Resistance calculation of a composite material structure for leisure crafts using finite element method

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Abstract. A naval architect is choosing the material taking into account various factors, some of them being the dimensions, weight, area of navigation, costs and impact strength. For leisure craft vessels, materials which are made of are mainly fibre reinforced composite materials. The composites show many advantages, being light, resistant to corrosion, resistant to impact, capable of vibration reduction and of course, it is very easy to use them in the construction process, to maintain and to repair. There are numerous general use programs which include finite element intended for calculation of the structures of which a composite is made of. Elements of the analysed structure are linear if they do not admit yielding of the layers and nonlinear if they admit yielding of the layers. Using finite element analysis, it was modelled and calculated the structure resistance of a power driven leisure craft with a length less than 24 m and will be compared with the “DNV GL Rules for Classification: High Speed and Light Craft” in force since 1 July 2016. Based on the mentioned rules, there were calculated the design loads, pressures and forces. It is noticed that the results achieved using finite element analysis are within DNV GL limits.

1. Introduction
Materials generally used in ships construction are steel and aluminium. Based on evolution and advancement of technology to produce composite materials, they began to replace the traditional materials, especially in small craft construction, in medium size vessels and sometimes in the structures of large vessels, where stresses are not reaching high values.

The composite materials used within the engineering design should prove their equivalence to traditional engineering materials, such as steel and that material could perform to the required standards in operational conditions. In the maritime sector, as in the others, the objective proof of performance relies on certain standards and guidelines. State regulations with reference to ship construction, repair and maintenance are established on rules and regulations developed by the International Maritime Organization, the United Nations’ specialised agency.

The leading IMO convention dealing with the structures of ships, SOLAS (Safety of Life at Sea), applies only to ships engaged on international voyages, with a tonnage over 500 GRT (Gross Register Tonnes). For vessels such as leisure crafts, construction standards are subject only to national regulations and changes in the materials used for their construction are easier to implement. As a
result, national authorities are relying mainly on the requirements of a classification society with reference to structural, mechanical and electrical requirements.

For leisure crafts, materials that are made of are mainly fibre reinforced composite materials. The composites show many advantages, being light, resistant to corrosion, resistant to impact, capable of vibration reduction and of course, it is very easy to use them in the construction process, to maintain and to repair. The composite materials are made of two main components: the fibres and the matrix. The fibre represents the reinforcement material and the matrix represents the binding agent in which the fibres are steeped in order to create together, after the polymerization process, the composite material.

Three approaches may be used in the calculation of mechanical behaviour of composite materials structures:

1. Ignoring of the layers of the composites plates - the plates are considered either isotropic or orthotropic and the calculation applied is as the one for a metallic structure.
2. The layering of composite plate is taken into account but the fibre direction within the matrix is ignored – such a suggestion needs a greater calculation effort and much more precise information about the material
3. Taking into account the direction of the fibres into the matrix and running at micro mechanical level – it has a very high accuracy and the calculated effort is considerably higher. Unfortunately, the method cannot be applied to complex structures [1].

2. Dimensions and characteristics of the calculated leisure craft
The calculated the structure resistance of a power driven leisure craft with a length less than 24 m was compared with the “DNV GL Rules for Classification: High Speed and Light Craft” in force since 1 July 2016.

It was used a power driven leisure craft designed for use in inland waters and on coastal waters up to a maximum sea state 5 on Beaufort scale.

The main dimensions of the leisure craft are:

- Maximum length 12.70 m
- Length on the waterline 10.92 m
- Maximum width 3.55 m
- Depth 2.10 m
- Draft 0.80 m
- Frame spacing 0.40, 0.50, 0.55, 0.60 m
- Displacement 11.76 t
- Block co efficient 0.526

Power and speed:
- Maximum power at 4,000 RPM: 2 x 191 kW (2 x 260 HP)
- Maximum speed: 27 knots

Capacities:
- Total persons on board 12
- Fuel 1115 l
- Drinking water 265 l
- Sewage 116 l
- Limber 73 l

The materials used, fibreglass reinforced polyester, have the following characteristics:
- Bending resistance 130 MPa
- Stretching resistance 95 MPa
- Coefficient of elasticity 70,000 MPa

Structural dimensions:
- Keel 120 x 110 x 13 mm
- Bottom thickness: 14 mm except 0.4L area from the transom where is 13 mm
- Side plate thickness 10 mm
- Deck thickness 8 mm
- Superstructure 6 mm
- Transom thickness 55 mm

3. Finite element analysis of the stresses and deformations

3.1 Description of finite element software used
To calculate the resistance of the boat structure it is used the software COSMOSM 2010. This software is a general use one for finite element analysis and it is part of SolidWorks 2010 package. There are available several versions, from COSMOSM 64k to COSMOSM 1024k, being different by the maximum number of nodes and elements, which can be selected for the structure mesh. For instance, COSMOSM 64k can use a maximum of 64,000 nodes and elements. Actually, COSMOSM is a group of software and GEOSTAR is being used for the interface. GEOSTAR uses other programs for the certain calculation or for the import/export of files. The software allows the execution of some macro commands and thus, the function can be extended. As an example, the capability of the software can be used when the boat calculation is carried out in order to apply the hydrostatic forces on the structure.

First, to simulate a structure, a geometric model must be designed using dots, lines contour lines, surfaces. Later on are specified the types of the elements which will be used within the mesh structure. In this particular case, beam elements (BEAM3D) and plate elements (SHELL3T) are used.

Further, the description of structures is carried out by specifying the material mechanical properties and the characteristics of the areas. At the end of the description, the calculations options are input, thus the calculation is performed and then the results can be analysed.

Based on DNV GL rules, the modelled leisure craft is corresponding to class notation R3 (coastal navigation). Structural strength shall be based on the external and internal pressures and forces as:
- Static and dynamic sea pressures
- Static and dynamic pressures from liquids in tanks
- Static and dynamic loads from dry cargoes, stores and equipment [9]

The internal pressures shall be applied irrespectively of possible simultaneous pressure from the opposite side.

Of importance for our calculations is slamming pressure on bottom [9]:

\[ P_s = \frac{a_{cg} \cdot \Delta}{0.14 \cdot A_{ref}} \cdot K_{red} \cdot K_l \cdot K_{\beta} \text{ (kN/m}^2\text{)} \]

(1)

where \( A_{ref} \) = reference area from impact loads
\[ A_{ref} = 0.7 \frac{\Delta}{T} \]

(2)

\( T \) = fully loaded draught in m at L/2 with the craft floating at rest in calm water

\( K_{red} \) = reduction factor for design load area

\[ K_{red} = 0.445 - 0.35 \left( \frac{u^{0.75} - 1.7}{u^{0.75} + 1.7} \right) \]

(3)
\[
u = 100 \cdot \frac{n \cdot A}{A_{ref}}
\]  

(4)

\[n = \text{number of hulls, 1 for mono hull, 2 for catamaran}
\]

\[A = \text{design load area for element considered in m}^2\]

and slamming pressure on flat cross structures[9]:

\[p_{sl} = 2.6k_c \left(\frac{\Delta}{A}\right)^{0.3} a_{st} \left(1 - \frac{H_c}{H_L}\right) \text{ (kN/m}^2\text{)}\]

(5)

\[H_c = \text{minimum vertical distance in m from WL to load point in operating condition}
\]

\[H_L = \text{necessary vertical clearance in m from WL to load point to avoid slamming}\]

Within the software COSMOSM, to generate the hydrostatic applied forces it is used the external command (macro command) HSPR. This macro command has a minus, thus the hydrostatic forces are applied both below and above the water level. Under the sea level the forces have one direction while over the sea level they have a reversed one.

Moreover, the HSPR is applying forces to all plate type elements, which is an inconvenient, because it imposes a thorough description of elements so the normal one at their surface to be persistent toward the outward of the hull or inward of the hull. Because of this reason, it was necessary to write a macro command, more exactly to change the existing macro command, which is applying correctly the hydrostatic force on the selected elements[1].

3.2 Description of structure using finite element software

To perform the calculation for verifying of the boat’s resistance, there were described the main components of the structure: bottom surface, side plate surface, deck surface and framing elements surface. It may be considered that the above mentioned surfaces may be accurately modelled by using finite plate elements and finite beam elements. There were neglected some of the structure elements as it was considered they are not having an important role in the boat’s strength.

![Figure 1. Beam elements.](image-url)
these, the regions were created. At the end, we had a mathematical description of the hull’s surface and transversal bulkheads by using surfaces and regions. COSMOSM software is applying a distinction between surfaces and regions, but finally both of them are still surfaces. In COSMOSM, surfaces with a simple contour are easier to create rather than surfaces with complicated contour. Finally, whether to choose surface or region is type contour dependent.

Discretization of the framing elements was carried out using beam elements (BEAM3D) as seen in figure 1 and plating (bottom, side, deck, bulkheads) elements (SHELL3T) as seen in figure 2. For the mesh structure there were used 2.090 finite beam elements, 13.666 finite plate elements, with a total of 6.968 nodes.

Figure 2. Plating elements.

3.3 General and local resistance calculation

For boundary conditions, there were used two groups. The first one was applied to calculate the general resistance for loads in calm water. The second group was applied for calculation of local resistance of bottom and side plating.

For the loads calculation there were also applied two groups. Within the general resistance calculation, corresponding to loading in calm water, the following were taken into account:

a) hydrostatic pressure. Hydrostatic forces are considered constant at the finite element level
b) construction’s own weight. We are considering the weight of the boat equal to her displacement, because at the moment of calculation there were not available sufficient data about weights distribution on board. Then, having available the volume and the weight of the structure, it was calculated an equivalent density. At the end, it is considered that weights are evenly distributed within the structure’s volume. For the weights calculation, the following were used: volume and equivalent density and gravitational acceleration and the precision was very good and it has been determined by the fact that boats’ hull weight has the highest proportion in total boat weight.

For local resistance calculation, the following were taken into account:

a) loads applied on the bottom plates, calculated according to DNV GL rules
b) loads applied on the side plates, calculated according to DNV GL rules.
Based on DNV GL rules for classification, for this particular type of light crafts, there is no requirement for any general resistance calculation. There are issued design principles and design loads applicable for all high speed and light crafts.

A general resistance calculation was carried out to be able to appreciate the general level of stress when the craft is sailing in calm water and to be able to modify the modelled shapes of the craft using finite elements.

The outcome of the finite element calculations is the displacement (as a resultant of the hydrostatic forces) and the position of the centre of buoyancy (coordinate x of the centre of buoyancy is calculated based on the reactions of imposed suspensions on the fore and aft extremities). The almost negligible errors, resulted in the displacement calculation and in the position on the longitudinal axis of the centre of gravity, confirmed the quality of the discretization with finite elements [1].

The hydrostatic pressures used in the general resistance calculation are very small compared with the ones used in the local resistance calculation and therefore, the tensions/deformations are also small.

![Figure 3](image3.png)

**Figure 3.** Loads applied on bottom and side plates in the local resistance calculation according to DNV GL rules.

![Figure 4](image4.png)

**Figure 4.** Equivalent stress on bottom and side plates in the general resistance calculation (N/mm²).
Figure 5. Displacements resultant on bottom and side plates in the general resistance calculation (mm).

Figure 6. Equivalent stress on bottom and side plates in the local resistance calculation (N/mm²).

Figure 7. Displacements resultant on bottom and side plates in the local resistance calculation (mm).
Based on DNV GL rules for classification, the pressures within local resistance calculations are used as loads. These pressures are slamming and pitching slamming on the bottom and dynamic pressure of the sea on the side plates.

4. Results and discussion
The calculation of the structure resistance of light craft was carried out with finite element method. COSMOSM software was used and more separate calculations were made, as:
- general resistance calculation for load in calm water
- local resistance calculation for load with slamming pressure on bottom
- local resistance calculation for load with slamming pressure on bottom and dynamic sea pressure on side plate [1].

The structure resistance of a high-speed light craft was analysed, based on the DNV GL Class rules. There were calculated design loads (pressures) for the direct calculation of the structure resistance according to the “DNV GL Rules for Classification: High Speed and Light Craft”, in force since 1 July 2016. Based on these rules, it was calculated:
- vertical acceleration $a_c = 14.4874715 \text{ m/s}^2$
- slamming pressure on bottom $P_{sl} \leq 43.39801 \text{ kN/m}^2$
- slamming pressure on bottom from pitching $P_{psl} \leq 43.86127 \text{ kN/m}^2$
- fore body side and bow impact pressure $P_{slb} \leq 43.86127 \text{ kN/m}^2$; $P_{slf} \leq 6.484291 \text{ kN/m}^2$
- dynamic sea pressure on bottom $p_{b} \leq 20.13004 \text{ kN/m}^2$; $p_{side} = 6.5 \text{ kN/m}^2$
- pressure generated by dry cargo, stores and equipment $p \leq 6.484318 \text{ kN/m}^2$

For the purpose of comparison, the maximum value of the hydrostatic pressure in calm water at maximum draft is $p = 7.5414375 \text{ kN/m}^2$.

Stresses and allowable displacements are calculated according to the DNV GL Class rules. Taking into account that tensile strength is $95 \text{ N/mm}^2$, it resulted that allowable equivalent stress is $\sigma_{allow} = 28.5 \text{ N/mm}^2$. From the rules, we may conclude that displacements are considered allowable if they comply with the condition $w/t \leq 2$, where $w$ and $t$ are the transversal displacement of a plate and its thickness.

For the stress, it was noticed that calculated value is $\sigma_{calc} = 16.46 \text{ N/mm}^2 < 28.5 \text{ N/mm}^2 = \sigma_{allow}$, so the maximum stresses induced in the structure by external forces are within limits. For the displacement calculated value is $[w/t]_{calc} = 1.27 < 2$, therefore the displacements are also within limits.

5. Conclusions
We may say that original structure is oversized as it was expected. Therefore, there is a possibility to reduce the dimensions of the structure elements as to consume less material in the building process. Reducing the dimensions of the structure elements, their weight will reduce as well and will be a reduction in the displacement of the craft and her draft. The decrease has at least two effects. First effect leads to a decrease of the pressures applied to the structure, creating a reduction of the stresses and displacements and finally to a new possibility to reduce again the dimensions. Second effect is that maximum speed increases due to the decrease of the displacement, if it is assumed that we are keeping the same engine. So, a faster and lighter craft can be achieved by redesign.

In lieu of existing materials used in the construction of leisure craft, it may be used a cheaper material which contains less fibreglass and of course with a tensile strength of less than $95 \text{ N/mm}^2$. Taking into account the maximum equivalent stresses and the relations connected to admittance according to DNV GL rules, there may be used a material which has a tensile strength of $3 \times 16.46 \text{ N/mm}^2 = 49.38 \text{ N/mm}^2$. In this case, it must be considered that classification societies
accept generally, as lower limit for tensile strength, a value of 85 N/mm². Reducing the concentration of fibreglass in the composite used in the leisure craft construction has an effect of reduction of longitudinal elasticity mode of the composite, which has a reduced effect on the stresses variation.

6. References
[1] Dumitrache R 2013 Research on the Mechanical Behaviour of Materials Used in Construction of Leisure Crafts (PhD Thesis) Constanta: Constanta Maritime University
[2] Karpov Y S, Stavichenko V G 2010 Procedure For Strength Calculation Of Laminated Composite Materials Under Thermomechanical Loading Conditions Strength of Materials 42 478-487
[3] de Morais A B 2006 Prediction of the longitudinal tensile strength of polymer matrix composites Composites Science and Technology 66 2990-96
[4] de Morais A B 2001 Stress distribution along broken fibres in polymer-matrix composites Composites Science and Technology 61 1571-80
[5] Gavrilescu I and Ionas O 1997 Numerical definition of the hull shape The Annals of “Dunarea de Jos” University of Galati Shipbuilding XI
[6] Gavrilescu I 1997 Modeling of naval structures by plate in elasto-plastic domain The Annals of “Dunarea de Jos” University of Galati Applied Mechanics X
[7] Szilard R 2004 Theories and Applications of Plate Analysis, Classical, Numerical and Engineering Methods, John Wiley & Sons, Inc. 1015
[8] Kaminski M M 2005 Computational Mechanics of Composite Materials Sensitivity, Randomness and Multiscale Behaviour, Springer-Verlag 418
[9] DNV GL 2016 Rules for classification: High speed and light craft – DNVGL-RU-HSLC-Pt3Ch1, Design principles, design loads Edition 2015, in force since 1 July 2016