



LEAST COST OPTIMUM DESIGN OF STIFFENED HYDRAULIC AND FLOATING STRUCTURES

by

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ABSTRACT

LBR-5 is a structural optimization tool dedicated to structures composed of stiffened plates and stiffened cylindrical shells. The LBR-5 optimization model consists of 3 basic modules (OPTI, CONSTRAINT and COST). The user has to select geometrical and structural constraints among standard sets of constraints of an external database. As the present optimization deals with least construction cost, unitary material costs, welding, cutting, ... and labor costs have to be specified by the user to define an explicit objective function. The optimum solution is found with an optimization technique using convex linearization and a dual approach (CONLIN). Optimum design of a 36 m wide floating gate for a new maritime lock in Oostende (Belgium) and a FSO unit (Floating Storage Off Loading) are presented as examples.

1. «LBR-5» - AN OPTIMIZATION TOOL FOR STIFFENED STRUCTURES

The LBR-5 software has been developed for structure optimization of hydraulic structures, ships, offshore structures and any other structures composed of stiffened cylindrical shells or orthotropic plates such as lock gates, mobile weirs, docks, pontoons,... [Rigo 1998]. The stress analysis is achieved with the LBR-4 code developed at the University of Liege by Ph. Rigo [1992a and b]. With LBR-5, optimization can be performed at the earliest stage of the design, as LBR-5 has been developed to be a user friendly tool. Preliminary Design Oriented is the main characteristic of LBR-5 compared with standard optimization packages.

LBR-5 consists of 3 basic modules (OPTI, CONSTRAINT and COST). OPTI is the optimization module based on a mathematical programming code (CONLIN) which solves constrained non-linear optimization problems with a reduced number of re-analyses (usually less than 15 even with hundreds of design variables). This approach is based on convex linearizations and a dual approach developed by C. Fleury [1986 and 93]. This module needs data from the constraints ($C(X_l)$) and the objective function ($F(X_l)$), respectively from the

CONSTRAINT module and the COST module. X_l are the design variables (dimensions of the longitudinal and transversal members, plate thickness and spacing between members). There are 9 design variables associated with each stiffened panel: 1) Plate thickness, 2) Web-height of the transverse frames, 3) Web-thickness of the transverse frames, 4) Flange-width of the transverse frames, 5) Transverse frame spacing, 6) Web-height of the longitudinals, 7) Web-thickness of the longitudinals, 8) Flange-width of the longitudinals, 9) Longitudinal spacing.

LBR-4 is the core of the CONSTRAINT module used to define all the constraints required by users. Practically, the user has to select the constraints in a large external database. There are technological, geometrical and structural constraints. To ease the procedure, standard sets of constraints are proposed to users. These sets are based on national or international standards (Eurocodes, ECCS Recommendations, Classification Societies,...).

Nowadays, for optimization purposes, a least-weight minimization is not relevant any longer (even at the preliminary stage) and should be replaced by a least-construction cost or, better, by a least-operational cost. In this study construction costs are considered. To establish an explicit objective function, unitary material costs (\$/kg), welding, cutting, fairing,..., productivity (men-hours/m) and basic labor costs (\$/man-hour) have to be specified by users. These values can vary according to the structure type (gate, pontoon, cargo, tanker, container, barge,...), the available technology (manual welding, robot welding,...), the yard facilities and experience, the country, ...

Ultimate strength of the main structure (box girder or hull girder) can be added to the standard constraints and is estimated with Paik's simplified formulation [Paik 1995]. A progressive collapse analysis of the global structure can also be performed after optimization as a post analysis process.

Figure 1 shows the basic configuration of the LBR-5 optimization model with the 3 modules and the database including the available constraints (geometrical and structural). After selection of the constraint in the database, Figure 2 shows the global model, designed according to the user's wishes. This model is ready to optimize the structure. Figure 3 presents the global flow chart of the LBR-5 model [Rigo 1998b].

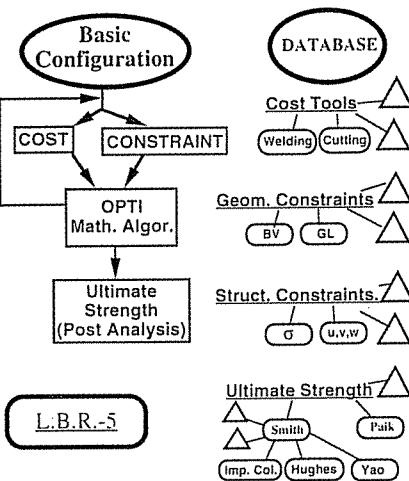


Figure 1 - The basic configuration of LBR-5 and the basic available tools and constraints of the database

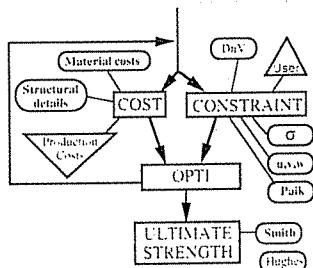


Figure 2 - The LBR-5 module after selection by the user of the suitable sub-modules and the constraints

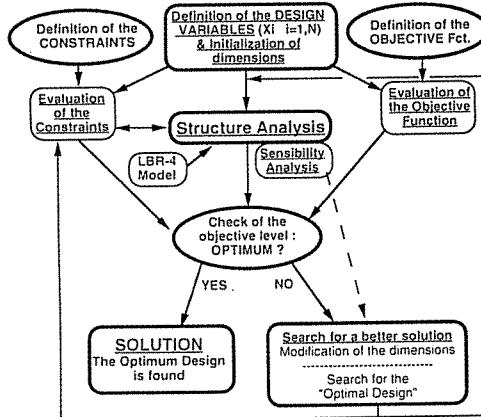


Figure 3 - Flow chart of the structural optimization model LBR-5 [Rigo 1998b]

2. «OPTI» - THE OPTIMIZATION MATHEMATICAL TOOL

The OPTI module is based on the CONLIN code developed by C. Fleury (1986 and 93) using a convex linearization of the constraints and the objective function combined with a dual approach in order to solve large unconstrained problems easily (see Figure 4).

To be able to consider non-linear implicit constraints ($C(X)$), Fleury proposes to replace these constraints by approximated explicit linear constraints by using a convex linearization. He

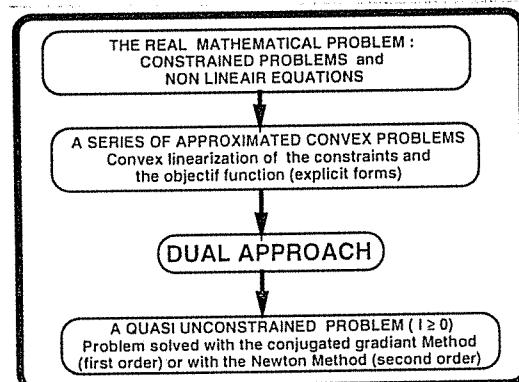


Figure 4 - The CONLIN model, Convex linearization and dual approach [Fleury 93]

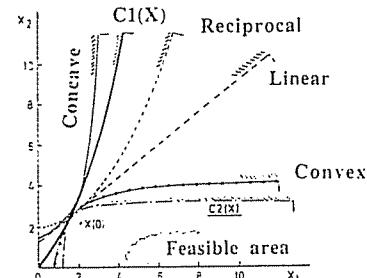


Figure 5 - Comparison of the different linearization models

suggests using the first term of the Taylor Series Expansion. Three linear alternatives are possible:

- Linearization with the standard variables $X_i, i=1,N$:

$$C(X_i) = \tilde{C}(X_i) = C(X_i(0)) + \sum [X_i - X_i(0)] \cdot \partial C(X_i(0)) / \partial X_i \quad (1)$$

- Linearization with reciprocal design variables $1/X_i, i=1,N$:

$$C(X_i) = \tilde{C}(X_i) = C(X_i(0)) + \sum [1/X_i - 1/X_i(0)] \cdot \partial C(X_i(0)) / \partial (1/X_i) \quad (2)$$

- Convex linearization with mixed variables $X_i, i=1,L$ and $1/X_j, j=L+1,N$ for $i=1,N$:

$$C(X_i) = \tilde{C}(X_i) = C(X_i(0)) + \sum [X_i - X_i(0)] \cdot \bar{\partial} C(X_i(0)) / \bar{\partial} X_i + \sum [1/X_j - 1/X_j(0)] \cdot (X_j(0))^2 \cdot \partial C(X_j(0)) / \partial X_j \quad (3)$$

As design variables refer to such elements as plate thickness or web height or ... it is clear that it is not suitable to use X_i to linearize constraints related to stresses or displacements. It is better to use reciprocal linearization ($1/X_i$). On the other hand, geometrical constraints (for instance $w-h<0$ with h the web height and w the flange width) must be linearized with standard variables instead of reciprocal variables.

Therefore it is obvious that a mixed linearization is the more suitable way. Fleury has demonstrated that an efficient convex linearization can be achieved by selecting the group of variables (X) and the group of reciprocal variables ($1/X$) according to the sign of the first derivative of the function to linearize $[\partial C(X(0)) / \partial X]$.



For a variable X_i : linearization with standard variable X_i is achieved if $\partial C(X_i(0))/\partial X_i > 0$, and linearization with reciprocal variable $1/X_i$ is performed if $\partial C(X_i(0))/\partial X_i < 0$.

The proposed convex linearization is very «user friendly» as only the value of $C(X_i(0))$ and $\partial C(X_i(0))/\partial X_i$ are required. The linearization is done automatically at each step (iteration) and the convergence order is 2. Main advantage of the convex linearization is the conservatism of the approximated function. For instance, C1 and C2 are 2 constraints to be linearized : $C1(X) = 5X_2 - X_1^2 - 10 \leq 0$ and $C2(X) = 5/4X_2^2 + 16/X_1^2 - 13 \leq 0$.

The initial point is $X(0)=(X_1, X_2)=(2,2)$. At this point, we have for the 2 constraints:

$$C1(2,2) = C2(2,2) = -4 \text{ and } \partial C1(2,2)/\partial X = \partial C2(2,2)/\partial X = (-4,5)$$

Then the two linearized equations of C1 and C2 are the same.

According to the linearization models (Eqs. 1 to 3), we obtain :

- standard linearization, X, (Eq.1) : $5X_2 - 4X_1 - 6 \leq 0$
- reciprocal linearization, $1/X$, (Eq.2) : $-20/X_2 + 16/X_1 - 2 \leq 0$
- convex linearization (Eq.3) : $5X_2 + 16/X_1 - 22 \leq 0$

with X_2 as $\partial C/\partial X_2 = 5 > 0$ and with $1/X_1$ as $\partial C/\partial X_1 = -4 < 0$.

Figure 5 shows that the convex linearization is the best one and the most conservative way even if it fails with regard to C2 which is initially more convex (quadratic function in $1/X$) than the linearized convex function.

3. «CONSTRAINT» - DEFINITION OF THE STRUCTURAL AND GEOMETRICAL CONSTRAINTS

In Table I, the constraints recommended by the Ship Structure Committee [Hughes 1988 and 94] are compared with those selected for the LBR-5 model. All are structural constraints derived from rational formulations based on linear and non-linear theory of mechanics and elasticity.

4. «COST» - DEFINITION OF THE OBJECTIVE FUNCTION

The main purpose of any optimization work is to obtain a set of design variables which is considered as the best set in relation to certain criteria within a set of given constraints. In floating structural design, the set of variables usually contains the scantlings of the ship hull and/or hull form, whereas the design criteria may be the minimization of weight, cost, space occupied, resistance offered to the waves and so forth.

The problems involved in the design of floating structures are different from those met by the designers of bridges, buildings and other land structures. The utmost economy in weight of material is important. Any excess of material over the minimum required for structural strength, including a suitable margin for corrosion and wear, diminishes carrying capacity and speed.

TABLE I - List of the constraints based on limit states (serviceability, yield and collapse)

Failure Modes of Principal Members	Failure Category	Computational Algorithm Source (SSD denotes Ship Structural Design) [Hughes 1994]	References of the present classification (LBR-5)
HULL GIRDERS: Ult. Strength	Collapse	SSD Sec. 17-1	3.3
PANEL Collapse Stiffener Flexure Combined Buckling Membrane Yield Stiffener Buckling	Collapse	(with longitudinal members) SSD Sec. 14.2 SSD Sec. 13.2 - 13.4 SSD Sec. 12.5 SSD Sec. 13.1 & 15.5	1.7 1.7 1.2 + 3.1 1.5 + 1.8
Stiffener Unserviceability (Initial Yield) Tension, Flange Tension, Plate Compression, Flange Compression, Plate	Yield	Beam Theory & SSD Sec. 8.6 " " " SSD Sec. 9.1 & 9.2	1.2 " " " " 1.2 + 3.1
Plate Unserviceability Yield, plate bending Local buckling Allowable Permanent Set	Yield Unserviceability Yield	SSD Sec. 12.6 SSD Sec. 9.3 - 9.5	1.4 1.3 (a) + 3.2
BEAM		(Transverse members & frames)	
Collapse Tripping Flexural-Torsional Buckling Plastic Hinge	Collapse	SSD Sec. 13.1 SSD Sec. 15.4 & 15.5 SSD Sec. 16.1 & 16.2	2.4 2.4 2.3 (b)
Unserviceability (Initial Yield) Bending. Web shear	Yield Yield	Beam Theory " "	2.3 2.3
GRILLAGE (Collapse) Overall Buckling Plastic Hinge	Collapse Collapse	SSD Sec. 10.2 & 13.5,6 SSD Sec. 16.1 - 16.4	1.6 + 2.2 3.1 (b)

(a) A constraint related to the elastic deformation is proposed.

(b) The proposed Limit State concerns first yield instead of the collapse stage.



The cost for construction is another criterion to be considered in designing of ships and floating structures. As a result, a large number of feasible solutions can be readily derived from a given set of requirements. A successful design process depends on the ability to make an effective appraisal of these solutions in order to arrive at the most satisfactory design. This is the goal of our optimization process.

Structure contributes significantly to the production cost of ships and floating structures. Steel and other structural materials account for up to 25% of the total first cost, while labor calculated in men-hours can vary from 55% of the total men-hours for a 14000 ton deadweight cargo ship to about 75% of the total for a 250000 ton tanker.

The conventional approach to the problem of the structural design is essentially that of determining a set of structural scantlings which is adequate to cope with the complex loading patterns which it will encounter during its life. Structural adequacy may be defined by a number of conflicting technical criteria such as stress levels in bending, shear and torsion, resistance to buckling and fatigue, etc. The weakness of an approach based on such limited view lies in the absence of an appraisal method or model, which would allow a proper choice to be made among all feasible designs.

One way to remedy this is to consider other factors, which have key influences on the design process. An improved approach in which technical criteria are complemented by operating and production factors and the whole is supported by an appraisal method. It is not difficult to understand why operating and production factors act as constraints in the selection of a structural design. However, it is particularly important that an appraisal method is able to identify feasible designs which can respond to the facilities of the yard in which they are to be fabricated, i.e., structures which are designed for efficiency in production.

The basic philosophy behind all the work on assessment of production costs for design has been embodied in the term 'design for production'. In the shipbuilding context the concept 'design for production' is now accepted as an integral part of structural design philosophy, and the overall objective can be defined as follows: «Design to reduce production costs to a minimum while compatible with the requirements of the structure to fulfil its operational functions with acceptable reliability and efficiency».

Ever since complex structures have been built there has been a pressure to reduce the costs of construction. For any useful decision concerning structural style and details intended to reduce costs, it is essential that realistic cost estimates can be made at the design stage. Traditionally yard costs have been recorded on the basis of the weight unit of the finished structure.

Builders are also aware of the problem of providing realistic labor cost estimation but records on which they can be based are generally lacking, although a few yards have begun to build up suitable databases. To achieve an objective estimate approach and to replace the current haphazard subjective one, it will be necessary to assemble more data. The costs are likely to be based on unit length, number or area, etc with weighting factors for the different controlling conditions. However, to enable a realistic estimate to be built up for a complete structure, there are many different processes to be considered and an enormous quantity of data to be collected and analyzed. In fact the recorded men-hours per unit steel weight vary enormously from hundreds of men-hours/ton for the most complex frigate down to less than 20 for standard merchant ships. There is also a strong size effect. This can be demonstrated simply when considering handling plates, the men-hours required to lift and to move a heavy plate are little

different from those for a light plate. The men-hours/ton will be almost inversely proportional to the plate thickness.

A further complication is the fact that cost recorded by the yard and the price paid by the client (owner) are not the same thing; the price quoted to the potential owner is only partly related to the actual yard costs, and includes profit. The price will often be adjusted to improve the yard's chance of obtaining an order and indeed may be subsidized to the extent that the price quoted is less than the actual cost. For practical purposes, it can be assumed that overheads are a direct percentage of total labor costs and the profits are an independent variable. Therefore both can be ignored in arguments concerning optimization or reduction of structural costs. But this appears not to be always the case. So, if possible, it is better to include the overhead cost while optimizing the construction cost.

Labor costs, measured in terms of men-hours/unit weight of structure, are strongly dependent on style and arrangement of structure, in particular the relative extent of compartmentation and ease of access, the number of equipment seatings and small structural components, the number of service penetrations, etc. The complexity and arrangement of stiffening details also has a significant effect. It is on these aspects that the structural designer can have a large influence. Availability of yard processes, such as automatic or semi-automatic welding, or assembling mode can also influence the result of a cost-minimization study.

With LBR-5, the equations for estimating the construction cost of the prismatic section of a structure are presented by Rigo, 1998. Using these equations the cost of each panel in which the hull is subdivided can be calculated and their summation will give the total cost of the hull. The equations for calculating the steel material cost, plate welding cost, cost for welding the frames and longitudinals on the plates, cost of painting and the cost of joining the stiffening members are given separately. If the stiffening members are fabricated in the shop, the equations for estimating their fabrication costs are also included.

At the present stage, operational costs are not considered by LBR-5, as a number of attempts have shown how difficult it is to include in the design process a reliable method for estimating these operational costs.

In LBR-5, the relative cost of panels associated with different scantlings is much more important than the absolute cost. Consequently, the LBR-5 COST module focuses on the costs that are directly related to the considered design variables.

5. OPTIMIZATION OF A 336 m FLOATING BARGE (Offshore FSO Unit)

The purpose of the FSO barge is to be used for loading or unloading VLCCs (Very Large Crude Carrier) of 2,000,000 barrels. Its main characteristics are the following:

Table 2 - Characteristics of the FSO barge (Floating Storage Off-loading)

L _{pp} (length between perpendiculars)	336 m (10 + 6 x 46 + 50 m)
B (width)	60 m (6 + 24 + 24 + 6 m)
H (depth)	30 m
T (draft)	20.5 m
C _b (bloc coefficient)	0.95
Weight (steel + machinery)	32 740 t ($\pm 320\ 000$ kN)
Number of tanks	12 x 33 782 m ³
Total volume of Crude Oil	405 389 m ³

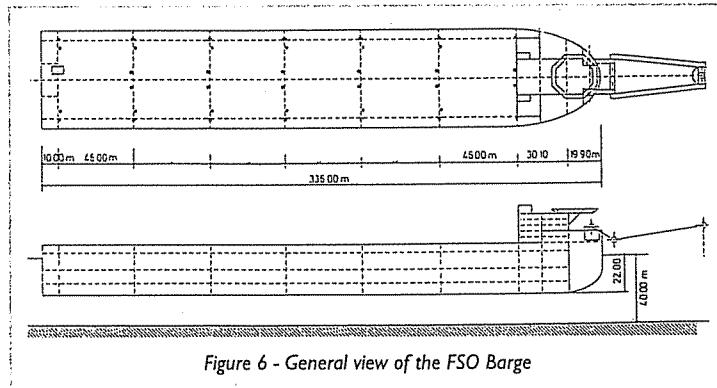


Figure 6 - General view of the FSO Barge

Figure 6 shows a general view of the FSO barge. At the preliminary design stage of this unit, we have proceeded to the optimization of the 46 m holds composed of tanks of 24 m x 30 m x 46 m and the lateral ballast zones (double-hull) of 6 m width (Fig. 7). The maximum bending moment was estimated at 1 000 000 t.m and the shear forces at 25 000 t. We have investigated the possibility to use different frame spacings (Δ_{tank} in the center part of the hold used for oil storage and Δ_{ballast} in the two lateral ballast zones).

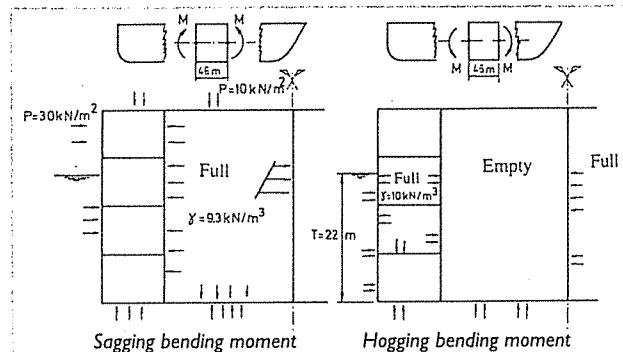


Figure 7 - Major load cases

Table 3 - Comparison of the optimum (after 10 iterations)

Type of optimization	Weight kN and %	Cost 10^6 BEF and %	Cost per kg BEF/kg	Δ_{tank} (m) and N(*)	Δ_{ballast} (m) and N(*)
$\delta \leq 40$ mm					
Minimum Cost C1 : $\Delta_{\text{tanks}} = \Delta_{\text{ballast}}$	29280 (109%)	255.83 (100%)	87.4	5.75 m N = 7	5.75 m N = 7
	29740 (111%)	267.54 (105%)	90.0	6.57 m N = 6	3.285 m N = 13
Minimum weight C3 : $\Delta_{\text{tanks}} = \Delta_{\text{ballast}}$	27150 (101%)	270.45 (106%)	97.7	5.11 m N = 8	5.11 m N = 8
	26850 (100%)	287.82 (113%)	105.2	5.75 m N = 7	2.875 m N = 15
$\delta \leq 30$ mm					
Minimum cost C5 : $\Delta_{\text{tanks}} = \Delta_{\text{ballast}}$	38870 (145%)	343.84 (134%)	88.5	3.07 m N = 14	3.07 m N = 14
	38500 (143%)	388.64 (114%)	100.9	3.07 m N = 14	3.07 m N = 14
Initial scantling (start of the optimization process)	39370 (147%)	392.76 (154%)	99.8	7.66 m N = 5	7.66 m N = 5

(*) N = number of frames in a 46 m long tank, $N = (46/\Delta) - 1$
 Δ_{tank} = frame spacing in the oil tank (center part of the hold)
 Δ_{ballast} = frame spacing in the lateral ballast

1 US\$ = ± 35 BEF

Most Suitable Scantlings

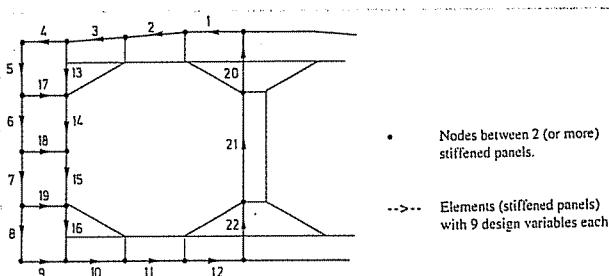


Figure 8 - Mesh modeling of the mid-ship section required for the optimization process with the LBR-5 model

For this optimization (FSO Barge), the LBR-5 model includes (Figure 8):

- 22 stiffened panels;
- 198 design variables (22×9);
- 48 equality constraints;
- 198 geometrical constraints (9×22);
- 396 structural constraints:
 - σ_c frame (web and flange), σ_c stiff. (web and flange) and σ_c (plate)
 - with : $\sigma_c \leq s \cdot \sigma_o$ ($s = 0.65$ and $\sigma_o = 355 \text{ N/mm}^2$);
 - local buckling of the plate : $\delta_{\min} \leq \delta$;
 - ultimate strength of the stiffened panels : $\sigma/\sigma_{ult} \leq (s = 0.55)$;
- 2 constraints on the ultimate strength of the ship girder : $M/Mult < s$ ($s = 0.55$).

6. OPTIMIZATION OF A MARITIME LOCK GATE

In Belgium, the Coastal Division of the Administration of Waterways and Marine Affairs of the Ministry of the Flemish Community (Waterwegen Kust, Oostende) plans the construction of a new maritime lock of $250 \times 36 \text{ m}$ with a minimal water depth of 10 m in the port of Oostende (Figures 9.a and 9.b). The lock is designed for ships of 10 000 tons deadweight ($\pm 100 000 \text{ kN}$). Use of floating lock gates for this new port facility is considered in this study.

Advantages of floating gates for maritime locks are well known by engineers and hydraulic structural designers. For

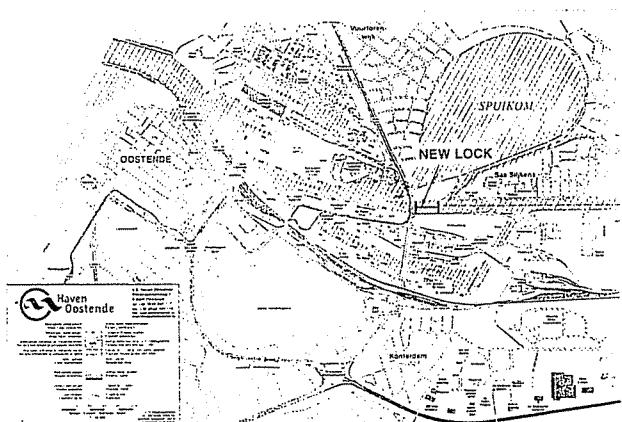


Figure 9a : Location of the new maritime lock of the Port of Oostende

over two decades, the Hydraulic Department (Civil Engineering) of the University of Liege has promoted the use of floating structures [Rigo 1998, Dehousse 1985, Grilli 1985]. Previous studies were related to locks of 50 m width (Zeebrugge) and 70 m (Berendrecht in Antwerp). In Oostende, as the width is only 36 m , a new specific study for this size is required [Da Ronch 1998].

For a 36-m-wide rolling gate (not floating), Da Ronch [DA98] has shown that the optimum least weight design corresponds to a gate of 3.25 m width (Figure 10). For such gate, floating stability is not a relevant design constraint. This width can therefore be considered as an optimum for a standard and conventional transversal rolling gate called "wheelbarrow gate".

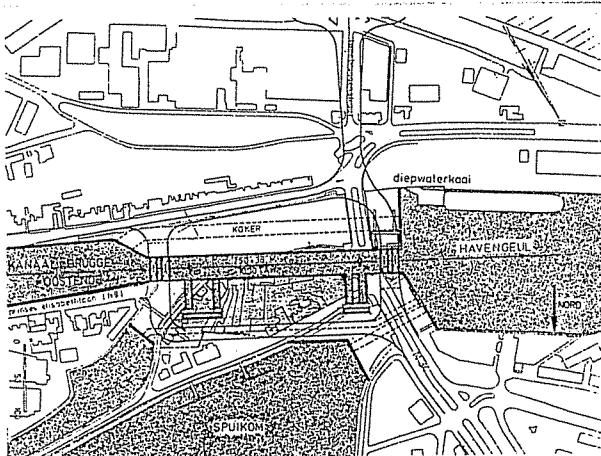


Figure 9b : Plan view of the $250 \times 36 \text{ m}$ maritime lock

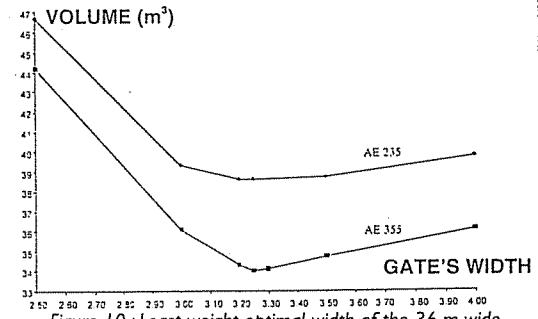


Figure 10 : Least weight optimal width of the 36-m-wide maritime lock [Da Ronch 1998]

For a floating gate, a 3.25-m width is not sufficient to guarantee stability in wave and wind. The gate must thus be enlarged. For the particular case of Oostende, as the gate height under the water ($\pm 9.7 \text{ m}$) is almost equal to the gate part above sea water level ($\pm 9.1 \text{ m}$), the floating stability becomes the main design criterion. Therefore, based on a recursive floating stability analysis, a width of 5.40 m was selected for the gate in addition of a fixed ballast of $\pm 1000 \text{ kN}$ (Figure 11). More detailed researches have to be achieved to confirm the optimum width and the ballast volume.

The present analysis concerns the structural optimization of the lock gates (least cost and least weight design) of 3.25 m and 5.40 m width for respectively rolling and floating gates. This paper focuses mainly on the



optimization process of the lock gate scantling. Main dimensions are considered as input data (height, width, length, size and position of the ballast tanks).

We will not discuss all the specific studies required for the design and the scantling of a floating gate (for instance: floating stability, seakeeping, propulsion, wave and current actions,...).

Use of high tensile steel has also been considered (AE355).

6.1 The modeling of the structure

The mesh model used for the optimization process includes:

- 18 stiffened panels (Figure 11);
- 1 additional panel to simulate a continuous support along the floor (at the bottom of the gate). This situation is defined as configuration n° 1. Configuration n° 2 corresponds to the gate without floor support (only a watertight system is assumed);
- 162 design variables (18 panels with 9 design variables each);
- 73 equality constraints between the design variables to model, for instance, symmetrical structure, standard frame spacing all over the gate Δ_c ...;
- 270 geometrical constraints (15 constraints for each panel);
- 246 structural constraints, i.e.:
 - deflection ≤ 3.60 cm;
 - $\sigma_c \leq s$. σ_o with σ_c (plate), σ_c (frame : JAS - JAB and SEM), σ_c (stiffener : JAS - JAB and SEM), JAS = in the web at the junction with the flange; JAB = in the web at the junction with the plate; SEM = in the top flange;
 - plate buckling (minimum plate thickness) : $\delta_{min} \leq \delta$;

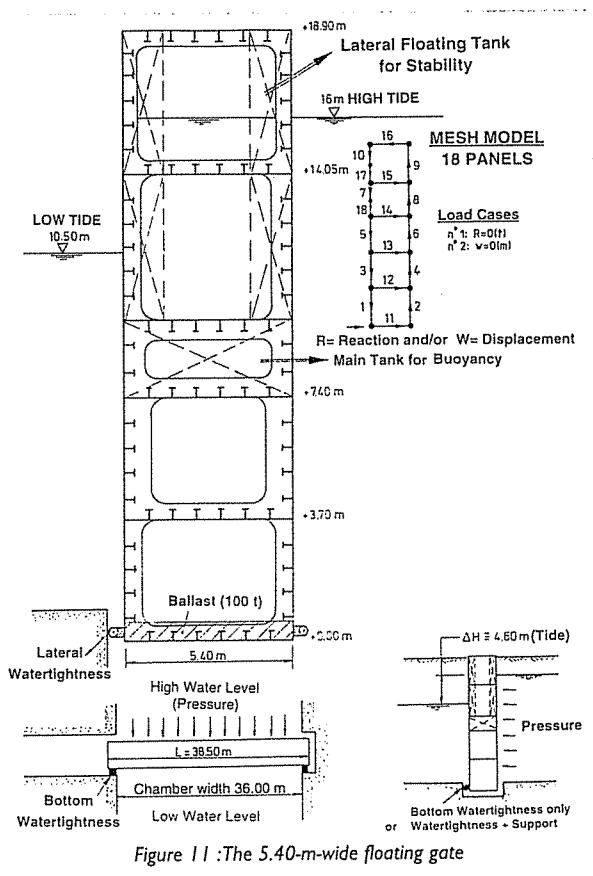


Figure 11 :The 5.40-m-wide floating gate

- ultimate strength of the stiffened panels : $\sigma/\sigma_{ult} \leq s$.

The ultimate strength of the complete structure (box girder) is not considered as relevant constraint. A post analysis calculation has confirmed that the structure can sustain an exceptional water pressure of 6.5 m (due to a difference of water level between both sides of the gate induced by high tide). A partial safety factor of 0.65 was considered for all the mentioned constraints (see above).

6.2 Boundary conditions

At its two ends ($x=0$ and 35 m), the gate is considered as continuously simply supported on vertical supports (recess in the side wall and gate chamber).

On the bottom, the designer has two alternatives: to consider the gate as simply supported on its bottom line (recess in the floor) or not supported. In this second case (configuration 2), a large deflection can occur at the bottom part and a reliable watertight system must be designed between the floor and the gate. In practice, it is usually assumed that a "simply supported bottom edge" is welcome to reduce the global average stress in the structure. In order to suppress any uncertainty as to the effectiveness of the bottom support, we consider that the gate must be able to hold in both configurations. The optimal design will therefore satisfy the two load cases.

6.3 Design of a conventional rolling gate 3.25 m wide

For a conventional rolling gate, the constraints related to floating stability and wave and wind actions are not considered and the optimum least weight gate is obtained for a 3.25-m-wide gate (Figure 10). This means that the ratio width/length is about 1/9 (if 37.25 m is considered as effective length).

Based on this optimum width (3.25 m), four "optimum" designs have been compared:

- Least weight with mild steel AE235 ($\sigma_o = 235$ N/mm²),
- Least weight with HTS steel AE355 ($\sigma_o = 355$ N/mm²),
- Least cost with mild steel AE235 ($\sigma_o = 235$ N/mm²),
- Least cost with HTS steel AE355 ($\sigma_o = 355$ N/mm²).

Least cost optimum designs were obtained with the following cost parameters:

- Standard plate thickness : 10 mm
- Ratio Labor Cost (BEF/man-hour)/Material Cost (BEF/ton) : $k = 0.08$
- Steel cost : $C_1 = 23$ BEF/kg and $\Delta C_1 = -0.6\%$ (AE235)
 $C_1 = 26$ BEF/kg and $\Delta C_1 = -0.6\%$ (AE355)
- Welding cost : $C_8 = 40$ BEF/m and $\Delta C_8 = 15\%$
- Labor cost :
 - Plate (shell plate) : $P_{10} = 0.5$ h-h/m² and $\Delta P_{10} = 7\%$
 - Stiffeners (yard made) : $P_4 = P_5 = 1$ h-h/m and $\Delta P_4 = \Delta P_5 = 10\%$
 - Stiffeners (standardized profiles) : $P_9 = 0.5$ h-h/m and $\Delta P_9 = 1\%$.



Table 4 compares the weights and the costs of the 4 optimum structures. It is noticed that:

- Use of higher tensile steel (AE355) generates a 13% reduction of both cost and weight.
- From the cost and weight point of view, it is observed that for AE355 steel, least cost and least weight optimum design are very close. On the other hand, for AE235 mild steel, the difference reaches 3 and 6% for respectively the cost and the weight.
- From the point of view of scantling, there is little difference between the least weight and the least cost optimum design. For the least cost, increase of plate thickness (δ) is compensated for by an increase of the stiffener spacing. But there is a significant change in the optimum scantling when the steel grade is modified (AE235 or AE355). Using high steel strength AE355 can significantly reduce plate thickness (plating or shell plate).

Table 4 - Least cost and least weight design for a 3.25-m-wide gate

Gate width and Steel grade	Least weight Design	Least Cost Design
Width = 3.25 m and AE235	Weight = 100 % (2966 kN) Cost = 103 % δ = 10 to 13 mm $\Delta_{\text{rade}} = 2.5$ m (max. value) $\Delta_{\text{rad}} = 0.5$ to 0.8 m	Weight = 106 % (3152 kN) Cost = 100 % δ = 10 to 16.5 mm $\Delta_{\text{rade}} = 2.5$ m (max. value) $\Delta_{\text{rad}} = 0.8$ m
Width = 3.25 m and AE355	Weight = 88 % (2616 kN) Cost = 89 % δ = 10 mm (minimum allowed thickness) $\Delta_{\text{rade}} = 2.5$ m (max. value) $\Delta_{\text{rad}} = 0.67$ to 0.8 m	Weight = 90 % (2657 kN) Cost = 88 % δ = 10 to 12 mm $\Delta_{\text{rade}} = 2.5$ m (max. value) $\Delta_{\text{rad}} = 0.8$ m

An example of the convergence of the optimization process is shown in Table 5. The convergence is quicker for the objective function and the plate thickness (δ) than for the other design variables such as the web height of the frames.

Table 5 - Example of the convergence of the optimization process for a 36.00-m-long lock gate

Iteration	Cost Objective Function (%)	Shell plate thickness Panel No 1 (mm)	Web Height of the frames Panel No 3 (mm)
Start	173.5	15.00	500.0
1	108.1	11.84	447.2
2	101.3	10.92	616.2
3	100.4	10.86	618.2
4	100.2	10.86	625.3
5	100.1	10.85	626.9
6	100.0	10.85	627.6
7	100.0	10.85	628.3
8	100.0	10.86	628.7
9	100.0	10.85	630.4
10	100.0	10.85	629.4
LEAST COST for $\sigma_o = 355$ N/mm ²			

Figure 12 shows the (δ) plate thickness distribution and the ($h_{\text{web frame}}$) frame size distribution for a 3.25 m wide gate with mild steel (AE235) and a least cost optimization.

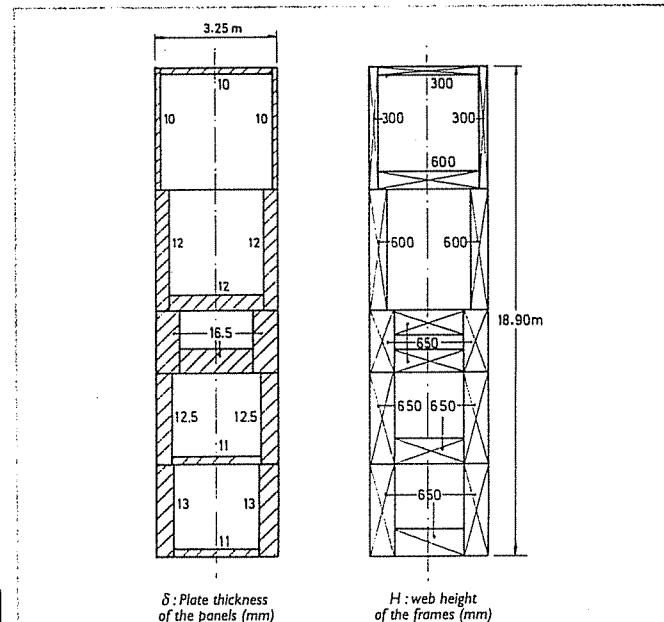


Figure 12 - Distribution of the transversal rigidity of the 3.25-m-wide gate (AE235 and a least cost optimization)

6.4 Optimization of a 5.40 m wide floating lock gate

In order to cope with the stability constraint, a minimum gate width of 5.40 m is required for a floating gate [Da Ronch 1998] (Figure 11). Larger width is required in the present case due to its important height compared to the minimum draft (18.90 m high compared to 10.50 m draft).

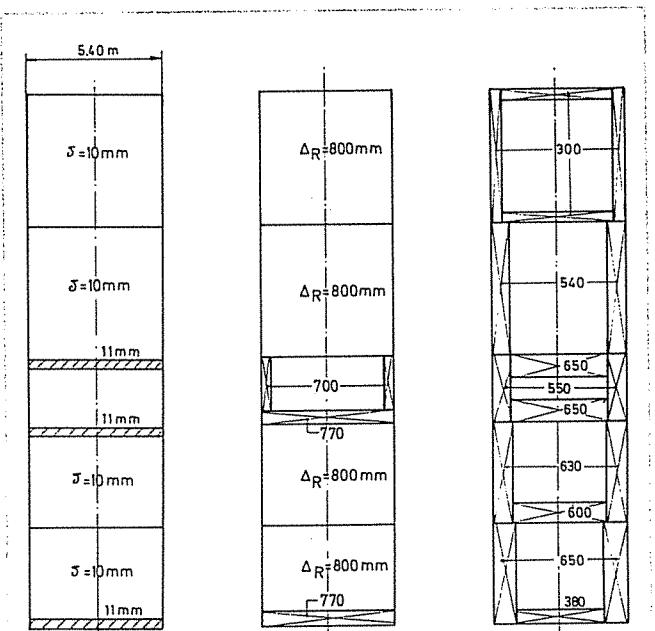
Table 6 presents the least weight and the least cost optimum design for the 5.40 m wide gate and compares these values to an optimized standard rolling gate 3.25 m wide. Costs of mechanical and manoeuvring systems are not considered in this analysis.

It is obvious that an increased cost of 20 or 25 % for the floating gate (5.40 m - AE355) compared to the rolling gate (3.25 m - AE355) is small with regard to all the economic and technical advantages provided (Dehouze 1985):

- Saving of the top and bottom carriage (not required for floating gate);
- No mechanical part in the water, neither permanent or temporary (rails, wheels);
- Saving one lock gate (3 gates are required instead of 4);
- Saving of one or two gate chamber(s) (2 or 3 chambers instead of 4);
- Easy to maintain and to repair;
- Reliable procedure;
- ...

Table 6 - Comparison between gate optimum designs for the Oostende 36.00-m-wide maritime lock

Gate width and steel grade	LEAST WEIGHT		LEAST COST		Average Variation of Cost (%)
	Weight	Cost		Cost	
B = 3.25 m AE235	100% (2966 kN) (weight reference)	103%	106% (3152 kN)	100% (cost reference)	Reference
B = 3.25 m AE355	88% (2616 kN)	89%	90% (2657 kN)	88%	-13%
B = 5.40 m AE355	108.50% (3221 kN)	112%	109% (3255 kN)	110%	+10%



δ : Plate thickness (mm) Δ_R : Spacing of stiffeners (mm) h : Web height of the frames (mm)
 $\delta \leq 10 \text{ mm}$ $600 \leq \Delta_R \leq 800 \text{ mm}$ $300 \leq h \leq 650 \text{ mm}$
 Spacing of frames: 2.50 m Web thickness of the frames : 5 to 9 mm
 Minimum stiffeners: 200 x 5.5 + 130 x 11 mm Flange section of the frames: 1200 to 2800 mm

Figure 13 - Optimum least cost design of a 5.40-m-wide floating lock gate

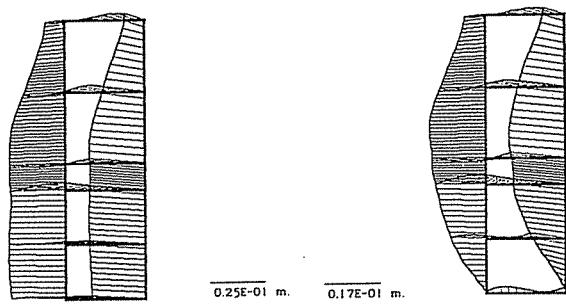


Figure 14 - Transversal deflection (with and without support)

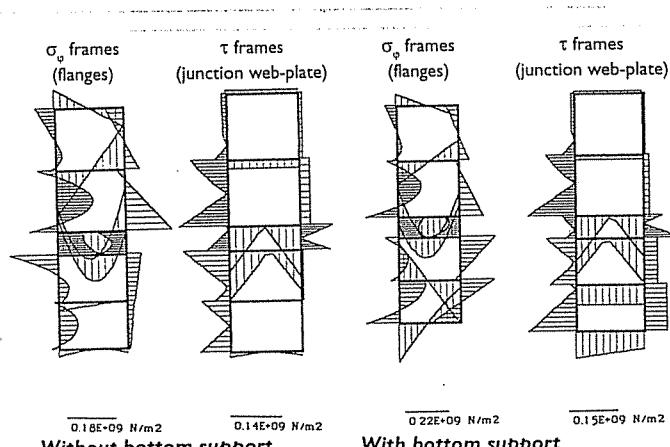
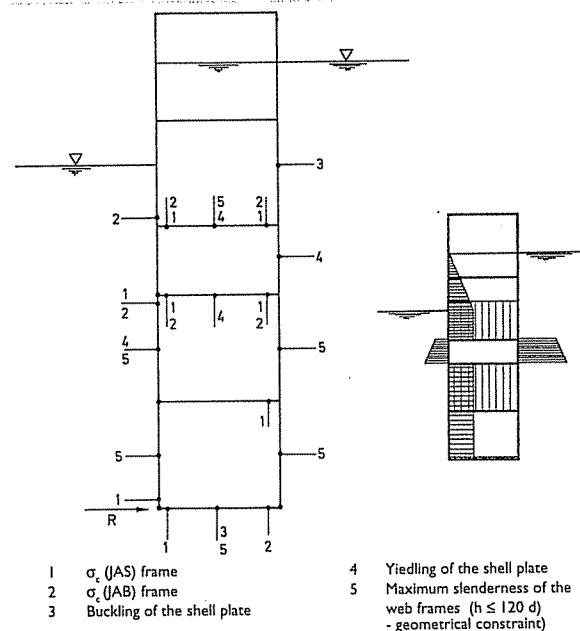


Figure 15 - Stress distribution in the frames - Comparison between the two configurations : with and without bottom support



The active geometrical constraints concern the frames ($h \leq 120 \text{ d}$) and the stiffeners ($h \leq 36 \text{ d}$) the web slenderness but also the ratio between the shell plate thickness and the web thickness ($\delta \leq 2 \text{ d}$). These two constraints are actives in each panel.

Within the non-active structural constraints, there are:
 - $(\sigma/\sigma_{cr})_{MAX}$ compressed panels : $0.41 \leq 0.65$ (ultimate strength of compressed panels)
 - $W_{MAX} = 2.5 \text{ cm} \leq 3.6 \text{ cm}$ (maximum deflection of the panel)

Figure 16 - Types and locations of the active constraints

Figure 13 shows synthetically the proposed optimum solution (scantling). As the gate was enlarged, several design variables have reached their minimum or maximum values (lower and higher bounds imposed to the design variables – technological constraints). This effect reduces the expected saving that the optimization process can provide. Larger benefits could be expected for larger locks and longer gate spans (40, 50 or 70 m long).

Figure 14 shows the transversal deflection of the gate for the two feasible configurations, respectively, with bottom support and without. Figure 15 presents the stress distribution of the combined stresses in the frame flanges (σ_c) and the shear stresses in the web frames-junction web/plate (τ). For the two configurations, the distributions are quite similar at the top and center part of the gate but important variations occur at the bottom part near the support area.

Analysis of the active constraints of the optimum design shows that there are about 40 geometrical active constraints on 270 geometrical constraints and 25 structural active constraints on 246 selected initially. The relevant active constraints are detailed on Figure 16.

7. CONCLUSIONS

LBR-5 is an operational optimization tool developed for practical design of hydraulic and floating structures and is more particularly oriented to preliminary design. All the structures composed of stiffened panels such as lock gates, mobile weirs, the cylindrical part (mid-ship section) of the commercial ship (barges, tankers, cargo,...)... can now be more easily designed at least cost.



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RESUME

L'optimisation du dimensionnement des structures orthotropes hydrauliques et flottantes sur base de leur coût de construction

Cet article traite du développement d'un outil intégré d'analyse et d'optimisation des structures navales et hydrauliques, c'est-à-dire le modèle LBR-5. Cet outil a la particularité de permettre l'optimisation du dimensionnement dès le stade de l'avant-projet, c'est-à-dire lors de la phase initiale de la conception.

Un prédimensionnement initial n'est pas requis. L'ingénieur peut débuter directement par la recherche automatique du dimensionnement optimum. Il n'est pas nécessaire que les dimensions initiales correspondent à une solution admissible. Le rôle de modèle LBR-5 est, d'abord de rechercher une solution admissible (qui respecte l'ensemble des restrictions imposées) et ensuite de proposer à chaque itération une solution meilleure qui continue à respecter ces restrictions. Finalement, la solution optimale est obtenue endéans 10 à 15 itérations et cela, quel que soit le nombre de variables de conception (X_i) et de restrictions ($C_i(X_i) \leq C_{i\max}$).

Le dimensionnement optimum obtenu correspond au minimum du coût de construction qui est défini comme étant la fonction objectif $F(X)$.

Les variables de conception (X_i), au nombre de 9 pour chaque élément, correspondent à l'épaisseur de la tôle du bordage, l'entredistance et les dimensions des renforts longitudinaux (4 variables) ainsi que l'entredistance et les dimensions des cadres transversaux (4 variables). Les éléments sont les panneaux raidis orthotropes qui composent la structure. Il peut s'agir de panneaux de grande taille.

LBR-5 permet donc :

- la recherche d'un ensemble de N variables de conception : $X_i(i), i = 1 \text{ à } N$,
- qui minimise la fonction objectif coût : $\text{MIN } [F(X)]$,
- et qui respecte un groupe de M restrictions : $C_j(X_i) \leq C_{j\max}, j = 1, M$.



Cet article introduit le concept d'optimisation orientée modules. Ainsi le modèle LBR-5 est basé sur les 3 modules de base suivants : OPTI – module d'optimisation mathématique ; RESTRI – module des restrictions et COUT – module de la fonction objectif coût de construction.

La partie 1 décrit les algorithmes mathématiques d'optimisation courants et plus particulièrement une méthode duale couplée avec une linéarisation convexe à savoir CONLIN® (module OPTI). La linéarisation convexe permet de remplacer le problème initial formé d'équations non linéaires implicites par une série de problèmes composés d'équations linéaires et explicites (approche itérative). La linéarisation convexe est la plus conservatrice ; elle garantit une convergence dans le domaine admissible. A chaque itération, le problème linéaire explicite et contraint est remplacé par un problème quasi non contraint grâce à l'approche duale (multiplicateurs de Lagrange).

La partie 2 reprend les fondements du logiciel des bordages raidis (LBR-4) destiné à l'analyse élastique des structures fortement raidies. LBR-4 repose sur la résolution analytique des équations différentielles des coques cylindriques orthotropes et les développements en série de Fourier. On y décrit aussi le processus du calcul analytique des sensibilités (dérivées premières des restrictions et de la fonction objectif par rapport aux variables de conception).

La partie 3 est consacrée à l'évaluation des restrictions (module RESTRI). Une présentation détaillée des restrictions technologiques, géométriques et structurelles y est faite avec une attention particulière pour la résistance ultime des panneaux raidis comprimés ainsi que celle de la structure d'ensemble. Une banque de restrictions est à la disposition de l'utilisateur. À chaque restriction est associé un code (de 1 à 300). L'utilisateur choisit les restrictions qu'il souhaite imposer à la structure (contraintes maximales, déformations, résistance ultime, élancement, ...) en associant à chaque élément une série de codes.

La partie 4 traite de l'évaluation des coûts de construction qui sont à la base de la fonction objectif coût nécessaire au processus d'optimisation (module COUT). Après une description de quelques modèles existants, on y détaille le module retenu qui permet un calcul direct du coût de construction en fonction des variables de conception.

Enfin, on y présente l'optimisation d'une porte flottante destinée à la nouvelle écluse maritime du Port d'Ostende ainsi que l'étude d'une barge FSO utilisée comme réservoir flottant en vue du transfert du fuel brut vers les pétroliers (parties 5 et 6).

RESUMEN

La optimización del dimensionamiento de estructuras ortótropas hidráulicas y flotantes en función de su coste de construcción

Este artículo trata del desarrollo de una herramienta integrada de análisis y optimización de estructuras navales e hidráulicas, es decir del modelo LBR-5. Este herramienta presenta la particularidad de permitir la optimización del dimensionamiento desde la etapa de anteproyecto, es decir desde la fase inicial de diseño.

No se requiere predimensionamiento inicial. El ingeniero puede comenzar directamente por la búsqueda automática del dimensionamiento óptimo. No se necesita por tanto que las dimensiones iniciales se correspondan con una solución admisible. La misión del modelo LBR-5 es en primer lugar encontrar una solución admisible que cumpla con el conjunto de restricciones impuestas y posteriormente proponer en cada iteración una solución mejorada que siga cumpliendo estas restricciones. Finalmente la solución óptima se obtiene tras un número de iteraciones comprendido entre 0 y 15, independientemente del número de variables de diseño (X_i) consideradas y restricciones impuestas ($C(X_i) \leq C_{\max}$).

El dimensionamiento óptimo obtenido corresponde con el mínimo del coste de construcción, el cual se define mediante la función objetivo $F(X)$.

Las variables de diseño (X_i) son 9 para cada elemento correspondiendo al espesor de la chapa de tablazón, a la distancia entre refuerzos longitudinales y dimensiones de éstos (4 variables) y a la distancia entre marcos transversales y sus dimensiones (4 variables). Los elementos considerados son los paneles rigidizados ortótropos que componen la estructura. Puede tratarse de paneles de grandes dimensiones.

El modelo LBR-5 permite por tanto:

- * Búsqueda de un conjunto de variables de diseño: $X_i(i), i=1, N$,
- * que minimice la función objetivo de coste: $\text{MIN } F(X)$,
- * que cumpla un conjunto de M restricciones $C_j(X_i) \leq C_{j\max}, j=1, M$.

Este artículo introduce el concepto de optimización orientada modularmente. Así el modelo LBR-5 se fundamenta sobre los tres módulos básicos siguientes: OPTI (módulo de optimización matemática); RESTRI (módulo de restricciones y coste) y COUT (módulo de la función objetivo de coste de construcción).

La parte 1 describe los algoritmos comunes de optimización y más particularmente un método dual acoplado con una linearización convexa CONLIN® (módulo OPTI). La linearización convexa permite reemplazar el problema inicial formado por ecuaciones no lineales implícitas por una serie de problemas compuestos por ecuaciones lineales explícitas (aproximación iterativa). La linearización convexa es la técnica más conservadora que garantiza una convergencia en el dominio admisible. En cada iteración el problema lineal explícito y coaccionado se reemplaza por un problema casi no coaccionado gracias a la aproximación dual (multiplicadores de Lagrange).



La parte 2 retoma los fundamentos del programa de cascos rigidizados (LBR-4) destinado al análisis elástico de estructuras fuertemente rigidizadas. El LBR-4 se basa en la resolución analítica de las ecuaciones diferenciales de las láminas cilíndricas ortótropas y desarrollos en serie de Fourier. Se describe aquí también el proceso de cálculo analítico de sensibilidades (derivadas primeras de las restricciones y de la función objetivo respecto de las variables de diseño).

La parte 3 está destinada a la evaluación de las restricciones (módulo RESTRI). Se presenta una descripción detallada de las restricciones tecnológicas, geométricas y estructurales poniendo una atención especial en la resistencia última de los paneles rigidizados comprimidos así como en la de la estructura en su conjunto. Se pone a disposición del usuario un banco de restricciones, asociando cada restricción con un código (de 1 a 300). El usuario elige las restricciones que desea imponer a la estructura (tensiones máximas, deformaciones, resistencia última, lanzamiento...) asociando a cada elemento una serie de códigos.

La parte 4 trata de la evaluación de los costes de construcción que constituyen la base de la función objetivo coste, necesaria para el proceso de optimización (módulo COUT). Después de una descripción de algunos modelos existentes se detalla aquí el modelo adoptado que permite un cálculo directo del coste de construcción en función de las variables de diseño.

Finalmente, se presenta la optimización de una puerta flotante destinada a la nueva esclusa marítima del Puerto de Ostende así como el estudio de una barcaza FSO empleada como depósito flotante para la transferencia de fuel en crudo a los petroleros (partes 5 y 6).

Riassunto

Linee d'ottimizzazione progettuale per la ricerca del costo minimo per le strutture idrauliche irrigidite e galleggianti

Quest'articolo tratta dello sviluppo di uno strumento integrato d'analisi e d'ottimizzazione delle strutture navali ed idrauliche, vale a dire il modello LBR-5. Questo ha la caratteristica di permettere l'ottimizzazione del dimensionamento sin dalla fase di progetto preliminare.

Non è necessario un predimensionamento iniziale. L'ingegnere può iniziare direttamente con la ricerca automatica del dimensionamento ottimale. Non è necessario che le dimensioni iniziali corrispondano ad una soluzione ammissibile. Il ruolo del modello LBR-5 è, inizialmente di ricercare una soluzione accettabile (che rispetti l'insieme dei vincoli imposti) ed in seguito di proporre ad ogni iterazione una soluzione migliore che continui a rispettare questi vincoli. Infine la soluzione ottimale è ottenuta in 10 - 15 iterazioni indipendentemente dal numero di variabili di progetto (X_I) e di vincoli ($C_I(X_I) \leq C_{I(\max)}$).

Il dimensionamento ottimale corrisponde al minimo del costo di costruzione che è definito come funzione la funzione-obiettivo $F(X_I)$.

Le variabili di progetto (X_I) in numero di 9 per ogni elemento, corrispondono allo spessore dei pannelli, le dimensioni e la spaziatura dei rinforzi longitudinali (4 variabili) così come le dimensioni e la spaziatura dei telai trasversali (4 variabili).

Gli elementi sono i pannelli rigidi che compongono la struttura. Può trattarsi di pannelli di grosse dimensioni.

LBR-5 permette dunque

- la ricerca di un insieme di N variabili di progetto: $X_I(i) = 1 \text{ a } N$
- che minimizza la funzione-obiettivo costo: $\text{MIN}(F(X_I))$
- e che rispetta un gruppo di M vincoli: $C_j(X_I) \leq C_{j(\max)}, j = 1, M$

Quest'articolo introduce il concetto d'ottimizzazione orientata sui moduli. Infatti il modello LBR-5 è basato sui tre moduli di base seguenti: OPTI - modulo di ottimizzazione matematica, RESTRI - modulo relativo ai vincoli e COUT - modulo della funzione-obiettivo costo di costruzione.

La parte 1 descrive gli algoritmi matematici di ottimizzazione correnti è più specificamente un metodo duale accoppiato con una linearizzazione convessa, CONLIN® (modulo OPTI). La linearizzazione convessa permette di sostituire il problema iniziale formato da equazioni non lineari implicite con una serie di problemi composti da equazioni lineari esplicite (approccio iterativo). La linearizzazione convessa è la più conservativa: garantisce una convergenza verso il dominio ammissibile. Ad ogni iterazione, il problema esplicito e vincolato è sostituito da un problema quasi non vincolato grazie all'approccio duale (moltiplicatori di Lagrange).

La parte 2 riprende i fondamenti del software del pannello di irrigidimento (LBR-4) destinato all'analisi elastica delle strutture irrigidite. LBR-4 poggia sulla risoluzione analitica delle equazioni differenziali delle superfici cilindriche irrigidite e sugli sviluppi in serie di Fourier. Vi si descrive anche il procedimento di calcolo analitico di sensitività (derivate prime di vincoli e della funzione-obiettivo in rapporto alle variabili di progetto).

La parte 3 è dedicata alla valutazione dei vincoli (modulo RESTRI). Viene fatta una presentazione dettagliata dei vincoli tecnologici, geometrici e strutturali, con particolare attenzione per la resistenza ultima dei pannelli rigidi compresi così come per quella della struttura nel suo insieme. Una banca dati dei vincoli è a disposizione dell'utente. Ad ogni restrizione è abbinato un codice (da 1 a 300). L'utente sceglie il vincolo che intende imporre alla struttura (tensioni massimali, deformazioni, resistenza ultima, ecc.) associando ad ogni elemento una serie di codici.



La parte 4 tratta della valutazione dei costi di costruzione che sono alla base della funzione-obiettivo costo, necessario al procedimento di ottimizzazione (modello COUT).

Dopo la descrizione di alcuni modelli esistenti, viene illustrato in dettaglio il modulo che permette un calcolo diretto del costo di costruzione in funzione delle variabili di progetto.

Infine vi si presenta l'ottimizzazione di una porta a galleggiamento destinata alla nuova conca marittima del porto di Ostenda, così come lo studio di una betta FSO utilizzata come serbatoio galleggiante in vista del trasferimento di grezzo verso le petroliere (parte 5 e 6).



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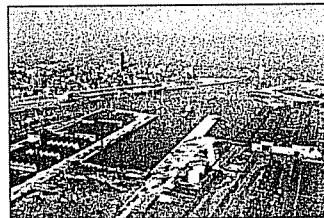


Photo : Foto Guido Coolens N.V.

Cover picture : Port of Ostend. Access channel and new Ro-Ro terminal

Photo de couverture : Port d'Ostende. Chenal d'accès et nouveau terminal Ro-Ro

