Advanced Materials Research Vols. 133-134 (2010) pp 295-300

doi:10.4028/www.scientific.net/AMR.133-134.295

Numerical Assessment of the Ebe Schooner-Brig

INVERNIZZI Stefano[1, a], BERTOLINI-CESTARI Clara[2,b] and CHIABRERA Emanuele[3,c]

[1] DISTR, Politecnico di Torino, Torino, Italy

[2] DIPRADI, Politecnico di Torino, Torino, Italy

[3] Faculty of Architecture 2, Politecnico di Torino, Torino, Italy

[a]stefano.invernizzi@polito.it, [b]clara.bertolini@polito.it, [c]emanuele.chiabrera@tiscali.it

Abstract The Ebe schooner-brig was built in 1921 and sailed the Mediterranean's sea for almost forty years, before being dissected into ninety parts to be transported in Milan (Italy). There, the schooner was reassembled and the naval pavilion of the National Museum of Science and Technology was built up all around the ship. After forty years in the museum, the ship presents significant deformations of both the deck and the keel, particularly in correspondence of the external supports. Despite several interventions in the past and a recent restoration, the deformation phenomenon is still worrying, and the understanding of the real cause is lacking from many aspects. Experts have already advanced some hypotheses, often in opposition to one another, and unfortunately, a continuous monitoring of the ship deformation has not been started yet. In the present paper, the schooner structure is modeled with the commercial finite element code Diana, considering a two-dimensional model of the ship cross-section. The obtained results allow for a deeper understanding of the stress-strain field in the schooner, providing a first safety assessment and useful hints for the design of the monitoring and future interventions.

Keywords: Finite element method, cultural heritage, wooden schooner-brig

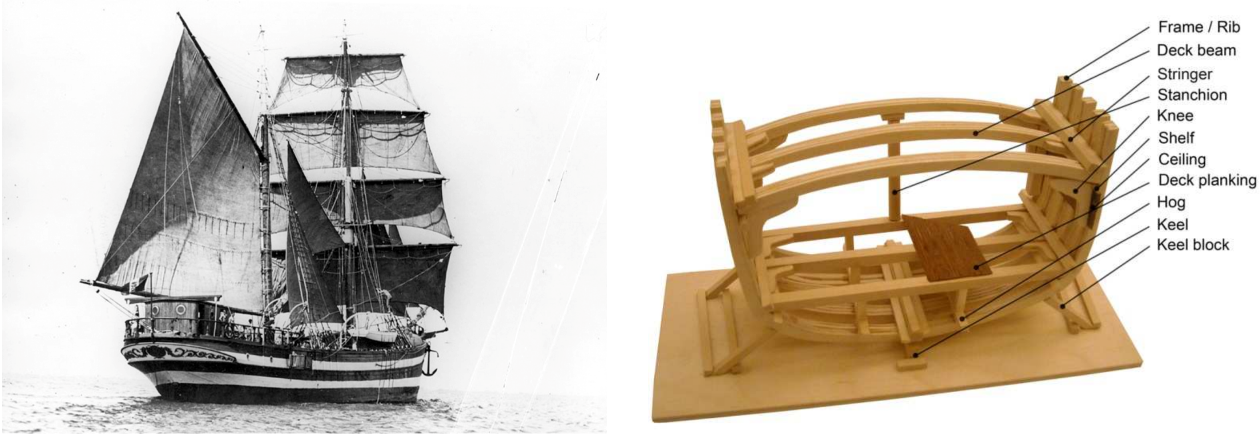
Introduction

The naval pavilion of the National Museum of Science and Technology Leonardo da Vinci in Milan was inaugurated on 12 April 1964, with the permanent exhibition of the ship Ebe. The Ebe is a schooner-brig built in the Viareggio shipyards in 1921. After almost forty years of navigation in the Mediterranean Sea it was dissected into ninety portions, in the port of La Spezia. Afterwards, it was transported to Milan and reassembled in the pavilion, which, at that time, was still under construction. After forty-five years in museum the ship presents significant deformation of the bridge and of the hull in correspondence of the topsides of the keel blocks (elements devoted to support the weight of the ship when it is in the basin or in dry). Despite several interventions in the past and a recent restoration the deformation phenomenon is still worrying, and the understanding of the real cause is lacking from many aspects. Unfortunately, up to now the ship is still not under monitoring, so there are no data available about the eventual worsening of the deformations. Experts have already advanced some hypotheses, often in opposition to one another. Some identify the cause of large deformations in the malfunction of the mechanical joints with which the hull was reassembled due to the withdrawal of the wood elements following the variation of moisture content (Fioravanti 2009). Others are convinced that rheological phenomena may have affected the wood in his long stay at the museum (Bertolini-Cestari 2009). In addition, the weight of the mast, of the forward, and of after parts may be at the origin of high stress concentration zones, in combination to the change of loading and constrain conditions. Other scientists have attributed the cause of these phenomena to the combination of some of these factors, while, until now, the inadequacy of keel blocks has not been considered enough. Nowadays, there is a growing consciousness that a monitoring plan is necessary to base a definitive program of interventions, regardless all the different opinions and the resulting uncoordinated actions. However, it is appropriate to have a clear picture of the static condition of the

ship prior to proceed with the monitoring. Therefore, we developed an extensive finite element model of the hull. This approach helps to define the monitoring plan with greater efficiency, optimizing the placement and minimizing the number of measuring points. In perspective, the understanding of the experimental results will be facilitated, and the assessment of the impact on the structure of certain intervention will be more robust.

The Ebe Schooner-Brig

The Ship Structure The ship Ebe is a schooner- brig with wooden hull (Fig.1). In order to have a clear picture of the structure, a scaled model was realized, which is represented in Fig. 2.



(a) (b)

Figure 1: The Ebe schooner-brig sailing (a); Wooden scaled model of the Ebe ship structure (b)

The model allows identifying each individual element that composes the structure. The definition of each structural element size, is not an easy task, in fact a direct measure is not possible for the hidden elements of the hull, as this would involve the removal of planking or other parts. Therefore, the information about hidden parts was derived from the geometrical rules of RINA (Cafiero 1952), re-designing the ship from beginning. In addition, some information were collected from the Navy survey performed during the works at the Arsenal of the Navy of La Maddalena (Italy), before being transformed into a training ship (Arsenale 1951). Table 1 give the dimensions of some structural elements of the Ebe ship obtained with the above procedure. The results are also compared with the corresponding data measured in a recent survey (Ceresa et al. 2008), of the external and internal shapes of the hull.

Table 1: Put your caption here

Elements	*Survey*	*RINA*	*Deviations*
	cm	*cm*	*cm*
Deck beams	20.5x20.5	21.5x21.5	≈ 1
Keel*	26.4	27.6	≈ 1
Keel hog*	35.9	33.1	≈ 3
*d***	16.5	16	≈ 0.5

* Width.

** Net distance between frame ribs.

Three main transverse section types can be recognized along the Ebe hull, which alternate proceeding fore and aft. The first kind is the simple cross section, which is characterized by having no additional elements. The second type is the cross sections with knee linking ribs with deck beams. The third kind is the cross sections with reinforced ribs and knee linking ribs with deck beams. The current scheme of sections of the ship is fatherly complicated by the discontinuous presence of side stanchions. The connection between ribs and deck beams is guaranteed by the presence of horizontal knee, while the wooden connections between the ribs and the lower deck beams are nowadays

missing, although, it is likely that these elements were present in the origin. These wooden connections were substituted by steel joining elements connected with bolts, which efficiency, as shown in the following, is very limited. In order to understand the actual present behavior of the structure, it is important to account for the reconnections and additions that were put in place at the time of the translation in the museum in correspondence of the cuts. The hull, as mentioned above, was cut into ninety parts by means of longitudinal and transverse cutting planes. The parts were then reconnected, during the reassembly operations, with steel elements bolted to the internal structure. Subsequently, the outer hull planking was restored. From a structural point of view, the main effect of the disconnections is to decrease the stiffness provided by the hull planking. The longitudinal cuts are more dangerous, respect to the transverse ones, since they cross the bearing elements of the hull, i.e. the deck beams and ribs. All the disconnections were reconnected with insufficient steel elements, joined by bolts to the hull, whose effectiveness appears nowadays to be quite limited. This is probably the reason of the presence of the lateral stanchions that were put in place. The efficiency of the steel connection can be considered vanishing, from a mechanical point of view. Therefore, internal hinge connections are adopted in the model.

The lower beams alone, due to their poor connection to the ribs, cannot prevent liability, if none of the stanchions are present, hence this scheme cannot be considered in the two-dimensional analysis. Even the keel blocks, being below the first cut, are not able to prevent the movement.

In the cross sections where only the central stanchion is present, the two halves of the ship behave according to the statically determined scheme of a three-hinged arch. This scheme can be considered for a two-dimensional analysis, in addition to the three and five stanchion configurations. The wooden models of Figure 2 clearly show the above-mentioned observations.

(a)

47%	oak *(Quercus petraea)*.
37%	pine *(Pinus pinea)*.
13%	pitch-pine *(Pitch pines)*.
1%	elm *(Ulmus)*.
1%	alder *(Alnus)*.
1%	douglas *(Pseudotsuga taxifolia)*.

(b)

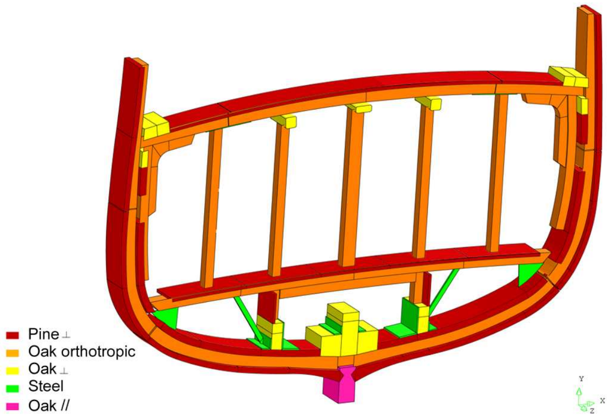
Figure 2: Wooden models: effect of the stanchions and collapse mechanism (a;. Relative presence of different species (b)

Materials Once that the geometry of the structural elements of the hull was assigned, it is necessary to identify the materials adopted for the different parts. The identification was performed by Fioravanti (Fioravanti 2009). The hull of the Ebe schooner-brig is composed as reported in Fig. 2b. More in details, the main structural elements (keel, deck beams, ribs, stanchions) are made of oak, while all the planking is made of pine. Other secondary connecting elements, like knees or forefoots, are made of elm, alder or douglas. The masts and the boom are mainly made of spruce *(Picea abies)*. Yardarms are made of douglas *(Pseudotsuga taxifolia)*. Finally, connecting elements are of oak *(Quercus petraea)* and of elm *(Ulmus)*.

The Finite Element Model

The two-dimensional plane-stress FEM model was built to estimate the local stresses and to assess the mechanical behavior in the presence of the cuts (Fig. 3a). The plane stress hypothesis was adopted due

to the presence of transverse cuts, which prevent the development of sensible longitudinal stresses. In correspondence of the structural cuts, interface elements were inserted in order to account for the unilateral behavior. The depth of the two-dimensional scheme was approximately equal to 0.51 m, which is equal to the rib spacing. The results of two different cross sections will be presented, where three or five stanchions are present. As far as the mechanical properties of materials is concerned, the wood should be considered as a hyper elastic transversely orthotropic material, which depends on the four parameters E_0, E_{90}, $\upsilon_{90,0}$, and G. Given the two-dimensional nature of the model, an isotropic simplified assumption can be adopted, assigning to all the structural elements with the fibers orthogonal to the model plane a Young's module equal to E_{90}. Fig. 3b lists the mechanical properties adopted for the two-dimensional FEM model.



(a)

Material	E_0	E_{90}	G	$\nu_{90,0}$	*Density**
	MPa	MPa	MPa		Kg/m^3
Oak	10000	600	625	0,03	950
Pine	9500	570	594	0,03	850
Steel	210000			0.3	7800

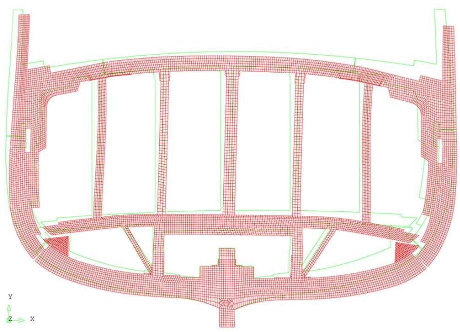
* Moisture content 12%

(b)

Figure 3: Extruded view of the cross section and materials assignment (a;. Mechanical properties adopted for the two-dimensional model (b)

In absence of better determination, the adopted Young's modules are quite low, to account for the little knowledge of the material and the state of conservation. For the same reason, the density at 12% moisture content is slightly overestimated.

Setions with Five Stanchions Interface elements are placed in correspondence of the cuts, characterized by unbounded strength in compression and vanishing tensile strength. The most regularly spaced ad well connected steel junction elements, added during the reassembling operations of the ship, were included in the model. Fig. 3a shows the resulting elastic deformation of a central section of the hull.

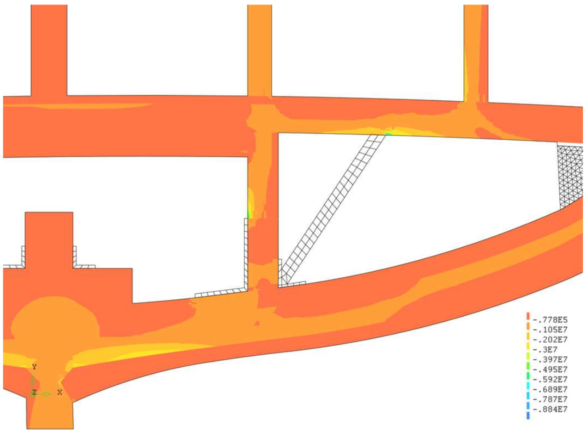


(a)

(b)

Figure 4: Elastic deformation of the section of the hull (a) and the opening mechanism of the plank (b)

The asymmetry of the hull results in non symmetric deformations, which are amplified by the fact that the two-dimensional model neglects the longitudinal constrain provided by the planking curvature and by the keel blocks. Therefore, the keel appears to be subjected to a dangerous bending perpendicular to the wood fibers. It is worth noting that thanks to the support provided by the lateral stanchions, the steel plate junction in correspondence of the deck beams cuts are compressed. On the contrary, an opening mechanism at the extrados is presents. The cuts in the lower region of the ribs open outwards. This mechanism is clearly recognized in Fig. 4b, which shows the opening of the planks. Fig. 4a shows that the stresses accumulate in the lower deck beam, which bears the weight of the frame-floor and of the upper deck, transmitted by the stanchions. The level of stresses, presented by Fig. 5b, is comparable to that of a fully loaded ship in calm water (Chiabrera 2009). In other words, the transverse stresses of the hull without loads in dry cannot be disregarded. The maximum displacements of stanchions and steel reinforcements are not reported since meaningless, due to the prevalent rigid motion component.



(a)

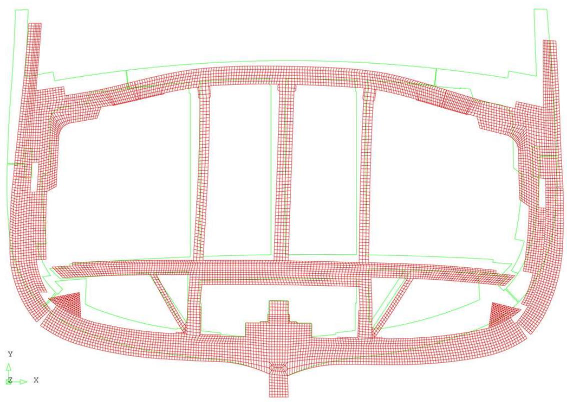
Structural element	σ_{1MAX} MPa	σ_{2MAX} MPa	η_{MAX} cm
Ribs	3.53	-2.75	0.89
Lower deck beam	3.54	-5.12	0.83
Upper deck beam	0.19	-0.11	0.68
Stanchions*	≈ 0	-0.15	
Steel	32.0	-46.7	

* Mean values.

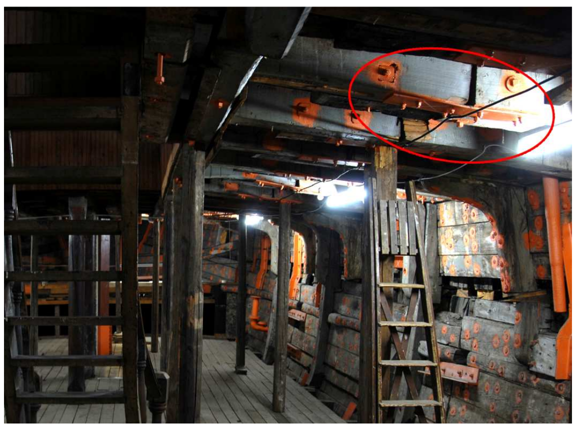
(b)

Figure 5: Principal tensile stress σ_2 in the lower deck beam (a); Five stanchions section: maximum principal stresses and displacements of the main structural elements of the hull (b)

Sections with Three Stanchions A section of the ship, with three stanchions is considered. The cuts and connections are modeled as in the previous case. The elastic deformed shape of a cross section is shown in Fig. 5a. Contrarily to the five stanchions cross-section case, the deck beams are not supported by the lateral stanchions. Therefore, the upper cuts open downward due to the bending stresses, and the steel plates carry the tensile tractions. This phenomenon has been recognized experimentally (Fig. 6b), and in some case the steel plate is even yielded.



(a)



(b)

Figure 6: Elastic deformed shape of the section with three stanchions (a); Deformation of the cut section of the upper deck beam, detail of the yielded steel plate (b)

The opening mechanism of the lower cuts in correspondence of the ribs, responsible for the phenomenon already shown in Fig. 3b, is also accentuated. The magnitude of stress in the lower deck beam decreases, compared to what is found for the sections with five stanchions. On the other hand, the stress is highly increased in the upper deck beam, especially near the cuts where up to 7 MPa can be reached. Therefore, the experimental behavior shown in Fig. 5b, takes place even more likely.

It is worth noting that the results obtained above are sensibly influenced by the efficiency of the joint between lower beams and ribs. Those connections were realized in an unsuitable way, since the deformation mechanism is such that the bolts are actually pulled from the wood, rather than being subjected to prevalent shear. The numerical model emphasizes that these joints are subjected to high tensile stresses. Therefore, due to the high degradation of wood in the proximity of the joint and its poor of connection to the original structure, an opening mechanism takes place and the magnitude of displacements sensibly increases.

Conclusions

A numerical model of the Ebe schooner-brig at the naval pavilion of the National Museum of Science and Technology in Milan (Italy) has been presented. The model allows for a detailed description of the main features of the structure, included the damage pattern and the fields of stress, strain and displacement. The results do not provide particular warning about the safety of the structure, although the level of stress cannot be disregarded. The obtained results can help to define the monitoring plan with greater efficiency, optimizing the placement and minimizing the number of measuring points. In perspective, the understanding of the experimental results will be facilitated, and the assessment of the impact on the structure of certain intervention will be more robust.

Acknowledgements

The contributions of Prof. Franca Ceresa and Prof. Marco Fioravanti, as well as the kind collaboration of the National Museum of Science and Technology Leonardo da Vinci in Milan (Itlay) is gratefully acknowledged.

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