configuration. This optimization technique can be readily used in the routine single hull or multihull ship design to minimize the wave drag.

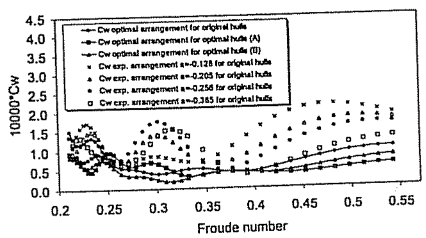

Figure 5: Wave drag coefficient for different hull forms and hull arrangements

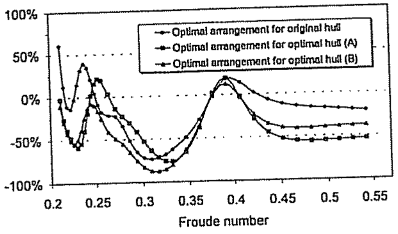

Figure 6: Wave drag reduction for different optimal hull arrangements

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Practical Design of Ships and Other Floating Structures
You-Sheng Wu, Wei-Cheng Cui and Guo-Jun Zhou (Eds)

PRADS'2001

A MODULE-ORIENTED OPTIMIZATION TOOL

Philippe Rigo

Deparment of Naval Architecture (ANAST) and NFSR[*], University of Liege,
Chemin des Chevreuils n°1, B52/3, B-4000 Liege, Belgium
(*) National Fund for Scientific Research

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 objective function. This paper focuses on the "Module-Oriented Optimization" methodology and on the rational constraints. 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. The optimization module is composed of 3 basic modules (OPTI, CONSTRAINT and COST).

KEYWORDS

Optimization, Preliminary design, Stiffened structure, Construction cost, Design methodology. Rational constraints, Structural constraints, Limit states.

1 INTRODUCTION

Floating structures are complex structures, generally composed of strongly stiffened plates, deck plates, bottom plates, and sometimes intermediate decks, frames, bulkheads, etc. 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 (Rigo 2001.a). "LBR-5" is the French acronym of "Stiffened Panels Software". Our 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/weight 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 (Figure 1) 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.

This paper describes briefly the rational optimization procedure, the innovative concept and methodology, and the way they are implemented. It focuses on the "Module-Oriented Optimization" concept and on the CONSTRAINT module. 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 Rigo (2001.b). Detailed information on the COST module is available in Rigo (2001.c).

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.

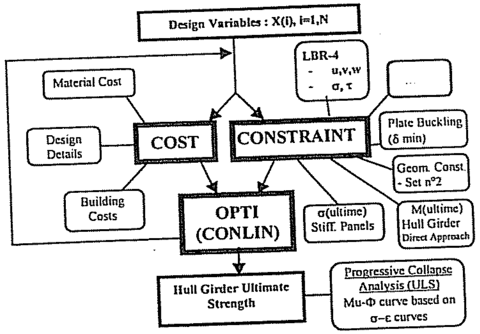

Figure 1: LBR-5 flow chart including some available sub-modules (constraints and cost data).

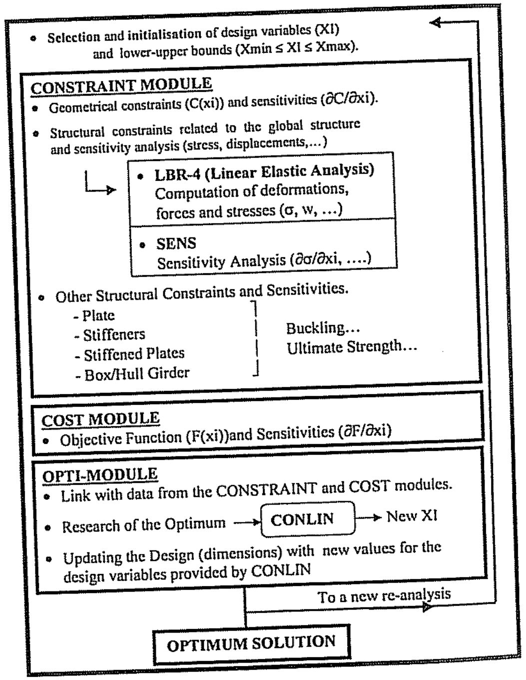

Figure 2: Chart of the LBR-5 model with CONSTRAINT. COST and OPTI modules.

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. In addition, LBR5 can be advantageously used for education and training purposes, for instance to support lectures on 'Ship Design Methodology', 'Structure Analysis', 'Ship Optimization', etc. Many papers and books have been written on design philosophy and methodology, both present and future. The most well known methodology for the design of naval and marine structures is the "Design Spiral". Despite its age, it is still used. However the current tendency is to break with this design process and move towards "Concurrent Engineering". A comprehensive bibliography review related to design methodology is presented in Rigo (2001.c).

LBR-4 (Rigo 1992), 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. The role of LBR-4 is to provide a fast and reliable assessment of the stress pattern existing in the 3D stiffened structure.

The LBR-5 software is the result of the integration inside the same package of the LBR-4 (Rigo 1992) and CONLIN (Fleury 1988) software and constitutes a new tool to achieve scantling optimization of midship section. Methods similar to LBR-5 are proposed by, for instance, Hughes and al (1992) and Rahman and al (1995). LBR-5 is essentially preliminary design oriented. The structure modelling is simple and fast, but not over-simplified.

The optimized scantling can be obtained within a couple of hours (maximum 1 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. 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.

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.

Figures 1 and 2 show 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. chôose the relevant constraints and cost data. After selecting the geometrical and structural constraints and cost assessment tools in the databanks.

3 DESCRIPTION OF THE 3 BASIC MODULES: OPTI, CONSTRAINT AND COST

The problems to be solved can be summarised as follows:

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

The structure (Figure 3) is modelled with stiffened panels (plates and cylindrical shells). For each panel one can associate up to 9 design variables (X_i). These 9 design variables are respectively:

- Plate thickness (*1*),
- For longitudinal members (stiffeners, crossbars, longitudinals, girders, etc.):
  - web height and thickness (*2, 3*),
  - flange width (*4*),
  - spacing between 2 longitudinal members (*5*)
- For transverse members (frames, etc.):
  - web height and thickness(*6, 7*),
  - flange width (*8*),
  - spacing between 2 transverse frames (*9*).

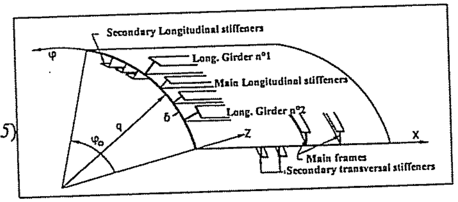

Figure 3: Basic stiffened panel (or basic element).

The **OPTI module** (Figure 2) 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 (X_i). CONLIN is based on a convex linearization of the non-linear functions (constraints and objective functions) and on a dual approach (Fleury 1989). This module uses as inputs the results/outputs of the two other basic modules, i.e. CONSTRAINT for the $C(X_i)$ constraints and COST for the $F(X_i)$ objective function. 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 ($C_j(X_i) \le CM_j$), which is particularly attractive.

The **COST module:** In 2001, 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). 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 (Rigo 2001-c). 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 (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.). 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.

4 STRUCTURAL AND GEOMETRICAL CONSTRAINTS

Constraints are linear or non-linear functions, either explicit or implicit of the design variables (X_i). 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: $X_{imin} = 4mm \le X_i \le X_{imax} = 40$ mm).
- 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, 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.
- 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.

The list of the structural 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 (Fig. 7).

- Stiffened longitudinally:
  - by stiffeners,

  and/or
  - by crossbars and girders, prompt elements of strong rigidity.
- Stiffened transversely:
  - by transverse bulkheads,

  and/or
  - by the main transverse framing,

  and/or
  - by secondary or local transverse stiffeners.

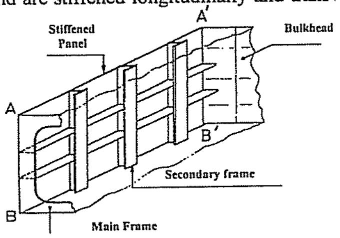

Figure 4: A stiffened panel.

When going from the "local" to the "general" (Figure 4), one differentiates three types of constraints: constraints on panels and components, constraints on frames and transversal stiffening, and constraints on the global structure.

- Constraints on stiffened panels (Figure 4).
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 (Figure 4)
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 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.

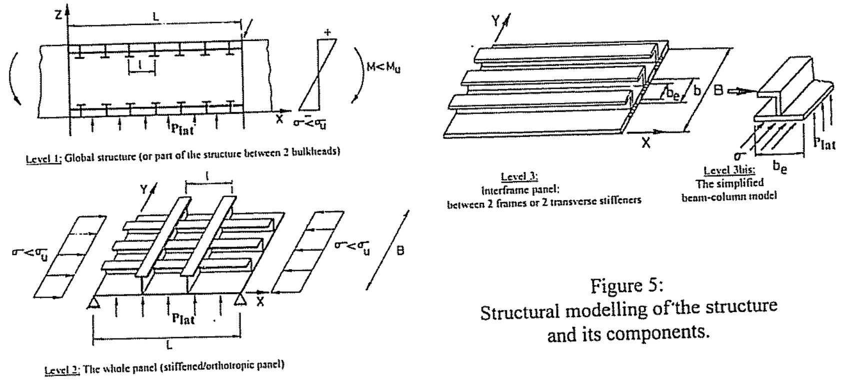

Figure 5:
Structural modelling of the structure and its components.

4.1 Ultimate Limit States

Figure 5 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 (hull girder): M_u
➧ Level 2: Ultimate strength of compressed orthotropic stiffened panels (σ_u).

$\sigma_u = \min [\sigma_u \text{(mode i)}, i = a, b, c \text{ and } d, \text{the 4 considered failure modes}]$

➧ Level 3: Mode a: Global buckling.
Mode b: P_{ult} of interframe panels (beam-column or orthotropic models)
  - 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).

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 ($X_{min} \le X \le X_{max}$),
   1.2. Maximum allowable stresses against yielding.
   1.3. Panel deflection (local deflection).
   1.4. Buckling of unstiffened plates,
   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 ($X_{min} \le X \le X_{max}$)
   2.2. Minimal rigidity to guarantee rigid supports to the interframe panels,
   2.3. Allowable stresses under the combined loads,
   Ultimate limit states
   2.4. Frame buckling of the compressed members and local buckling (web, flange).
3. General constraints
   Service limit states
   3.1. Allowable stresses,
   3.2. Global structure deflection 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.

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

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. 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,
- Rational formulation of the constraints (technologic, geometric and structural 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).

A 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. Using new 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.

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Practical Design of Ships and Other Floating Structures
You-Sheng Wu, Wei-Cheng Cui and Guo-Jun Zhou (Eds)

THE FINE OPTIMIZATION OF SHIP HULL LINES IN RESISTANCE PERFORMANCE BY USING CFD APPROACH

L. Xu and Y. Y. Wang

Department of Naval Architecture Dalian University of Technology
Dalian 116024, China

ABSTRACT

In order to complete the fine optimization of ship hull lines, a classified optimization procedure is developed in this paper. Altogether 5 levels are included in this procedure. *Level 0* is optimization of hull dimensions based on the method of experience or statistical formulae. *Levels 1*, *2* and *3* are optimizations of naked hull lines, local hull lines and appendage lines respectively. The method of Navier-Stokes equations is used with thick-layer approximation and integral numerical approach for *Level 1*, with thick-layer approximation and differential numerical approach for *Level 2*, and with partly-parabolic approximation and differential numerical approach for *Level 3*. *Level 4* is optimization of finalized hull lines by using model test with flow field measurements. The practical design of ship hull has shown that CFD code is applicable for optimization of ship hull lines in the view of hull resistance performance.

KEYWORDS

Hull resistance, Regressive analysis, Reynolds Average Navier-Stokes equations, Integral numerical approach, Differential numerical approach, Optimization procedure, Ship design.

1 INTRODUCTION

The optimization of ship form is a traditional approach in ship design and one of contents is the optimization of ship hull lines. It can be seen that the optimization technique is continuously improved along with the development of engineering science especially with the development of computer and numerical techniques.

So called optimization of ship hull lines may be regarded as lines fairing only, but this is not comprehensive both in theoretical category and in engineering practice. In fact optimization or fairing of ship hull lines can not be seen as pure mathematical or geometrical problem because it should satisfy so many engineering requirements, such as loading, general arrangement, hydrodynamic performance, and structure consideration. From this viewpoint it may be more suitable that the optimization approach is called the weighing design for ship hull lines.

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You-Sheng Wu
China Ship Scientific Research Center,
Wuxi, Jiangsu, China

Wei-Cheng Cui
School of Naval Architecture & Ocean Engineering,
Shanghai Jiao Tong University,
Shanghai, China

and

Guo-Jun Zhou
China Ship Scientific Research Center,
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