STRENGTH CONTRIBUTION OF COMPOSITE STRUCTURAL TANKS ON SUPERYACHTS

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ABSTRACT

Large motor yachts have become faster and lighter with time. Weight savings of the structural arrangement can be a key factor when advanced materials are used. A correct balance of panel stiffness, longitudinal structural elements, transverse web frames and bulkheads can provide an optimum structural layout for high performance motor yachts. To improve hull bottom strength and provide extra room for the interior arrangement, many builders have used structural fuel and water tanks. The basic concept of integrated tanks is to use the hull's main structure as the tank walls, and a liner, laminated with high performance resins, to provide chemical resistance. Internal transverse and longitudinal baffles and sandwich tank top complete the integrated structure. A major difficulty in understanding the structural behavior of a hull bottom subject to dynamic loads is the large number of reinforcing members, connections and the complex loading transfer associated with integrated tanks. This paper uses the Finite Element Method to determine the structural contribution of integrated tanks on a lightweight 130 feet motor yacht built in sandwich construction. Design criteria, construction details and comparative testing for tank construction are presented. The results indicate that significant advantages can be achieved with integrated tanks when compared with traditional non-composites construction methods.

Figure 1 - 130 ft motor yacht

INTRODUCTION

There is no question that the use of composite materials in the marine industry has increased the length and speed of new boats. These days boats up to 200 feet in length have been built using lightweight core construction under vacuum infusion method. Actually, it is quite impossible to reach high speeds and performance levels with traditional construction.

Built light does not mean using only lightweight materials, but also involves study of the construction methods, details and finding acceptable solutions to improve boat performance. The first steps of a hull structural design start with optimization plating of the hull, determining the face materials and thickness, core density and thickness, core adhesive, infusion strategy, and finally the resin type. For the structural arrangements, designers and builders must check the compatibility between the stringer system, transverse bulkheads, floors and other reinforcing members with the layout of accommodation spaces, equipment, engines and tanks.

In the particular aspect of tank design and construction there is another point to consider on fast boats. To cruise at high speed it is necessary to have high horsepower rates as well as large amounts of fuel. The weight of fuel and water in some superyachts are almost 40% of the hull's displacement, which requires some engineering work to arrange all these volumes.

The idea of designing integrated tanks can have several advantages but also some potential problems. Main advantage certainly is space saving of the internal layout because the tanks are built below deck level and between the longitudinals. Weight savings can be achieved by using the hull bottom and topsides as the tank walls. Lateral stability can be improved because of a reduction in the overall center of gravity, this also offers better seakeeping and an increase in bottom strength.

An important aspect to be evaluated when designing integrated tanks is to consider the strength contribution of the tank structure on the global hull structure: In fact the use of large integrated tanks on motor yachts would be similar to the construction of a double bottom, however the complexity of the structural connections make the analytical solution quite impossible. In this case, it becomes necessary to use numerical methods of analysis in order to obtain approximate solutions, such as the Finite Element Method.

There are not only advantages when dealing with integrated tanks, there is a price to pay for all these benefits. The fabrication of integrated tanks does not allow mistakes and any problems or leaks will be detected only after the tank is closed, making the repair a difficult and expensive job. In the particular case of fuel tanks, it is very important to specify the correct resin type and lay-up schedule to avoid chemical attack to the laminate. Builders cannot allow a tank failure after the boat starts operation. Hydrostatic testing and chemical resistance testing must be performed during construction stages.

TANK DESIGN

There are some critical points designers and builders must consider when they are dealing with integrated composite fuel and water tanks. Items such lay-up schedule, resin chemical resistance and mechanical behavior of the composites must be reviewed. It is important to consider some additional chemical resistance of the original hull construction. Usually, the hull’s last layer produced by infusion method is a multiaxial fabric at 60% fiber content, which is not enough to obtain the maximum chemical barrier. It is recommended to use one or two layers of mat, in addition to original laminate. Over these layers a surface of “C” glass or synthetic veil is applied to provide a resin rich barrier to reduce chemical attack and absorption of water and fuel. After the application of the veil it is essential to avoid direct contact of the air with the cured resin surface, since this is going to reduce the resin's chemical resistance. A coating of resin with paraffin wax is normally applied immediately after the application of the veil.

Regarding chemical resistance it is essential to choose a resin recommended for handling the type of fuel involved, gasoline or diesel. A mistake in this choice would lead to chemical attack of the hull and a serious performance problem in the future. The chemical resistance (CR) evaluation is usually tested with ASTMC-581, and an approved resin is expected to retain at least 70% of its original flexure strength after twelve months immersed in the fuel. Besides this, weight and thickness variation and flexural modulus retention are also evaluated. The resin selected to the test was a modified epoxy vinyl ester resin Derakane due to the excellent resistance to diesel fuel as demonstrated in CR evaluation, shown in Figure 2. Notice that flexural strength and modulus, after twelve months, are still high and that thickness and weight variation are very low.

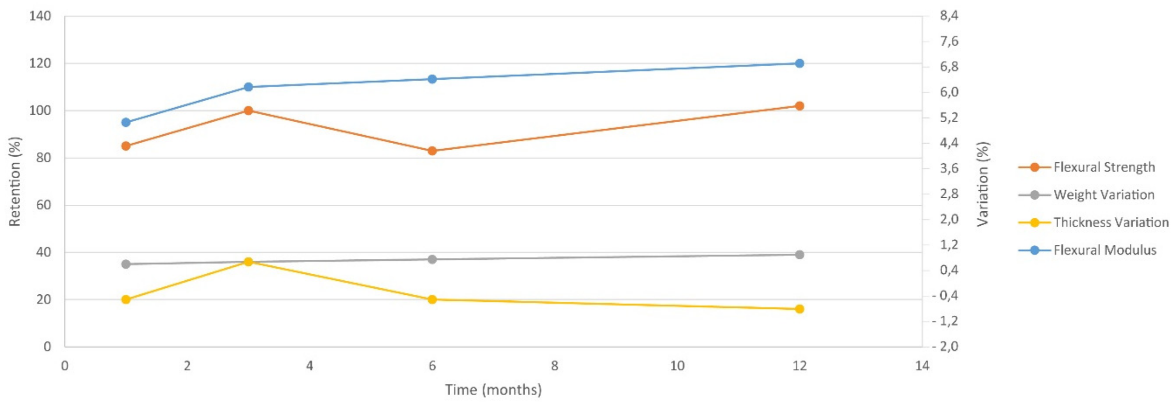

Figure 2 - CR evaluation: 12 months - diesel

Considering the compromise of this kind of construction with the boat life span, it is also essential to consider the mechanical behavior of the resin to be used. Two aspects must be considered during the evaluation: impact resistance and critical stress points. For impact resistance, unreinforced samples of different resins were submitted to an impact and energy test necessary to break the samples as per AST D-3029. The results are shown in Figure 3. The importance of the impact resistance is to avoid micro cracks on the resin matrix. A low resilient resin system could allow the liquid to permeate up to the hull's structural layers, which could accelerate the mechanical properties degradation.

The critical stress point is also important to evaluate the actual maximum stress that the resin system when reinforced can sustain without cracking. This evaluation was carried out through acoustic emission (AE) analysis in six millimeters laminates, and the critical point criteria was considered of 10 events above 70 dB. The results can be seen in Figure 4. From this test can be concluded that when designed to an allowable strain of 0,1%, the laminate made from epoxy vinyl ester resin has safety allowance of approximately 14:1 compared to polyester laminates at approximately 5:1.

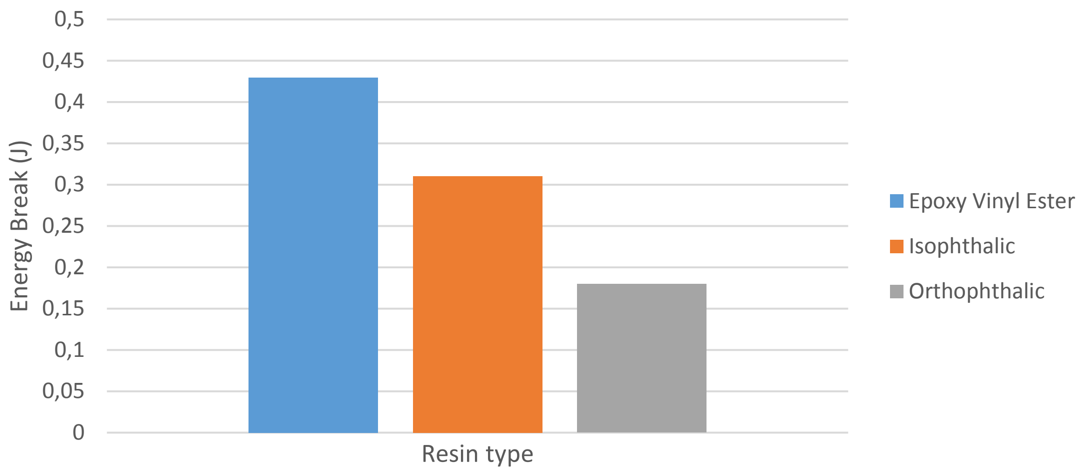

Figure 3 - Impact Resistance

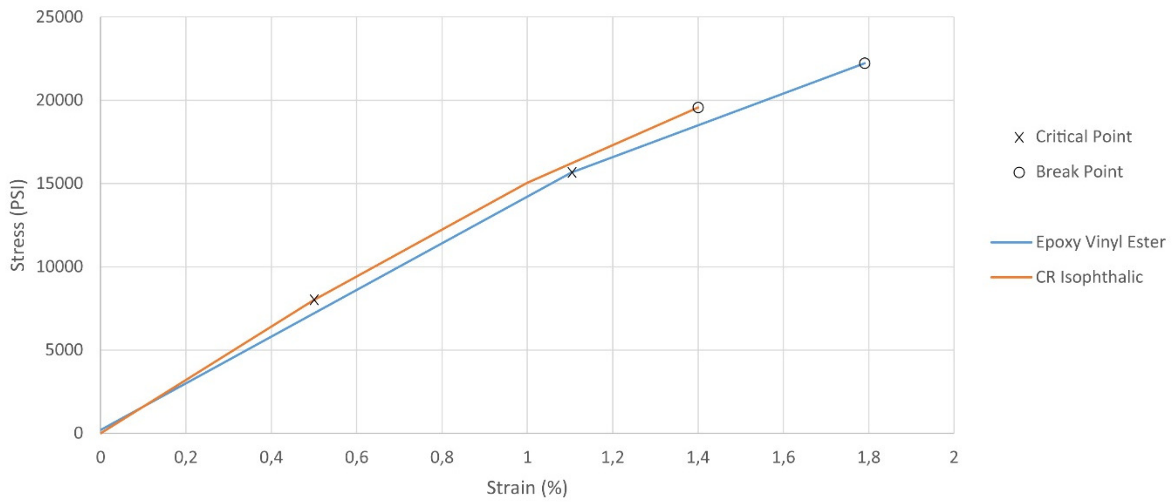

Figure 4 - Critical stress point

INTEGRATED STRUCTURAL TANK CONCEPT

The use of composite integrated tanks in marine industry has increased in the last 20 years, there are some critical points designers and builders must consider. The layup schedule, chemical resistance of the resin and the mechanical behavior of the laminate are the most important items to consider. This paper will cover the study of a 130 feet motor yacht with six integrated tanks, as shown in Figure 5 - Fuel and water tanks. The hull has three diesel and three fresh water tanks totaling over 30.000 liters of liquids. Table 1 shows the capacity of the tanks. The concept of integrated tanks use the hull itself as the structure of the tank and a rich resin layer barrier can be incorporated to allow chemical resistance. The Figure 6 shows the chemical barrier with two extra layers of 300g/m² chopped strand mat, a surface veil to guarantee a rich resin barrier and a coating of resin with paraffin wax. The total weight of the fiberglass integrated tanks is 1.484,56 kg while aluminum tanks to the same capacity has approximately 6.696,00 kg, what represents a reduction of 5.211,44 kg or 4,17% of the total displacement of the yacht.

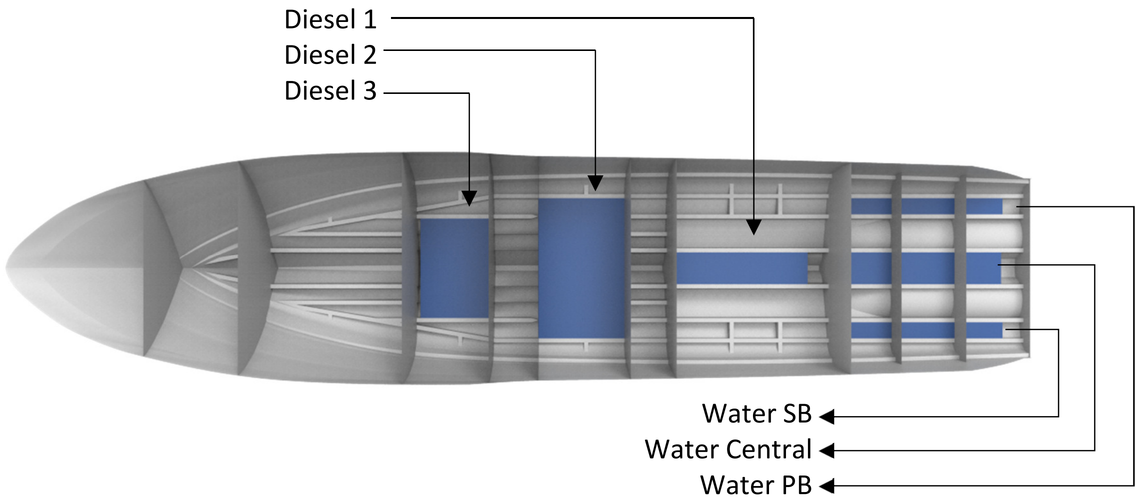

Figure 5 - Fuel and water tanks

Table 1 - Tanks capacity

Tank	Capacity (L)
Diesel 1	5000
Diesel 2	12000
Diesel 3	8000
Water portside	700
Water starboard	700
Water central	4500

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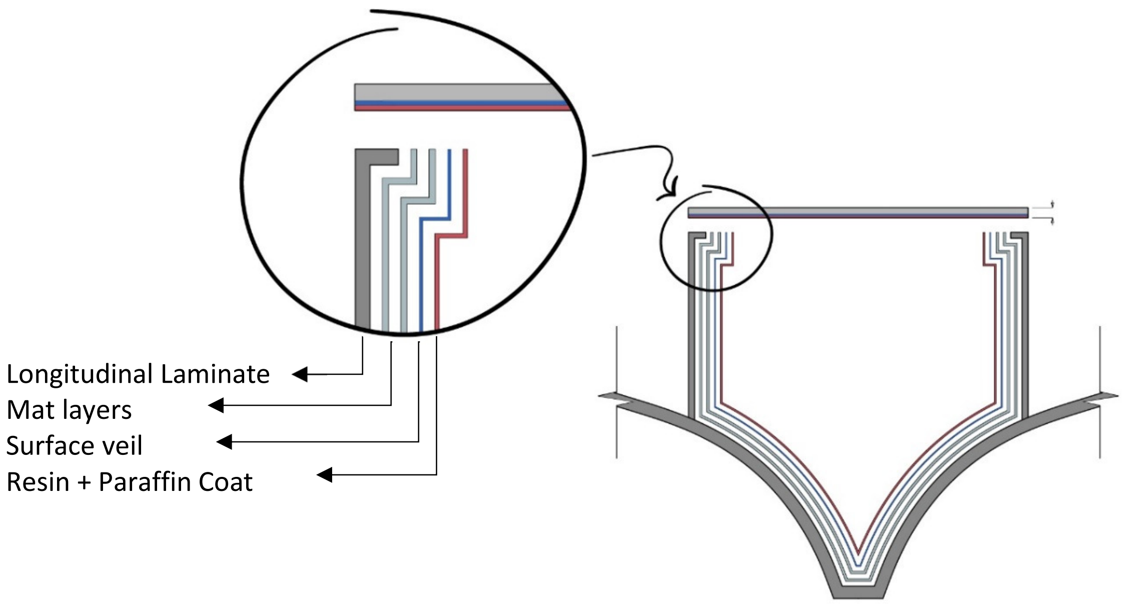

Figure 6 – Integrated tanks reinforcement

STRUCTURAL ANALYSIS

In order to compare the strength contribution of the composite integrated structural tanks a structural analysis of a 130 feet motoryacht was performed. The boat is a three deck profile with 125 tons of displacement and powered by two 1825 HP diesel engines. The maximum cruise speed of the boat is considered 28 knots. Total water tank capacity is 5900 kgs and fuel capacity of 25000 kgs. Riostar Boatworks in Rio de Janeiro Brazil engineered and built the yacht. A profile for the boat is shown in Figure 1. The boat was built under vacuum infusion system using fiberglass multiaxial fabrics, vinyl ester resin and PVC foam core. The structural arrangement is completed by the installation of 4 longitudinal frames in the engine room and 6 longitudinal frames ahead of engine room and slamming area. A set of 6 transversal bulkheads and 4 open frames, composite floors, dividers, and interior furniture all integrated to the main structure complete the structural arrangement. All parts built by vacuum infusion system. Structural tanks are located in the entire bottom area between longitudinal. A set of composite baffles and a tank top panel were also laminated along the tank providing a solid box structure for the bottom.

MODELING

Two different models of the same boat were created to compare the results of strength contribution and the weight reduction on the hulls bottom. The first model consider the hull bottom, hull sides, stringers and bulkheads and the second models, the same parts of first model with the integrated composite tanks. Figure 7 and Figure 8 shows both models used in the structural analysis.

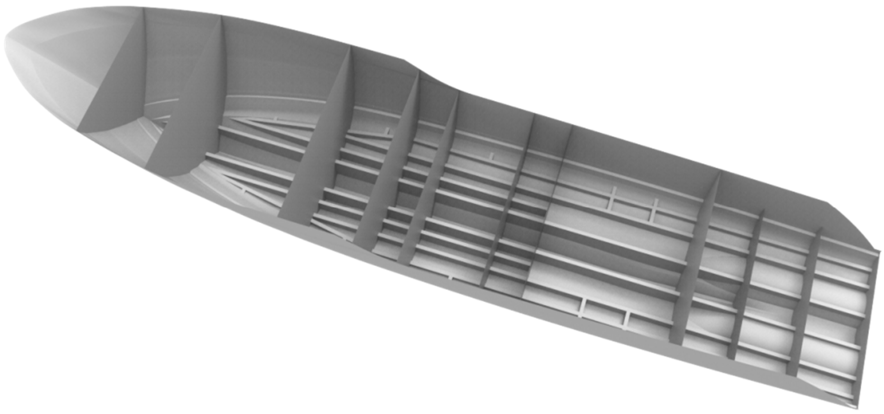

Figure 7 - Hull structure

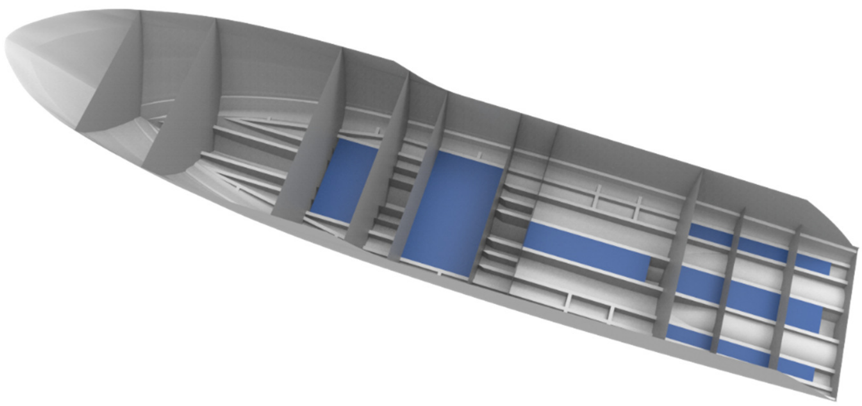

Figure 8 - Hull structure with integrated tanks

HULL COMPOSITE CONSTRUCTION

The hull bottom, sides and bulkheads are constructed in sandwich material, built in fiberglass skins with 100 kg/m³ PVC foam core and the stringers has a solid/cored fiberglass laminate. The Figure 9, Figure 10, Figure 11 and Figure 12 show the respective areas of each component.

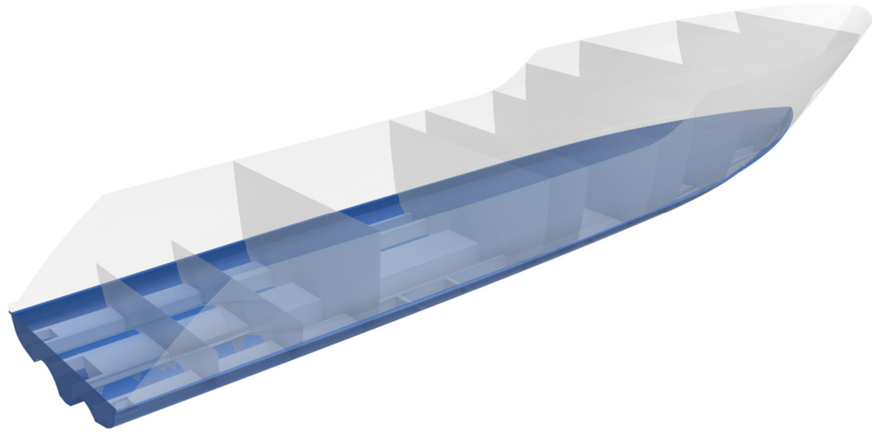

Figure 9 - Hull's Bottom

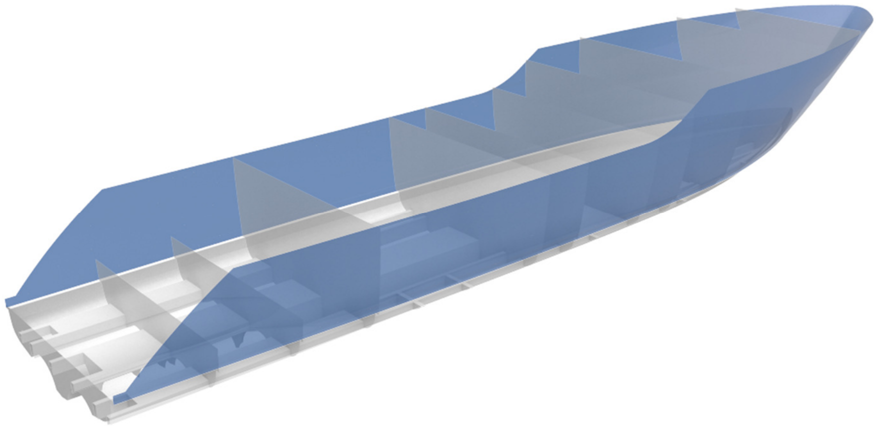

Figure 10 - hull's side

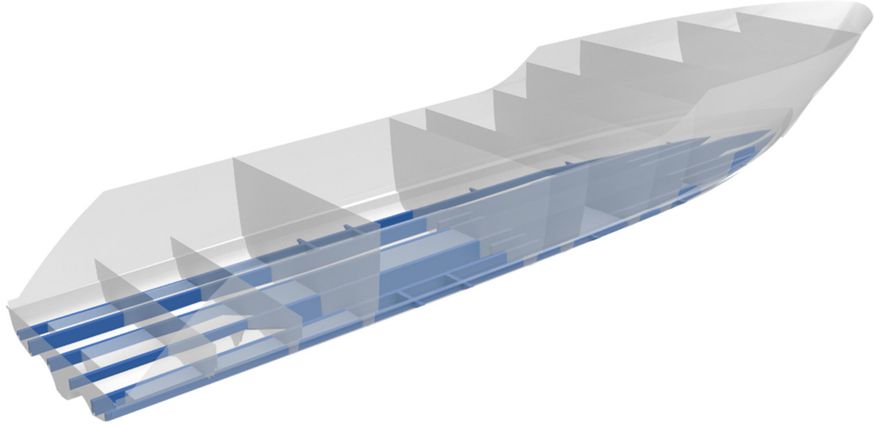

Figure 11 - Stringers

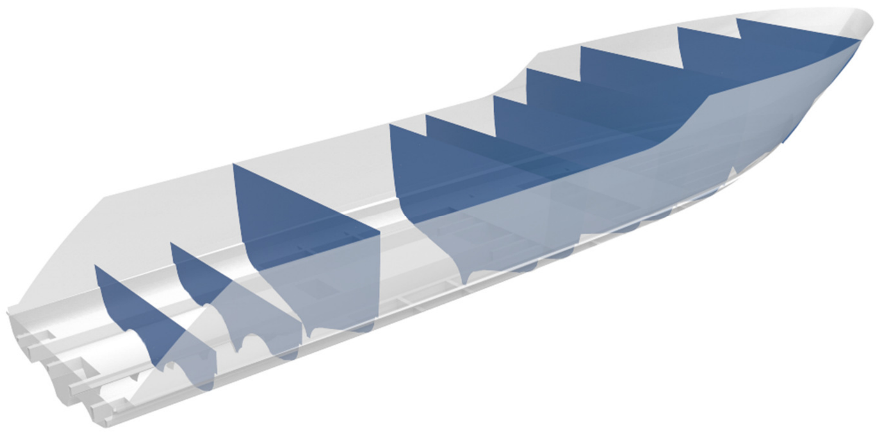

Figure 12 - Bulkheads

SLAMMING LOADS

In order to determinate the loads applied in the bottom surface due to slamming loads the works of Heller and Jasper [1], Savitsky and Brown [2], Allen and Jones [3], and Spencer [4] were used to calculate the values of slamming and dynamic pressures.

Wave Loads [P_s]

$$P_s = 9{,}807 * n * \left[T + \left(\frac{C_w}{X_i} + h_2\right) - z\right] \geq P_{dmin}$$

Where:

C_w = wave height, in m, to be taken equal to:

- $C_w = 10*\log(L_w) - 10$ for $L_w >= 18$ m
- $C_w = 0{,}65*L_w + 1{,}5$ for $L_w < 18$ m

X_i = Wave load coefficient, defined in Table 2, in relation to the area considered

z = Height, in m, of the calculation point, measured as defined in Figure 14 in relation to the type of yacht

h_2 = Distance, in m, equal to:

- For bottom and external side shell of hull:
  $h_2 = 0$
- For internal side shell of catamaran and bottom of cross deck of catamaran:
  $h_2 = (B_w\left(T + \frac{C_w}{X_{wi}}\right) * C_B)/B_i$

n = Coefficient depending on the navigation notation

Table 2 - Wave load coefficient

Type of Yachts	Area 4 X_4	Area 3 X_3	Area 2 X_2	Area 1 X_1
Monohull motor yacht	2,8	2,2	1,9	1,7
Monohull sailing yacht	2,2	1,9	1,7	1,4
Multihull motor yacht	2,8	2,2	1,9	1,4
Multihull sailing yacht	2,5	2,2	1,7	1,2

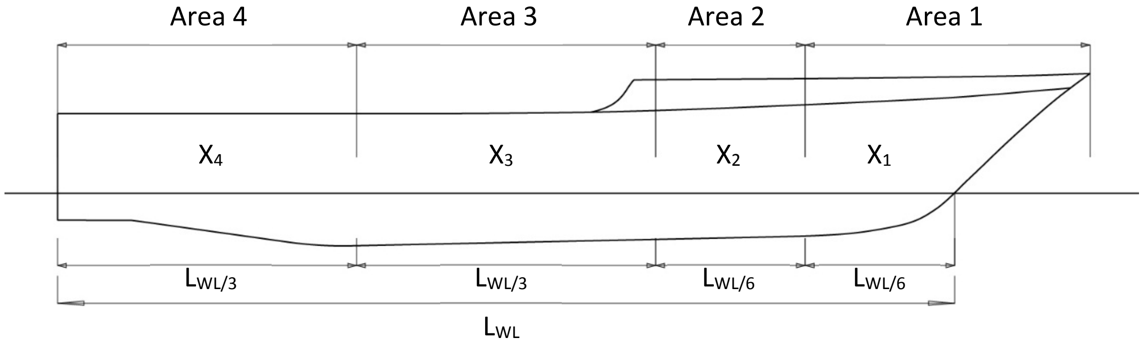

Figure 13 - Load areas and coefficient X_i for the sideshell and bottom sea pressure

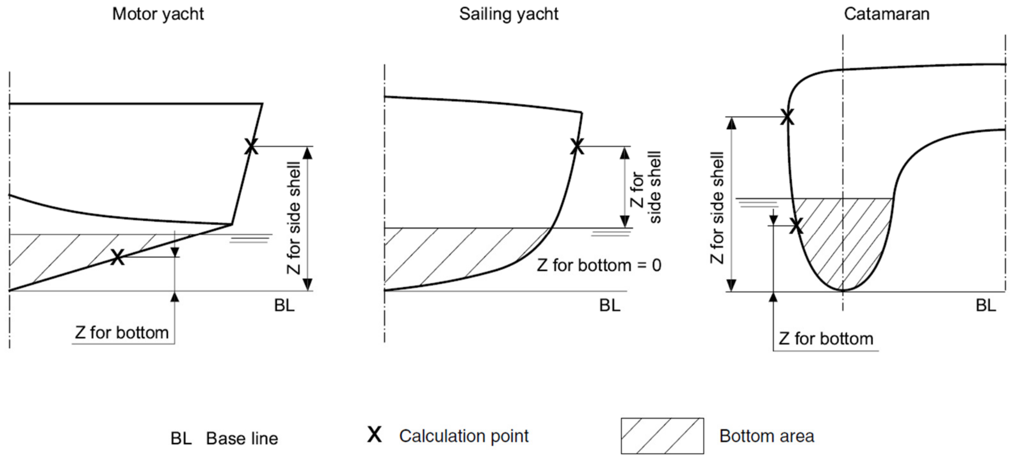

Figure 14 - Vertical distance z

Dynamic loads [P_{sl}] are calculated taking into account the different coefficients K_1, K_2 and K_3.

Distribution factor K_1, aka: longitudinal slamming pressure distribution factor K_1 for the calculation of the slamming of high speed motor yacht in planning hull mode is defined by the following formula or by Figure 15.

- For $x/L_{WL} < 0,5$: $k_1 = 0,5 + x/L_{WL}$
- For $0,5 <= x/L_{WL} <= 0,8$ $K_1 = 1,0$
- For $x/L_{WL} > 0,8$ $K1 = 3,0 – 2,5*x/L_{WL}$

Where:
x = Distance, in m, between the aft end (AE) and the bottom transversal section considered.

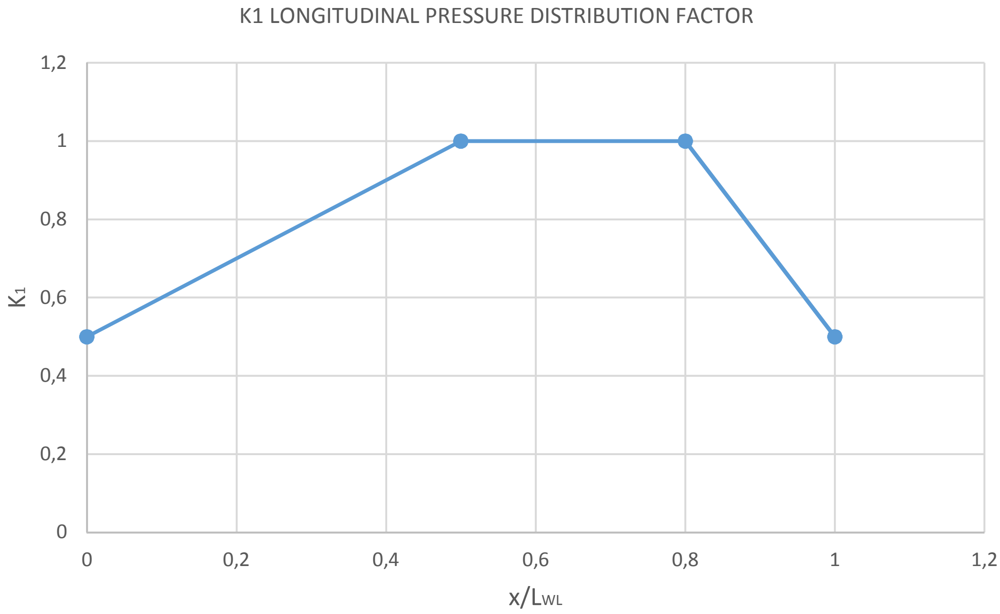

Figure 15 - K_1 distribution factor

	Area 4	Area 3	Area 2	Area 1
x/L_{WL}	0,33	0,67	0,84	1
K_1	**0,83**	**1,00**	**0,9**	**0,50**

Table 3 - K_1 Value

Area factor K_2

The factor K_2 is a coefficient taking into account the dimension and the material of the structure element submitted to bottom slamming load or side shell and cross deck impact. This factor is defined by the following formula:

$$K_2 = 0{,}455 - 0{,}35 * \frac{U^{0,75} - 1{,}7}{U^{0,75} + 1{,}7} > K_{2min}$$

With:

$$u = 100 * \frac{S_a}{S_r}$$

Where:

S_a = Area, in m², supported by the element (plating, stiffner, floor or bottom girder)

S_r = reference area, in m², equal to:

$$S_r = 0{,}7 * \frac{\Delta}{T}$$

With K_{2min}:

For composite and plywood structure, and for plastic sidescuttle:

K_{2min} = 0,35.

	Value	Unit
S_a	89,35	m²
S_r	64,57	m²
K_2	**0,133**	-

Table 4 - K_2 calculation

Since $K_2 < K_{2min}$

$K_2 = 0{,}35$.

Bottom shape factor K_3 for all types of yacht

The bottom shape and deadrise factor K_3 for the calculation of the bottom slamming of high speed yacht and for the bottom slamming of monohull sailing yacht is defined by the following formula:

$$K_3 = \frac{50 - \alpha_d}{50 - \alpha_{dCG}} \leq 1$$

Where:

α_{dCG} = Deadrise angle, in degrees, measured at ship's longitudinal centre of gravity L_{CG}, as shown on Figure 16.

α_d = Deadrise angle at the considered transversal section, in degrees, measured as shown on Figure 16.

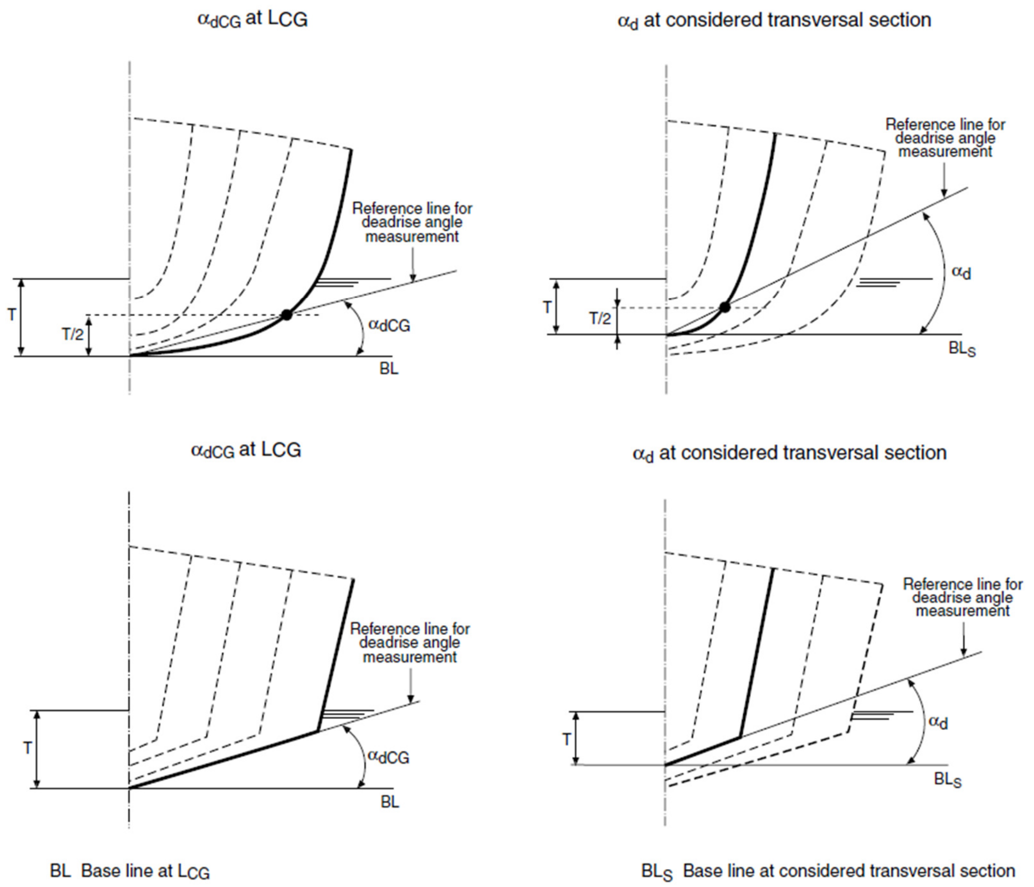

Figure 16 - Deadrise angle

Table 5 - K_3 value

	Unit	Area 4	Area 3	Area 2	Area 1
α_d	Degrees	47,2	32,1	35,2	46,1
α_{dCG}	Degrees	37,0	37,0	37,0	37,0
K_3	-	0,22	1,38	1,14	0,30
K_3'	**-**	**0,22**	**1,00**	**1,00**	**0,30**

Bottom slamming for motor yacht

$$P_{sl} = 70 * \frac{\Delta}{T} * K_1 * K_2 * K_3 * a_{CG}$$

Where:

a_{CG} = Design vertical acceleration at L_{CG}

*According to the Table 4 of Ch 4, Sec 3 of the 4760.5.NR500_2012-03 regulation, the maximum value of a_{CG} for cruise motor yacht is considered 1,0g.

The total loads on each area is defined in Table 6.

Table 6 - Loads on hull's bottom

Loads	Unit	Area 1	Area 2	Area 3	Area 4
Wave Loads [P_s]	kN/m²	38,636	35,178	31,171	25,732
Dynamic Loads [P_{sl}]	kN/m²	6,675	45,893	60,078	11,126
TOTAL	**kN/m²**	**45,311**	**81,071**	**91,248**	**36,857**
	PSI	**6,570**	**11,755**	**13,231**	**5,344**

The load distribution is shown is Figure 17.

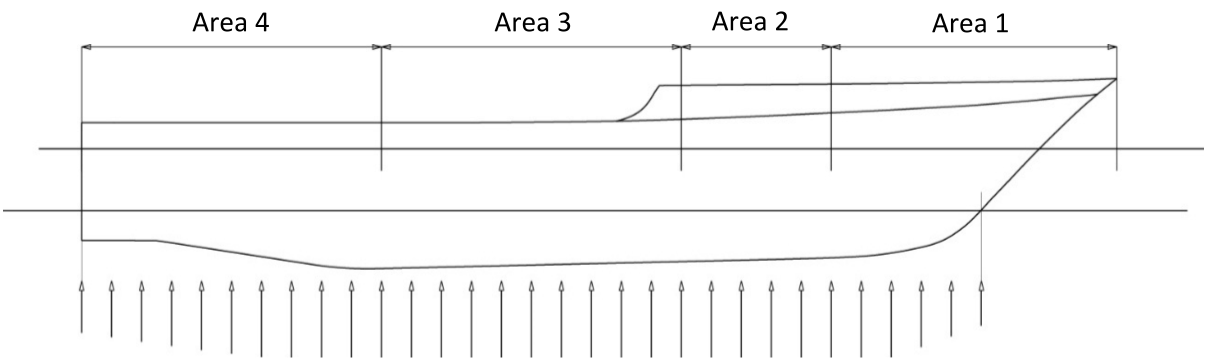

Figure 17 - Load distribution

RESULTS

To compare the results of the analysis, the maximum stress, displacement and strain of each component were analyzed. As seen in Figure 18 and Figure 19, the maximum stress and displacement are in the area 3 which is near the engine room area.

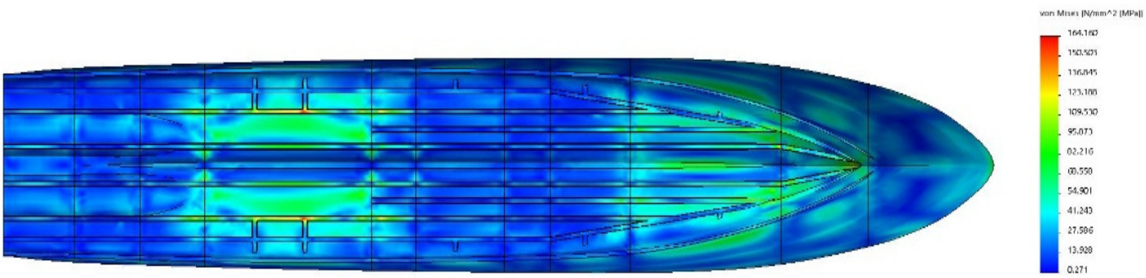

Figure 18 - Maximum stress analysis to the version without tanks

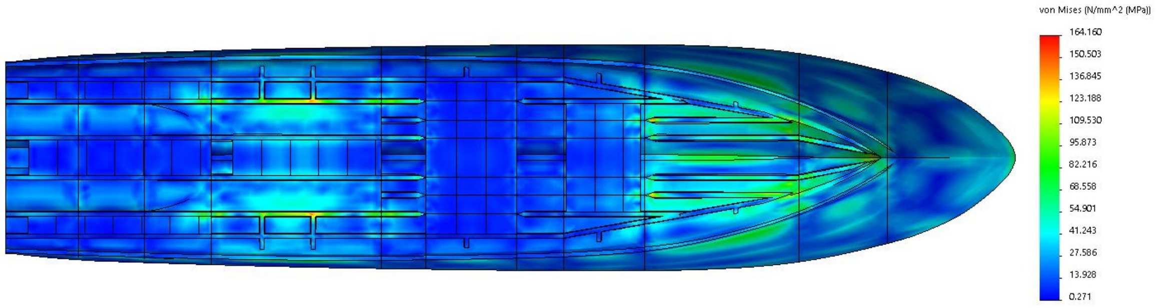

Figure 19 - Maximum stress analysis to the version with integrated tanks

The analysis showed a low stress level in the entire bottom structure. The Table 7 presents the maximum values for stress and displacement to each component of the hull's structure.

Table 7 - Analysis results

Component		Maximum Stress (MPa)	Displacement (mm)
Hull's bottom	Version without Tanks	110,06	73,46
	Version With Integrated Tanks	88,19	54,86
Hull's Side	Version without Tanks	82,29	50,13
	Version With Integrated Tanks	72,26	40,38
Stringers	Version without Tanks	164,16	72,06
	Version With Integrated Tanks	131,17	54,67
Bulkheads	Version without Tanks	132,06	13,26
	Version With Integrated Tanks	112,46	8,27

Figures 20, 21, 22 and 23 show the graphics difference of displacement of the engine area for the analysis with the versions without tanks and with integrated tanks.

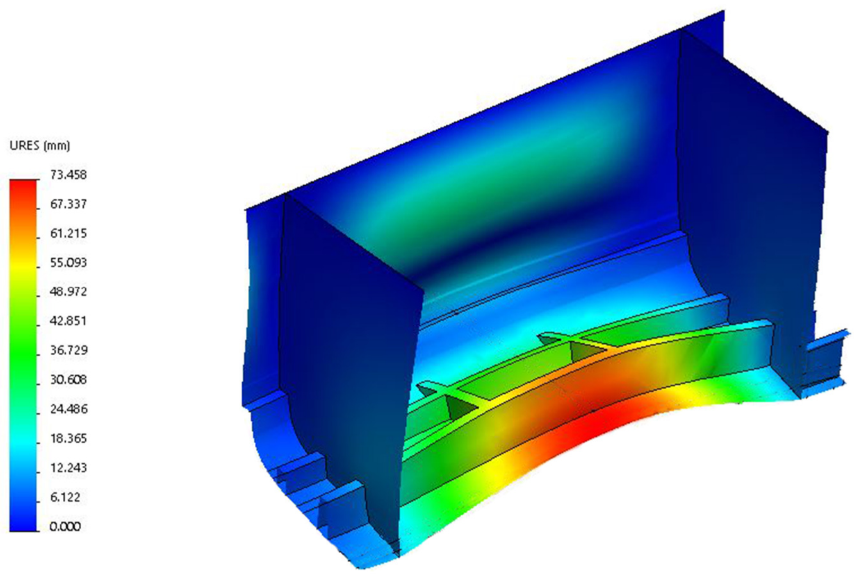

Figure 20 - Hulls' botton and strigers displacement in the version without tanks

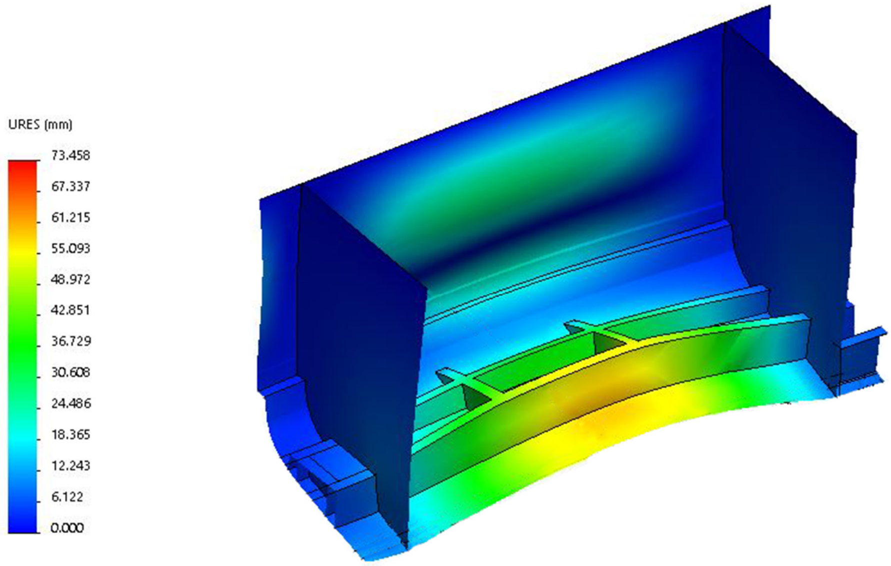

Figure 21 - Hulls' bottom and stringers displacement in the version with integrated tanks

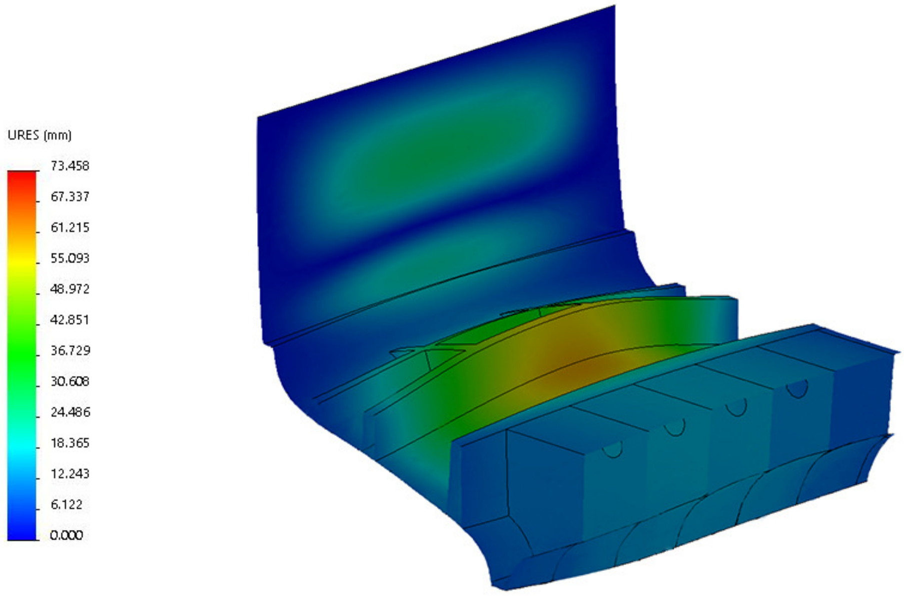

Figure 22 – Displacement at Integrated Fuel Tank area

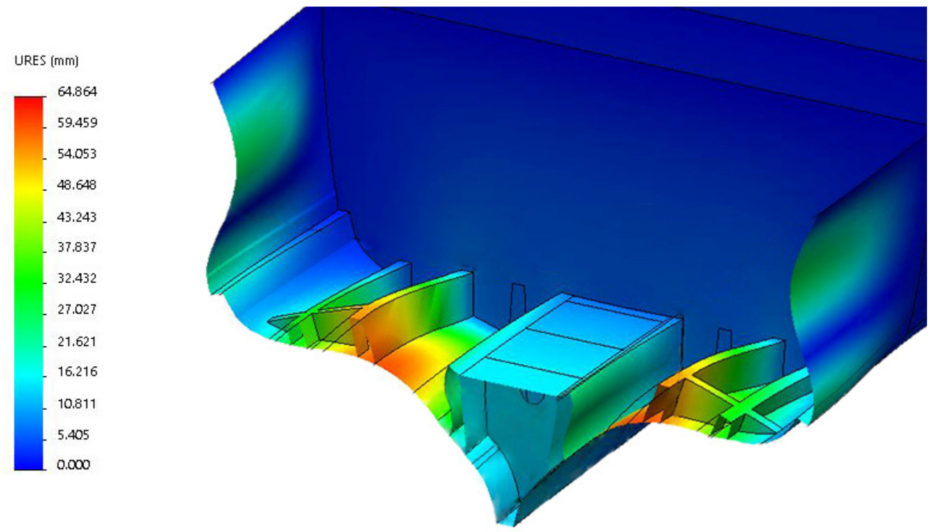

Figure 23 - Displacement at Integrated Fuel Tank area

CONCLUSIONS

Based on the study and analysis performed, the following points can be highlighted.

- By using integrated composite tanks on the 130 feet motor yacht, a substantial structural weight savings was obtained. There will be a weight saving over 4% of the total displacement.

- By using integrated tanks, it was also possible to save approximately 8 % of internal space when compared with tanks built conventionally. The space optimization using a double bottom provide a real upgrade for the interior arrangement.

- Regarding structural behavior, the use of integrated tanks allows a reduction of the stress level in the entire bottom structure, offering a possibility for laminate optimization, which can increase speed and performance. The overall improvement in rigidity was around 40%. The study shows also that the boat with integrated tanks provide a higher safety factor.

- On the other side, the use of integrated tanks requires a rational design for stress prediction and the use of a high performance resin to guarantee the integrity of both hull and tank structure during the life span of the vessel.

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