11th International Conference on Fast Sea Transportation
FAST 2011, Honolulu, Hawaii, USA, September 2011

Optimization of Hull Structures for a 60 meters MegaYacht

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ABSTRACT

As well known already in earliest phases of a ship project many aspects and choices depend on the structural design which has been defined only at a preliminary level. This trend appears to be similar for merchant ships, passenger ships and motor yachts. Only in the final part of the project some shipyards begin to apply optimization processes, more or less sophisticated, in order to refine the structural design in view of reducing the weight and/or the construction cost. The weight in particular has a very important impact on pleasure vessels, both motor and sailing. Structural modifications suggested by such optimization procedures imply a number of second order changes in related items such as plant, outfitting and others. As a consequence the structural optimization could be particularly useful if it can be applied during the first stages of the project, this way avoiding very expensive time losses and changes caused by any structural modifications.

In this paper the structural optimization of a 60 meters megayacht is presented, performed by LBR-5 code developed by the University of Liege. This code is an optimization tool specifically designed for structures composed by stiffened plates and stiffened cylindrical shells. The optimal solution is reached through an optimization algorithm based on convex linearization and a dual approach.

The LBR-5 software has been successfully utilized to optimize hull structures of a 60 meters megayacht. Differently from large ships, the mega yacht has not a "cylindrical body" in the central part of the hull. So, a new module of the software has been used in order to analyze several sections of the ship and to perform an overall optimization.

For this application the optimization analysis has been carried out by different approaches: assuming the weight as the objective function a gain of about 8% has been achieved, while a least cost optimization allowed a reduction of 15%.

KEY WORDS

Structures, Preliminary Design, Scantling Optimization, Yacht

1. INTRODUCTION

Ship designers have to face several problems due to the structural complexity of a ship. Since the earliest phases most aspects of a ship project is influenced by the structural design. Any modification to this respect implies a certain number of second order changes in related items such as plant, outfitting and other. As a consequence, the advantages of a structural optimization are particularly useful if they can be applied during the first stages of the project.

LBR-5 software is an optimization tool specifically designed for this purpose "(Rigo 1998)". It's specifically designed for structures composed of stiffened plates and stiffened cylindrical shells "(Rigo 2001)". In order to find an optimal solution we need to define design variables (plate thickness, stiffener dimensions and their spacing), constraints (structural and geometrical), and the objective function (e.g. minimum weight, minimum cost and maximum inertia). Starting from these data, the optimal solution is found using an optimization algorithm based on convex linearization and a dual approach "(Rigo & Fleury 2001)". Independently by the number of design variables and constraints, a complete structural re-analysis is achieved with only 10 to 15 iterations.

LBR-5 software has been widely used to optimize the structures of various kinds of merchant ships in the first stage of the design such as LNG carriers, cruise ships or chemical tankers "(Richir et al. 2007)","(Caprace et al. 2010)". In this paper the use of the software to optimize the structures of a 60 meter megayacht built by Benetti Yachts is described.

In the first part of the paper a short description of the software is given; in the second part the main characteristics of the yacht under investigation and its numerical model are presented; finally results of the optimization analysis are reported and discussed.

2. DESCRIPTION OF THE SOFTWARE LBR-5

Generally speaking an optimization problem is defined by an objective function $F(X_j)$ to be minimized and a list of constraints which, in the case of ship optimizations, are represented by structural and geometrical constraints. The design variables X_j can assume values in a defined range chosen by the structural engineer. These are known as technological bounds or side constraints. Then the optimization problem can be summarized as:

X_i i=1,N	the N design variables
$F(X_i)$	the objective function to minimize
$C_j(X_i) \leq CM_j$,j=1,M	the M structural and geometrical constraints
$X_{i\,min} \leq X_i \leq X_{i\,max}$	technological bounds

The first step consists in modelling the structure and choosing the variables. The structure of a ship is modelled with stiffened panels (plates and cylindrical shells). For each panel one can associate up to 9 design variables:

- plate thickness δ;
- for longitudinal members (stiffeners, crossbars, longitudinal, girders): web height and thickness, flange width, spacing between two longitudinal members;
- for transverse members (frames, web frames, transverse stiffeners, etc.): web height and thickness, flange width, spacing between two transverse members (frames).

Then one can define the optimization problem using the appropriate software modules. LBR-5 is built around three basic modules:

- Cost Module
- Constraint Module
- Opti Module

The basic organization of LBR-5 software is shown in Fig.1.

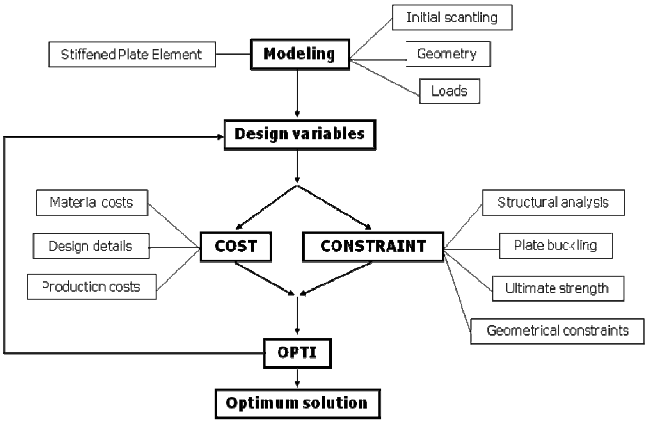

Fig.1 – LBR-5 flowchart

2.1.Opti Module

This module contains the mathematical optimization algorithm CONLIN "(Rigo, Fleury, 2001)" that allows to solve non-linear constrained problems. CONLIN is based on convex linearization of the non-linear functions (objective functions and constraints) and on a dual approach. Explanations of this technique can be found in "(Bertsimas 1997)". Inputs for this module are the constraints and the objective function, which means the results/outputs of the other two modules.

2.2 Constraint Module

In this module the user defines the constraints to be applied to the variables (among constraints available in the database). Constraints are linear or non-linear functions, either explicit or implicit in the design variables. The software distinguishes between three types of constraints:

- technological constraints: they provide the upper and lower bounds of the design variables. For instance, plate thickness of deck plating has to be contained between 4 and 20 mm. Minimum values are generally determined by classification rules minimum requirements. Maximum values are chosen, for example, to avoid great differences in thickness between adjacent panels;
- geometrical constraints: they impose relationships between design variables in order to guarantee a functional, feasible, reliable structure. They are generally based on "good practice" rules to avoid local strength failures (web or flange buckling, stiffener tripping, etc.), or to guarantee welding quality and easy access to the welds:
- structural constraints: they are used to limit stress level in the elements, deflections in the points of the structure and to impose safety level related to buckling, yielding, etc. These constraints are based on solid-mechanics phenomena and modelled with rational equations.

LBR-5 generally considers two limit states for elements:

- "service limit state", which corresponds to a situation where the section can no longer assure the service for which it was conceived;
- "ultimate limit state", which corresponds to the collapse/failure.

2.3 Cost Module

In this module the user decides the objective function to be used. Possible objective functions are represented by: minimum weight, minimum cost (construction cost plus operational cost) and maximum inertia. It's possible to consider multi-objective optimization as well, in which two or more objective function can be weighted in a proper way.

When considering cost as objective function, in order to link the cost to the design variables the user must specify the unit cost of raw material, the productivity rates for welding, cutting, etc. and labour costs. These unit costs vary according to the type and size of the structure, the manufacturing technology, the experience and facilities of the construction site, the country, etc. It's therefore obvious that the result of this optimization process will be valid only for the specific economic and production data under construction.

3. SHIP DESCRIPTION

The motor yacht FB240 is a 60 metres notable steel yacht manufactured by Benetti Yachts. The exterior lines have been created by Stefano Natucci, while the interior design have been realised by Studio Massari. FB240 have been built in Italy and successfully launched in Viareggio in 2007. The yacht hull is fabricated from steel, the superstructures from aluminium. With a width of 10.4 m FB240 has fairly large size. She was designed with accommodation for up to 12 passengers and 15 crew members.

The ship considered is shown in Fig.2. The main dimensions and characteristics of the ship are described in Table 1.

Fig.2 Benetti Yacht – 60 meters

Table 1. Nominal properties of core materials.

Main Characteristics	
Length Overall (m)	60
Waterline Length (m)	51.78
Rule Length (m)	50.27
Beam (m)	10.4
Draft (max) (m)	3.10
Depth	5.45
Displacement (tons)	945
Speed (kn)	17
Classification Rules	ABS
Material	AH36

4. OPTIMIZATION ANALYSIS

The most important difference (relevant to the software) between this ship and a typical merchant ship is that the mega yacht has not a "cylindrical shell" along her length. Therefore it is not enough to analyse the main section of the ship (which, in case of a merchant vessel, is considered representative of the entire ship), but it's necessary to analyse several sections of the hull and to perform an overall optimization.

In this application the central part of the hull has been divided into 5 modules (numbered from 1 to 5) and, for each module, a representative section has been chosen to be processed by LBR-5 software. Considering that the ship under study is divided into 49 frames, we chose the middle frame as representative of each module, i.e.:

1. Frame 11 as representative of frames from 7 to 15
2. Frame 18 as representative of frames from 15 to 21
3. Frame 23 as representative of frames from 21 to 26
4. Frame 29 as representative of frames from 26 to 31
5. Frame 35 as representative of frames from 31 to 39

The transversal section corresponding to frame 18 and its model in LBR-5 are shown, as an example, in Fig. 3 and Fig. 4. In this way the ship is represented by 5 short cylindrical shells. Fig. 5 shows, as an example, the 3D model of module 2. Links between the scantling dimensions and spacing between these sections have been performed using the Multistructures routine of LBR-5, imposing the so-called "equality constraints" between the design variables.

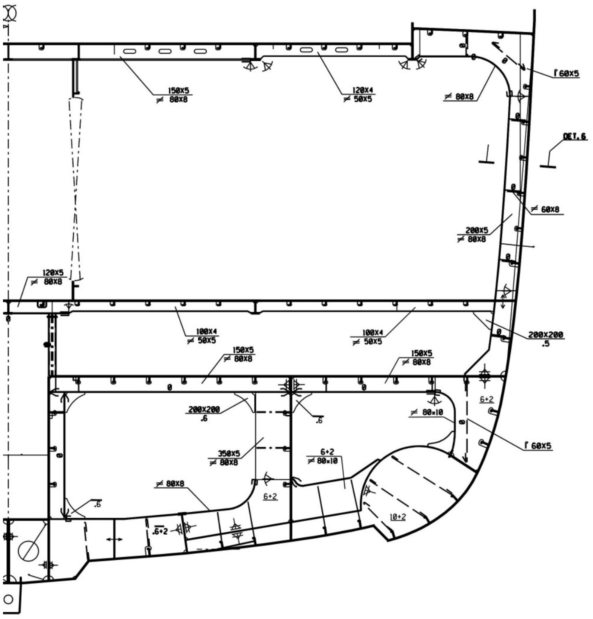

Fig.3 Frame 18

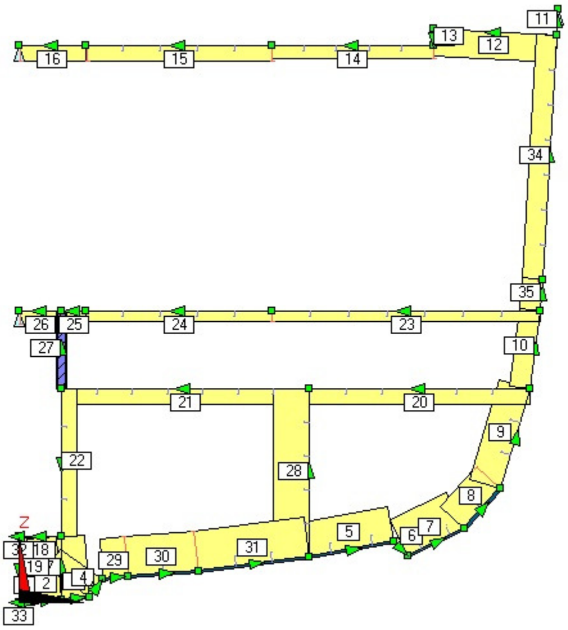

Fig.4 Frame 18 – model in LBR-5

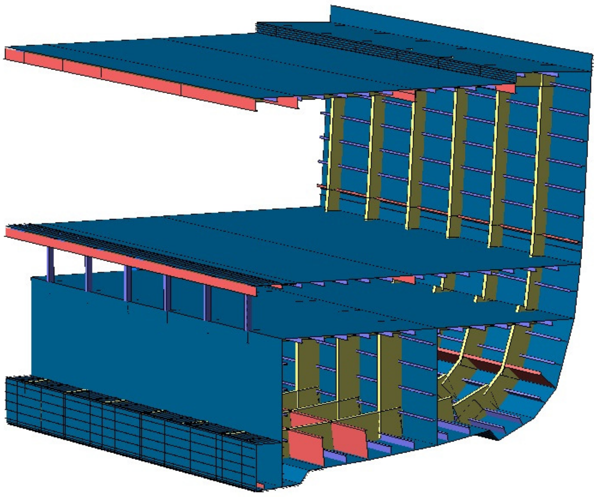

Fig. 5 – 3D model representative of Frames 15 to 21

The ship is loaded with the Hull Girder Bending Moments and the Sea Pressures. Hull Girder Bending Moments (Still water bending moment, $M_{SWM,H}$ and $M_{SWM,S}$, and Wave bending moment, $M_{WV,H}$ and $M_{WV,S}$ in Hogging and Sagging conditions) have been evaluated in accordance with the following formulas "(RINA Rules)":

$$M_{WV,H} = 190\ F_M\ n\ C\ L^2\ B\ C_B\ 10^{-3}$$

$$M_{WV,S} = -110\ F_M\ n\ C\ L^2\ B\ (C_B + 0,7)\ 10^{-3}$$

$$M_{SWM,H} = 175\ n_l\ C\ L^2\ B\ (C_B + 0,7)\ 10^{-3} - M_{WV,H}$$

$$M_{SWM,S} = 175\ n_l\ C\ L^2\ B\ (C_B + 0,7)\ 10^{-3} + M_{WV,H}$$

In the previous formulas F_M is a distribution factor that depends on the longitudinal position of the section; C is a wave parameter; C_B the block coefficient of the ship.

Sea pressures (still water pressures and wave pressures) are evaluated in accordance with RINA rules "(RINA 2011)" for the ship in upright condition (Table 2).

Upper and lower bounds on design variables ("technological constraints") have been evaluated in accordance with ABS rules: for plate thickness a minimum thickness has been evaluated; frames and stiffener dimensions lower bounds are evaluated in terms of minimum section modulus.

Geometrical constraints have been applied in order to have coherent dimensions of frame and stiffeners and of their parts (web and flange).

Structural constraints have been applied to the panels in order to avoid yielding and buckling on the panels, and to have maximum stresses on panels, stiffeners and frames lower than the allowable ones (used criteria are maximum longitudinal stress, σ_x, and maximum Von Mises stress).

Equality constraints are used, section by section, in order to have a simpler (but not simplified) scantling. Equality constraints between scantling of different transversal frames have been used (in Multistructures optimization) in order to have coherent scantling in the whole central part of the ship (for example they are used to have the same stiffener dimensions and spacing).

Table 2. Still water and wave pressures

Location	Still water pressure (kN/m^2)	Wave pressure (kN/m^2)
Bottom and side below the waterline ($z \leq T$)	$\rho g(T - z)$	$\rho g h_1 e^{(-2\pi(T-z)/L)}$
Side above the waterline ($z \geq T$)	0	$\rho g(T + h_1 - z)$
Exposed decks	Pressure due to the load carried	$17,5 n\varphi$ for $0 \leq x \leq 0,5L$ $\{17,5 + [(19,6\ (H_F)^{0,5} - 17,5)/0,25](x/L - 0,5)\} n\varphi$ for $0,5L \leq x \leq 0,75L$ $19,6 n\varphi H^{0,5}$ for $0,5L \leq x \leq 0,75L$

Note 1:

ρ : sea water density, in t/m^3

H_F : value of H calculated at x = 0,75L

V : contractual service speed, in knots, to be taken not less than 13 knots

φ : coefficient for pressure on exposed decks

$H = [2,66(x/L-0,7)^2 + 0,14]*(VL/C_B)^{0,5} - (z - T)$

We independently considered two objective functions: Weight and Cost. Weight is the main objective function for this kind of ship. Cost optimization has minor relevance; it has been performed in order to check the difference in the optimized scantling. In both cases we made the optimization using the "Multistructure Optimization" routine, in order to perform an overall optimization of the five sections. According to this routine, in order to perform the optimization analysis we followed the steps listed in the following.

- Model each section with LBR-5
- Establish all the equality constraints between the sections. To obtain this one need also to assume one of the sections as the "master" one. This means that this section is the one that determines the value of the design variables in the optimization process. For this purpose frame 18 has been chosen, being the main

section of the ship. All the other sections must respect the equality constraints.

- Run the optimization process (it takes 10 iterations to find the optimal solution)
- Make the "standardization" of the structures. This means that at the end of the optimization process, all the dimensions of the final scantlings are changed into standard "commercial" values. For example, a plate thickness of 8.83 mm must be increased to 9 mm. The starting point of the standardization is the final scantling of the optimization. In this study, all the design variables are standardized in the same time and the final scantling is verified (in term of stresses).

5. RESULTS

The Multistructures Optimization routine provides for each module the final scantling of all frames considered in the analysis. As expected, the scantlings of these frames are linked by the equality constraints considered by the program. In addition, the variation of the objective function of the optimization analysis is provided for each section. Starting from these results it is then possible to evaluate gain/loss of cost and weight for the entire ship.

Two optimizations have been performed: least cost and least weight optimization. They led to different solutions. Least cost optimization led to a cost gain of 22.7% and a weight increase of 3.7%. Least weight optimization led to a weight decrease of 8% and a cost gain of 8%. Comparison of the final scantling obtained with cost and weight optimization lead to some remarks:

i. in the weight optimization option the software reduces plate thickness, frames and stiffeners dimensions as much as possible in order to reduce the weight, and it reduces the stiffener spacing (so it increases the number of stiffeners) to satisfy the allowable stress;

ii. conversely, in least cost optimization option, the software first increases the stiffener spacing (thus reducing the number of stiffeners), while it increases (with respect to weight optimization, but is still a lower reduction with respect the unoptimized case) plate thickness, frames and stiffeners dimensions in order to reduce the construction costs (considered by LBR-5 software).

Therefore, plate thickness results to be generally lower in weight optimization; stiffener dimensions are lower in cost optimization, but their spacing is generally minor; frame dimensions are very similar in the two optimizations.

As said in Sect.4, after the optimization process, final scantlings have been standardized. This final step produces small changes in the values of the final objective function.

Final results (before and after the standardization) are shown in Table 3.

Table 3. Results of the optimization

	Cost (euro)	Weight (T)	Cost Variation (%)	Weight Variation (%)
Init. Scantling	259239	52.9	-	-
Cost Optim.	200258	54.95	22.75	-3.75
Weight Optim.	237028	48.5	8.6	8
Cost One-step Standardization	201844	56.2	22.14	-6.2
Weight One-step Standardization	235894	49.4	9	6.65

Note that in cost variation, a positive number means a gain; in weight variation, a positive number means a weight decrease.

An example of the results of the optimization procedure is shown for the module n. 2. The initial scantling of the mid section (frame 18) is shown in Fig. 6. Figures 7 and 8 show the variation of the plate thickness after the optimization process and the standardization (both for cost and weight optimization). Similar figures can show the variation of the others "design variables".

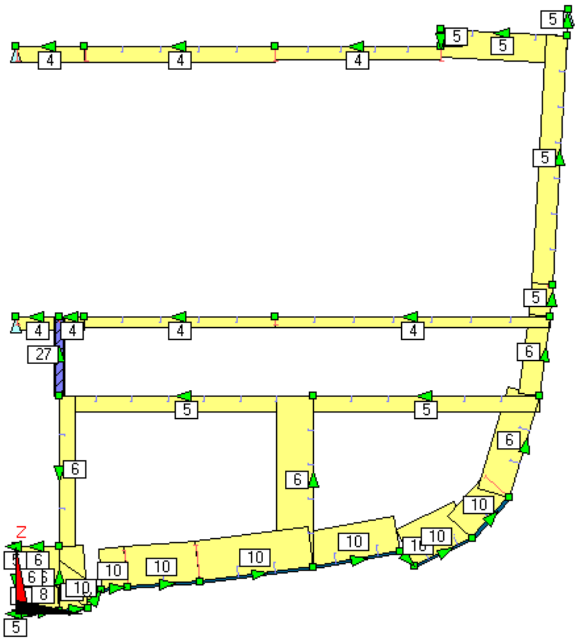

Fig.6 Frame 18 – Initial frame plate thickness

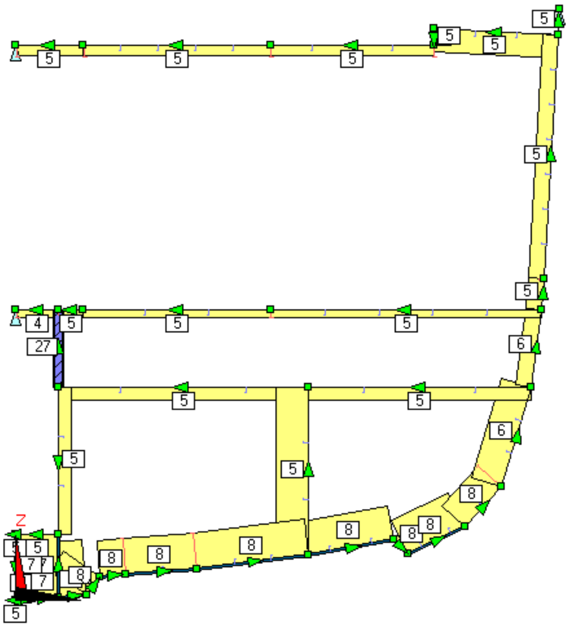

Fig.7 Frame 18 –Plate thickness after Weight Opt.

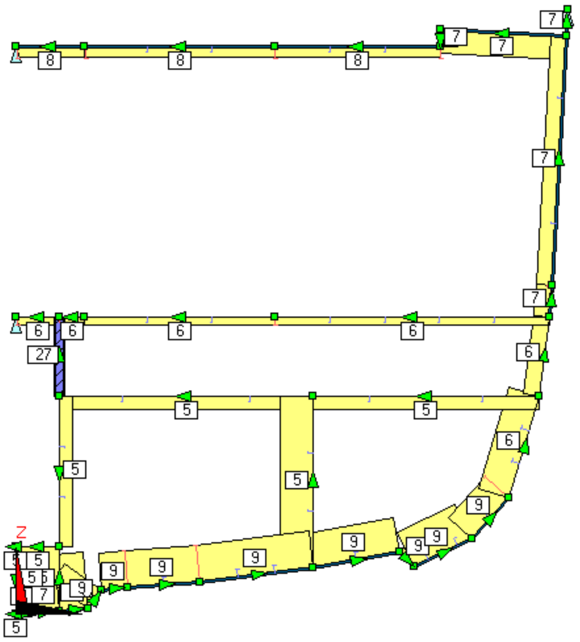

Fig.8 Frame 18 –Plate thickness after Cost Opt.

Other than design variables variation, LBR-5 allows to display the following results: longitudinal and transversal displacements, transversal and longitudinal stress in plates, Von Mises stress in plates and frames (both in web-flange and web-plate junction), transversal and shear stress in frames.

Figures 9 and 10 show, as an example, the Von Mises stresses in Plates of module n.2 in hogging and sagging conditions respectively, after the weight optimization.

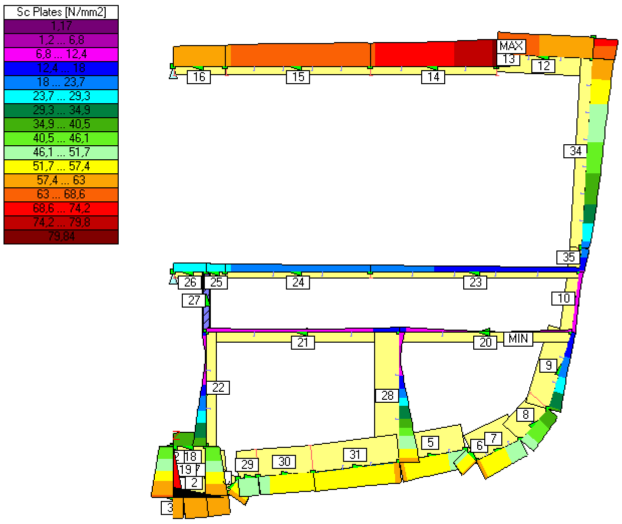

Fig. 9 Frame 18 –Von Mises Stresses in Plates, Hogging condition

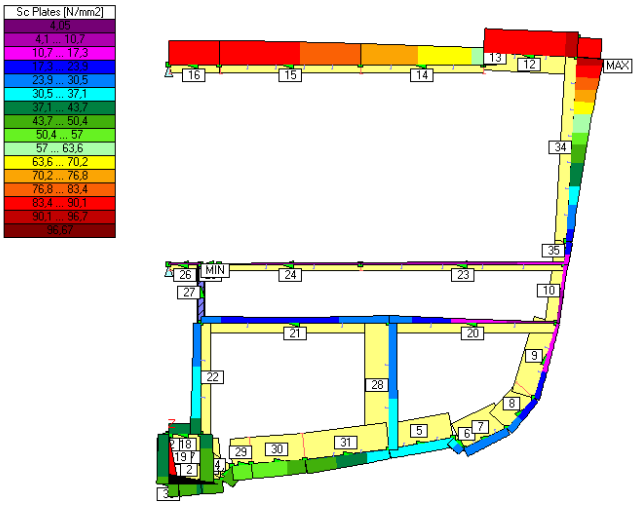

Fig. 10 Frame 18 –Von Mises Stresses in Plates, Sagging condition

Figures 11 and 12 show the objective function variation of module n.2 after the optimization process (both for cost and weight optimization). LBR-5 software performs ten iterations. In this application there's a fast convergence to the optimal solution, reached in two or three iterations. Similar drawings are available for other sections. The global variation of the objective function is not available in the interface, but it can be easily obtained through the average of the single results.

As shown by the results, in this study we obtained important gains in term of weight and cost. However some aspects may reduce this gain:

- in the optimization process, shear forces are not taken into account, so the loads are underestimated mainly for

frames far from the middle section; this explains the important gains in these frames.
- Multi-structures routine of LBR5 is simplified: there are only equality restrictions between variables, while there is no equality for stress and other structural properties.

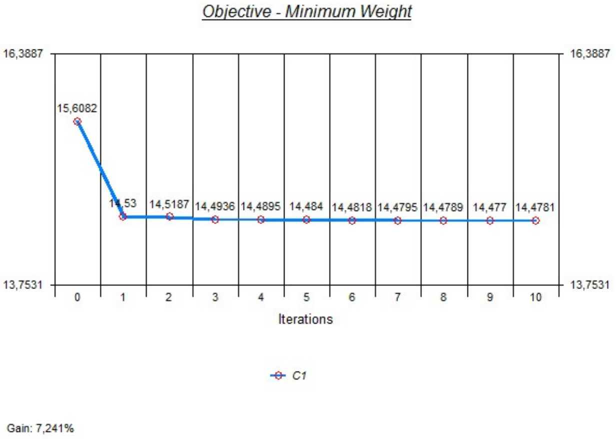

Fig.11 Weight Variation

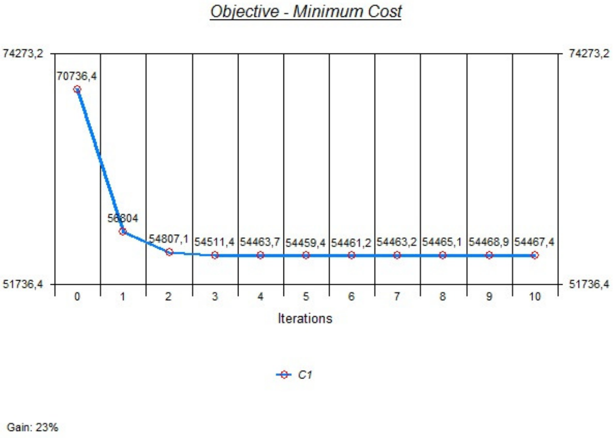

Fig.12 Cost Variation

6. CONCLUSION

Structural optimization is a useful tool in structural design when applied during the first stages of the ship project. LBR-5 is software which has been widely utilized to optimize the structures of passenger ships in the first stage of their design. In this paper a first attempt in using LBR-5 software for Mega Yacht has been shown.

The module of the software that we utilize is the Multistructures Optimization, which allows us to optimize a ship without a long cylindrical body. The optimization analysis leads us to important gains in terms of cost (20%) and weight (8%) with respect to the initial scantlings. Our results show that structural optimization is a relevant analysis also for smaller ships.

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ACKNOWLEDGEMENTS

The authors would like to thank Prof. Philippe Rigo for his helpful suggestions and continuous support. Further thanks to Frederic Bair for continuous help are due as well.