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Comparison of Rational-based and Rule-based Optimum Design of Ship Structures

D. G. Karr, Member, University of Michigan, **Ph. Rigo,** Member, University of Liege, Belgium, **S. S. Na,** Member, Mokpo National University, South Korea, and **R. Sarghiuta,** Visitor, University of Liege

ABSTRACT

Rule-based design and rational-based design are two methodologies commonly used in the structural design of ships. The rule-based design method is widely used to design existing ship types and their modifications, especially for merchant ships. The rational-based design method can be used to design new ship types and are needed for some ships for which difficulties arise in applying the rule-based design method. It is therefore meaningful to compare the design results of these two methodologies in order to better understand their advantages, disadvantages and their limitations. An appreciation of the accuracy, effectiveness, and efficiency of the methodologies should be established and verified, in part by comparing the design results with each other. In this paper, a rational-based design system (LBR-5) and a rule-based design system (ISSMID) are applied to obtain optimum designs of a VLCC double-hull oil tanker. The design results are compared for the longitudinal and transverse members spacing and sizing for an existing hold. Similarities and differences in the resulting designs are discussed.

1. INTRODUCTION

There exist essentially two basic methodologies to perform analysis and design of ship structures. The first one is rule-based design. It is mainly based on the rules defined by the classification societies. The second one is "rational-based" design. It relies much more heavily upon direct structural analyseS and the results of physics based simulations of the response of the vessel to loading conditions (Hughes 1988).

Although the rule-based design can be applied well by using simplified formulas, it is sometimes difficult to express complex failure modes with the formulas. Classification societies are now encouraging and contributing to the development of direct analysis and rational-based methods. Also, ship designers strive to develop rational and optimal designs based on direct analysis methods using the latest technologies. It is necessary for the classification societies to clarify the strength that a hull structure should have with respect to each of the various steps taken in the analysis process, from load estimation through strength evaluation. Based on recognition of this need, extensive research has been conducted regarding the strength evaluation of hull structures. The results of this work have been presented in papers regarding direct strength evaluation of ship structures (Arai 2000, DnV 1999).

In this paper, a rational-based design system (LBR-5) and a rule-based design system (ISSMID) are applied to optimum design of a double-hull oil tanker. Results are compared with an existing tanker. Our analyses are restricted to the design of longitudinal and transverse members.

For the early stages of the structural design process, the LBR-5 called "Stiffened Panels Software" allows an optimization of the scantlings of the structure's constituent elements. Relevant limit states of the structure are taken into account using three dimensional analyses of the structure based on general application of solid and structural mechanics (Rigo 1992). The optimization module is composed of 3 basic modules OPTI, CONSTRAINT and COST (see Rigo 2001, and Rigo and Fleury 2001) and a group of sub-modules in external databases. The LBR-5 optimization deals with least construction costs (as objective function) using an explicit objective function based on unitary labor costs (unitary material costs, welding, cutting, etc.).

The ISSMID is used for the optimum design of the mid-ship part of double-hull oil tankers by adding an optimization algorithm from the existing ISSMID (Na et al. 1994). A relative fabrication cost concept (Winkle and Baird 19886) is adopted for the estimation of structural fabrication costs of the ship. A new structural cost model is built considering welding technique, welding poses and assembly stages for the several erection blocks being made simultaneously. A random search method (RS), a kind of multi-objective function method (Schwefel 1994), is newly developed to find the minimum structural weight and fabrication cost. Thus, ISSMID produces several structural designs based on the Pareto optimal set obtained by the RS method.

2. RATIONAL-BASED OPTIMUM DESIGN OF SHIP STRUCTURES

Guidelines and major orientations of a ship structural design are always defined during the earliest phases of a project, i.e. the preliminary design stage or the first draft that corresponds in most cases to the offer. It is thus easy to understand why an optimization tool is attractive, especially one designed for use at the preliminary stage. This is precisely the way the LBR-5 optimization software for stiffened hydraulic and naval structures was conceptualized, created and developed. 'LBR-5' is the French acronym of "Logiciel des Bordages Raidis", i.e. "Stiffened Panels Software", version 5.0.

The final 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. Rigo (2001) discusses more extensively this important aspect. 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 scantlings are not mandatory. Designers can start directly with an automatic search for optimum sizing (scantlings). 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) (Figure 1). Presently, detailed information on these 3 modules can be found in sited references.

The "stiffened panel method" (Rigo 1992) for elastic analysis of stiffened structures, was the starting point for the development of the LBR-5 optimization module. Its role is to provide in the CONSTRAINT module a fast and reliable assessment of the stress pattern existing in the 3D stiffened structure. So, the LBR-5 software is the result of the integration inside the same package of the LBR and CONLIN software and constitutes a new tool to achieve a structural optimization, i.e. to define the optimum scantlings.

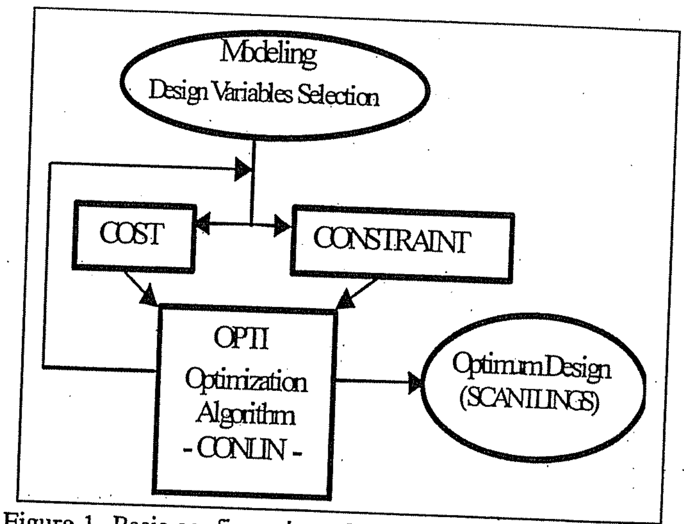


Figure 1. Basic configuration of the LBR-5 model and database presentation.

The development of the LBR-5 module is also included in the development of a new design framework proposed for general simulation based design environments (Karr et al. 2002).

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

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,
- $Cj(X_i) \leq CM_j$ $j = 1,M$ 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 is modeled with stiffened panels (plates and cylindrical shells) (Figure 2). For each panel one can associate up to 9 design variables (XI). These 9 design variables are respectively:

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

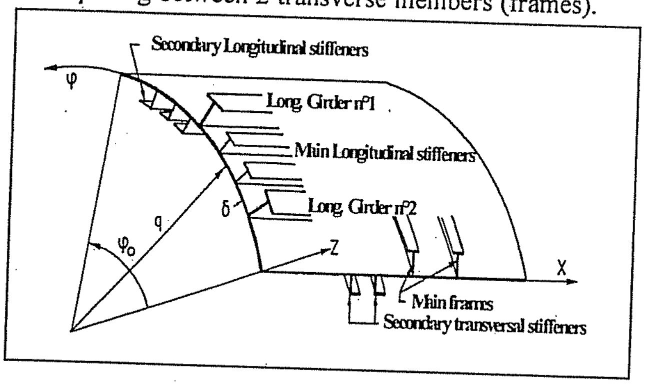


Figure 2. Basic stiffened panel (or basic element) used to model the structures.

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). In addition, due to the choice of a dual algorithm (CONLIN), the treatment of side constraints (Xi min and Xi max) is particularly easy. Thus we can dissociate them from other constraints (Cj (Xi) ≤ CMj), which is particularly attractive.

The OPTI module is based on the CONLIN code developed by C. Fleury [6] using a convex linearization of the constraints and the objective function combined in a dual approach. With this algorithm, large constrained problems with implicit and non-linear constraints can be easily solved. The main difficulty in solving a dual problem is dealing with the non-linear and implicit constraints. In order to avoid a large number of time-consuming re-assessments of these non-linear and implicit functions, Fleury suggests applying convex approximations. At each iteration, all the functions (objective function and constraints) are replaced by an approximation called "convex". In essence, the complex initial optimization problem is decomposed in a sequence of more simple convex optimization problems (obtained through a convex linearization) that can be easily solved using a dual approach.

In order to consider non-linear implicit constraints ($C(X_i)$), we replace the constraints with approximated explicit linear constraints by using convex linearization using the first term of the Taylor Series Expansion.

- Convex linearization with mixed variables (X_k, k= 1,L) and ($1/X_j$, j= L+ 1,N) is formulated by:

$$C(X_i) = \tilde{C}(X_i) = C(X_i(0)) + \sum_{k=1}^{L} \left[X_k - X_k(0)\right] \cdot \partial C(X_k(0))/\partial X_k + \sum_{j=L+1}^{N} \left[1/X_j - 1/X_j(0)\right] \cdot \partial C(X_j(0))/\partial(1/X_j) \qquad (1)$$

The substitution design space is conservative, this leads to a solution that is still admissible, but that could be "slightly" different from the real optimum. Step by step, this conservatism is released as one comes closer to the real optimum.

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

For a given design variable X_i :

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

The **COST module** [7]: Presently many agree that 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 or life cycle cost optimization.

Up to now, the objective function of the LBR-5 software can be the construction costs (COST module)

or the weight (example: 60% of the cost and 40% of the weight). In order to link the objective function (Euro) to the design variables (Xi), the unit costs of raw materials (Euro/Kg), the productivity rates for welding, cutting, assembling, etc. (man-hours/unit of work = m-h/unit) and labor costs (Euro/mh) must be specified by the user.

These unit costs vary according to the type and the size of the structure, the manufacturing technology (manual welding, robots, 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 scantlings can also be performed, thus providing the manager with valuable information for improving the yard.

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

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

So one can distinguish:

- Technological constraints (or side constraints) that provide the upper and lower bounds of the design variables. For example: Xi min = 4mm ≤ Xi ≤ Xi max = 40 mm, with: Xi min a thickness limit dues to corrosion, etc; Xi max a technological limit of manufacturing or assembly.
- Geometrical constraints impose relationships between design variables in order to guarantee a functional, feasible, reliable structure. They are generally based on "good practice" rules to avoid local strength failures (web or flange buckling, stiffener tripping, etc.), or to guarantee welding quality and easy access to the welds.
- Structural constraints represent limit states in order to avoid yielding, buckling, fracture, etc. and to limit deflection, stress, etc. These constraints are based on solid-mechanics phenomena and modeled with rational equations. By rational equations, we mean a coherent and homogeneous group of analysis methods based on physics, solid mechanics, strength and stability treatises, etc. and that differ from empirical and parametric formulations.

Thus, these rational structural constraints can limit:

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

The limit states 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.

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

1. Stiffened panels constraints:

Service limit states

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

Ultimate limit States

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

2. Frames constraints.

Service limit states

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

Ultimate limit states

2.4. Frame buckling,

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

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

<u>General constraints</u>

<u>Service limit states</u>

3.1. Allowable stresses,

3.2. General deflection of the global structure and relative deflections of components and panels.

<u>Ultimate limit states</u>

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.

Application of the LBR-5 to the VLCC vessel:

The mesh model (Figure 3) of the tanker hold includes 47 stiffened panels (Figure 2) and on average 9 design variables per panel:

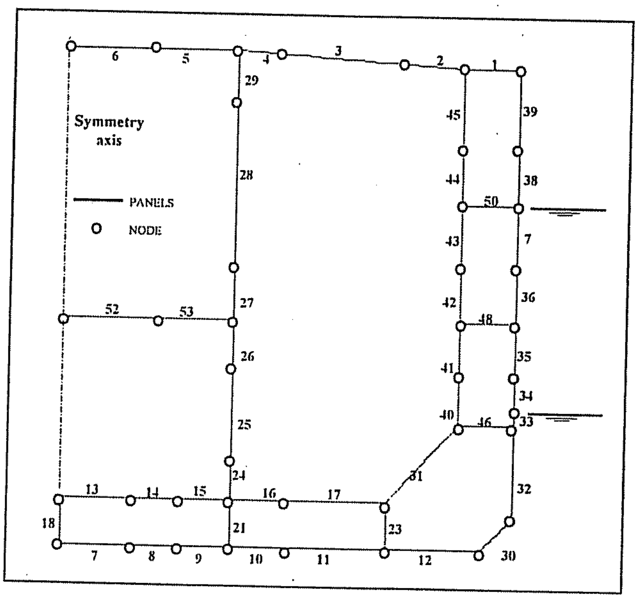


Figure 3. LBR5 product mesh model

- NT = 423 design variables (9 x 47 panels);
- NE = 70 to 250 equality constraints between design variables. This number changes according to level of standardization. For instance, uniform deck plating requires 5 equality constraints and identical stiffeners in the double bottom needs 44 equality constraints.
- NI = 173 to 353 independent design variables (NI= NT-NE).
- 2015 structural constraints (403 x 5 load cases; 8~11 constraints per panel);
- 2 constraints on the hull ultimate bending moment;
- 1 constraint on the vertical position of the gravity center, 198 geometrical constraints (7 x 47 panels).

Structural constraints mainly concern:

- plate yielding (von-Mises) and plate buckling,
- stiffener yielding (web and flange),
- frame yielding (web and flange),
- stiffener ultimate strength.

Geometrical constraints deal with:

- slenderness of the web stiffeners,
- ratio between web height and flange width (for stiffener only),
- ratio between plate and web thickness' (for stiffeners and frames),
- ratio between flange and web thickness' (for stiffeners and frames).

Figures 4a and 4b gives the transverse deflection and the longitudinal stress distribution (including primary and secondary bending stresses).

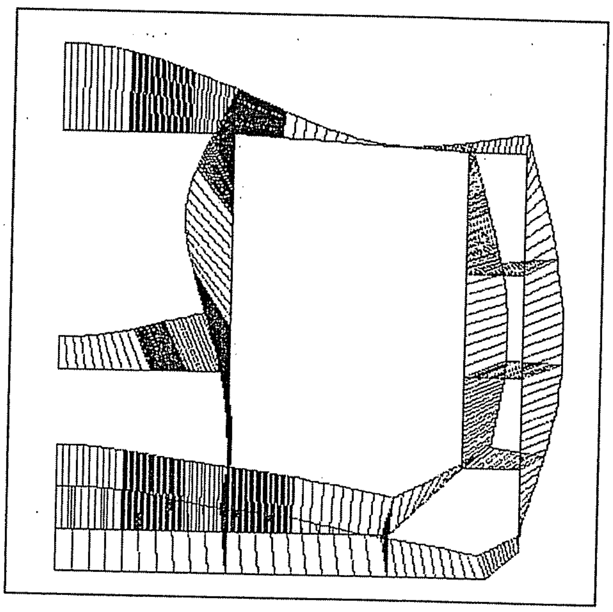


Figure 4a. Transversal displacement (δ)

At mi-span of a block, δ_{max} = 30 mm, 2D analysis using a refined mesh model, (Load case 1)

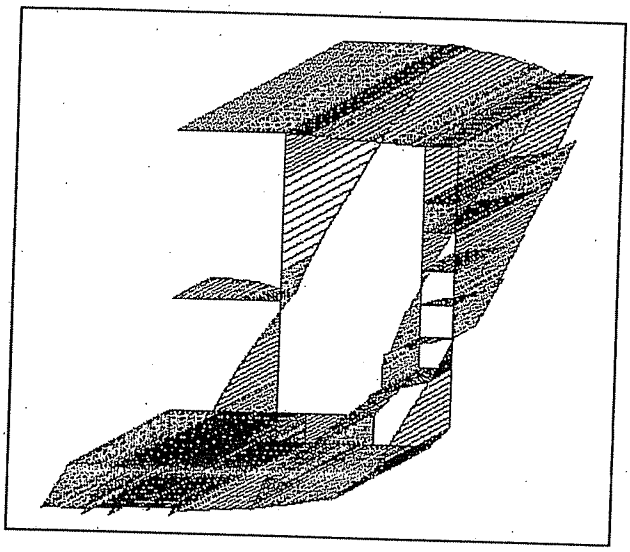


Figure 4b. Longitudinal stress $\sigma(x)$ = 210 N/mm^2, 3D analysis (Sagging + load case 2)

3. RULE-BASED OPTIMUM DESIGN OF SHIP STRUCTURES

3.1 ISSMID System

3.1.1 Structural Arrangement Module

A convenient graphic user interface is developed by using the X-Window OSF/MOTIF. Users can handle the program easily with the graphic user interface windows by using the pull down menus. The main menus contain functions grouped under these titles: ship data input, design mode selection, structural part selection, scantlings calculations, results output and design data storage. The ship's structural members can be grouped into three major parts: longitudinal, transverse and transverse bulkhead members. Each one is divided into sub-parts. Users can manipulate the design data of each sub-part in three different modes - configuration, plate and stiffener modes.

When users design some structural parts, they first define the configuration and then define the plate and stiffener data. The configuration data are height and breadth of the structural members. The plate data are material, seam and thickness. The stiffener data are material, space, type and size.

3.1.2 Scantlings Module

The scantlings module is designed to determine the scantlings of the longitudinal, transverse members. The scantlings of the longitudinal members such as the plate thickness and the shape of longitudinals, except the deck plate thickness, is determined by the rule minimum requirements for the DnV, Lloyd and ABS classifications. The deck plate thickness, the longitudinal and web frame spaces are determined to minimize the mid-ship section area within the longitudinal hull girder strength.

The scantlings of the transverse web frame members such as web height and thickness is determined to minimize the volume of web frame within the allowable stresses. The generalized slope deflection method, which considers the axial deformation from the existing slope deflection method, is adopted to obtain the bending, shear and equivalent stresses.

As shown in Figure 5, the middle part of the ship structure for one web frame space can be modeled as web frame structure using beam elements. The rule loading conditions for the DnV classification are used to obtain the stresses.

3.1.3 Interface Module

The interface module is designed to produce the data for the structural analysis (ANSYS/NASTRAN) and the CAD system (TRIBON). The analysis data such as key points and patches are produced by using the structural arrangement and scantlings module. Also, the CAD data such as scantlings of structural members are produced.

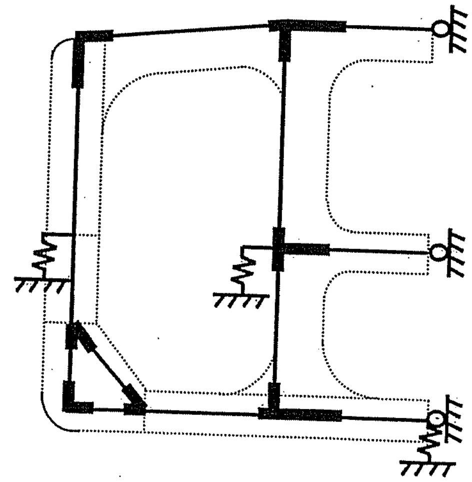


Figure 5. Modeling of transverse member

3.2 Optimization Method

3.2.1 Objective Functions (F_1, F_2)

The object functions are structural weight (F_1) and fabrication cost (F_2). The structural weight represents hull weight of one cargo hold except transverse bulkhead member.

The fabrication cost is obtained by summation of the material and labor costs for each block. The material and labor costs are based on welding technique, welding pose and assembly stages.

The material cost (C_M) and labor cost (C_L) are calculated as follows.

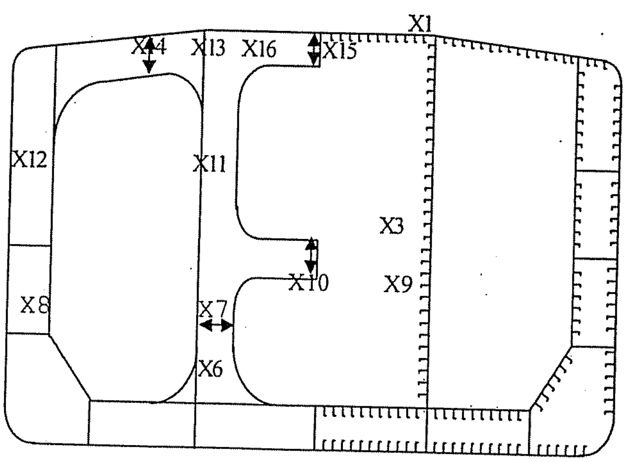
C_M = Structural Weight x Unit Material Cost
C_L = Joint Length x Unit Joint Man-Hour
x Unit Labor Cost
+ Weld Length x Unit Weld Man-Hour
x Unit Labor Cost

3.2.2 Design Variables (X)

As shown in Figure 6, the design variables are: deck plate thickness (X1), longitudinal spaces (X2~X3) for the longitudinal members; height and thickness of each web (X4~X16) for the transverse members.

3.2.3 Constraints (G)

The minimum deck plate thickness (T_D), minimum hull section modulus (S_B, S_D) at bottom and deck are considered as the constraints of the longitudinal members. Also, the allowable equivalent stress (σ_a), allowable shear stress (τ_a) and minimum web thickness (t_m) to prevent buckling of each web are considered as the constraints of the transverse members.



X5 X4 X2

Figure 6. Design variables

3.2.4 Multi-objective Function Method

A multi-objective function method, random search (RS) method, is developed to find the minimum structural weight and fabrication cost. The RS method is developed based on the Pareto optimal set when producing the points of the next iteration.

The optimization process is as follows:

1) Generate initial points randomly throughout the design space, and make discrete design variables.

$$(x_j)_i = (x_j)_{\min} + r_1 * \{(x_j)_{\max} - (x_j)_{\min}\} \qquad (2)$$

r_1 = RAN( ) : $0.0 < r_1 < 1.0$
$(x_j)_{min}$ = Minimum value of each design variable
$(x_j)_{max}$ = Maximum value of each design variable
i = Current number of design point ($1 \le i \le NPI$)
j = Current number of design variable ($1 \le j \le N$)
NPI = Number of initial points
N = Number of design variables

2) Calculate the object functions, constraints and penalty functions, and select good points, which satisfy the constraints.

$$\left.\begin{aligned}(P_1)_i &= F_1((x_j)_i) + \lambda_1 \sum_{ic=1}^{NC} \max\{-G(ic),0\} \\ (P_2)_i &= F_2((x_j)_i) + \lambda_2 \sum_{ic=1}^{NC} \max\{-G(ic),0\}\end{aligned}\right\} \qquad (3)$$

λ_1, λ_2 : Lagrange multiplier
NC : Number of constraints

3) Generate new points based on the good points (or pareto optimal points), and make discrete design variables.

$$(x_j)_i = (x_j)_m + \alpha * r_2 * \{(x_j)_{\max} - (x_j)_{\min}\} \qquad (4)$$

m = RAN( ) * NPAR + 1
r_2 = 2.0 * RAN( ) − 1.0 : $-1.0 < r_2 < 1.0$
α = Search step size ($0.0 < \alpha < 0.5$)
NPAR = Number of Pareto optimal set
i = Current number of design point
($NPAR + 1 \le i \le NPS$)
NPS = Number of search points

4) Calculate the objective functions, constraints and penalty functions, and choose the points in the Pareto optimal set by checking the Pareto

optimality. The Pareto optimal set is the range of points within which it is impossible to decrease the value of a certain objective function without increasing that of other objective functions. These points become the good points for the next iteration.

5) Check the convergence conditions. When the difference of average between current and next iteration is smaller than convergence limit ε_1, reduce the step size (δ). The average ($\overline{d_n}$) is obtained by calculating the distance (d_n) from the origin to the every point in the Pareto optimal set. When δ is smaller than another convergence limit ε_2, finish the search.

$$\alpha = \alpha * c \quad (0.0 < c < 1.0)$$

$$d_n = \sqrt{\{(W_{\max} - W_m)/W_{\max}\}^2 + \{(C_{\max} - C_m)/C_{\max}\}^2} \qquad (5)$$

$$\overline{d_n} = \sum_{m=1}^{NPAR} (d_n)_m / NPAR$$

ε_1, ε_2 = Convergence limit
W_m, C_m = Current weight and cost of each Pareto optimal point
W_{max}, C_{max} = Maximum weight and cost among the good points of initial points

6) Repeat 3)~5), until these points satisfy the convergence conditions.

3.3 Estimation of Fabrication Cost

Ship cost consists of production cost (manufacturing cost plus marketing cost) and general management cost. The manufacturing cost includes material, labor and operating costs.

The concept of relative structural fabrication cost is adopted to find better designs based on only the major factors of ship cost. To estimate the cost, the direct manufacturing cost which includes material and labor costs is only considered, and the work content is limited to jointing and welding only.

Jointing and welding man-hour should be calculated considering the conditions of welding technique, welding pose and each assembly stage for better estimation of fabrication cost. In order to accomplish the above task, ship structure is divided into several erection blocks, and each erection block is divided into pre-erection block, assembly, medium-assembly, component, and fabrication. Then, work contents for each assembly stage should be classified, and joint and weld length should be obtained for each stage.

Shipbuilding companies use the Standard Fabrication Man-Hour Table as shown in Table 1, 2 for unit joint and weld length to calculate fabrication cost, according to welding technique, welding pose, and assembly stage. ISSMID uses the Standard Fabrication Man-Hour Table to estimate the fabrication cost.

Table 1 Standard Man-Hour table (Fillet welding)

Unit : mh/m

Weld Tech	Stage	Pose	Joint	Weld			
		Throat Thickness (mm)		4.0	4.5	5.0	5.5
CO_2	Assem	F	0.2	0.2	0.2	0.2	0.3
		V	0.3	0.3	0.4	0.5	0.5
	Erect	F	0.5	0.2	0.2	0.3	0.3
		V	0.6	0.4	0.5	0.6	0.7
Manual	Assem	F	0.2	0.5	0.6	0.7	0.8
		V(Up)	0.3	0.9	1.1	1.2	1.4
		V(Down)	0.3	0.3	0.4	0.5	0.6
		O	0.6	0.8	0.9	1.0	1.1
	Erect	F	0.5	0.6	0.8	0.9	1.0
		V(Up)	0.6	1.2	1.4	1.5	1.7
		V(Down)	0.6	0.4	0.5	0.6	0.7
		O	1.0	1.0	1.1	1.2	1.4

F : Flat, V : Vertical, O : Overhead, H : Horizontal

Table 2 Standard Man-Hour table (Butt welding)

Unit : mh/m

Weld Tech	Stage	Pose	Joint	Weld			
		Plate Thickness (mm)		18	20	22	24
Manual	Assem	F	0.3	5.3	6.2	7.3	8.4
		V	0.7	6.5	7.6	8.9	10.2
		H	0.7	6.1	7.2	8.4	9.7
		O	0.8	6.8	8.0	9.2	10.6
	Erect	F	1.6	6.6	7.8	9.1	10.6
		V	2.3	8.1	9.6	11.1	12.8
		H	2.2	7.7	9.1	10.6	12.2
		O	2.8	8.5	10.0	11.6	13.3
CO_2	Assem	F	0.3	2.7	3.0	3.4	3.8
		V	0.7	4.4	5.0	5.7	6.4
		H	0.7	4.3	4.9	5.5	6.2
	Erect	F	0.8	3.4	3.8	4.3	4.8
		V	1.1	5.6	6.3	7.1	8.0
		H	1.2	5.4	6.1	6.9	7.7

4. VLCC EXAMPLE RESULTS

4.1 Ship Design Parameters

Table 3 shows the principal particulars of the design ship.

Table 3 Principal particulars

Length (L)	320 m

Breadth (B)	58 m
Depth (D)	31 m
Scantlings Draft (T)	22 m
Block Coefficient (C_B)	0.826
Tank Length (T_l)	51.2 m
Web Space (F_s)	5.12 m
Total Bending Moment (M_T)	1.694 x 10^6 T-m

Figures 7 and 8 show the midship section of existing ship (300K double-hull VLCC), designed using DnV classification.

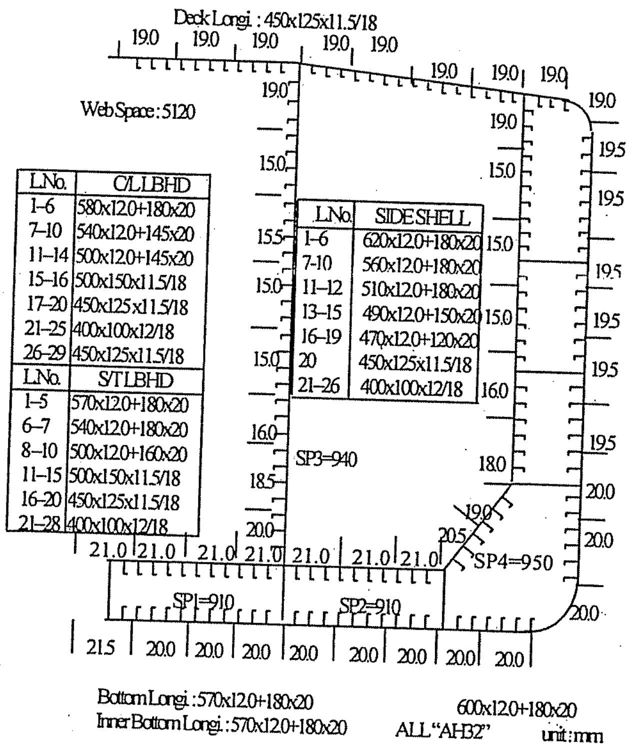
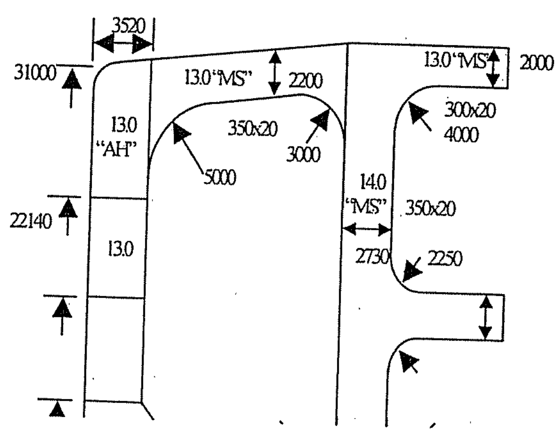


Figure 7. Midship section of existing ship (Longitudinal member)



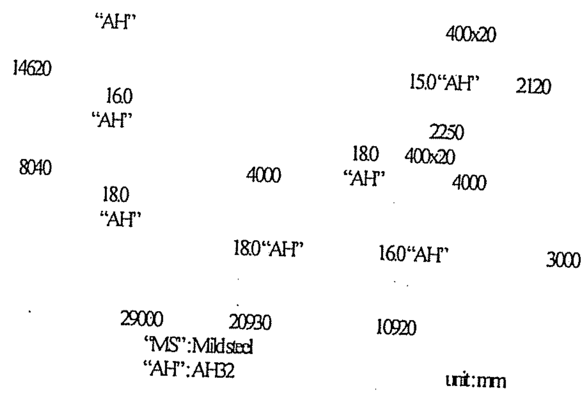
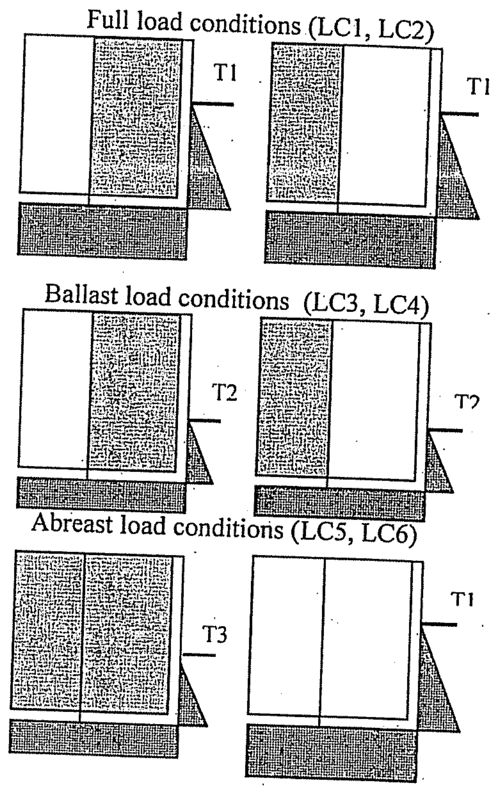


Figure 8. Midship section of existing ship (Transverse member)

4.2 Loading Conditions



$T1 = T_s + T_d$ $T2 = 0.3D$ $T3 = 0.35D$
T_s = Static draft T_d = Dynamic draft

Figure 9. Loading conditions (DnV)

As shown in Figure 9, six kinds of severe loading conditions are selected from the DnV loading conditions.

4.3 Finite Element Model

A 3D structural FE model of two cargo-holds was considered in the finite element analysis (FEA). All main longitudinal and transverse geometry was included in the model including the transverse bulkheads. The geometry of one half breadth of the structure was modeled with a total of 33065 elastic shell elements and 11000 beam elements (Figure 10).

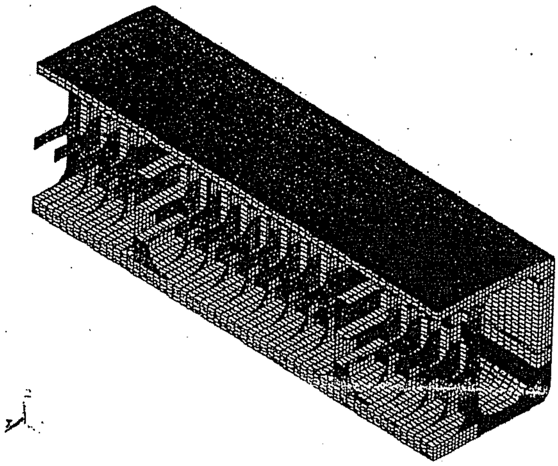


Figure 10. Finite element model (Cargo hold)

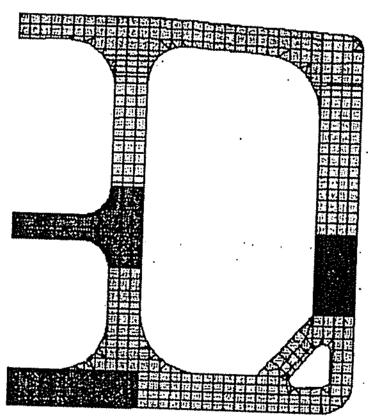


Figure 11. Finite element model (Web frame)

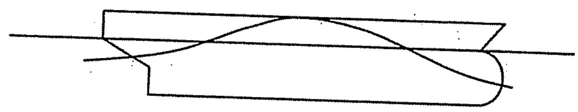
The four nodes shell element has bending and membrane capabilities. The shape shell elements were generally kept rectangular in order to have accurate element stiffness properties. The beam elements are tapered unsymmetrical beam, with tension, compression, torsion, and bending capabilities. All the webs, flanges and stiffeners properties are modeled according to the real geometry.

The mesh size was decided considering proper stiffness representation and load distribution of tank and sea pressure on shell elements. Figures 10~11 show the finite element mesh model used in the analyses. The FEM results are compared with the results obtained with through similar analysis performed with LBR-5 and ISSMID (see section 5.5: Comparison with FEM).

5. RESULTS AND DISCUSSIONS

5.1 Comparison of stress of longitudinal members

5.1.2 Ship bending stress (primary stress under hull girder bending moment)



$$\sigma_1 = \frac{M_{TH}}{Z} \; OR \; \frac{M_{TS}}{Z} \qquad (6)$$

$$M_{TH} = M_{wH} + M_{sH}$$
$$M_{TS} = M_{wS} + M_{sS}$$
$$M_{wH} = 1.9\, C_w\, L^2\, B\, C_B \times 10^5 \quad (N-mm)$$
$$M_{wS} = 1.1\, C_w\, L^2\, B\, (C_B + 0.7) \times 10^5 \quad (N-mm)$$
$$Z_{min} = C_w\, L^2\, B\, (C_B + 0.7) \times 10^3 \quad (mm^3)$$
$$M_{sH} = \frac{175\, f_1}{1000} Z_{min} - M_{wH}$$
$$M_{sS} = \frac{175\, f_1}{1000} Z_{min} - M_{wS}$$

M_{TH} = *Total bending moment (Hogging)*
M_{wH} = *Wave bending moment (Hogging)*
M_{sH} = *Still-water bending moment (Hogging)*
M_{TS} = *Total bending moment (Sagging)*
M_{wS} = *Wave bending moment (Sagging)*
M_{sS} = *Still-water bending moment (Sagging)*
Z = *Actual section modulus at bottom and deck*
Z_{min} = *Rule minimum section modulus*

The ship bending stress is obtained in equation (6). The maximum bending moments for the hogging and sagging condition are calculated according to the IACS regulations. As shown in Table 4, the ship bending stresses are compared and are very similar. The stresses are slightly different because the calculated hull section moduli are a little different.

Table 4 Comparison of ship bending stress

Unit : N/mm²

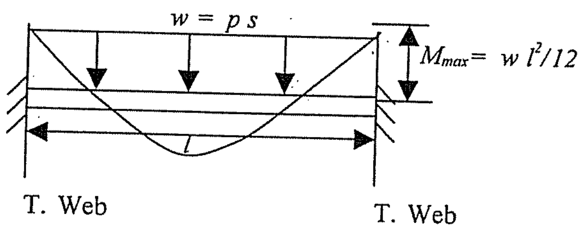
Location / Method	Bottom		
	σ_l	σ_a	Remark
LBR-5	-160		

ISSMID	-163	224	$\|\sigma_1\| < \sigma_a$

Location / Method	Deck		
	σ_1	σ_a	Remark
LBR-5	198		
ISSMID	214	224	$\|\sigma_1\| < \sigma_a$

In the usual practice, the LBR-5 rational model does not decompose the longitudinal stresses induced by the primary hull girder bending moment and stress components induced by the transverse bending moments (through the Poisson coefficient effect) and the local plate bending moment (tertiary stresses). In order to compare the LBR-5 and ISSMID results, the LBR-5 results has been obtained through "simplified analysis" to obtain separately the primary, secondary and tertiary stresses. Normally only the combined stress is compared to the allowable stress.

5.1.2 Stiffener bending stress

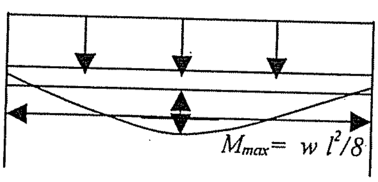


$$\sigma_2 = \frac{M_{max}}{z_l} = \frac{p\,s\,l^2\,w}{12\,z_l} = \frac{83\,p\,s\,l^2\,w}{1000\,z_l} \quad (ISSMID) \qquad (7\text{-a})$$

$w = corrosion\ factor\ (= 1 + 0.1\,t_k)$

$z_l = section\ modulus\ of\ stiffener\ at\ the\ flange$

$t_k = corrosion\ thickness$



$$\sigma_2 = \frac{M_{max}}{z_l} = \frac{p\,s\,l^2}{10\,z_l} \quad (LBR-5) \qquad (7\text{-b})$$

$$M_{max} = (1/8 \sim 1/12)\,wl^2 \Rightarrow wl^2/10$$

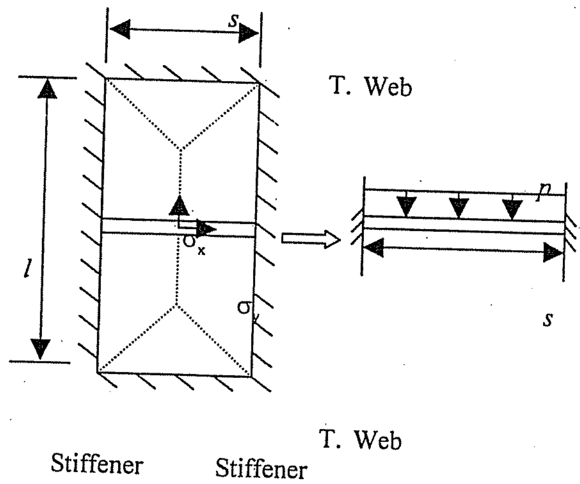
The stiffener bending stress can be obtained as equations (7-a,b). As shown in Table 5, the stiffener bending stress is compared each other. Each stress is slightly different due to the different equations.

Table 5 Comparison of stiffener bending stress (flange)
Unit : N/mm²

Location / Method	Bottom		
	σ_2	σ_a	Remark
LBR-5	-168		
ISSMID	-157	149	$\|\sigma_2\| > \sigma_a$
Location / Method	**Deck**		
	σ_2	σ_a	Remark
LBR-5	44		
ISSMID	54	158	$\sigma_2\| < \sigma_a$

5.1.3 Plate bending stress

The plate bending stress for the ISSMID is obtained by considering plastic plate theory as equation (8-a).



$$\sigma_3 = \sigma_y = \frac{M_P}{Z_P} = \frac{p\,s^2}{4\,(t-t_k)^2} = \frac{15.8^2\,p\,s^2}{1000\,(t-t_k)^2} \quad (ISSMID)$$

(8-a)

$$M_P = \frac{p\,s^2}{16}$$

$$Z_P = \frac{(t-t_k)^2}{4}$$

The plate bending stress for the LBR-5 is based on the plate bending theory considering the actual aspect ratio (l/s) and boundary conditions between clamped edges and simply supported edges (equation 8-b), (See Supplement to Chap.9: Plate Bending of [11]).

$$\sigma_3 = \sigma_y = \frac{M}{Z}$$

$$= \frac{6}{t^2}\frac{16p}{\pi^2}\sum_m^\infty\sum_n^\infty \frac{(m/l)^2 + \nu(n/s)^2}{mn[(m/l)^2 + (n/s)^2]^2} \quad m,n = 1,3,5,\ldots \qquad (8\text{-b})$$

Table 6 Comparison of plate bending stress

Unit : N/mm²

Location / Method	Bottom σ_3	Bottom σ_a	Remark
LBR-5	-144		
ISSMID	-143	154	$\lvert\sigma_3\rvert < \sigma_a$
Location / Method	**Deck σ_3**	**Deck σ_a**	**Remark**
LBR-5	20		
ISSMID	20	154	$\lvert\sigma_3\rvert < \sigma_a$

5.1.4 Total bending stress (along x)

The total bending stress is obtained as equation (9). As shown in Table 7, each total bending stress is slightly different but it is within the allowable stress. Therefore, in structural design viewpoint, the LBR-5 and ISSMID are good methods for the design of longitudinal members.

$$\sigma = \sigma_1 + \frac{y_1}{y_2}\sigma_2 + \nu\sigma_3 \ (ISSMID) \qquad (9)$$

y_1 = distance from neutral axis of stiffener to plate

y_2 = distance from neutral axis of stiffener to flange

Table 7 Comparison of total bending stress

Unit : N/mm²

Location / Method	Bottom σ	Bottom σ_a	Remark
LBR-5	-264	315	$\lvert\sigma_c\rvert < \sigma_a$
ISSMID	-253	290	$\lvert\sigma\rvert < \sigma_a$
Location / Method	**Deck σ**	**Deck σ_a**	**Remark**
LBR-5	215	315	$\lvert\sigma_c\rvert < \sigma_a$
ISSMID	236	290	$\lvert\sigma\rvert < \sigma_a$

$$\sigma_c = \sqrt{\left(\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau^2\right)}$$

5.1.5 Comparison of Stress of Transverse Members

Figure 12 compare the bending stress in the transverse members (web-frames) obtained by LBR-5 and ISSMID. These stresses are also compared with a finite element analysis (FEA) in section 5.5.

As ISSMID evaluates the stress in the frame areas having an uniform beam section and not in the bracketed parts (see Figure 5), the present comparison concerns only the uniform beams. With LBR-5, brackets can be modeled by using additional panels (2 or 3 per bracket, see Figure 17). Then, the stresses in the bracket flange and web of the bracket can also be obtained with LBR-5.

Figure 12 shows that the LBR-5 stresses are slightly higher than the ISSMID ones obtained at a few locations. On average, the stresses are almost the same at each location. Therefore, from a structural design viewpoint, the two methods can be considered valid for practical design.

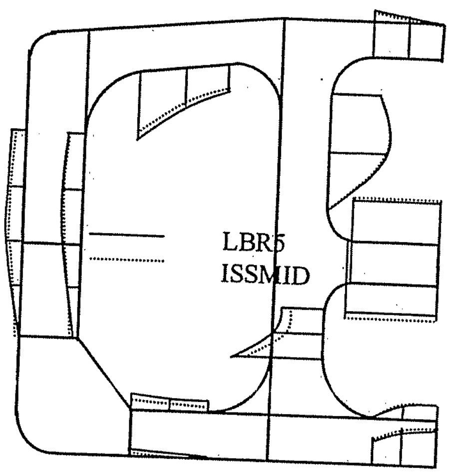
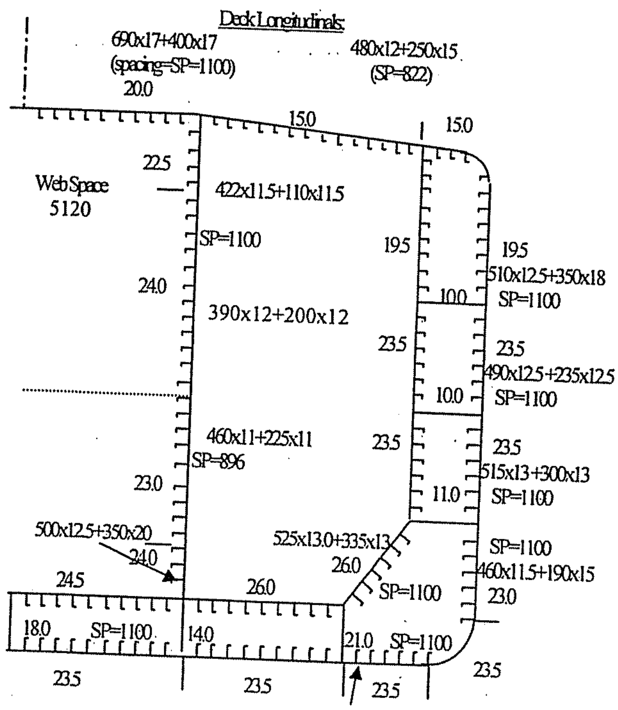


Figure 12. Comparison of bending stress along flanges (for load case LC1)

5.2 Comparison of Scantlings

As shown in Figures 13 and 14, the scantlings of longitudinal members is considerably different at some locations.



Inner and Outer Bottom Longi.: 525x13+335x13 465x12+225x18
Steel: All in "AH32" Unit: mm

Figure 13. Longitudinal members of the least cost design obtained with LBR-5 (for C= 40$/mh)

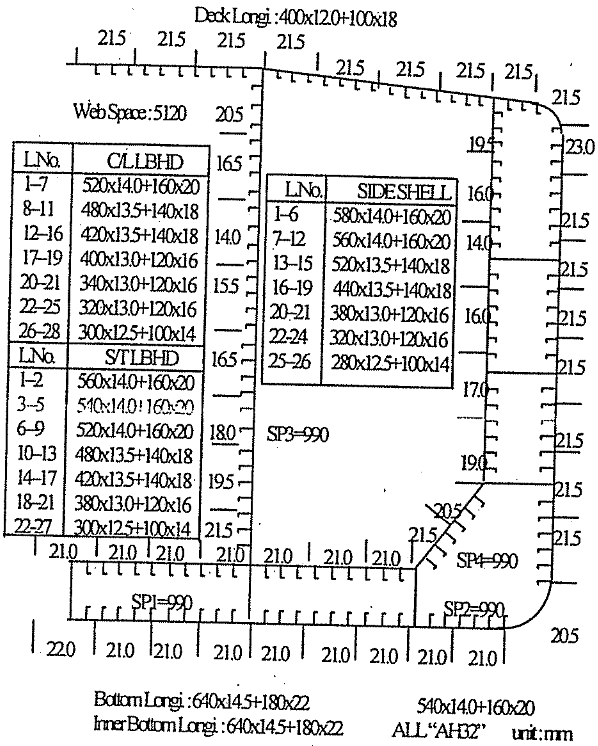
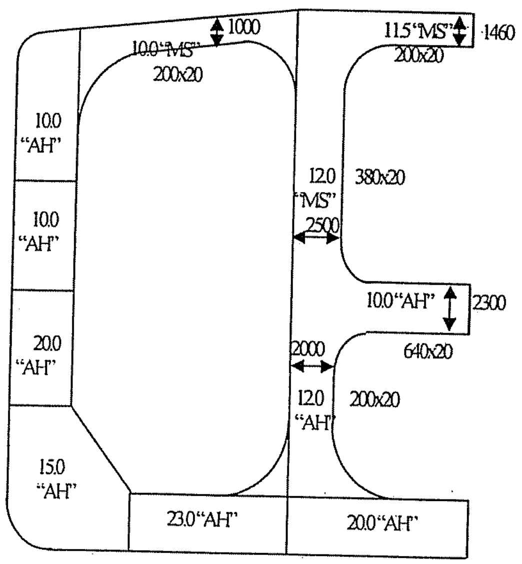


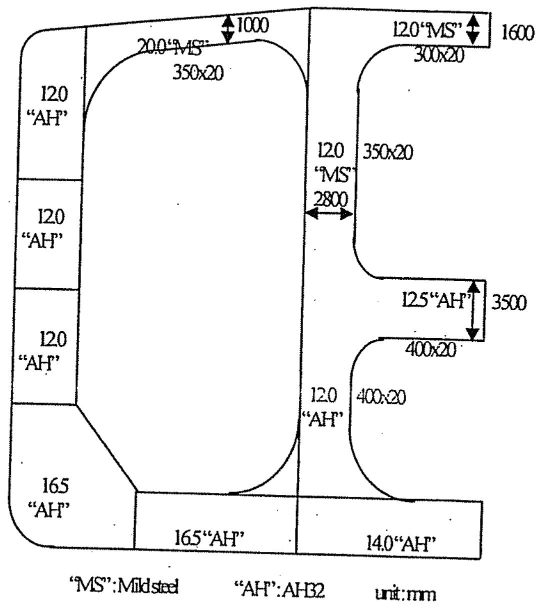
Figure 14. Longitudinal members of the least cost design obtained with ISSMID (for C= 40$/mh)

Also, as shown in Figures 15 and 16, the scantlings of transverse members are considerably different at some locations.



"MS": Mild steel "AH": AH32 Unit: mm

Figure 15. Transverse members of the least cost design obtained with LBR-5 (for C= 40$/mh)



"MS": Mild steel "AH": AH32 unit: mm

Figure 16. Transverse members of the least cost design obtained with ISSMID (for C= 40$/mh)

5.3 Comparison of Minimum Weight Design

Table 8 Comparison of minimum weight design

Frame Space (m)			3.94	4.27	4.65	5.12	5.69	Initial Scantling (5.12m)
Least Weight (Ton)		LBR-5 (%)	92.0	93.1	95.3	99.7	105.7	4825 (100%)
		ISSMID (%)	92.3	93.1	93.3	94.3	95.3	4980 (100%)
Cost (M$)	C=15 $/MH	LBR-5 (%)	100.2	99.8	99.6	99.4	101.6	3.988 (100%)
		ISSMID (%)	100.6	100.2	100.4	98.9	98.8	3.408 (100%)
	C=25 $/MH	LBR-5 (%)	102.9	102.1	101.4	100.5	102.1	4.751 (100%)
		ISSMID (%)	103.2	101.2	99.4	100.4	99.8	4.083 (100%)
	C=40 $/MH	LBR-5 (%)	105.6	104.5	103.3	101.7	102.6	5.897 (100%)
		ISSMID (%)	106.8	103.2	101.8	102.2	101.5	5.096 (100%)

As shown in Table 8, the ratio of weight based on the initial scantlings is obtained according to the frame space. The optimum frame spacing, which gives the least weight, is obtained for the LBR-5 and ISSMID. The optimum frame spacing for the LBR-5 is same as ISSMID. The cost is calculated by the scantlings of the minimum weight design.

5.4 Comparison of Minimum Cost Design

Table 9 Comparison of minimum cost design

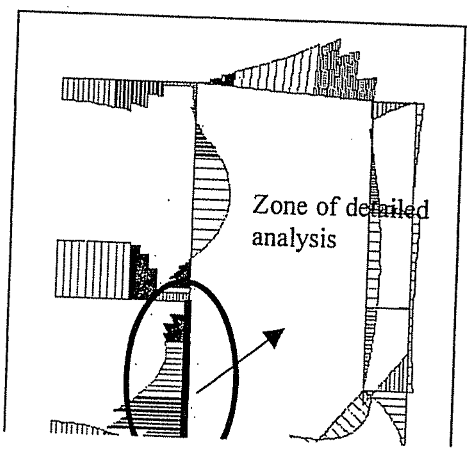
Frame Space (m)			3.94	4.27	4.65	5.12	5.69	Initial Scantling (5.12m)
Least Cost (M$)	C=15 $/MH	LBR-5 (%)			96.9	97.2		3.988 (100%)
		ISSMID (%)	99.0	97.8	97.8	98.1	98.1	3.408 (100%)
	C=25 $/MH	LBR-5 (%)				96.2		4.751 (100%)
		ISSMID (%)	99.9	97.9	97.9	96.2	97.2	4.083 (100%)
	C=40 $/MH	LBR-5 (%)				94.9	95.9	5.897 (100%)
		ISSMID (%)	101.9	100.9	98.2	96.8	96.4	5.096 (100%)

As shown in Table 9, the ratio of cost based on the initial scantlings is obtained according to the frame space and unitary cost per man-hour. The optimum frame spacing, which gives the least cost, is obtained for the LBR-5 and ISSMID. The optimum frame spacing is increased from 4.65m to 5.69m when the unitary cost per man-hour is increased. For LBR-5, only the optimum solutions are mentioned in the table.

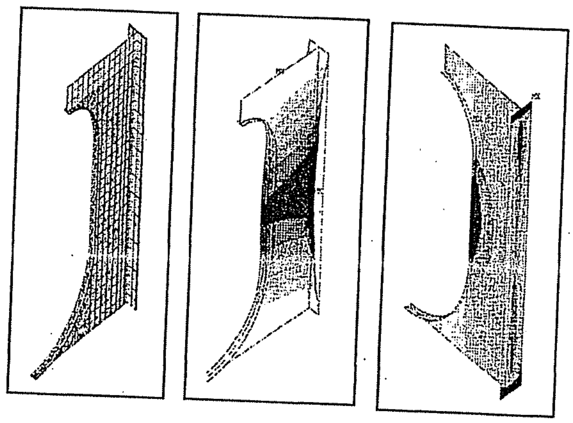
5.5 Comparison with FEM

In order to validate the comparison between the optimum design obtained respectively by ISSMID and LBR5, a series of tests (benchmark) has been achieved. First, concerned the behavior of a part of the longitudinal bulkheads. Only transversal loads are considered. Results are compared to standard FEM analysis.

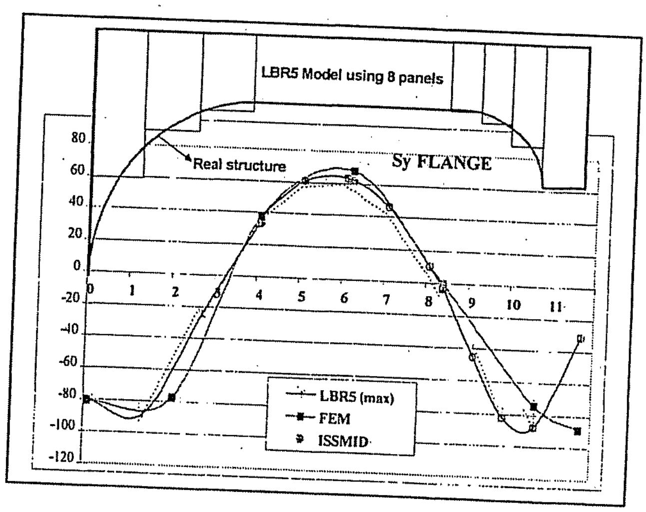
5.5.1 Local analysis (comparison between FEM, LBR-5 and ISSMID)



This comparison deals with a bracketed web-frame, analyzed with LBR-5 and the FEA. For design purposes, the results can be considered as identical and they validate the accuracy of the LBR-5 analytical rational-based method.



Comparison analysis of a structural detail (with FEM-ANSYS) of the longitudinal bulkhead.



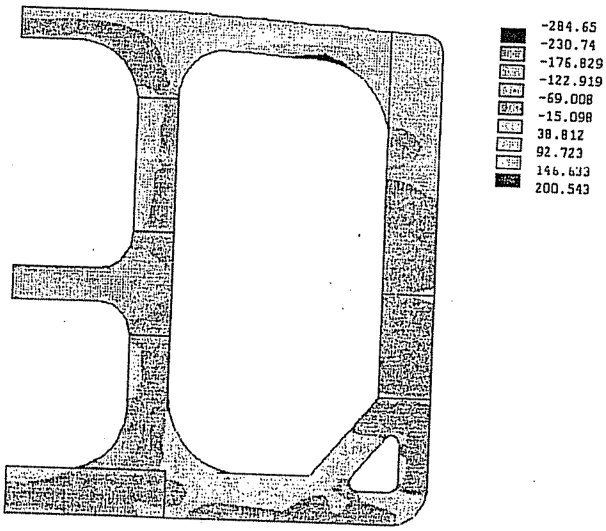
Comparison (FEM, LBR5 and ISSMID)

Figure 17. Local analysis: comparison between FEM, LBR-5 and ISSMID

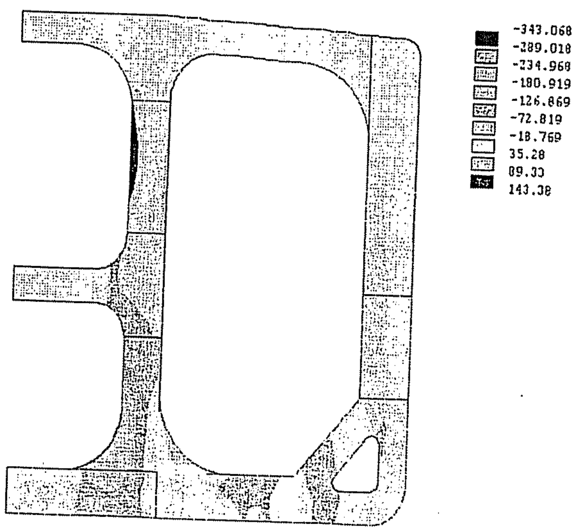
-14-

5.5.2 Stress level in the frame flanges (Transverse Bending)

Figure 18 shows the stress distribution obtained with the FEA and used to assess the uncertainty of the two methods (LBR-5, ISSMID). The bending stress in the transverse web frames obtained by LBR-5 and ISSMID are compared with a finite element analysis (FEA). Among the points in the flanges shown in Figure 19, only the high stressed flanges which take place over half of the allowable stress are selected to compared the stresses. Table 10 shows that the stresses of LBR-5 and ISSMID are almost the same as those of FEM.



Local stresses SY (horizontal)
(Max = -284 to + 200 N/mm^2)



Local stresses SZ (vertical)
(Max = -143 to + 343 N/mm^2)

Figure 18. Local vertical and horizontal stresses in the transverse frame (for load case LC1)

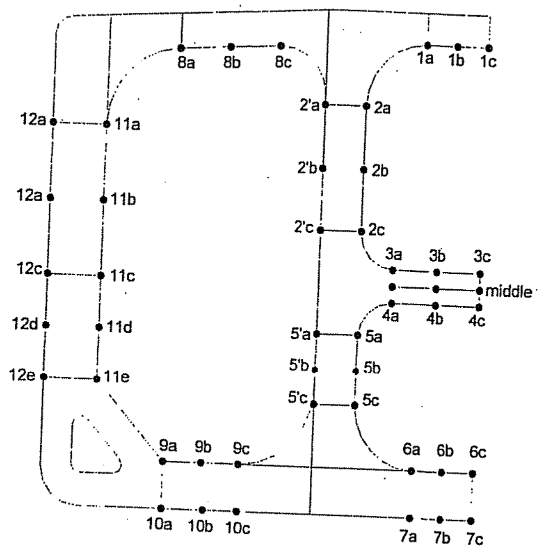


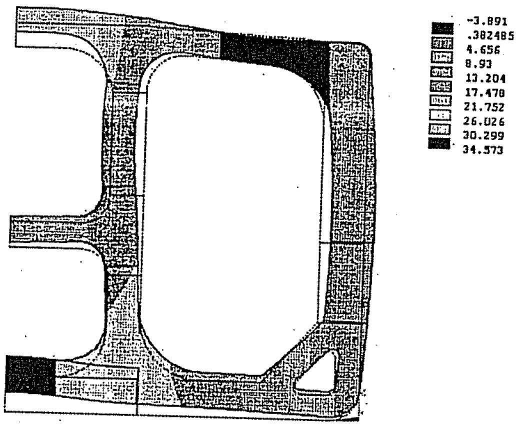
Figure 19. Locations of the points where LBR-5 and ISSMID are assesses with regards to a FEA.

Table 10 Stress comparison (FEM, LBR-5 and ISSMID)

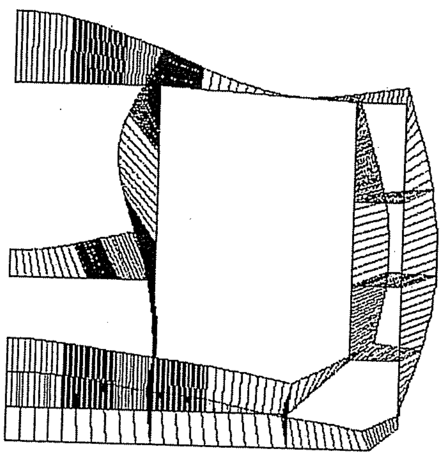
Point Number	FEM N/mm^2	LBR-5 N/mm^2	LBR-5/FEM	ISSMID N/mm^2	ISSMID/FEM
1 a	**-111**	**-115**	**1.036**	**-106**	**0.955**
b	-94	-95	1.011	-86	0.915
c	-89	-98	1.101	-79	0.888
2 a	91	111	1.220	113	1.242
b	**142**	**144**	**1.014**	**143**	**1.007**
c	-18	0		0	
3 a	-236	-230	0.975	-231	0.979
b	-241	-230	0.954	-231	0.959
c	**-241**	**-230**	**0.954**	**-231**	**0.959**
4 a	-175	-152	0.869	-200	1.143
b	-178	-152	0.869	-200	1.124
c	-178	-152	0.869	-200	1.124
5 a	-89	-98	1.101	-57	0.640
b	-99	-111	1.121	-66	0.667
c	**-242**	**-213**	**0.880**	**-184**	**0.760**
7 a	-80	-59	0.741	-64	0.800
b	-100	-82	0.820	-87	0.870

c	**-101**	**-89**	**0.881**	**-93**	**0.921**
8 a	**181**	**208**	**1.147**	**174**	**0.961**
b	135	125	0.927	100	0.741
c	99	60	0.604	46	0.465

Figure 20 compares the deflection in the transverse frames (FEA versus LBR-5). Once more, the shape of deformation and the maximum displacement are quite similar.



Vertical displacement (FEA)
(Max = 34.5 mm)



Transverse deflection (LBR-5)
(Max = 30.5 mm)

Figure 20. Deflection of the transverse frame (for load case LC1)

6. CONCLUSIONS

Two different design methodologies, rational-based and rule-based design method, are compared for the optimum design of longitudinal and transverse members of an existing ship structure (a tanker hold). The optimum scantlings of longitudinal members are considerably different, although the total bending stress of the longitudinal member is almost the same for each. The optimum scantlings of transverse members are also considerably different, although the bending stresses of the transverse members are almost same.

This indicates that the existing rule-based design method (ISSMID) works quite well for the tanker design although the analytical method also offers an efficient design tool. For some specific aspects, the rational-based design tool (LBR-5) is able to consider more complex failure modes. So obviously such rational-based design methods is definitively most promising alternative to for the design of ship structures, especially, the design of new ship types.

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