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The main results presented are the influence of the position of the transverse structural elements in the thickness of the hull and in the structural weight, establishing recommendations for optimum structural design.

One among the objectives to this study is to present semi-empirical regressions to estimate weight and vertical position of the center of gravity in function of the design variables. This information is very important to engineers, especially in the early stages of the conceptual design.

3. THE STRUCTURAL DESIGN

The difference between a planing hull and a displacement hull is the balance of the weight and the static buoyancy. The first one balances the weight with static buoyancy plus a dynamic lift that results from the interaction between sea and the hull when enough propulsion power is supplied. So, this type of boat is designed to take off and glide on top of the water, reducing the drag.

The difference between the two hulls is also observed in Froude's number. A planing hull presents a high value while a displacement hull presents a low/medium value. Higher Froude numbers requires a greater installed power to surpass the resistance from the wave formed on the bow.

3.1 Bibliographical references

The objective is to understand the hydrodynamic pressure that solicits the structure along the hull's length and consequently determination of the dimensions of the structural elements: shells and stiffeners.

The classical work of Savitsky (1964) is a very important reference to understand the overall design of planing hulls, especially about the resistance and seakeeping of prismatic hulls, with no special attention to the structural aspects. However, he proposes a first estimative the dynamic forces along the length of the hull.

To take off and achieve the planing condition, the hull must have a flat bottom. However, a flat bottom causes a very high vertical movement with great accelerations, due to the slamming pressure of the waves over the hull. To decrease this impact, most speedboats have a V-shape bottom, cutting through the waves. The excessive V-shape value diminishes the longitudinal stability of the hull, making it very uncomfortable and even hazardous. Generally, speedboats have a sharp entry close of the bow for a smooth vertical movement and becoming progressively flatter aft; creating an efficient surface that generates lift and has good longitudinal stability.

So, the lift acts mainly on the hull bottom, mostly at aft and permits to take off the boat achieving the planing condition. The planing condition reduces the static forces on the structure because there is less hull surface in the water. However, the main force that solicits the structure is the slamming of the waves, which is not constant through the time.

The slamming force is resulted from the impacts of the hull on waves and is called "slamming pressure" in Savitsky's works. As mentioned, slamming pressure depends of the V-shape angle, called deadrise angle and the velocity of the vessel. The slamming pressure is the main generator of stress in the bottom material, thus it determines the dimensions of the structural design.

3.2 Technical visits to shipyards

Three visits to shipyards were made with the purpose to observe how the structural arrangement is designed and constructed.

During the first visit, a hull without decks was analyzed, which permitted to measure the main structural elements of the hull. In the others visits, technical aspects of the construction and material proprieties was analyzed.

The bottom is made out of single skin laminated. It means that it is exclusively made of layers of woven and loose fiberglass held together by epoxy resin. The sides are made out of sandwich structure. It is a polymeric foam core with two slim fiberglass laminates on each side. The foam core reduces weight and still has shear stress resistance. This technique of construction is only used on the sides, given that this part of the vessel does not suffer much with hydrodynamic forces.

The structural grid is composed by frames and stiffeners. Both have about the same depth, making it hard to classify them as heavy girders or light stiffeners. Some parts of the structural grid have its depth slightly cut out to accommodate the vessel engine, equipment or even the deck. These components are manufactured as the bottom, but with smaller thickness: the layers of fiber glass are molded into foam parallelepipeds, forming an inverted U-shape, with the open side attached to the bottom.

Lastly, the bulkheads are manufactured as the sides, but with slimmer laminates.

An example of the structural arrangement of a high speed boat built in composite material is shown in Fig.1.

Figure 1. Structural arrangement of high speed boat built with composite material (Garcia, 2010).

In the second and third visits, the construction or "lamination" of the hull was observed. The process used is called "infusion". This process starts with the setting of woven and loose fiberglass layers without the resin over the mold. Then, a plastic film covers the layers forming a wrapped hull. An air compressor is used to decrease the air pressure inside the wrap, resulting in a relative vacuum. The resin and a catalyst agent are mixed in a barrel and connected to the wrap by flexible ducts. The low pressure inside forces the yet liquid mix to spread throughout the layers until all the fiber is drenched in resin. The curing process of the resin is an exothermic reaction that heats up, which is monitored with a laser thermometer. The lamination of the vessel's sides is made the same way, but in this case there is a foam core between two fiberglass laminates.

The last step is the construction of the frames and stiffeners. These are made in a more handcrafted manner: the builders put the foam molds on the hull's bottom and then start interlaying fiberglass and the resin. After the curing, the hull achieves structural continuity thanks to the resin that bonds all the elements together.

The infusion method has some disadvantages over the handcrafted method: a long time of preparation, a big volume of resin and the necessity to use an air compressor. Despite all that, the quality of the outcome of this process is much higher due to the lack of air bubbles in the material. The traditional method leaves some air pockets that decrease the resistance properties of the material.

After the lamination, the dimensions of the structural arrangement were measured. The main dimensions are the spacing and spans of the structural elements.

4. TECHNICAL RULES STUDY AND ANALISYS OF THE 42 FEET HULL CASE

In this section is presented the results of the case analyzed. In the Table 1 are listed the main characteristics of the hull analyzed.

Table 1. Characteristic of the hull analyzed.

Characteristic	**Symbol**	**Value**
Length	L	12,4 m
Maximum speed	V	31knots
Maximum breadth in water line	Bwl2	3,4 m
Displacement	Δ	15,5 ton

At this stage, the "DNV Rules for Classification of High Speed, Light Craft and Naval Surface Craft" were studied; specifically the chapters regarding the design loads (Part 3, Chap 1) and the structural design (Part 3, Chap 4). The methodology used was to apply the formulation proposed by (DNV, 2012) to calculate the loads along the length of the hull and calculate the dimensions of the structural elements.

To retrieve the geometrical information of the hull, the software Friendship was used. A 3D model of the 42 feet hull (Fig. 2) was modeled and analyzed. With this model, all the dimensions (lengths, breadths and angles) were measured. The operation conditions of the vessel, such as the draft, maximum speed and the material rupture tension was estimate based in the literature.

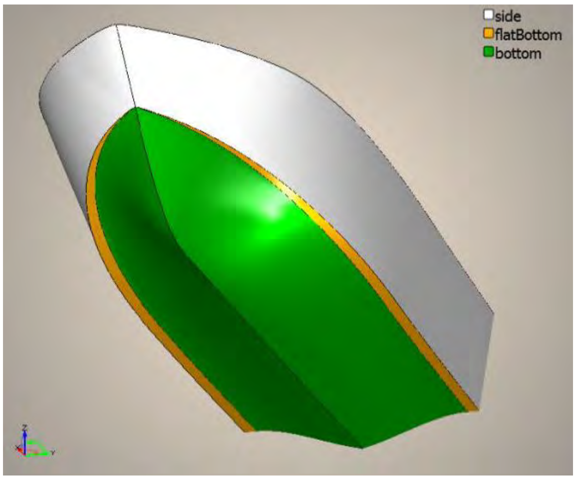

Figure 2. The CAD model built in FriendShip software to retrieve the geometrical information of the hull analyzed.

4.1 Vertical acceleration

The design loads analysis starts with the determination of the vertical acceleration along the length of the hull. The vertical acceleration is a result from the impact of the vessel on the sea waves, causing it to accelerate upwards for a short time. This impact's force is denominated as "slamming pressure" by the rules and other authors.

On Part 3, Chapter1, Section 2 of the rules there is formula B201. This formula gives the design vertical acceleration at the craft's center of gravity. It says that the vertical acceleration should not be taken less than:

$$a_{cg} = \frac{V}{\sqrt{L}} \frac{3.2}{L^{0.76}} f_g g_0 \qquad (1)$$

Where a_{cg} is the vertical acceleration at center of gravity in m/s²; $V/\sqrt{L}$ is a quotient used throughout the rules, being V the maximum operation speed in knots and L is the length at waterline in meters; f_g is an acceleration factor depending on the type of vessel, being 1 for passenger vessels; g_0 is the acceleration of gravity in m/s².

The equation B202 transports this acceleration to the other parts of the vessel:

$$a_v = k_v a_{cg} \qquad (2)$$

Where a_v is the vertical acceleration along the length of the hull and k_v is a factor given by a graphic in the rules that makes possible to calculate the acceleration on places other than the center of gravity.

The acceleration was calculated with Eq.(1) and applied on Eq.(2) using the maximum operational speed is 31 knots, length is 12.4 m and acceleration of gravity is 9.81 m/s². The results are shown in Figure 3.

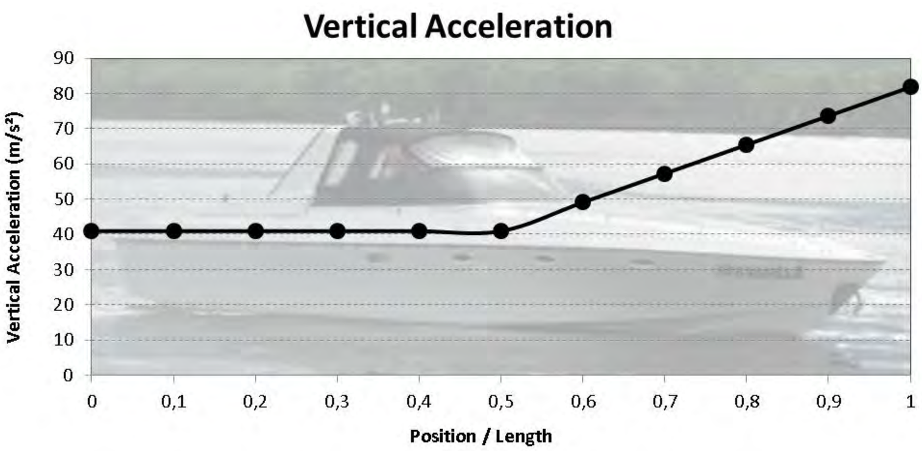

Figure 3. Graphic of vertical acceleration versus length

The horizontal axis of the graphics shown here represents the non-dimensional length of the vessel, being 0 the stern and 1 the bow. In this graphic there can be observed an amplification of the vertical acceleration at the bow.

The Section 2B also has important formulae regarding the significant wave height. There is an allowable operational speed given the significant wave height that the vessels bow is slamming on. The higher the wave, the slower the craft could to move overwater. The purpose is to reduce the risk of structural fail caused by impact. Nowadays, some speedboats and yachts have a force gage at the vessel's bow that emits a sound warning if the speed is too high for the waves that the hull is facing. There are two formulae relating velocity and wave height, each one for a different speed zone. The Eq.(3) if applied for $V/\sqrt{L} \geq 3$ and the Eq.(4) for the other cases:

$$a_{cg} = \frac{k_h g_o}{1650}\left(\frac{H_S}{B_{WL2}} + 0.084\right)\left(50 - \beta_{cg}\right)\left(\frac{V}{\sqrt{L}}\right)^2 \frac{L \cdot B_{WL2}^{\ 2}}{\Delta} \quad (3)$$

$$a_{cg} = 6\frac{H_S}{L}\left(0.85 + 0.35\frac{V}{\sqrt{L}}\right) g_o \quad (4)$$

Where: H_S is the height of the significant wave in meters; β_{cg} is the deadrise angle at the center of gravity; B_{WL2} is the waterline breadth at amidships in meters; Δ is the displacement in tons; k_h is the hull type factor equal to 1 in monohulls.

Using the result of Eq.(1), a relation between the speed and wave height is achieved. The geometrical and operational information used was: B_{WL2} = 3.4m; β_{cg} = 19.3°; Δ = 15.5 ton.

The result for a 31 knot speed is a significant wave height of 0.78m. For example, when the speed decreases to 15 knots, the same hull is allowed to make way through 1.91m waves.

4.2 Design pressures

The only forces considerate in the analyze are described in Part 3, Chapter 1, Section 3 of the technical rules, that makes a clear statement that hull girder loads are not to be considered in vessels with L/D less than 12 and with length less than 50 m. That is the 42 feet hull case, so global stress is not taken in consideration. The rules state that, for these vessels, the "minimum strength standard is normally satisfied for scantlings obtained from local strength requirements".

The design pressure for the bottom and side is the greater of the hydrostatic pressure, slamming pressure, or the fore end slamming pressure. The chapter makes possible to calculate all kinds of pressure and the greater one for the bottom is the slamming pressure, meanwhile the greater for the sides is the hydrostatic. There is a formula that gives equivalent hydrostatic pressure for plating above waterline. The slamming pressure is given also on Section 2, formula C201:

$$P_{sl} = 1.3 k_l \left(\frac{\Delta}{nA}\right)^{0.3} T_O^{\ 0.7} \frac{50 - \beta_x}{50 - \beta_{cg}} a_{cg} \quad (5)$$

Where: P_{sl} is the slamming pressure in kN/m²; n is the number of hulls, in this case, 1; A is the design load area, approximated by 0.1L * (local breadth); T_o is the draft at rest at amidships; β_x is the local deadrise angle; k_l is a longitudinal distribution factor given by the rule in a graphic. The entry data used was T_o=0.85m. The angles and areas vary along the length. The results were plotted in Fig. 3.

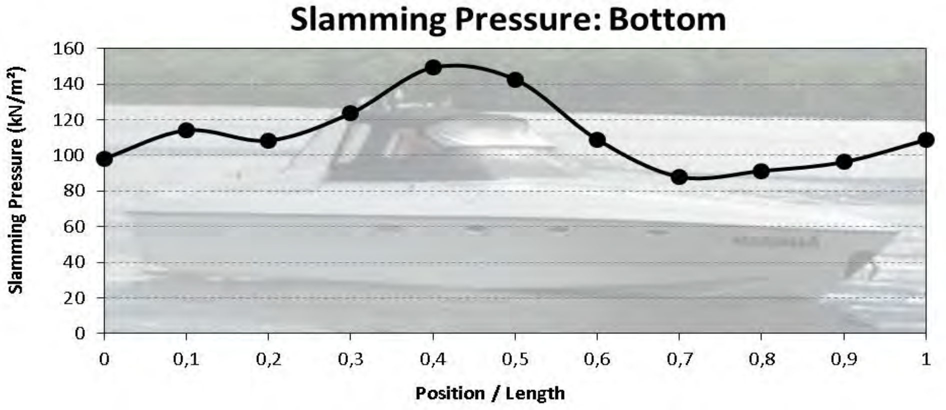

Figure 4. Graphic of slamming pressure on bottom versus length

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The slamming pressure has intermediary intensity at the stern due to lower k_l values. The logic is that the impact on the waves does not happen mostly at the stern. The bow has low intensity because of the sharp V-angle at this position, making the hull cut through the waves. This is represented by high deadrise values. The intensity at amidships is high because that is where the hull suffer most impacts, due to its positive pitch during operation. The flatter surface also causes the pressure to be higher at this zone.

Concerning the design pressure for the sides, the rules also give formulae to calculate slamming and hydrostatic pressures. However, the hydrostatic pressure is higher than the slamming on the sides. For load points above waterline, there is an equation that gives an equivalent pressure on C501:

$$p = 10 h_0 + \left(k_s - 1.5 \frac{h_0}{T} \right) C_W \tag{6}$$

For load points below waterline:

$$p = a \cdot k_s \left(C_W - 0.67 h_0 \right) \tag{7}$$

Where: p is the sea pressure in kN/m²; h_0 is the distance from the chine to the waterline in meters, having a different values along the length; k_s is a longitudinal distribution factor given by the rules; T is the draft in meters; C_W is the wave coefficient calculated in other part of the rules; a is a factor, being 1 for the sides.

The entry data used was the one obtained by the 3D model and the results were plotted in Fig. 4.

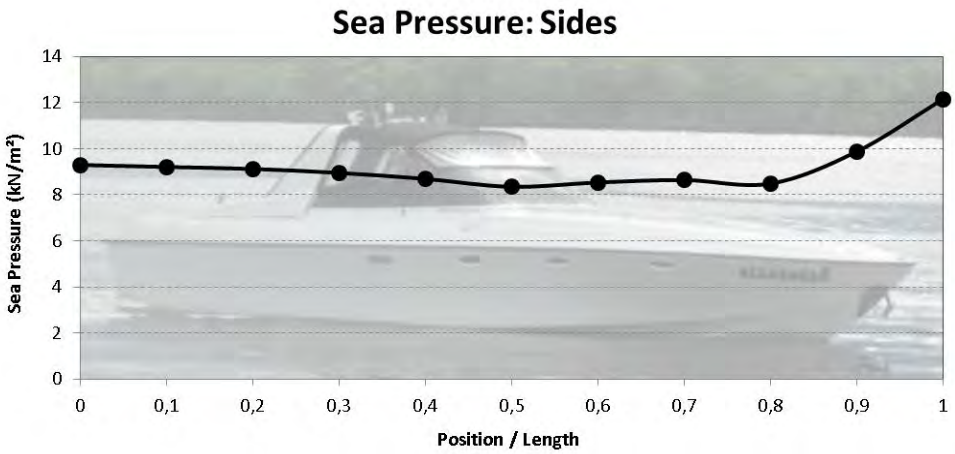

Figure 4. Graphic of slamming pressure versus length

4.3 Structural design – Plating thickness definition

The design pressures calculated make possible to determine the hull's plating thickness. The formulae given in Part 3, Chapter 4, Section 6 is related to the single skin construction. This means that the plating does not have a core material different from the exterior material. These calculations demand the knowledge of the fiberglass plus resin properties. The information obtained is shown in Table 2:

Table 2. Material properties used in 42 feet hull's construction.

	Fiberglass	Epoxy resin
Rupture Stress	122.5 MPa	-
Density	2600 kg/m³	1300 kg/m³
Percentage in mass	50%	50%
Poisson's coefficient	0.3	-

Section 6 of this chapter contains formula C202 that relates the ultimate allowed stress with the plating thickness. The rules state that, for this kind of vessel, the ultimate stress is equal to 0.3 times the rupture stress, so the number used is 36.75 MPa.

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$$\sigma = C_3 \cdot 1000 \frac{b^2}{t^2} p \qquad (8)$$

Where: σ is the ultimate tensile stress; t is the thickness in mm; b is the width of the structural panel that was measured on the 42 feet hull, it varies along the length; p is the design local pressure calculated; C_3 is a factor that concerns the panel edge condition given by the rules, in this case is used the "partial edge fixity".

The equation was manipulated so the thickness is determined given the tensile stress and the width of the panels. The results were plotted in Fig. 5.

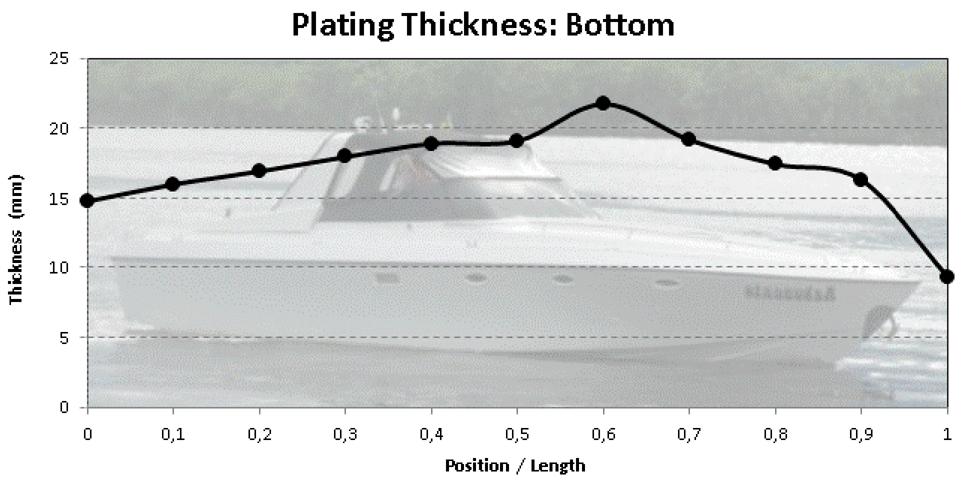

Figure 5. Graphic of bottom thickness versus length

The required thickness is higher around amidships, since this area suffers most from the slamming pressure.

Section 5 of this chapter contains formulae to determine the sandwich panels thickness. Such type of structure is used on the sides of the hull. It requires the section modulus W, that is equal to d times t on simmetrical structures, being d the thickness of the core material and t the regular fiberglass plating thickness. The formula given is:

$$\sigma = \frac{160 p b^2}{W} C_N C_1 \qquad (9)$$

Where C_N and C_1 are factors regarding panel edge condition. In this case, the number used is the one related to partial edge fixity. C_N calculation depends on the Poisson's coefficient obtained from literature.

The equation was manipulated to relate tensile stress and thickness and the results are shown in Fig. 6. It is important to highlight that the thickness showed in Fig. 6 is of just one side. The sandwich structure is made of two plating.

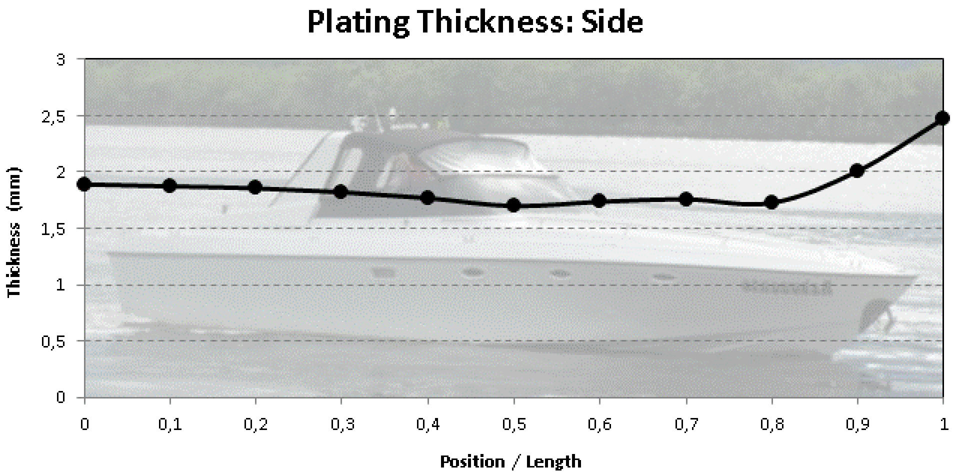

Figure 6. Graphic of side plating thickness versus length

4.4 Structural design – Stiffeners and frames dimensions

The last components of the structural design are the frames and stiffeners. These are beam elements allocated at the bottom of the hull. The sides don't have stiffening elements. The section of these elements has an inverted U-shape, with its opening attached to the bottom.

The rules do not give formulae that give the dimensions right away. On Part 3, Chapter 4, Section 7 there are formulae that makes possible to calculate a required section modulus. So, with the help of the spreadsheet, the dimensions are acquired given the thickness of the stiffeners plating. A catalog of stiffeners sections was made so the spreadsheet could look up the modulus that most approximates the required.

Firstly, the bending moment to the members subjected to pressure loads must be calculated by formula given in B201:

$$M = \frac{pbl^2}{c_1} \tag{10}$$

Where: b is the load area, meaning the spacing between frames or stiffeners; l is the beam's span; c_1 is a factor related to the analysis on the ends or mid-span of the beam. The analysis is made at the ends, where c_1=12.

The next step is the determination of the required section modulus. The formula is at B601 in this same chapter. The tensile stress present in the equation is the ultimate allowed stress, already calculated for the determination of plating thickness. The section modulus Z is determined by:

$$Z = \frac{M}{\sigma} \tag{11}$$

All stiffeners sections on the catalog have their area moment of inertia calculated given a specific thickness. A thickness of 15mm was chosen, because it is close to the bottom thickness average. The area moment divided by the height of the neutral axis gives the calculated section modulus. The results are shown on Fig. 7 and Fig. 8.

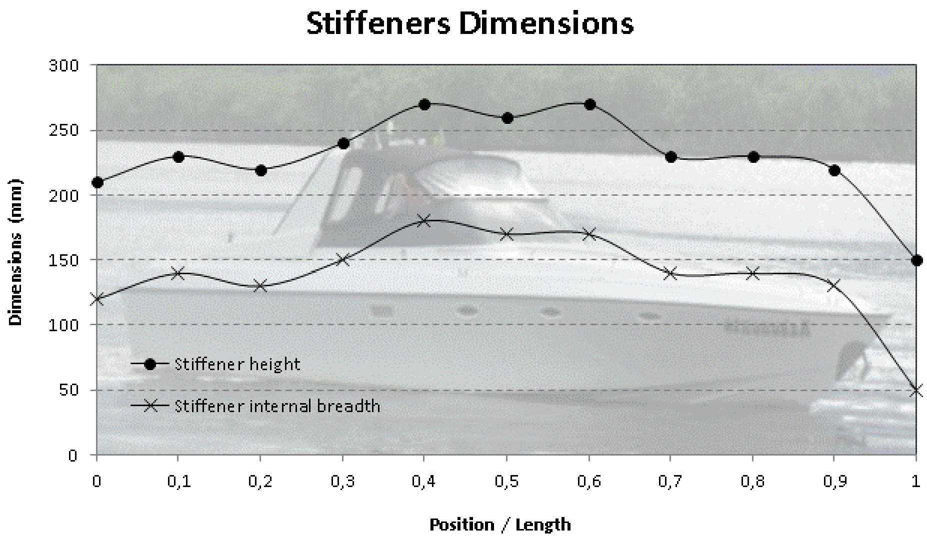

Figure 7. Graphic of longitudinal stiffener dimensions versus length

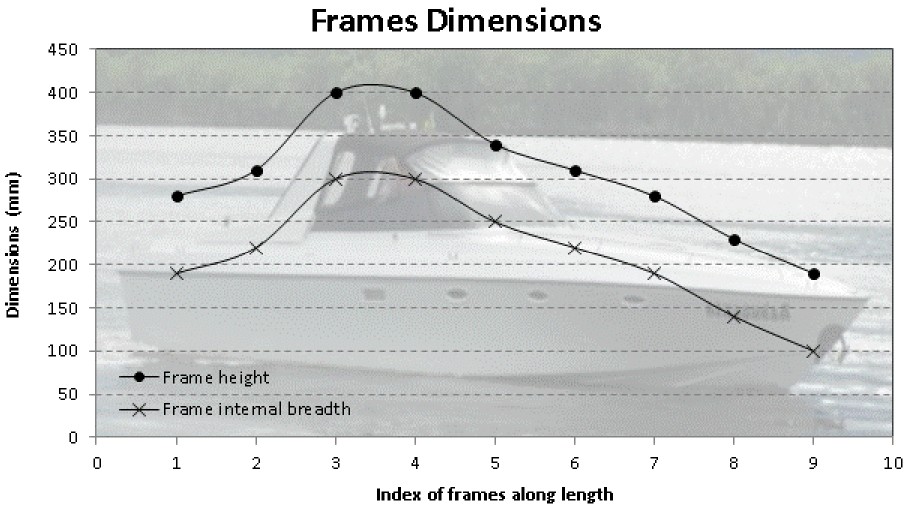

Figure 8. Graphic of the dimensions of the frames versus frame position. There are 9 frames in the 42 feet hull

As noticed, the larger stiffeners are the ones at amidships, where the slamming pressure is higher.

5. OPTIMIZATION OF STRUCTURAL DESIGN

5.1 Structural design variables

The main structural design variables are the distances between frames and stiffeners. It was considered 9 frames and 4 stiffeners and it is important to highlight that the length of the last panel is a dependent variable that result of the subtraction of sum of all panels (including the stiffeners' thickness) from the ship's dimension.

The original structural arrangement of the 42 feet hull analyzed is shown in Fig. 9.

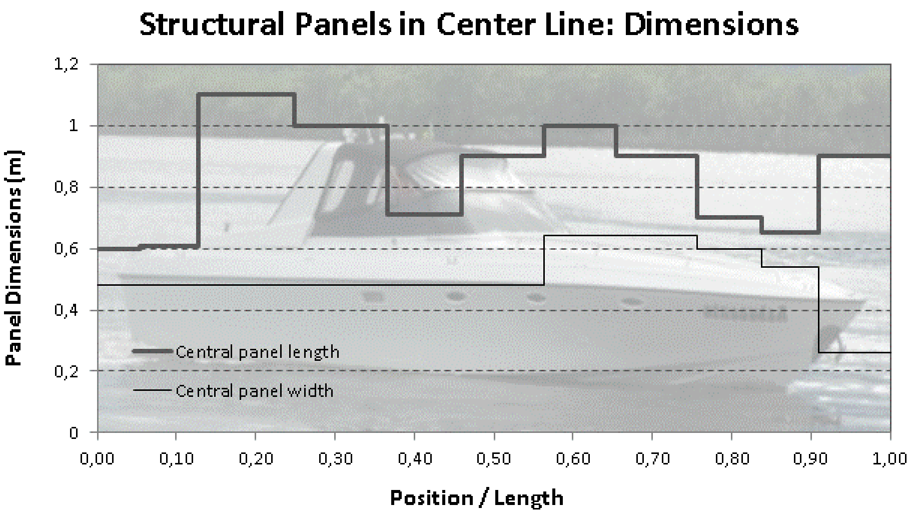

Figure 9. The original structural arrangement of panels in center line of the 42 feet hull

5.2 Structural mass and vertical center of gravity estimation

With all the dimensions of structural design calculated and with the geometrical information of the hull, an estimation of mass and VCG (Vertical center of gravity) position is possible. The dimensions are used to calculate the volume along the vessel's length. With the specific mass of the material is possible to calculate the structural mass along the length. The VCG position estimate was made with the locals deadrise angles. The VCG position was estimated on each subdivision of the hull and then a weighted average was made to estimate the VCG position of the entire vessel.

The structural mass of the case analyzed was estimated in 2225 kg. The information of the literature said that the plain hull, without engine, decks and accommodations weights about 2 tons. So, the estimate gets close to the real value. The VCG position estimate was 0.49 m from the keel line. A comparison with reality was not possible because there is no information available in the literature.

5.3 Statistic study

Firstly, it was done a correlation study between mass and VCG position with the panel lengths. The algorithm used was the Sobol. The difference between Random and Sobol algorithms is that the latter tries to achieve a wide spread of design variables.

Each design arrangement propose by Sobol algorithm is evaluate by the model propose and the results are used in correlation study. Since the panels length are being analyzed, the restriction was that the sum of panel lengths can't be too far from the original 42 feet. So a tolerance of plus or less 0.5 m from the original 12.8 m (42ft) was applied.

The results of correlation with panel lengths are shown in Fig. 10.

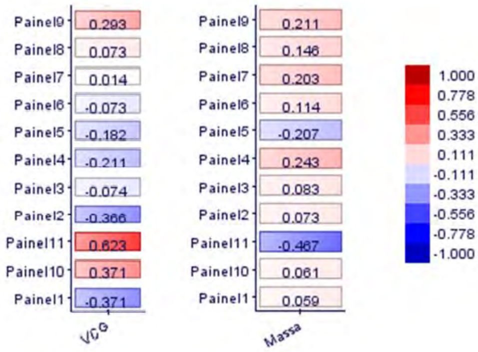

Figure 10. Correlation analyzed with modeFrontier between Mass / VCG position with panel lengths

The VCG position has a higher positive correlation with the panels at the bow, the ones that have a sharp deadrise angle. This happens because the higher the angle, logically, the higher the center of gravity. Flatter panels have almost no correlation.

The structural mass has a higher negative correlation with the bow's panel length. Since this panel is not subjected to such high pressures, its thickness is low. So, larger and thinner panels result in a lighter hull.

After this study, the mass and VCG position were correlated with the breadth of the panels. The restriction was not to generate panel breadths too far from the original. A plus or less 0.2 m restriction was applied.

The results of correlation with panel breadths are shown in Fig. 11.

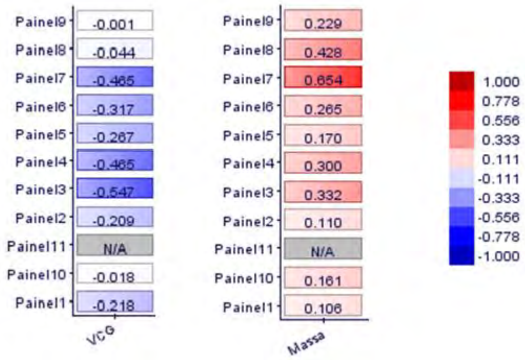

Figure 11. Correlation analyzed with modeFrontier between the Mass / VCG position with panel breadths

The mass analysis is the same with the panel breadth. On higher pressure areas, panels are thicker. So, wider panels means higher mass. The VCG decreases with the widening of panels that suffer more from slamming pressure. That happens because the deadrise angle decreases with the widening, also decreasing the VCG position.

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5.4 Optimization process

Lastly, a NSGA2 optimization algorithm was applied to the model, searching the optimum structural arrangement with low structural mass and low vertical center of gravity position. It was used 100 generations with 40 individuals in each generation. The results from the optimization process are shown in Fig. 12.

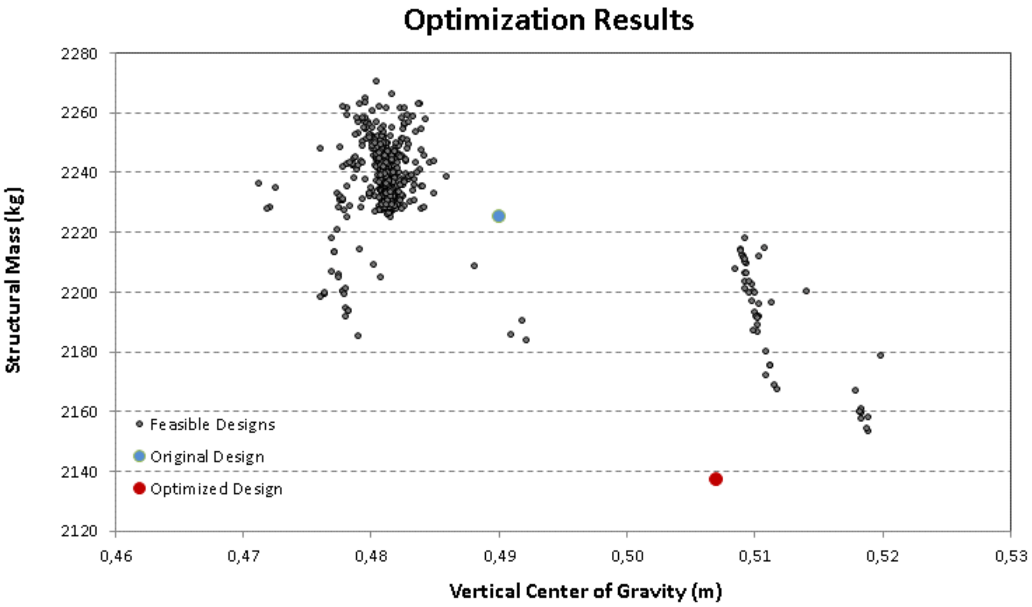

Figure 12. Optimization results: structural mass and vertical center of gravity

In Fig. 12 are shown the results evaluated in optimization process and two solutions are highlighted: the original design and the optimized design.

The comparison between the structural design variables of the optimized solution and original solution are shown in Fig. 13, 14 and 15. In the figures are shown the dimensions of the structural panels of the center line of the hull.

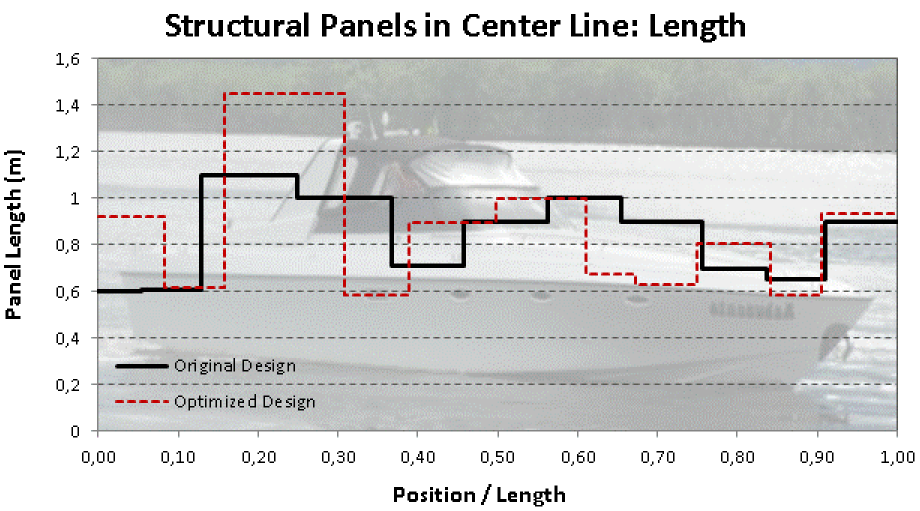

Figure 13. Comparison between original and optimized design: central panels length

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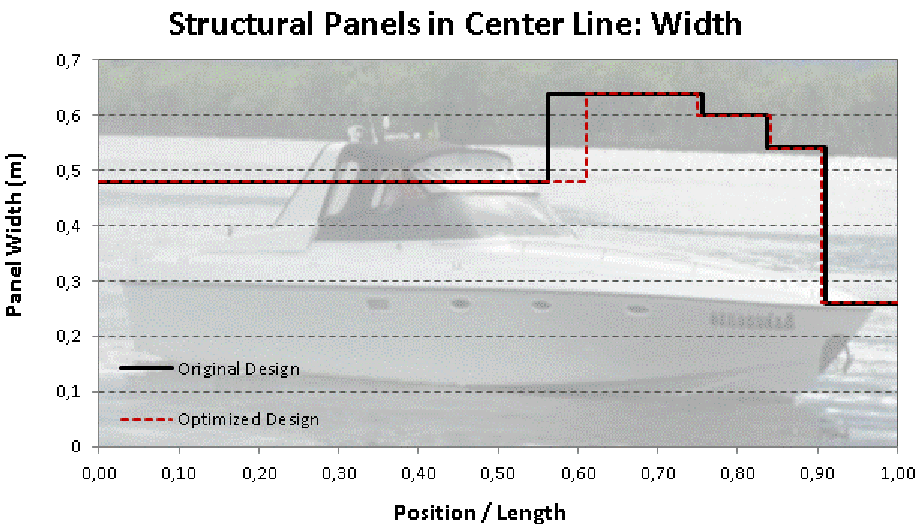

Figure 14. Comparison between original and optimized design: central panels width

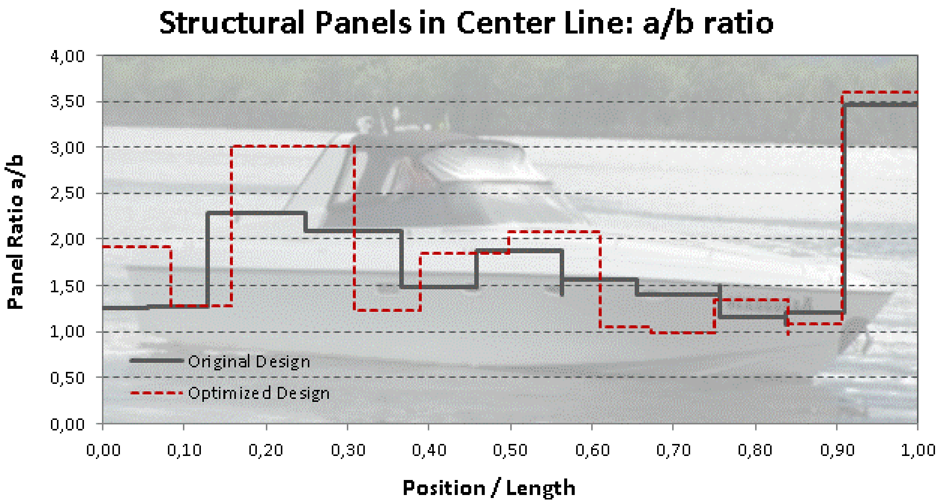

Figure 15. Comparison between original and optimized design: a/b central panels ratio

6. CONCLUSION

It is presented in this paper a study of structural design of high speed boats built in composite material.

The model proposed has a satisfyingly accurate estimate of the mass and VCG.

Also, a statistic study was done to evaluate the influence of the structural arrangement in the structural mass and in the VCG position. The VCG position and structural mass have a higher positive correlation with the bow's panel length and breadth. The flatter panels length have almost no correlation with VCG.

The optimization process resulted in a structural arrangement that satisfies the classification rule with almost 7% less mass than the original structural arrangement. This weight reduction will eventually represent a gain in maximum speed, which is the more important characteristic of a high speed boat.

7. ACKNOWLEDGEMENTS

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