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A module-oriented tool for optimum design of stiffened structures—Part I

Philippe Rigo*

University of Liege, Department of Naval Architecture (ANAST), Chemin des Chevreuils No. 1, B52/3 B-4000 Liege, Belgium

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Abstract

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. This paper is the first part of a series of two articles. It focuses on the '*Module-Oriented Optimization*' methodology and on *the rational constraints*. The second paper presents the optimization technique using convex linearization and a dual approach, and the optimization of an FSO unit as an example (Rigo and Fleury, Marine Stuructures, 2001). LBR-5 allows, as of the first draft, an optimization of the scantling of the structure's constituent 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 behaviour. The optimization module is composed of 3 basic modules (OPTI, CONSTRAINT and COST) and a group of sub-modules (in external databases). Among these the user selects a set of relevant sub-modules (i.e. geometrical and structural constraints). Since the present optimization deals with least construction costs (as objective function), and uses an explicit objective function (not empirical), the user must specify labor costs (unitary material costs, welding, cutting, etc.). © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Optimization; Preliminary design; Stiffened structure; Construction cost; Design methodology; Rational constraints; Structural constraints; Limit states

*Tel.: +32-43-66-93-66; fax: +32-43-66-91-33.
E-mail address: ph.rigo@ulg.ac.be (P. Rigo).

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1. Introduction

Ship sizing (scantling) always poses numerous problems to designers. Floating structures are indeed complex, 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 into two, or even three layers. Each stiffener group has its own function and is characterised by a different geometry and size. Optimization of these complex structures is the purpose of this paper.

Structural design is always defined during the earliest phases of a project. It is thus not difficult to understand why a preliminary design stage optimization tool is attractive. This is precisely the way the LBR-5 optimization software for stiffened structures was conceptualised [1–3]. "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 and a minimum construction cost objective function. Alternatively a least weight objective function can be used. 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 [4,5]. 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.

This paper describes the scientific aspects of the rational optimization procedure, the innovative concept and methodology, and the way they are implemented. It focuses on the "Module-Oriented Optimization" concept (see Section 2) and on the CONSTRAINT module (see Section 4.). The LBR-5's major uniqueness is how the different modules interact. A detailed application on the optimization of a floating storage offloading unit (FSO) and the relevant information on the mathematical algorithm of the OPTI module are available in the second paper [5]. Soon, a third paper will be published with advanced information on the COST module. Presently, detailed information on these 2 modules can be found in [1–3].

The second major aspect is 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 5.3) 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, modelling speed and ease of use provide precious help to designers. At this moment, few parameters/dimensions have been definitively fixed and a coarse modelling by standard finite elements is often unusable. For ships, the application domain is clearly the ship's central part (cylindrical and prismatic zone of cargo ships, passenger vessels, etc.). This zone is the most important in length for the big floating units (FSO). For smaller units (sailboats, small craft, etc.), the cylindrical 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 [1,2,6–11]. The most well known methodology for the design of naval and marine structures is the "Design Spiral" [12–18]. Despite its age, it is still up-to-date. However the current tendency is to break with this design process and move towards "Concurrent Engineering" [19,20]. As this paper is oriented towards stiffened structures, especially naval and hydraulic structures, we limit the bibliographic analysis to problems of these types, with special attention to linear elastic analysis of orthotropic structures. For other limit states (buckling, vibration, ultimate strength) we refer the reader to the author's references [1,2].

LBR-4 [21,22], the previous version of the "stiffened panel method" for elastic analysis of stiffened structures, was the starting point for the development of the LBR-5 optimization module presented in this paper [1,2]. The role of LBR-4 is to provide a fast and reliable assessment of the stress pattern existing in the 3D stiffened structure. The selection of relevant cost-effective stress and strain models is indeed a difficult problem that has been considered in many studies [23,24]. Analytic approaches similar to LBR-4 were also proposed [25–27]. Other valuable references are [28–31] and the ISSC reports (International Ship Offshore and Structures) [32–34].

The first ship structure optimization studies were made essentially by hand [35]. Then, with computer assistance, researchers tried to develop design and optimization algorithms [13,33–39]. The works of Moe and Nowacki [38] long served as a reference for naval structure optimization [38]. An important step for naval structure optimization appeared with Hughes' works [29,41–43]. The evolution of design techniques and optimization are also reported by ISSC [44–50].

The term "ship structural optimization" has a different meaning according to the person or the group for whom the study is done. 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 used as topological design variables.

The LBR-5 software is the result of the integration inside the same package of the LBR-4 and CONLIN [4] software and constitutes a new tool to precisely achieve this type of optimization, i.e. to define the optimum scantling [1,2]. Concerning such optimization, one notes that since 1980 the FEM has become a standard to evaluate constraints on stress, displacement and ultimate strength at each iteration [29,41]. 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 [4,51], or to divide the optimization problem of the structure into two levels [41,52–56]. The first alternative is used in this study.

Methods similar to LBR-5 are proposed by Hughes [41–43] with Maestro, Rahman [53,54], Sen [55] and more generally in [52–54,57–62,64]. Compared to Maestro [41–43], LBR-5 is more preliminary design oriented. The structure modelling is so simple and fast, but not simplified, that optimized scantling can be obtained 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 regard to 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 [63]), 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. Sen's model [55,64] 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 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.

2. 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, naval, 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 himself to build the tool he needs.

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 user can do his "shopping", i.e. 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 organisation 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.

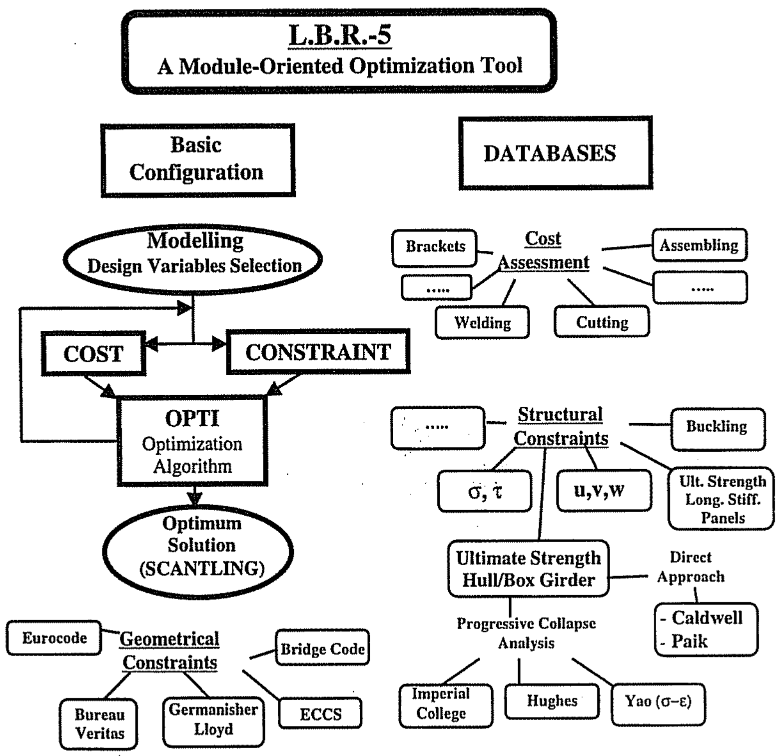


Fig. 1. Basic configuration of the LBR-5 model and database presentation.

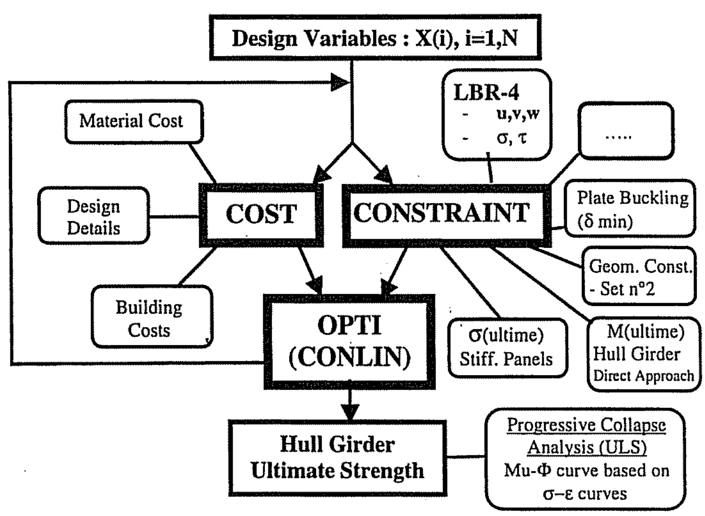


Fig. 2. LBR-5 flow chart after sub-module selection (constraints and cost data).

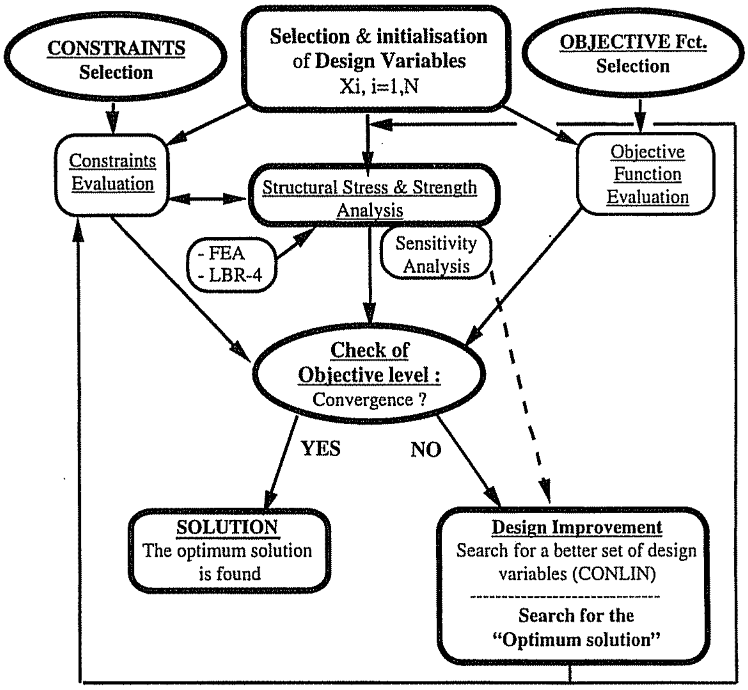


Fig. 3. General organisation flow chart of a structure optimization process.

3. Description of the 3 basic modules: OPTI, CONSTRAINT and COST

The problems to be solved can be summarised as follows:

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

The structure is modelled with stiffened panels (plates and cylindrical shells) (Fig. 5). 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,

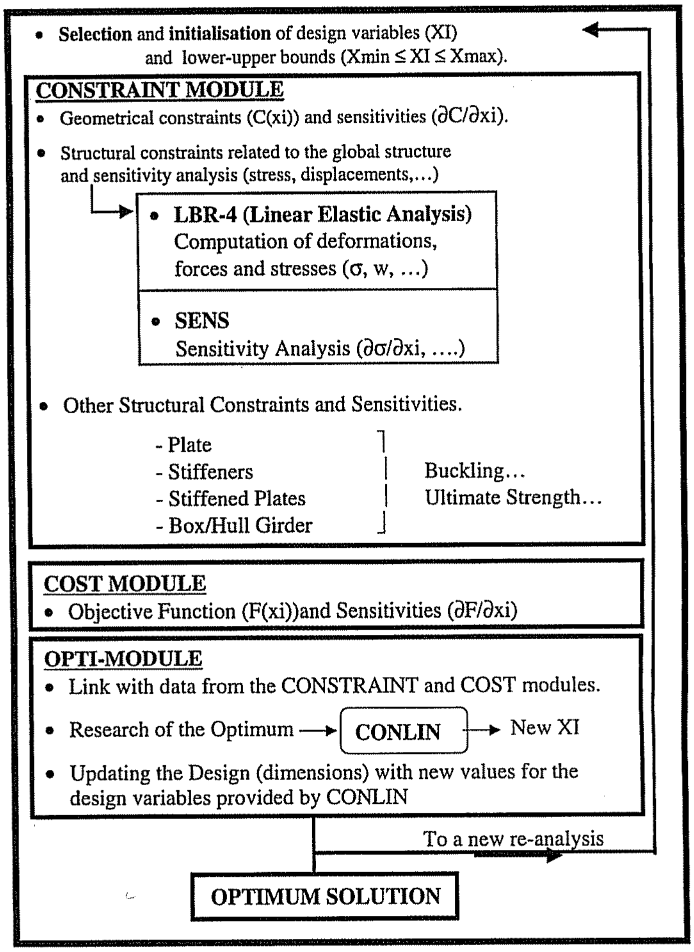


Fig. 4. Chart of the LBR-5 model with CONSTRAINT, COST and OPTI modules.

- flange width,
- spacing between 2 transverse members (frames).

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 [4,51,63]. This module uses as inputs the results/outputs of the two other basic modules, i.e. CONSTRAINT for the C(XI) constraints and COST for the F(XI) objective function.

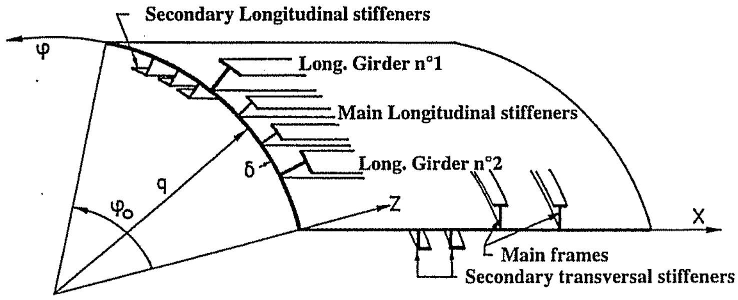


Fig. 5. Basic stiffened panel (or basic element) used to model the structures.

Due to the choice of a dual algorithm (CONLIN), the treatment of side constraints ($X_{i\,min}$ and $X_{i\,max}$) is particularly easy. Thus we can dissociate them from other constraints ($Cj(X_i) \leqslant CM_j$), which is particularly attractive.

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).

Up to now, 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 (X_i), 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 [40].

These unit costs vary according to the type and the size of the structure, the manufacturing technology (manual welding, robots, etc.), 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.

The **CONSTRAINT module** (see next section) 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 (Eurocodes, ECCS Recommendations, Classification Societies, etc.)

4. Structural and geometrical 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: $X_{i\,min} = 4\,\text{mm} \leqslant X_i \leqslant X_{i\,max} = 40\,\text{mm}$,
  with: $X_{i\,min}$ a thickness limit dues to corrosion, etc.
  $X_{i\,max}$ 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 thickness with one that is 5 mm thick is not recommended.
  Example: $0.5 \leqslant X2/X1 \leqslant 2$
  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 modelled 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 $\sigma_c = \sigma_{\text{von Mises}}$),
- Safety level related to buckling, ultimate resistance, tripping, etc.

(Example: $\sigma/\sigma_{ult} \leqslant 0.5$).

For each constraint (or solid-mechanics phenomenon), the *selected behaviour model* is especially important since this model fixes the quality of the constraint modelling.

These behaviour 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 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 behaviour 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. 6 and 7).

- Stiffened longitudinally
  - by stiffeners
    and/or
  - by crossbars and girders, prompt elements of strong rigidity.
- Stiffened transversely:
  - by transverse bulkheads, (Fig. 6a)
    and/or
  - by the main transverse framing, (Fig. 6b)
    and/or
  - by secondary or local transverse stiffeners, (Fig. 6c).

When going from the "local" to the "general" (Fig. 7), one differentiates three types of constraints:

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

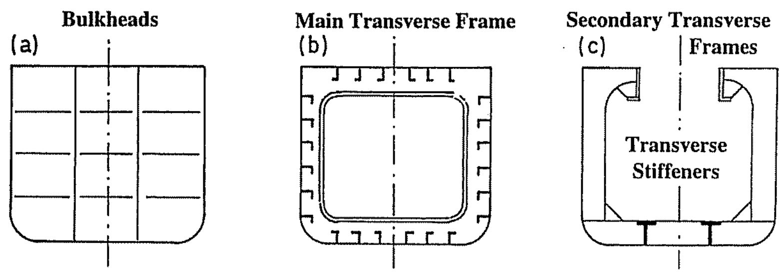


Fig. 6. Types of transverse framing.

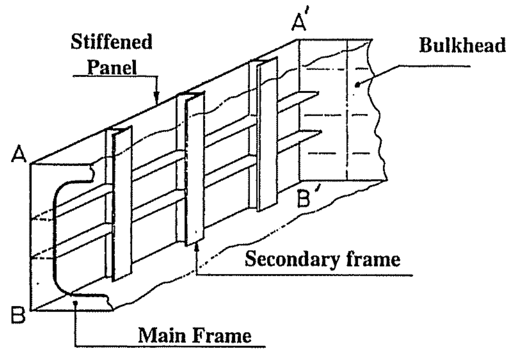


Fig. 7. A stiffened panel.

- *Constraints on stiffened panels (Fig. 7).*
  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. 7 and 8)*
  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)*
  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 state that are 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.

4.1. 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 ($M-\Phi$) shown at

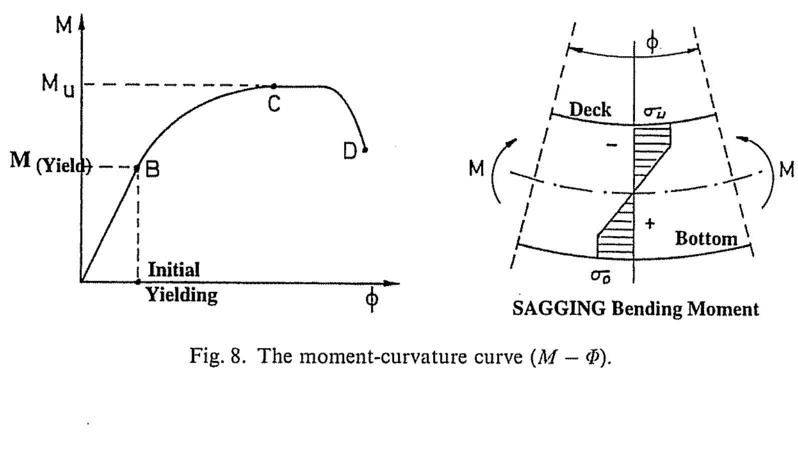


Fig. 8. The moment-curvature curve ($M-\Phi$).

Fig. 8. The ultimate state is reached when the structure can no longer support a complementary increase in the bending moment without "collapsing" completely (point D).

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 [65]. Fig. 8 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, $\sigma_{bottom} = \sigma_0$ (σ_0 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. 9 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 modelling: the beam-column (level 3 and 3bis).

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

Level 1: Ultimate bending moment of the global structure: M_u

Level 2: Ultimate strength of compressed orthotropic stiffened panels (σ_u).
$\sigma_u = \min$ [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).

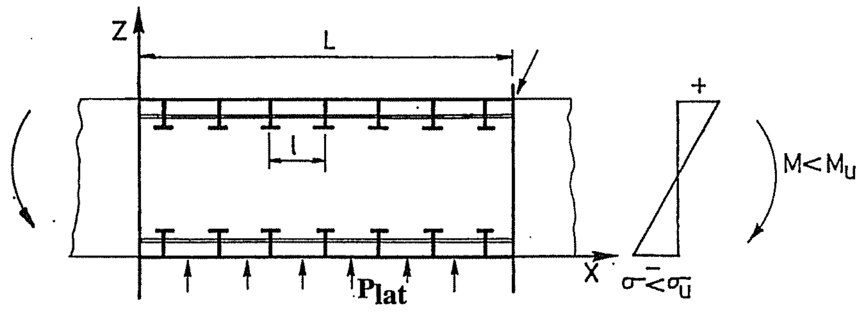
Mode c: Instability of stiffeners (local buckling, tripping, etc.).
Mode d: Yielding.

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).

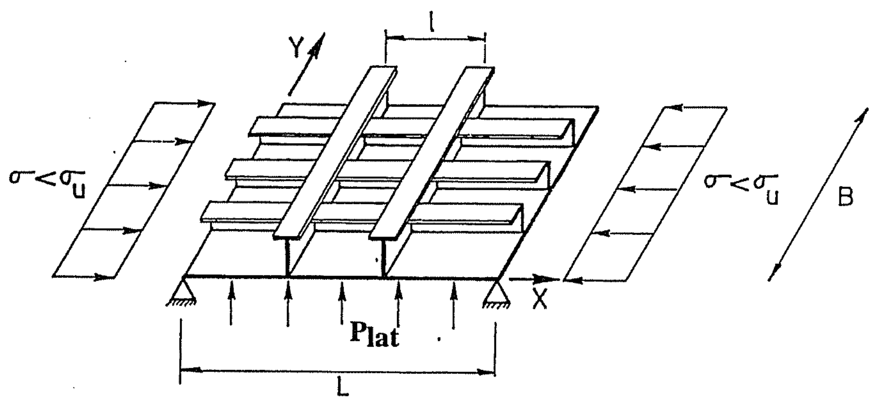
Let's note that the "b" failure mode is influenced by the buckling strength of the unstiffened plate (elementary unstiffened plate). This limit state is usually not considered as the ultimate limit state, but rather as a service limit state.

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

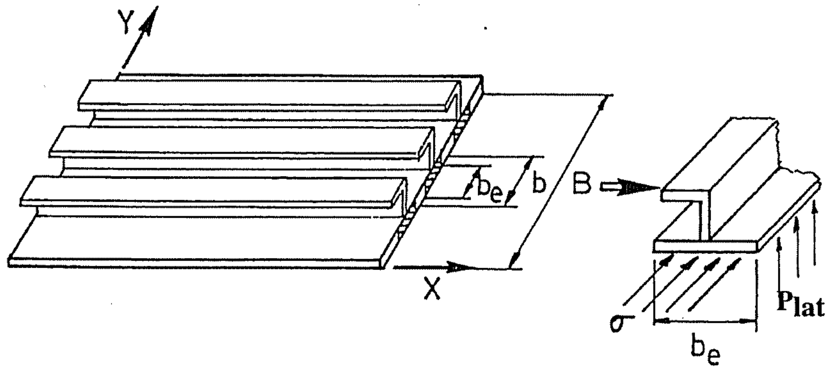
1. *Stiffened panels constraints: Service limit states*:
   1.1. Upper and lower bounds ($X_{min} \leqslant X \leqslant X_{max}$): plate thickness, dimensions of longitudinals and transverse stiffeners (web, flange and spacing).
   1.2. Maximum allowable stresses against yielding.



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. 9. Structural modelling of the structure and its components.

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 ($X_{min} \leqslant X \leqslant X_{max}$)
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, the "Ship Structure Committee [66]" presents the rational limit states selected by Hughes [29] to impose constraints (ultimate or service). Although different in several aspects (principles and methods), the two classifications perfectly match and exclude any collapse associated with a limit state not considered.

5. Summary

Within the framework of the new "module-oriented optimization" concept, the multi purpose LBR-5 optimization model is presented in this paper. The COST, CONSTRAINT and OPTI modules are the 3 basic modules. The global optimization process is presented including an emphasis on the CONSTRAINT module. The OPTI module is detailed in a second paper [5].

Advantages and main characteristics of the LBR-5 are:

- Preliminary design oriented (easy and fast modelling, 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),

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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,

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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,

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