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Least Cost Optimisation of a Medium Capacity Gas Carrier

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Abstract

To be attractive for shipyards, scantling optimisation has to be performed at the preliminary design stage. It is indeed the most relevant period to assess the construction cost, to compare fabrication sequences and, to find the best frame/stiffener spacings and most suitable scantlings to minimize the production costs. The LBR5 package performs such early design least cost optimisation.
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.
This paper presents the optimisation of a medium capacity LNG ship designed by ALSTOM France (Chantiers de l'Atlantique). In addition to scantling optimisation, sensitivity analysis on frame/stiffener spacings are presented. This industrial optimisation example shows that 5 to 9% of the construction cost of the hull manufacturing can be saved by performing scantling optimisation at the preliminary design stage.

1. Introduction

LBR5 is a rationally based optimisation module that, in 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 solid-mechanics theory;
- an optimisation of the sizing/scantling (profile sizes, dimensions and spacing) of the structure's constituent elements;
- to include the unitary construction costs and the production sequences in the optimisation process (through a production-oriented cost objective function).

Design variables are the dimensions of the longitudinal and transversal members, plate thickness and spacing between members.

Extensive information on the proposed model is available in the literature: *Rigo (2001a and b), Rigo and Fleury (2001), Karr et al. (2002).*

2. LBR5, a tool for least cost scantling optimisation

LBR5 is built around three basic modules, respectively, OPTI, CONSTRAINT and COST (Figure 1). The OPTI module contains the mathematical optimisation algorithm to solve non-linear constrained optimisation problems, *Fleury (1989), Rigo and Fleury (2001).*

The CONSTRAINT module includes (1) technological constraints (or side constraints) that provide the upper and lower bounds of the design variables; (2) 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; (3) structural constraints that represent limit states in order to avoid yielding, buckling, cracks, etc. and to limit deflection, stress, etc.
In the COST module the objective function is the construction cost that includes labour costs and material cost *(Rigo 2001b).*

Fig.1 shows the basic configuration of the LBR5 software with the 3 fundamental modules (COST, CONSTRAINT and OPTI). It describes the general organisation chart of a structure optimisation process and the LBR5 software chart.

With regard to structural constraints, the user must first choose the types of constraints (yielding, buckling, deflection, etc.) then, for each type of constraint, select the method, the code or the rules to use and finally the points/areas/panels where these constraints will be applied.

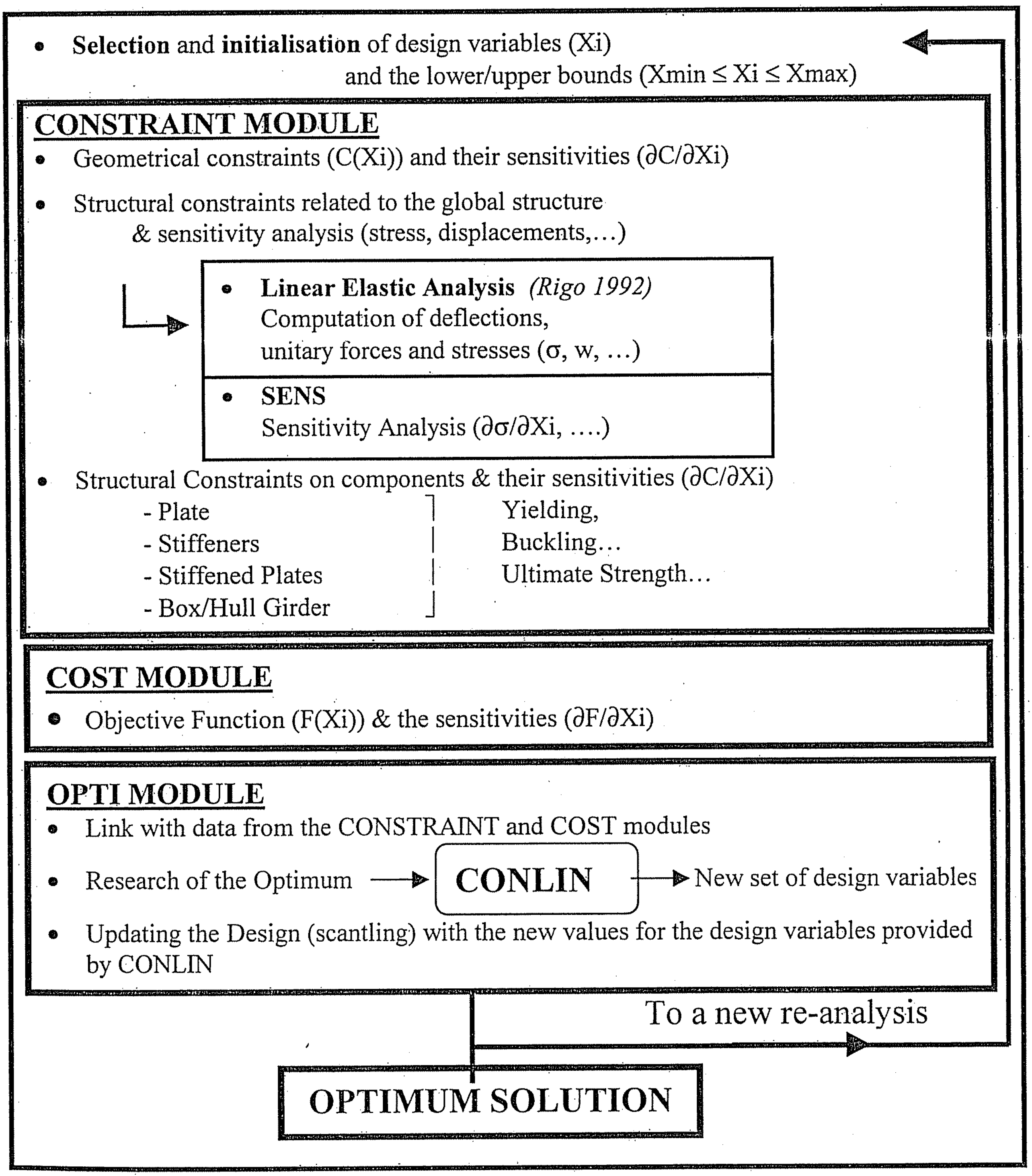


Fig.1: Chart of the LBR5 model with CONSTRAINT, COST and OPTI modules

LBR5 is also an efficient tool to assess and compare different alternatives. For instance Figure 2 gives the cost and the weight as functions of the web-frame spacing. Other major capability of the method is to quantitatively assess a change of the production technology on the construction cost. For instance, effect of an improved welding procedure (lower unitary welding cost) can be assessed by comparing the least cost optimum scantling obtained with and without the improvement.

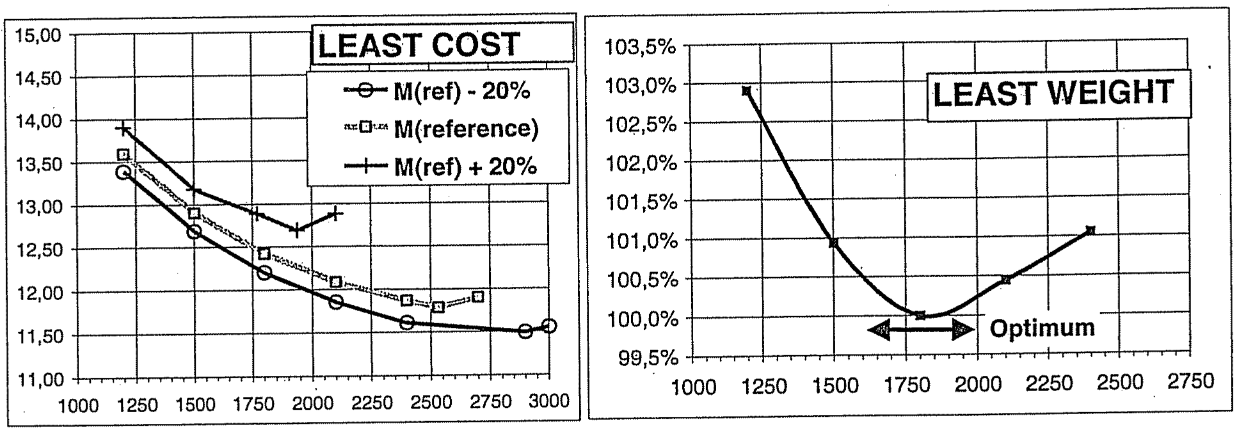


Fig.2: Sensitivity analysis: Cost and weight as a function of the web-frame spacing

Figure 3 (left) shows the simple and fast mesh modelling methodology used by the LBR5 software to optimise a fast ferry (right), which may latter be modelled using standard finite elements (for advanced analysis).

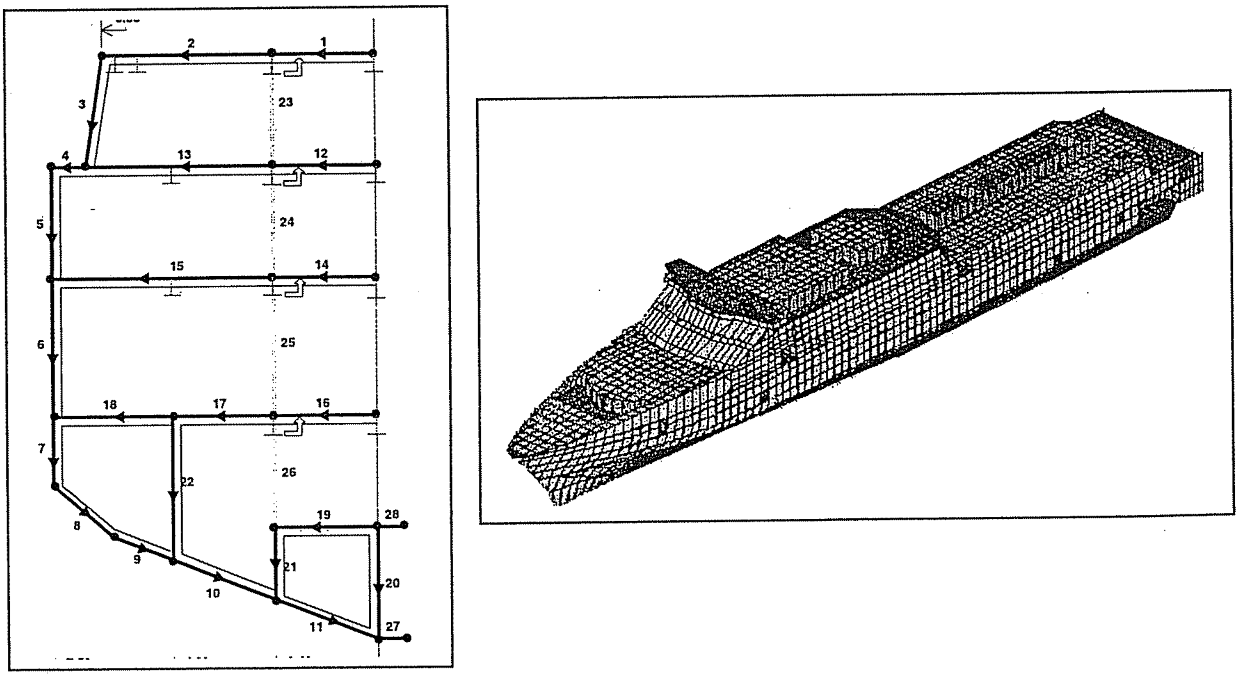
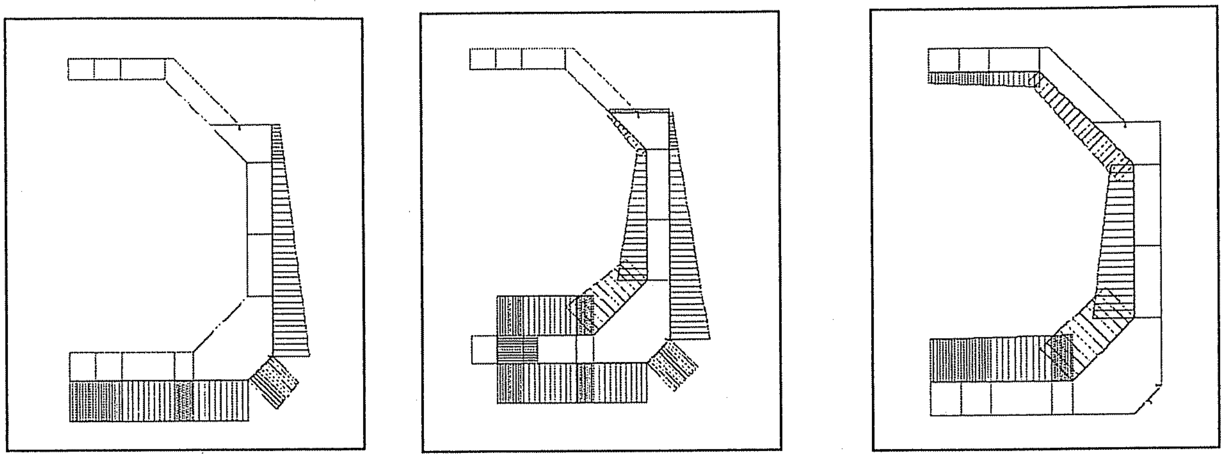


Fig.3: LBR5 Mesh model of a fast ferry (Principia Marine)

Principia Marine (France) and University of Liège have furthermore engaged in cooperation to jointly develop their software and integrate them as part of an early design suite (*Goubault et al.* 2003).

Figure 4 illustrates the use of AVPRO and LBR5 in early design. Although the level of precision of AVPRO is not as fine as those software, the ability of this software to handle all the tasks in one single environment provides this tool with a unique capability for early design. AVPRO is completed with LBR5 with regard to structural design. Further into the design phase the 3DPRO methodology



Sea Loads (BV's rules)

Internal pressure in BALLAST (BV's rules)

Dynamic Internal Pressure in GAS Tank (BV's rules)

Fig.7: Unitary Load Cases

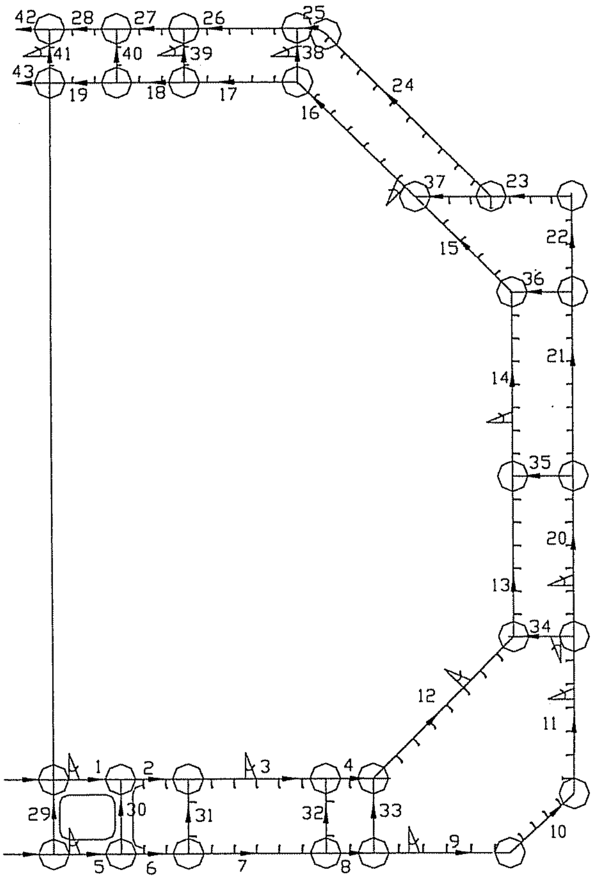


Fig.8: LBR5's Mesh Model
of a Medium Capacity Gas Carrier

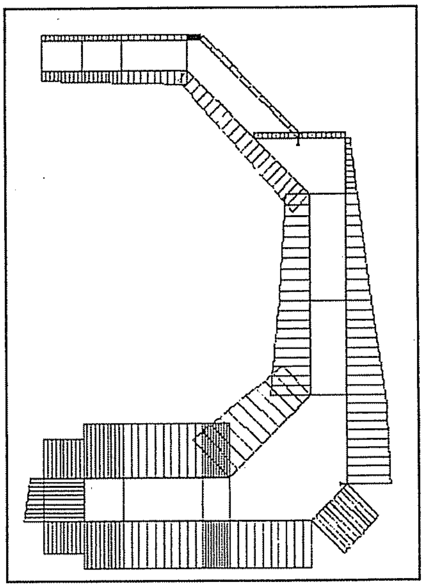
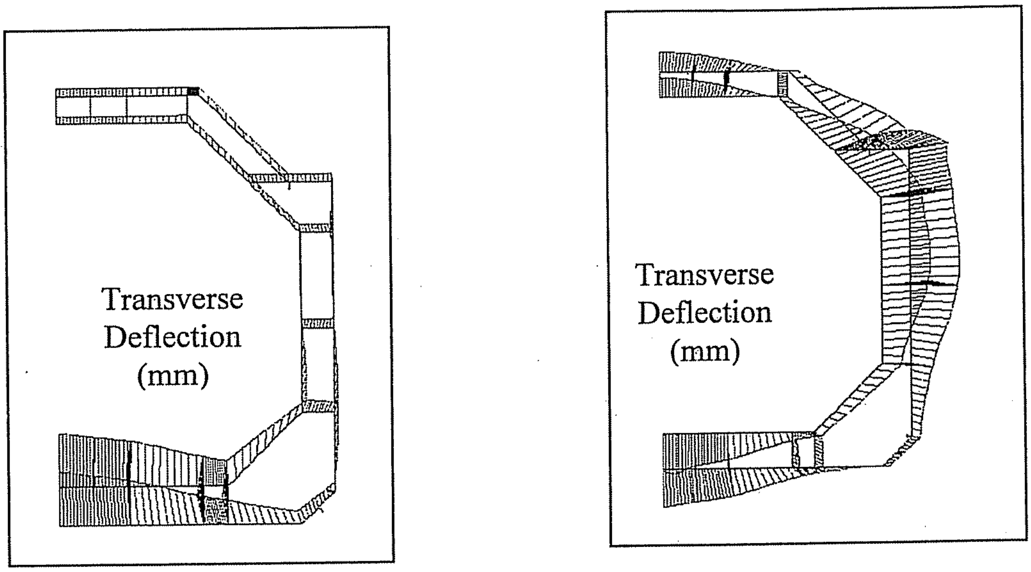


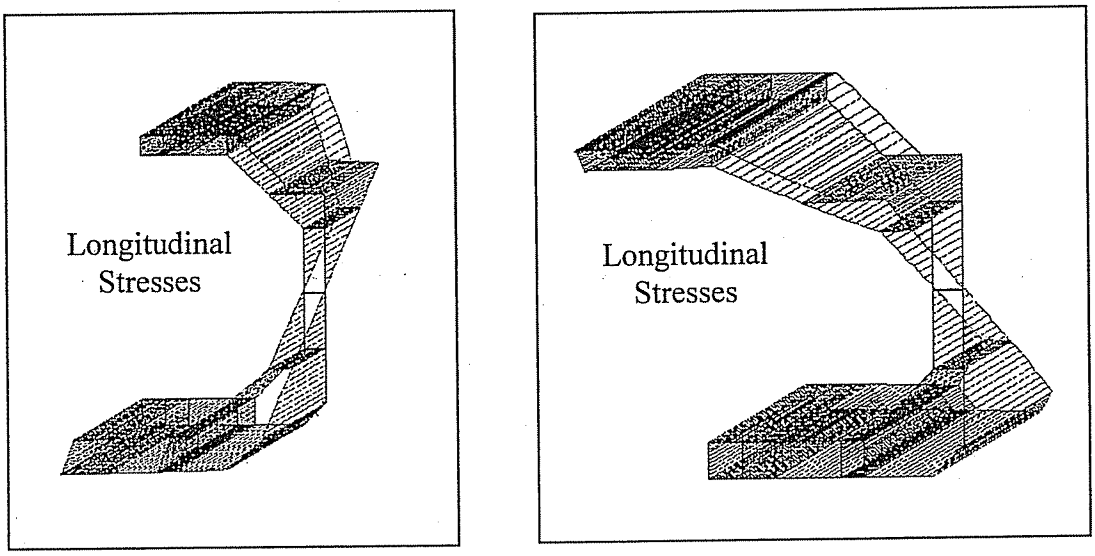
Fig.9: LBR5's Load Case 1:
Maximum lateral pressure
provided by MARS (BV)



Max. Bending of the double bottom
Load Case 2

Max. Bending of the side tank
Load Case 3

Fig.10a: LBR5's Load Cases 2 and 3:
Maximum bending moments of the web-frames.



Hogging
Load Case 4

Sagging
Load Case 5

Fig.10b: LBR5's Load Cases 4 and 5:
Encountering Sea with Max. Hogging and Sagging Hull Girder Bending Moment

The mesh model of the medium capacity gas carrier (LNG) includes:

- 41 stiffened panels with 9 design variables each (some are not considered as variables);
- 4 additional panels to simulate the symmetry axis (boundary conditions);
- 278 design variables (on average 5 to 9 design variables per panel);

- 106 equality constraints between design variables are used, e.g., to impose uniform frame spacing for the deck, bottom and the side ballast tanks.
- 203 geometrical constraints (about 5 to 6 x 41 panels). For instance, longitudinal web heights are limited by such constraints to control the web slenderness.
- 1900 structural constraints (380 per load case):
    - σ_c frame (web/plate junction – web/flange junction and flange),
    - σ_c stiffener (web/plate – web/flange and flange) and σ_c plate, which verified that $\sigma_c \leq s_1.\sigma_o$ (with s_1 a partial safety factor and σ_o the yield stress);
    - local plate buckling: $\delta_{MIN} \leq \delta$ (with δ_{MIN} the minimum plate thickness to avoid buckling and yielding);
    - ultimate strength of stiffened panel: $\sigma / \sigma_{ULT} \leq s_2$ with s_2 a partial safety factor.

In addition 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 25 mm. Other selected limits (side constraints) are:

$2.00\ \text{m} \leq \Delta_{\text{Frames}} \leq 4.00\ \text{m}$

$0.50\ \text{m} \leq \Delta_{\text{Stiffeners}} \leq 1.00\ \text{m}$

$0.10\ \text{m} \leq h_{\text{web stiffeners}} \leq 0.50\ \text{m}$

$8.0\ \text{mm} \leq \text{Web-frames thickness} \leq 25.0\ \text{mm}$

..... etc.

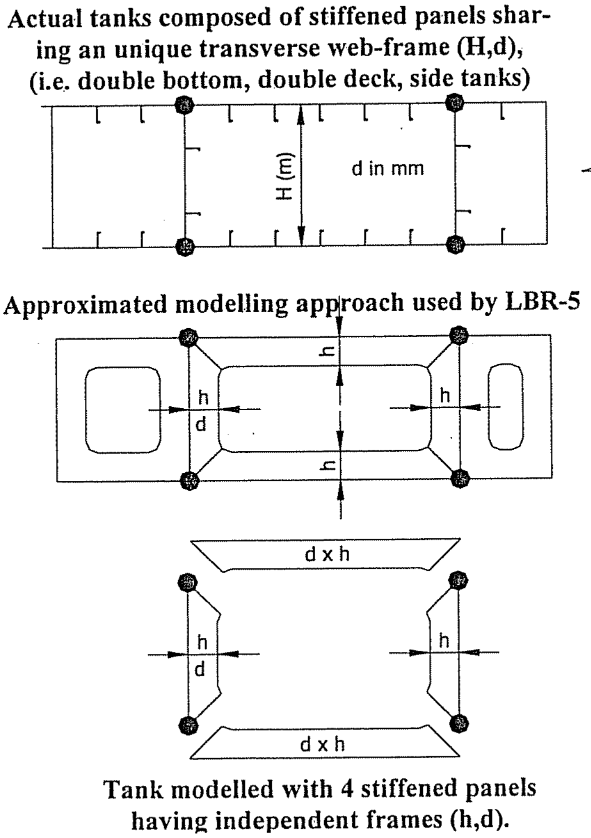


Fig.11: LBR5's Principle to Model
a Double Sided Stiffened Tank

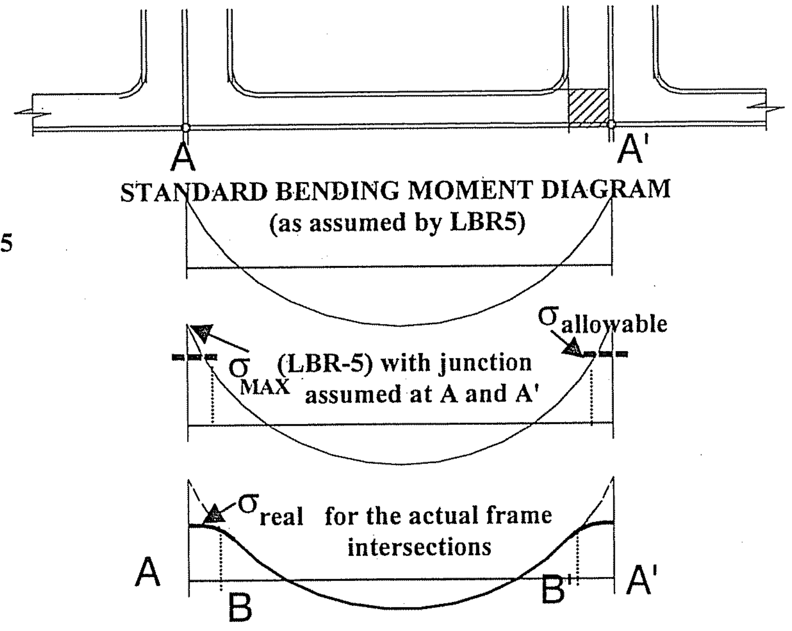


Fig.12:
LBR5's stress distribution
at the junction between framed panels.

Figure 11 points out a major difficulty to use LBR5 for double hull ships. Being a principle of the method *(Rigo 1989)* each web-frame is attached to a unique panel and cannot be shared by all the constitutive panels of a double bottom (Figure 11). Thanks to ALSTOM support, a new methodology is under development to face this problem.

Figure 12 explains another LBR5 assumption, that is, the junction between frames coincides with the panel's node (A or A') and not to B (or B'). This means that around the frame' junction, the stresses are overestimated. To fix this problem, two approaches may be used; (a) to consider in the constraints the stress at point B (B') instead of A (A'), (b) to consider points A and A' but to increase the allowable stress by a ratio (σ_A/σ_B) or ($\sigma_{A'}/\sigma_{B'}$).

3.1. How to Minimise the Construction Costs of the LNG Ship.

Tracks to reduce the construction cost of the medium capacity LNG ship are:

- To increase the web-frame spacing:
  - ($N_w - 2$) web-frames instead of N_w web-frames → Cost saving: 4.85 %
  - ($N_w - 3$) web-frames instead of N_w web-frames → Cost saving: 6.40 %
- To increase the stiffener spacing (Δ_L):
  - 1.09 Δ_L instead of Δ_L → Cost saving: 1.61 %
  - 1.15 Δ_L instead of Δ_L → Cost saving: 2.40 %
  - 1.28 Δ_L instead of Δ_L → Cost saving: 2.97 %

    NB: *straightening cost are not considered.*

Note: 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.

3.2. Steps of the LBR5 Optimisation Process

Aim of the LBR5 optimisation analysis is to provide a *least construction cost* and *feasible scantlings* of the 4 tanks. This optimisation is performed within a series of constraints. There are technological (minimum thickness, corrosion, etc.), geometrical (rule based) and structural constraints (rational based → direct calculation).

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 Alstom's initial design, step by step, parameters are released and the layout modified (see Tables 1 to 3). Initially, the upper limit of each design variable is fixed at the Alstom's initial scantling value. 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 ALSTOM, 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 2 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).

Table 1: Steps of the Optimisation Process (with sub-optimisations)

	SEARCH FOR THE LEAST COST DESIGN (with continuous design variables)				STEPS OF THE OPTIMIZATION PROCESS
		SPACINGS			
	Optimum Type	Number of Web-frames	Secondary Frames (Δ_C)	Stiffeners (Δ_L)	N_W= Numer of Web-frames and Δ_W= Web-frame Spacing Δ_C = Secondary Web-frame Spacing (=$\Delta_W/4$ or $\Delta_W/3$)
1- ALSTOM	MARS BV	N_W	Δw/3	Δ_L (Alstom)	Initial "ALSTOM" layout used as reference point (before optimisation) With discrete design variables.
2- MET8 E00	Least Cost (*)	N_W	Δw/3	Δ_L (Alstom)	After optimisation of the ASTOM initial design with Δ_W, Δ_C and Δ_L unchanged. The design variables become continuous.
3- MET8 E90	Least Cost	N_W	Δw/3	1.15 Δ_L (*)	The stiffener spacings are released (1.15 the initial value)
4- MET8 B90	Least Cost	N_W -3 (*)	Δw/3	1.15 Δ_L (*)	The web-frame spacing is released (upper limit corresponds to 9 frames).
5- MET8 F90	Least Cost	NW -3	Δw/4 (*)	1.15 Δ_L (*)	As the web-frame spacing becomes larger, one additional secondary frame spacing is added (Δ_C = $\Delta_W/4$ instead of $\Delta_W/3$).
6- MET8 F	Least Cost	N_W -3	Δw/4	1.28 Δ_L (*)	The stiffener spacing's upper limit is increased to 1.25 the initial value

(*) Shows the modified parameter (or variable) between two successive steps

Table 2: Cost Saving at Each Step of the Optimisation Process

SEARCH FOR THE LEAST COST DESIGN (with continuous design variables)									
		SPACINGS			Duct keel bulkhead. Plate Thickness	LEAST COST		WEIGHT	
CONFIGURATIONS	Optimum Type	Number of Web-frames	Second. Frame (Δ_C)	Stiffeners (Δ_L)		COST SAVING (%) (see 1)		(%)	
	Shown change(s) between 2 successive steps					Between 2 successive steps	Cumulated saving		
1- ALSTOM	MARS BV	N_W	Δw/3	Δ_L (Alstom)	100%	0.00%	0.00%	100% (ref)	Initial Design (used as reference)
2- MET8 E00	Least Cost	N_W	Δw/3	Δ_L (Alstom)	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	NW -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 occured between two configurations.

Unfortunately, the global optimum (MET8-F90) is characterised by an increase of the weight of 3.4%. To avoid this negative effect, ALSTOM proposed some layout improvement to keep the hull weight almost unchanged. One alternative to avoid an increase of hull weight is to select configuration MET-12b presented in Table 3. MET-12 is characterized by a new structural layout and (N_W-2) web-frames (instead of N_W, see Table 3). Cost saving still reaches 6.9 % with, in addition, a small weight reduction (99.68% on the initial weight).

Table 3: Additional optimum solutions including weight constraint

SEARCH FOR THE LEAST COST DESIGN (with constraint on the weight)									
		SPACINGS			Duct keel bulkhead. Plate Thickness (mm)	LEAST COST		WEIGHT	
CONFIGU-RATIONS	Optimum Type	Number of Web-frames	Second. Frame (Δ_C)	Stiffeners (Δ_L)		COST SAVING (%) (see 1)		(%)	
	Shown change(s) between 2 successive steps					Between 2 successive steps	Cumulated saving		
ALSTOM	MARS BV	N_W	$\Delta w/3$	Δ_L (Alstom)	100%	0.00%	0.00%	100.00%	Initial Design (used as reference)
MET8 E-78	Least Cost	N_W	$\Delta w/3$	Δ_L (Alstom)	105%	-1.39%	-1.39%	98.34%	
MET8 C-78	Least Cost	N_W -2	$\Delta w/3$	Δ_L (Alstom)	122%	-4.85%	-6.24%	100.21%	Duct-keel plate thickness too large
MET 12 (*) Continuous	Least Cost	N_W -2	$\Delta w/3$ (*)	Δ_L (Alstom)	88% (*)	-0.68%	-6.92%	99.68%	OPTIMUM SOLUTION (with discrete design variables)
MET 12.b (*) Discrete	Least Cost	N_W -2	$\Delta w/3$ (*)	Δ_L (Alstom)	88% (*)	0.45%	-6.47%	100.88%	OPTIMUM SOLUTION (with continuous design variables)
	(*) Layout is modified (1) Variation induced by the changes occured between two configurations.								

Figures 14 and 15 compare, respectively, the COST and WEIGHT of the different configurations. Sub-optimisations and optimum solutions are marked.

Based on the LBR5's proposals, ALSTOM modified their initial design and structure layout to define a revised solution that was used for the final design stage.

Expected savings predicted by LBR5 are confirmed through ALSTOM's additional workload assessment.

Figures 16-18 show typical results provided by LBR5 at the end of the optimisation procedure. These results correspond to the 3D rational analysis of a cargo hold.

4. Conclusions

This paper presents an industrial example of scantling optimisation performed using the LBR5 software. The target is to ease and improve the preliminary design stage allowing least cost optimisation. As the general structural layout is defined during the earliest phases, it is easy to understand why a least cost optimisation tool is attractive, especially one designed for use at the preliminary stage.

Optimum analysis of a medium capacity LNG ship is presented as application of the LBR5 least cost optimisation model. Alternatives like modified web-frame spacing, larger stiffener spacing, and improved layout have been assessed. Starting from the original shipyard's structural layout, LBR5's analysis has provided an effective cost saving of 8.5% for the hull tank construction. Main sensitive parameters are frame spacing and stiffener spacing. Using the LBR5 package, optimum scantlings for different configurations were easily compared based on their cost and weight, taking into consideration the shipyard standards (stiffener profiles, shop efficiency and availability, etc.).

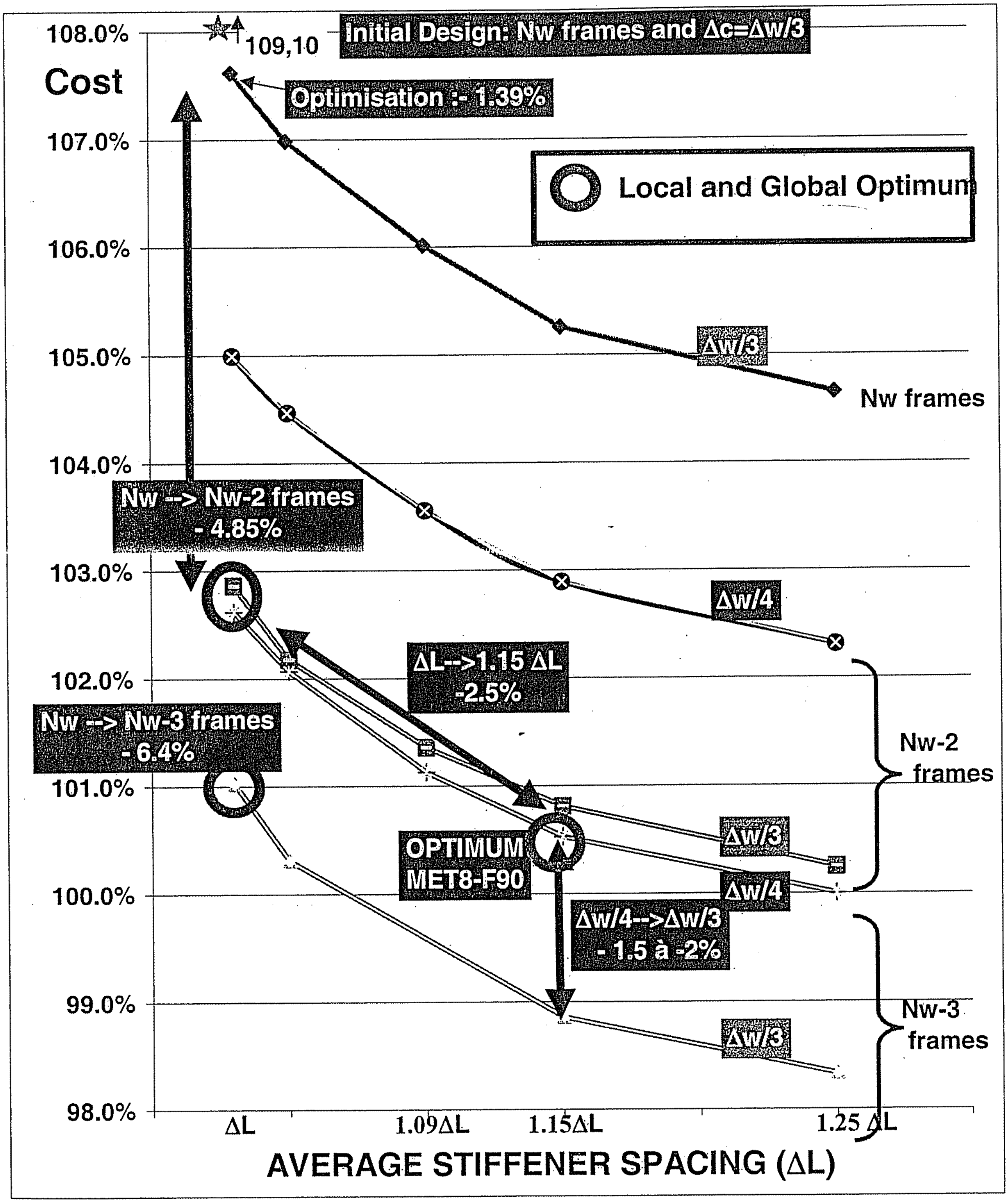


Fig.14: Sensitivity analysis of the stiffener spacing on the construction cost of a medium capacity LNG carrier (one hull tank)

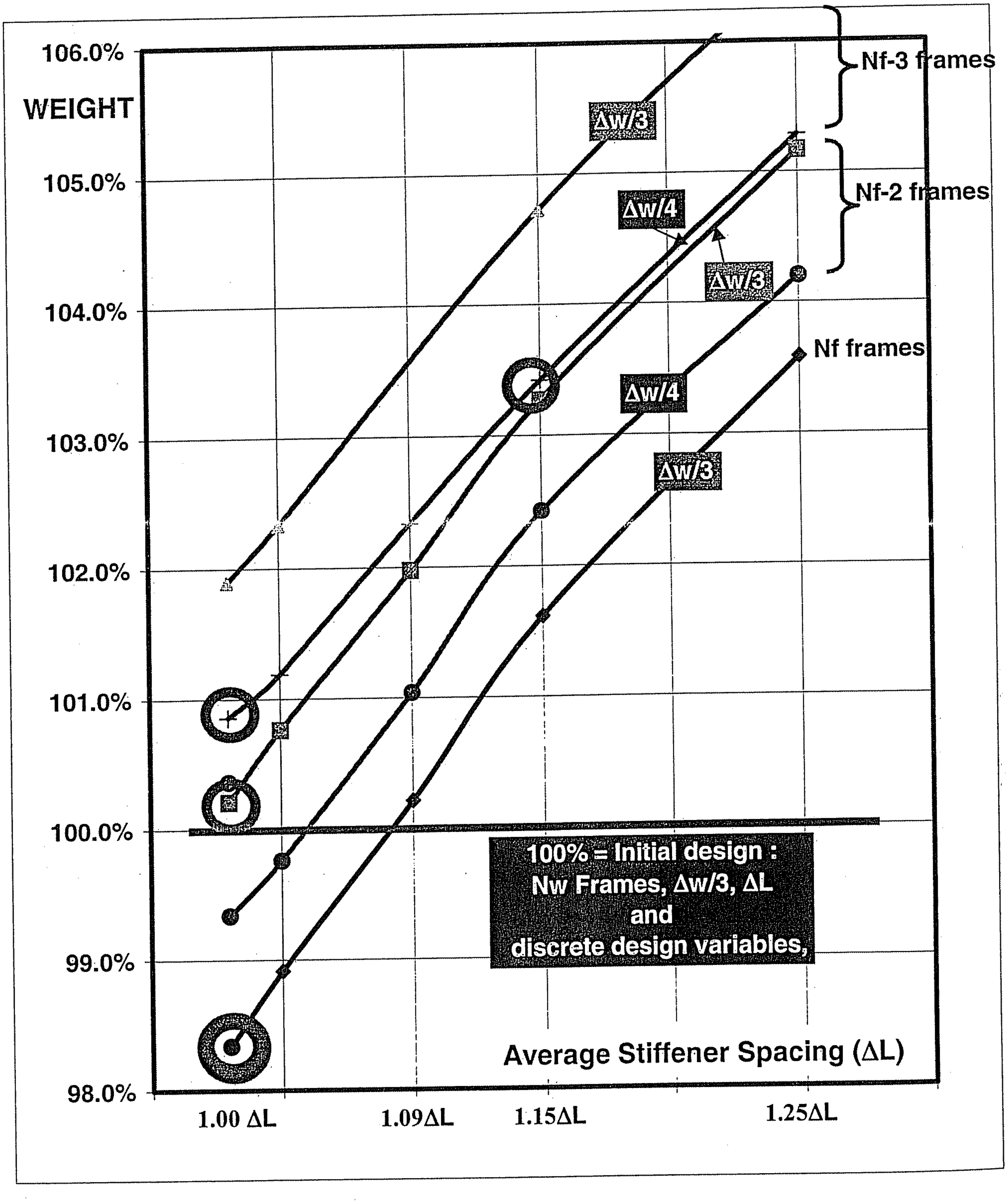


Fig.15: Sensitivity analysis of the stiffener spacing on the hull weight of a medium capacity LNG carrier (one hull tank)

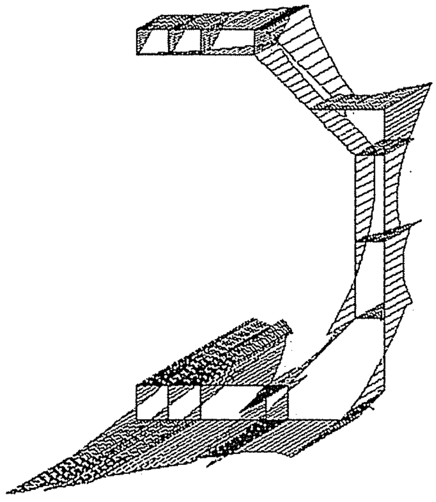


Fig.16:
Longitudinal Stresses (σ_x in plating):
Local bending of the double bottom combined with a global hogging bending moment

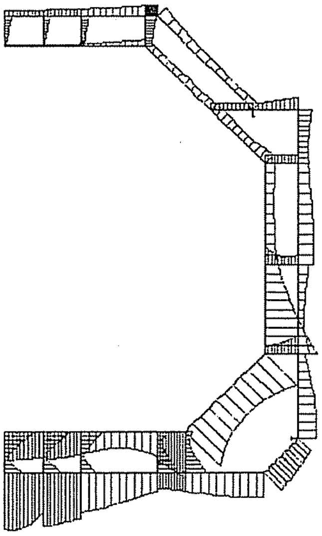


Fig.17:
Von Mises Stresses
(Combined stresses in plating)

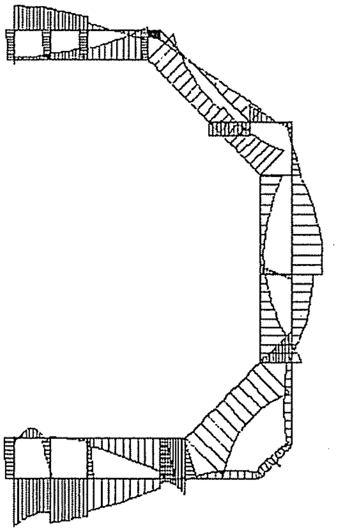


Fig.18:
Transverse Stresses (σ_y);
(Bending of web-frames)

5. Acknowledgments

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