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OPTIMIZATION OF STIFFENED STRUCTURES
&
Application to Preliminary Ship Design

by

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ABSTRACT

This report presents an optimization method of stiffened structures (ship structures and hydraulic structures) from which the LBR-5 software is issued. Its target is to ease and improve the preliminary design stage allowing least cost optimization.

LBR-5 is a computer design package that provides optimum mid-ship scantlings (plating, longitudinal members and frames). Basic characteristics such as L,B,T,C_b , the global structure layout, and applied loads are the requested data. It is not necessary to provide a feasible initial scantling. Within about 1 hour of computation time with a usual PC or laptop the LBR-5 provides automatically a rational optimum design.

This software is an optimization tool dedicated to preliminary design. It provides the optimization scantling of the structure's constituent elements and, in the early stage of design, its main advantages are ease of structural modeling, rapid 3D rational analysis of a ship's hold, and scantling optimization. Preliminary design is the most relevant and the least expensive time to modify design scantling and to compare different alternatives. Unfortunately, it is often too early for efficient use of many commercial software systems, such as FEM. This paper explains how it is now possible to perform optimization at the early design stage including a 3D numerical structural analysis.

LBR-5 is based on the "Module Oriented Approach". It contains 3 major modules and the design variables are the dimensions of the longitudinal and transversal members, plate thickness and spacing between members.

First, there is the "Opti Module" which contains a mathematical programming code (CONLIN) to solve constrained non-linear optimization problems with a reduced number of re-analyses. Usually less than 15 analyses are required even with hundreds of design variables and hundreds of constraints.

Then, there is the "Constraint Module" to perform a rational analysis of the global structure. This structure is modeled using stiffened plate and stiffened cylindrical shell elements. Relevant limit states of the structure are taken into account thanks to a 3D rational analysis of the structure based on the general rules of solid-mechanics and structure behavior. Ultimate strength of stiffened panels and hull girder are considered as constraints.

Finally there is the "Cost Module" to assess the construction cost which is the objective function (least construction cost). So, unit material costs (Euro/kg or $/kg), welding, cutting, fairing, productivity (man-hours/m) and basic labor costs (Euro/man-hour) have to be specified by the user to define an explicit objective function.

The development of the LBR-5 "Stiffened Panels Software" is included in the development of a new design methodology to ease and to improve preliminary studies of naval structures and floating hydraulic structures. The ultimate target is to link standard design tools (steel structure CAD, hull form, hydrostatic curves, floating stability, weight estimation, etc.) with a rational optimization design module and a minimum construction cost (or minimum weight) objective function.
Optimum analysis of a FSO unit (Floating Storage Offloading) and optimization of a lock gate (Civil Engineering application) are presented as examples of the performance of the LBR-5 tool.

Keywords: Optimization, preliminary design, design methodology, construction cost, scantling, rational constraints, structural constraints, limit states.

Note: This document is based on the Rigo's thesis (Agrégation de l'Enseignement Supérieur, 1998) and on a compilation of several papers (Marine Structures, Elsevier, 2001 and Ship Production Symposium, SNAME, 2001).

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INTRODUCTION

Determination of the scantlings of marine structures always poses numerous problems to designers. Ships and floating structures are indeed complex structures, generally composed of strongly stiffened plates, deck plates, bottom plates, and sometimes intermediate decks, frames, bulkheads, etc. The stiffening system is also particularly sophisticated. There are several stiffener groups divided in two, or even three layers. Each stiffener group has its own function and is characterized by a different geometry and size. Optimization of these complex structures is the purpose of this paper.

The major orientations of a ship structural design are usually defined during the earliest phases of a project. That is 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 optimization tool is attractive, especially one designed for use at the preliminary design stage. This is precisely the way the LBR-5 optimization software for stiffened structures was conceptualized [7-8, 60]. "LBR-5" is the French acronym of "Logiciel des Bordages Raidis", i.e. "Stiffened Panels Software", version 5.0. The National Fund for Scientific Research of Belgium (NFSR), whose goal is to promote applied, advanced and innovative researches, sponsors this study.

The ultimate target is to link standard design tools (steel structure CAD, hull form, hydrostatic curves, floating stability, weight estimation, etc.) with a rational optimization design module that, as of the first draft, allows:

- an optimization of the sizing/scantling (profile sizes, dimensions and spacing) of the structure's constituent elements;
- integration of construction and manufacturing costs in the optimization process (through the cost objective function).

LBR-5 is this rational optimization module for structures composed of stiffened plates and stiffened cylindrical shells. It is an integrated model to analyze and optimize naval and hydraulic structures at their earliest stages: tendering and preliminary design. Initial scantling is not mandatory. Designers can start directly with an automatic search for optimum sizing (scantling). Design variables (plate thickness, stiffener dimensions and their spacing) are freely selected by the user.

LBR-5 is composed of 3 basic modules (OPTI, CONSTRAINT and COST). The user selects the relevant constraints (geometrical and structural constraints) in external databases. Standard constraint sets are also proposed to users. When the optimization deals with least construction costs, unitary material, welding, cutting and labor costs must be specified by the user to define an explicit objective function (not empirical). For least weight, these unitary costs are not used and the objective function depends only on the geometrical parameters. Using all these data (constraints, objective function and sensitivity analysis), the optimum solution is found using an optimization algorithm based on convex linearizations and a dual approach [56, 66]. Independent of the number of design variables and constraints, the number of iterations requiring a complete structural re-analysis is limited to 10 or 15.

The LBR-5's major uniqueness is how the different modules interact and how to integrate the LBR-5 module with existing tools (CAD, etc.). This work is now under completion with the collaboration of industrial partners (mainly from France). The link between LBR-5 (version 5.5) and the CAD model, hull form and other preliminary tools is actually done through a manual data file exchange procedure. In the near future, a series of '*Interface Programs*' will automatically achieve these tasks. Using these interfaces, LBR-5 will be able to receive the geometric data (node co-ordinates, scantling, etc.) from, for instance, an AUTOCAD, FASTSHIP, MAXSURF file or even by a simple EXCEL or ASCII file. These interfaces are developed according to the user specifications.

As its advantages appear mainly at this level, application fields of LBR-5 include hydraulic structures and naval structures and concern the preliminary design stage. It is indeed during the first stages of the project that flexibility, modeling speed and ease of use provide valuable help to designers. At this time, few parameters/dimensions have been definitively fixed and a coarse modeling by standard finite elements is often unusable, particularly for design offices and modest-sized yards. For ship's structures, the application domain is clearly the ship's central part (parallel zone of cargo ships, passenger vessels, etc.). This zone is the most important in length for the large floating units (FSO). For smaller units (sailboats, small craft, etc.), the parallel zone is smaller, or even non-existent. In this case, the LBR-5 model can be used to perform transverse cross-section optimization (midship section). The module can also be used in the final stage of the project to perform a general verification or to refine the scantling. Nevertheless, at this final design stage, LBR-5 must imperatively be used as a complement to other specific analyses to get, for instance, stress concentration factors, fatigue strength, noise and vibration level, etc. In addition, LBR-5 is advantageously used for education and training purposes. For instance to support lectures on 'Ship Design Methodology', 'Structure Analysis', 'Ship Optimization', etc.

Many papers have been written on design philosophy and methodology, both present and future [1-8]. The most well known methodology for the design of naval and marine structures is the "Design Spiral" [9-15]. Despite its age, it is still used. However the current tendency is to break with this design process and move towards "Concurrent Engineering" (Rigo 1998a and 98b).

LBR-5 is the result of the integration inside the same package of the LBR-4 and CONLIN [56] software and constitutes a new tool to precisely achieve this type of optimization, i.e. to define the optimum scantling [7, 8].

The term "ship structural optimization" has a different meaning according to the person or the group for whom the study is done. For ship-owners, to optimize the structure of a new ship means determining the main ship dimensions in order to attain the highest profitability rate (Mandel and Leopold 1966, Buxton 1976 and Sen 1978). For the designer, "structural optimization" simultaneously concerns both the hull forms and the structural components (scantling) (Keane et al. 1991). For the structural engineer, "structural optimization" essentially consists in defining optimum scantling of the decks and the bottom and side shells.

In this analysis, "structural optimization" essentially consists of defining optimum scantling of the decks and the bottom and side shells (including the framing). In this ship-sizing optimization, the general dimensions and the hull forms are considered as fixed. Only the frame and stiffener spacing are use as topological design variables.

Methods similar to LBR-5 are proposed by Hughes [37-39] with Maestro, Rahman [52-53], Sen [58] and more generally in [47-55, 64]. Compared to Maestro [37-39], LBR-5 is more preliminary design oriented. The structure modeling is so simple and fast, but not simplified, that optimized scantling can be obtain within a couple of hours (maximum one day for complex structures if starting from scratch). LBR-5 does not have the capability of a finite element analysis and is restricted to prismatic structures and linear 3D analysis. But, on the other hand, LBR-5 uses explicit exact first order sensitivities (derivatives of the constraint and objective functions by the hundreds of design variables). Heavy and time consuming numerical procedures are not required. Sensitivities are directly available as the method is based on an analytic solution of the differential equations of cylindrical stiffened plates using Fourier series expansions. So, sensitivity formulations are known analytically. In addition LBR-5 does not need to use the concept of local and global design variables used by Hughes, Rahman and Sen. Due to the efficient CONLIN mathematical optimization algorithm (convex linearization and dual approach), optimization of the full structure can be performed with hundreds of design variables and constraints using less than 10~15 global structure re-analysis (iterations).

With regards to the Rahman's model, LBR-5 concept is much more advanced, i.e. full 3D rational stress analysis, complex model, ultimate strength of plate, stiffened panels and hull girder are included as constraints, advanced optimization approach (CONLIN [61]), multi-purpose tool, etc. On the other hand Rahman gives the possibility to achieve rules based optimization and his tool is specific for inland navigation vessels. The Sen's model [58, 64] has the advantage of being a multi-criteria optimization model including use of discrete variables. But this model seems to be limited to a single stiffened panel with reduced number of design variables and only few constraints are available. In addition the simplex algorithm used by this model needs a large number of re-analysis and is not compatible with large 3D-structure optimization including hundreds of variables and non-linear constraints.

This report describes the scientific aspects of the rational optimization procedure, the innovative concept and methodology, and the way they are implemented. First a state of the art is presented (PART i), then the report focuses on the "Module-Oriented Optimization" concept (PART ii). After, it contains relevant information on the mathematical algorithm of the OPTI module (PART I), a presentation of the CONSTRAINT module (PART II) and advanced information on the COST module (PART III).

Finally detailed applications on the optimization of a floating storage offloading unit (FSO) and a gate of a ship lock are presented, respectively, in Part IV and Part V.

PART i STATE OF THE ART

Design Philosophy

The most well known methodology for the design of ship and other marine structures is the "Design Spiral" (Buxton 1976, Evans et al. 1963, Greene 1997, Lewis 1988, Rawson and Tupper 1994, Taggart 1980 and Vanderplaats 1984). However the current tendency is to break with this design process and move towards "Concurrent Engineering" (Bennet and Lamb 1996, Elvekrok 1997, Parsons et al. 1999). In addition, several CAD tools have been developed to assist the designer, and some pay special attention to the preliminary design and the tender phase (LUNAIS [Hage et al. 1993] and IKBS [Hills and Buxton 1989]).

Many other papers have been written on design philosophy and methodology, both present and future (Francescutto 1993, Mamo 1993, Masson 1997, Push 1996, Rains and Johnson 1991, Rigo 1998a and Watson 1998); production (Caldwell 1978, Shenoi 1984 and Blomquist 1995); design and sizing approaches (Lamb 1969, Pattison et al. 1986, Welsh et al. 1991, Kim et al. 1992, Wada et al. 1992, Melitz et al. 1992, Rigo 1998b); new structures (Hori et al. 1990) and applications (Niho et al. 1994 and Tanigushi et al. 1994). An excellent discussion is presented by Birminghman et al. 1997

Technique and economic analysis

For the technical and economic analysis of the ship, the design phase and production (Benford H. 1970), the works by Professor Buxton and his team comprise an excellent reference (Buxton 1966, 1976, 1984b and 1987; Hills et al. 1990). Buxton treats all the problems linked to cost evaluation (design, manufacturing and exploitation) with a CAD tool (Intelligent Knowledge Base System [Hills and Buxton 1989]) that integrates a cost evaluation module based on an analytic calculation.

Methods of Structure analysis

Every three years, the ISSC (International Ship Offshore and Structures) publishes a comprehensive report on the latest techniques and developments for naval and marine structures (Moan et al. 1988, 1991 and 1994).

As this report is oriented towards stiffened structures, especially ship and other marine and hydraulic structures, the bibliographic analysis will be limited to problems of these types of structures, with special attention to linear elastic analysis of orthotropic structures. For other limit states (buckling, vibration, ultimate strength) we refer the reader to Rigo (1998a , 2001a,b and c).

The "stiffened plate method" (LBR-4) for elastic analysis of stiffened structures is used for the development of the LBR-5 optimization module presented in this paper (Rigo 1998a and b). The role of the LBR-4 module is to provide a fast and reliable assessment of the stress pattern existing in the stiffened structure (Rigo 1989 and 92). The selection of cost-effective stress and strain models is indeed a difficult problem that has been considered in many studies (Faulkner 1975 and the Ship Structure Committee [Yee et al. 1997]). Analytic approaches similar to LBR-4 are proposed by Hinton et al. (1993) with a strip model; Smith (1966), solving the plate differential equations with Fourier series expansions and Ohga, Shigematsu et al. (1993) with buckling analysis of tapered plates. Other major references are Chalmers 1993, Evans 1975, Eyres 1994, Hughes 1988, Marchal 1988, Rawson and Tupper 1994, Taggart 1980 and Watson 1998.

Optimization of Naval Structures

The first ship structure optimization studies were made practically by hand (Harlender 1960). Then, with computer assistance, researchers tried to develop design and optimization algorithms. Optimization first appears in the works of Evans (1963), Mandel and Leopold (1966), Moe and Lund (1968) and Nowacki et al. (1970). The works of Moe and Nowacki long served as a reference for naval structure optimization (Winkle and Baird 1986). An important step for naval structure optimization appeared with Hughes' works (Hughes 1980, 88, 92 and Mistree et al. 1992).

The evolution of design techniques and optimization are reported by ISSC: Catley et al. (1988, 90 and 97); Moan et al. (1988 and 91); Pittaluga et al. (1994), Hughes et al. (1994); Beghin et al. (1997) and Pradillon et al. (2000). As major references works on optimization: Jelen 1970, Gill et al. 1974 and 81, Rozvany 1979, Bunday 1984, Vanderplaats 1984, Save et al. 1985 and 90 and Wisniewski et al. 1990; and as examples of ship structure optimization: Lyons 1982, Hung 1987, Frieze et al. 1987, Jang and Na 1991, Kriezis 1991, Krol 1991, Park et al. 1991, Rahman and Caldwell 1992 and 1995, Hatzidakis and Bernitsas 1994, Nobukawa et al. 1995, Na et al 1994, etc.

It is interesting to note that the most of the scientific literature deals with optimization mathematical tools and analysis methods for limit states assessment (strength, deflection, etc.). Few accessible articles, on the other hand, concern the choice of the objective function, and more precisely a construction cost objective function. So, it is paradoxical to note that most studies show the necessity of establishing objective criteria integrating production costs and to compile a meaningful database of unitary construction costs. On this subject, we can cite the works of Southern 1980, Kuo et al. 1984, Winkle and Baird 1986, Bunch 1989 and 1995, Hills and Buxton 1989, Blomquist 1995, Hengst et al. 1996, Kumakura et al. 1997 and the PODAC model (Keane and Fireman 1993, Ennis et al. 1998).

The term "ship structural optimization" has a different meaning according to the person or the group for whom the study is done. For ship-owners, to optimize the structure of a new ship means determining the main ship dimensions in order to attain the highest profitability rate (Mandel and

Leopold 1966, Buxton 1976 and Sen 1978). For the designer, "structural optimization" simultaneously concerns both the hull forms and the structural components (scantling) (Keane et al. 1991). For the structural engineer, "structural optimization" essentially consists in defining optimum scantling of the decks and the bottom and side shells.

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Sizing optimization: Concerning ship-sizing optimization, the general dimensions and the hull forms (shapes) are considered as fixed and it should be noted that since 1980 the FEM has become a standard to evaluate constraints on stress, displacement and ultimate strength at each iteration (Hughes 1980 and 88, Zanic et al. 2000). With FEM, structure analysis of a large structure is quite demanding and thus represents the major portion of computing time. Thus two options have appeared: either to develop more effective mathematical algorithms in order to reduce the number of FEM re-analyses (Fleury 1993), or to divide the optimization problem of the structure into two levels (Hughes 1980, Sen et al. 1989a and 1989b, Krol 1991, and Rahman et al. 1992 and 1995). The first alternative is used in this study.

Multi-objective Optimization: The University of Newcastle-Upon-Time is a well-known research center for multi-objective optimization (Multi-Object Decision Model and Multi Criteria Decision-Making) (Sen 1978, 92, 95 and 1998). The use of genetic algorithms for large size multi-criteria optimization has recently become popular (Goldberg 1989 and Okada et al. 1992). Concerning multi-criteria optimization applied to ship structures, some valuable works are Parsons and Singer (2000), Shi 1988 and 92, Trincas, Zanic et al. 1994, Kim and Han 1994, and Ray and Sha 1994.

Shape Optimization: For more than 15 years, shape optimization has witnessed the most important progress in the domain of structure optimization (Beckers 1991). Thus, it is now possible to automatically search for optimal hull forms (Project European OPTIM 1994). Fluid-structure interaction is a difficult matter that, within the framework of a shape optimization procedure, makes the problem quite complex, thus explaining the reduced number of industrial applications.

Topological optimization: Thanks to the continuous development of computer capabilities, topological optimization is a research field that, in the last few years, has enabled us to discern various industrial applications. Topological optimization is a dream that is slowly becoming a reality, but the applications are, unfortunately, still much too "academic" (Bensoe and Kikuchi 1988, and Duysinx 1996).

PART ii LBR-5 and THE CONCEPT OF "*MODULE-ORIENTED OPTIMIZATION*"

A multi-purpose optimization model, open to users and compatible with different codes and regulations must contain various analysis methods for strength assessment that could be easily enriched and complemented by users. The user must be able to modify constraints and add complementary limitations/impositions according to the structure type studied (hydraulic, ship, offshore structures, etc), the code or the regulation in force and to his experience and ability in design analysis. The objective is to create a user-oriented optimization technique, in permanent evolution, i.e. that evolves with the user and his individual needs. We define this as "Module-Oriented Optimization".

The LBR-5 optimization model is based on this new concept and is composed of several modules. Neither the module number nor their type is imposed. At the start, the whole model is made up of 3 basic modules (Fig. 1) and forms the framework of the tool (COST, CONSTRAINT and OPTI).

Around the COST and CONSTRAINT modules there are a large number of sub-modules. Each of these sub-modules is specific to a type of constraint. In principle, it is necessary to have at least one sub-module for each constraint type. To date, only a limited number of modules are available (in general 1 or 2 for each constraint type). It is up to the user to complete, adapt and add new modules according to his specific requirements (type of structure, codes and regulations to be followed, technical and scientific level, available hardware, etc.). The objective is to enable the user to build the needed tool.

Fig. 1 shows the basic configuration of the LBR-5 software with the 3 fundamental modules (COST, CONSTRAINT and OPTI) and the "DATABASES" in which the users can "shop", that is, choose the relevant constraints and cost data. After selecting the geometrical and structural constraints and cost assessment tools in the databanks, Fig. 2 gives an example of a ready-to-use model. Fig. 3 describes the general organization chart of a structure optimization process and Fig. 4 succinctly shows the LBR-5 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.

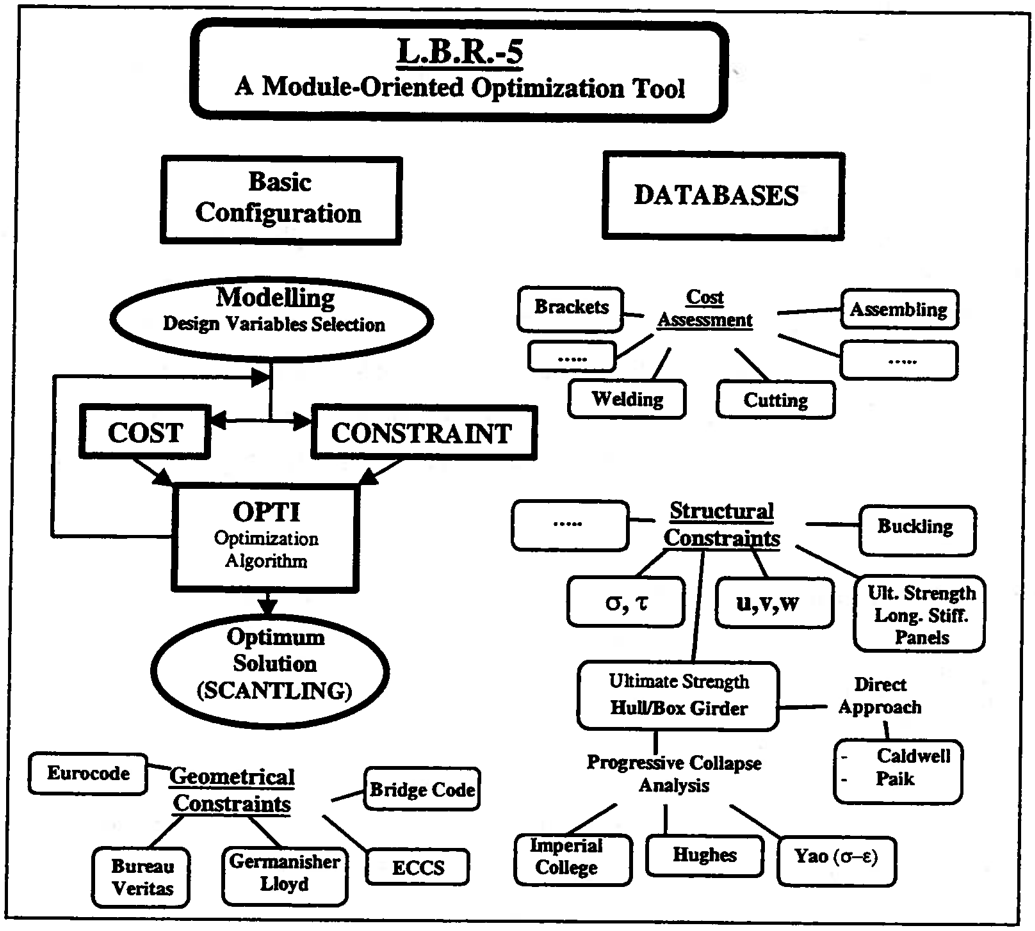


Figure 1 Basic configuration of the LBR-5 model and database presentation

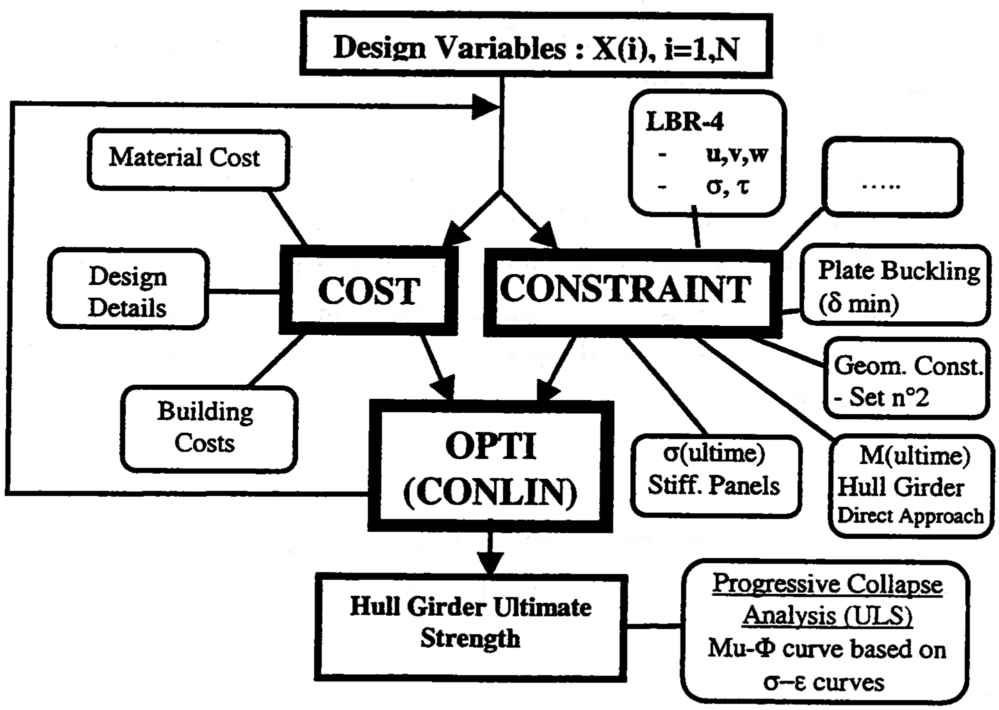


Fig. 2. LBR-5 flow chart after sub-module selection (constraints and cost data).

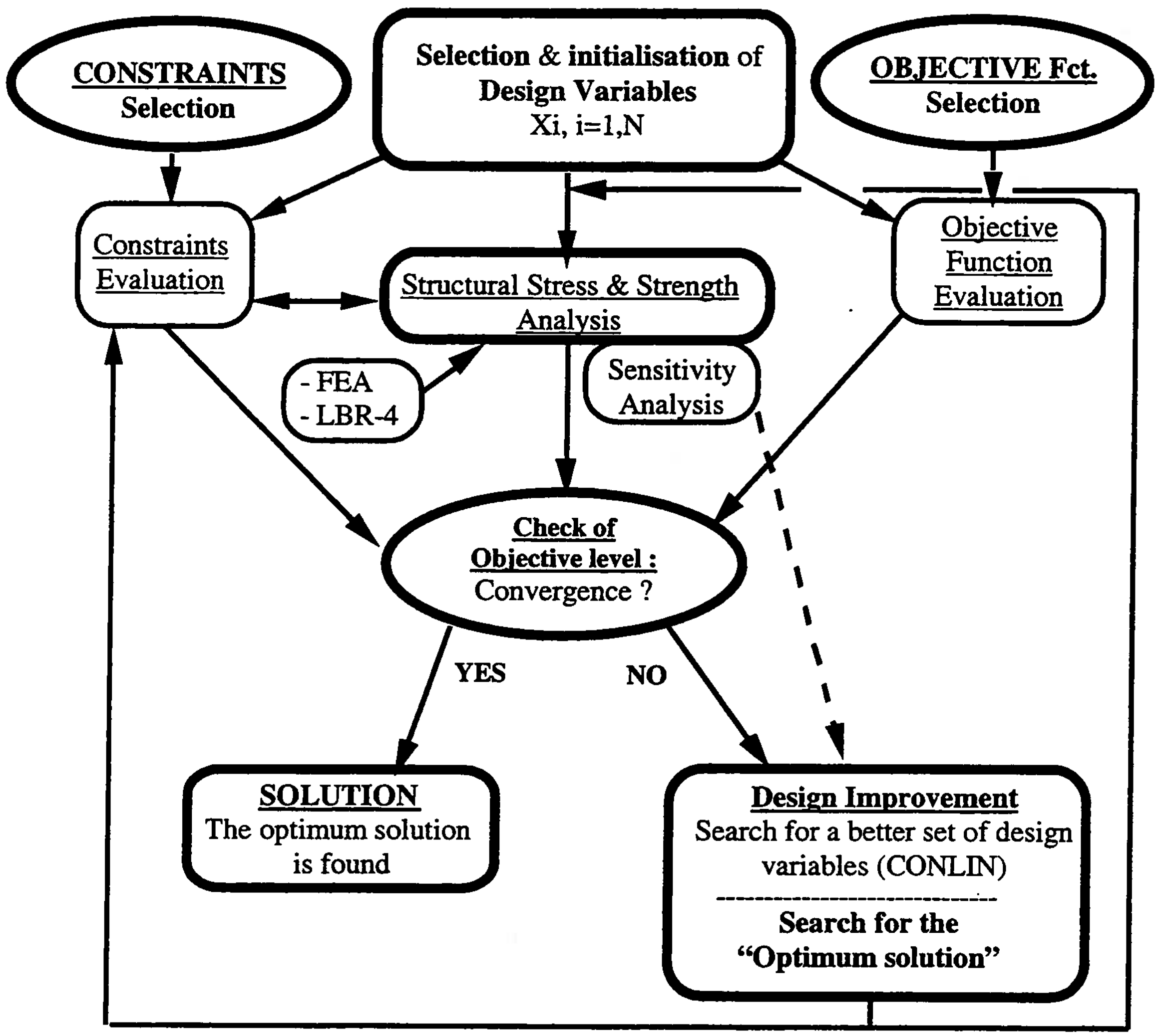


Fig. 3. General organization flow chart of a structure optimization process

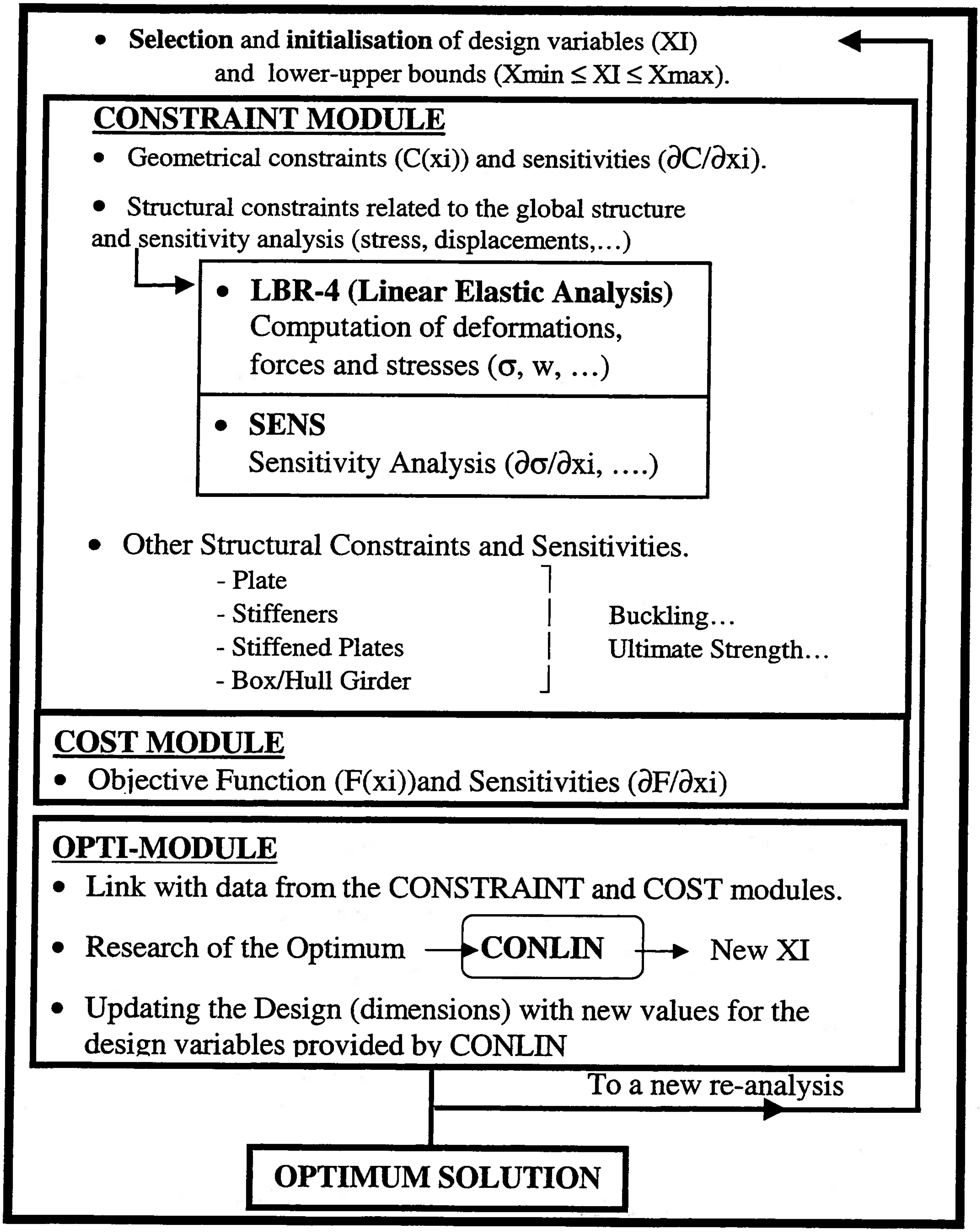


Fig. 4. Chart of the LBR-5 model with CONSTRAINT, COST and OPTI modules.

DESCRIPTION OF THE 3 BASIC MODULES

The optimization problem can be summarized as follows:

- X_i $i = 1, N$, the N design variables,
- $F(X_i)$ the objective function to minimize,
- $Cj(X_i) \leq CM_j$ $j = 1, M$ the M structural and geometrical constraints,
- $X_{i\ min} \leq X_i \leq X_{i\ max}$ upper and lower bounds of the X_i design variables: technological bounds (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 (XI). These 9 design variables are respectively:

- Plate thickness.
- For longitudinal members (stiffeners, crossbars, longitudinals, girders, etc.):
  - web height and thickness,
  - flange width,
  - spacing between 2 longitudinal members.
- For transverse members (frames, transverse stiffeners, etc.):
  - web height and thickness,
  - flange width,
  - spacing between 2 transverse members (frames).

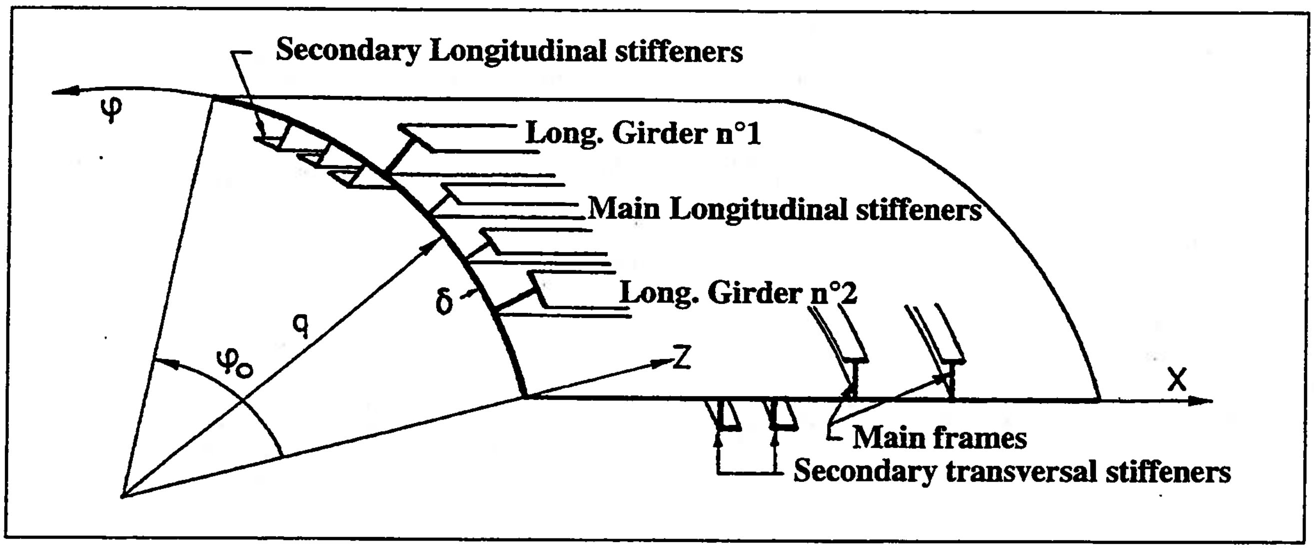


Fig. 5. Basic stiffened panel (or basic element) used to model the structures.

The 3 basic modules are *OPTI*, *CONSTRAINT* and *COST* (Figure 1).

The *OPTI module* contains the mathematical optimization algorithm (CONLIN) that allows solving non-linear constrained optimization problems. It is especially effective because it only requires a reduced number of iterations. In general, fewer than 15 iterations, including a structure re-analysis, are necessary, even in presence of several hundred design variables (XI).

CONLIN is based on a convex linearization of the non-linear functions (constraints and objective functions) and on a dual approach (C. Fleury 1989 and 1993). This module uses as inputs the results/outputs of the two other basic modules, that is, CONSTRAINT for the C(XI) constraints and COST for the F(XI) objective function.

The *CONSTRAINT module* helps the user to select relevant constraints within constraint groups at his disposal in a databank (Figure 1). In fact, the user remains responsible for his choice. However, in order to facilitate this selection, several coherent constraint sets are proposed to the user. These sets are based on national and international rules/codes (Eurocodes, ECCS Recommendations, Classification Societies, etc.).

Constraints are linear or non-linear functions, either explicit or implicit of the design variables (XI). These constraints are analytical "translations" of the limitations that the user wants to impose on the design variables themselves or to *parameters* like displacements, stresses, ultimate strength, etc. Note that these *parameters* are functions of the design variables.

So one can distinguish:

- Technological constraints (or side constraints) that provide the upper and lower bounds of the design variables.
- Geometrical constraints impose relationships between design variables in order to guarantee a functional, feasible, reliable structure. They are generally based on "good practice" rules to avoid local strength failures (web or flange buckling, stiffener tripping, etc.), or to guarantee welding quality and easy access to the welds.
- Structural constraints represent limit states in order to avoid yielding, buckling, cracks etc. and to limit deflection, stress, etc. These constraints are based on solid-mechanics phenomena and modeled with rational equations.

For each rational structural constraint (or solid-mechanics phenomenon), the selected behavior model is especially important since this model fixes the quality of the constraint modeling. These behavior models can be so complex that it is no longer possible to explicitly express the relation between the parameters being studied (stress, displacement,...) and the design variables (XI). This happens when one uses mathematical models (FEM, LBR-4,...). In this case, one generally uses a numeric process that consists in replacing the implicit function by an explicit "approximated function" adjusted in the vicinity of the initial values of the design variables (for instance using the Taylor series expansions). This way, the optimization process becomes an iterative analysis based on a succession of local approximations of the behavior models.

The *COST module:* In 2000, even for a first draft, a least weight optimization 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 objective function of the LBR-5 software can be the construction costs (COST module) and/or the weight (example: 60% based on cost and 40% based on weight). The weight objective function is in fact a simplified form of the cost objective function. In order to link the objective function (Euro) to the design variables (Xi), the unit costs of raw materials (Euro/Kg), the productivity rates for welding, cutting, assembling, etc. (man-hours/unit of work = m-h/unit) and labour costs (Euro/m-h) must be specified by the user.

These unit costs vary according to the type and the size of the structure, the manufacturing technology (manual welding, robots,...), the experience and facilities of the construction site, the country, etc. It is therefore obvious that the result of this optimization process (sizing optimization) will be valid only for the specific economic and production data under consideration. Sensitivity analysis of the economic data on the optimum scantling can also be performed, thus providing the manager with valuable information for improving the yard.

PART I OPTI MODULE
A DUAL OPTIMIZATION ALGORITHM with CONVEX LINEARIZATION

This handout explains why CONLIN (a general–purpose mathematical optimization algorithm) has been selected to solve our engineering problem (ship scantling optimization).

LBR5: AN OPTIMIZATION TOOL FOR PRELIMINARY SHIP DESIGN

The LBR–5's purpose is to provide an optimum scantling of the central part of the ship (midship section) and the objective function is the least construction cost. As the LBR–5's target is the preliminary design stage, heavy and time–consuming analysis does not fit with the LBR–5's optimization framework.
Detailed information on LBR–5 are available in a series of papers published by Rigo (2001).

The normalized problem (*primal problem*) to solve is the following:

min $[F(x_i)]$	with	N	design variables x_i (scantling variables),	(1)
		F	the objective function (Construction cost),	(2)
subject to	$C_j(x_i) \leq CM$		M constraints (structural constraints)	(3)
	$x_{i\,min} \leq x_i \leq x_{i\,max}$		the lower–upper bounds (technologic constraints)	(4)

Design variables:

Midship section can be easily modeled in stiffened panels that include plating, stiffeners and frames. Scantling of these panels corresponds to the selected (x_i) design variables (9 design variables per panels). In practice, a midship section can be modeled using 10 to 100 panels. So, our optimization problem concerns about 90 to 900 design variables).

Constraints:

Our wish is to design using rational formulations and not using empirical rules from Classification Societies. That means that most of the structural constraints are:

- Nonlinear:The relationships between design variables (x_i) and constraints (C_j) are nonlinear.
- Implicit: As stress analysis is performed to solve the governing differential equations of stiffened plates, the displacements and the stresses are obtained through a complex numerical process and there is no explicit equation between design variables (x_i) and constraints (C_j).

A treatment of the Finite Element Method (FEM) is not a goal here (preliminary design stage) but, to clarify the explanations, we can say that the constraints results from a numerical structural analysis similar to those preformed with usual finite element packages. It is therefore obvious that the number of re–analysis has to be limited (re–analysis means a new complete analyses of the structure with up–dated design variable values).

The number of constraints is usually about 10 for each panel. This means for a structure modeled with 100 panels and with 5 load cases, about 100x10x5=5000 constraints.

Objective functions:

Weight and construction cost, which is typically also based upon weight, are the available objective functions. These functions are simple compared to the constraints. They are explicit but sometimes nonlinear.

CONLIN: A DUAL OPTIMIZATION ALGORITHM with CONVEX LINEARIZATION

A dual approach with convex linearization was chosen as the mathematical optimization algorithm to be implemented with the LBR–5 software for various reasons. Before explaining the reasons for that choice, remember that we need an algorithm that:

- solves a problem including hundreds of design variables (500) and thousands of constraints (5,000),
- deals with highly nonlinear constraints,
- deals with implicit constraints.

And, above all, this algorithm must not need too much structure re–analysis (practical limit about 10).

Reasons of not choosing other methods:

- As the number of re–analyses has to be limited, methods using random generation of design variable values are discarded (Genetic algorithm, MonteCarlo simulation,...). For the same reason, methods having a low convergence level (1^{st} order) cannot be selected (steepest gradient, conjugate gradient, etc.).
- Many efficient methods (Newton second order, SQP, etc.) use quadratic approximations and need the first and the second derivatives of the constraints and the objectives functions (called sensitivities). When complex structural analysis is used (FEM or LBR–5), it is hard and time consuming to get the sensitivities. For that reason, convex linearization are attractive as only the first derivatives are used.

To understand the other reasons of selecting CONLIN, we have to explain what is the convex linearization and what is a dual approach. These methods are presented in the next two sections.

CONLIN is an optimization technique developed by C. Fleury (1989, 93) using convex linearization of the constraints and objective function combined with in a dual approach. With this algorithm, large constrained problems with implicit and nonlinear constraints can be more easily solved (Figure 1).

The main difficulty in this optimization deals with the **nonlinearities** (1) and the **constraints** (2).

The nonlinearities: In order to avoid a large number of time–consuming re–assessments of the nonlinear and implicit functions, Fleury suggests applying convex approximations. At each iteration (sequential procedure), all the functions (objective function and constraints) are replaced by an approximation called "convex". In a word, the complex initial optimization problem is decomposed into a sequence of more simple convex optimization problems (obtained through a convex linearization) that can be easily solved using a dual approach (Figure 1). So, using linearizations we replace the constrained nonlinear and implicit problem by a series of constrained linear and explicit problems.

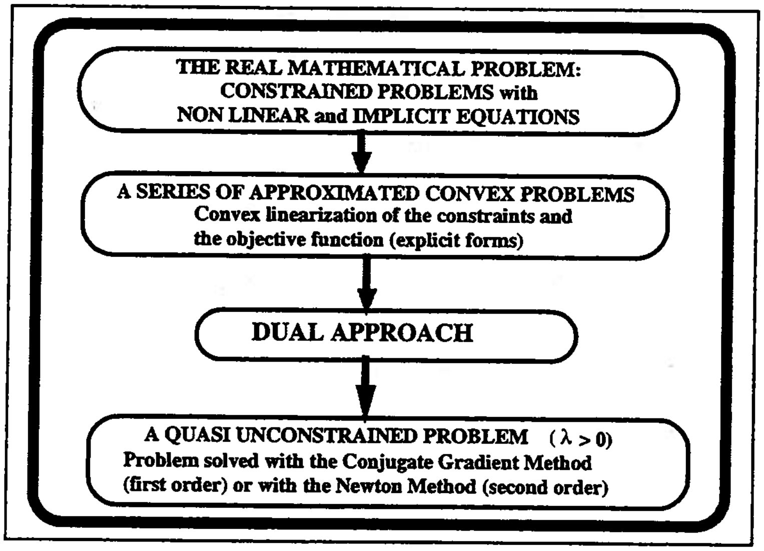


Figure 1. The CONLIN model: Convex approximations and dual approach.

Constrained problem: The second difficulty is the fact that the problem is highly constrained. One alternative would be to use a penalty function to transform the constrained problem in an unconstrained one. The dual approach is a second alternative. We replace the *primal constrained problem* (N design variables, M constraints) by the *dual quasi–unconstrained problem* (M dual design variables and no constraint, except that the dual variables must be >0). For large FEM problems, usually N>> M. So, in addition of having an unconstrained problem, the equation system to solve is smaller in size. For LBR–5, many load cases are considered, so we have N<M and we do not get advantage of the fact that the dual problem has less design variables than the primal problem.

In conclusion, using both *convex linearization* and the *dual approach*, we replace the constrained nonlinear and implicit problem by a quasi–unconstrained linear and explicit problem that can be solved using the conjugate gradient method or second–order Newton method.

CONLIN is a sequential approach. There is an external loop that requires structural re–analysis of the structure with the current values of the design variables. In this loop, the constrained nonlinear and implicit problem is replaced by an approximated, quasi–unconstrained, linear and explicit problem (convex linearization and the dual approach). Then, in the interior loop, the dual problem is used to solve the approximated problem using a standard algorithm for unconstrained optimization. This latter problem being explicit, no matter of the number of steps to get the solution of the approximated problem, it only requires tenths of second. The solution of the approximated problem (inner loop) is used for the next external iteration.

Practical advantages of CONLIN:

- Convergence is guaranteed to be within the feasible space. This means that, at each iteration, the solution is feasible. This is very important for the engineering application. The optimization procedure can be stopped at any time and the solution is feasible and better then the initial point,
- Optimum solution is found within 10 to 15 iterations even for large problems (convergence = order 2),
- The Initial design point needs not be in the feasible space. First iterations (1 or 2) are used to move inside the feasible space (no matter of the objective function) and than optimization is performed,
- The method is robust. *"Relaxation"* can be used if the convergence fails. Up to now, such a problem has never occured using LBR–5.

CONVEX LINEARIZATION

In order to handle nonlinear implicit constraints ($C(x_i)$), Fleury proposes replacing these constraints with approximated explicit linear constraints by using convex linearization. He suggests using the first term of the Taylor Series Expansion. Three linear alternatives are possible:

- Linearization with standard design variables (x_i , i=1,N) :

$$C(x_i) = \tilde{C}(x_i) = C(x_i(0)) + \sum \left[x_i - x_i(0)\right] \cdot \partial C(x_i(0))/\partial x_i \qquad (5)$$

- Linearization with reciprocal design variables ($1/x_i$, i=1,N) :

$$C(x_i) = \tilde{C}(x_i) = C(x_i(0)) + \sum [1/x_i - 1/x_i(0)] \cdot \partial C(x_i(0)) / \partial(1/x_i) \tag{6}$$

- Convex linearization with mixed variables (x_k , k=1,L) and ($1/x_j$, j=L+1,N)

$$\begin{aligned} C(x_i) = \tilde{C}(x_i) = C(x_i(0)) &+ \sum_{k=1}^{L} [x_k - x_k(0)] \cdot \partial C(x_k(0)) / \partial x_k \\ &+ \sum_{j=L+1}^{N} [1/x_j - 1/x_j(0)] \cdot \partial C(x_j(0)) / \partial(1/x_j) \end{aligned} \tag{7}$$

As design variables refer to dimensions such as plate thickness, web height, etc., it is not suitable to use x_i to linearize constraints related to stress, strength and displacement. 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 design variables (x_i) instead of reciprocal ones ($1/x_i$). Therefore, for a general case, it is obvious that mixed linearization will occur. But the problem remains how to determine which linearization is the most suitable (reciprocal variable 1/x or direct variable x) for each design variable. C. Fleury has responded to this, proposing to make this selection in a way that replaces the actual design space (feasible domain for the design variables) by a smaller domain, included in the actual one, but convex (Figure 2). One can summarize in this way: since the substitution design space is conservative, this leads to a solution that is still admissible, but that could be "slightly" different from the real optimum. Step by step, this conservatism is released as one comes closer to the real optimum.

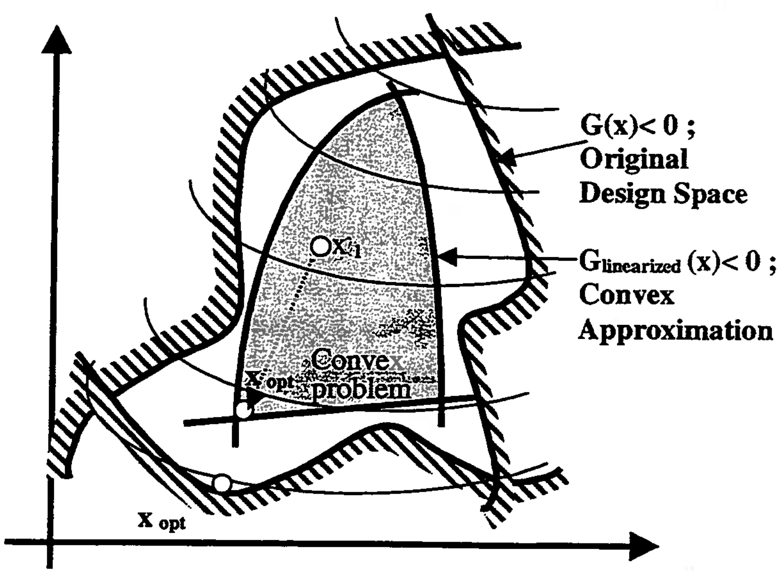


Figure 2. Convex linearization of the feasible space.

The convexity of the design space and conservatism allow a safe and fast convergence. The convergence is safe because, at each iteration, the updated solution has a tendency to still remain in the feasible domain. Fleury has demonstrated that an efficient convex linearization can be achieved by selecting the group of variables (x_i) and the group of reciprocal variables ($1/x_i$) according to the sign of the first derivative of the function to linearize, that is $\partial C(x_i(0))/\partial x_i$.

For a given design variable x_i :

- a linearization with standard variable x_i is achieved if $\partial C(x_i(0))/\partial x_i > 0$;
- a linearization with reciprocal variable $1/x_i$ is performed if $\partial C(x_i(0))/\partial x_i < 0$.

Therefore, Eq.(3) becomes:

$$C_l(x_i) = \tilde{C}_l(x_i) = C_l(x_i(0)) \;+\sum_{+}\left[x_k - x_k(0)\right]\cdot \partial C_l(x_k(0))/\partial x_k \;-\sum_{-}\left[1/x_j - 1/x_j(0)\right]\cdot \left(x_j(0)\right)^2 \cdot \partial C_l(x_j(0))/\partial x_j \qquad (8)$$

with $\partial C(x_k(0))/\partial x_k > 0$ $(1 \le k \le L \le N)$;
$\partial C(x_j(0))/\partial x_j < 0$ $(L+1 \le j \le N)$, for i=1,N and l=1,M.

The proposed convex linearization is very "user friendly" as only the values of $C(x_l(0))$ and $\partial C(x_k(0))/\partial x_k$ are required. The linearization is done automatically at each step (iteration) and the convergence order is 2. In addition, the main advantage of the proposed convex linearization is the conservatism of the approximated function. Let's note, however, that conservatism is only guaranteed with regards to initial linear functions in x_k and in $1/x_j$. To avoid numerical problem the equations have to be normalized before starting the convex linearization. Fleury (1987, 1993) explains this procedure.

As an example (Figure 3), consider the C1 and C2 constraints (eq.(9a) and eq.(9b)) and some feasible linearizations (eq.(9c) to eq.(9f)):

$$C1(x) = 5\,x_2 - x_1^2 - 10 \le 0 \qquad (9a)$$

$$C2(x) = 5/4\,x_2^2 + 16/x_1^2 - 13 \le 0 \qquad (9b)$$

The considered initial point of the design variables is $x(0)=(x_1, x_2)=(2,2)$. At this point, the two constraints and their first derivatives are the same as:

$C1(2,2) = C2(2,2) = -4$ and

$\partial C1(2,2)/\partial x = \partial C2(2,2)/\partial x = (-4, 5)$.

Based on these equalities, all the linearized equations of C1 and C2 [eqs.(9c–9f)] are the same. According to the linearization models [eqs.(5–8)], we obtain for both C1 and C2:

- Standard linearization, x [eq.(5)]: $5\,x_2 \;-4\,x_1 \;-\;6\;\leq 0$ (9c)
- Reciprocal linearization, 1/x [eq.(6]: $-20/x_2 + 16/x_1 - \;2\;\leq 0$ (9d)
- Convex linearization [eq.(8)]: $5\,x_2 \;+16/x_1 - 22\;\leq 0$ (9e)

  The variables are: x_2 as $\partial C/\partial x_2 = \;5 > 0$

  $1/x_1$ as $\partial C/\partial x_1 = -4 \;< 0$
- Concave linearization, with x_1 and $1/x_2$ $5\,x_2 \;+16/x_1 - 22\;\leq 0$ (9f)

Figure 3 shows that the convex linearization [eq.(9e)], is the best linearization and the most conservative way, even if it fails with regards to C2, which is initially more convex (a quadratic function in x_2 and 1/x [eq.(9b)]) than the approximated convex function (a linear function in x_2 and $1/x_1$ [eq.(9e)]).

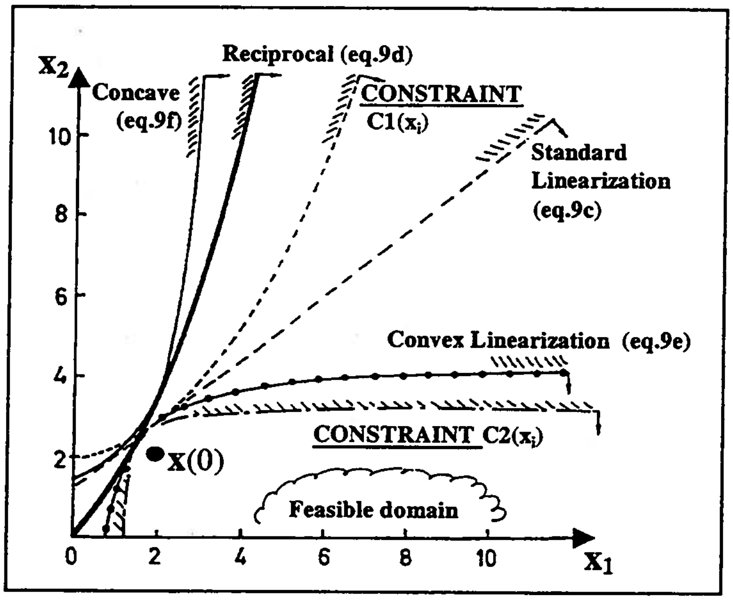


Figure I.3. Comparison between different linearizations.

Example 1: $C(x) = 5\,x_2 \;-\; x_1^{\,2} \;-10\;\leq 0$ (9a)

$$\frac{\partial C(x_1,x_2)}{\partial x_1} = -2x_1 \quad \text{and} \quad \frac{\partial C(x_1,x_2)}{\partial x_2} = 5$$

Linearization at $\mathbf{x}^0 = (x_1, x_2) = (2,2)$

$\partial C(x^0)/\partial x_1 = -4$ (negative value → convex linearization using the $1/x_1$ variable)

$\partial C(x^0)/\partial x_2 = +5$ (positive value → convex linearization using the x_2 variable)

- Convex linearization using $1/x_1$, x_2 as variables

$$\tilde{C}_{convex}(\mathbf{x}^0) = 6-(x_1^0)^2(-2x_1^0)\left(\frac{1}{x_1}-\frac{1}{x_1^0}\right)+5(x_2-x_2^0)-10 \le 0$$

$$\text{as } \frac{\partial C(x_1^0,x_2^0)}{\partial(\frac{1}{x_1})} = -(x_1^0)^2 \frac{\partial C(x_1^0,x_2^0)}{\partial x_1} = -(x_1^0)^2(-2x_1^0) = 16$$

then we obtain (eq.9e): $\boxed{5x_2 + 16/x_1 - 22 \le 0}$

- Standard linearization using x_1, x_2 as variables

$$\tilde{C}_{linear}(\mathbf{x}^0) = 6-2x_1^0(x_1-x_1^0)+5(x_2-x_2^0)-10 \le 0$$

then we obtain (eq.9c): $\boxed{5x_2 - 4x_1 - 6 \le 0}$

Example 2 (Figure I-4):

The original Problem

$\min\ x_1 + 4x_2$

with $\quad x_1 - x_2 \le 0$

$\quad -3x_1 + 2x_2 \le 1$

The convex & linearized subproblem

$\min\ x_1 + 4x_2$

with $\quad x_1 + \frac{16}{x_2} \le 8$

$\quad \frac{27}{x_1} + 2x_1 \le 17$

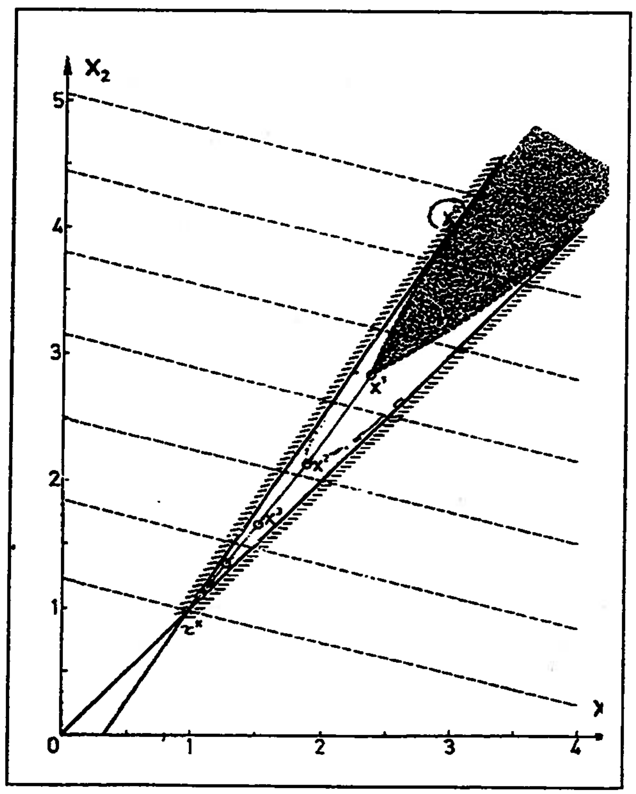


Figure I-4 : Example of convergence process using convex linearization.

A DUAL ALGORITHM FOR OPTIMIZATION PROBLEM

- At each iteration, the normalized problem to solve (after convex linearization) is the following:

  min $[\Sigma F_j / x_j - \Sigma F_i . x_i]$ with N design variables x_i, i=1,N

  subject to M constraints: $\Sigma C_{jk} / x_j - \Sigma C_{ik} . x_i \leq CM$, k=1,M

  and $x_{i\,min} \leq x_i \leq x_{i\,max}$ the lower–upper bounds.

This problem is called a primal problem with reference to the x_i design variables, called primary or primal design variables. It is a constrained problem with N design variables and M constraints. This problem cannot be solved easily with classic methods such as, for example, the Conjugated Gradient. A dual approach will be used here to replace the primal *constrained problem* with N unknowns by an *unconstrained problem* with M unknowns (called the dual problem). This technique is especially advantageous when M << N. Unfortunately, with regard to the applications considered in this paper, this last advantage is not relevant since M > N when multiple load cases are considered.

- To the primal problem (convex with separable variables), one can associate the dual problem:

  max(λ) [min(x) de L(x,λ)] and $x_{i\,min} \leq x_i \leq x_{i\,max}$

  with L(x,λ) the Lagrangian,
  λ_k the M Lagrange multipliers (*dual variables*)

$$L(x,\lambda) = \sum_j \frac{F_j}{x_j} - \sum_i F_i \cdot x_i + \sum_{k=1}^{M} \lambda_k \left(\sum_j \frac{C_{jk}}{x_j} - \sum_i C_{ik} \cdot x_i - CM_k \right)_k \tag{10}$$

which is also a function with separable variables.

Because the Lagrangian is separable [eq.(10)], the single dual problem with N design variables (N dimensions) is replaced by a series of N problems with a single dimension:

$$\Im(\lambda) = \min(x)\,[L(x)] = \sum_{i=1}^{N} \min[L_i(x_i)] \qquad \textit{for } x_{i\min} \leq x_i \leq x_{i\max} \tag{11}$$

$$\textit{as } \; L(x) = \sum_{i=1}^{N} L_i(x_i) \qquad \text{(As function with separable variables)}$$

Each term of the L(x) minimization [eq.(10)] can be written in an explicit form:

min[$L_i(x_i)$] = $A_i\, x_i + B_i / x_i$ where A_i and B_i are defined as: $\sum_{k=1}^{N} C_i \lambda_k + F_i = fct(\lambda_k)$ (12)

Note that the minimization related to each x_i variable requires that $\partial L_i/\partial x_i = 0$. Then,

$$x_{i\min} \le x_i = \sqrt{B_i/A_i} \le x_{i\max} \qquad and \quad x_i = fct(\lambda_k) \tag{13}$$

PART II THE CONSTRAINT MODULE
- Structural and Geometrical Constraints -

The problems to be solved can be summarised as follows:

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

Constraints are linear or non-linear functions, either explicit or implicit of the design variables (XI). These constraints are analytical *translations* of the limitations that the user wants to impose on the design variables themselves or to *parameters* like displacement, stress, ultimate strength, etc. Note that these *parameters* are functions of the design variables.

So one can distinguish:

- Technological constraints (or side constraints) that provide the upper and lower bounds of the design variables.

  for example: $Xi\ min = 4mm \leq Xi \leq Xi\ max = 40$ mm,

  with: Xi min   a thickness limit dues to corrosion, etc;

  Xi max   a technological limit of manufacturing or assembly.

- Geometrical constraints impose relationships between design variables in order to guarantee a functional, feasible, reliable structure. They are generally based on "good practice" rules to avoid local strength failures (web or flange buckling, stiffener tripping, etc.), or to guarantee welding quality and easy access to the welds. For instance, welding a plate of 30 mm thick with one that is 5 mm thick is not recommended.

  Example: $0.5 \leq X2 / X1 \leq 2$

  with X1, the web thickness of a stiffener and X2, the flange thickness.

- Structural constraints represent limit states in order to avoid yielding, buckling, cracks etc. and to limit deflection, stress, etc. These constraints are based on solid-mechanics phenomena and modeled with rational equations. By rational equations, we mean a coherent and homogeneous group of analysis methods based on physics, solid mechanics, strength and stability treatises, etc. and that differ from empirical and parametric formulations.

Thus, these rational structural constraints can limit:

- Deflection level (absolute or relative) in a point of the structure,
- Stress level in an element (σ_x, σ_y and $\sigma_c = \sigma_{von\ Mises}$),
- Safety level related to buckling, ultimate resistance, tripping, etc. (Example: $\sigma / \sigma_{ult} \leq 0.5$).

For each constraint, or solid-mechanics phenomenon, the selected behavior model is especially important since this model fixes the quality of the constraint modeling.

These behavior models can be so complex that it is no longer possible to explicitly express the relation between the parameters being studied (stress, displacement, etc.) and the design variables (XI). This happens when one uses mathematical models (FEM, LBR-4, etc.). In this case, one generally uses a numeric process that consists of replacing the implicit function by an explicit "approximated function" adjusted in the vicinity of the initial values of the design variables (for instance using the Taylor series expansions). This way, the optimization process becomes an iterative analysis based on a succession of local approximations of the behavior models.

The list of constraints included in the LBR-5 model is intimately bound to the types of structures targeted by this research. Let's recall that these are mainly metallic, prismatic (box girders) and stiffened (orthotropic) structures used for hydraulic and marine structures.

These structures are composed of stiffened panels that are either cylindrical or plane. The panels are joined one to another by generating lines (edges of the prismatic structure) and are stiffened longitudinally and transversely (Figs. II.1 and 2).

- Stiffened longitudinally:
  - by stiffeners,

  and/or
  - by crossbars and girders, prompt elements of strong rigidity.
- Stiffened transversely:
  - by transverse bulkheads, (Fig. II.1a).

  and/or
  - by the main transverse framing, (Fig. II.1b).

  and/or
  - by secondary or local transverse stiffeners, (Fig. II.1c).

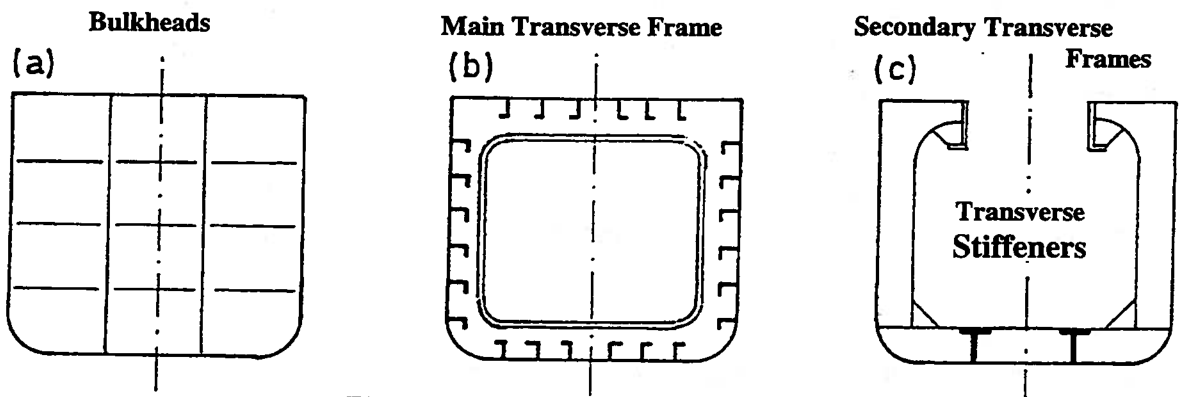


Fig. II.1. Types of transverse framing.

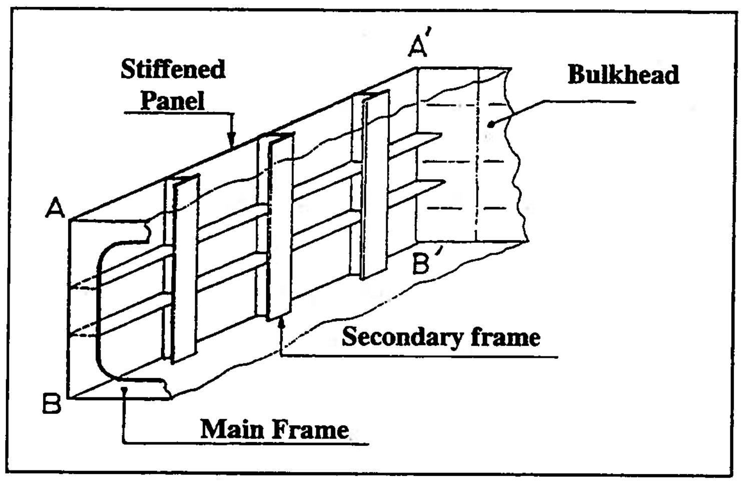


Fig. II.2: A stiffened panel.

When going from the "local" to the "general" (Fig. II.2), one differentiates three types of constraints:

- constraints on panels and components,
- constraints on frames and transversal stiffening,
- constraints on the global structure.

- Constraints on stiffened panels (Fig. II.2).

Panels are limited by their lateral edges (junctions with other panels, AA" and BB") either by watertight bulkheads or transverse frames. These panels are orthotropic plates and shells supported on their four sides, laterally loaded (bending) and submitted, at their extremities, to in-plane loads (compression/tensile and shearing).

Global buckling of panels (including the local transverse frames) must also be considered.

Panel supports, in particular those corresponding to the reinforced frames, are assumed infinitely rigid. This means that they can distort themselves significantly only after the stiffened panel collapse.

- Constraints on the transverse frames (Figs. II.1 and 2)

The frames take the lateral loads (pressure, dead weight, etc.) and are therefore submitted to combined loads (large bending and compression). The rigidity of these frames must be assured in order to respect the hypotheses on panel boundary conditions (undeformable supports).

- Constraints on the global structure (box girder/hull girder) (Figure II.3).

The ultimate strength of the global structure or a section (block) located between two rigid frames (or bulkheads) must be considered as well as the elastic bending moment of the hull girder (against yielding).

The limit states that will be considered are:

- A *service limit state* that corresponds to a situation where the structure can no longer assure the service for which it was conceived (examples: excessive deflection cracks).
- An *ultimate limit state* that corresponds to collapse/failure.

It is important to differentiate *service limit states* to *ultimate limit states* because safety factors associated to these two limit states are generally different.

Ultimate Limit States

For a structure submitted to a global bending moment, the ultimate limit state is usually symbolised by point C of the moment-curvature curve (M-Φ) shown at Fig. II.3. The ultimate state is reached when the structure can no longer support a complementary increase in the bending moment without "collapsing" completely (point D).

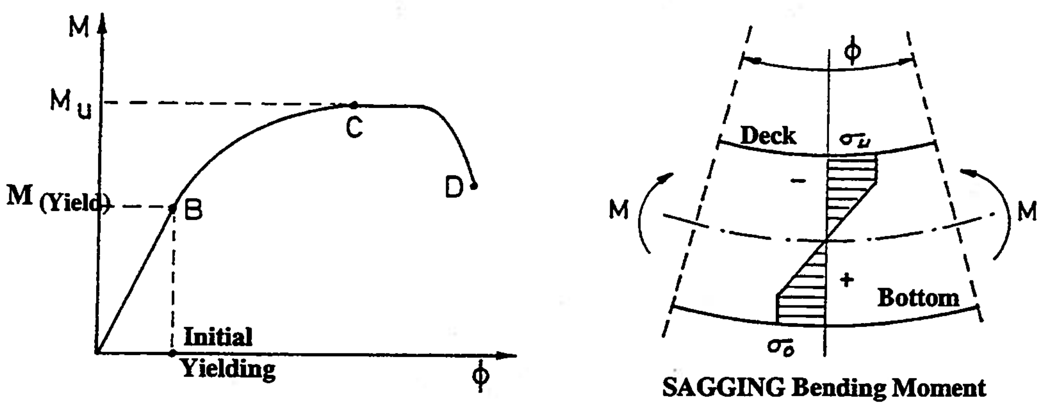


Fig. II.3. The moment-curvature curve (M-Φ).

M_u is therefore the ultimate bending moment of the global structure. Its computation depends closely on the ultimate strength of this structure's constituent panels, and particularly on the ultimate strength in compression of these panels or components [63]. Fig. II.3 shows that in "sagging", the deck is compressed (σ_{deck}) and reaches the ultimate limit state when $\sigma_{deck} = \sigma_u$. On the other hand, the bottom is in tensile and reaches its ultimate limit state after complete yielding, $\sigma_{bottom} = \sigma_o$ (σ_o being the yield stress).

In conclusion, to determine the global ultimate bending moment (M_u), one must know in advance both the ultimate strength in compression of each panel (σ_u) and the average stress-average strain relationship ($\sigma-\varepsilon$) in order to perform a progressive collapse analysis.

Fig. II.4 presents the different structure levels: the global structure or general structure (level 1), the orthotropic stiffened panel (level 2) and the interframe longitudinally stiffened panel and its simplified modeling: the beam-column (level 3 and 3bis).

The relations between the different limit states and structure levels can be summarized as follows:

➡ Level 1:

Ultimate bending moment of the global structure: M_u

➡ Level 2:

Ultimate strength of compressed orthotropic stiffened panels (σ_u).

σ_u = min [σ_u (mode i), i = a, b, c and d, the 4 considered failure modes]

➡ Level 3:

Mode a: Global buckling.

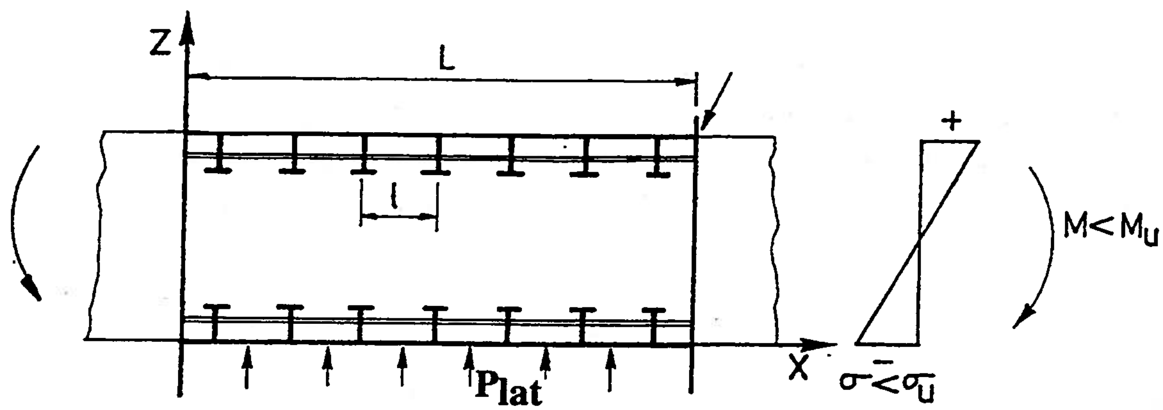
Mode b: P_{ult} of interframe panels:

Beam-column models or orthotropic models considering:

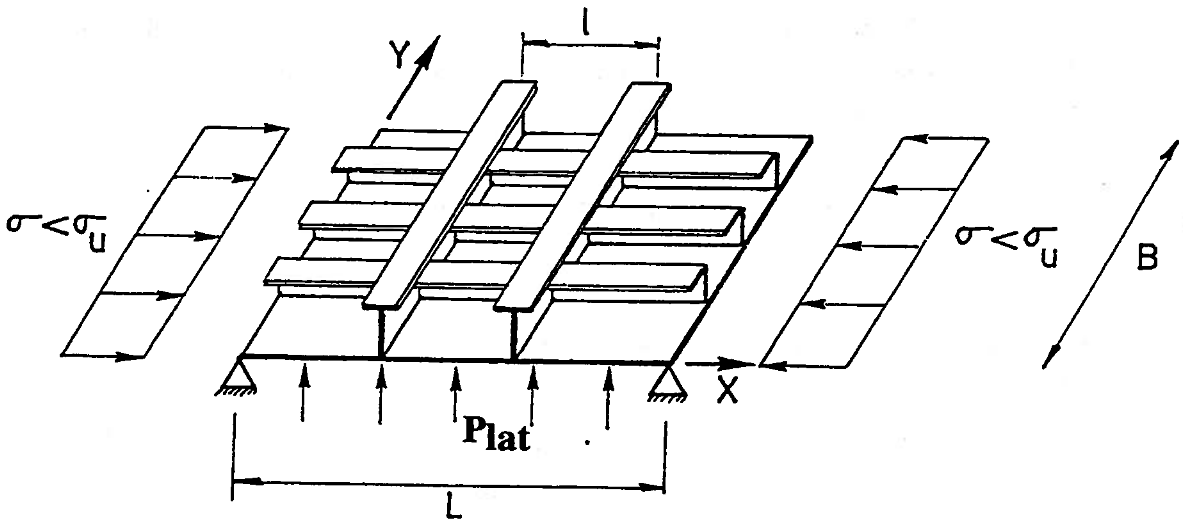
- plate induced failure (buckling),
- stiffener induced failure (buckling or yielding).

Mode c: Instability of stiffeners (local buckling, tripping, etc.).

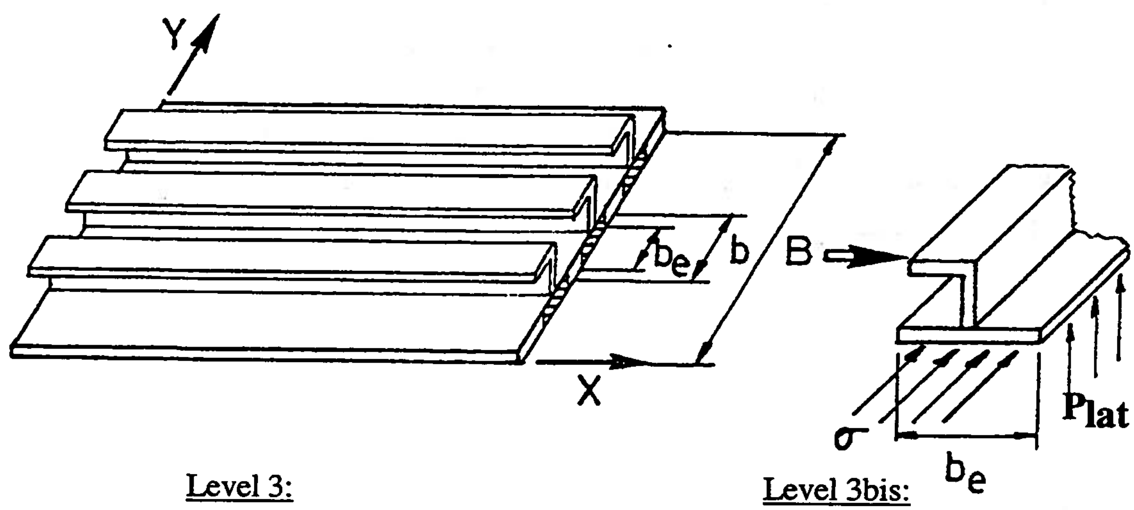
Mode d: Yielding.



Level 1: Global structure (or part of the structure between 2 bulkheads)



Level 2: The whole panel (stiffened/orthotropic panel)



Level 3:
Interframe panel:
between 2 frames or 2 transverse stiffeners

Level 3bis:
The simplified
beam-column model

Fig. II.4. Structural modeling of the structure and its components.

To avoid constraints related to the “a” mode, one generally imposes a minimal rigidity for the transverse frames so that an interframe panel collapse (mode b) always appears before global buckling (mode a). It is a "simple" and "easy" constraint to implement, thus avoiding any complex calculation of global buckling (mode a).

Let's note that the “b” failure mode is influenced by the buckling strength of the unstiffened plate (elementary unstiffened plate). This limit state is usually not considered as the ultimate limit state, but rather as a service limit state.

In the LBR-5 model, all the available constraints are classified as follows:

1. Stiffened panels constraints:

   Service limit states

   1.1. Upper and lower bounds (Xmin ≤ X ≤ Xmax): plate thickness, dimensions of longitudinals and transverse stiffeners (web, flange and spacing*)*.
   1.2. Maximum allowable stresses against yielding.
   1.3. Panel deflection (local deflection).
   1.4. Buckling of unstiffened plates situated between two longitudinals and two transverse stiffeners (frames/bulkheads)
   1.5. Local buckling of longitudinal stiffeners (web and flange).

   Ultimate limit States

   1.6. General buckling of orthotropic panels (global stiffened panels).
   1.7. Ultimate strength of interframe longitudinally stiffened panel.
   1.8. Torsional-flexural buckling of stiffeners (tripping).

2. Frames constraints.

   Service limit states

   2.1. Upper and lower bounds (Xmin ≤ X ≤ Xmax)
   2.2. Minimal rigidity to guarantee rigid supports to the interframe panels (between 2 transverse frames).
   2.3. Allowable stresses under the combined loads (M, N, T),
      - Elastic analysis,
      - Elasto-plastic analysis.

Ultimate limit states

2.4. Frame buckling,
   - Buckling of the compressed members,
   - Local buckling (web, flange).

N.B.: These limit states are considered as ultimate limit states rather than a service limit state. If one of them appears, the assumption of rigid supports is no longer verified and collapse of the global stiffened panels can occur.

3. General constraints

Service limit states

3.1. Allowable stresses,
3.2. General deflection of the global structure and relative deflections of components and panels.

Ultimate limit states

3.3. Global ultimate strength (of the hull girder/box girder) between 2 frames or bulkheads.

NB: Collapse of frames is assumed to only appear after the collapse of panels located between these frames. This means that it is sufficient to verify the box girder ultimate strength between two frames to be protected against a more general collapse including, for instance, one or more frame spans.

As a relevant comparative reference, Table 1 shows the limit states selected by the "Ship Structure Committee (SSC n° 375 of 1994) [Hughes 1994]". For each limit state, the third column of this table makes references to a rational approach selected by O. Hughes to impose constraints (ultimate or service). As a comparison with the proposals achieved in the SSD (Ship Structural Design, [Hughes 1988]), Table II.1 also contains the constraint list selected for the LBR-5 model. Although different in several aspects (principles and methods), the two classifications perfectly match and exclude any collapse associated with a limit state not considered.

Failure Modes of Principal Members	Failure Category	Computational Algorithm Source (SSD = Ship Structural Design) [Hughes 1988]	Reference to available constraints in LBR-5
<u>GLOBAL STRUCTURE</u> : (Box girder/hull girder) Ultimate Strength	Collapse	SSD Sec. 17-1	3.3
PANEL	(with	Longitudinal members)	
Collapse			
Stiffener Flexure	Collapse	SSD Sec. 14.2	1.7
Combined Buckling	Collapse	SSD Sec. 13.2 - 13.4	1.7
Membrane Yield	Collapse	SSD Sec. 12.5	1.2 + 3.1
Stiffener Buckling	Collapse	SSD Sec. 13.1 & 15.5	1.5 + 1.8
Stiffener Unseviceability			
(Initial Yield)			
Tension, Flange			
Tension, Plate	Yield	Beam Theory & SSD Sec. 8.6	1.2
Compression, Flange	Yield	"	"
Compression, Plate	Yield	"	"
Plate Unserviceability	Yield	"	"
Yield, plate bending			
Local buckling	Yield	SSD Sec. 9.1 & 9.2	1.2 + 3.1
Allowable Permanent Set	Unserv.	SSD Sec. 12.6	1.4
	Yield	SSD Sec. 9.3 - 9.5	1.3 (a) + 3.2
BEAM	(Transverse	Members & frames)	
Collapse			
Tripping	Collapse	SSD Sec. 13.1	2.4
Flexural-Torsional Buckling	Collapse	SSD Sec. 15.4 & 15.5	2.4
Plastic Hinge	Collapse	SSD Sec. 16.1 & 16.2	2.3 (b)
Unserviceability (Initial Yield)			
Bending	Yield	Beam Theory	2.3
Web shear	Yield	" "	2.3
<u>GRILLAGE</u>	(Orthotropic	stiffened panels)	
Collapse			
Overall Buckling	Collapse	SSD Sec. 10.2 & 13.5,6	1.6 + 2.2
Plastic Hinge	Collapse	SSD Sec. 16.1 - 16.4	3.1 (b)

(a) A constraint on the relative elastic deflection is proposed.
(b) The considered limit state relates to the initial yielding and to ultimate strength

<u>Table II.1:</u> Identification of the collapse modes selected for the main components of the structure [Hughes 1994].

PART III: THE COST MODULE – Objective Function -

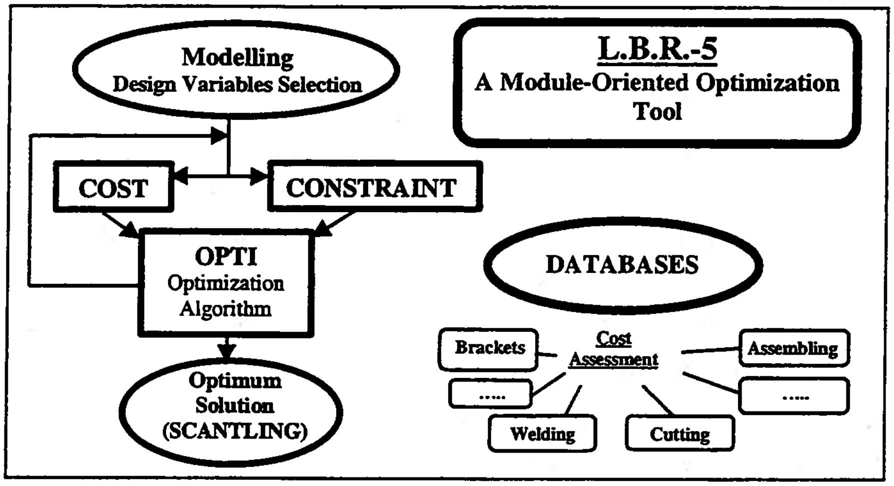


Figure III.1 - Basic configuration of the LBR-5 model and the COST module.

Global construction costs can be subdivided into three categories:

- Cost of raw materials,
- Labor Costs,
- Overhead Costs.

Cost of raw materials

The evaluation of material costs consists in quantifying volumes required for construction and obtaining prices from suppliers and subcontractors.

This task is a priori simple, but includes numerous uncertainties and inaccuracies result in the following impacts:

- Accuracy for quantities improves with the time and project progress. Note that a posteriori, accuracy is often appropriately assessed.
- Any inaccuracy in requirement lists provided to suppliers involves cost overestimation, which results in higher uncertainty for the global evaluation. This is especially true for electric and mechanical features as well as for the propulsion system.
- Scrap parts constitute an important unknown, especially at the beginning of a project. A classic evaluation is 5 to 10%, but the percentage can be higher, depending on the zone studied (aft and fore, machinery area) and the selected design details (bracket shape, slot type, etc.).

Labor Costs

The best alternative to using empirical formulations to evaluate labor costs is analytic evaluation. Such an approach requires knowing the work time required for each standard labor task associated with a workstation as well as the subdivision by stations of the entire construction process. All operations should be included.

The keys to a reliable evaluation of labor costs are as follows:

- Split the entire construction into the different manufacturing tasks and quantify the work to be performed for each task. For example: cutting lengths should be classified according to plate thickness, welding length according to welding systems: manual, semiautomatic, automatic,.... For such an analysis, the evaluator must be perfectly familiar with production unit habits and potentialities. If possible, discussions should be held in advance with those responsible for scheduling and the supervisors.
- Obtain a reliable productivity evaluation (quantified in "man-hours") for each workstation. As this assessment is also required for production scheduling, a productivity evaluation seems, a priori, obvious. Unfortunately, experience shows that uncertainties are the highest. Here a double evaluation could be anticipated, first at the level of the evaluator in order to make the offer and then, some months later, at the scheduling level. But, sometimes, there is no agreement between these two evaluations. If a search for the least cost structural optimum takes place, it is imperative that evaluations done at the early design stage reflect production realities.

Overhead Costs

Overhead includes expenses that cannot be attributed to work stations of the construction process, but that are, however, linked to construction. It is necessary to distinguish between variable costs and fixed costs.

- By variable costs, we mean expenses that vary with production labor such as fringe benefits, workman's insurance, product insurance and fluids (water, electricity, gas, heating),...
- The fixed costs are loads incumbent to the yard, but that are independent of production level. They include maintenance of the production plan, rent, staff members, accounting, secretariat, etc.

Analytic evaluation of manufacturing costs

The real construction cost of a structure can be expressed by:

$$\begin{aligned}\text{Total Cost} \quad = \quad & \text{Material costs} \\ & + \text{Labor Costs} \\ & + \text{Overhead Costs} \qquad [1]\end{aligned}$$

$$\mathbf{TC} = \mathbf{MatC} + \mathbf{LabC} + \mathbf{OvC}$$

The purpose of this analysis is essentially to allow a relative and objective comparison, on basis of cost, of the successive designs resulting from the optimization process. So, the absolute cost is not needed and only the two first terms of Eq.1 are significant. The overhead cost (**OvC**), though far from negligible, can be ignored by the analytic cost model. This means that the considered cost in this analysis will be:

$$\mathbf{TC} = \quad \mathbf{MatC} \quad + \quad \mathbf{LabC} \qquad [2]$$

$$= \sum_{j=1}^{K} \underset{\text{Number of units}}{Qj} \;.\; \underset{\text{Euro/unit}}{Pj} \;+\; \sum_{i=1}^{NT} \underset{\text{Man-hours per task}}{Ti} \;.\; \underset{\text{Task frequency}}{Mi} \;.\; \underset{\text{Euro/m-h}}{Si}$$

j = a given material (For instance: 1 ton of steel plate, 1-m long of angle bar of 60x60x5,...),
K = number of different materials, j=1,K,
Qj = expected quantity of the j material,
Pj = unit price of the j material (Euro/unit),
NT= number of different standard tasks,
i = reference number of a task, i=1,NT,
Ti = required working load for the i standard task (man-hours),
Mi = number of times that the Ti task happens (frequency),
Si = hourly cost of labor (Euro/man-hour) of a person doing the i standard task.

Even if Eq.2 faithfully represents total manufacturing costs, it does not show the diversity and the multitude of materials, and especially the multitude of elementary standard tasks included in the global manufacturing process. Thus, the difficulty does not reside in equation calculation (Eq.2), but rather in the identification and subdivision of tasks into sub-tasks and, finally, into elementary standard tasks. An elementary standard task is defined as a task that cannot be subdivided further.

Eq.2 is therefore a condensed equation of a more general one in which the description of tasks, sub-tasks and the elementary tasks explicitly appears, that is (Eq.3):

$$LabC = \left(\sum_{i1=1}^{NT1} Mi1 . \left[\sum_{i2=1}^{NT2} Mi2 \left[.... \left[\sum_{ik=1}^{NTk} Mik \left[.... \left(\sum_{in=1}^{NTn} Min . Tin . Sin \right) \right] \right] \right] \right] \right) \qquad [3]$$

where k is the hierarchical level of the task,
k = 1 superior level (block),
k = 2,3,..., intermediate levels (panels,...),
k = n elementary level.

Thus, the of 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 (Figure III.2). Several blocks can be identical (M_{i1} = 1,2,3...);
- 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 than one does not choose to divide further);
- to define the hourly unit cost (S_i) of each "i" elementary task, (i = 1 to NTn).

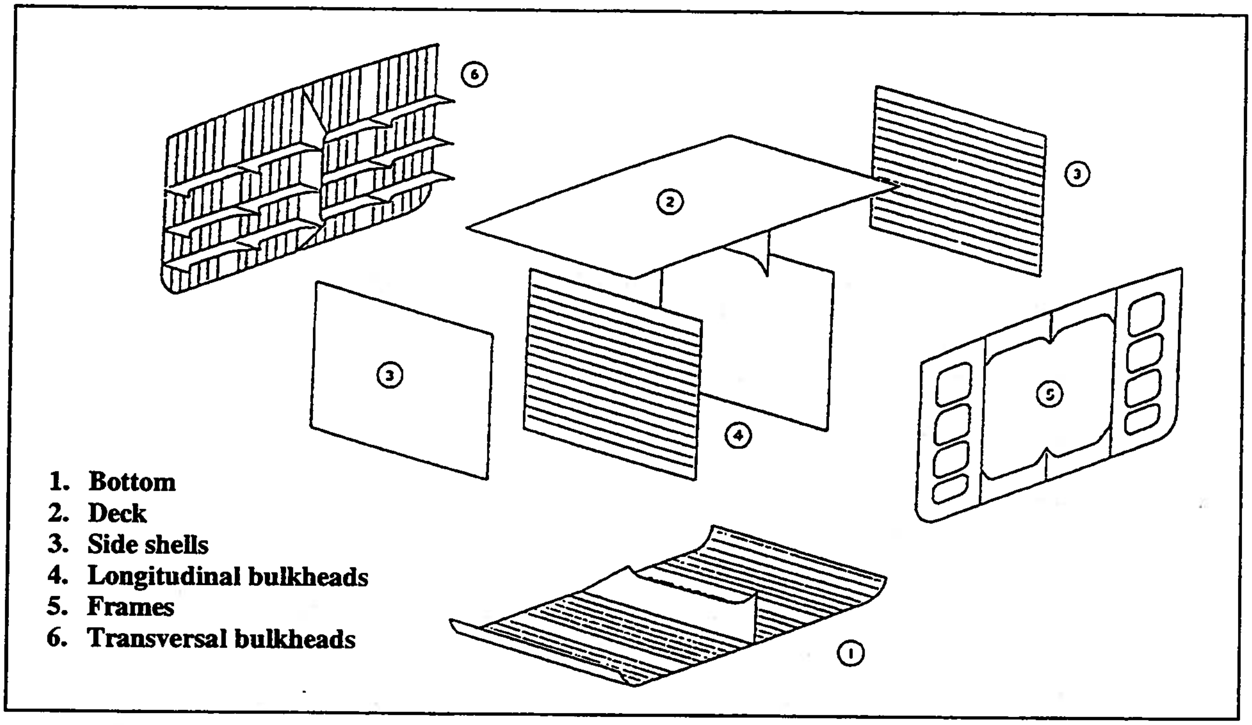


Figure III.2- Subdivision of a block into elements (Buxton 1966)

Normalized cost

Moe and Lund [1968] introduced the "Cost Equivalent Relative Weight (CERW)":

TC = Total Cost (Euro)

TC = [Unitary Mat. Cost] . [Weight] + [Unitary Lab. Cost] . [Working Load]

(Euro/ton) (tons) (Euro/manhour) (Manhours)

$$CERW = \frac{TC}{Q} = \underset{(t)}{P} + \underset{(t/_{m-h})}{k} \cdot \underset{(m-h)}{(T.M)} \quad \text{(tons)} \qquad [4]$$

$$\text{with} \quad k = \frac{S}{Q} = \frac{\text{Unitairy Lab. Cost (Euro/m-h)}}{\text{Unitairy Mat. Cost (Euro/ton)}} \quad (t/_{m\text{-}h}) \qquad [5]$$

This equivalent weight allows an easy evaluation of the total cost for a series of material unit prices (Q) and labor (S), thus permitting a comparison between countries where the k coefficient varies. For Western countries, the k coefficient varies between 0.03 and 0.10 t/man-hour.

In spite of what the k coefficient units (t/m-h) could lead us to believe the k coefficient is absolutely not linked to productivity, but only to the cost of living.

For this reason, as Mac Callum and Mac Gregor [Winkle and Baird 1986] suggest, it is recommended to introduce a coefficient η that permits taking into account production site productivity. The expression of the equivalent weight becomes:

$$TC = [\text{Unitary Mat. Cost}] \,.\, [\text{EQP}] \quad (\text{Euro}) \tag{6}$$

with

EQP = Mat. Weight + η. k. WLoad (tons)

η = an efficiency parameter to characterize the production yard ($\eta = 1$ for the reference yard)

Wload = the global working load (man-hours)

Modeling of the objective functions used by the LBR-5 model

Here are presented the two basic objective functions used by the LBR-5 model:

- a weight objective function,
- a cost objective function.

Weight Objective Function

The weight objective function can be easily defined as an explicit function of the design variables (plate thickness (δ), spacing (Δ_x, Δ_y) and dimensions of the longitudinal and frame cross sections (h,d,w,t). Thus, Fp, the weight objective function can be written for an orthotropic stiffened panel as:

$$Fp = \gamma . L . B . \left[\delta + \frac{(h.d + w.t)_X}{\Delta_X} + \frac{(h.d + w.t)_Y}{\Delta_Y} \right] \tag{7}$$

where

L = length of the panel according to the X co-ordinate (m),

B = breadth of the panel according to the Y co-ordinate (m),

δ = plate thickness (m),

γ = specific weight (N/m^3),

$(h,d,w,t)_X$ = dimensions of web and flange of the longitudinals (stiffeners) fitted along X,

$(h,d,w,t)_Y$ = dimensions of web and flange of the transverse frames fitted along Y,

Δ_X= spacing between two longitudinals (stiffeners) fitted along X,

Δ_Y= spacing between two transverse frames fitted along Y, Use of the weight objective function is particularly simple and easy because it requires no additional parameters, and is therefore particularly adapted to perform comparative and academic analyses. For industrial applications, it is, however, desirable to replace it by a cost objective function.

Cost Objective Function – "COST MODEL"

Theoretically, the cost model should be established in close relation to the specified production plan. Unfortunately, it doesn't seem possible to define a general model, valid in all situations. 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 model (COST MODEL), currently used in the LBR-5 model, includes three components (Eq.8):

$$FC = F_{MAT} + F_{CONS} + F_{LAB} \quad \text{(in Euros)} \qquad [8]$$

where

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

a) Cost of materials: F_{MAT}

The cost of materials is directly derived from the weight function (Eq.7). Each term of Eq.7 should be multiplied by the relevant C_i unitary material cost (plate, bar,...). Thus, from Eq.7, one gets:

$$F_{MAT} = \gamma . L . B . \begin{bmatrix} C_1 . \delta \\ + C_2 . \dfrac{(h.d + w.t)_X}{\Delta_X} \\ + C_3 . \dfrac{(h.d + w.t)_Y}{\Delta_Y} \end{bmatrix} \quad \text{(Euro)} \qquad [9]$$

where

C1 = cost per kg of a plate δ mm thick,

C2 = cost per kg of the longitudinals/stiffeners,

C3 = cost per kg of the transverse frames.

In order to take into account a possible variation of the price per kg of the plates according to their thickness, the parameter C1 is defined as follows:

$$C_1 = C_1^o \left[1 + \Delta C_1 \left(\delta - E_0\right) \ 10^3\right] \text{ (Euro/kg)} \qquad [10]$$

where

C1°	= cost per kg of a plate with a thickness δ = Eo,
Eo	= reference thickness (of the plate), to be defined by the user (in m),
DC1	= change in % of C1° (cost/kg) between plates of Eo and Eo +1 mm thick.

In order to take into account the difference between the price of plates and the price of standard profiled members [IPE, HEA,...], the C2 and C3 coefficients are defined as:

$$C_2 = C_1^o \left[1 + \alpha_X . \Delta_{C_2}\right] \quad \text{(Euro/kg)} \qquad [11.a]$$

for longitudinals/stiffeners, girders and cross-bars

$$C_3 = C_1^o \left[1 + \alpha_Y . \Delta_{C_3}\right] \quad \text{(Euro/kg)} \qquad [11.b]$$

for frames and transversal stiffeners.

where

α_X, α_Y =0,	if the members are manufactured on the yard from standard plates. In this case, the welding costs are considered separately (see the P4 and P5 coefficients);
α_X, α_Y =1,	if the members are standard members [IPE, HEA,...];
ΔC2, ΔC3 =	change in % of the cost/kg of the longitudinals and the frames by comparison to the unitary cost of the reference plate (C1°), (ΔC2, ΔC3 > 0 or <0).

$$WLoad = L.B \begin{bmatrix} \frac{1}{\Delta_X}.P_4 + \frac{1}{\Delta_Y}.P_5 \\ + \frac{1}{\Delta_X.\Delta_Y}(P_6 + \beta_X.\beta_Y.P_7) \\ + \frac{1-\alpha_X}{\Delta_X}.P_9(X) + \frac{1-\alpha_Y}{\Delta_Y}.P_9(Y) \\ + P_{10} \end{bmatrix} \quad [15]$$

where:

P4 = working load to weld 1 meter of a longitudinal stiffener on the plating (side shell,...) (m-h/m)
= 0.6 to 1.2 m-h/m;

P5 = working load to weld 1 meter of a transversal stiffener on the plating (m-h/m)
= 0.6 to 1.2 m-h/m;

P6 = working load to cut a slot to allow the intersection between a longitudinal and a transversal and to join these members (m-h/intersection).
= 0.2 to 0.6 m-h/intersection;

P7 = working load to fix bracket(s) at the intersection between a longitudinal and a transversal (m-h/intersection).
= 0.3 to 1.2 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);

P9 = working load to build 1 meter of stiffener (assembling flange and web) from standard plates in the production plan (m-h/m). Note: If α_X and α_Y = 1 (Eq.11), P9 is not required;

P10 = working load to prepare 1 m^2 of plating (m-h/m^2). Generally this working load is linked to plate thickness and the ratio of the half-perimeter of the available plates (a.b) on its surface [(a+b)/(a.b)].
= 0.3 to 1.5 (m-h/m^2).

These working loads are defined as follows:

$$P_4 = P_4^o \left[1 + (d_X - E_o).10^3.\Delta P_4\right] \quad [16]$$

$$P_5 = P_5^o \left[1 + (d_Y - E_o).10^3.\Delta P_5\right]$$

$$P_9(X) = P_9^o \left[1 + (d_X - E_o).10^3.\Delta P_9\right]$$

$$P_9(Y) = P_9^o \left[1 + (d_Y - E_o).10^3.\Delta P_9\right]$$

where:

d_X, d_Y = web thickness for stiffeners along X and Y;

P_4^o, P_5^o and P_9^o = P4, P5, P9 working loads for the Eo reference plate thickness (m-h/m)
= 0.6 to 1.2 m-h/m;

ΔP_4, ΔP_5, ΔP_9 = change (in %), by mm of d, of P_4^o, P_5^o and P_9^o working loads.

$$P_{10} = P_{10}^o \left[1 + (\delta - E_o).10^3 . \Delta P_{10}\right] \quad [17]$$

where:

δ = plate thickness;

P_{10}^o = working load to prepare 1 m^2 of plating having the Eo reference thickness (m-h/m^2).

ΔP_{10}= change (in %), per mm of δ, of the P_{10}^o working load.

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 [Winkle and Baird, 1986; Rahman and Caldwell, 1992]. Unfortunately, nothing seems available in books and papers to determine reliable sensitivity of these working loads according to plate thickness (ΔP_4, ΔP_5, ΔP_9 and ΔP_{10}) is more difficult to establish. Nevertheless, with the WELDCOST program, it was possible to quantify the order of magnitude of these parameters by evaluating working loads related to welding with high accuracy (Fig. III.4).

PART IV LEAST COST OPTIMIZATION OF A FLOATING STORAGE OFFLOADING UNIT (FSO)

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 (Figs. IV.1 and 2). 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. The main characteristics of the barge are given on Table IV.1.

Lpp (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 (block coefficient)	0.95
Light Weight (Hull + propulsion devices)	32,740 t
Number of crude oil tanks	12 x 33,782 m^3
Unit length of crude oil tanks	46 m
Unit breadth of crude oil tanks	24 m
Unit volume of crude oil tanks	405,389 m^3
Number of barrels (bbl)	2,549,819 bbl (1 bbl = 0.1589873 m^3)
Crude oil density	0.93 t/m^3 (9.3 kN/m^3)
Water ballast : side hull	59,600 m^3
Water ballast : aft deep-tanks	9,500 m^3
Water ballast : fore deep-tanks	20,000 m^3
Tanks (fresh water and diesel-oil)	1000 m^3 et 2000 m^3
Pumps	4 x 1800m^3/h and 977 kW
Total installed Power	8880 kW
Thrusters (transversal thrust only)	2 x 2500 kW et 300 kN/unit
Accommodation	50 persons

Table IV.1. Main characteristics of the FSO barge

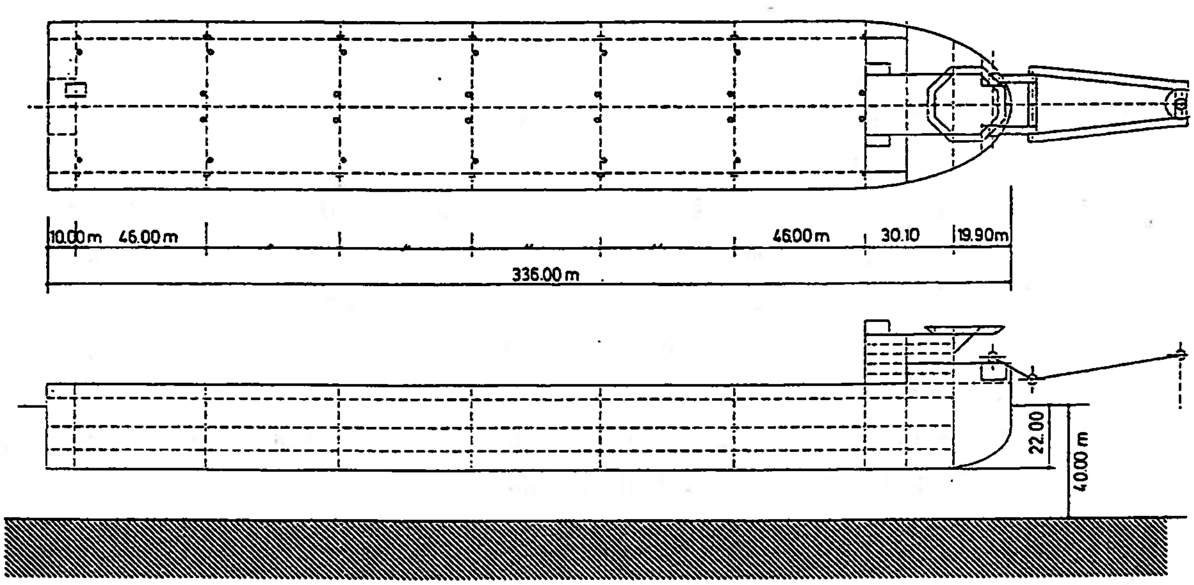


Fig. IV.1. General view of the FSO barge

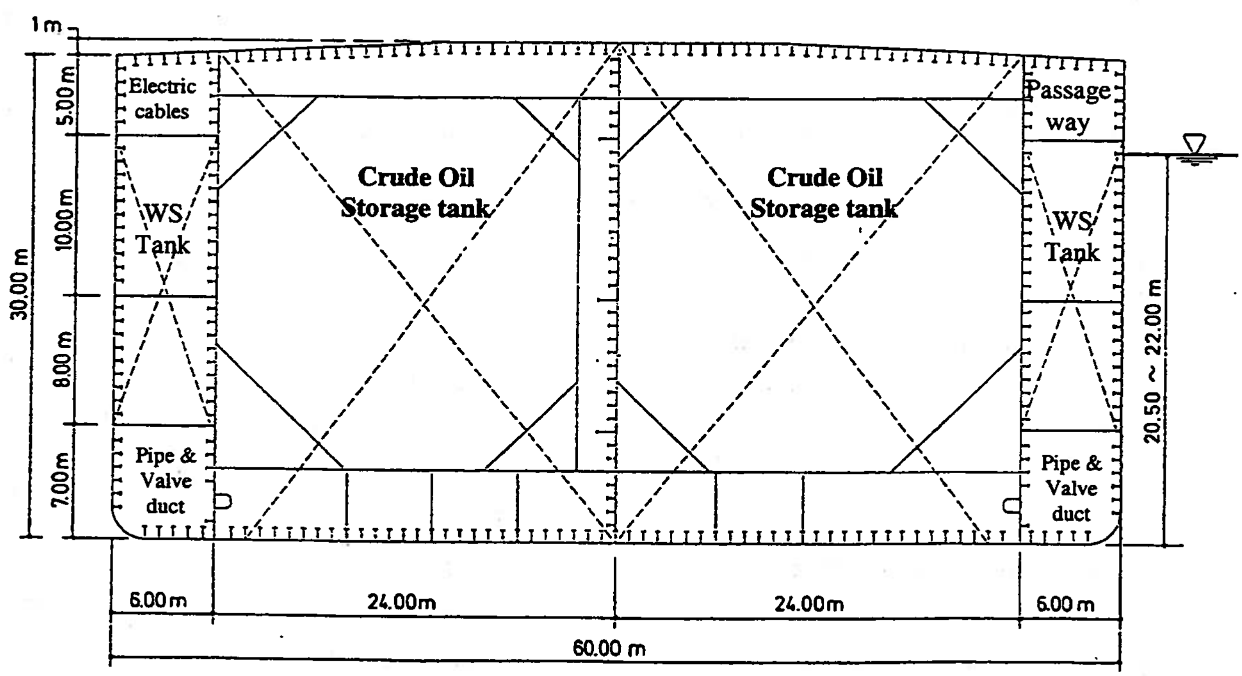


Fig. IV.2. Midship section of the FSO barge

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. IV.3 and the modeling is shown on Fig. IV.4. 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 670,000 t-m (6.57

10^6 kN-m) and the shear force at 25,000 t (245,200 kN). This bending moment is particularly high by comparison to standard VLCC bending moment (±3 Mio kN.m). 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).

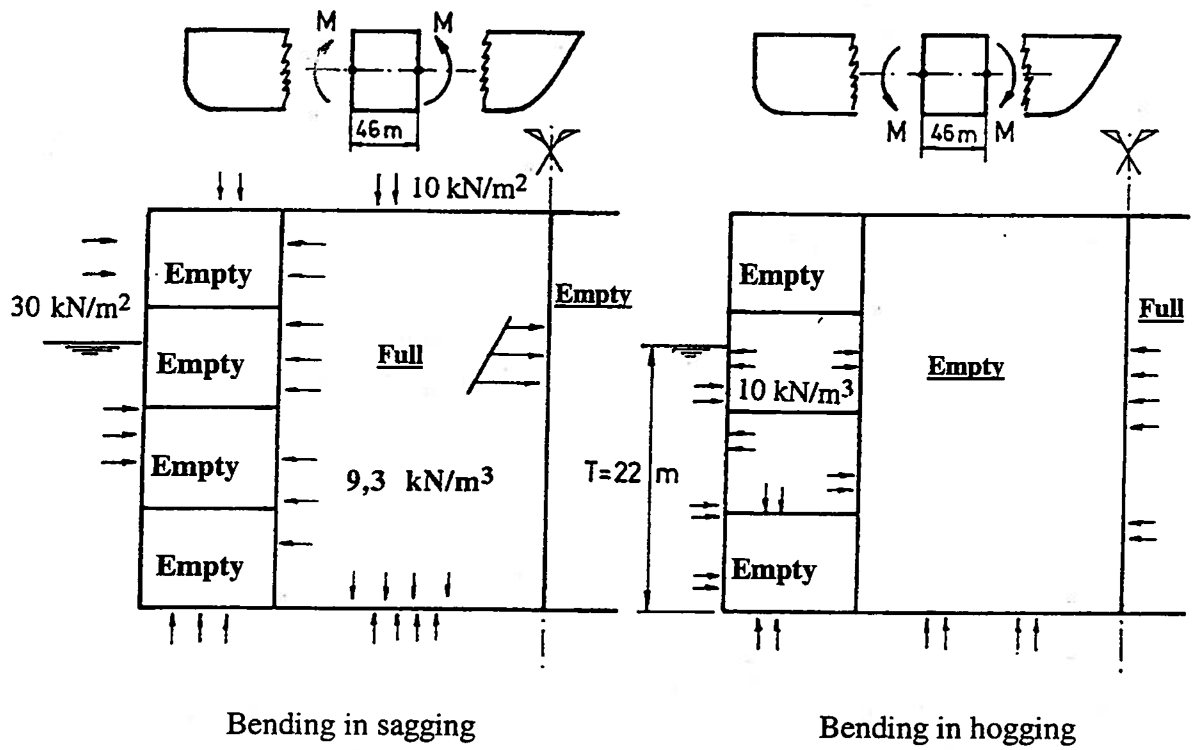


Fig. IV.3. Considered loading cases.

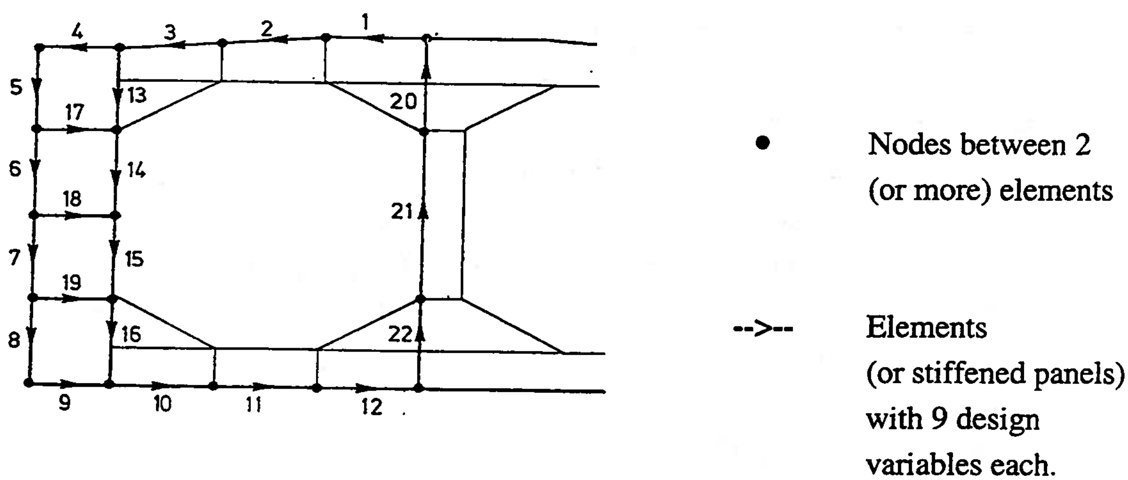


Fig. IV.4. Mesh Modeling used for LBR-5 for the FSO Midship Section.

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.

Optimum costs are calculated using the following cost and productivity data:

- Reference plate thickness: 10 mm
- Unitary Labor Cost (Euro/m-h)/Material Cost (Euro/t): $k = 0.08$
- Unitary price of steel: $C1 = 0.57$ Euro/kg , $\Delta C1 = -0.6\%$ (if AE235)
  $C1 = 0.65$ Euro/kg, $\Delta C1 = -0.6\%$ (if AE355)
- Price of welding (materials only): $C8 = 1.00$ Euro/m , $\Delta C8 = 15\%$
- Manpower:
  - plate: $P10 = 0.5$ m-h/m^2 , $\Delta P10 = 7\%$
  - frames (assembling with plate) : $P4 = P5 = 1$ m-h/m, $\Delta P4 = \Delta P5 = 10\%$
  - frames (if built on site): $P9 = 0.5$ m-h/m, $\Delta P9 = 1\%$

The mesh model of the FSO unit includes:

- 22 stiffened panels with 9 design variables each;
- 2 additional panels to simulate the symmetry axis (or boundary conditions);
- 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 junction – web/flange junction and flange),
    σ_c stiffener (web/plate – web/flange and flange) and σ_c plate,
    which should verified that $\sigma_c \le s.\sigma_o$ (with $s = 0.65$ and $\sigma_o = 355$ N/mm^2);
  - local plate buckling: $\delta_{MIN} \le \delta$ (with δ_{MIN} the minimum plate thickness to avoid buckling);
  - ultimate strength of stiffened panel: $\sigma / \sigma_{ULT} \le s$ with $s = 0.55$;
- 2 constraints on the ultimate hull girder/box girder strength: $M/M_{ULT} \le s$ ($s = 0.55$).

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 (except in panels 13, 16, 18)
8.0 mm	≤	Web thickness	≤	30.0 mm (or 40 mm)
..... etc.				

Since the first results showed the importance of the "$\delta \leq 40$ *mm*" side constraints, a second analysis was performed, imposing $\delta \leq 30$ 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:

Δc (side tanks) = Δc (center tanks) / α with α an integer number lower than 3 ($\alpha \leq 3$).

Table 1 compares optima for six different configurations (C1 to C6):

- Optimum for δ (plating) ≤ 40 mm
  - Least cost: C1: Δ_{FRAMES} (side tanks) = Δ_{FRAMES} (center tanks)
    C2: Δ_{FRAMES} (side tanks) = ½ Δ_{FRAMES} (center tanks)
  - Least weight: C3: Δ_{FRAMES} (side tanks) = Δ_{FRAMES} (center tanks)
    C4: Δ_{FRAMES} (side tanks) = ½ Δ_{FRAMES} (center tanks)
- Optimum for δ (plating) ≤ 30 mm
  - Least cost: C5: Δ_{FRAMES} (side tanks) = Δ_{FRAMES} (center tanks)
  - Least weight: C6: Δ_{FRAMES} (side tanks) = Δ_{FRAMES} (center tanks)

Note that costs and weights refer to a half-structure (30-m wide) and that stiffening and bracketing (transverse members, webs, etc.) are not included in the weight.

Detailed optimal scantlings are presented in Figs. IV.5a-5b, Figs. IV.6a-6b and Figs. 10a-10b for, respectively, $\delta \leq 40$ mm (least cost), $\delta \leq 40$ mm (least weight) and $\delta \leq 30$ mm (least cost). The "raw" scantlings presented in these figures are not "*ready to use*". They require minor changes such as rounded brackets in the corners, slow variation of the web height, etc. So, to establish execution plans and for practical and constructive reasons, greater standardization is advisable (examples: uniform thickness for the deck plate, side shell and bottom plate, uniform frame height, etc.).

Such standardization could have been selected as requirements for the optimization process, but were not intentionally, in order to amplify optimization process potentialities and to better differentiate optimum weight and optimum cost.

Analysis of the comparative table and of the scantling shows that (see Table IV.2):

- The maximal plate thickness (30 mm or 40 mm) is an active constraint that strongly conditions the optimum (active constraints). Thus, there is more than a 30% increase in weight and cost when selected ($\delta \leq 30$ mm) as a side constraint.
- If one selects $\delta \leq 40$ 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 (that is, the space of the design variables) is so reduced that the optimum cost and weight are nearly identical.
- Optimization of the frame scantling in the large tanks generally involves tall webs at mid span (large bending moment) and thick webs near their extremities (important shear forces).
- Doubling the number of frames in the side tanks ($\Delta_{\text{side tanks}} = 0.5\ \Delta_{\text{center tanks}}$) 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 $\delta \leq 40$ mm and 18% for $\delta \leq 30$ mm. On the other hand, for weight, the least cost scantlings lead to feasible structures: weights in the least cost solution are only 1 or 2% higher than in the least weight one. 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
- Concerning the cost per kilo or unitary cost (Euro/kg), least cost optimization leads to unitary costs 10 to 15% lower than for least weight optimization (2.17 Euro/kg instead of 2.42 Euro/kg).

Table 3 gives an example of the convergence process observed at the time of optimization of this FSO barge. This analysis concerns a least weight optimization with $\delta \leq 40$ mm.

Fig. IV.8 presents 3 different frame optimum designs for the FSO midship section. These designs are the result of optimizations performed with the LBR5 model, followed by a standardization of the frame size and by adding brackets.

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 : $\Delta_{\text{side tank}} = \Delta_{\text{center tanks}}$	29280 (109 %)	6.34 (100 %)	2.17	5.75 m N = 7	5.75 m N = 7
C2 : $\Delta_{\text{side tank}} = \frac{1}{2}\Delta_{\text{center tanks}}$	29740 (111 %)	6.63 (105 %)	2.23	6.57 m N = 6	3.285 m N = 13
Least weight					
C3 : $\Delta_{\text{side tank}} = \Delta_{\text{center tanks}}$	27150 (101 %)	6.70 (106 %)	2.42	5.11 m N = 8	5.11 m N = 8
C4 : $\Delta_{\text{side tank}} = \frac{1}{2}\Delta_{\text{center tanks}}$	26850 (100 %)	7.13 (113 %)	2.61	5.75 m N = 7	2.875 m N = 15
$\delta \leq 30$ mm					
Least Cost C5 : $\Delta_{\text{side tank}} = \Delta_{\text{center tanks}}$	38870 (145 %)	8.52 (134 %)	2.19	3.07 m N = 14	3.07 m N = 14
Least weight C6 : $\Delta_{\text{side tank}} = \Delta_{\text{center tanks}}$	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 = $(46/\Delta) - 1$

Most advisable scantlings (design)

Table IV.2. Comparison between the different optimum (after 10 iterations)

Iteration n°	Weight 10^6 N	Δ_{FRAMES} Tank frame spacing (m)	δ Panel 1 (mm)	δ Panel 12 (mm)	$\Delta_{stiffeners}$ Panel 1 (m)	$\Delta_{stiffeners}$ Panel 4 (m)
START	39.37 (145 %)	7.660	15.00	15.00	0.900	0.900
1	28.04	7.660	15.21	22.90	1.000	0.954
2	29.95	5.794	29.18	37.36	Max. value = side constraint	1.000
3	28.47	5.874	31.06	40.00	-	1.000
4	27.82	5.589	30.46	Max. value = Side constraint	-	0.950
5	27.50	5.346	29.97	-	-	0.913
6	27.32	5.279	30.04	-	-	0.884
7	27.24	5.230	39.92	-	-	0.860
8	27.20	5.190	29.90	-	-	0.843
9	27.17	5.166	29.83	-	-	0.832
10	27.15 (100 %)	5.138	29.95	-	-	0.825

Final cost (after optimization):
6.70 10^6 Euro for a 46-m long hold.
(a half-structure is considered, without bulkheads).

Cost per kg: 2.42 Euro/kg

Table IV.3.
Convergence of the optimization process of the FSO barge (Least cost and $\delta \leq 40$ mm)

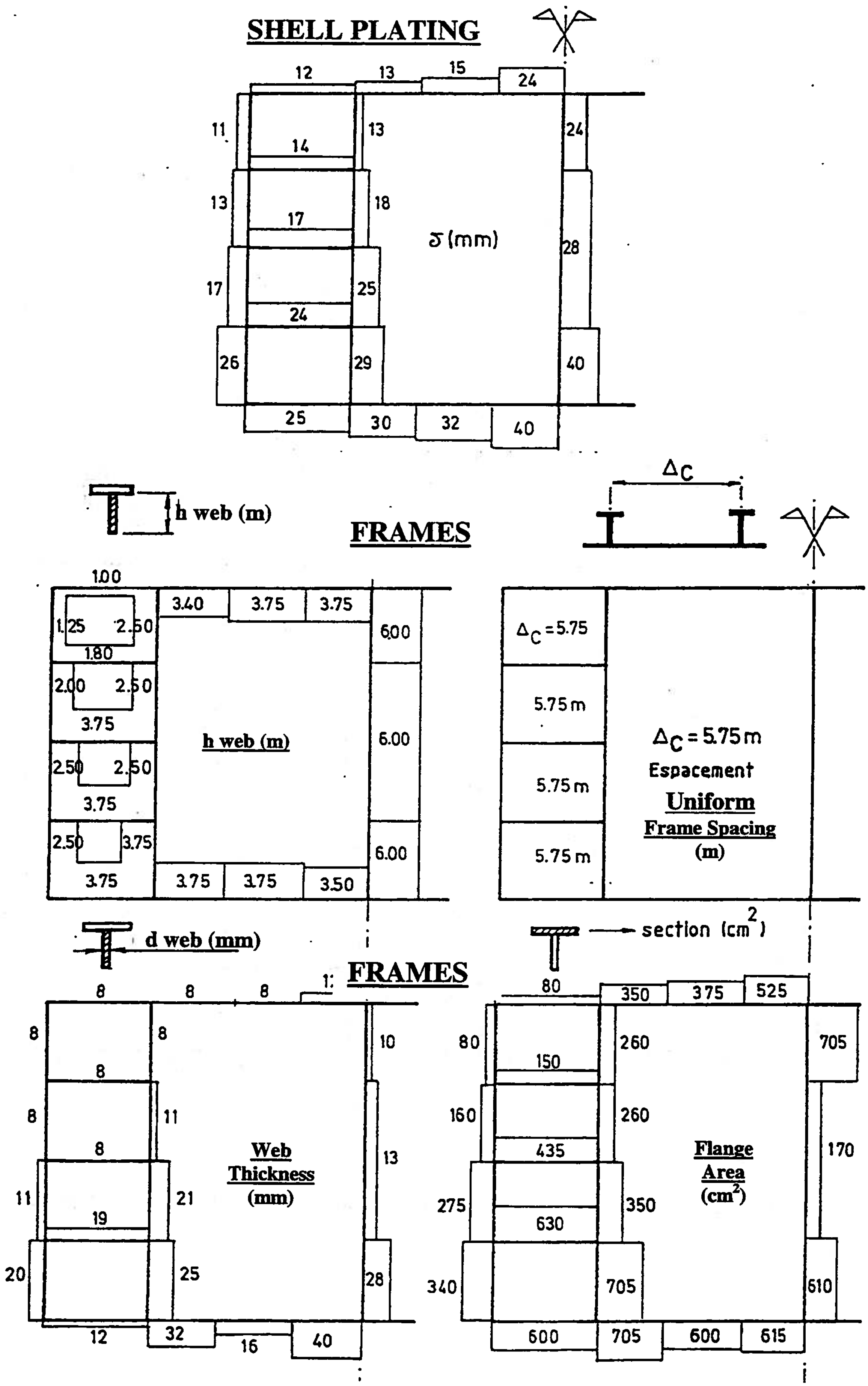


Fig. IV.5a. Optimal scantling of the FSO barge (Least cost - $\delta \leq 40$ mm, $\Delta = 5.75$ m)

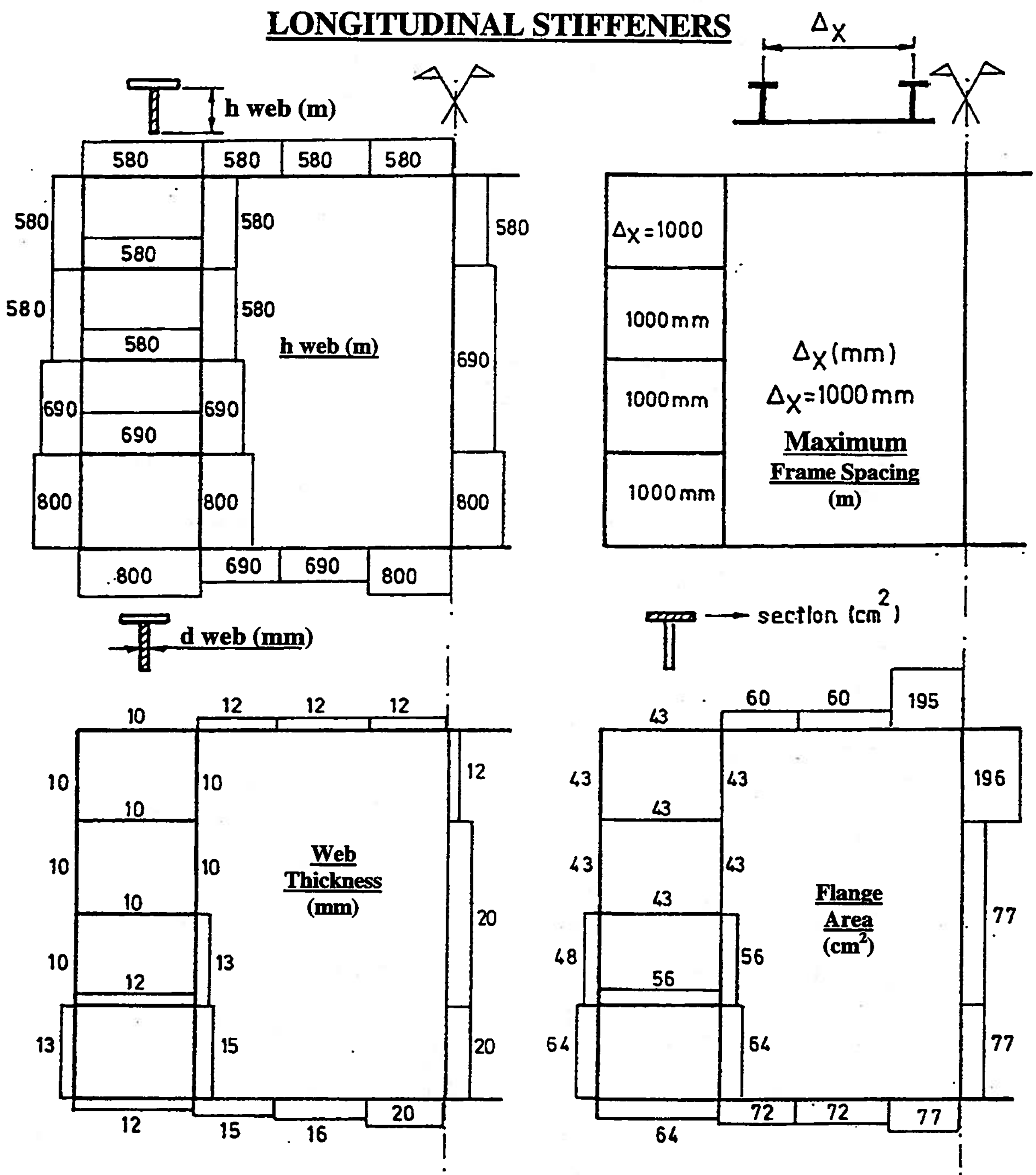


Fig. IV.5b. Optimal scantling of the FSO barge (Least cost - δ ≤ 40 mm, Δ = 5.75 m)

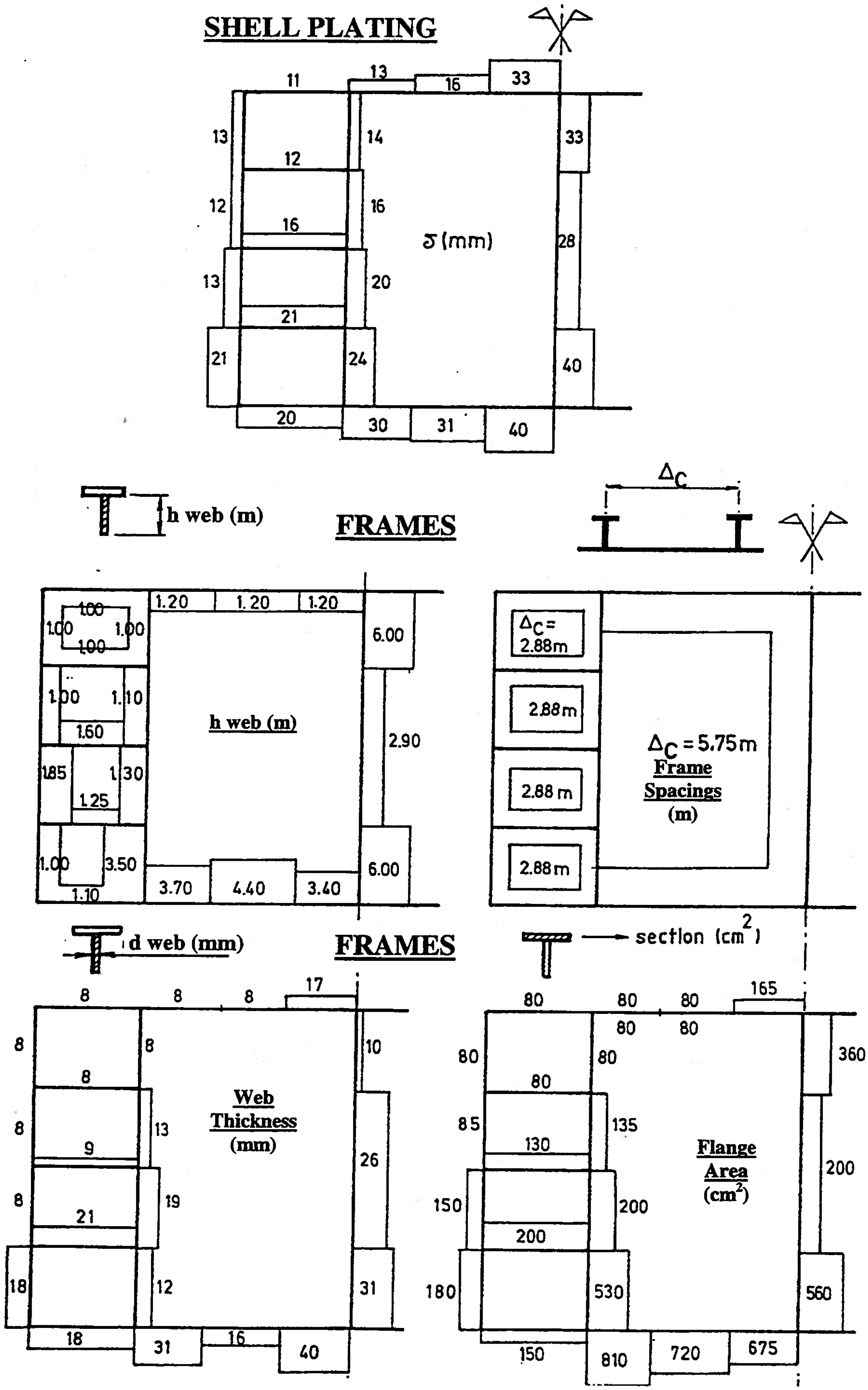


Fig. IV.6a. Optimal scantling of the FSO barge (Least weight - δ ≤ 40 mm, Δ = 5.75 m and 2.875 m)

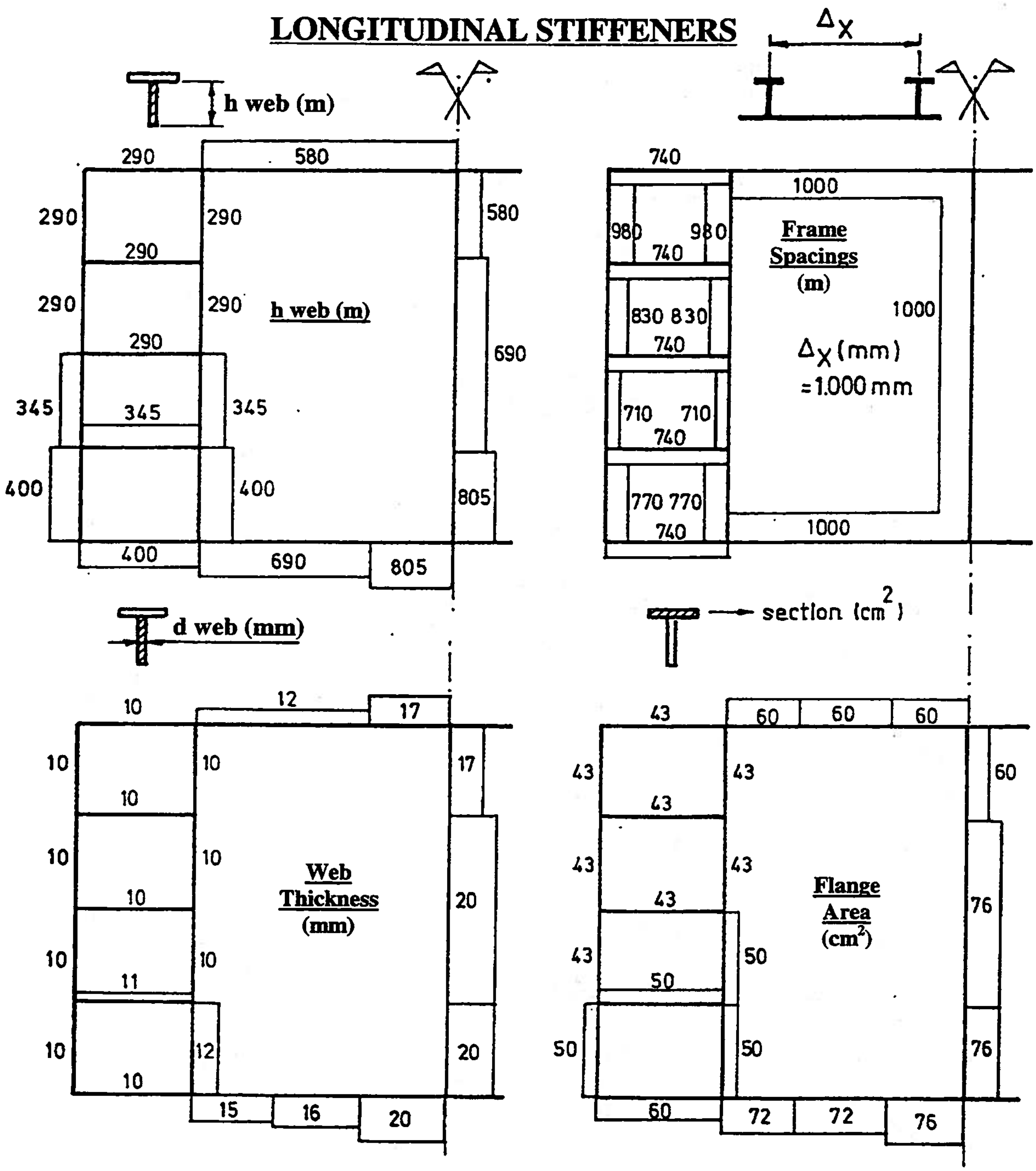


Fig. IV.6b. Optimal scantling of the FSO barge (Least weight - δ ≤ 40 mm, Δ = 5.75 m and 2.875 m)

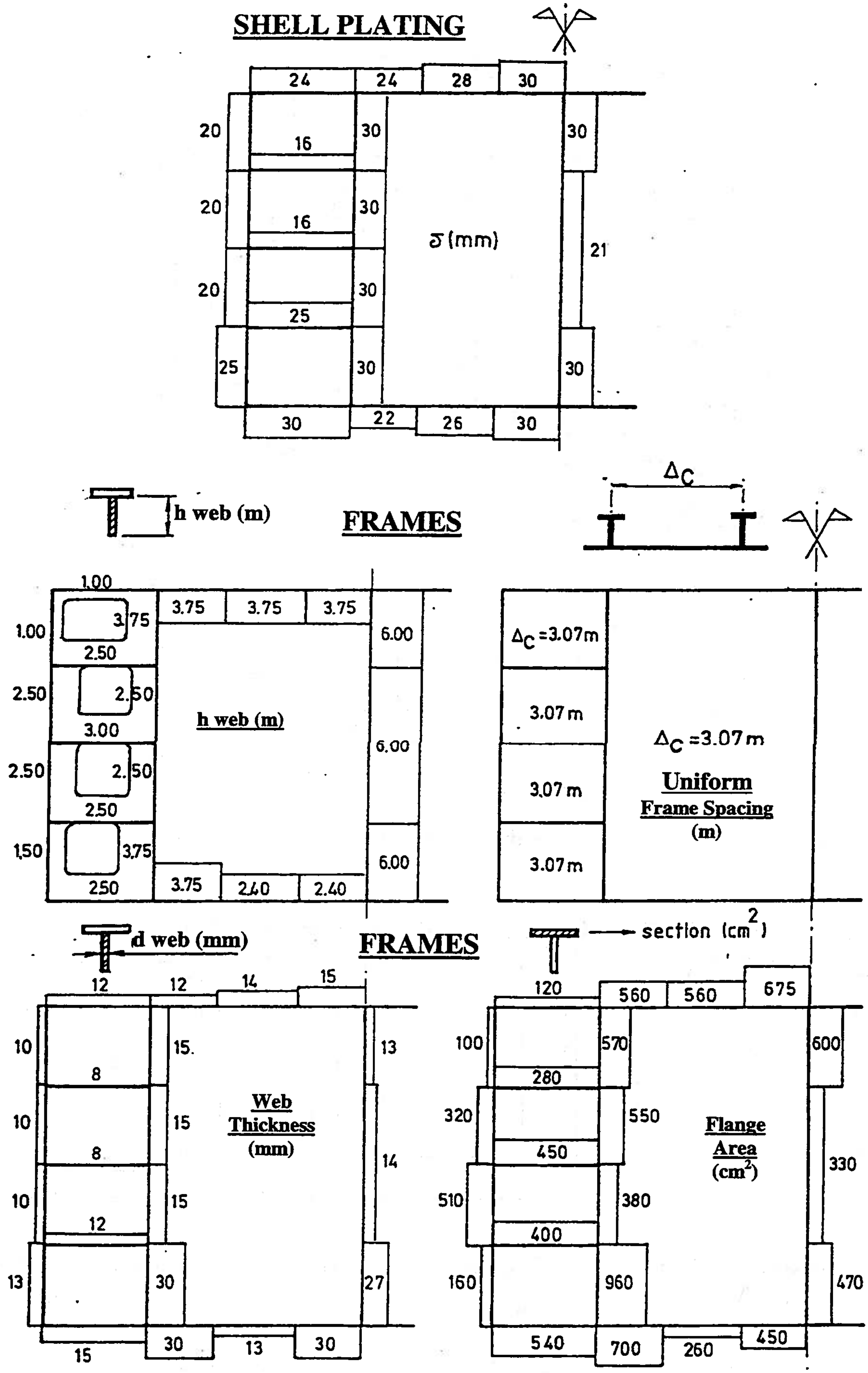


Fig. IV.7.a. Optimal scantling of the FSO barge (Least cost - δ ≤ 30 mm, Δ = 3.07 m)

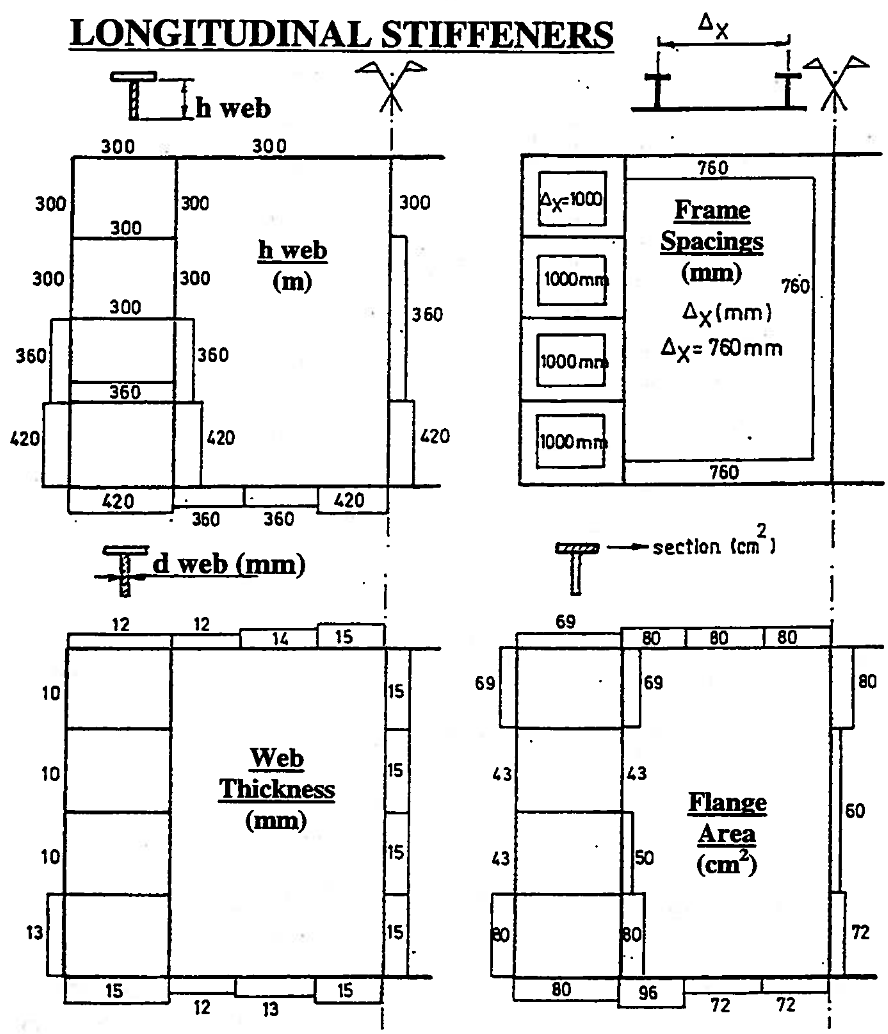
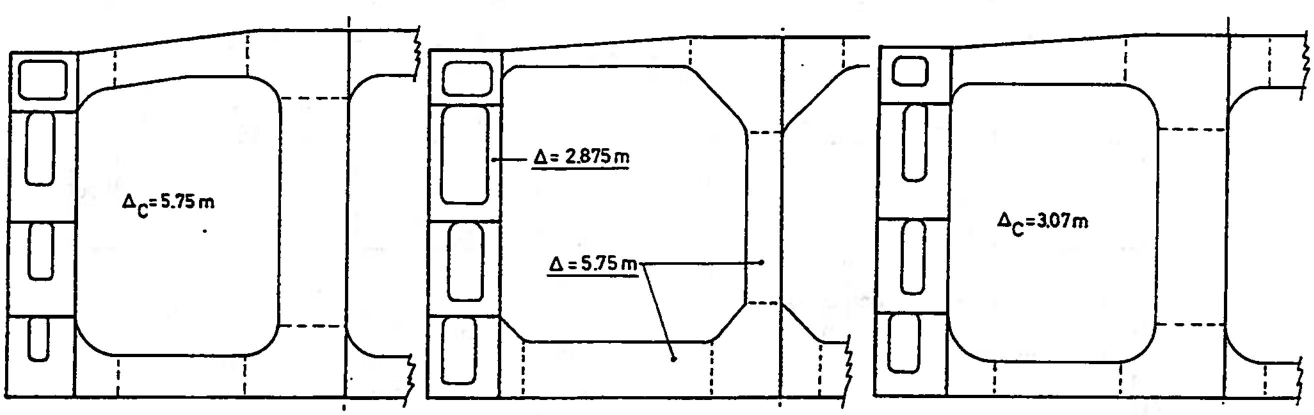


Fig. IV.7.b. Optimal scantling of the FSO barge (Least cost - $\delta \leq 30$ mm, $\Delta = 3.07$ m)



Least cost - $\delta \leq 40$ mm, $\Delta = 5.75$ m

Least weight - $\delta \leq 40$ mm, $\Delta_{center\ tanks} = 5.75$ m; $\Delta_{side\ tanks}$ 2.875 m

Least cost - $\delta \leq 30$ mm, $\Delta = 3.07$ m

Fig. IV.8. Optimum mid-ship sections for the FSO barge.

PART V LOCK GATE OPTIMIZATION
- A Civil Engineering Application -

Two examples of optimization with the LBR-5 model are presented in this section. The first one shows the optimization of a floating gate of a sea-lock for the Oostende harbor. The second application concerns the optimization of a FSO barge of 336 m with a capacity of 370,000 t (±3.7 Mio kN), designed to serve as floating reservoir (provisory storage area) in view to receiving crude oil before being transferred on board tankers (FSO = Floating Storage Offloading).

Optimization of a Floating Gate for the Maritime Lock of Oostende

In Belgium, the Public Coast and Waterways Department (Waterwegen Kust, Oostende) projects building a new lock of 250 x 36 m having a minimal depth of 10 m in the Oostende harbor (Figures V.1 and V.2). This lock is designed to receive boats of 10,000 tons deadweight (±100,000 kN). Designing it with floating gates is under consideration.

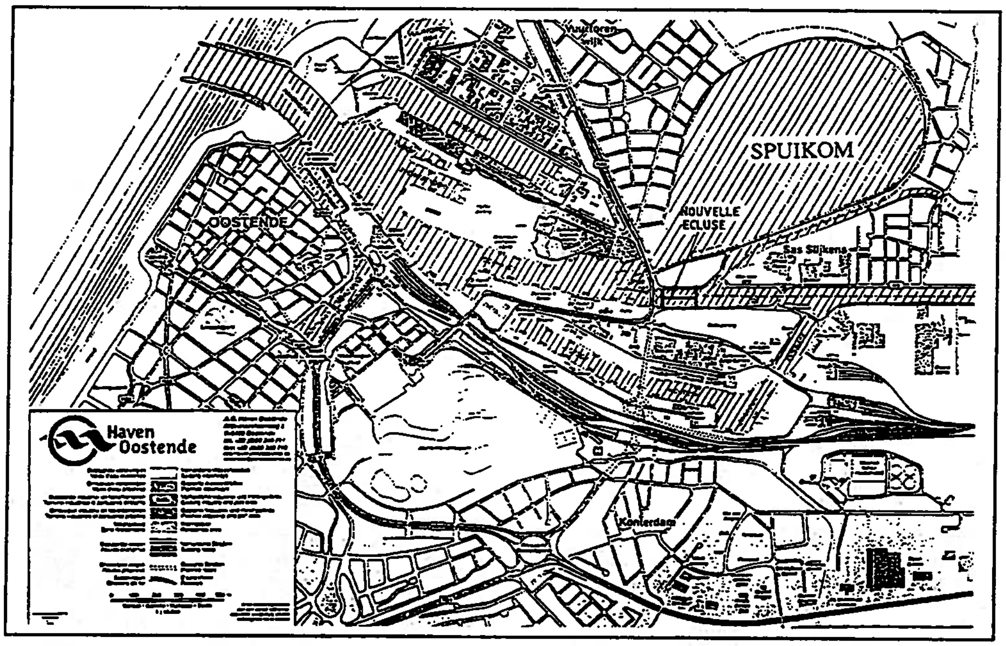


Figure V.1: Implantation of the new lock of the Oostende harbor

The advantages of floating gates have been well known for over 20 years and have been advanced by the University of Liege [ANAST 1995, Dehousse and Rodriguez, 1985; Rigo et al. 1996]. Previous studies were carried out on locks of 50 m (Zeebrugge) and 70 m in width (Berendrecht in Antwerp). In the present application, the lock width is only 36 m, and an updated study for this size is necessary [Da Ronch 1998].

The study of the entire floating gate including stability, ballast procedure, seakeeping, propulsion, effects of waves and currents, etc. is not detailed here. We mainly concentrate our analysis on the structural optimization of the gate scantling, when the main dimensions (height, width, length, sizes and locations of the floating tanks and ballast tanks) are fixed by other considerations such as floating stability with wave action.

References:

ANAST (1995), Self-Propelled Floating Gate - Parts 1 and 2, Internal Report 95-1, University of Liege, Belgium, pp1-9 and pp1-21 (in French).

Da Ronch C. (1998), Avant-projet d'une porte flottante pour écluse maritime de taille moyenne, Thesis, Engineering Faculty, University of Liege, Belgium (in French).

Dehousse N.M., Rodriguez S. (1985), Construction des grandes écluses maritimes. Quelques suggestions en vue d'en simplifier la réalisation par l'emploi de portes-robots, PIANC, bul. n°49.

Rigo Ph., Marchal J., Rodriguez S. (1996), The Use of Floating Gates for Storm Surge Barrier, Barrages: Engineering Design & Environmental Impacts, Edt. N. Burt & J. Watts, John Wiley & Sons (Publ.), pp421-430.

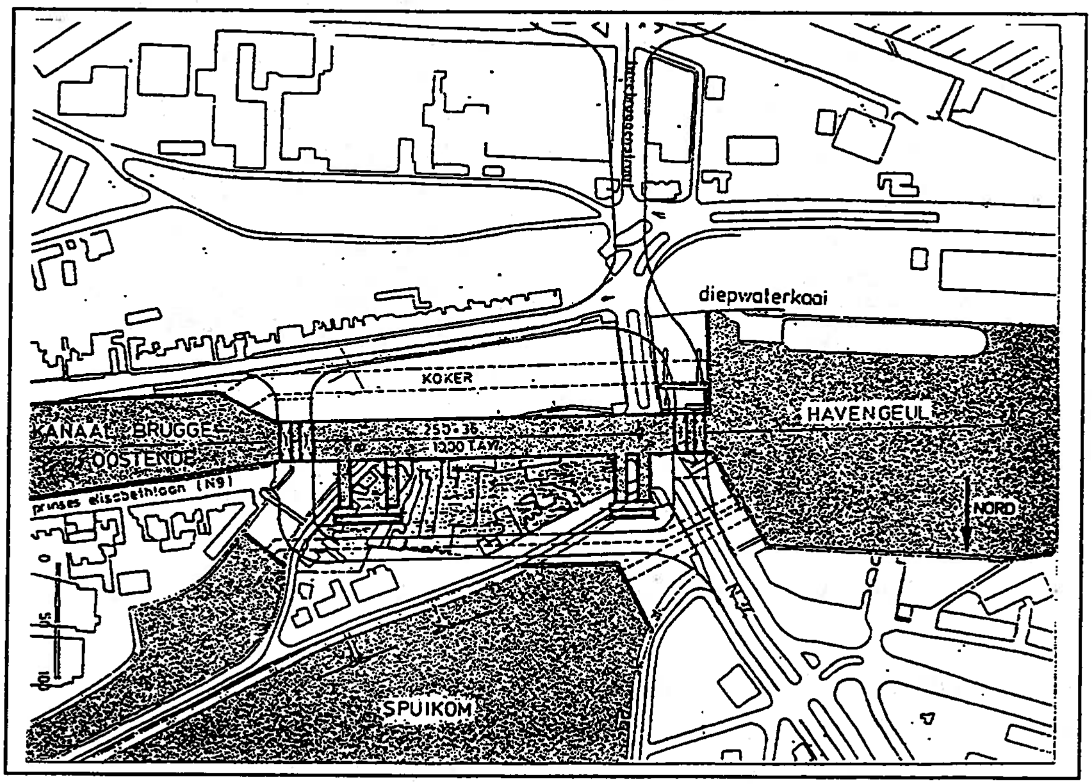


Figure V.2: Implantation plan of the 250 x 36-m sea lock.

For a gate span of 36 m, Da Ronch [1998] showed that, if one disregards problems linked to floating stability, the optimum weight corresponds to a gate 3.25-m wide (Figure V.3). Therefore, this width could be recommended for the construction of a standard rolling gate, the so-called "wheelbarrow" or "lateral displacement gate" that does not have to float.

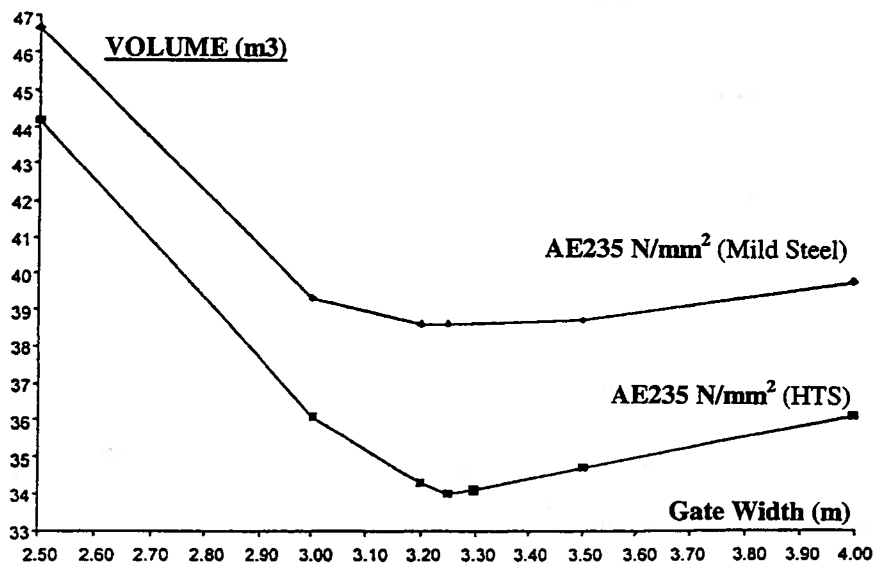


Figure V.3: Search for the optimal width of a 36-m wide sea lock (Optimum least weight).

For a floating gate, a width of 3.25 m doesn't provide sufficient stability in the presence of wind and waves; therefore it is necessary to widen it. In the case of the Oostende gate, problems of floating stability are critical, as the height of the gate under the water (± 9.7 m) is nearly equal to the part above water level (± 9.1 m). Consequently, after assessment of buoyancy and stability requirements, a gate of 5.40 m in width with about 1000 kN ballast at the lower part of the gate is selected (Figure V.4). Research on this matter must continue in order to confirm the validity of the selected width and ballast size.

The present analysis of sea locks relates to optimization (least weight and least cost) of a rolling gate of 3.25 m in width and a floating gate of 5.40 m in width. The opportuneness of using high tensile steel is also considered (AE355).

Modeling description

The selected modeling requires:

- 18 stiffened panels with 9 design variables each (Figure V.4);
- 1 additional panel to eventually simulate a lower support (at the bottom floor) located at the lower part of the gate;
- 162 design variables (9 x 18 panels);
- 73 equality constraints between design variables (symmetrical structure, uniformity of the frame spacing Δ_c...);
- 270 geometrical constraints (15 constraints per panel);
- 246 structural constraints, such as:
  - deflection $\leq$ 3.60 cm;
  - $\sigma_c \leq \sigma_0$ with σ_c (shell plate), σ_c (frames) and σ_c (stiffeners) the von-Mises combined stresses;
  - local instability of plate : $\delta_{min} \leq \delta$ (the minimum plate thickness requirement);
  - ultimate strength of the stiffened panels: $\sigma/\sigma_{ult} \leq s$;

Two configurations are considered (same structure but different boundary conditions):

- the gate is free at its foot (no contact with the floor),
- the gate is supported on the bottom floor.

The ultimate bending moment of the general structure (box-girder) is not considered as a constraint, but a post-optimization assessment has confirmed that the structure could resist an exceptional difference of water level of 6.50 m. The "s" partial safety factor related to ultimate strength is equal to 0.65 for the aforementioned constraints.

Boundary Conditions

At the two vertical extremities, the gate is considered as simply supported on the two side walls. In principle such a gate is usually designed to be either supported on its foot or to be free. Here, only a watertight contact between the gate and the floor is required.

It is usually assumed that a support on the floor (at the foot of the gate) allows reducing the global stress level and general deflection. In the present analysis, to consider the uncertainties on the effectiveness of the loads acting on the floor, the proposed optimal design has to simultaneously satisfy the requirements of the two extreme configurations (with or without floor support).

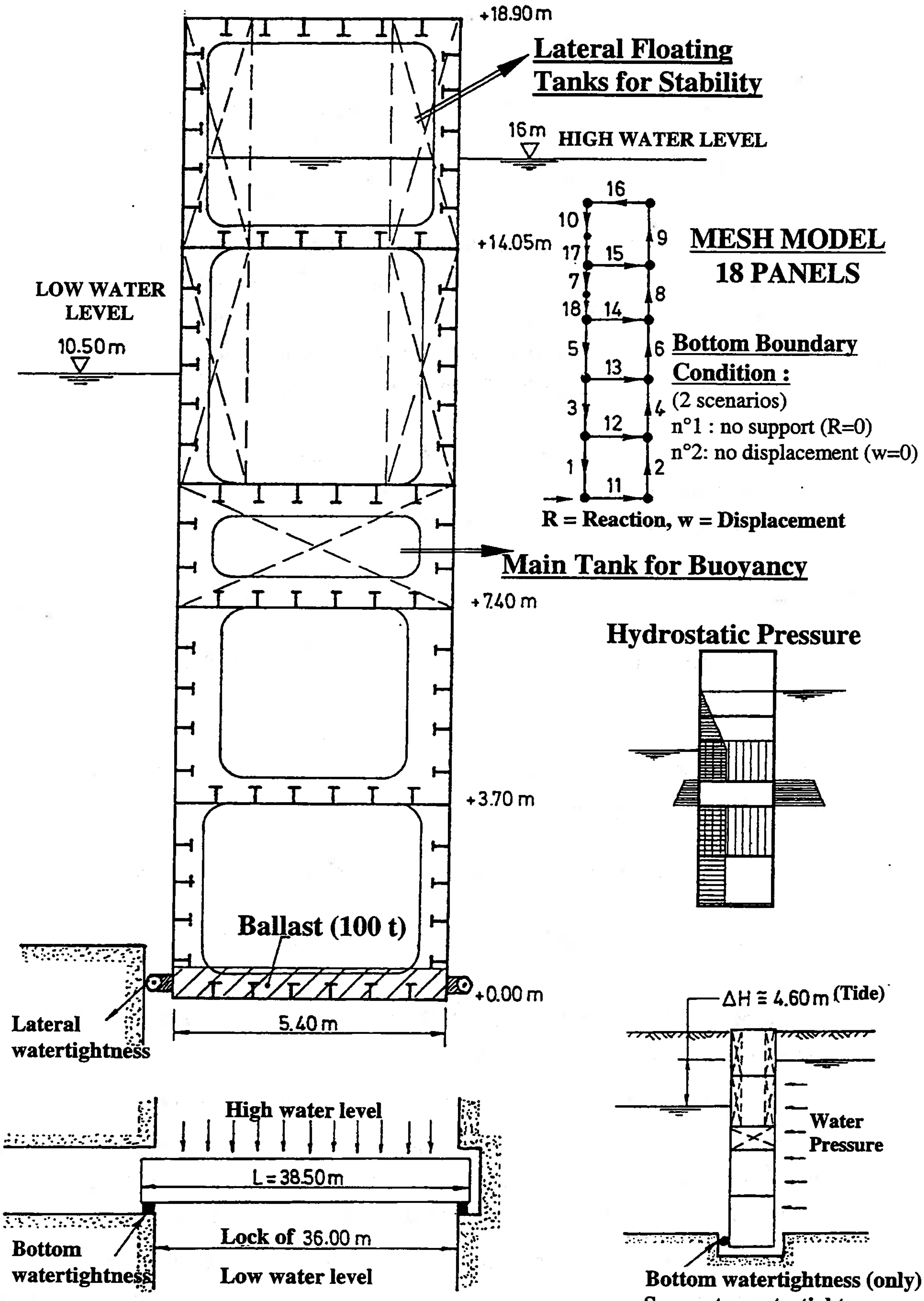


Figure V.4: The 5.40-m wide floating gate.

Assessment of the 3.50 m wide floating gate

If the requirements on floating stability of the gate are not considered, the optimal width for a least weight objective function is about 3.25 m (see Figure V.3). This means a width of 1/9 of the total span (37.25 m between supports).

On the basis of this 3.25-m width, 4 different optimum designs can be compared:

- Least weight and a AE235 steel grade ($\sigma_o = 235$ N/mm^2),
- Least weight and a AE355 steel grade ($\sigma_o = 355$ N/mm^2),
- Least cost and a AE235 steel grade ($\sigma_o = 235$ N/mm^2),
- Least cost and a AE355 steel grade ($\sigma_o = 355$ N/mm^2).

Optimum costs are calculated using the following cost and productivity data:

- Reference plate thickness: 10 mm
- Unitary Labor Cost (Euro/m-h)/Material Cost (Euro/t): $k = 0.08$
- Unitary price of steel: $C1 = 0.57$ Euro/kg , $\Delta C1 = -0.6\%$ (if AE235)
  $C1 = 0.65$ Euro/kg, $\Delta C1 = -0.6\%$ (if AE355)
- Price of welding (materials only): $C8 = 1.00$ Euro/m , $\Delta C8 = 15\%$
- Manpower:
  - plate: $P10 = 0.5$ m-h/m^2 , $\Delta P10 = 7\%$
  - frames (assembling with plate) : $P4 = P5 = 1$ m-h/m, $\Delta P4 = \Delta P5 = 10\%$
  - frames (if built on site): $P9 = 0.5$ m-h/m, $\Delta P9 = 1\%$

Table V.1 compares least weights and least costs corresponding to the 4 variants. One notes that:

- Use of high tensile steel (HTS, grade AE355) provides a 13% decrease in weight and cost.
- On the other hand, for mild steel (AE235), the gain varies from 3% to 6% for least weight and least optima costs respectively.
- For AE355 steel grade, the optimum weight and the optimum cost are nearly identical.
- Concerning the scantling itself, for both AE235 and AE355, there is very little difference between optimum weight and optimum cost. For the optimum cost, an increase in plate thickness is compensated by an increase in stiffener spacing.
- On the other hand, there are some significant differences according to steel grade (AE235 or AE355). It is essentially plate thickness that can be reduced by using high tensile steel AE355.

Steel Grade	LEAST WEIGHT	LEAST COST
Mild steel AE 235	Weight = 100 % (2966 kN) Cost = 103 % δ = 10 to 13 mm Δ_{frame} = 2.5 m (max. value) Δ_{stiff} = 0.5 to 0.8 m	Weight = 106 % (3152 kN) Cost = 100 % δ = 10 to 16.5 mm Δ_{frame} = 2.5 m (max. value) Δ_{stiff} = 0.8 m (max. value)
HTS AE 355	Weight = 88 % (2616 kN) Cost = 89 % δ = 10 mm (min. value) Δ_{frame} = 2.5 m (max. value) Δ_{stiff} = 0.67 to 0.8 m	Weight = 90 % (2657 kN) Cost = 88 % δ = 10 to 12 mm Δ_{frame} = 2.5 m (max. value) Δ_{stiff} = 0.8 m (max. value)

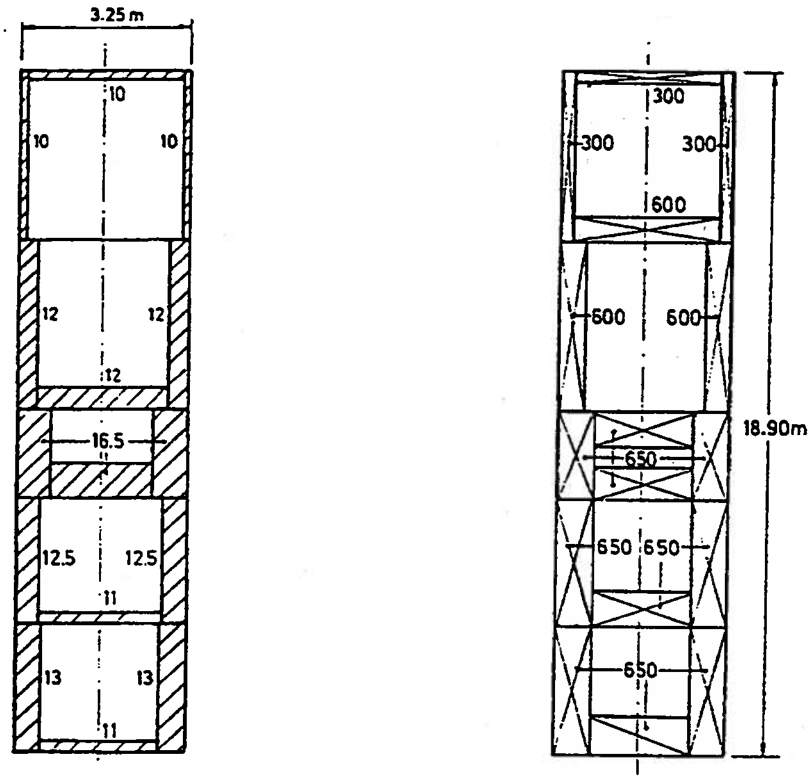
Table V.1: Comparison between optimum least weight and least cost of a 3.25-m wide gate.

An example of the convergence of the optimization process is presented on Table V.2. The convergence is quite fast concerning the objective function and plate thickness (δ), but it is a little slower for the other design variables such as frame web height.

Iteration	Objective Function Minimum Cost (%)	Plate thickness panel n°1 (mm)	Web height of frames (Transverse members) Panel n°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 & $\sigma_o = 355$ N/mm^2			

Table V.2: Example of convergence of an optimization process of a 36.00-m span lock gate.

Figure V.5 shows distributions of (δ) plate thickness and ($h_{web\ frames}$) frame web height for a 3.25-m wide gate, mild steel (AE 235) and a least cost optimization.



δ: Panel plate thickness (mm) h: Frame web height (mm)

Figure V.5: Distribution of gate transverse rigidity of a 36.00-m span sea-lock (Gate width = 3.25 m, σ_o = 235 N/mm^2, least cost)

Assessment of the 5.40-m wide floating gate

In order to assure floating stability during gate maneuvering, it has been shown that a structure of 5.40 m in width is required (see Figure V.4). This larger width is partially due to the important gate height (18.90 m), with regards to its minimal draft (10.50 m).

Table V.3 compares optimum weight and optimum cost of the *5.40-m wide floating gate* with the *3.25-m wide standard rolling gate*. Costs of mechanisms and maneuvering systems are not taken into account in this comparison.

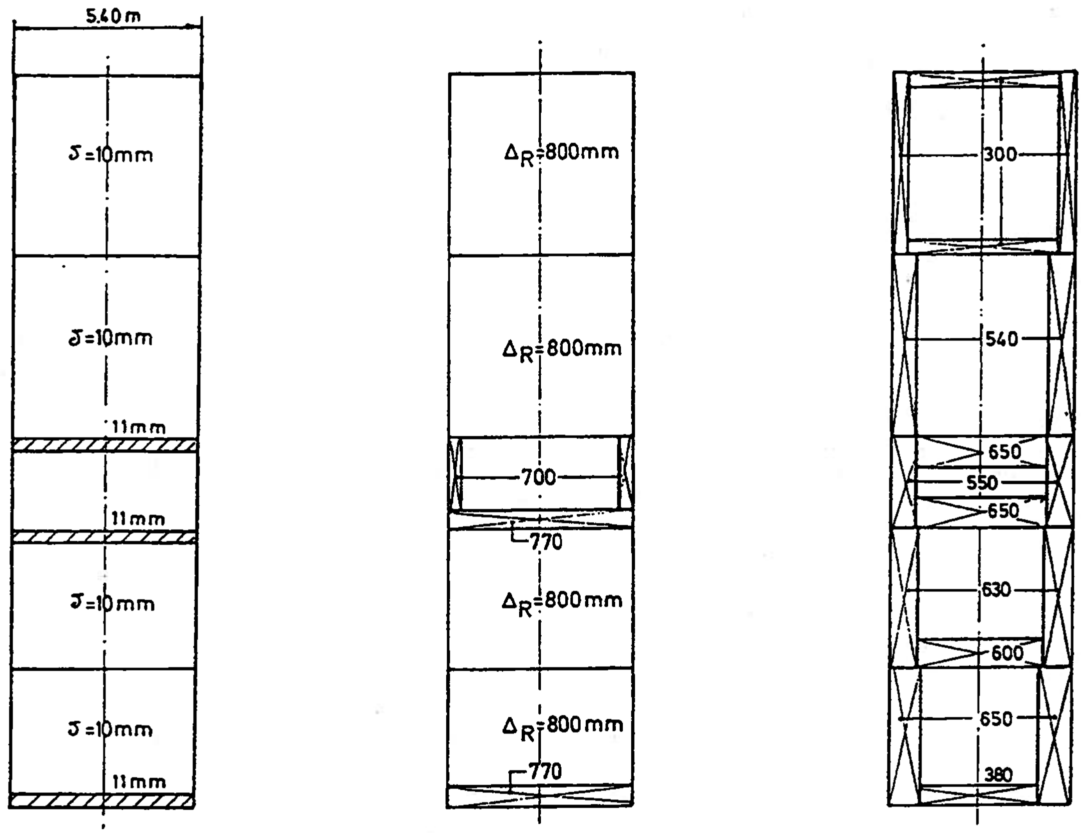
The 20 to 25% cost increase of the floating gate (5.40 m and AE355) with regards to the standard gate (3.25 m and AE355) is not significant, compared to the advantages floating gates provide [ANAST 1995]:

- sparing the upper and lower movable carriages,
- no mechanism underwater (rails, wheels, ...),
- sparing of 1 gate for the lock (3 gates are required instead of 4),
- sparing 1, or even 2 chamber(s),
- safe, reliable and easy maintenance and repair procedures,
- ...

Gate Width and Steel Grade	LEAST WEIGHT		**LEAST COST**		**COST Variations (%)**
	Weight	**Cost**	**Weight**	**Cost**	
B = 3.25 m AE235	100% (2966 kN) (reference weight)	103%	106% (3152 kN)	100% (reference cost)	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 %

Table V.3: Comparison between optimum gates for a 36.00-m wide lock.

Figure V.6 presents the least cost optimal design (optimum scantling). As the gate widening is based on a buoyancy constraint and not on a structural constraint, most of the design variables reach their minimal or maximal value (side constraints on the design variables). This phenomenon limits the potential savings that the optimization procedure can provide.



δ: Plate thickness (mm) $\delta \leq 10$ mm

Δ_{Stiff}: Spacing between stiffeners (mm) $600 \leq \Delta_{Stiff} \leq 800$ mm

h: Web height of frames (mm) $300 \leq h \leq 650$ mm

Frames spacing:	2.50 m
Plate thickness:	5 to 9 mm
Flange width of frames:	1200 to 2800 mm
Minimum stiffeners:	200 x 5.5 + 130 x 11 mm

Figure V.6: Scantling of the optimum least cost floating gate (5.40-m wide).

Figure V.7 shows the transversal deflection of the gate for the two considered configurations (with and without support on the floor). In the transverse frames, Figure V.8 presents for the two configurations the distribution of the σ_c comparison stresses in the flange and the τ shear stresses in the web at the junction with the plate. Deflections and stresses are similar in the upper part of the gate, but large differences occur in the lower part, there where the gate could be in contact with the floor.

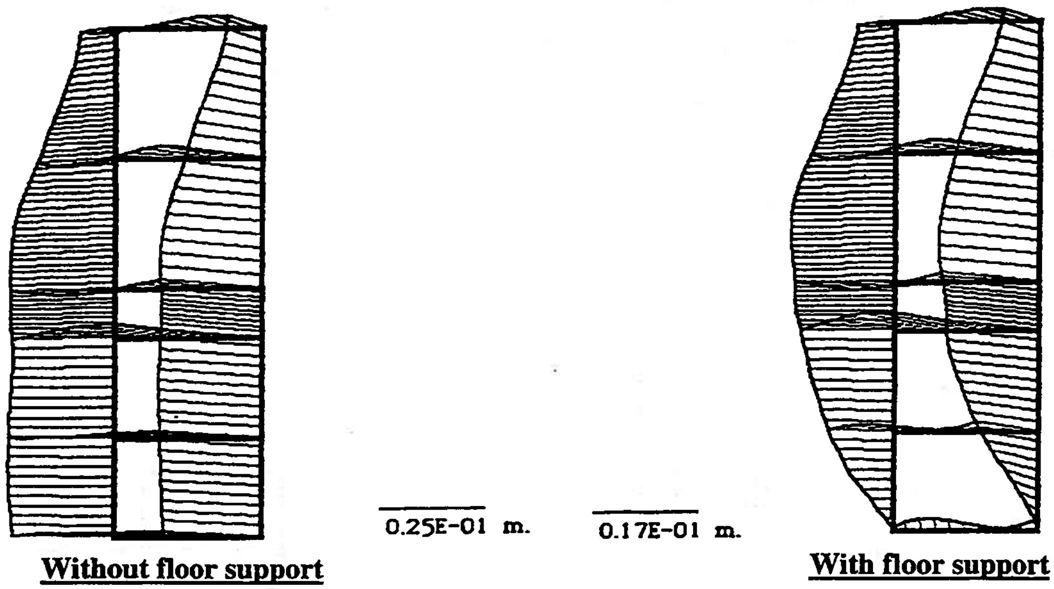


Figure V.7: Transversal deflection (with and without floor support)

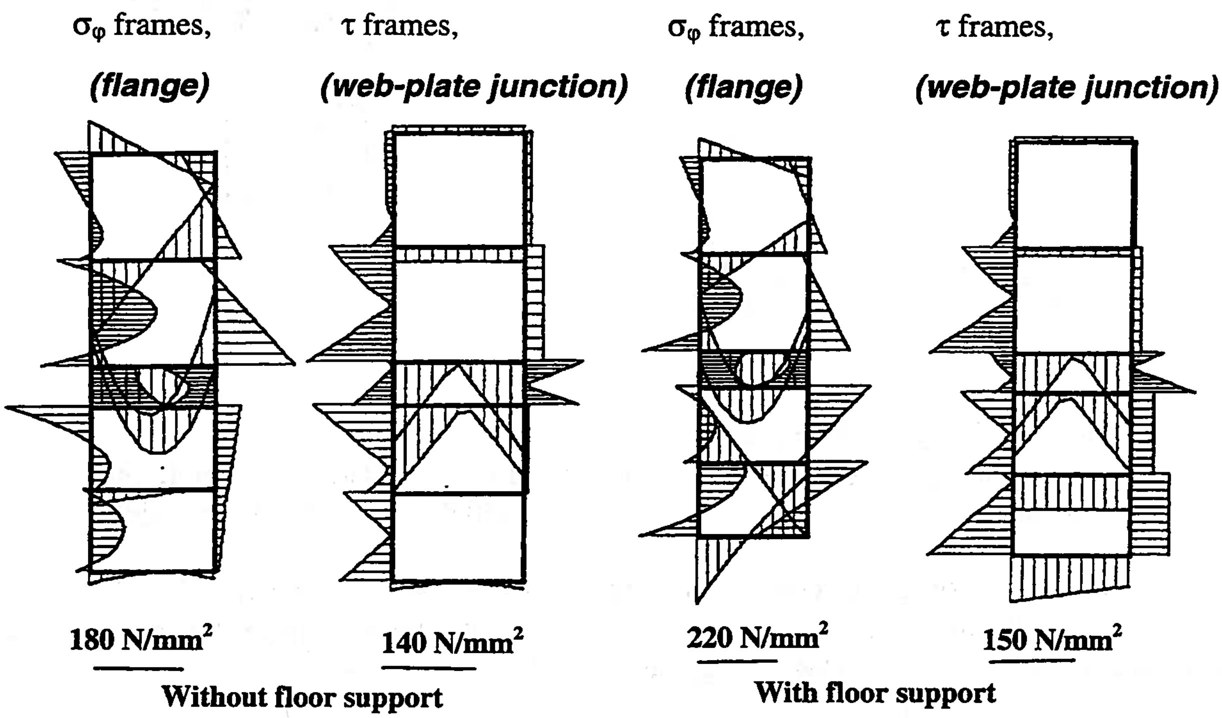
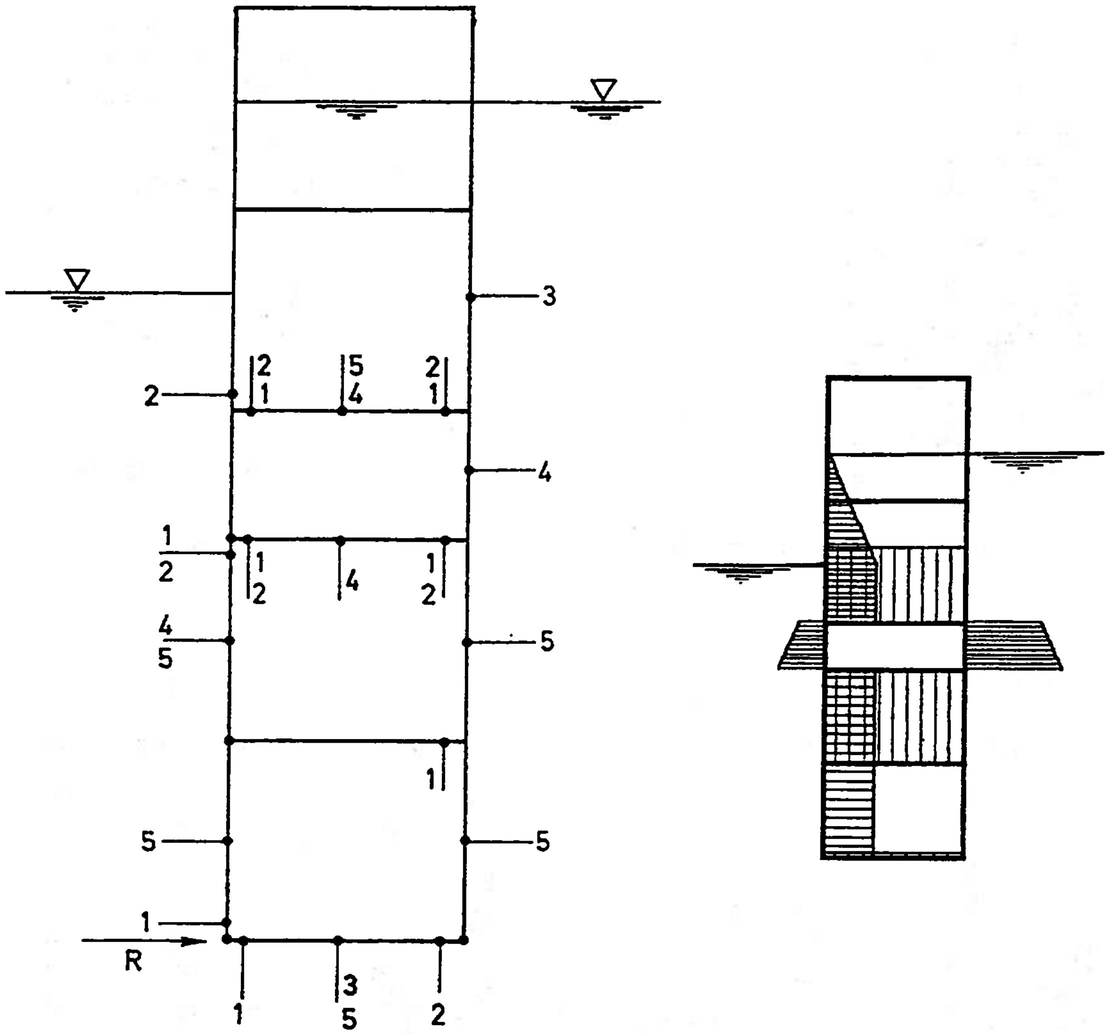


Figure V.8: Stress distributions in the transverse frames.
Comparison between the 2 configurations (with and without floor support).

At the end of the optimization process, when optimum scantling is obtained, there are 40 active geometrical constraints on the 270 imposed and 25 active structural constraints on the 246 selected. The active constraints are shown on Figure V.9.



1 Frame yielding: σ_c (web-flange)
2 Frame yielding: σ_C (plate-web)
3 Plate buckling
4 Plate yielding
5 Maximum slenderness of web frames ($h \leq 120$ d) - geometrical constraint

Active geometrical constraints concern the web slenderness of the frames ($h \leq 120$ d), the web slenderness of the stiffeners ($h \leq 36$ d) and the ratio between plate thickness and web thickness ($\delta \leq 2$ d). These two last constraints are active in each panel of the structure.

Among structural constraints that are not active, there are:

- $(\sigma/\sigma_{ult})_{MAX} = 0.41 \leq 0.65$ (ultimate strength of compressed stiffened panels)
- $W_{MAX} = 2.5$ cm ≤ 3.6 cm (deflection)

Figure V.9: Locations of the active constraints.

CONCLUSIONS

LBR-5 is a structural optimization 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 analyze and optimize naval and hydraulic structures at their earliest design stages: tendering and preliminary design.

Within the framework of the new "Module-Oriented Optimization" concept, the multi purpose LBR-5 optimization model is presented in this paper. It is composed of 3 basic modules (OPTI, CONSTRAINT and COST). The user selects the relevant constraints (geometrical and structural constraints) in external databases. Standard constraint sets are proposed to users. Since the present optimization deals with least construction costs, unitary material costs, welding, cutting and labor costs must be specified by the user to define an explicit objective function. Using all this data (constraints, objective function and sensitivity analysis), an optimum solution is found using an optimization technique based on convex linearizations and a dual approach. Independently of the number of design variables and constraints, the number of iterations requiring a complete structural re-analysis is rather small.

Advantages and main characteristics of the LBR-5 are:

- Preliminary design oriented (easy and fast modeling, reduced amount of input data, etc.),
- Structure optimization 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 as constraints,
- User oriented (user constraints can be easily implemented),
- Efficient and reliable optimizer (only 10~15 iterations 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),
- Frame and stiffener spacing are design variables (topological design variables),
- ....

Limitations and shortcomings of the module are:

- Only prismatic structure can be considered, analyzed and optimized (as ship hold, box girder, etc.),
- Loads are external data. Then they are often rule based (no direct analysis is considered),
- Loads are considered as static or quasi-static,
- Only linear 3D analysis of the global structure are performed,
- ...

Future developments are:
- Integration with industrial CAD packages and preliminary design tools. Such interfaces are now under development,
- Hull shape optimization including fluid structure interaction,
- Multi-criteria analysis (construction cost, weight, generalized cost including operational costs, etc.) will be available using updated version of CONLIN,
- Reliability-based optimization (based on the ship life cycle),
- To introduce fatigue limit state in the rational constraints,
- ...

Optimum analysis of a FSO barge (Floating Storage Offloading) is presented as application of the LBR-5 least cost optimization model. It shows that is it feasible to perform scantling optimization of large structures with a minimum cost objective function at the preliminary design stage. Alternative designs like reduced frame spacing in lateral tanks and impact of the maximum plate thickness on the optimum solution have been assessed. Least cost and least weight optimum are compared. It shows that starting from a least weight initial design, the cost is reduced by at least 15% without significant penalty on the weight.

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