailing vessels.

The stability analysis requires an estimation of the location of the ship's centre of gravity, which is a particularly difficult task, taking into account that there is some uncertainty regarding the ship's precise forms and dimensions, wood scantlings, amounts of cargo and passengers, provisions and artillery. The task is accomplished collecting and analyzing information from contemporary texts, including data on the ship subdivision and general arrangement, ship structure, masts and rigging, cargo distribution and people onboard. After an estimate of all of these has been made, the modeling of the ship's hull, sail plan, non-watertight openings and weight distribution can be made and the stability criteria applied.

This 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 comes in the same line of previous studies, some of which became classics in this field, such as those of Mendonça (1892), Barros (1933), Fonseca (1939) and Barata (1989). However, due to the substantial difficulties involved in interpreting the ancient shipbuilding treatises and the scarce archeological remains available up to now, little is known about the details of Portuguese ships involved in the India route traffic. This has triggered modern studies by Branco (1994), Blot (1994), Blot *et al.* (1994), Castro (2003) 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, which was the main objective of the study presented by Fonseca *et al.* (2005) and is further developed in the present study.

2 *THE SINKING OF THE NOSSA SENHORA DOS MARTIRES AND THE PEPPER WRECK*

On the 14th September 1606 a Portuguese ship of the *Nau* type named *Nossa Senhora dos Mártires* sunk off Lisbon, at the entrance of the river Tagus near the S. Julião da Barra fortress, in heavy weather. Figure 3 shows the location of the wreck near Lisbon. The ship had left from the harbour of Cochim (India) loaded with pepper and a large number of returning passengers, to complete the homebound leg of the so-called India Route.

Figure 3. Location of the *Pepper Wreck* site at the entrance of river Tagus near the S. Julião da Barra fortress.

It is known that *Nossa Senhora dos Mártires*, probably a new ship at the time, had left Lisbon on the 21st of March 1605 and arrived in Goa on the 28th September 1605. The voyage was completed in six months and one week and no special incidents were registered. After loading in Cochim, the ship departed from that harbor together with another *nau* called *Salvação* on 16th January 1606, taking on board the ceasing Vice-king of India, an indication that the ship was in good condition. This officer died aboard the ship on June 18, shortly before arriving at Terceira in the Azores Islands. The two ships delayed there for some months and finally sailed for Lisbon at the end of August or beginning of September. *Salvação* arrived in sight of Cascais on the 12th September in the middle of a severe storm. Under these conditions it was impossible to tow the ship up the river entrance and the ship laid anchor off Cascais. The next day the ship mooring broke and the ship grounded.

Nossa Senhora dos Mártires arrived to Cascais on the 13th September and also dropped anchors, but two days later the mooring cables broke and the ship's captain decided to attempt sailing up the river mouth with a low tide. On the morning of 15th September, the ship grounded on the north coast at the entrance of river Tagus, near the *São Julião da Barra* fortress (see Figure 3), while attempting to enter into the river 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 Spetember, about 200 bodies had already been washed ashore together with a large peppercorn black tide.

Archeological excavations carried out in 1994 and reported by Alves *et al.* (1998) and Filipe Castro (2005a) unveiled a large number of artifacts and ship equipment at the precise site where the *Nossa Senhora dos Mártires* is supposed to have sunk. The artifacts, some of which are shown in Figure 4, were exhibited in the Portuguese pavilion at EXPO'98, in Lisbon. The analysis of the artifacts found at the Pepper Wreck established that, most probably, they belong to the *Nossa Senhora dos Mártires*.

Figure 4. Some of the over 2000 artifacts found on the Pepper Wreck, Castro (2005).

3 *RECONSTRUCTION OF THE NAU SUNK AT THE PEPPER WRECK SITE*

The archaeological excavation of the *Pepper Wreck* site also revealed part of the ship's hull structure, shown in Figure 5, namely a portion of the bottom, including a section of the keel, an apron, eleven frames, and some of the planking extending over an area measuring 7×12m. Alves *et al.* (1998) and Castro (2005a) analyzed the hull fragment and concluded that this is the portion of the ship's bottom immediately forward of the midship frame. Thus, for the first time, a significant part of a Portuguese *Nau* dating from the early XVII century has been identified, allowing a comparison with the information contained in the ancient Portuguese treatises on shipbuilding.

Following this work, a reconstruction of the hull was proposed by Castro (2003) derived from an analysis of the timbers dimensions and carpenters' marks, helped by a collection of Iberian texts on shipbuilding from the late 16th and early 17th centuries. A number of these texts suggest explanations for both the dimensions and the shipwrights' marks found on the *Pepper Wreck* site. The first text considered was Fernando Oliveira's *Liuro da Fabrica das Naus*, dating from 1580. The second was an anonymous list of the timbers necessary to build a three-decked, 600-ton *Nau* for the India route included in the *Livro Náutico*, a codex of Lisbon's National Library, dating from the 1590s. The third was the manuscript titled *Livro Primeiro da Arquitectura Naval*, by João Baptista Lavanha, written sometime around 1610, which includes two contracts for the building of India *Naus* by two well-known shipwrights, Valentim Loureiro and Gonçalo Roiz, dating from 1598. The fourth was Manoel Fernandez' *Livro de Traças de Carpintaria*, dated to 1616.

Figure 5. Remains of the hull found at the *Pepper Wreck* site, Alves (1998).

When checked against the measurements found on the Pepper Wreck, the model proposed by Fernando Oliveira for a *Nau* of 18 rumos of keel (27,72 m) fitted well the archeological remains. The unit in Portuguese shipyards of the late 16th and early 17th centuries was the rumo (1,54 m). Once Oliveira's model was chosen for the bottom of the vessel, the preserved portions of the frames could be placed over the body plan of the lines drawing and faired. The remaining hull was then reconstructed from the list of proportions supplied by Oliveira and the resulting reconstructed lines plan is presented in Figure 6.

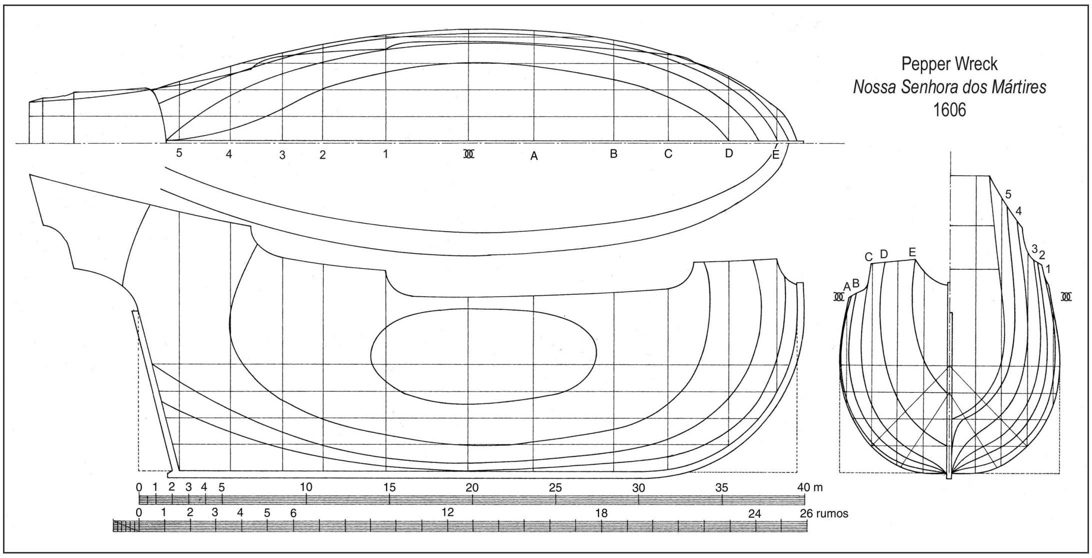

Figure 6. Reconstruction of the lines plan of the *Pepper Wreck Nau*, Castro (2003b).

Figure 7 shows a contemporary drawing of the hull of a similar Portuguese *Nau*, extracted from Manoel Fernandez *Livro de Traças de Carpintaria* (1616). It may be seen that the ship shown in Figure 6 resembles closely this ancient drawing.

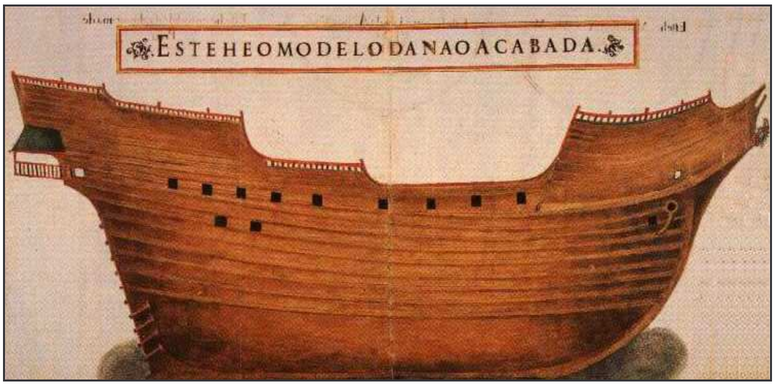

Figure 7. Hull of a Portuguese ship of the *Nau* type, Manoel Fernandez (1616).

Table 1 presents the main particulars of the vessel together with the same information for some other well-known sailing ships. It may be seen that the ship has a relatively high breadth in relation to its length.

Table 1. Main particulars of *Nossa Senhora dos Mártires* and other significant sailing vessels.

	***Nossa Senhora dos Mártires* (1606)**	***Wasa* (1628)**	***Gothemborg* (1738)**	***L'Avenir* (1908)**	***Eagle* (1936)**
Length between perpendiculars (m)	38.0	-	40.55	84.79	70.23
Breadth, extreme (m)	13.2	11.70	10.84	14.87	12.01
Moulded draught (m)	5.00	4.7	4.5	7.21	4.84
Displacement (t)	1330.0	1210.0	1213.6	5507	1731
Sail area (m^2)	1789	1275.0	1900	3000	2355
Vertical position of CG (m)	5.13	-	3.95	5.78	4.97
Metacentric height (m)	-	-	1.33	-	1.22
Ballast (t)	175 (?)	~120	400	-	-

Figure 8 shows the reconstruction of the general arrangement of the *Nossa Senhora dos Martires* according to Oliveira's treatise (Oliveira, 1580). The ship probably had three decks, a poop deck at the stern and a forecastle. According to Castro (2001), it was a 600 *toneis* vessel. The number of *toneis* represented the cargo capacity of the ship. The main dimensions of the ship are given in the sketch of Figure 8.

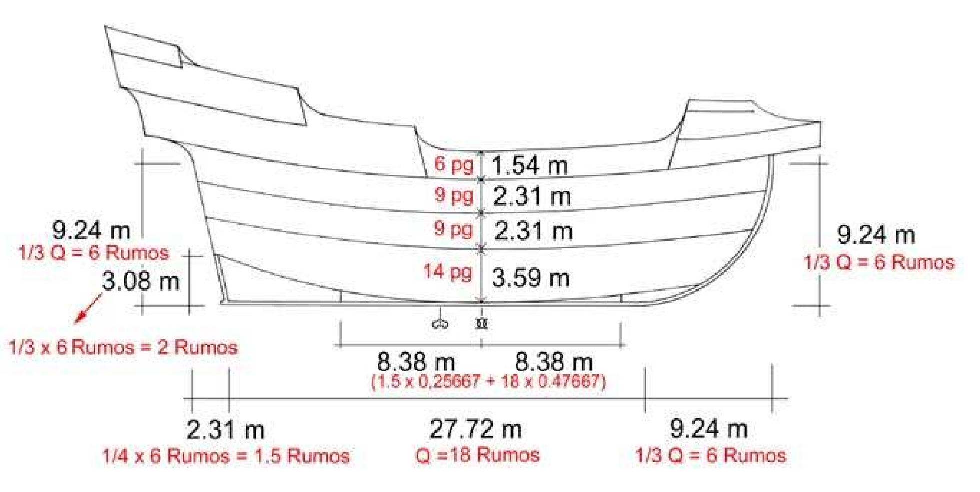

Figure 8. Reconstruction of the general arrangement of the *Pepper Wreck Nau*, Castro (2001).

Figures 9 and 10 show the reconstruction of the masts and yards of a Portuguese *Nau*, and of the corresponding sail plan. The ship has three masts and is fitted mostly with square sails, except for the mizzen mast, which holds a Latin sail. The characteristics of the masts and yards were taken by Castro (2005b) from the book of Manoel Fernandez (1616) and other contemporary texts.

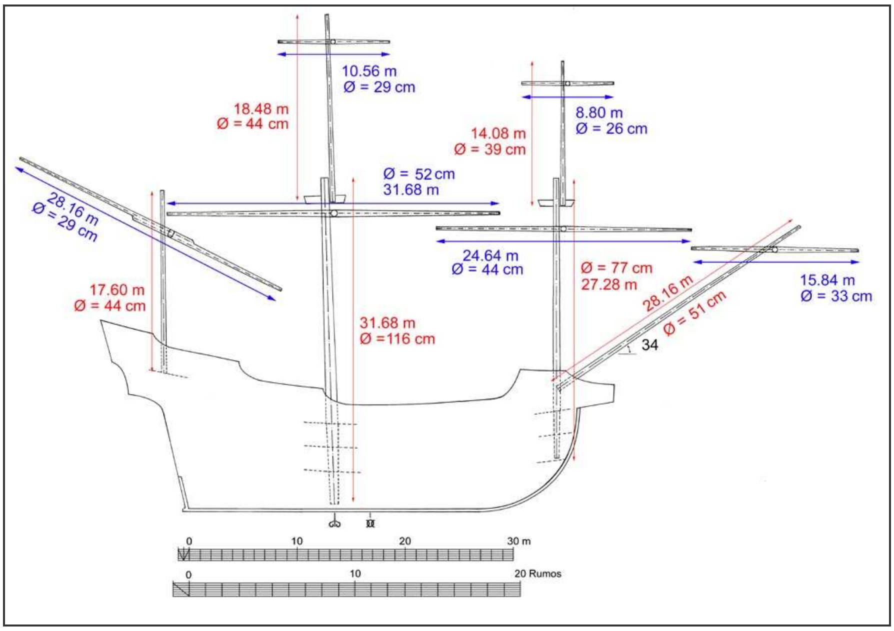

Figure 9. Reconstruction of the masts and yards of the *Pepper Wreck Nau*, Fonseca *et al.* (2005).

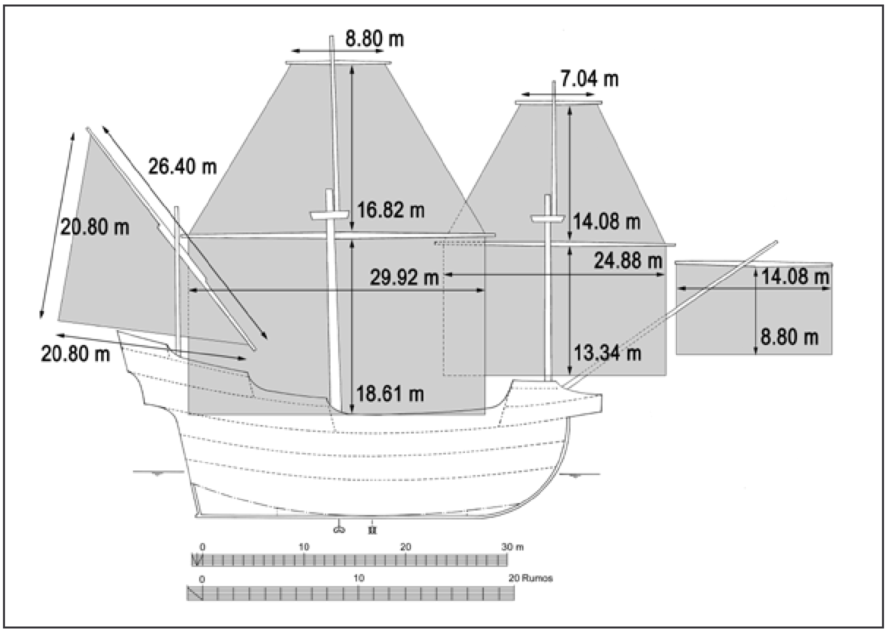

Figure 10. Reconstruction of the sail plan of the *Pepper Wreck Nau,* Fonseca *et al.* (2005).

4 *EVALUATION OF THE SHIP'S CARGO CAPACITIES*

4.1 *Cargo Capacities According with XVI Century Empirical Methods*

One of the few ways to evaluate the validity of the lines plan given in Figure 6 is to calculate the capacity of the interior spaces of the ship and estimate if the ballast, cargo and provisions that these ships were known to transport, could be carried inside the reconstructed hull. This can be made using a combination of the old Portuguese tonnage measurement techniques and modern cargo capacity calculations. This section also presents an analysis of the distribution of ballast and cargo inside the hull form and cargo spaces. Besides being an interesting exercise on its own, this analysis is necessary to estimate the position of the centre of gravity of the ballast and cargo. Additionally it is one more way of checking that the reconstructed hull represents correctly a Portuguese Nau of the late XVI and early XVII centuries.

Costa (1997) cites several XVI century documents, which describe in variable depth the empirical tonnage measurement techniques used at the time. These consisted in measuring each of the fixed decks of the ship using arcs of *tonel*, *pipa* and *quarto*. The *tonel* was a barrel with a height of one *rumo* (1.5m) and a maximum diameter of 1m, but the dimensions of the other two types of barrel are not known with certainty, although it is known that 2 *pipas* are equivalent in capacity to one *tonel*.

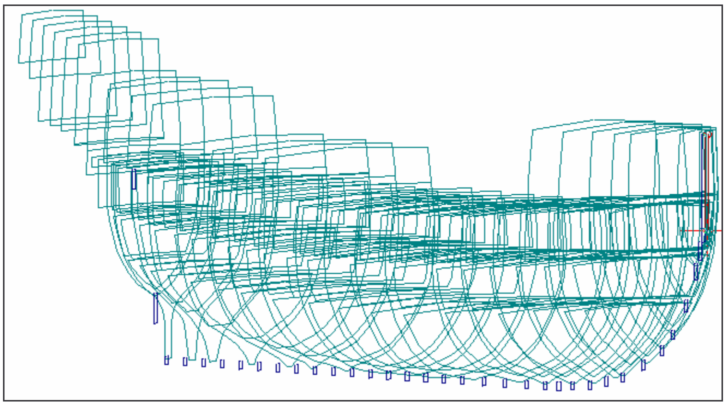

Figure 11. Model of the ship's hull and cargo spaces.

For the purpose of applying these measurement techniques, a numerical model of the ship‘s hull and decks was created, see Figure 11, allowing a “virtual” measurement of the capacity of the ship's inner spaces. Within each deck, the space was divided in transverse sections of 1.5m in length, and the net breadth of each section was measured using the arcs. The values obtained for each transverse section were then added to attain the total tonnage capacity of each deck. This procedure was then repeated for all decks and the values summed to yield a total tonnage for the ship. The capacities of the three decks were found to be those shown in Table 2 and the total tonnage is slightly higher than 600 *toneis*. If the allowance for unusable spaces is made, then a value slightly below 600 is obtained.

Table 2. Tonnage capacity of the decks of the *Pepper Wreck Nau*.

Space	**Capacity (*toneis*)**	**Area (m^2)**
Third deck	250	378
Second deck	212	319
First deck (hold)	142	216
Total	604	913

The numerical model used for this estimation takes into account the floors, frames and beams, which reduce the useful space aboard the ship. These structural elements are described in some detail in Oliveira (1580) and in the *Livro Náutico* (1590). However, it ignores pieces of the structure, masts, hatches and other un-useful areas, which are known to have been deducted from the useful cargo spaces by XVII century calculations of the tonnage capacity, at least when this tonnage measurement was carried out according with the rules used at the Lisbon shipyards, where the *Nossa Senhora dos Mártires* most probably was built. Unfortunately, these rules are only known in an indirect manner by means of texts, reproduced in Costa (1997), containing short accounts of the procedures used in Lisbon when evaluating the tonnage of specific ships. For this reason it is expected that the results presented in table 2 slightly overestimate the tonnage numbers that can found in some old documents.

Regarding the actual tonnage capacity of the XVI and XVII centuries Portuguese ships, authors such as Barata (1989) give tables which relate the length of the keel of different vessels with its capacity expressed in *toneis*. For this type of ship, with a keel length of 18 *rumos*, the indicated tonnage capacity is 600 *toneis*, a value corroborated both by Oliveira (1580) and by the shipbuilding instructions contained in the *Livro Nautico* (1590). One concludes that there is a close agreement between the tonnage estimation based on the hull reconstruction presented here and the tonnage referred in several historical documents for an 18 *rumos* of keel *Nau*. This result enhances the confidence in the body lines reconstruction and general arrangement presented in figures 6 and 8.

4.2 *Cargo Capacities Obtained by Modern Naval Architecture Methods*

Table 3 shows the cargo capacities of the three decks, modeled as above, and calculated using modern mathematical techniques, current in naval architecture. Information of this type, relative to the lower deck (hold), can be used to verify if the ballast could be easily accommodated inside the hold and to estimate the location of its centre of gravity. The same applies to the pepper cargo and to the substantial amount of water, wine and provisions carried onboard.

Table 3. Capacity of cargo spaces and centers of gravity

Space	**Volume(m^3)**	**LCG(m)**	**TCG(m)**	**VCG(m)**
Lower deck	719.2	19.88f	0.00	2.55
Middle deck	735.9	19.54f	0.00	5.23
Gun deck	881.7	19.47f	0.00	7.71

The exact amounts of ballast carried in these ships are not known, but Blot (1994) indicates that a XVIII century ship with 64 guns carried 270t of ballast. Taking into account the dimensions of that ship and the dimensions of the *Nossa Senhora dos Martires*, the ballast could be estimated, with a considerable incertitude, to amount to 154t. Castro (2001) indicates that taking into account the ballast found in the Molasses Reef and Highborn Cay wrecks (Oertling 1989a, 1989b), the ballast for this ship could be in the region of 200t. In this study, a value of 175t has been considered.

The ballast consisted, generally, of broken limestone (1.55t/m^3) and was carried directly above the keel, inside the lower hold. The 175t of ballast then take 113m^3 and would occupy the lower hold up to a height of 1.46m. The centre of gravity would be 21.2m forward of the aft perpendicular and 1.03m above the baseline. This height of the ballast allows the conclusion that a substantial portion of the lower deck was still available for cargo, with a usable free height of around 2m (after taking into account that generally a layer of wood was added on top of the rocks to smooth the surface where the cargo was to be laid).

The cargo aboard this *Nau* consisted mainly of pepper, weighting between 3000 and 5000 *quintais* (1 *quintal* equals to 58.75kg), as indicated by Castro (2005a). Costa (1997) indicates some cargo weights for ships returning from India and 4500 *quintais* (265t) is a usual cargo weight for ships of this size. The available volume in the hold above the ballast can be found to be 606m^3 and, taking into account that the pepper density can be estimated to be 0.5kg/dm^3, the volume required for the 4500 *quintais* is 530m^3. This indicates that the estimated cargo of pepper could be carried entirely in the lower hold, which is according to the loading scheme described by Falcão (1607). The centre of gravity of the pepper can be estimated to be located 19.6m forward of the aft perpendicular and 2.83m above the baseline.

These results indicate that the lines plan derived from the archeological remains and contemporary shipbuilding treatises is plausible, given that the estimated ballast and cargo can indeed be accommodated inside the hold, as prescribed in Falcão (1607).

5 *ESTIMATION OF THE LOADING CONDITIONS*

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. Furthermore, as usual, a considerable number of loading conditions are possible. In this study, the loading condition at the departure from India for the return voyage was selected because the 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 arrival condition is also considered 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. The hull of the ship, shown in Figure 8, has been estimated to weight 398t according with the hull structure description given by Castro (2001). An extensive list of components, comprising the hull planking, decks and structure, was identified together with their individual weights and positions of the centre of gravity. The various types of wood employed in the different structural elements were also considered. The hull's centre of gravity has been estimated to be located 18.0m forward of the aft perpendicular and 5.9m above the baseline.

The weight of the masts and yards has been estimated by Castro (2005b) at around 26t by calculating the volumes of wood involved in each component and considering the specific weight of the wood to be 0.52t/m^3. Taking into account the dimensions given in Figure 9, the centre of gravity of the mast and yards can be estimated to be located 20.25m forward of the aft perpendicular and 19.45m above the baseline. The weight of the sails, corresponding to the sail plan shown in Figure 10, was calculated by taking the total area of the sails (1789m^2) and multiplying it by 1.0Kg/m^2, resulting thus into 1.8t. The areas and centers of mass of the various sails are shown in Table 4. The sail plan of Figure 10 has the centre of gravity located 22.5m forward of the aft perpendicular and 24.0m above the baseline. Furthermore, two sets of sails were considered to be carried onboard, resulting in a total weight of 3.6t.

Table 4. Centre of sailing areas.

Sail	**Area (m^2)**	**Z_g(m)**
Mizzen sail	226	22.3
Main sail	325	35.0
Main topsail	557	19.0
Fore sail	332	19.0
Fore topsail	225	32.4
Spritsail	124	20.3
Total	1789	24.0

The rigging of the ship was estimated to weight 5t, as a rough estimate. The location of its centre of gravity is obviously very difficult to find, so it was assumed that it is located at the same location that the centre of gravity of the sails. The anchors carried by a ship of this type are, according with the documents presented by Domingues (2004), 4 anchors weighting 17 *quintais* each and 4 anchors weighting 16 *quintais* each, with a total weight of 7.8t. The corresponding anchor lines weighted approximately 10.2t. Both these weights were usually carried inside the forecastle and were assumed to be located at 36.5m from the aft perpendicular and 9.5m above the baseline. The ship also carried two small boats called *batel* and *esquife* weighting around 10t. These were assumed to be located at the centre of the main deck, between the two castles, 24.0m from the aft perpendicular and 8.5m above the baseline.

The artillery carried in this ship is not known, but Domingues (2004) presents several documents detailing the artillery carried by the *Nau* type of ship, which is given in Table 5. The artillery was subdivided into 21 heavy weapons and 16 light weapons, with a total estimated weight of 34.9t. Ships of the galleon type were generally better armed, but *Nossa Senhora dos Mártires* was a merchant ship.

Table 5. Artillery of a 600 *toneis Nau*.

Type	**Weight (quintais)**	**Z_g(m)**
1 camelo	30	6.9
12 esperas	25	6.9
8 pedreiros	13	6.9
10 falcões	7.5	9.5
6 berços	1.8	9.5
Total	519.8	

Note: One *quintal* is equivalent to 58.75Kg.

The ammunitions for these weapons can be estimated to weight 3t and the gunpowder carried onboard weights approximately 0.5t. The 21 large guns, one of which is shown in Figure 12, were located in the main deck, with the aggregated centre of gravity located at 20.0m forward and 6.90 above the keel, while the lighter guns were carried in the main and upper decks, 20.0m forward and 9.5m above the baseline.

Figure 12. One of the guns of the *Pepper Wreck Nau*.

Castro (2001) estimates that this ship could be carrying a crew of 150 men and 230 soldiers. Furthermore, 75 passengers could also be onboard. Each men of the crew or soldier could weight 60Kg and carry a baggage weighting 20Kg. The passengers could carry 100Kg each and weighted the same as the crewmembers. The total weight of the crew, soldiers and passengers (plus their baggage) is then 42.4t. The passengers made the voyage in the poop deck, quarterdeck and some of their baggage in the main deck. The centre of gravity of them and their baggage can be estimated to be located 8.0m forward and 9.3m above the baseline. The crew and their baggage were located in the lower deck, 17.0m forward and 4.6m above the baseline. The soldiers made the voyage in the main deck (gun deck), with a centre of gravity 17.0m forward and 6.9m above the baseline.

Table 6. Summary of Loading Condition (departure from India)

	Weight(t)	Lcg(m)	Vcg(m)
Hull	398.0	18	5.9
Masts and yards	26.0	20.25	19.45
Sails	3.6	22.5	24
Rigging	5.0	22.5	24
Anchors	18.0	36.5	9.5
Boat	10.0	24	8.5
Light Artillery	12.9	20	9.5
Heavy Artillery	25.5	20	6.9
Ballast	175.0	21.2	1.03
Cargo	265.0	19.6	2.68
Crew	14.4	17	4.6
Soldiers	21.0	17	6.9
Passengers	7.0	8	9.3
Water/Wine	186.0	21	4.75
Biscuit	106.0	20	7.1
Other supplies	58.0	20	7.1
Total:	**1331.4**	**19.75**	**5.13**

Table 7. Summary of Loading Condition (arrival at Lisbon).

	Weight(t)	Lcg(m)	Vcg(m)
Hull	398.0	18	5.9
Masts and yards	26.0	20.25	19.45
Sails	3.6	22.5	24
Rigging	5.0	22.5	24
Anchors	18.0	36.5	9.5
Boat	10.0	24	8.5
Light Artillery	12.9	20	9.5
Heavy Artillery	25.5	20	6.9
Ballast	175.0	21.2	1.03
Cargo	265.0	19.6	2.83
Crew	14.4	17	4.6
Soldiers	21.0	17	6.9
Passengers	7.0	8	9.3
Water/Wine	18.6	21	4.75
Biscuit	10.6	20	7.1
Other supplies	5.8	20	7.1
Total:	**1016.4**	**19.5**	**4.94**

The supplies carried onboard for six months of navigation comprised mainly water, wine and biscuits. It is assumed that each person on board consumed 1.8 liters of water a day, resulting in a total of 146t of water. Regarding the wine, the average consumption was 0.5 liters a day, resulting in a weight of 40t. The biscuit was consumed at a rate of 1.3Kg per person each day, requiring a total of 106t. These three items (292t) where supplemented by many other less significant items, in an estimated total of 350t. The water and wine (186t) were carried in the lower deck, 21.0m forward of the aft perpendicular and 4.8m above the baseline. Since the capacity of this space was found to be 212 *toneis*, whose capacity ranges between 1050 and 1250 liters, it can be seen that the water and wine would occupy 177 *toneis*, in the worst case, so these could all be in the lower deck. The biscuit was probably carried in the main deck, 20.0m forward of the aft perpendicular and 7.1m above the baseline. These are average values obtained taking into consideration the distribution scheme outlined in Falcão (1607). Tables 6 and 7 summarize the estimated loading condition when departing from India (100% consumables) and at the arrival in Lisbon (10% consumables).

Figure 13 shows graphically the weight distribution expressed in percentage of the total displacement at the departure from India. The largest weight is the hull, with approximately 30% of the total displacement, followed by the cargo (pepper) with 20%, the water and wine with 14% and ballast with 13%. These four weights amount to 77% of the ship's displacement. Therefore, the floatation and stability characteristics of the ship are very sensitive to changes in any of these weights and the respective centers of gravity.

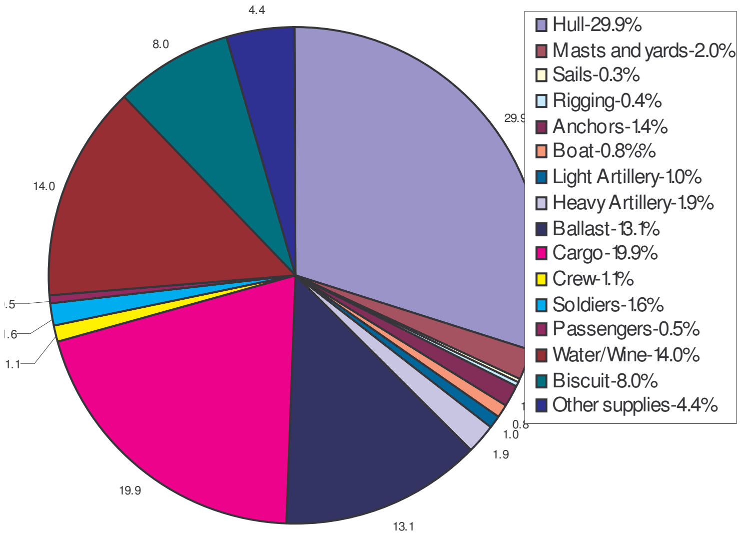

Figure 13. Weight distribution analysis for loading condition at the departure from India.

6 *FLOATATION AND STABILITY ANALYSIS*

6.1 *Floatation and Stability Characteristics in Still Water*

For the hydrostatic calculations the planking thickness (11cm) was taken into consideration when defining the hull sections. The large forecastle and the three-decked aft superstructure are clearly visible but were not considered watertight. The calculations show that the ship, for the loading condition shown in Table 6, which corresponds to the departure from Cochin, would float with a draft amidships of 5.0m and an aft trim of 0.50m. This gives the ship a freeboard up to the gun deck amidships of around 1.1m and 3.6m of m up to the main deck. For this draught and loading condition, the ship's metacentric height would then be 1.0m.

Considering the condition upon arrival in Lisbon, which corresponds to only 10% of supplies left, as shown in Table 7, the ship would have a draft amidships of 4.21m and a trim by the stern of

0.94m. In this condition, the metacentric height would be 1.13m, the freeboard up to the gun deck would be 1.9m and 4.4m up to the main deck.

Figure 14 shows the ship’s hydrostatic properties. It may be seen that both the centre of buoyancy and centre of floatation are located slightly forward of midship (midship is located 19m forward of aft perpendicular). Cross curves of stability and curves of form were also calculated. The ship has a block coefficient of 0.54 for a displacement of 1331.4t and 0.51 for a displacement of 1016.4t.

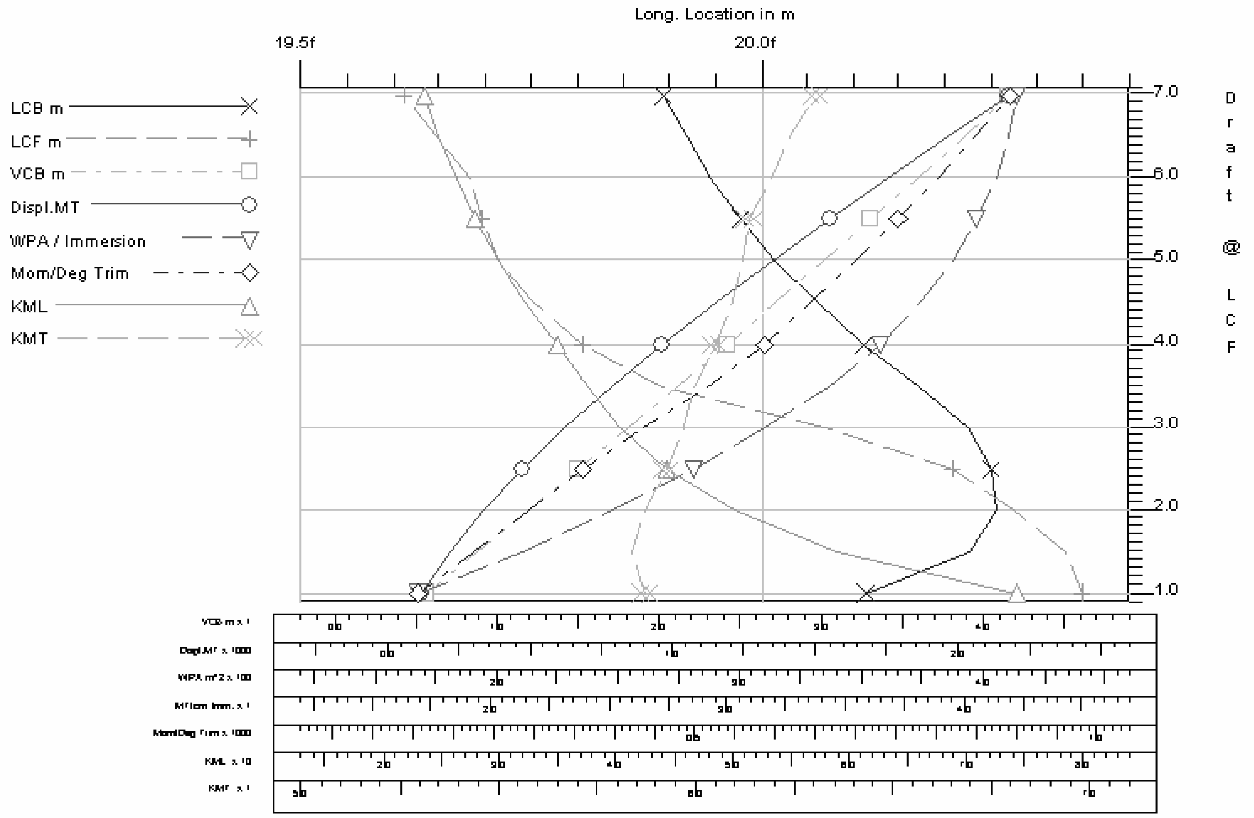

Figure 14. Hydrostatic properties of the *Pepper Wreck Nau*.

Figure 15 shows the righting lever curves for the *Nossa Senhora dos Mártires* in both loading conditions. Also shown are the righting lever curves for the large sailing vessels *Gotheborg* and *Eagle*.

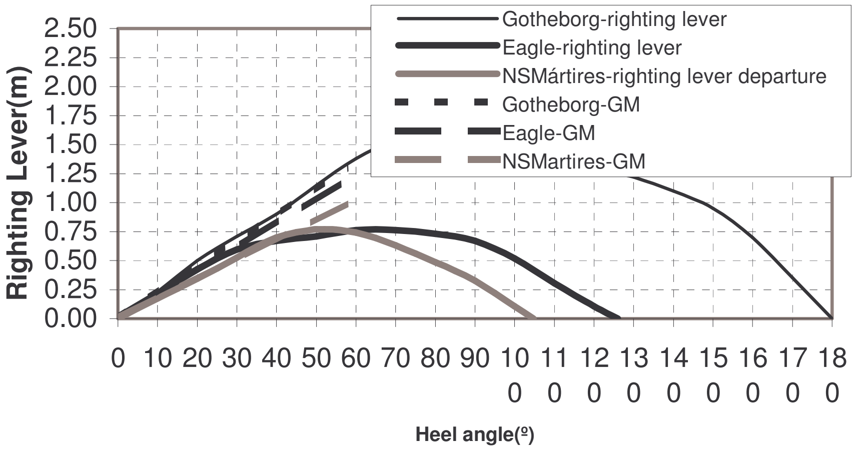

Figure 15. Righting lever curves for different ships including the *Nossa Senhora dos Mártires*.

Figure 16 shows the righting lever curves for both loading conditions of the *Nossa Senhora dos Mártires* considering or not the gun deck watertight. It is possible to see that the righting levers and ranges of stability are much smaller if the gun deck in not considered watertight. It is also possible to conclude that the ship's stability improves as the consumables decrease because these are located mainly in the mid deck and gun deck.

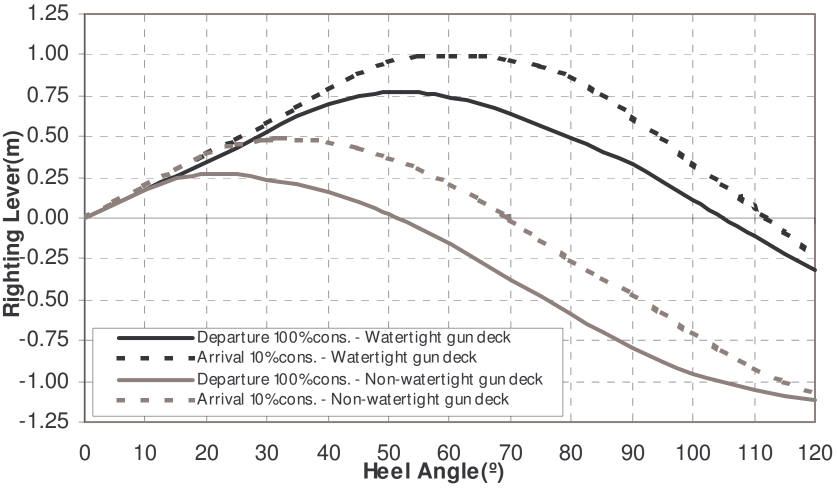

Figure 16. Righting lever curves for the different loading conditions with and without a watertight gun deck.

6.2 *Stability Characteristics in Waves*

The stability characteristics of the ship in the presence of a wave are now studied in order to evaluate the reduction or increase of the metacentric height in the presence of a longitudinal wave, a situation which probably occurred when the ship attempted to enter river Tagus in the morning of 15th September 1606. This situation is known to reduce or increase significantly the ship's stability. The height of the sinusoidal wave considered in this study is 5m and the wavelength is 38m (equal to the ship's length). This is a very steep wave in the limit of breaking condition. The loading conditions are those given in Tables 6 and 7.

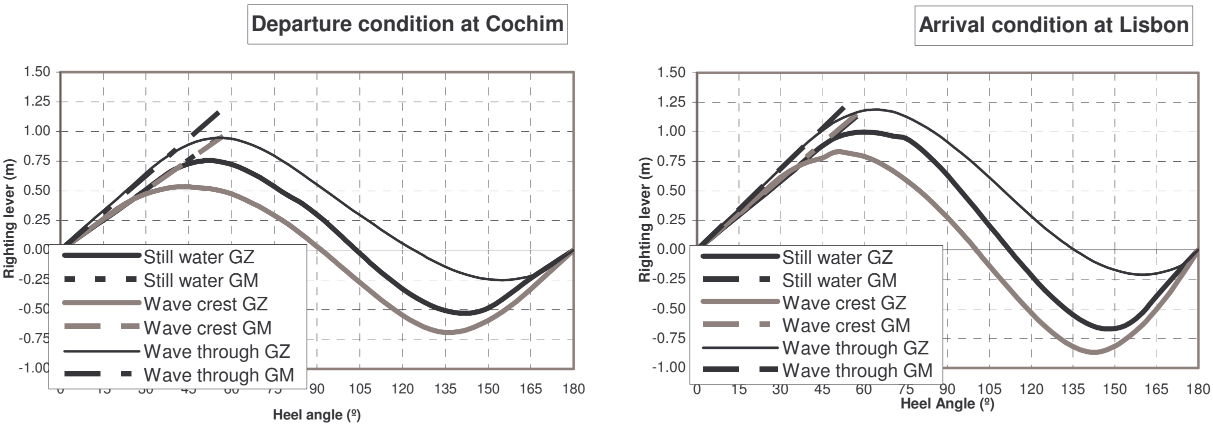

Figure 17. Righting arm curves in still water, wave crest and wave through for both loading conditions.

Figure 17 shows the righting arm curves for this ship without wave, with a wave crest located amidships and with a wave through located amidships. It can be seen that the righting arms increase for large angles of stability when the wave through is located amidships and decrease when the wave crest is located amidships, as generally occurs in modern ships. The metacentric height does not show very large variations with the location of the wave crest amidships: the still water GM is 0.97m and with the wave crest amidships the GM is 0.96m. However, with the wave through amidships the GM increases significantly to 1.19m. This indicates that the righting arms at small angles are not affected by the presence of the wave crest but rise significantly when the wave though is amidships. Figure 20 also shows the righting arm curves for the loading condition at the arrival at Lisbon. It can be seen that the righting arms and range of stability are generally larger than in the previous case but, otherwise, the trends are the same.

Similar calculations have been made for a trochoid wave having the same characteristics of the sinusoid wave above, leading to similar conclusions regarding the stability of the ship. The only difference is that the changes in metacentric height and righting levers are slightly more pronounced. From these results it is possible to conclude that the presence of a longitudinal wave, probably similar to those *Nossa Senhora dos Mártires* encountered when the accident occurred, do not degrade significantly the stability of the vessel. Thus this was not probably the cause of the ship wreck.

6.3 *Intact Stability Assessment using a Modern Criterion*

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. Their knowledge was largely empirical and qualitative. Therefore, 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 established a criterion contained in the Code of Federal Regulations (1983), 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:

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

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:

$$HZ_a = \frac{GZ_c}{\cos^2\theta_c} \qquad HZ_b(or \quad HZ_c) = \frac{I}{((\theta_v/2) + 14{,}3.\sin 2\theta_v)}$$

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:

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

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. Figure 18 shows the righting arm and energy curves for the ship in the loading conditions specified in Tables 6 and 7. The angles of extinction are 104º and 112º, clearly above the minimum required angle of extinction of 90º.

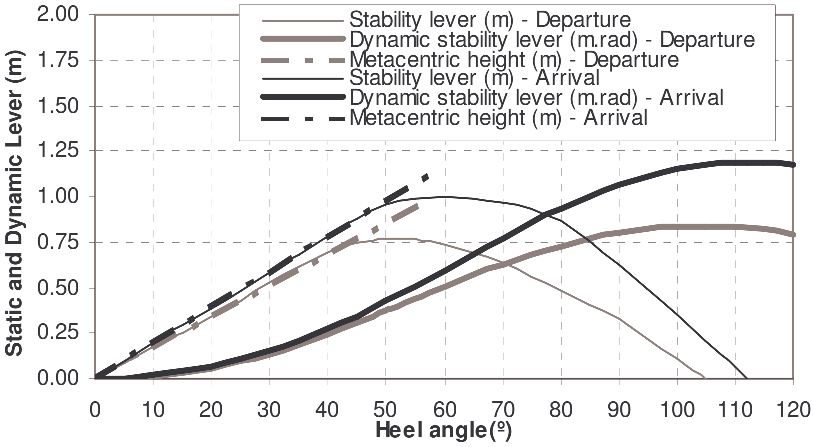

Figure 18. Righting lever curves for *Pepper Wreck Nau*.

The ship numerals can now be calculated and are given in Table 8. 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).

Table 8. Numerals and angles of extinction for different 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

6.4 *Qualitative Assessment of the Possible Causes of the Pepper Wreck*

The *Nossa Senhora dos Mártires* was lost in the morning of 15th September, due to grounding on the north shore of the river Tagus mouth. This occurred while attempting to enter into the river, during a southerly storm, thus in heavy following or stern quartering wind and seas and, possibly, against a strong tidal current. The entrance of the river is reduced by two large submerged sand banks over which the large waves often increase in height dangerously and break. The ship was probably overwhelmed by the sea, lost her headway and was pushed to the rocks bordering the north shore of the narrow river entrance. 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.

The draft of the ship was not excessive since it might have been only 4.6m at the aft extreme, assuming that the ship was not taking water on board. This indicates that the ship most probably did not ground in the middle of the river entrance due to the low tide. The most probable cause for the accident is that the stern waves caused the ship to loose directional stability and broach, pushing her to the north shore. It is possible that the ship during the broaching might have started taking water by unsecured openings. The calculations shown above indicate that the ship's metacentric height was not significantly decreased by the presence of large waves, indicating that the ship was not especially susceptible to capsize caused by loss of transverse stability.

This is what can be said regarding the causes of the ship's loss. Further studies of the ship's characteristics and sailing performance are expected to cast some light on the possible cause for these unfortunate events.

7 *CONCLUSIONS*

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

A reconstruction of the hull form of this ship is presented based in the archaeological remains and in ancient Portuguese shipbuilding treatises. The structure of the ship was studied and the hull weight estimated. It was found that the weight of the ship hull is around 400t, which is approximately 30% of the total displacement. This weight was determined by summation of the hull's component weights. The reconstruction of the general arrangement and rigging, together with data from contemporary texts on the loading of this type of ships, allowed an approximate evaluation of the other weights aboard, obtaining finally a displacement of 1333t at the departure from India and 1016t at the arrival in Lisbon. These displacements give the ship plausible draughts, indicating that the reconstructed hull form is approximately correct.

The cargo capacities of the interior spaces of the ship were evaluated using both the ancient Portuguese tonnage measurement techniques and modern mathematical methods. Using the tonnage measurement technique, it was found that the tonnage of the ship was approximately 600 *toneis*, a result in very close agreement with the value given in contemporary shipbuilding texts. The capacity calculations for the same hull form using modern Naval Architecture methods and taking into account the floors, frames and beams, which all reduce the cargo capacity, indicate that the pepper cargo (4500 *quintais*) could be stowed in the hold, over the ballast. These calculations were also used to estimate the location of the centre of gravity of these weights.

The ship's stability in two loading conditions was also calculated and compared with other ships. The righting arm curves were also studied for the ship in the crest and in the through of a wave having the length of the ship and a height of 5m. It was found that the ship does not loose its small angle stability when in the crest, but is considerably more stable at small angles with the through amidships. However, at large angles, in the crest, righting arms are reduced, while in the opposite case, the righting arms increase significantly. Therefore, for large angles, this is in line with the behaviour of most modern ships. For the same loading conditions, the righting arm and energy curves are presented and the US Coast Guard intact stability criterion for large sailing vessels is applied to this ship. Under the assumption of watertightness up to the main deck, implying watertightness of the gun holes, the ship complies with the modern criterion, leading to the general conclusion that this ship had good stability characteristics.

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