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Least Construction Cost of FSO Offshore Structures and LNG Gas Carriers

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ABSTRACT

In this paper, scantling optimization a FSO offshore structure and a medium size capacity LNG gas carrier are presented. Optmization is based on the LBR5 least cost optimization package. Main originality and advantage is to combine the minimization of the construction cost with the preliminary design stage. The optimum scantling (least cost) is determined at the earliest design stage, this means before the signature of the contract. Cost savings of 5 to 10% are currently recorded.

Relevant information on the methodology and applications to a FSO unit and a LNG carrier are presented in the paper.

KEY WORDS

Optimisation; Early Design Stage; Least Cost; LNG; FSO; Scantling optimization; Rational Design

INTRODUCTION

Guidelines and major orientations of a structural design are always defined during the earliest phases of a project, i.e. the preliminary design stage or the first draft that corresponds in most cases to the offer. It is thus not difficult to understand why an optimisation tool is attractive, especially one designed for use at the preliminary stage.

LBR5 (Rigo, 2001a and b and Rigo, 2003) provides optimum mid-ship scantlings (plating, longitudinal members and frames). It is not necessary to provide a feasible initial scantling. Within about 1 hour of computation time with a standard PC, the "LBR-5" software provides automatically rational least cost optimum scantlings.

The target is to link early design tools (like MARS of Bureau Veritas) with a rational optimization design module that, as of the preliminary stage, allows for:

- a 3D analysis of the general behaviour of the structure (usually one cargo hold);
- to explicitly take into account all the relevant limit states of the structure (service limit states and ultimate limit states) thanks to a rational analysis of the structure based on the general rules of solid-mechanics and structure behaviour;
- an optimisation of the sizing/scantling (profile sizes, dimensions and spacing) of the structure's constituent elements;
- to include the manufacturing costs and the production procedure in the optimisation process (through a production cost objective function).

The advantages of this optimisation module appear mainly at the preliminary stage. It is indeed during the first stages of the project that flexibility, modeling speed and method's easy use provide precious help to designers. At this moment, few parameters/dimensions have been definitively fixed and a coarse modeling by standard finite elements is often unusable and this, particularly for design offices and small and medium-sized shipyards.

The LBR-5 package performs such least cost optimization at early design stage. Design variables are the dimensions of the longitudinal and transversal members, plate thickness and spacing between members. The software contains 3 modules. The "*Cost Module*" to assess the construction cost which is the objective function (least construction cost). The "*Constraint Module*" performs rational analyses of the considered structure, and the *"Opti Module*" contains the mathematical optimiser code. More extensive information on the LBR5 model is available in the literature (Rigo 2001c, Fleury 1989).

Relevant information on the methodology and applications to a FSO unit and a LNG carrier are presented in the paper.

LBR-5 AND ITS 3 BASIC MODULES

The optimisation problem can be summarized as follows:

- X_i i = 1, N the N design variables,
- $F(X_i)$ the cost objective function to minimize,
- $Cj(X_i) \leq CM_j$ j = 1,M the M structural and geometrical constraints,
- $X_{i\,min} \leq X_i \leq X_{i\,max}$ the upper and lower bounds of the X_i design variables, that is, technological limits (also called *side constraints*).

The structure is modeled with stiffened panels (plates and cylindrical shells). For each panel one can associate up to 9 design variables (X_i), that is:

- plate thickness (δ),
- for longitudinal members (stiffeners, crossbars, longitudinals, girders, etc.):
  - 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).

LBR5 is built around three basic modules, respectively, *OPTI*, *CONSTRAINT* and *COST*.

The *OPTI module* contains the mathematical optimisation algorithm (CONLIN) that allows solving non-linear constrained optimisation problems. It is especially effective because it only requires a reduced number of iterations. In general, less than 15 iterations, including a structure re-analysis, are necessary, even in the presence of several hundred-design variables (X_i). CONLIN is based on a convex linearisation of the non-linear functions (constraints and objective functions) and on a dual approach (Fleury, 1989; Rigo and Fleury, 2001).

The *CONSTRAINT module* asks the user to select relevant constraints within constraint groups available in a database Rigo, 2001a).

Constraints are linear or non-linear functions, either explicit or implicit in the design variables (X_i). One can distinguish:

- Technological constraints (or side constraints) that provide the upper and lower bounds of the design variables.
- Geometrical constraints that impose relationships between design variables in order to guarantee a functional, feasible and 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 that represent limit states in order to avoid yielding, buckling, cracks, etc. and to limit deflection, stress, etc. These constraints are based on direct analyses and are modelled with rational equations.

The *COST module* (Rigo 2001b; Rigo 2003): In 2005, even for a first draft, a least weight optimisation process can no longer be justified and should be replaced by a least construction cost or, even better, by a minimum global cost (including operational costs).

The Cost Module and the Objective Function

Global construction costs can be subdivided into three categories: (a) cost of raw materials, (b) consumable costs, (c) labour costs, and (d) overhead costs. For optimisation purpose, the absolute cost is not needed, the overhead cost, though far from negligible, can be ignored by the analytic cost model.

Theoretically, the global cost evaluation procedure requires:

- to divide the whole construction process in NT1 standard tasks of level 1, for example, dividing the whole structure into blocks. Several blocks can be identical.
- to subdivide each of these NT1 standard tasks into NT2 sub-tasks;
- to repeat this process until reaching a group of elementary standard tasks (that cannot be subdivided further, or that one does not choose to divide further);
- to define the hourly unit cost (S_i) of each "i" elementary task,

Therefore, the cost model should be established in close relation to a specified production plan. Unfortunately, it doesn't seem possible to define a general model, valid for all yards. That is why a more global model was developed, not specific to a production plan, but that is able to accurately assess the relative cost and is sensitive to any changes in the scantling (design variables).

The cost module, currently used in the LBR-5 model, includes three components (Eq.1):

$$FC = F_{MAT} + F_{CONS} + F_{LAB} \quad \text{(in Euros)} \qquad (1)$$

where:

- FC: global cost function (in Euros);
- F_{MAT}: cost of basic materials (plates, bars, etc.);
- F_{CONS}: cost of consumables necessary for the construction process (energy, welding materials, etc.);
- F_{LAB}: cost of labour used for the building of the entire structure.

Cost of materials: F_{MAT}

The cost of materials (Eq. 2) is directly derived from the weight function. Each term is multiplied by the relevant C_i unitary material cost (plate, bulb profile, etc.). Thus, one gets:

$$F_{MAT} = \gamma . L . B . \left[\begin{array}{c} C_1 . \delta + C_2 . \dfrac{(h.d + w.t)_X}{\Delta_X} \left[1 + DW_2\right] \\ + C_3 . \dfrac{(h.d + w.t)_Y}{\Delta_Y} \left[1 + DW_3\right] \end{array} \right] \quad (2)$$

where:

- γ = Density,
- $(h.d+w.t)_X$ = the cross section area of a longitudinal,
- $(h.d+w.t)_Y$ = the cross section area of a transverse frame,
- Δ_X = Distance between longitudinals/stiffeners,
- Δ_Y = Distance between transverse frames,
- C_1 = cost per kg of a plate δ mm thick,
- C_2 = cost per kg of the longitudinals/stiffeners,
- C_3 = cost per kg of the transverse frames,
- DW_2 = corrective factor (ratio of C_2) of the longitudinals/stiffeners for additional weight,
- DW_3 = corrective factor (ratio of C_3) of the transverse frames for additional weight.

DW_2 and DW_3 are used to adjust the member weight, of respectively, the longitudinals and frames, to consider the extra weight induced by brackets (TAP), local stiffening as flat bars to stiffen high web-frames.

In order to take into account a possible variation of the price per kg of the plates according to their thickness, the C_1, C_2 and C_3 parameters (Euro/kg) are defined as follows:

$$C_1 = C_1^o \left[1 + \Delta C_1 \left(\delta - E_0\right)\ 10^3\right] \quad \text{for plating} \quad (3a)$$

$$C_2 = C_2^o \left[1 + \Delta C_2 \left(dx - E_{0X}\right)\ 10^3\right] \quad \text{for longitudinals} \quad (3b)$$

$$C_3 = C_3^o \left[1 + \Delta C_3 \left(dy - E_{0Y}\right)\ 10^3\right] \quad \text{for frames} \quad (3c)$$

where:

- C_1^o = Cost per kg of a plate with a thickness δ = Eo, (in m),
- C_2^o = Cost per kg of longitudinal members having a web thickness = Eox,
- C_3^o = Cost per kg of transverse members having a web thickness = Eoy,
- Eo = Reference thickness for the plates (mean plate thickness), (in m),
- Eox = Reference thickness for the longitudinal members (mean web thickness),
- Eoy = Reference thickness for the transverse members (mean web thickness),
- d_X,d_Y= Actual web thickness for stiffeners along X (long.) and frames along Y (transverse);
- ΔC_1 = Change in % of C_1^0 (cost/kg) between plates of Eo and Eo +1 mm thick,
- ΔC_2 = Change in % of C_2^0 (cost/kg) of the longitudinals between web of Eox and Eox +1 mm thick,
- ΔC_3 = Change in % of C_3^0 (cost/kg) of the frames between web of Eoy and Eoy +1 mm thick,

Cost of Consumables: F_{CONS}

The welding cost per meter includes energy, gas, electrodes, provision for the equipment depreciation, ...), excluding labour cost

Labour Costs: F_{LAB}

$$F_{LAB} = W_{Load} \cdot \text{Hourly Rate} \quad (\text{Euro/m} - \text{h}) \quad (4)$$

where " W_{Load}" is the global working load (m-h), (Eq.5).

$$W_{Load} = L . B . \left[\begin{array}{l} \dfrac{1}{\Delta_X} . P_4 + \dfrac{1}{\Delta_Y} . P_5 \\ + \dfrac{1}{\Delta_X . \Delta_Y} \left(P_6 + \beta_X . \beta_Y . P_7\right) \\ + \dfrac{1}{\Delta_X} . P_{9X} + \dfrac{1}{\Delta_Y} . P_{9Y} + P_{10} \end{array} \right] \quad (5)$$

where:

- Δ_X = Distance between longitudinals/stiffeners
- Δ_Y = Distance between transverse frames
- P_4 = working load to weld 1 meter of a longitudinal stiffener on the plating (side shell,...), (m-h/m)
- P_5 = working load to weld 1 meter of a transversal stiffener on the plating (m-h/m)
- P_6 = working load to prepare the intersection (slot) between a longitudinal and a transversal and to join these members (m-h/intersection).
- P_7 = working load to fix bracket(s) at the intersection between a longitudinal and a transversal (m-h/intersection).
- β_X,β_Y = ratio (in %) of the longitudinal stiffeners (β_X) and transverse stiffeners (β_Y) that requires brackets (e.g.: β_X = 0.33 means one bracketed longitudinal on 3 and β_Y = 1.0 a bracket on each frame);
- P_{9X},P_{9Y}= working load to build 1 meter of stiffener/frame (assembling flange and web) from standard plates in the production plan (m-h/m).
- P_{10} = working load to prepare 1 m^2 of plating (m-h/m^2).

The aforementioned average values of P_4^o, P_5^o, P_6^o, P_7^o, P_9^o and P_{10}^o working loads are available in the literature (Rigo, 2001). Unfortunately nothing seems available in books and papers to determine the first derivative of these working loads according to plate thickness (ΔP_4, ΔP_5, ΔP_9 and ΔP_{10}). Hopefully using shipyard database, it is possible to quantify these parameters by calibrating the working loads with regards to weld sizes.

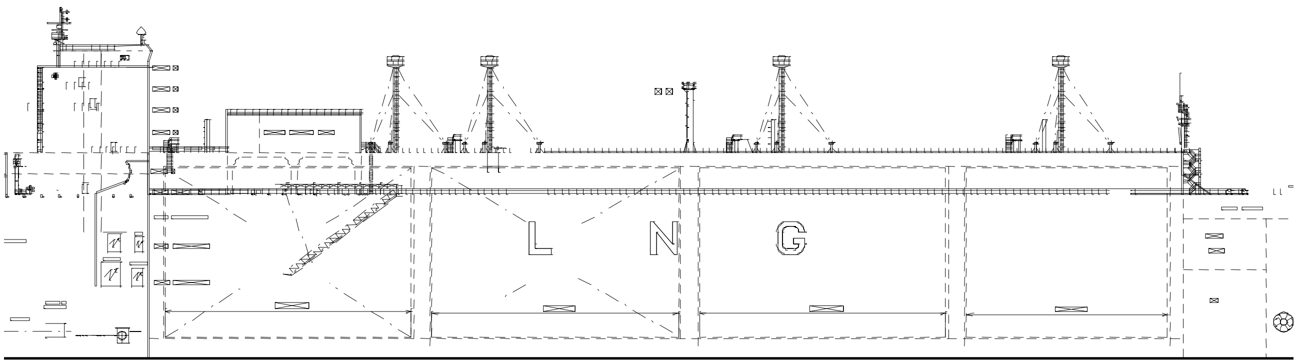

Figure 1: General view of a ship gas carrier

This least cost optimisation example concerns the optimisation of a gas carrier (LNG).

The present optimisation concerns one of the four tanks (Figure 1). The goal is to define the optimum tank scantlings corresponding to the minimum construction cost. An additional aim is to assess feasible alternative designs (that is, improved general structural layouts).

To calibrate the current LBR5's cost module with the shipyard unitary costs, the cost of a standard stiffened panel was assessed using the unitary production costs. These unitary costs relate to:

- plate assembling and welding,
- longitudinal stiffener assembling and welding,
- transverse frame prefabrication,
- transverse frame assembling and welding (for different assembling sequences as the structure is mainly composed of double bottom, double deck and double side plates),
- slots, brackets, etc. (cutting, assembling and welding),
- ….

The ship is classified Bureau Veritas and the MARS2000 software is used to define the initial scantlings to be used by LBR5 as reference values. After optimisation, the new scantlings (optimum) are validated using MARS2000 to confirm the feasibility of the new layout and scantlings. This control fully confirms the LBR5 results and the possibility to save about 8 % of the tank's construction cost (cofferdam excluded).

Five loading cases were considered by LBR-5. They were obtained combining unitary load cases. The structural mesh model is shown on Figure 2. Based on structure symmetry, only half of the structure is modelled for structure optimisation with the LBR-5 model. The maximal sagging and hogging hull girder bending moments (still water level) were valued through direct calculation (loading manual). The wave bending moments were obtained from classification rulebook.

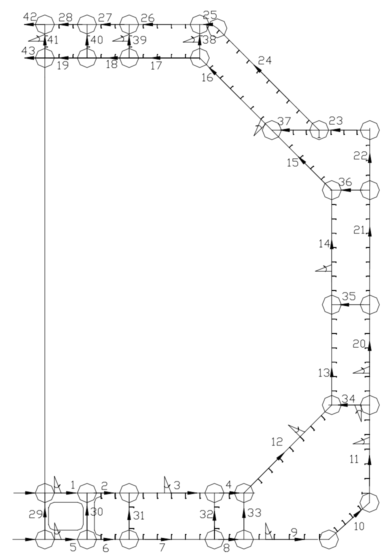

Figure 2: LBR5's Mesh Model of a LNG Ship

The mesh model of the LNG ship includes:

- 41 stiffened panels with 9 design variables each (some are not considered as variables);
- 278 design variables (on average 5 to 9 design variables per panel);
- 203 geometrical constraints (about 5 to 6 x 41 panels).
- 1900 structural constraints (380 per load case):

In addition side constraints are imposed on the design variables (XI_{MAX}, XI_{MIN}).

Minimizing the Construction Costs of the LNG Ship

Tracks to reduce the construction cost of the considered LNG ship are:

- To increase the web-frame spacing:
  ($N_w - 2$) or ($N_w - 3$) web-frames instead of N_w web-frames
- To increase the stiffener spacing (Δ_L):
  1.09 Δ_L , 1.15 Δ_L or 1.28 Δ_L instead of Δ_L

N_w and Δ_L refer to the initial design (before optimisation). N_w is the number of web-frames, Δ_W the frame spacing and Δ_L the average longitudinal stiffener spacing.

Aim of the LBR5 optimisation analysis is to provide a *least construction cost* and *feasible scantlings* of the 4 tanks. In principle, LBR5 directly provides the global optimum. In that case, it is not possible to assess the cost saving of each individual parameter like frame spacing, stiffener spacing, plate thickness, duct-keel layout, etc.

To assess these individual cost savings, the present optimisation was split in several sub-optimisations. So, starting from the initial design, step by step, parameters are released and the layout modified (see Table 1). Initially, the upper limit of each design variable is fixed at the shipyard initial scantling values. Then, the upper limits of a group of design variables are released (typically starting with the frame spacing and stiffener spacing).

Main sub-optimisations are presented in Table 1. They are:

- Least cost optimisation (starting from the initial scantlings provided by the shipyard, with fixed frame and stiffener spacings),
- Web-frame spacing (Δ_W) is released: N_w → (N_w – 2) frames,
- When feasible, the stiffener spacing is released: 1.15 Δ_L and 1.28 Δ_L instead of Δ_L,
- General structural layout is modified,
- Spacing of secondary frames is modified (typically 2 or 3 secondary frames between web-frames are considered, that is, respectively, $\Delta_C = \Delta_W/3$ and $\Delta_W/4$),

Table 1 assesses the cost saving associated with each sub-optimisation and with the global optimisation (cumulated cost saving). It shows clearly that the way to reduce construction cost of the concerned LNG ship is to increase the web-frame spacing (N_W-3) and to standardize the stiffener spacing at 1.15 Δ_L (in average). Such changes induce a cost saving of about 8.50% (material and labour costs).

The global optimum (MET8-F90) is characterised by an increase of the weight. To avoid this negative effect, a modified layout was proposed to keep the hull weight almost unchanged without a significant reduction of the cost saving.

The influence of the variation in the price of steel has been studied. It was observed that an increase in the price from 600$/Ton to 1000$/Ton does not change so much the trends. Optimization continues to induce a large variation in the structure scantling and important differences of cost still appear between least cost and least weight design: 10.7% and 5.9% for 600$/ton and 1000$/ton respectively
Table 2 shows this influence for a country having a high labor cost (USA/Europe)

Table 2: Influence of the steel price

Steel price	Frame space (m) LEAST COST (LC)	Frame space (m) LEAST WEIGHT (LW)	Cost (1000US$) LEAST COST (LC)	Cost (1000US$) LEAST WEIGHT (LW)	Cost (1000US$) DIFFERENCE LC vs. LW
600$/Ton	5.15	4.08	5600	6200	9.7%
1000$/Ton	4.90	4.08	7480	7980	6.2%

Table 1: Cost Saving at Each Step of the Optimisation Process

SEARCH FOR THE LEAST COST DESIGN (with continuous design variables)

CONFIGU-RATIONS	Optimum Type	SPACINGS: Number of Web-frames	SPACINGS: Second. Frame (Δ_C)	SPACINGS: Stiffeners (Δ_L)	Duct keel bulkhead. Plate Thickness	LEAST COST: COST SAVING (%) (see 1) Between 2 successive steps	LEAST COST: COST SAVING (%) (see 1) Cumulated saving	WEIGHT (%)	
	Shown change(s) between 2 successive steps								
1-Reference	MARS BV	N_W	Δw/3	Δ_L	100%	0.00%	0.00%	100% (ref)	Initial Design (used as reference)
2- MET8 E00	Least Cost	N_W	Δw/3	Δ_L	105%	-1.39%	-1.39%	98.34%	
3- MET8 E90	Least Cost	N_W	Δw/3	1.15 Δ_L	105%	-2.46%	-3.85%	101.61%	
4- MET8 B90	Least Cost	N_W -3	Δw/3	1.15 Δ_L	130%	-6.40%	-10.25%	104.73%	plate thickness too large
5- MET8 F90	Least Cost	N_W -3	Δw/4	1.15 Δ_L	100%	1.67%	-8.58%	103.42%	OPTIMUM SOLUTION
6- MET8 F	Least Cost	N_W -3	Δw/4	1.28 Δ_L	100%	-0.53%	-9.11%	105.29%	(*) Poor efficiency
	(*) Stiffener spacing too large ==> cost savings of 0.5% but increased straightening work ==> not efficient !!								
(1) Variation induced by the changes occurred between two configurations.									

LEAST COST OPTIMIZATION OF A FSO UNIT

This least cost optimization example concerns the optimization of a FSO barge of 336 m with a capacity of 370,000 t, designed to serve as floating reservoir (provisory storage area) in view to receive crude oil before being transferred on board tankers (FSO = Floating Storage Offloading). It is a moored barge, without its own propulsion system with a 2,500,000-barrel capacity.

The anchorage, independent of the barge, permits an almost free motion (Fig. 3). The barge is filled using a pipeline connected to the shore. The small discharge of the pipeline induces uniform and slow loading. On the other hand, the discharge of the FSO unit that corresponds to the filling of a 2,000,000 barrels VLCC (Very Large Crude Carrier), is very fast and not uniform.

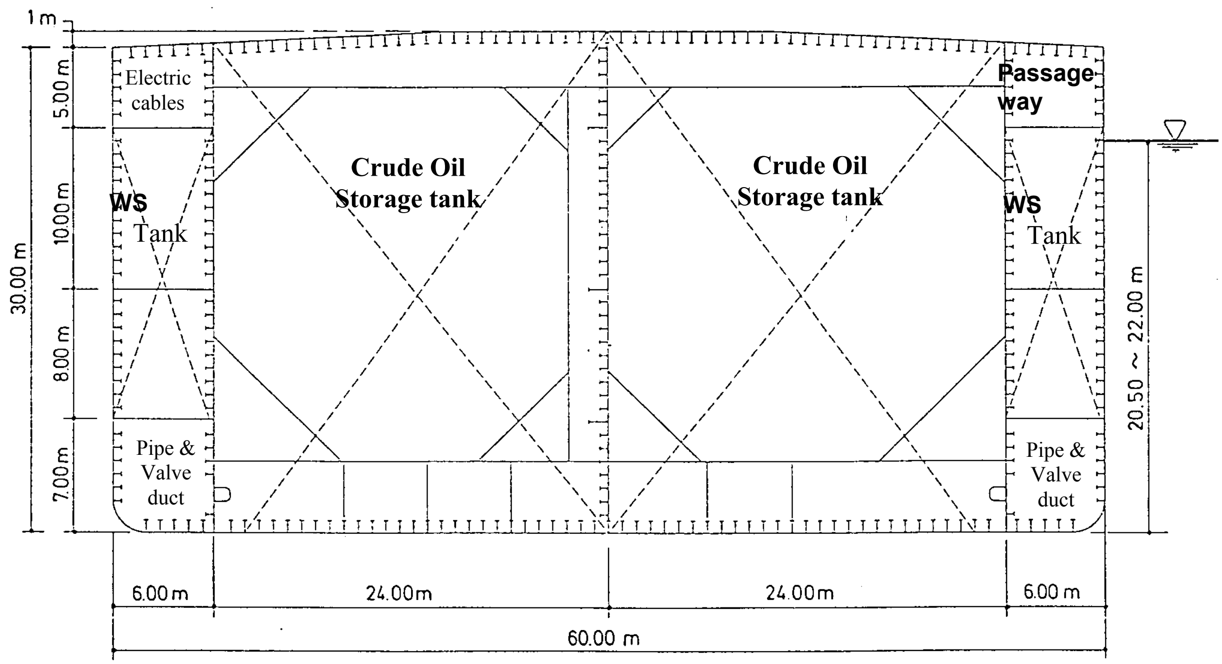

Fig. 3. Midship section of the FSO barge

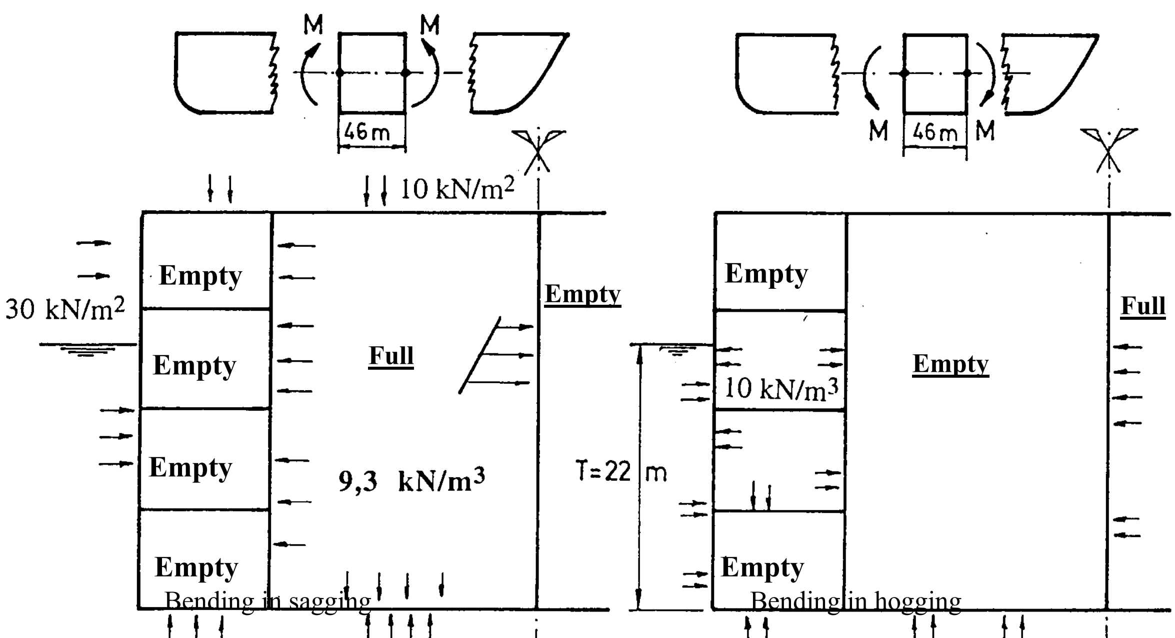

Fig. 4. Considered loading cases.

The optimization of a 46-m hold composed of two center tanks of 24 m x 30 m x 46 m and two lateral ballast tanks of 6 m in width was performed. The two considered loading cases are presented on Fig. 4 and the modeling is shown on Fig. 5. Based on structure symmetry, only half of the structure is modeled for structure optimization with the LBR-5 model. The maximal hull girder bending moment (without waves) has been valued at 6.57 10^6 kN-m and the shear force at 245,200 kN. In addition, to take into account the wave bending moment, the optimum scantling was performed for a maximum bending moment of 10 Mio kN.m (hogging and sagging).

In order to model the strong rigid bracket at each extremity of the tanks' transverse girders, the bottom panel of these center tanks (24 m in width) is modeled with three stiffened panels of 8-m wide in order to simulate a variable rigidity of these transverse members. Similarly, the longitudinal bulkheads and the deck are modeled with three elements each. Since the central bulkhead is on the symmetry axis, only half of its rigidity is taken into account in the model.

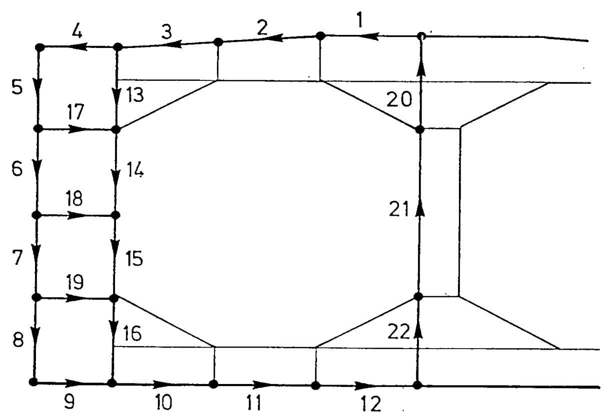

Fig. 5. Mesh Modeling used for LBR-5 for the FSO Midship Section.

Optimum costs are calculated using the following cost and productivity data (values 2001):

- Reference plate thickness: $\delta = 10$ mm
- Unitary price of steel
  - C1 = 0.57 Euro/kg , ΔC1 = -0.6% (if AE235)
  - C1 = 0.65 Euro/kg, ΔC1 = -0.6% (if AE355)
- Price of welding (materials only):
  - C8 = 1.00 Euro/m , ΔC8 = 15%
- Manpower:
  - plate: P10 = 0.5 m-h/m^2 , ΔP10 = 7%
  - frames (assembling with plate) : P4 = P5 = 1 m-h/m, ΔP4 = ΔP5 = 10%
  - frames (if built on site): P9 = 0.5 m-h/m, ΔP9 = 1%

The mesh model of the FSO unit includes:

- 22 stiffened panels with 9 design variables each;
- 198 design variables (9 x 22 panels);
- 48 equality constraints between design variables are used, e.g., to impose uniform frame spacing for the deck, bottom and central bulkhead in the center tanks and another one in the side ballast tanks.
- 198 geometrical constraints (9 x 22 panels). Since the web heights of longitudinal and transversal members are quite important, no geometrical constraints were selected for web slenderness. Web buckling stability and possibly their bracketing are then verified afterwards (post-optimization);
- 396 structural constraints (198 by load case):
  - σ_c frame (web/plate & web/flange junctions),
  - σ_c stiffener (web/plate – web/flange and flange) and σ_c plate : $\sigma_c \leq s.\sigma_o$ (with $s = 0.65$ and $\sigma_o = 355$ N/mm^2);
  - local plate buckling: $\delta_{MIN} \leq \delta$ (with δ_{MIN} the minimum plate thickness to avoid buckling);
  - ultimate strength of stiffened panel: $\sigma/\sigma_{ULT} \leq s$ with s = 0.55 ;
- 2 constraints on the ultimate hull girder/box girder strength: $M/M_{ULT} \leq s$ (s = 0.55).

In order to define optimal scantlings (least cost and least weight), side constraints are imposed on the design variables (XI_{MAX}, XI_{MIN}). For instance, the upper limit for the (δ) plate thickness is fixed at 40 mm.

Other selected limits (side constraints) are:

2.87 m	≤	Δ_{Frames}	≤	7.66 m
0.50 m	≤	$\Delta_{Stiffeners}$	≤	1.00 m
1.20 m	≤	h_{web} frames (center tanks)	≤	6.00 m
0.50 m	≤	h_{web} frames (side tanks)	≤	2.50 m
8.0 mm	≤	Web thickness	≤	30 or 40 mm

Since the first results showed the importance of the "*δ ≤ 40 mm*" side constraints, a second analysis was performed, imposing δ ≤ 30 mm. In addition, the frame spacing in the center tanks [Δc (center tanks)] and those in the side tanks [Δc (side tanks)] are considered to be independent. However, it is imposed that:

$$\Delta c \text{ (side tanks)} = \Delta c \text{ (center tanks)} / \alpha$$

with α an integer number lower than 3 (α ≤ 3).

Table 2 compares six different configurations (C1 to C6). Analysis of the various results (see Table 2) shows that:

- The maximal plate thickness (30 mm or 40 mm) is an active constraint that strongly influences the optimum (active constraints). Thus, there is more than a 30% increase in weight and cost when "*δ ≤ 30 mm*" is selected as constraint.
- If one selects *δ ≤ 40 mm*, the optimum scantling varies considerably depending on whether one searches for optimum weight or optimum cost. On the other hand, with a maximal plate thickness of 30 mm, the feasible design space is so reduced that the optimum cost and weight are nearly identical.
- Doubling the number of frames in the side tanks ($\Delta_{side\ tanks} = 0.5\ \Delta_{center\ tanks}$) allows, in some cases, to reduce the weight. Unfortunately, this is also always synonymous with higher costs. Therefore, it doesn't seem feasible to envision this solution.
- Least weight scantlings are in general not economic solutions. Thus, the cost variation between least weight and least cost is 5% for δ ≤ 40 mm and 18% for δ ≤ 30 mm. This demonstrates the attractiveness of least cost

optimization, compared to standard least weight optimization.

♦ Finally, the recommended scantlings are:
- for least cost (C = 100%, P = 109%):
  - $\delta \leq 40$ mm with 7 frames ($\Delta = 5.75$ m)
  - cost per kilo: 2.17 Euro
- for least weight (C = 106%, P = 101%):
  - $\delta \leq 40$ mm with 8 frames ($\Delta = 5.11$ m)
  - cost per kilo: 2.42 Euro

Table 2: Results of the optimization of the FSO unit

Configurations	Weight KN (%)	Cost 10^6 Euro (%)	Cost per kg Euro/kg	Δ(side tanks) + N(*)	Δ(center tanks) + N(*)
$\delta \leq 40$ mm					
Least Cost					
C1 : $\Delta_{side\ tank} = \Delta_{center\ tanks}$	29280 (109 %)	6.34 (100 %)	2.17	5.75 m N = 7	5.75 m N = 7
C2 : $\Delta_{side\ tank} = ½\ \Delta_{center\ tanks}$	29740 (111 %)	6.63 (105 %)	2.23	6.57 m N = 6	3.285 m N = 13
Least weight					
C3 : $\Delta_{side\ tank} = \Delta_{center\ tanks}$	27150 (101 %)	6.70 (106 %)	2.42	5.11 m N = 8	5.11 m N = 8
C4 : $\Delta_{side\ tank} = ½\ \Delta_{center\ tanks}$	26850 (100 %)	7.13 (113 %)	2.61	5.75 m N = 7	2.875 m N = 15
$\delta \leq 30$ mm					
Least Cost C5 : $\Delta_{side\ tank} = \Delta_{center\ tanks}$	38870 (145 %)	8.52 (134 %)	2.19	3.07 m N = 14	3.07 m N = 14
Least weight C6 : $\Delta_{side\ tank} = \Delta_{center\ tanks}$	38500 (143 %)	9.64 (152 %)	2.50	3.07 m N = 14	3.07 m N = 14
Initial Scantling (Start of the Opt. Process)	39370 (147 %)	9.74 (154 %)	2.47	7.66 m N = 5	7.66 m N = 5

(*) N = Number of frames for a 46-m long hold, N = (46/Δ) –1

Most advisable scantlings (design)

CONCLUSIONS

LBR-5 is a structural optimisation tool for structures composed of stiffened plates and stiffened cylindrical shells. Design variables are plate thickness, longitudinal and transversal stiffener dimensions and their spacing. It is an integrated model to analyse and optimise ship structures at their earliest design stages: tendering and preliminary design.

Advantages and main characteristics are:
- Preliminary design oriented (easy and fast modelling, reduced amount of input data, etc.),
- Structure optimisation at initial design (initial feasible scantling is not required, etc.),
- Least construction cost and least weight (objective functions) based on a rational explicit formulations of the cost,
- Rational formulation of the constraints (technologic, geometric and structural constraints). They are not rule based. Ultimate strength of stiffened panels and ultimate bending moment are considered thought rational constraints,
- Efficient and reliable optimiser (only 10~15 iterations and 1 hour are necessary to get the optimum). Large structures can be studied (100 panels, 900 design variables and 5000 constraints to cover up to 10 loading cases).
- Least cost optimization of LNG ship can induce a cost saving of more than 8% on the hull structure.

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