Structural Optimization: LBR-5 Software and its application

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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.

The LBR-5 software has been successfully used to optimize hull structures of a 60 meters mega yacht. 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, Structural Optimization, Yacht

1. Introduction

In a ship project, designers have to face several problems due to the complexity of a ship. The structural design is one of fields which mostly influences the ship project. Any modification of the structures implies a certain number of changes in related items such as plant, outfitting and other. As a consequence, a structural optimization would be very useful if 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 naval 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.

One of the great advantages of LBR-5 software is that only basic characteristic such a L, B, T, C_B, the global structure layout, and applied loads are the required data. It's not necessary to provide a feasible initial scantling. This allows to quicken the optimization and to perform it in an initial phase of the project, where the structural details of the ship are not available yet.

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)".

Firstly in this paper a typical application of LBR-5 is described. The optimization tool has been applied to a Bulk Carrier previously dimensioned with Rina '99 Rules and verified through a finite element analysis (by using the FEA software MSC – Nastran). Aftwerwards, a stress analysis has been performed to the optimized ship using again a finite element analysis.

In the second part of the work the structural optimization of a 60 meter Mega Yacht is presented. In order to perform such optimization, a new module of LBR-5 has been successfully used. The differences between the typical application of the optimization software and this new one are highlighted in this paper.

Both works have been accomplished at the University of Genoa in collaboration with the University of Liege.

2. LBR-5 Software

Generally speaking in a linear optimization problem is defined by a linear objective (or "cost") function $F(X_j)$ to be minimized over a certain number of variables X_j subject to a set of linear equality and inequality constraints. The variables X_j are called 'decision variables', and a vector $\underline{X} = (X_j,...,X_n)$ satisfying all the constraints is called a 'feasible solution'. A feasible solution $\underline{X}^*$ that minimizes the objective function is called an 'optimal feasible solution'.

In the case of the structural optimization of ship (like LBR-5 does), the objective function is the weight or the cost. The constraints, both equality and inequality ones, are 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

In an optimization procedure, 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 (Rigo, 2001).

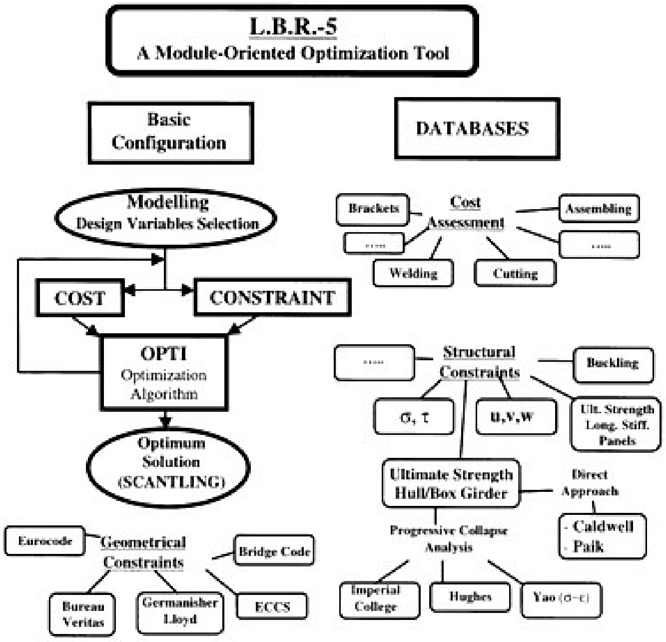


Fig.1 – Basic configuration of the LBR-5 model and database presentation

The OPTI 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.

In the CONSTRAINT 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.

The constraints proposed by LBR-5 are based on Classification Rules. Therefore the optimized structure will meet the requirements of the followed classification society.

In the COST 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. Structural Optimization of a Bulk Carrier using LBR-5

As stated in Section 1, commercial vessels are the typical application of LBR-5 software. In this paper the optimization of a double bottom and double side Bulk Carrier is presented. This optimization allows to understand the general behaviour of LBR-5. It fits within a more complete work, which can be summarized in five steps:

1. Structural dimensioning with Rina '99 Rules
2. FEM Analysis (using MSC – Nastran)
3. Optimization of the structure (LBR-5)
4. Stress Analysis after optimization
5. Structure modification to minimize high stress concentrations.

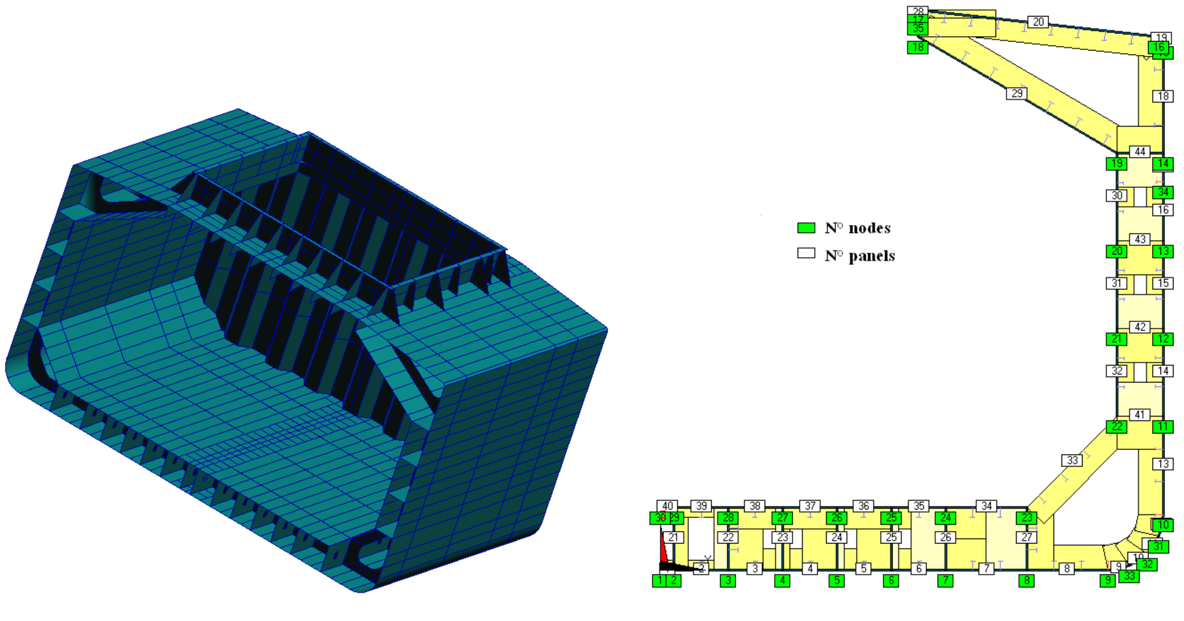
The final aim of this work is to carry out a detailed structural analysis of a bulk carrier in order to define the stress concentrations and identify the critical areas on the strength deck. As regards to the optimization analysis several optimizations have been performed, with different objective functions.

3.1 Ship Description and FE model

The initial point for the optimization analysis is the complete geometrical model of the ship built wit MSC – Patran (Fig.2 a), which is the pre-processer used for the finite element analysis of the ship. This geometry is a feasible one, as it has been determined by the rules, but it is not the optimal scantling.
As previously explained, this model has been dimensioned with Rina Rules '99. Using the plate – element dimension so obtained, the LBR-5 model has been built. The basic element in the software is the *panel*, which is defined between two nodes. Once the panel is created, its geometry is determined and it can be saw and/or edited. For each panel one can associate stiffeners, frames and girders (up to 2 set of stiffeners and frames for element). Each element can be assigned to a material property and to some dimensions.

Because of the geometry of this kind of ship, which is characterized by a long cylindrical body, the main section has been chosen as representative of the entire ship (Fig.2 b). The central hold of the ship (between two transversal bulkheads) has been thus modeled and analysed.

The load cases chosen to perform the optimization is the "Full Load Condition" (according to RINA Rules). This is the worst condition that can occur during the ship's life. The corresponding Still Water and Wave Bending Moments, (both in Hogging and Sagging Conditions) and pressures (still water pressures, wave pressures and internal pressures due to the dry cargo) are applied to the structures of the section.



(a) (b)

Fig. 2. Ship Model: a) Patran model – geometry ; b) LBR-5 model

3.2 Results of the optimization

In this work three different optimizations have been performed: least cost, least weight and maximum inertia optimization. Cost, weight and inertia are thus the objective functions used in the optimization analysis. The optimizations performed using LBR-5 lead to the following significant advantages in all the three cases. :

- gain of 1.2 % in the minimum Cost Opt.
- gain of 10.3 % in minimum Weight Opt.
- increase of 11.3 % in maximum Inertia Opt.

The optimized section in terms of weight has been chosen. Afterwards a stress analysis of this section has been performed both using LBR-5, both performing a FE analysis using MSC – Nastran.
The ship considered is critical, in terms of stresses, in the hatch corners. Therefore, either a global stress check and a stress check of details have been performed with NASTRAN. As an example, Von Mises Stresses in plates in Hogging Conditions are shown in Fig. 3 for the optimized section in the least weight optimization.

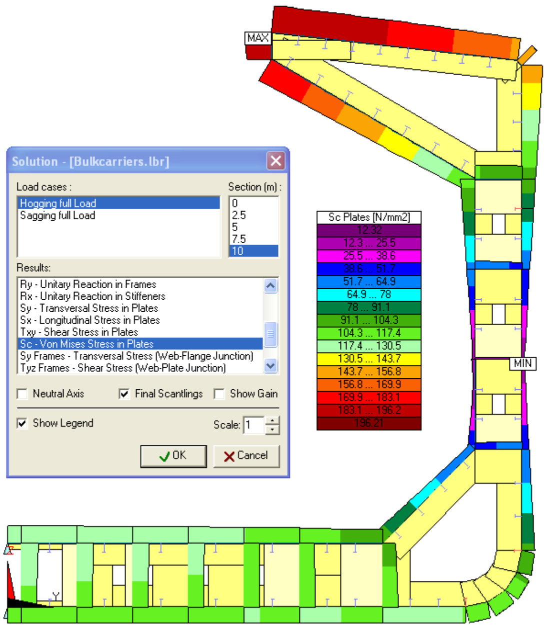
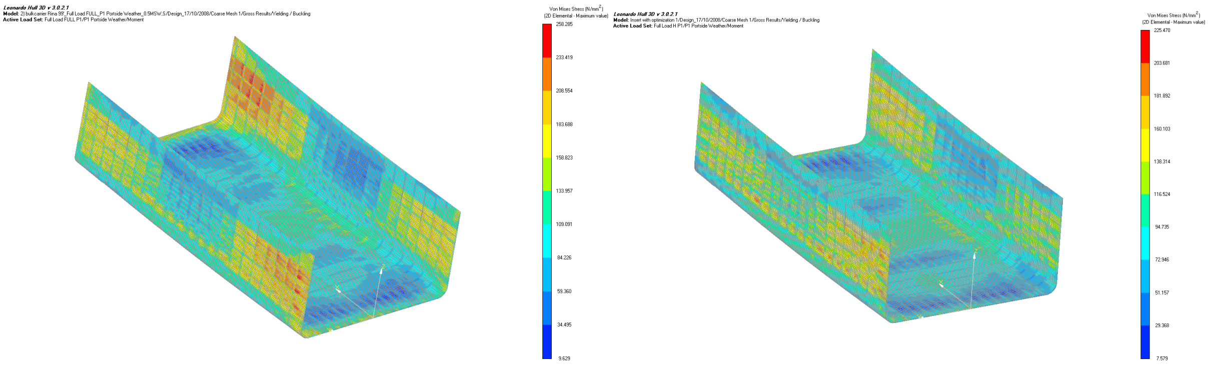


Fig. 3. Von Mises Stresses in Plates in Hogging condition

A stress comparison of the intial and optimized ship performed with Nastran shows that the optimization analysis not only allowed a reduction of the hull weight, but also allowed to reduce significantly the maximum stresses acting on the structures (Fig. 4). This is due to a better disposition of the elements, obtained through BR-5 optimization, that allows a greater strength in the area mostly stresses, like the hatch corners are.



a) b)

Fig. 4. Stress Analysis: a) Side and Bottom plating of "Initial Scantling"; b) Side and Bottom plating of "Optimized Scantling"

4. Structural Optimization of a 60 meters mega Yacht using LBR-5

In this part of the paper a new application of LBR-5 software is described. LBR-5 has been used to optimize a 60 meters mega yacht. As it will be explained in the following, it has been necessary to create and use a new Module of the software, called " Multistructures Module".

4.1 Yacht Under Investigaion: main Characteristics

Fig.5 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

The motor yacht FB240 (Fig. 5) 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 main dimensions and characteristics of the ship are described in Table 1.

4.2 Optimisation Procedure

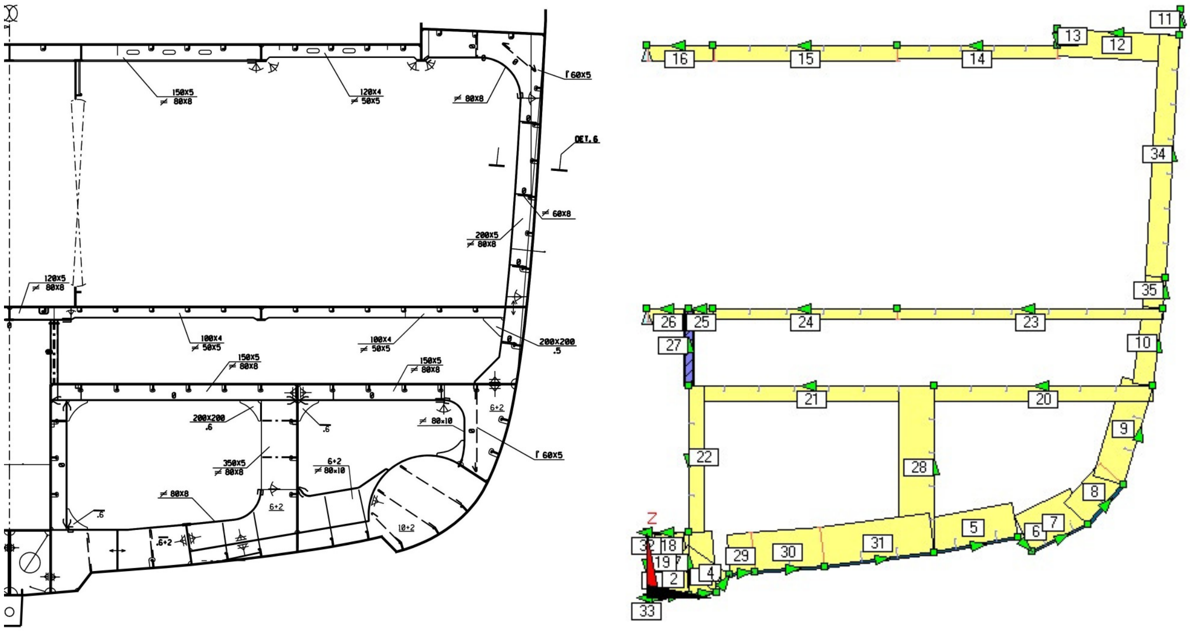
As one can imagine, the structures of a 60 meters mega yacht are very different from a large commercial ship ones. One of the main structural differences of this yacht from a large commercial vessel is the absence of a long "cylindrical body". This aspect strongly influenced the optimization analysis. In fact in this case is not enough to analyse the main section of the ship (which, in the case of a merchant ship, is considered representative of the entire ship), but it's necessary to analyse several sections of the hull and to perform an overall optimization.

Therefore the central part of the hull has been divided into 5 portions (numbered from 1 to 5) and, for each portion, 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 starting point in this application are the 2D drawings of the transversal sections of the ship. Starting from them, the LBR-5 models of the five sections have been created. The transversal section corresponding to frame 18 and its model in LBR-5 are shown, as an example, in Fig. 6. The 3D model of the ship's portion n. 2 is represented in Fig.7.

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 RINA Rules 2010 "(RINA Rules)". Sea pressures (still water pressures and wave pressures) are evaluated in accordance with RINA rules "(RINA 2011)" for the ship in upright condition.



(a) (b)

Fig. 6. Frame 18: a) real; b) LBR-5 model

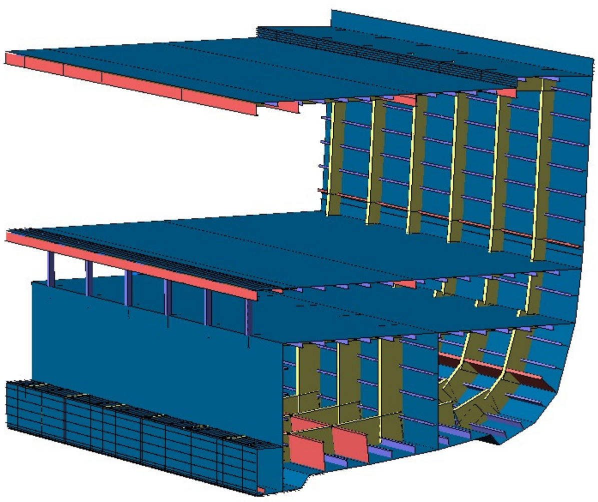


Fig. 7 – 3D model of module 2 (frames from 15 to 21)

Upper and lower bounds on design variables ("technological constraints") have been evaluated in accordance with RINA 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, to keep coherent scantlings after the optimization

Two different optimization analysis have been performed, using the following 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.

As previously explained, 5 sections have been considered for the optimization. This requires the use of a new module of the software, called "Multistructures Module", which allows to have coherent scantlings in the whole part of the ship by imposing additional "equality constraints" between the design variables of the five frames. For instance, using the equality constraints it's possible to keep the same stiffener dimensions along the whole ship. Otherwise, each "single frame" optimization leads to a specific optimized set of dimension for that stiffener. This kind of optimization is called "Multistructures optimization".

According to the Multistructures Optimization 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. At this point it's necessary 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.

4.3 Results

Final scantling of all frames considered in the analysis are provided by the the Multistructures Optimization routine. As expected, scantlings of the frames are coherent thanks to the equality constraints.

Moreover, the variation and the global gain/loss of the objective function of the optimization analysis are provided for each frame. It is possible to compute the overall gain/loss of weight and starting from these results. 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. These results are in accordance with a general LBR-5 behaviour. Therefore the multistructures optimization, even if provides different results from a "single frame optimization", leads to reliable results.

As said in Sect.4.2, 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 2.

Table 2. 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.

In Fig. 8 and Fig. 9 the objective function variation of portion n.2 after the optimization process (both for cost and weight optimization) is presented. 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.

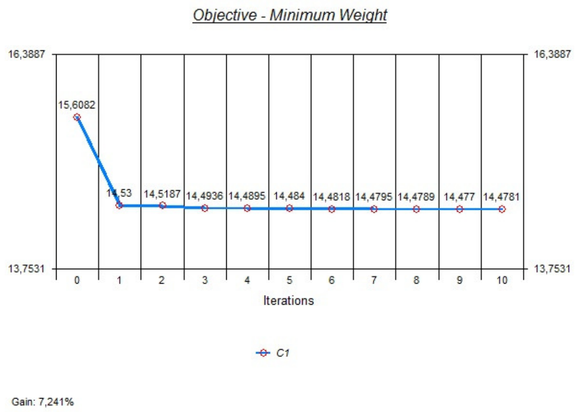


Fig.8. Weight Variation

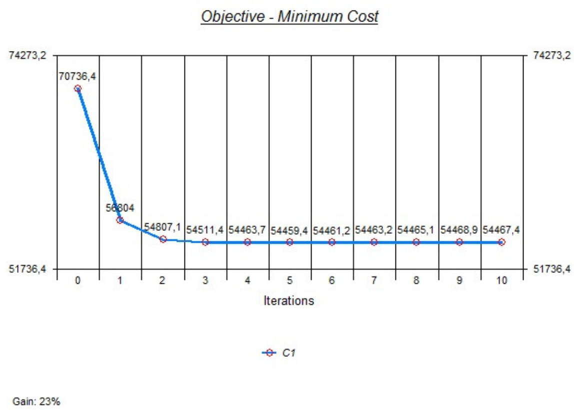


Fig.9. Cost Variation

Conclusion

Structural optimization is a useful tool in a ship design when applied during the first stages of the project. LBR-5 is software which has been widely utilized to optimize the structures of commercial ships. In this paper a first attempt in performing an optimization of a 60 meters Mega yacht using LBR-5 is presented. Moreover, differences between this optimization and a typical Bulk Carrier optimization have been described.

The pecualiarity of the ship considered (absence of cylindrical body) imposed the use of a new module of the software, called Multistructures Module. The optimization analysis leads to important gains in terms of cost (20%) and weight (8%) with respect to the initial scantlings. The results confirmed that structural optimization is a useful tool also for Mega Yacht and similar ships. As for commercial vessel the optimization can be integrated with a Finite Element Analysis for a more detailed analysis.

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