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Least-Cost Structural Optimization Oriented Preliminary Design

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A computer design package is presented that provides optimum midship 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 one hour of computation time with a usual PC or laptop the LBR-5 software automatically provides a rational optimum design. This software is an optimization tool dedicated to preliminary design. Its main advantages, in the early stage of design, are ease of structural modeling, rapid 3-D 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 3-D numerical structural analysis. LBR-5 is based on the Module Oriented Approach. Design variables are the dimensions of the longitudinal and transversal members, plate thickness and spacing between members. The software contains three major modules. First, 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. 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. Finally, the Opti Module which contains a mathematical programming code (CONLIN) to solve constrained nonlinear 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. Optimum analysis of a FSO unit (Floating Storage Offloading) is presented as an example of the performance of the LBR-5 tool.

Introduction

THE DETERMINATION of the scantlings of marine structures always poses numerous problems to designers. Ships are indeed complex structures and their stiffening system is also particularly sophisticated. The major orientations of a ship structural design are always 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 hydraulic and naval structures was thought through, created and developed (Rigo 1998a,b). LBR-5 is the French acronym of "Stiffened Panels Software," version 5.0.

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

- an optimization of the sizing/scantling (profile sizes, dimensions and spacing) of the structure's constituent elements;

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◦ integration of construction and manufacturing costs in the optimization process (through the cost objective function).

The advantages of this optimization module appear mainly at the preliminary stage. It is indeed during the first stages of the project that flexibility, modeling speed and the method's easy use provide valuable help to designers. At this time, few parameters (dimensions) have been definitively fixed, and complex analysis (FEM) is often unusable, particularly for design offices and modest-sized yards.

For ship's structures, the application domain is clearly the ship's central parts (parallel zones of cargo ships, passenger vessels, etc.). This zone is the most important in length for the large floating units. For smaller units (sailboats, small craft, etc.), the parallel zone is smaller, or even nonexistent. In this case, the LBR-5 model can be used to perform midship section optimization.

The development of the LBR-5 module is included in the development of *a new design methodology* (A Module-Oriented Optimization Approach). The goal is to create a multi-purpose optimization model, open to users and compatible with different structure analysis modules based on codes and specific regulations. Such a model 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 according to the structure type (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 these as Module-Oriented Optimization.

Figure 1 shows the basic configuration of the LBR-5 software with the three fundamental modules (COST, CONSTRAINT and OPTI) and the "DATABASES" in which the users can "shop," that is, choose the relevant constraints and cost data.

Around the COST and CONSTRAINT modules there are a large number of submodules. Each of these submodules is specific to a type of constraint.

In principle, it is necessary to have at least one submodule 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.

The present paper focuses on the COST module required to perform least cost scantling optimization. In the near future two other papers with more advanced information on the CONSTRAINT and OPTI modules will be published (Rigo 2001a,b). Presently, detailed information on these two modules can be found in Rigo (1998a,b).

State of the art

Design philosophy

The most well known methodology for the design of ship and other marine structures is the "Design Spiral" (Evans et al 1963). However the current tendency is to break with this design process and move towards "Concurrent Engineering" (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 & Buxton 1989).

Many other papers have been written on design philosophy and methodology, both present and future (Francescutto 1993, Rigo 1998a), production (Caldwell 1978, Blomquist 1995), design and sizing approach (Lamb 1969, Welsh et al 1991, Wada et al 1992), new structures (Hori et al 1990) and applications (Niho et al 1994, Tanigushi et al 1994). An excellent discussion is presented by Birmingham et al (1997).

Technique and economic analysis

For the technical and economic analysis of the ship, the design phase and production (Benford 1970), the works by Professor Buxton and his team comprise an excellent reference (Buxton 1976, Buxton et al 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 & Buxton 1989]) that integrates a cost evaluation module based on an analytic calculation.

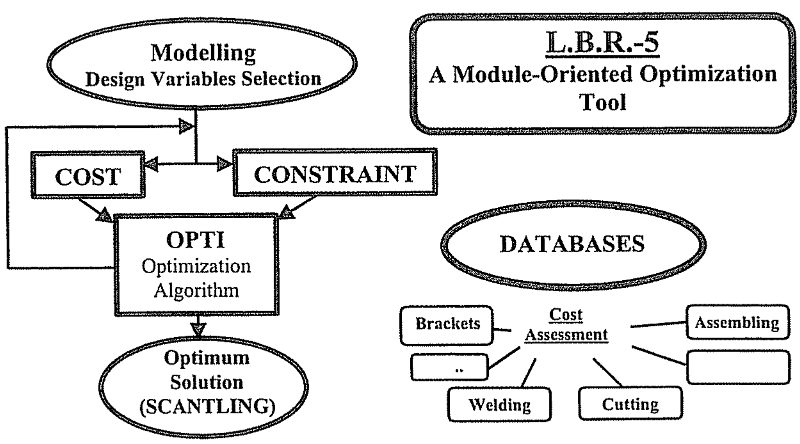


Fig. 1 Basic configuration of LBR-5 model and database presentation

Methods of structure analysis

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

As this paper is oriented towards stiffened structures, especially ship and other marine 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) the reader is referred to Rigo (1998a, 2001a).

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. 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 1992a,b). The selection of cost-effective stress and strain models is indeed a difficult problem that has been considered in many studies (Faulkner 1975, 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 Hughes (1988) and Rawson & Tupper (1994).

Optimization of naval structures

The first ship structure optimization studies were made practically by hand. Then, with computer assistance, researchers tried to develop design and optimization algorithms. Optimization first appears in the works of Evans (1963), Moe & Lund (1968), and Nowacki et al (1970). The works of Moe & Nowacki long served as a reference for ship structure optimization (Winkle & Baird 1986). An important step for ship structure optimization appeared with Hughes' works (Hughes 1980, 1988, Mistree et al 1992).

The evolution of design techniques and optimization are reported by ISSC: Catley et al (1988, 1997), Moan et al (1991), Pittaluga et al (1994), and Pradillon et al (2000). As major references works on optimization: Vanderplaats (1984), Save et al (1985, 1990) and Sen et al (1998), and as examples of ship structure optimization: Lyons (1982), Hung (1987), Jang & Na (1991), Kriezis (1991), Krol (1991), Rahman et al (1995), Hatzidakis & Bernitsas (1994), and Nobukawa et al (1995).

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 & Baird (1986), Bunch (1989, 1995), Hills & Buxton (1989), Blomquist (1995), Hengst et al (1996), Kumakura et al (1997) and the PODAC model (Ennis et al 1998).

Different optimization approaches

The term "ship structural optimization" has a different meaning according to the person or the group for whom the study is done. For shipowners, to optimize the structure of a new ship means determining the main ship dimensions in order to attain the highest profitability rate (Mandel & Leopold 1966, Buxton 1976, 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.

Sizing optimization: In ship-sizing optimization, the general dimensions and the hull forms are considered as fixed. The software integration of LBR-4 and CONLIN (Fleury 1989), that are the object of the present research, constitutes a new tool (LBR-5) to precisely achieve this type of optimization, i.e., to define the optimum scantling (Rigo 1998a,b, 2001b).

Concerning sizing optimization, 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, 1988, 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,b, Krol 1991, Rahman et al 1995). The first alternative is used in this study.

Multi-objective optimization: The University of Newcastle upon Tyne is a well-known research center for multi-objective optimization (Multi-Object Decision Model and Multi Criteria Decision-Making) (Sen 1995, 1998). The use of genetic algorithms for large size multi-criteria optimization has recently become popular (Goldberg 1989, Okada et al 1992). Concerning multi-criteria optimization applied to ship structures, some valuable works are Parsons & Singer (2000), Shi (1992), Trincas, Zanic et al (1994), and Ray & 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 (European Project, 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 & Kikuchi 1988).

Description of the three basic modules

These three basic modules are OPTI, CONSTRAINT and COST (Fig. 1).

The *OPTI module* contains the mathematical optimization algorithm (CONLIN) that allows solving nonlinear 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 nonlinear functions (constraints and objective functions) and on a dual approach (Fleury 1989, 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 structure is modeled with stiffened panels (plates and cylindrical shells). For each panel one can associate up to nine design variables (XI). These nine design variables are respectively:

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

The *CONSTRAINT module* helps the user to select relevant constraints within constraint groups at his disposal in a databank (Fig. 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 (Euro codes, ECCS Recommendations, Classification Societies, etc.).

Constraints are linear or nonlinear 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 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 problems to be solved can be summarized as follows:

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

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 LBR-5 software can perform optimization for minimum construction cost (COST module) or minimum weight. In order to link the cost objective function (Euro) to the design variables (X_i), the unit costs of raw materials (Euro/kg), the productivity rates for welding, cutting, assembling, . . . (man-hours/unit of work = m-h/unit) and labor 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, robot . . .), 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. A detailed description of *the COST Module* will now be presented.

The cost module

Global construction costs can be subdivided into three categories:

- cost of raw materials,
- labor costs, and
- 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, and product insurance, 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:

$$\begin{aligned}\text{Total Cost} &= \text{Material Costs}\\ &\quad + \text{Labor Costs}\\ &\quad + \text{Overhead Costs}\end{aligned} \tag{1}$$

$$TC = MatC + LabC + OvC$$

The purpose of this analysis is essentially to allow a relative and objective comparison, on basis of cost, of the successvie designs resulting from the optimization process. So, the absolute cost is not needed and only the two first terms of equation 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:

$$TC = MatC + LabC = \sum_{j=1}^{K} \underset{\text{Number of units}}{Qj} \cdot \underset{\text{Euro/unit}}{Pj} + \sum_{i=1}^{NT} \underset{\text{Man-hours per task}}{Ti} \cdot \underset{\text{Task frequency}}{Mi} \cdot \underset{\text{Euro/m-h}}{Si} \tag{2}$$

where

j = a given material (For instance: 1 ton of steel plate, 1-m long of angle bar of 60 × 60 × 5 . . .),
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 equation (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 [equation (2)], but rather in the identification and subdivision of tasks into subtasks and, finally, into elementary standard tasks. An elementary standard task is defined as a task that cannot be subdivided further.

Equation (2) is therefore a condensed equation of a more general one in which the description of tasks, subtasks and the elementary tasks explicitly appears, that is [equation (3)]:

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

where k is the hierarchical level of the task:

$k = 1$	superior level (block)
$k = 2,3, \ldots,$	intermediate levels (panels . . .)
$k = n$	elementary level

Thus, the global cost evaluation procedure requires:

- to divide the whole construction process in $NT1$ standard tasks of level 1, for example, dividing the whole strucure into blocks (Fig. 2). Several blocks can be identical ($M_{i1} = 1,2,3 \ldots$);
- to subdivide each of these $NT1$ standard tasks into $NT2$ subtasks;
- 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).

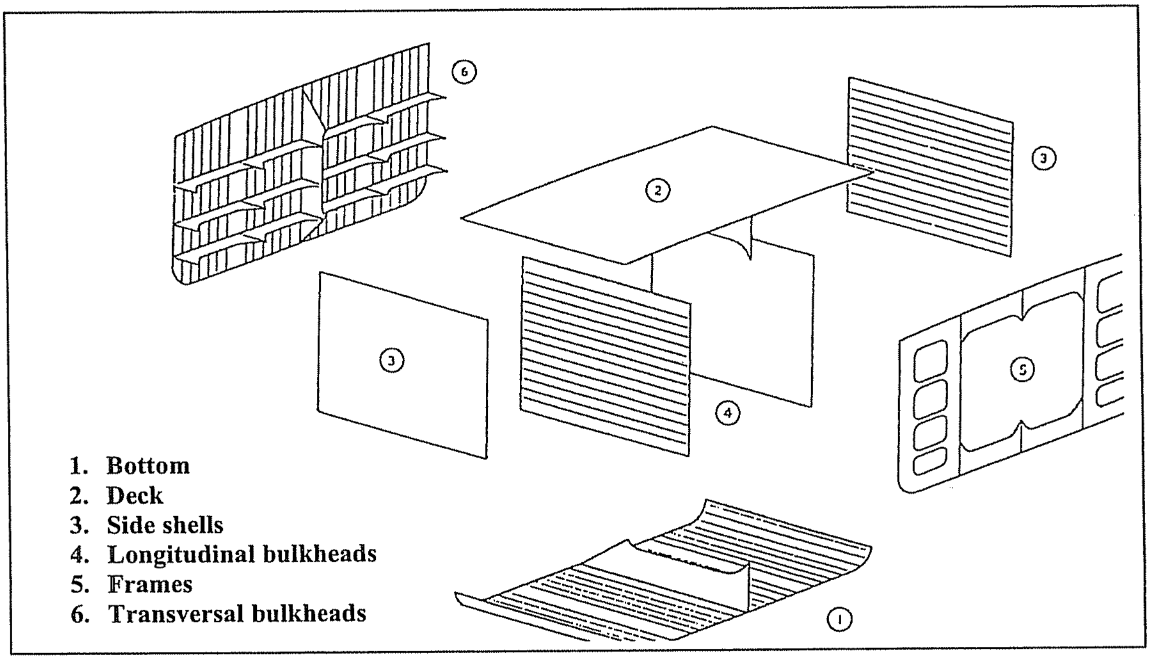


Fig. 2 Subdivision of a block into elements (Buxton 1966)

Normalized cost

Moe & Lund (1968) introduced the "Cost Equivalent Relative Weight (CERW)":

TC = Total Cost (Euro)

$$TC = \underset{\text{(Euro/tons)}}{[\text{Unitary Mat. Cost}]} \cdot \underset{\text{(tons)}}{[\text{Weight}]} + \underset{\text{(Euro/man-hours)}}{[\text{Unitary Labor Cost}]} \cdot \underset{\text{(man-hours)}}{[\text{Working Load}]}$$

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

where

$$k = \frac{S}{Q} = \frac{\text{Unitary Lab. Cost (Euro/m-h)}}{\text{Unitary Mat. Cost (Euro/ton)}} \text{ (t/m-h)} \tag{5}$$

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 MacCallum and MacGregor (Winkle & 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:

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

where

$$EQP = \text{Mat. Weight} + \eta \cdot k \cdot \text{Wload} \quad \text{(tons)}$$

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

Wload = Global Working Load (man-hours)

Modeling of objective functions used by 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), longitudinal and frame spacings (Δ_X, Δ_Y), and longitudinal and frame scantling [$(h,d\ w,t)_X$, and $(h,d,w,t)_Y$]. Thus, Fp, the weight objective function can be written for an orthotropic stiffened panel as:

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

where

L = length of the panel according to the X coordinate (m),
B = breadth of the panel according to the Y coordinate (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 [equation (8)]:

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

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.

Cost of materials: F_{MAT}

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

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

where

C_1 = cost per kg of a plate δ mm thick,
C_2 = cost per kg of the longitudinals/stiffeners,
C_3 = cost per kg of the transverse frames.

In order to take into account a possible variation of the price per kg of the plates according to their thickness, the parameter C_1 is defined as follows:

$$C_1 = C_1^0\,[1 + \Delta C_1(\delta - E_0)\,10^3]\ \text{(Euro/kg)} \tag{10}$$

where

C_1^0 = cost per kg of a plate with a thickness $\delta = E_0$,
E_0 = reference thickness (of the plate), to be defined by the user (in m),
DC_1 = change in % of C_1^0 (cost/kg) between plates of E_0 and E_0 + 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 C_2 and C_3 coefficients are defined as:

$$C_2 = C_1^0\,[1 + \alpha_X \cdot \Delta C_2] \quad \text{(Euro/kg)} \tag{11a}$$

for longitudinals/stiffeners, girders and cross-bars

$$C_3 = C_1^0\,[1 + \alpha_Y \cdot \Delta C_3] \quad \text{(Euro/kg)} \tag{11b}$$

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 P_9 coefficient and equation (15)];
α_X, α_Y = 1, if the members are standard members [IPE, HEA, . . .] (Eqs. 11a and 11b)
$\Delta C_2, \Delta C_3$ = change in % of the cost/kg of the longitudinals and the frames by comparison to the unitary cost of the reference plate (C_1^0), ($\Delta C_2, \Delta C_3 > 0$ or <0).

Cost of consumables: F_{CONS}

The welding cost per meter (energy, gas, electrodes, amortization of equipment, . . .), excluding labor costs, is estimated by

$$C_8 = C_8^0\,(1 + \Delta C_8) \qquad \text{(Euro/m)} \tag{12}$$

where

C_8^0 = the cost/m of consumables to weld an E_0 plate thick (E_0 being the reference thickness) on a thicker plate (e.g., to weld a web with its flange). Continuous welds on both sides (double filled) are considered. In the first approximation, the thickness of the weld is fixed at 50% of the thickness of the thinnest plate.
ΔC_8 = change in % C_8^0 (cost/m) between (E_0) and (E_0 + 1 mm) plate thickness.

Then we have

$$F_{CONS} = L.B.\left(\frac{2-\alpha_X}{\Delta_X} + \frac{2-\alpha_Y}{\Delta_Y}\right) \cdot C_8\ \text{(Euro)} \tag{13}$$

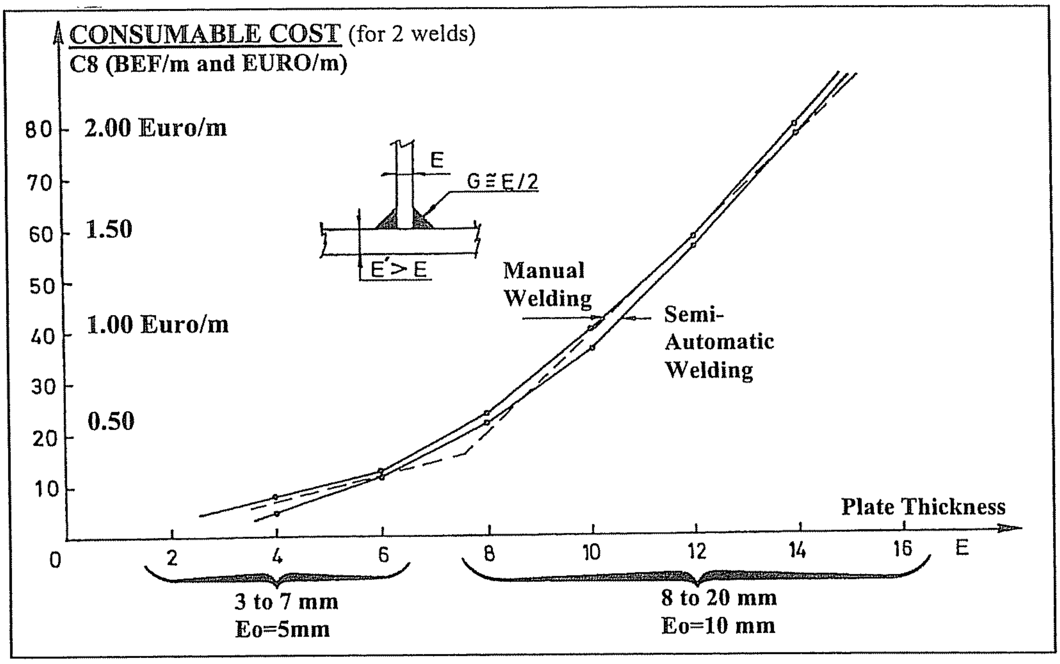
Coefficients C_8^0 and ΔC_8 were defined with the WELDCOST program and used to evaluate welding costs (E.S.A.B. S.A.) for both semiautomatic welding (GMAW) and manual welding. In western countries, we observed that the cost of consumables (Fig. 3) is small compared to the cost of labor (productivity in min/m) (Fig. 4).

Labor costs: F_{LAB}

With an efficiency parameter ($0 < \eta \leq 1$) for the considered production plan, we have:

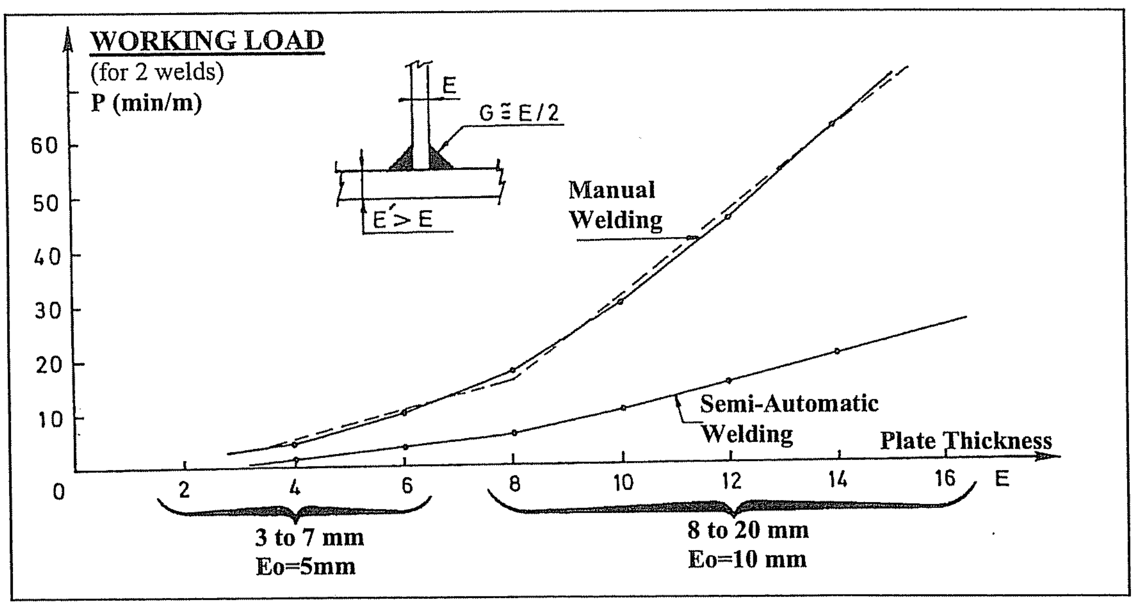
$$F_{LAB} = \eta \cdot k \cdot C_1^0 \cdot WLoad \tag{14}$$

where WLoad [equation (15)] is the global working load (m-h).



Welding semiautomatic:	C8° = 10 BEF/m (0.25 Euro/m) (C8 = 17% by mm	C8° = 36 BEF/m (0.90 Euro/m) (C8 = 30% by mm
Manual Welding:	C8° = 12 BEF/m (0.30 Euro/m) DC8 = 22% by mm	C8° = 40 BEF/m (1.00 Euro/m) DC8 = 24% by mm

Fig. 3 Consumable costs for 1 m of welding of a stiffener (two welds)



Semiautomatic Welding:	P	=	2 min/m	P	=	10 min/m
	ΔP	=	32% by mm	ΔP	=	25% by mm
Manual Welding:	P	=	8 min/m	P	=	31 min/m
	ΔP	=	29% by mm	ΔP	=	20% by mm

Fig. 4 Variation in welding work load (labor) according to plate thickness (for two welds)

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

where

P_4 = 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;

P_5 = working load to weld 1 m of a transversal stiffener on the plating (m-h/m)
= 0.6 to 1.2 m-h/m;

P_6 = 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;

P_7 = 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., $\beta_X = 0.33$ means one bracketed longitudinal on 3 and $\beta_Y = 1.0$ a bracket on each frame);

P_9 = working load to build 1 m of stiffener (assembling flange and web) from standard plates in the production plan (m-h/m). Note: If α_X and $\alpha_Y = 1$ [equation (11)], P_9 is not required;

P_{10} = 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:

$$P_4 = P_4^0 [1 + (d_X - E_0) \cdot 10^3 \cdot \Delta P_4]$$

$$P_5 = P_5^0 [1 + (d_Y - E_0) \cdot 10^3 \cdot \Delta P_5]$$

$$P_9(X) = P_9^0 [1 + (d_X - E_0) \cdot 10^3 \cdot \Delta P_9]$$

$$P_9(Y) = P_9^0 [1 + (d_Y - E_0) \cdot 10^3 \cdot \Delta P_9]$$

where

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

P_4^0, P_5^0 and P_9^0 = P_4, P_5, P_9 working loads for the E_0 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_4^0, P_5^0 and P_9^0 working loads. (16)

$$P_{10} = P_{10}^0 [1 + (\delta - E_0) \cdot 10^3 \cdot \Delta P_{10}] \quad (17)$$

where

δ = plate thickness;

P_{10}^0 = working load to prepare 1 m^2 of plating having the E_0 reference thickness (m-h/m^2).

ΔP_{10} = change (in %), per mm of δ, of the P_{10}^0 working load.

The aforementioned average values of P_4^0, P_5^0, P_6^0, P_7^0, P_9^0 and P_{10}^0 working loads are available in the literature (Winkle & Baird 1986, Rahman & 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. 4).

Example of least-cost optimization

The least-cost optimization example concerns the optimization of a Floating Storage Offloading (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 tansferred on board tankers. It is a moored barge without its own propulsion system with a 2 500 000-bbl capacity. The anchorage, independent of the barge, permits an almost free motion (Fig. 5).

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 optimization of a 46-m hold composed of two center tanks of 24 m × 30 m × 46 m and two lateral ballast tanks of 6 m in width was performed. The two ballast tanks of 6 m in width was performed. The two considered loading cases are presented on Fig. 6 and the modeling is shown on Fig. 7. The maximal hull girder bending moment (without waves) has been valued at 670 000 t · m (6.57 Mio kN · m) and the shear force at 25 000 t (245 200 kN).

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

- Reference plate thickness = 10 mm
- $k = \frac{\text{Unitary Labor Cost (Euro/m-h)}}{\text{Material Cost (Euro/t):}} = 0.08$
- Unitary price of steel:
  —C_1 = 0.57 Euro/kg, ΔC_1 = −0.6% (if AE235)
  —C_1 = 0.65 Euro/kg, ΔC_1 = −0.6% (if AE355)
- Unitary price of welding (materials only):
  —C_8 = 1.00 Euro/m, ΔC_8 = 15%
- Unitary working load (labor):
  —plate: P_{10} = 0.5 m-h/m^2, ΔP_{10} = 7%
  —frames (assembling with plate):
  $P_4 = P_5 = 1$ m-h/m, $\Delta P_4 = \Delta P_5 = 10\%$
  —frames (if built on site):
  $P_9 = 0.5$ m-h/m, $\Delta P_9 = 1\%$

The mesh model of the FSO unit includes:

- 22 stiffened panels with nine design variables each;
- two additional panels to simulate the symmetry axis (or boundary conditions);
- 198 design variables (9 × 22 panels);
- 48 equality constraints between design variables;

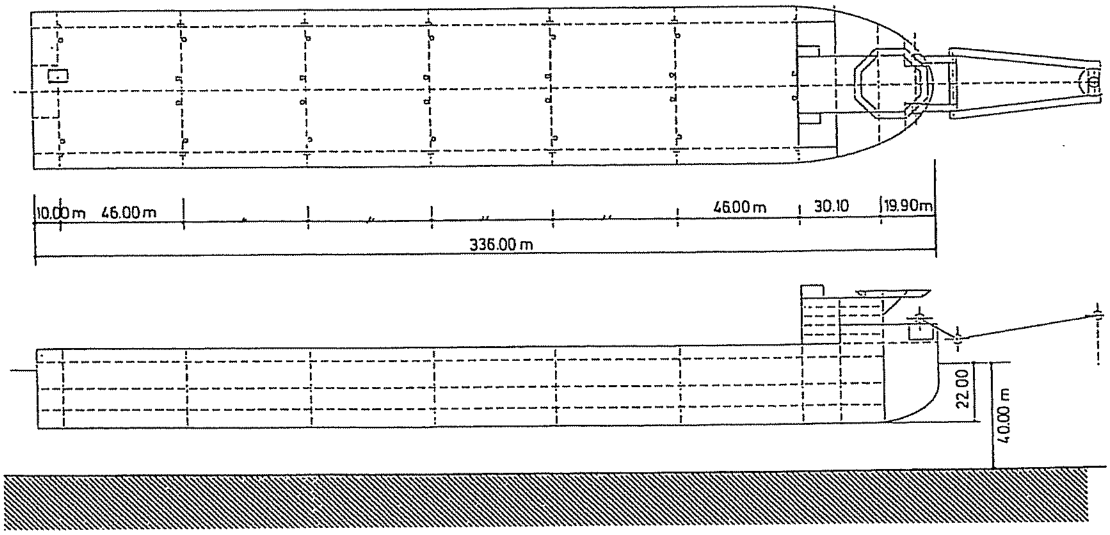


Fig. 5 General view of FSO barge

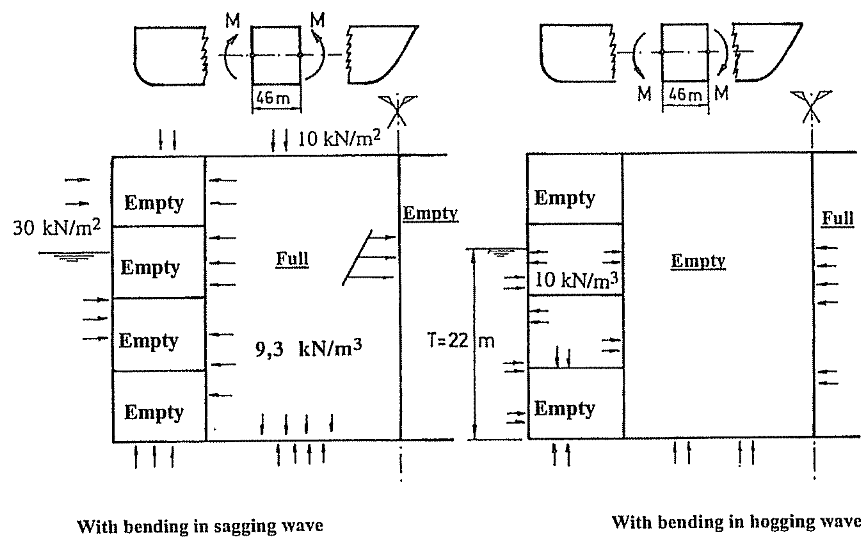


Fig. 6 Considered loading cases

- 198 geometrical constraints (9 × 22 panels);
- 396 structural constraints (198 by load case);
- two constraints on the hull ultimate strength.

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) concern Δ_{Frames}, $\Delta_{Stiffeners}$, h_{web} frames (center tanks), h_{web} frames (side tanks), web thicknesses, 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 (C_1 to C_6):

- Optimum for δ (plating) ≤ 40 mm
  - —Least cost:
    - $C_1 = \Delta_{FRAMES}$ (side tanks) $= \Delta_{FRAMES}$ (center tanks)
    - $C_2 = \Delta_{FRAMES}$ (side tanks) $= \frac{1}{2}\Delta_{FRAMES}$ (center tanks)
  - —Least weight:
    - $C_3 = \Delta_{FRAMES}$ (side tanks) $= \Delta_{FRAMES}$ (center tanks)
    - $C_4 = \Delta_{FRAMES}$ (side tanks) $= \frac{1}{2}\Delta_{FRAMES}$ (center tanks)
- Optimum for δ (plating) ≤ 30 mm
  - —Least cost:
    - $C_5 = \Delta_{FRAMES}$ (side tanks) $= \Delta_{FRAMES}$ (center tanks)
  - —Least weight:
    - $C_6 = \Delta_{FRAMES}$ (side tanks) $= \Delta_{FRAMES}$ (center tanks)

Note that costs and weights (Table 1) refer to a half-structure (30-m wide) and that stiffening and bracketing (transverse members, webs, etc.) are not included in the weight.

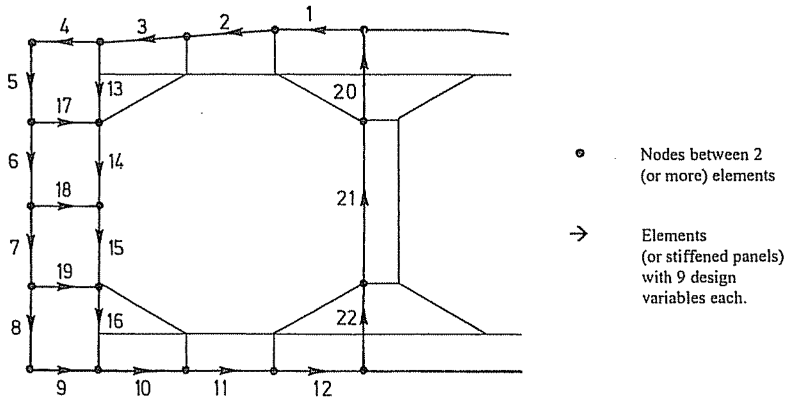


Fig. 7 Mesh modeling used for LBR-5 for FSO midship section

Table 1 Comparison between the different optimum (after 10 iterations)

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

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

Most advisable scantlings (design)

As an example of typical LBR-5 outputs, the optimal scantling of three design variables is presented in Fig. 8 for δ ≤ 40 mm (least cost).

The "raw" scantling presented in this figure is not *ready to use.* It requires minor changes (Fig. 9) 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 shells 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 shows that (Table 1):

- 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 (δ ≤ 30 min) as a side constraint.
- If one selects δ ≤ 40 mm, the optimum scantling varies considerably depending on whether one searches for optimum weight or optimum cost. For instance, the optimum number of frames varies from N = 6 to N = 15.
- 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 scantlings are nearly identical. This is particularly the case for the frame scantling (as N = 14 for each optimum design).
- 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).

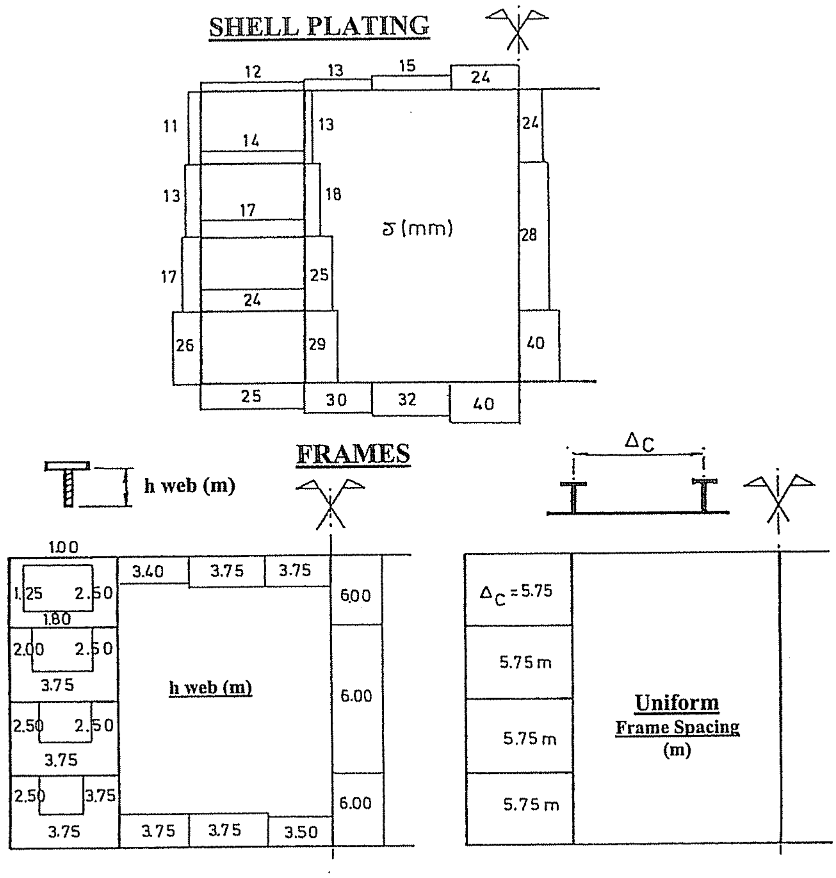


Fig. 8 Optimal scantling of FSO barge (least cost –δ ≤ 40 mm, Δ = 5.75 m)

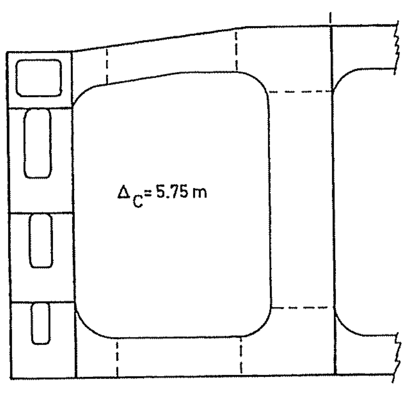


Fig. 9 Optimal scantlings of FSO barge (least cost –δ ≤ 40 mm, Δ = 5.75 m)

• 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 δ ≤ 40 mm and 18% for δ ≤ 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%):
—δ ≤ 40 mm with seven frames (Δ = 5.75 m)
—cost per kilo: 2.17 Euro/kg
for least weight (C = 106%, P = 101%):
—δ ≤ 40 mm with 8 frames (Δ = 5.11 m)
—cost per kilo: 2.42 Euro/kg

• 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).

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.

LBR-5 is composed of three 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 these 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 reanalysis is rather small.

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