Fluid-Structural Interaction Study of the Structural Arrangement of a Riverine Low-Draft Combat Boat for Coastal Transit Conditions

Estudio de Interacción Fluido-Estructural por Condiciones de Transito Costero en el Arreglo Estructural de un Bote de Combate Fluvial de Bajo Calado

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Abstract

The Riverine low draft combat boats are aluminium-built crafts designed to operate exclusively in low-depth riverine environments. Given the Colombian geography, these operations might be extended to estuaries or coastal transit conditions. Consequently, there is a need of studying the structural integrity of the hull in the case of coastal transit. A fluid-structural interaction study was performed in which the hydrodynamic hull pressures are associated as an input in a static structural finite element analysis. The obtained hull pressures were compared with the values suggested by the classification rules.

Key words: Hydrodynamic pressure, direct analysis, aluminum hulls, Fluid- Structural Interaction.

Resumen

Los botes de combate fluvial de bajo calado son embarcaciones fluviales con un arreglo estructural en aluminio exclusivamente diseñado para operar en ríos de baja profundidad. No obstante, debido a la geografía nacional, estas operaciones pudieran extenderse a condiciones de estuario o tránsitos costeros. De esta manera, surge la necesidad de evaluar la resistencia estructural del casco en condiciones de tránsito costero. Para tal fin, se realizó un estudio de interacción fluido estructural en la que se enlaza las presiones hidrodinámicas en el casco como entrada para un análisis por elementos finitos. Las presiones en el casco fueron contrastadas con los valores obtenidos con el uso reglas de las Sociedades de Clasificación.

Palabras claves: Presión Hidrodinámica, análisis directo, cascos en aluminio, Interacción Fluido – Estructura.

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Introduction

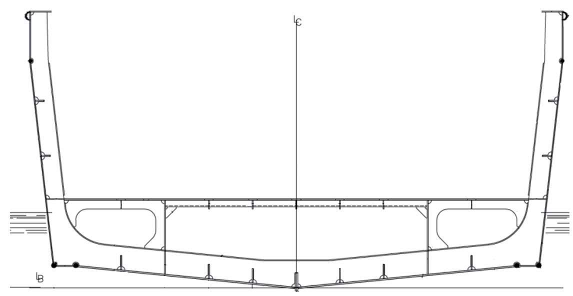
The riverine low draft combat boat designed with naval- grade aluminium and 10 m^2 polymeric ballistic protection panels on deck, can develop riverine patrolling and reconnaissance operations in low-depth waters. the technical feature of this boat includes a 24 knots maximum speed, an operative range of 300 km, and the capability to provide tactical fire support [1].

The structural arrangement of this boat was designed to maintain a low weight while the security of the crew, the structural integrity of the hull and the boat performance remain preserved at riverine conditions. To ensure the structural integrity of the hull, the scantling was performed according to recommendations and requirements of the classification societies ABS in "Rules for Building and Classing, High- Speed Craft; Hull Construction and Equipment" [2] and ISO 12215 "Small craft – Hull construction and scantlings – Part 5: Design pressures for monohulls, design stresses, scantlings determination" [3]. Given the structural arrangement obtained, its structural integrity was evaluated and improved by direct analysis in a global model according to "Class Guideline- Finite Element Analysis" by DNV-GL [4].

The hull scantling refers to the assessment of selected plates and stiffeners' geometrical dimensions in accordance with their mechanical properties and section modulus. The strength of the hull to environmental and duty external loads depends largely on the structural arrangement and its capability to withstand bending and shear stresses [5]. First, the hull girder strength was assessed according to cross-section inertial properties followed by local calculation of plates thickness and cross-section of primary and secondary stiffeners. In this way, the plates of the structure and the respective primary and secondary structural reinforcements are to be designed in such a way their mechanical strength is high enough to prevent crack initiation due to wave pressures on the hull [6].

The bottom structure of the vessel consists of a keel, a AW 5083 H321 bottom plate, six AW 6082 –T6 longitudinal stiffeners, and two side girders. The side hull structure consists of AW 6082-T6 flat-bar longitudinal stiffeners which purpose is to provide the required stiffness to the plates of the side. These side plates are to be vertically supported AW 5083 H321 frames [see Fig. 1]. Four of these frames are watertight bulkheads [7].

Fig. 1. Typical frame.



The deck is composed of a AW 5083 H321 plate and seven flat-bar longitudinal stiffeners. This deck is transversally supported by profiles deck beams and bulkheads and longitudinally supported by two side girders.

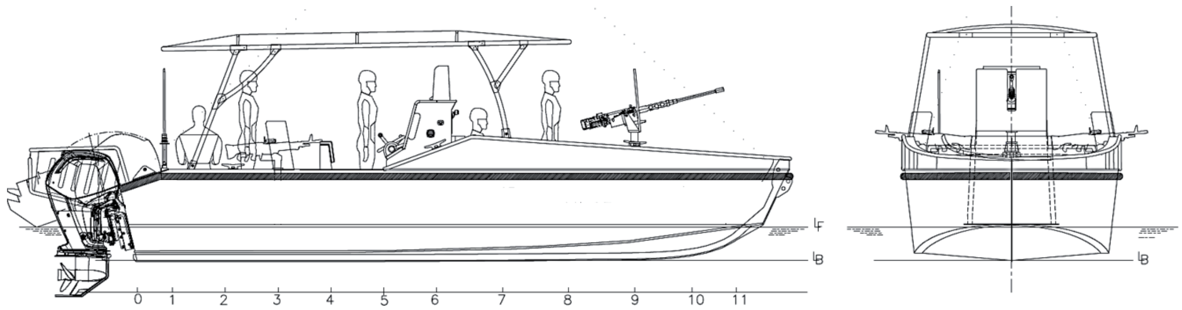
The principal particulars of this combat boat are summarized in the next table [see table 1] [see Fig. 2].

Table 1. Riverine combat boat principal characteristics.

Principal particulars	Values
Length over all	8.68 m
Length at waterline	7.05 m
Beam	2.42 m
Amidship depth	1.03 m
Draught	0.34 m
Installed power	134 kW
Full load displacement	3650 kg

Although the vessel was designed to operate in a riverine environment, it might occur the cases where the vessel is assigned to operate in estuaries or develop an occasional coastal transit between river mouths.

Fig. 2. Riverine low-draft combat boat.



In those cases, the hull could be subject to loads or pressures that overcome the structural arrangement resistance even though the assessment from rules and guidelines of the classification societies, which calculations are generally of semi-empirical nature and also are calibrated to secure the lifespan expected, allow a simplified approach of complex structural problems with a wide safety factor [8].

For the scantling of small crafts under riverine conditions, classification societies' rules dictate a design wave height of 0.5 m [2]. This wave height can be classified as a Beaufort sea state 2 scale but changes in wave frequency and direction will affect the level of pressure on the hull and hence, the stress levels along the structural arrangement [9].

Waves are an external agent with a considerable influence on the behavior of ships in a marine environment. The wave frequency is inversely proportional to the wavelength and celerity. The latter, given by the relation between wavelength and period, is a distinctive factor among surface waves and other types of wave motions [10]. The relative boat speed in relation to the waves is defined as the encounter frequency. The encounter frequency is a function of boat speed (Vs) and the encounter angle (β). This frequency is only zero when the velocity of the observer in the direction of wave propagation and the wave velocity are equal. On the other hand, when the wave speed is lower than the parallel component to the wave direction of the boat speed, the encounter frequency is negative and the boat overtakes the waves [11].

In the boat, each degree of freedom that has a restoring force has an associated natural frequency. These natural frequencies depend on the mass and stiffness properties of the system [10]. The interaction between the encounter frequency and the natural frequencies of the ship leads to a boat amplitude response. When the encounter and the natural frequencies present equal values might occur resonance phenomena. When the encounter frequency is very low, at head seas conditions, the dynamic effect associated with damping is virtually negligible and the boat motion amplitude is on the same order as the wave amplitudes. In the case of high wave frequencies, the boat responses are reduced because the short wavelength does not excite the hull motion [11].

Hence, the main aim of this work is to evaluate, by computational methods, the effects of hydrodynamic pressures on the hull's structural integrity at different headings and wave frequencies. The hydrodynamic behavior study was developed with the software Ansys Aqwa and the pressures were exported to the static structural model of Ansys Mechanical to evaluate the strength of the structural arrangement by the finite element method.

Methodology

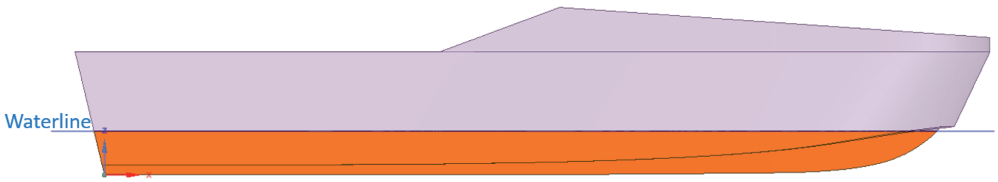
In the present methodology it was detailed the hydrodynamic diffraction computational model and the linked structural finite element development.

Hydrodynamic Diffraction model

Geometry

Shell modeling was carried out by using ANSYS

Fig. 3. Hull surface cut by the water surface.

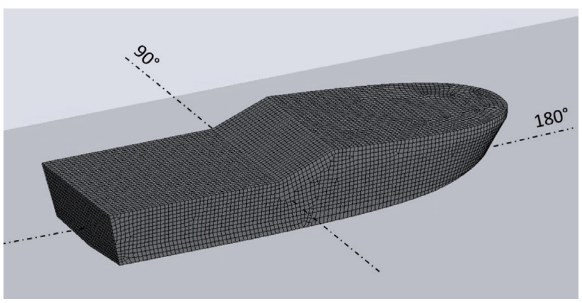


SpaceClaim 2022 software. Only external hull surfaces were included. These hull surfaces are divided by the waterline [see Fig. 3].

Meshing

The surfaces were meshed with 10029 elements and a defeaturing tolerance of 0.005 m. This element size allows a maximum frequency of 1.55 Hz for the analysis [see Fig. 4].

Fig. 4. Meshed model for the hydrodynamic analysis.



Hydrodynamic Response Analysis

The computations of the wave-induced motions were carried out by utilizing three- dimensional potential flow based in diffraction-radiation theory. The computations of the hydrodynamic pressures took into account all six degree of freedom rigid-body motions of the full. The environmental constants and mass properties are detailed in the next table [see table 2 & 3].

This analysis considers the operational profile at full load capacity. Wave headings (β) were evaluated with increments of 15°, the wave encounter frequencies (ω_e) covers a range from 0.015 Hz to 1.2 Hz with increments of 0.1 Hz [2]. For this study the wave pattern was simplified with a regular wave with 0.5 m amplitude as a first approach [2].

Table 2. Mass properties for the model.

Parameters	Values
Total mass	3650 kg
Longitudinal center of gravity	2.6 m
Transversal center of gravity	0.0 m
Vertical center of gravity	0.55 m
Radius of gyration –roll	0.82 m
Radius of gyration –pitch	1.76 m
Radius of gyration –yaw	1.84 m

Table 3. Environmental constants.

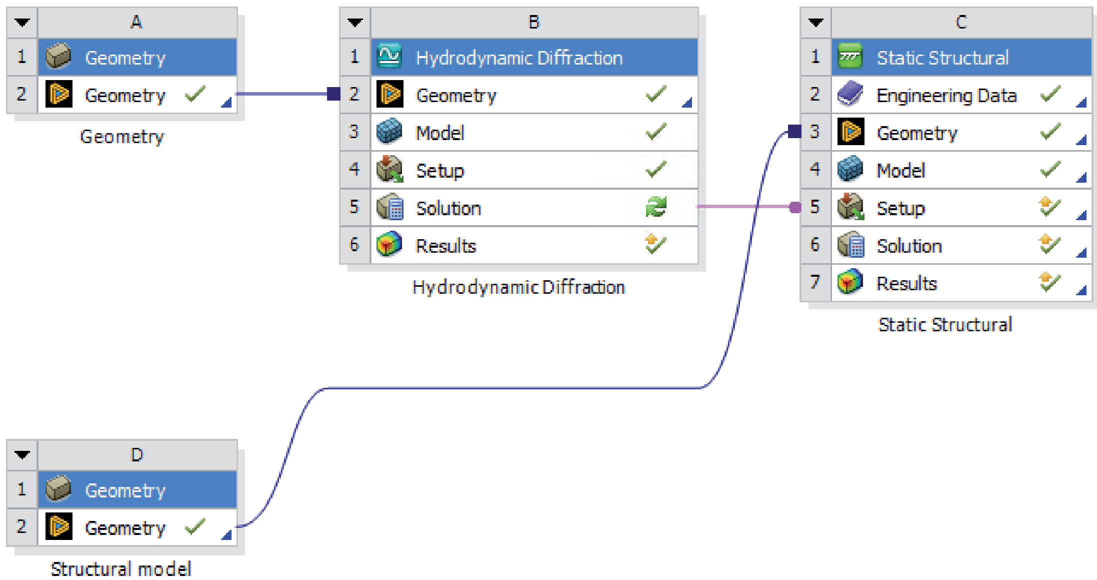
Characteristics	Values
Water Depth	4 m
Water density	1025 kg/m^2
Longitudinal water size	40 m
Transversal water size	25 m
Radius of gyration –yaw	1.84 m

The worst frequency-heading combination at which the hull's response amplitude is a maximum, was evaluated by direct analysis to obtain the effect on the structural arrangement according to the next block diagram [see Fig. 5].

Direct Analysis

Global modeling of the boat and the subsequent finite element method analysis are explained in detail in this section. The analysis is subjected to plain stress and linear-elastic mechanics simplifications.

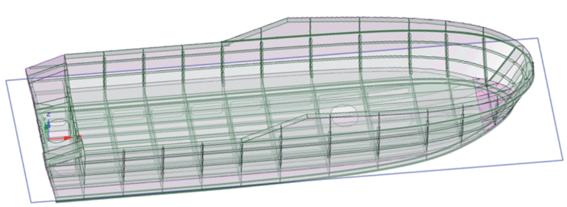
Fig. 5. Ansys Workbench block diagram.



Structural model Geometry

Shell modeling was carried out by using ANSYS SpaceClaim 2022 software [see Fig. 6]. Bonded contacts were used among structural elements given their welded connections.

Fig. 6. Global modelling using Ansys SpaceClaim.



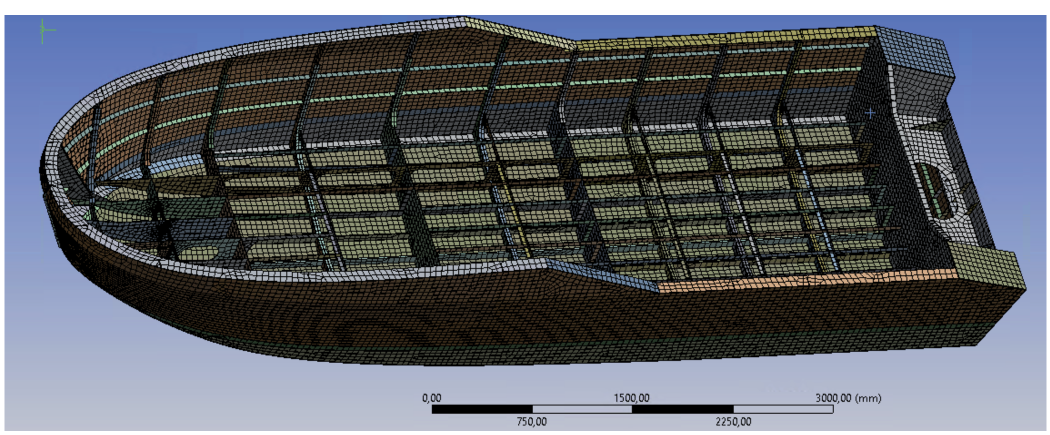
Meshing of the structural model

SHELL181 elements were used for meshing. This four-node element with six degrees of freedom at each node is suitable for analyzing thin to moderately thick shell structures [see Fig. 7]. After a convergence test, a 30 mm meshing element size was used. The shell geometry is represented by 4 Node Linear Quadrilateral elements; the degenerate 4 Node Linear Triangular option was only used as filler in mesh generation [4] [12].

Boundary Conditions

The boundary conditions for the global structural model should reflect simple supports that will

Fig. 7. Mesh of the structural model.



avoid built-in stresses so the reaction forces in the boundaries are to be minimized [4]. ANSYS Inertia relief option allows to exactly balance the force differences on the supports creating a state of static equilibrium. Two of these fixation points were applied at transom intersecting the main deck at portside and starboard, and the last one, in the bow centerline intersecting waterline.

Materials

5083- H321 aluminum alloy mechanical properties were assigned to plates whereas aluminum alloy 6082 T6 properties were set to stiffeners. The mechanical properties of both aluminum alloys are detailed in the next table [see table 4].

Table 4. Aluminum alloys mechanical properties defined for the model [10].

Properties	Al 5083-H321	Al 6082-T6
Density [g/cm^3]	2.66	2.7
Poisson's ratio	0.33	0.33
Young's Modulus [GPa]	70	70
Tensile yield strength [MPa]	220	260
Tensile yield strength (welded) [MPa]	145	125
Tensile ultimate strength [MPa]	305	310
Tensile ultimate strength (welded) [MPa]	290	190

Allowable Stress

This analysis is completed using the Maximum-Distortion- Energy Criterion in order to assess the structure against failure. This criterion takes both shear and normal stresses into account to develop a combined equivalent stress, σ_e A class allowable stress factor (*FP=0.85*) is added in such a way yield strength of the material is reduced [2]. The maximum allowable stress for plates is 123 MPa and 106 MPa for stiffeners specifically in heat-affected zones [see table 5].

Table 5. Allowable stresses on structural members.

Properties	Al 5083-H321	Al 6082-T6
Heat- affected zones	123 MPa	106 MPa
Non heat- affected zones	187 MPa	220 MPa

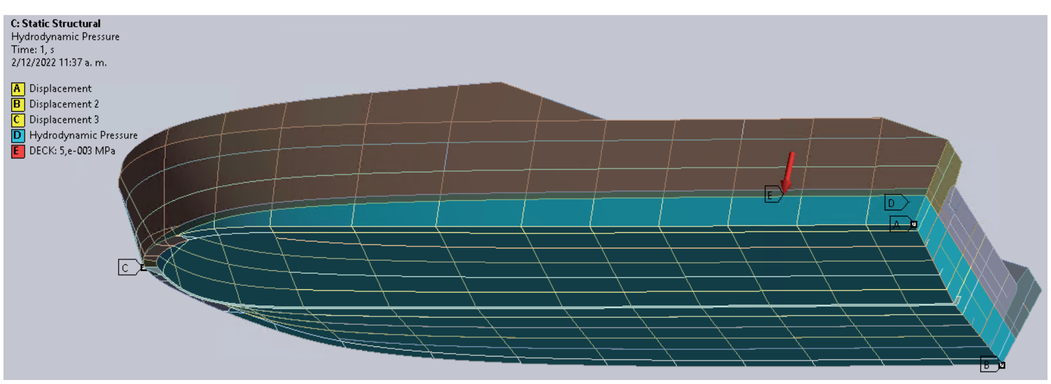
Load Conditions

Hydrodynamic pressure, imported from the Ansys Aqwa software, was applied on the hull below de waterline. Design pressure calculations from class requirements was assigned on the deck with a value of 5 kN/m2 [2] [3] [see Fig. 8].

Results and Discussion

In this section, the results of the hydrodynamic response analysis and the use of the obtained hull pressures results as an input of a structural analysis are detailed.

Fig. 8. Imported hydrodynamic pressures on the hull.



Hydrodynamic Response Analysis

Hydrostatic Results

From the hydrodynamic diffraction analysis, it was obtained the hydrostatic characterization of the boat. Some of these are summarized below [see table 6].

Table 6. Allowable stresses on structural members.

Characteristics	Values
Longitudinal center of gravity	2.6 m
Longitudinal center of Buoyancy	2.9 m
Actual volumetric displacement	3.78 m^3
Equivalent volumetric displacement	3.55 m^3
Cut water plane area	14.6 m^2

Hydrodynamic Pressures

Different wave frequencies and headings were tested in the proposed interval and it was found that the wave frequency of 0.44 Hz produces the highest pressure levels with a wave amplitude of 0.5 m [see Fig. 9].

Regarding the headings, the highest hull pressures were obtained with beam seas [see Fig. 10 & Fig. 11]. The lowest hull pressures were reported with head seas [see Fig. 12 & Fig. 13]. All with a wave height set in 0.5 m. The hydrodynamic pressure magnitude difference between both load cases is close to 7.5 times.

On the other hand, the obtained motions at different waves frequencies and headings showed that there are intervals in which the boat would present unsecure navigation and must be avoided.

Fig. 9. Hydrodynamic pressures as function of frequency.

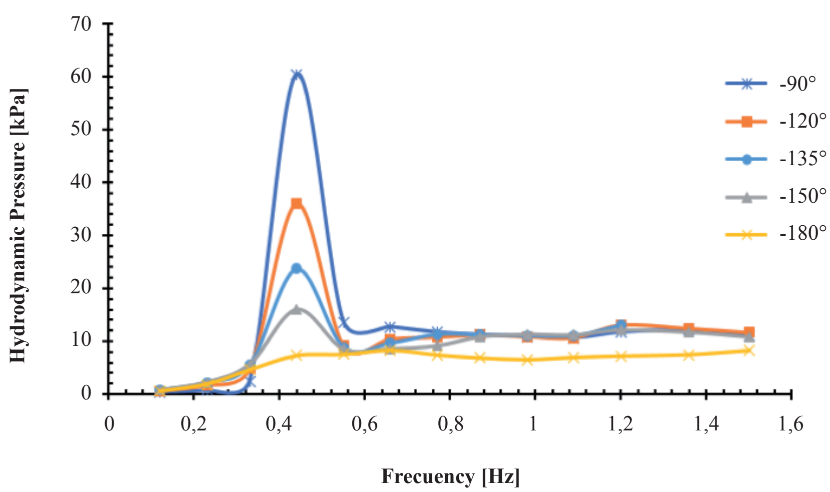


Fig. 10. Pressures and motions at 0.87 Hz and 180° heading – head seas condition.

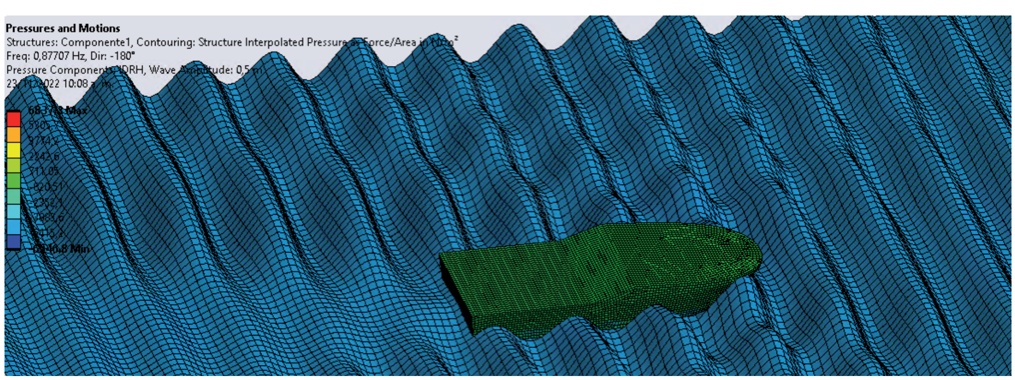


Fig. 11. Imported hydrodynamic pressures at 0.44 Hz and 180° heading – head seas condition.

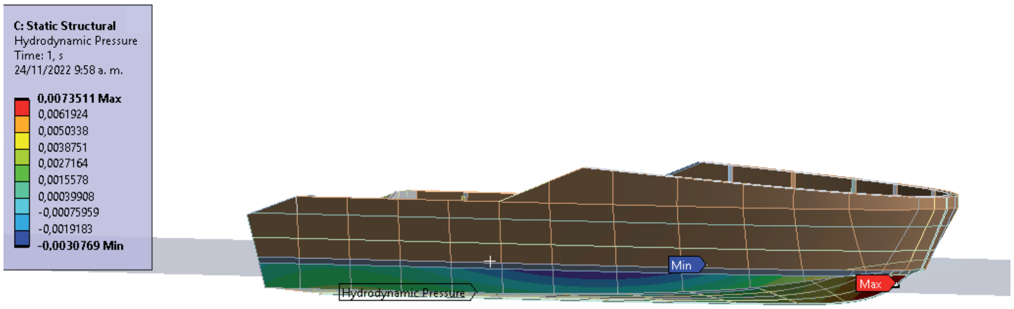


Fig. 12. Pressures and motions at 0.66 Hz and 90° heading– beam seas condition.

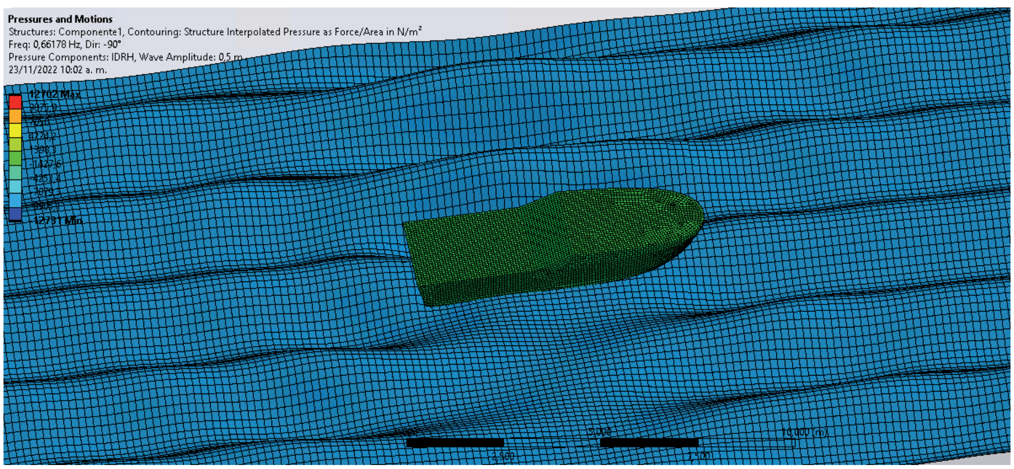
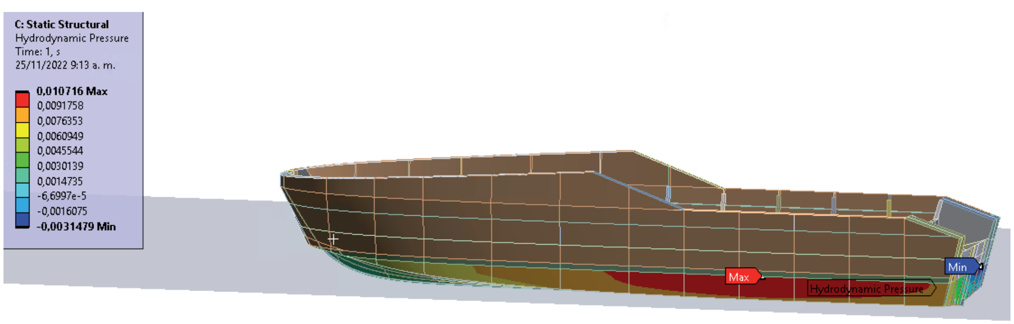
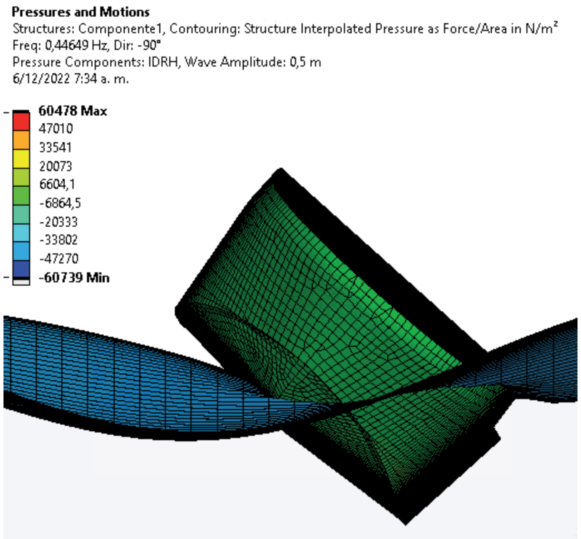


Fig. 13. Imported hydrodynamic pressures at 0.44 Hz and 90° heading – beam seas condition.



because the roll motion in a resonance frequency and due to the low draft of the hull and its flat bottom, the boat would avoid navigation with beam seas with a range of ±60° and a frequency interval from 0.44 to 0. 55 Hz [see Fig. 14]. Besides motion and load conditions there are additional conditions, such as crew comfort standards, that may generate additional affectations in the coastal transit navigation capabilities of the craft. These effects might be evaluated with further studies.

Fig. 14. Roll motion with beam seas (90°) at 0.44 Hz.



The calculation of hydrodynamic wave pressures according to classification rules such as ABS in [2] and LR in [14] at head sea conditions and also neglecting slamming pressure factors, present the both bottom pressures estimations as two times higher than obtained with the software [see table 7]. Additionally, because the time-dependent nature of loads and the hydro-elastic response of the structure under slamming conditions, the computational models used by the software are unable to estimate the resultant hydrodynamic pressure [15]. Considering the slamming pressure in Classification Society rules calculation would imply a local increase in the hull pressure close to 70 kPa [1].

Table 7. Hydrodynamic pressures on the bottom.

Method	Bottom Pressure	Difference [%]
Ansys AQWA	7.7 kPa	---
ABS “HSC”	16.7 kPa	116.8
LR “Special Service Craft”	10.3 kPa	33.76

In the case of incrementing the wave height from a typical sea state 2 with 0.5 m of wave height to a sea state 3 with 1.25 m of wave height, the hull presented an increase of 2.7 times in the hydrodynamic pressure from sea state 2 and 12.7 times higher from a sea state 1 at head seas conditions [see Fig. 15]. Analyzing the motions of the hull under sea state 3 conditions it was found that the boat would present an unsafe navigation in a wide range of headings and frequencies [see Fig. 16].

Fig. 15. Hydrodynamic pressure as a function of frequency and sea states.

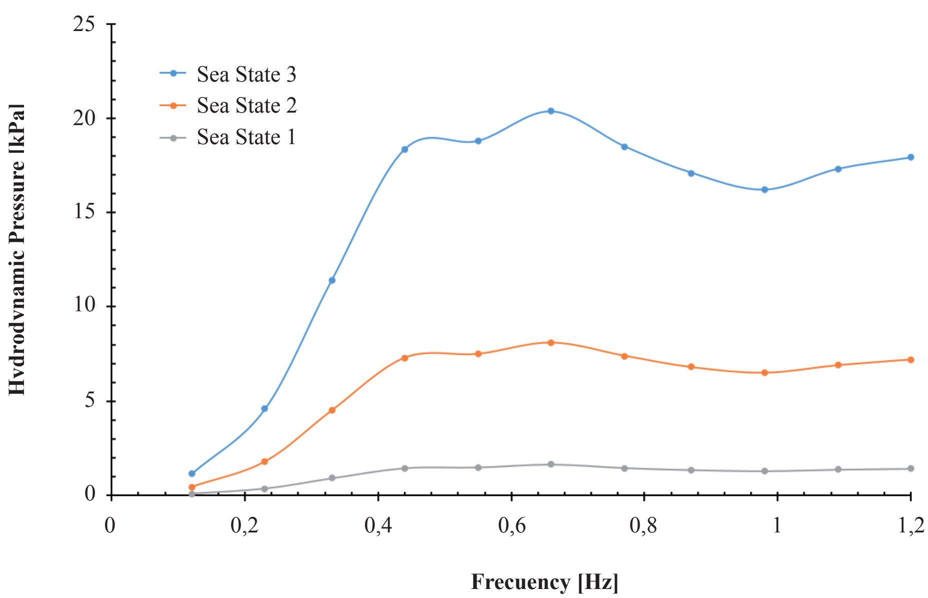
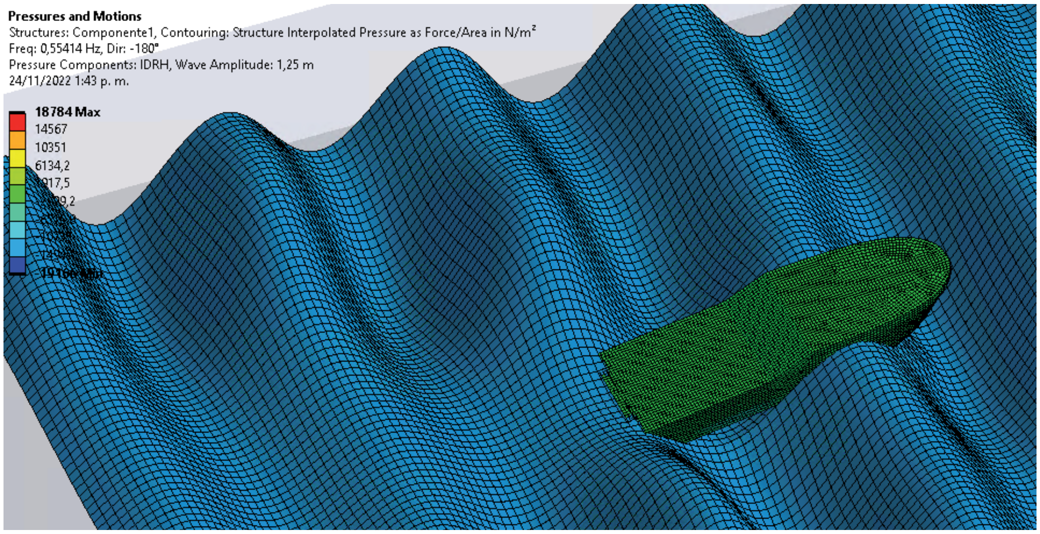


Fig. 16. Pressures and motions at 0.55 Hz and 180° heading with a wave amplitude of 1.25m.



Direct Analysis

Given the results of the hydrodynamic pressures on the hull as function of heading, frequency, and a wave amplitude of 0.5 m, critical direct analysis was carried out with a heading of 90° and a frequency of 0.44 Hz. At this load case, the highest pressures were found in the vicinity of the bottom – side connection. The side panels presented an equivalent maximum stress near to 84 MPa with a consequent 2.7 safety factor [see Fig. 17].

Frames and bulkheads showed stress values between 25 MPa to 45 MPa in the hull pressure influence zone. Nevertheless, there is a spot in the frame above deck in a bulkhead station where equivalent stresses close to 140 MPa are reported, but given the local effect of this spot, the structural integrity of the frame is deemed unaffected because of local plastic deformation in the profile [see Fig. 18].

On deck, the assemble with the side frames bring as consequence maximum equivalent stress values under 80 MPa located in temperature welding affected zones leading to a safety factor of 1.81 [see Fig. 19].

Regarding a heading of 120°, stress levels increases towards the bow reaching values up to 97 MPa [see Fig. 20]. At this load case the transversal stiffeners located at the stern showed a stress increase close to 31% in comparison to the load case at 90° [see Fig. 21].

Fig. 17. Stress distribution on the sides with beam seas.

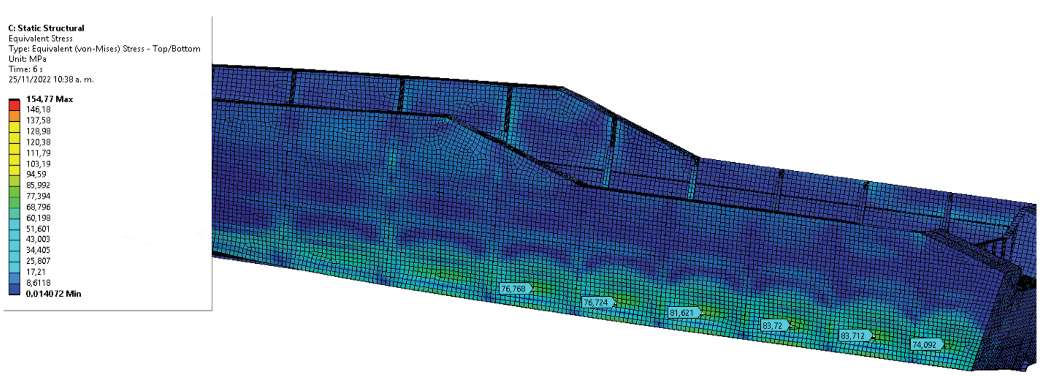


Fig. 18. Stress distribution in the frames with beam seas.

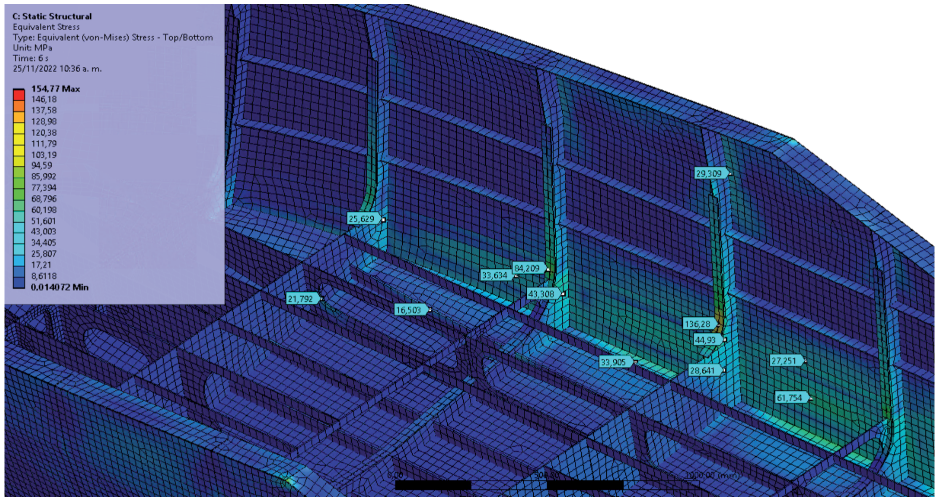


Fig. 19. Stress distribution over the deck.

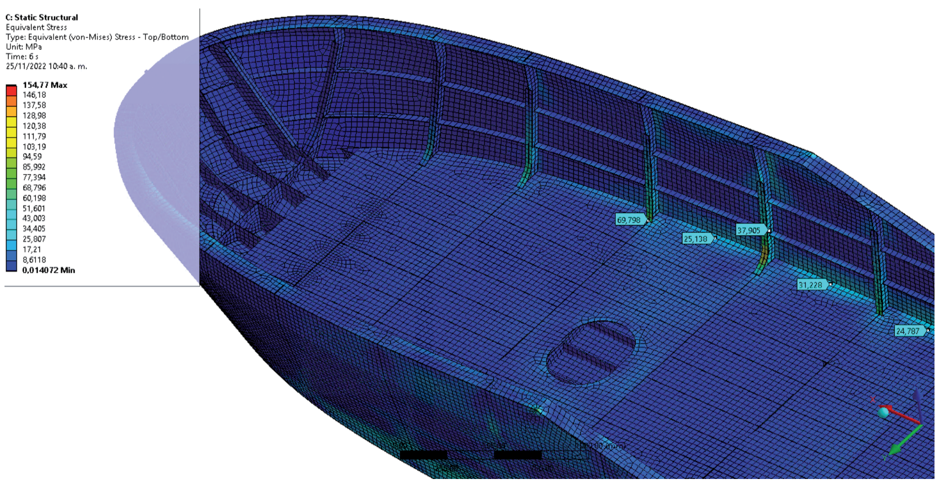


Fig. 20. Stress distribution above 20 MPa with a 120° heading..

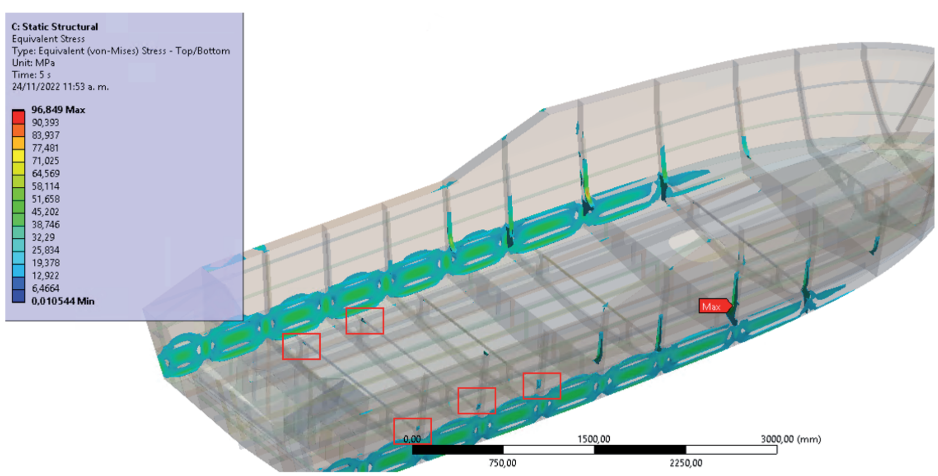


Fig. 21. Stress distribution in side's plates and internals.

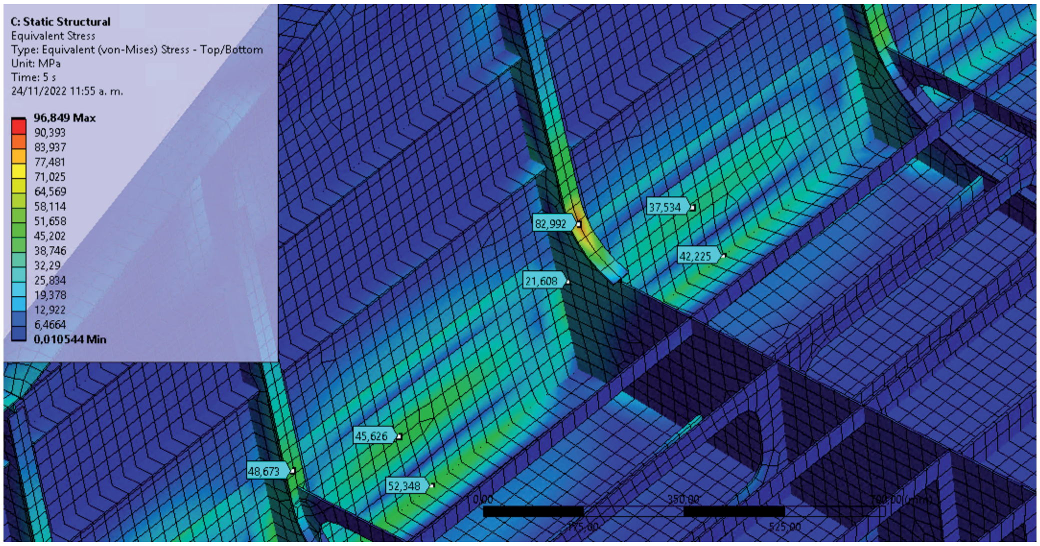


Fig. 22. Hydrodynamic pressure distribution on the bottom.

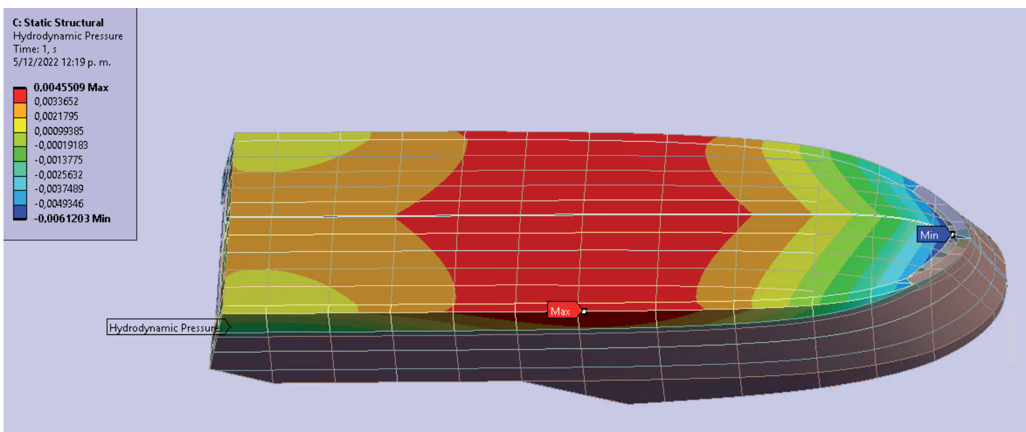
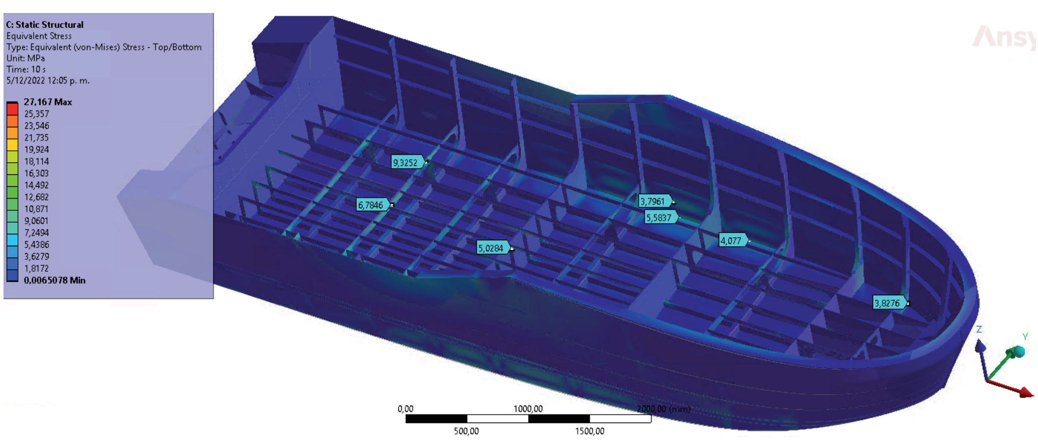


Fig. 23. Stress distribution in internals below deck.



At head seas conditions, the effect of hull's hydrodynamic pressures on the structural arrangement stress levels decreases in comparison with others load cases and this behavior is consistent with the pressure levels showed in Fig. 9. Higher stresses are reported in the bottom – side assembling [see Fig. 22 & Fig. 23].

With a different phase angle at the same heading and frequency, it was found a maximum hull pressure with a value of 7.7 kPa [see Fig. 24 & Fig. 25]. Nonetheless, given the reinforced structure at bow zone designed to withstand slamming pressures and beaching maneuvers, the stress levels in the affected zone showed in Fig. 26 are up to 5 MPa.

Structural details are characterized by high stiffness at their end connections and sharp corners. That ends might produce singularities; which means, there are points in the model where stress values tend towards non-real infinite values. If mesh convergence cannot be reached in certain high-stress points even with mesh refinement, these points are deemed to be singularities.

A high gradient stress zone was spotted at the portside gunwale, after mesh convergence was not reached; the reported high stress values are deemed as a singularity [16] [see Fig. 27].

At sea state 3, with a consequent wave amplitude of 1.25 m, a resonance frequency of 0.44 Hz, and a heading of 120°. Stress levels increase in such a way reach values up to 126 MPa in the chine and 115 MPa in the side plates. Given the allowable stresses stated in table 5, the lowest safety factor in plates

Fig. 24. Hydrodynamic pressures on the hull as a function of the wave phase angle.

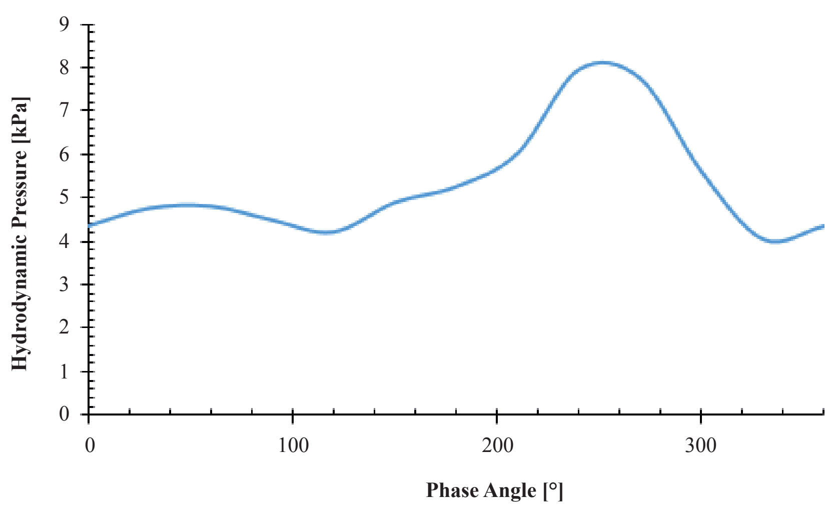


Fig. 25. Location of the maximum hydrodynamic pressure on the bottom with a 260° wave phase angle.

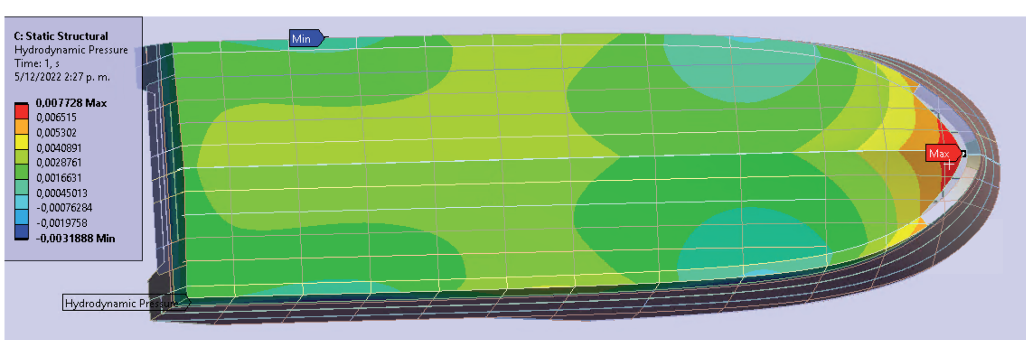


Fig. 26. Stress levels at aft section of the boat.

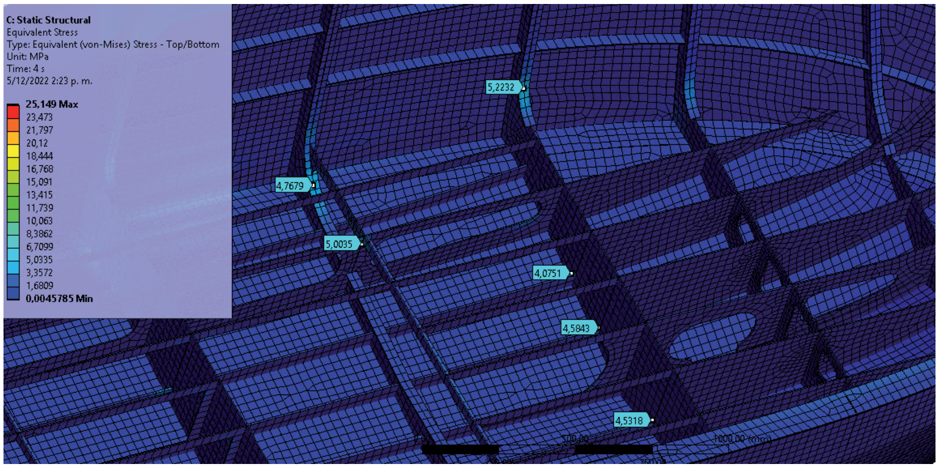


Fig. 27. Stress levels at aft section of the boat.

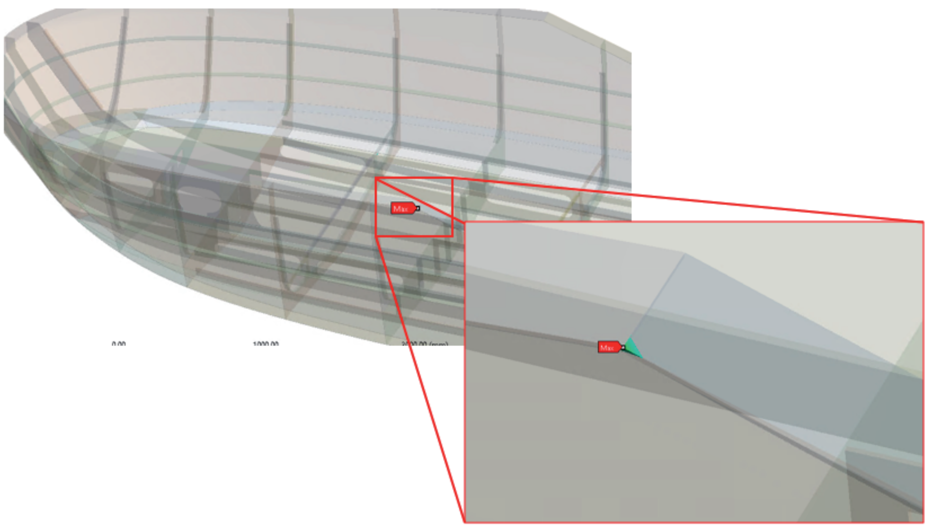
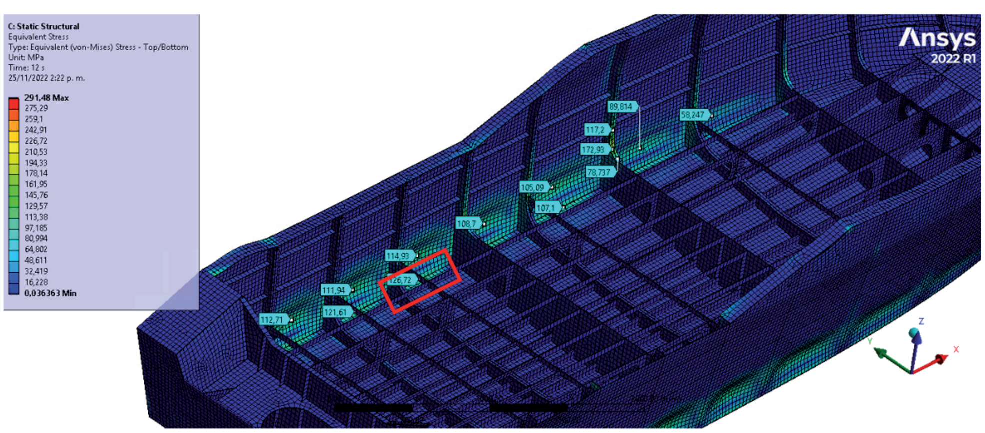


Fig. 28. Stress levels at sea state 3 and 120° heading conditions.



is 0.98 in the chine and 1.62 in the side plates. Regarding profiles, the lowest safety factor is about 1.27 in non-affected zones. Higher stresses than the allowed are situated in heat-affected zones in one of the side frame stiffener; however, given the focused nature of these, their localized plastic deformation will not compromise overall strength. Nevertheless, the insufficient safety factor of a chine plate zone, the pressures exceed the strength of the structural arrangement [see Fig. 28].

Conclusions

The structural arrangement strength for a riverine low-draft combat boat was analyzed by a hydrodynamic response analysis and direct analysis. It can be concluded that the structure of the hull can withstand sea state 2 conditions. Nevertheless, the low draft of the vessel and its flat bottom might imply unsecure navigation specially under beam waves ± 60° conditions within frequencies from 0.44 Hz.to 0.55 Hz, thus the design performance will be drastically reduced at estuaries and coastal transit conditions. Further considerations, such as crew comfort standards, might reduce even more the coastal transit capabilities of the boat.

According to the obtained hydrodynamic pressures on the hull by this computational model, Classification Societies Rules apply safety factors up to 2, this without having into account slamming pressures components. Given the time-dependent loads and the hydro-elastic structural response characteristic of slamming, the calculation of this phenomenon outpaced the computational model used by the software.

Sea state 3 present unsafe navigating conditions in a wide range of frequencies and headings because the boat motions. Additionally, at 120° of heading at resonance frequency of 0.44 Hz the structural arrangement strength of the side- bottom assembly is not enough to withstand the imported hydrodynamic pressures.

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