

ON ADVANCED GLOBAL STRENGTH ANALYSIS OF A PLEASURE YACHT BY USER’S PROCEDURES IMPLEMENTED IN FEMAP / NX NASTRAN

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ABSTRACT

The objective of this study is to analyze the global structural strength of a pleasure yacht by advanced FEA approach. This is accomplished by developing and implementing a user FEMAP API script for equilibrating the FEA ship model, in calm water and sagging and hogging wave conditions, for different wave design heights, up to a maximum height of 6.5 meters. The FEA strength is assessed by yielding stress and buckling criteria.

Keywords: yacht, unrestricted navigation, head waves, Femap API user’s script.

1. INTRODUCTION

In this study, the global strength of a 75.6m pleasure yacht is analyzed, using FEMAP API user’s scripts [1] to equilibrate the FEA model structural in different sea state conditions.



Fig.0 General view of the yacht design.

The main characteristics of the yacht are:

- Maximum length 75.6 m;
- Unrestricted navigation;
- Pleasure yacht,
- Monaco-Panama route, range of 6500 NM;
- Autonomy 30 days;
- 12kn cruise speed;

- 17kn max speed at full load;
- 12 passengers with accommodations.

1.1 Ship main data

To determine the initial dimensions of the ship, we used the Watson method [3]. A yachts database with 200 vessels was used to generate graphs with relations between the principal dimensions, presented from **Fig.1** to **Fig.3**. Final dimensions that fit the yacht requirements are presented in **Table.1**.

Table.1 Yacht principal dimensions.

Dimension	Value	Unit
LOA length overall	75.6	m
LBP length bet.perp.	70.0	m
B design breadth	12.0	m
T design draft	3.5	m
D design height	6.0	m

The ship will be built under Cayman Island flag and will be classified by Bureau Veritas [2] with the class notation:

I ✕ HULL ✕ MACH, YACHT-MOTOR-S, UNRESTRICTED NAVIGATION, AUT-UMS

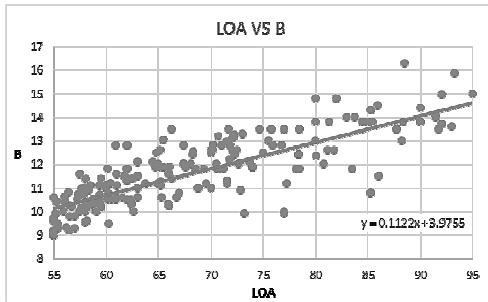


Fig.1 Yachts database LOA vs B

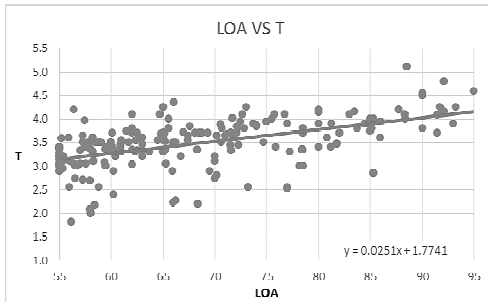


Fig.2 Yachts database LOA vs T

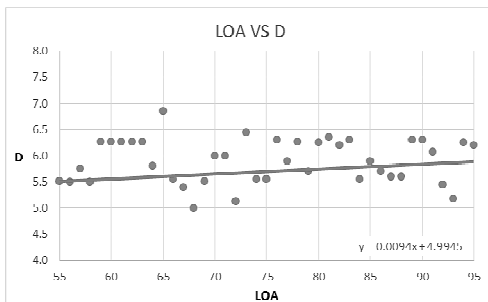


Fig.3 Yachts database LOA vs D

1.2 Lines plan

The design intended for the yacht's exterior was to be a modern looking, with elements that are unique to this project, and fitted with all the owner's requirements, without being too eye-catching. No bulbous bow was fitted to the hull shape. The ship has twin propeller propulsion, so the aft area of the ship must be raised enough to allow an adequate propeller-sized disk to be fitted. The hull forms are very fine, without any visible midship zone. The hull form lines are presented in Fig.4.

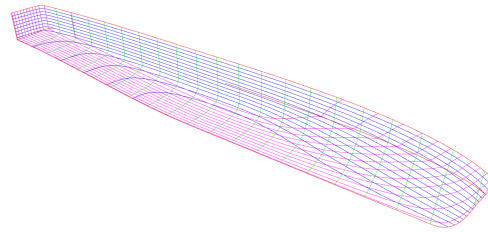


Fig.4 3D Lines plan of the yacht

1.3 General arrangement plan

To assess the space requirements and determine the overall location of the structural elements on the ship, a Vessel General Arrangement Plan is developed. Special care was taken to provide the maximum comfort for the passengers. Listed below are the main onboard arrangements:

- Cinema, main dining room, tender storage;
- Big owner suite with a view of the bow and pool;
- Private owners dining room and office;
- Passengers' guests' cabins accommodation;
- Lift for guests;
- The crew in single cabins accommodation;
- The crew area is separated from the guest area as much as possible;
- Pool and Jacuzzi.

1.4 Deadweight estimation

To estimate the fuel requirement, a preliminary power and speed prediction is performed. The ship is designed to reach a maximum speed of 17kn, with the cruising speed at 12kn. For crossing the Atlantic Ocean, a sea margin of 15% was adopted for the ship resistance. The method for estimating the ship's resistance is Holtrop-Mennen's. The results are presented in Table.2.

Table.2 Holtrop-Mennen resistance prediction

v_s [kn]	Fr [-]	R_T (w/o SM) [kN]	R_T (w/ SM) [kN]
12.0	0.2356	80.45	92.52
13.0	0.2552	100.05	115.06
14.0	0.2748	125.88	144.76
15.0	0.2945	154.07	177.18
16.0	0.3141	180.88	208.01
17.0	0.3337	212.61	244.50

Using Wageningen B-Series Propellers diagrams, the propulsion coefficient can be estimated in these early stages of the project. The propeller diameter is 2m, with 5 blades. The wake coefficient w is 0.15, with a thrust deduction factor t of 0.12 and an expanded area ratio A_E/A_0 of 0.7. The shafting efficiency η_s is taken at 0.98% and a gearbox with a gearing efficiency η_G of 0.95 is considered. The final propulsion and power characteristics are presented in **Table.3**.

Table.3 Propulsion coefficients estimation

v_s [kn]	J [-]	P/D [-]	K_T [-]	K_Q [-]	n [rpm]
12	0.700	1.070	0.228	0.041	225
17	0.619	1.009	0.235	0.039	360
v_s [kn]	η_o [-]	P_T [kW]	P_D [kW]	P_S [kW]	P_B [kW]
12	0.628	276	448	457	481
17	0.593	1033	1775	1811	1906

The power used for dimensioning the installed engines is $P_B = 1906\text{kW}$ per engine, to reach the required 17 knots. The chosen engines are two Caterpillar 3516C, 1995kW, V-16, 4-Stroke-Cycle-Diesel engines. The power used for fuel capacity estimation is $P_B = 481\text{kW}$, the power used to ensure the ship at the cruising speed of 12 knots. Considering the fuel needs for propulsion and the onboard electrical facilities, along with all the needs for various tanks, the minimal capacities for tanks are presented in **Table.4**.

Table.4 Minimal tank capacities

Tank	Volume	Unit
DO Tank	200.0	m ³
DO Overflow Tank	10.0	m ³
FW Tank	39.0	m ³
Urea Tank	14.0	m ³
Lube Oil	3.3	m ³
Dirty Lube Oil	3.3	m ³
Sewage Tank	19.5	m ³
Bilge Tank	4.0	m ³
Sludge Tank	0.8	m ³
Water Mist Tank	13.0	m ³
Jacuzzi Water Tank	15.0	m ³
Pool Water Tank	45.0	m ³

1.5 Lightship weight estimation

A CAD Rhino model, **Fig.5**, was used to model a basic arrangement of enclosed volumes, used for estimating the steel weight for the yacht.

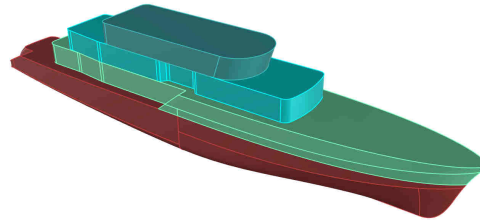


Fig.5 Volumetric model used for steel lightship weight estimation

The equivalent coefficients for panels density were chosen, one for the volumes below the Main Deck and another for the volumes above the Main Deck. An additional 7% contingency for panels weight is added to account for the early stage of the estimation. The weights and equivalent coefficients used for the estimation are presented in **Table.5**.

Table.5 Preliminary panels weight estimation

Volume below	Volume [m ³]	Coef. [t/m ³]	Weight [t]
Main Deck	3476	0.110	382.4
Upper Deck	1713	0.075	128.5
Sun Deck	971	0.075	72.9
Mast Deck	610	0.075	45.7
TOTAL W_{ST}			629.4
TOTAL $W_{ST} + 7\%$ Contingency			673.5

The rest of the lightship categories, such as outfitting, and machinery can be estimated as percentages, based on values from statistical data [3]. A table with the resulting weight groups and their percentage of lightship is presented below in **Table.6**, along with the resulting percentages from the lightship.

Table.6 Lightship weight distribution

Weight group	Weight	Unit	% from W_L
Displacement	1722.2	t	-
W_L	1354.6	t	-
W_{ST}	673.5	t	50%
W_{OT}	392.8	t	29%
W_M	288.3	t	21%

1.6 Ship compartmentation

Considering the web frame spacing of the yacht is every fourth frame, every bulkhead is placed in the location of a web frame. For damage stability reasons, the position of the transverse bulkheads must be such as to split the ship into zones with volume as even as possible. The following transversal bulkheads location were chosen:

FR12, FR28, FR52, FR76, FR100, FR120, FR132 (Collision bulkhead)

A double bottom was fitted to ensure enough volumes for tanks and to ensure the ship damage stability criteria to be satisfied. The Tank Top deck height was kept at a minimum of 2.5m, with estimated headroom of 2.2m, and the Lower Deck height is at 2.8m.

1.7 Tanks arrangement plan

Tanks compartments are arranged in such a way that they respect the following rules or recommendations:

- Cofferdams must be placed between fuel oil tanks and lubrication oil, and between hydrocarbon tanks and freshwater or liquid foam for fire-extinguishing systems.
- The tank for urea cannot be adjacent to fuel oil or freshwater tanks. Additionally, the walls of the urea tank cannot be adjacent to the sea and need to be kept away from high temperatures.
- DO tanks adjacent to ER, for ease of access to fuel storage.

- DO not adjacent to accommodation compartments.
- Deadweight is spread across the ship as much as possible and placed in a way that the utilization of the deadweight elements, in all loading conditions doesn't affect the trim or stability of the ship.
- The tanks are placed symmetrically from the CL, so the displacement does not induce any healing moment to the ship, in any loading case.
- Special care was taken to ensure adequate access to tanks for inspections and maintenance and ensure enough height for strengthening elements.

1.8 Loading cases definition

For each of the 3 loading cases considered, Lightship (LSW), Departure (DEP) and Arrival (ARR), a different set of tanks are loaded, with different percentages. For each loading case, a summary of the total deadweight and its centroid position can be seen in **Table.7**.

Table.7 Loading cases deadweight summary

WEIGHT [t]	LCG [m]	TCG [m]	VCG [m]
LIGHTSHIP CASE			
0.000	0.000	0.000	0.000
DEPARTURE CASE			
367.523	24.075	0.000	1.858
ARRIVAL CASE			
71.016	31.334	0.000	1.567

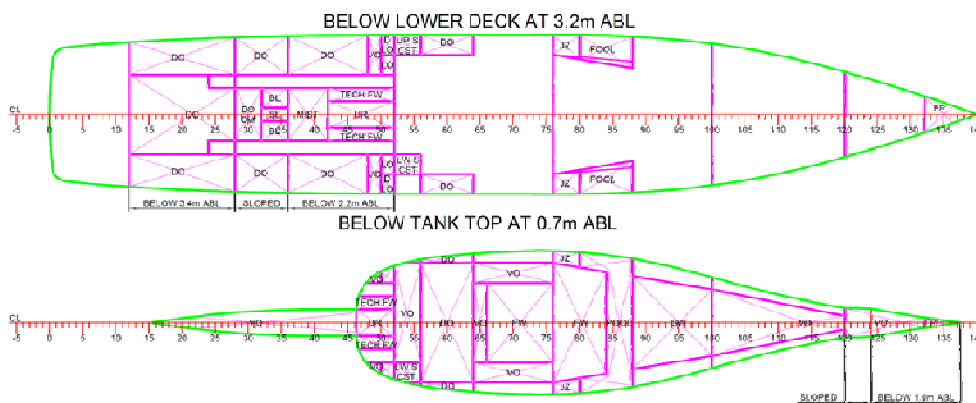


Fig.6 Yacht tank arrangement plan

1.9 Ship scantling

The ship is built using a longitudinal framing system below the Main Deck, and the superstructure in combined system with the walls in transverse framing and decks in longitudinal framing. The material used for scantling is steel type A.

Ordinary frame spacing was adopted at $a_0=500\text{mm}$ with web frames spaced at $4 \times a_0=2000\text{mm}$, starting from FR0, at the transom. The longitudinal spacing used is also of 500mm.

Bulkheads are placed on the web frame's location. The fore of the ship, starting from FR.120, is built in a transversal system.

The structure calculation was performed with Mars 2000 software from BV [3] and in Excel. The resulting midship section is presented in Fig.7.

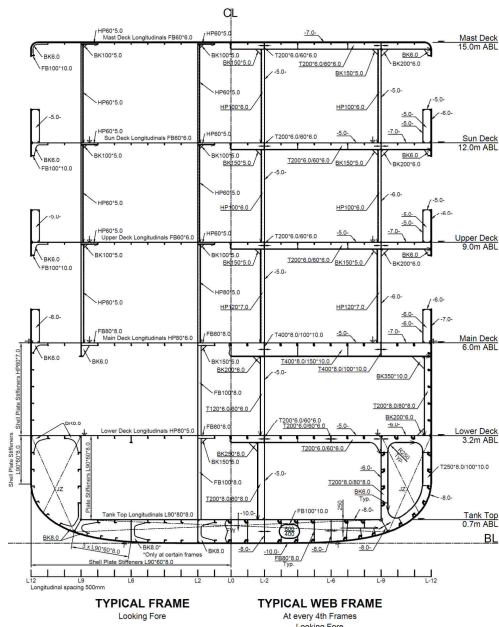


Fig.7 Yacht Midship Section

2. USER API PROCEDURES

2.1 Rhino FEM model export/import script

This method of importing a FEA model from Rhino geometry to Femap elements [4] consists of two scripts. The first one, a Python script for CAD Rhino model, exports the geometry into a text file with element information that can be read into Femap using a second Femap API user script [1].

The script is most suitable for small to medium-sized FEA models that are made using coarse mesh sizing but is not limited to other types of projects. This is due to the vast manual amount of work required to split the surfaces into individual elements.

The script can be used to import plate and beam-type elements with certain common shapes. The material is automatically created along with all the element properties used in Rhino, with information from the layer names. The beam elements are also automatically positioned accordingly in 3D FE model, adjusting their neutral axis with information from Rhino positioning. The beam element types that can be used are Flat Bars, L-shaped profiles, and T-shaped profiles. For beam elements, an additional curve is added that will indicate the direction of the element. It can also have an arrowhead added in Rhino, to better illustrate the desired direction as presented in Fig.8.

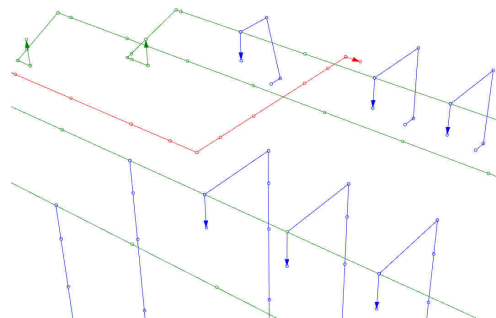


Fig.8 Beam elements direction curves

The Python script will ask for a selection of surfaces and curves that represent the plates and beam elements. An example of model for this script is in Fig.9.

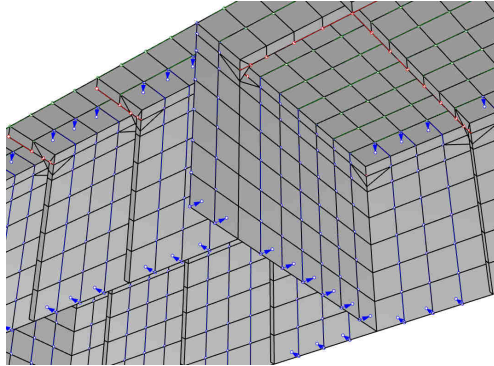


Fig.9 Rhino Overview of plates and beam elements polylines.

The layers names for the Rhino model, used to extract elements properties is presented in Fig.10.

Mast_Deck_plate-7.0			
Mast_Deck_coaming_plate-7.0			
Mast_Deck_int_walls_plate-5.0			
Mast_Deck_deck_LG_PSM-6.0			
Mast_Deck_deck_FR_PSM-6.0			
Mast_Deck_deck_PSM_FB60x6-FB60x6.0			
Mast_Deck_deck_LG_FB60x6-FB60x6.0			
Mast_Deck_deck_FR_FB60x6-FB60x6.0			
Mast_Deck_ext_walls_plate-5.0			
Mast_Deck_ext_front_walls_plate-6.0			
Mast_Deck_BK200x6-6.0			
Mast_Deck_BK150x5-5.0			
Mast_Deck_int_LG_HP60x5-L60x16.3x5x10.5			
Mast_Deck_int_FR_HP60x5-L60x16.3x5x10.5			
Mast_Deck_int_LG_PSM_HP100x6-6.0			
Mast_Deck_int_FR_PSM_HP100x6-6.0			

Fig.10 Rhino layer names with properties

To import the geometry into Femap, an existing, already populated file or an empty one can be used. The import script will ask the user for the text file generated with the script described above. It then proceeds to create a material property that will be used in the property definitions that will be imported.

If the material with the name “Steel-A” is already created, it will use the existing one.

Each property is created, with the thickness or shape from the export file. For beams, the direction vector calculated by the Python script is used to change the property information and have it placed correctly. If a property with the same name already exists in the model, the existing one will be used instead. The FEMAP model after import is presented in Fig.11 and Fig.12.

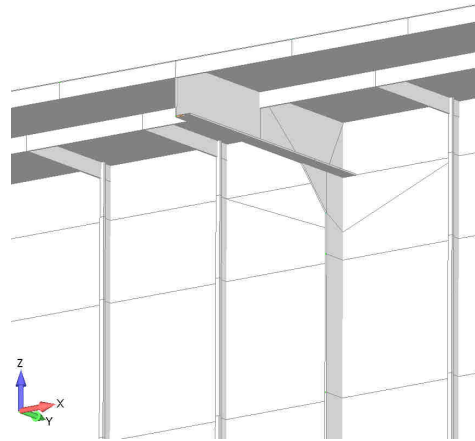


Fig.11 Femap import result

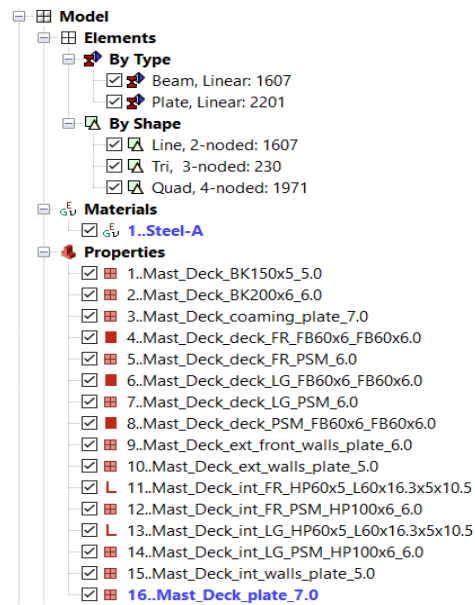


Fig.12 Femap import result, model properties

2.2 Ship equilibration script on head wave

This script is created specifically for balancing a ship model, only half of it, on a head wave, using an iterative procedure. The result is an equilibrated model with a combined residual reaction force, on the Z axis, of no more than 10N on the control nodes.

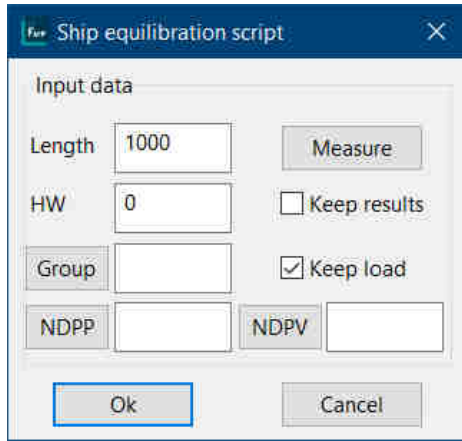


Fig.13 Ship Equilibration script user interface

In Fig.13 the interface of the script shows the input data required for running the script. It also displays a set of options for dealing with the analysis results and the final load. Loads that must be added to the ship (example: cargo, water ballast, fuel, etc.). There can be added to the same loads set and are taken into consideration when going through iterations. It will not be deleted. Only the equiv. quasi-static load added by the program will be deleted between iterations. Hogging and sagging wave condition can be controlled by the sign of the *HW*.

NDPP and NDPV, control nodes at aft and fore peak (master nodes) [5], must have their Z-axis displacement constrained, because reaction forces that appear there will be monitored by the program.

Other boundary conditions can be placed (mirror X0Z plane) but for the program to work correctly, only the two nodes mentioned must have the Z-axis displacement fixed. The NDPP node has also the longitudinal displacement restrained [5].

The script uses two loops, one for checking the draft and one for checking the trim [5]. An initial Analysis set must be made, and it will be used by the script to check the reaction forces on the nodes. After each Draft change, the analysis will be run again, it will check the results, and delete the results before proceeding to the next iteration. The script flow chart is presented in Fig.14.

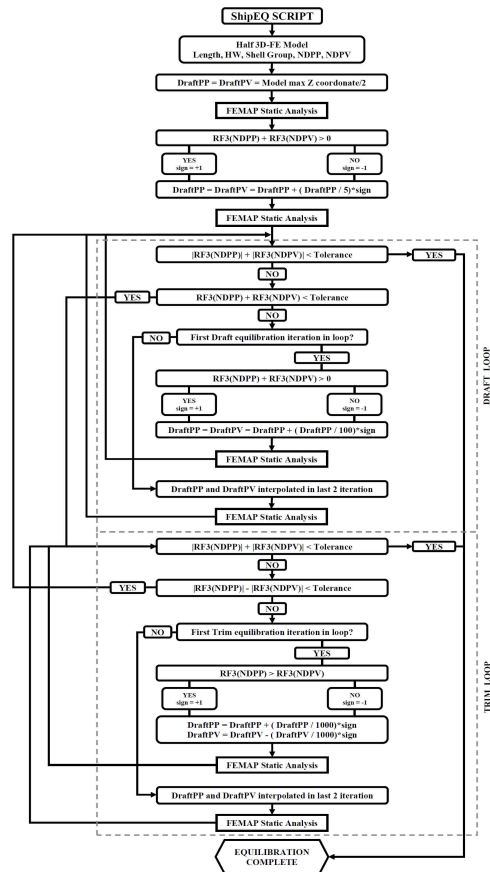


Fig.14 Ship equilibration script flow chart

The main disadvantage of this script, at this moment, is the inability to evaluate the heeling angle at oblique waves, taking only into consideration the trim and draft values when iterating, because the nodes checked for Z-axis resultant forces must be in the CL plane and a third heel angle loop is required.

2.3 Tank pressure script

This script is designed to add equivalent quasi-static (hydrostatic) pressure on a group of elements in multiple ways. It can add pressure on a head wave pattern, with a certain wave length and height. The pressure can be applied on a certain face of the plate element or towards or away from a given point [4, 5]. Using a simple graphics user interface, the usability of the script is increased.

This script was designed to be used in conjunction with the ship equilibration script, with the values for drafts calculated after model equilibrium, but it later became obvious that other types of hydrostatic equivalent pressure could be added much simpler with it, so it became more general in its utilization. The difference and flexibility came with how the pressure can be applied to the group of FE elements.

The user can decide if it is worth orienting the faces before applying the pressure or if the script will automatically add the pressure based on a control point and its position concerning the element's face [4].

The wave equivalent pressure load is added to the active load set, with a name that has both the draft values marked. The script interface is presented in **Fig.15**.

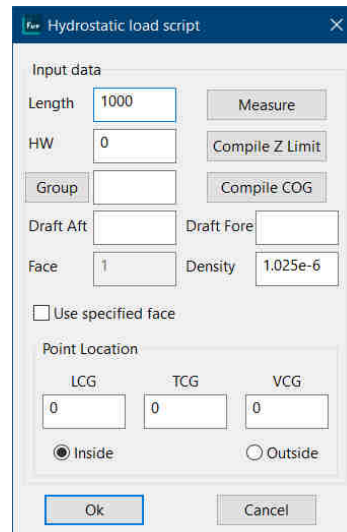


Fig.15 Wave load script user interface

3. 3D-CAD MODEL OF THE YACHT STRUCTURE

The 3D-CAD yacht model, used for the final mesh generation, is based on an extended scantling of the midship scantling calculated in section 1.9, taking into account the bulkheads adopted in section 1.6 and tank locations from section 1.7. The 3D-CAD yacht model is presented in **Fig.16**.

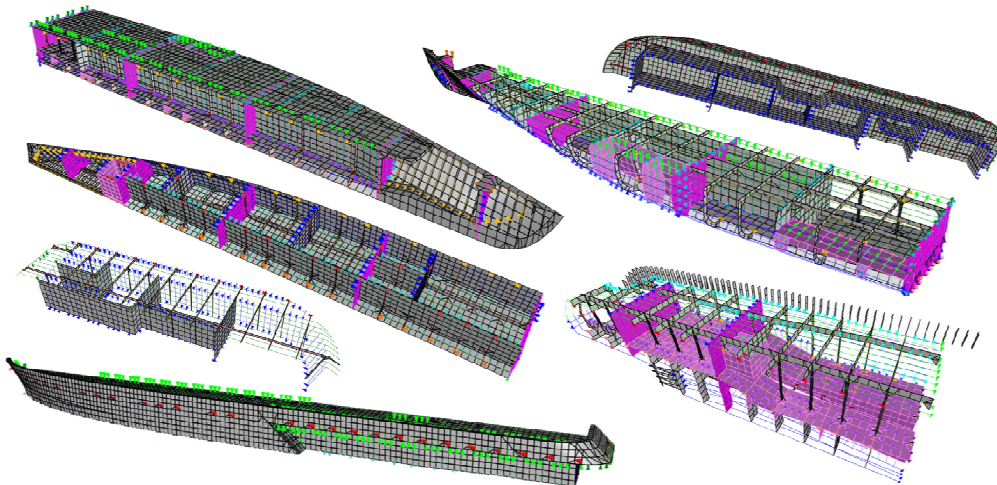
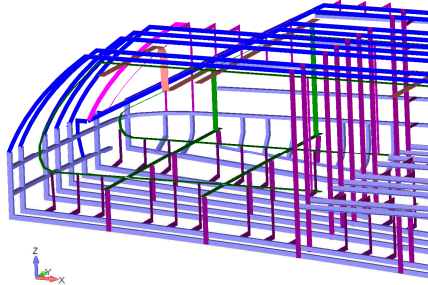


Fig.16 3D-CAD Yacht Rhino Model

4. 3D FEM MODEL OF THE YACHT STRUCTURE

4.1 Overview

For this analysis only one side of the model is necessary, with symmetry in CL. A coarse mesh size of approximately 500 x 500mm is used for the FE model (Figs17-20).



Output Set: Model Data to Contour
Fig.17 FE Yacht Model Overview 1

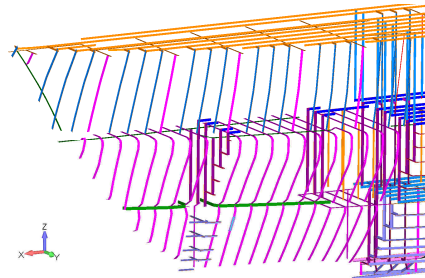


Fig.20 FE Yacht Model Overview 3

Table.8 FEMAP Model overview table

Type	Number
Nodes	22792
Beam elements	18837
Plate elements	27297
Total Elements	46134
Materials	3
Properties	218

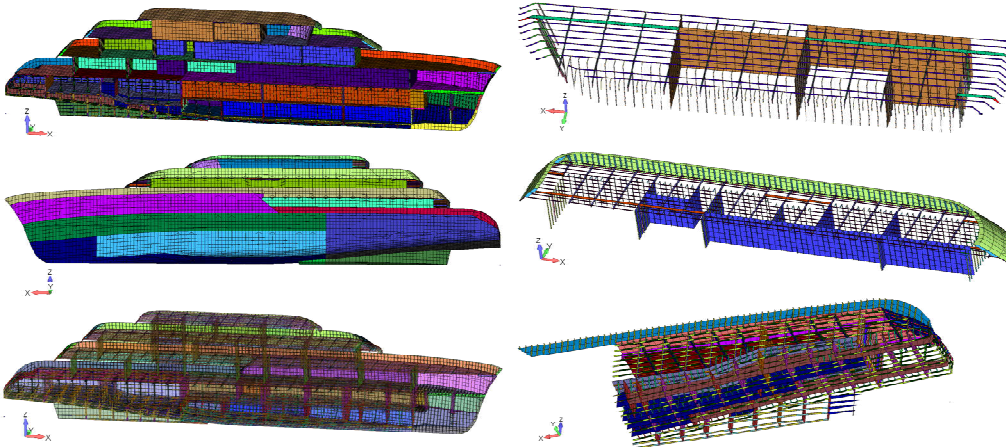


Fig.18 FE Yacht Model overview 2

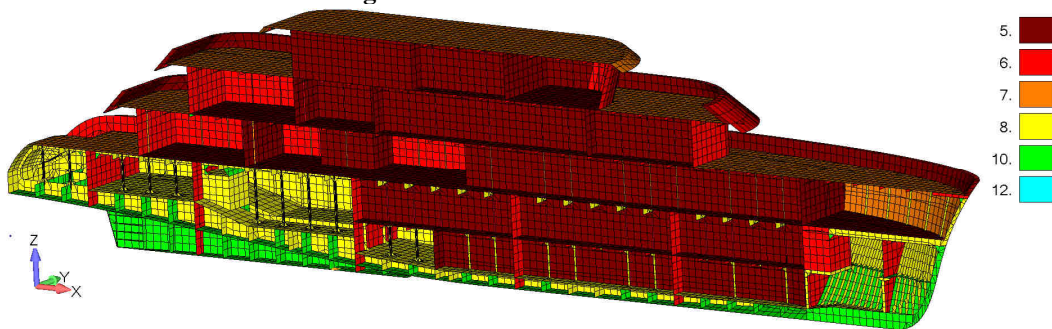


Fig.19 FE Yacht Model Thickness contour

4.2 Equalization of the model weight

The final model weight must be adjusted with equipment and outfitting elements that were not modelled in FEMAP. This is done by considering equivalent ship's panels material density to account for the missing non-structural elements on board the ship.

Using at least two material properties for elements, in different positions of the model, the longitudinal center of gravity of the model can be adjusted to fit the desired calculated Lightship centroid. This model uses 3 materials to better emulate the centroid and match it even in the Z-axis direction. The materials and the elements that are designated to them are presented in Fig.21.

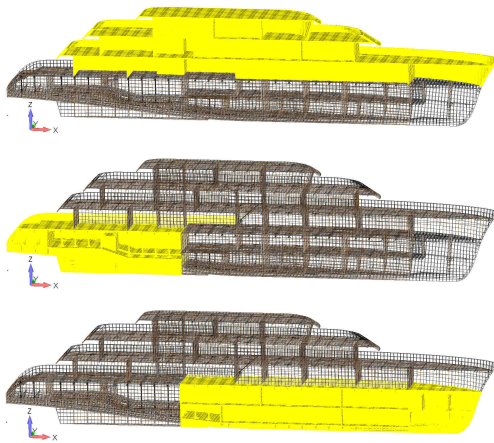


Fig.21 Equivalent material density distribution over the yacht panels

Each equivalent material in its different zone has the density scaled with a factor bigger than 1, which will shift the centroid of the entire FE model. The density equivalent factors applied are presented in Table.9.

Table.9 Equivalent density factors

Material Location	Original	Factor	Final
TOP	7.80E-06	2.910	2.27E-05
BOT AFT	7.80E-06	1.224	9.55E-06
BOT FORE	7.80E-06	2.719	2.12E-05

The final model weight and the center of gravity are illustrated in Table.10.

Table.10 Model weight and center of gravity

Mass [kg]	Center of Gravity [mm]		
	X	Y	Z
693980.5	36799.24	3038.057	6447.605

4.3 Loading cases determination

The deadweight of the ship is added to the model as pressure loads inside the tanks.

For the Lightship case, no loads inside the tanks are considered. Where tanks are loaded to 100%, the fill level is at the air ventilation height, at the Main Deck. Each of the three loading cases, Light Ship (LSW), Departure (DEP) and Arrival (ARR) have the tanks from Fig.22 with a different pressure load, based on the height and density of the liquid inside.

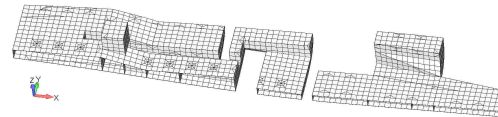


Fig.22 FEMAP Yacht model tanks

4.4 Boundary conditions

In Fig.23 an overview of the constraints is shown, with a detailed view of the degrees of freedom in Table.11.

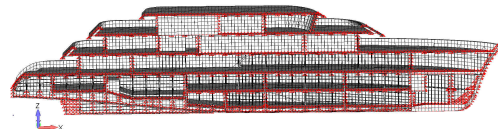


Fig.23 FE Yacht model boundary conditions

Table.11 Boundary conditions table [5]

Boundary condition	TX	TY	TZ	RX	RY	RZ
CL Symmetry SYM		×		×		×
Node aft NDPP	×	×	×	×		×
Node fore NDPV		×	×	×		×

5. STRENGTH ANALYSIS

The yacht is designed for unrestricted navigation. The max. design H_w value is 6.5 m. The ship is also examined at the following H_w values: 6m, 5m, 4m, 3m, 2m, 1m. The stresses must be lower than yielding limit 235 MPa. A maximum displacement of $LOA/300$ was considered, resulting in a maximum admissible vertical displacement of 252mm. The buckling factor must be higher than 1.3.

Table.12 Calm water summary

$H_w = 0.0m$	LSW	DEP	ARR
T3 Displacement [mm]	6.465	6.650	6.504
Von Mises [MPa]	113.6	115.6	113.9
Beams Stress [MPa]	143.8	143.1	143.5
Buckling Factor [-]	3.854	3.841	3.852

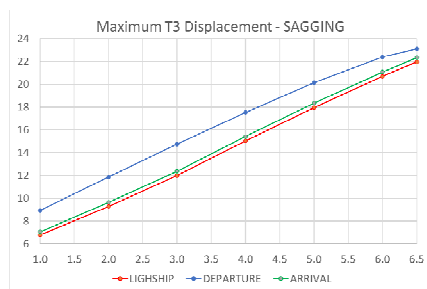


Fig.24 Sagging T3 Displacement Summary

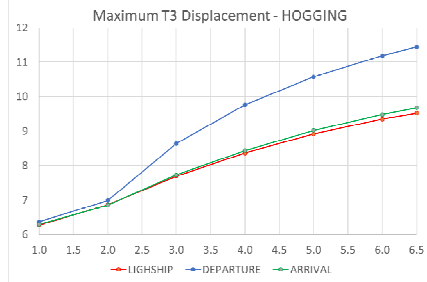


Fig.25 Hogging T3 Displacement Summary

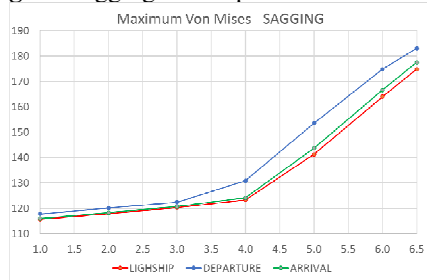


Fig.26 Sagging Plates Von Mises Summary

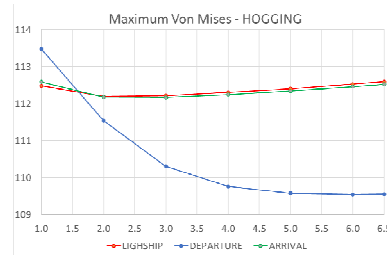


Fig.27 Hogging Plates Von Mises Summary

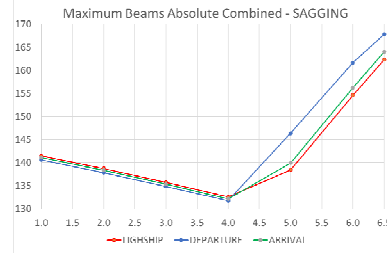


Fig.28 Sagging Beams stress Summary

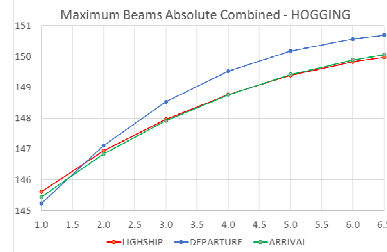


Fig.29 Hogging Beams stress Summary

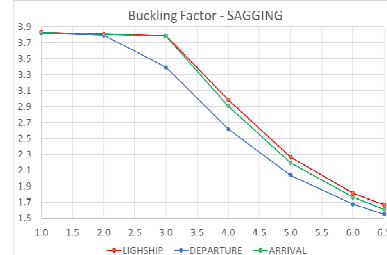


Fig.30 Sagging Buckling factor Summary

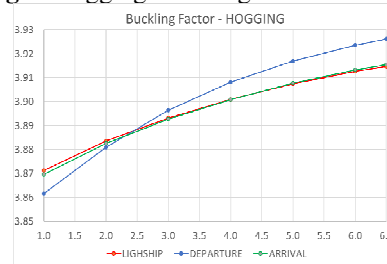


Fig.31 Hogging Buckling factor Summary

6. CONCLUSIONS

According to admissible values for stress, displacement and buckling factor, the yacht satisfies Bureau Veritas rules [2] for global strength analysis at the loading cases analyzed. In Fig.33 are shown the constraints reaction forces on the Z axis for the analyzed load cases. The residual values for vertical T3 reaction forces are lower than the limit imposed in the script for accuracy, of 5N.

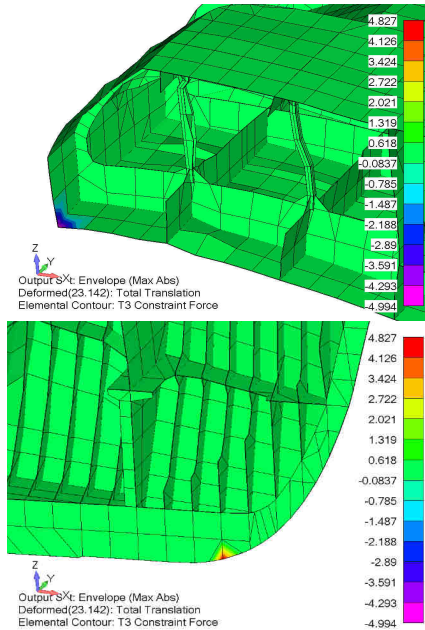


Fig.32 Envelope T3 Vertical constraint force

The average number of iterations, over the 45 cases is **18.5** and with an average time for equalization of **3 minutes and 53 seconds**. There does not appear to be any correlation between the H_w of the equivalent wave

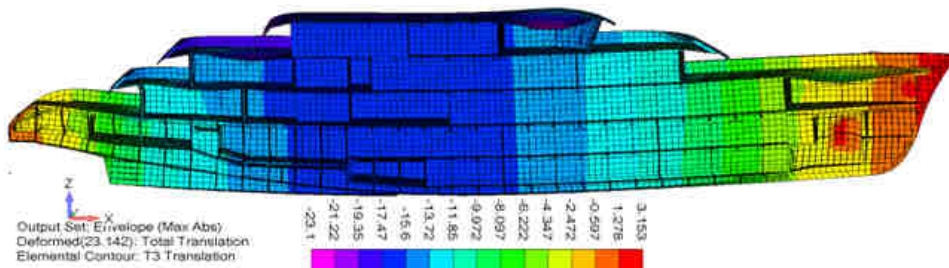


Fig.33 Envelope T3 Vertical displacements

load on and the number of iterations required and time for equalization.

The hardware configuration of the PC used for the analysis is:

- Intel Core i5 4670k @3.4 GHz
- 16GB DDR3 RAM @1600MHz
- 500GB SATA SSD

A limitation of the script for equalization on head waves is the unimplemented option for solving the drafts in oblique waves. That would require an additional loop for checking the reaction on an additional node in the aft or forward needed for controlling the heeling angle of the ship. This additional loop, with the current algorithm, will likely produce extremely long running times. An idea for optimizing the script and reducing the iterations number is to keep in memory the reaction results for every step, and interpolate between the closest values.

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