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OPTIMUM DESIGN OF BULK-CARRIER MIDSHIP SECTION WITH DnV RULE CONSTRAINTS AND DOUBLE BOTTOM STRENGTH ASSESSMENT AS AN ORTHOTROPIC PLATE*)

SUMMARY

DWKO computer program used for structural optimization of bulk-carrier midship section was developed at Ship Design and Research Centre (CTO) during realization of purpose project administered by Gdynia and Szczecin Shipyards with financial support of Scientific Research Committee, entitled: "Developing and implementation of optimization in preliminary ship structural design". Program DWKO runs together with SHIPC system developed at Technical University of Szczecin under commission of CTO. Zone strength of double bottom is determined according to the orthotropic plate theory developed by O. F. Hughes [1]. A nonlinear programming methods (Tangent Search Method) is used for structural optimization. Examples of practical application of DWKO program to pre-contract design are described in this paper.

Introduction

Designers are often forced to make a preliminary design in too short time to be able to perform a detailed analysis of the structure. Even materials must be ordered basing on estimated data. However, the biggest possible savings can be achieved during preliminary design process. At this stage designers should have a possibility to study a sufficient number of different solutions to search for possible savings which is a very time-consuming process (often even impossible) when using traditional methods of designing. It is necessary to use in preliminary design approximate methods of structural analysis. In the market economy quick and reliable methods of preliminary design are as important as efforts in commercial activities. This enables the shipyard to prepare well documented cost estimation for alternative design solutions almost immediately.

Structural optimization is especially important for large tankers and bulk-carriers the hull cost of which is 50% (or more) of production costs. As the initial costs are even 80% of operational costs of the ship, the cost of production of the hull is the most important item of operational costs. The main part of steel weight is determined at the moment of designing the midship section. Therefore cost of the unit length of the hull within the midship region should be an objective of optimization in the preliminary ship structural design.

The Polish shipyards did not use structural optimization with regard to the above mentioned issues. Completion of the described purpose project will enable them to answer shipowner's enquiries immediately, to shorten the time of designing at its early stages resulting from wider use of CAD and to decrease construction costs by reducing steel weight and labour. All these elements should improve competitiveness of the shipyard.

Design structural model

The complete structure analysis is required according to the DnV rules [7] for scantling determination of strength members in complex two- or three-dimensional structural systems to find out whether the stress values calculated for rule load conditions are acceptable. Any recognized method of analysis or computer program may be used provided the effects of bending, shear, axial and torsional deformations are considered in all cases where it is important.

DnV published the structural analysis method for bulk-carriers and container ships [6] application of which is necessary for class assignment. The method concerns the analysis of basic structural members in the midship region of bulk-carriers and container ships with a double bottom and single or double sides and includes: determination of design loads, structural model and permissible stresses. Analysis of the three-dimensional structure of a bulk-carrier is made on the basis of separate calculations of the two-dimensional frame of the transverse bulkhead (with the stool) and side structure framework (with the top wing and hopper tanks) and for the double bottom grillage. In the last case influence of the bulkhead and side structure

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is taken into account by introduction of equivalent elastic supports.

For optimization purposes the structural model of the bottom flat grillage is replaced with an orthotropic plate of the double bottom with a rigid support at the periphery of the flat part of the inner bottom (i.e. without taking into account hopper tanks and bottom structural members under the bulkhead stool). Such assumption enables to simplify calculations considerably as instead of solving the system of equations with use of the finite element method (FEM) for the grillage in each optimization cycle (and there can be a thousand of such cycles in the TSM method) it is possible to use ready solutions for orthotropic plates useful for the analysis of the double bottom. For the same boundary conditions such calculations are more accurate than for the grillage because the assumed model of an orthotropic plate enables not only to consider 2-dimensional state of stresses in the outer and inner bottom but accounts also for influence of shear in the bottom girders and floors to the torsional rigidity of the bottom, which is important for ship structures. Both these factors cannot be considered in the structural model of the beam element grillage. It is also important that the structural model of the double bottom as an orthotropic plate (as the only one) enables to optimize of the structural configuration in the TSM method - as the distances between longitudinal stiffeners (and also distances between floors and bottom girders) can be considered as design variables.

On the other side the double bottom grillage model enables according to [6] to better represent boundary conditions and local reinforcements. Ready solutions for orthotropic plates are available only for some boundary conditions of the plate edges: simply supported, clamped against rotation, opposite edges elastically restrained against rotation or deflection and certain combinations of these boundary conditions, which can differ from the real ones. Therefore the structural model of an orthotropic plate was verified by comparison with the results of the FEM analysis of the 2 1/2 hold structural model of the bulk-carrier performed with use of MAESTRO [3].

The results of the analysis of the bulk-carrier double bottom in the hold 5 (loaded with ore) and the hold 4 (empty hold, sea loads only) are shown in the Tab. 1 and 2. The results of the simply supported orthotropic plate (upper numbers in the Tables) and for the clamped floors and simply supported girders (lower numbers) are compared with the results of calculations made with the use of MAESTRO. The total (due to hull girder bending and double bottom bending) longitudinal stresses σ_{ux} in the inner bottom, transverse (due to double bottom bending) stresses σ_{uy} in the inner bottom, and adequate stresses σ_{lx} and σ_{ly} in the bottom (all calculated in the centre of the bottom) are presented in MPa, and maximum deflections of the double bottom w - in mm. Comparison of the results of calculations made with use of both methods shows a good conformity of the total longitudinal stresses and maximum deflections for all considered cases if in the orthotropic plate model of the double bottom floors are assumed as clamped in the case of a loaded hold and as simply supported in the case of an empty hold. Stresses in the transverse direction are in all cases higher in comparison to these calculated with use of MAESTRO. This is not decisive however as scantlings of the double bottom depend on the total longitudinal stresses.

The longitudinal stresses due to bending of the double bottom do not exceed according to [6] the permissible level if the following conditions are met:

- total longitudinal stresses due to the hull general bending, double bottom bending and local bending of longitudinals (Fig. 1) do not exceed 225 f1 [N/mm^2];
- total longitudinal stresses due to hull girder bending and double bottom bending do not exceed 190 f1 [N/mm^2] (where f1 material factor acc. to [7]).

Tab. 1. Comparison of the results of the structural analysis (of the double bottom orthotropic plate model) with these obtained with use of MAESTRO for a fully loaded hold.

Loading condition	MAESTRO σ_x	PLATE σ_x	MAESTRO σ_y	PLATE σ_y	MAESTRO w_{max}	PLATE w_{max}
1 U	-135.2	-188	-10	-113	-26.4	-35.9
		-135		-105		
L	154	224	98.5	111		-27
		158		131		
2 U	85	-151	-42	-119	-28.2	-37.9
		-96		-111		
L	225	299	109	149		-28
		230		139		
3 U	-160	-223	-50.1	107	-23.2	-34
		-173		-103		
L	94	153	77	134		-25
		91		124		

Tab. 2. Comparison of the results of the structural analysis (of the double bottom orthotropic plate model) with these obtained with use of MAESTRO for an empty hold.

Loading condition	MAESTRO σ_x	PLATE σ_x	MAESTRO σ_y	PLATE σ_y	MAESTRO w_{max}	PLATE w_{max}
1 U	123	138.6	22.6	89.6	22.45	24.49
		97		83		
L	-130	-153	-82	-89		18
		-112		-83		
2 U	182	185	28.8	84	20.9	22.9
		146		78		
L	-54.5	-71	-72.9	-83		17.1
		-33		-78		
3 U	93.5	129	17	95	24.15	25.8
		85		88		
L	-179	-172	-94	-94		19.4
		-129		-88		

The following denotation is used in Fig. 1:

- σ_s – stresses in the bottom due to hull girder still water bending,
- σ_w – stresses in the bottom due to hull girder wave bending,
- σ_{db} – longitudinal stresses in the bottom due to double bottom bending,
- σ_l – stresses due to local bending of longitudinal stiffeners.

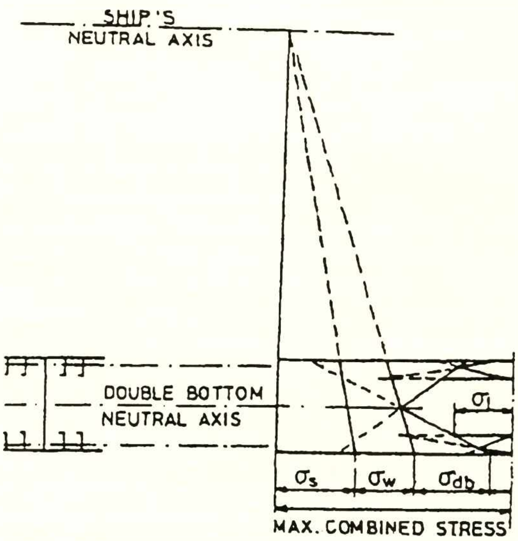

Fig. 1. Principle of summing up stresses in double bottom

Description of DWKO program

The DWKO program is used to optimum determination of midship section scantlings within the hold region of a bulk-carrier. It takes into account the requirements of DnV Rules of 1992 concerning local(zone) and general strength (bending and shear of the hull) and strength of the double bottom as an orthotropic plate. When choosing elements of the midship section the program uses the catalogues of steel sheets and profiles assumed by the user. Program operation is based on cooperation with the following programs composing the SHIPC system developed by the team of the Technical University of Szczecin under commision of CTO: - ShipC (for reading data, generating and graphic edition of elements of midship section, creating and editing catalogues of steel sheets, profiles, cut-outs and standard elements), - DWK_WSP (task of which is determining and saving in the file structural relations of strength members), - DWK program modules (determination of scantlings). The DWKO program was developed through adding to and modifications of DWK program in order to account for the double bottom strength and structural optimization.

It is necessary to choose three basic elements to formulate the optimization problem: design variables describing structure, optimization criteria, (thus objective function) and constraint conditions. All the above elements may be chosen in different way and depending on the considered type of the structure. Taking into consideration the publication [4] concerning optimization of the midship section of 128,000 t OBO carrier not more than 10 decision variables were accepted for bulk-carriers,i.e.:

- height of the double bottom,
- bottom girder spacing,
- floor spacing,
- longitudinal stiffener spacing,
- section area of the inner bottom longitudinal stiffeners,
- section area of the outer bottom longitudinal stiffeners,
- thickness of the inner bottom plating,
- thickness of the outer bottom plating,
- thickness of the deck plating,
- section area of longitudinal reinforcements of the deck.

In the particular calculations some dimensions from the above list may be assumed as variables and then the remaining are treated as set and constant in the optimization process.

In the DWKO program 9 constraints of behavioural type (i.e. concerning dependent variables) were accepted i.e.:

- 3 constraints for strength of the double bottom as an orthotropic plate (as assumed in this paper),
- 3 constraints for local strength of the deck, outer and inner bottom plating (important only in case of optimization of stiffener spacing),
- 1 constraint for local strength of the deck longitudinal stiffeners,
- 2 constraints for longitudinal strength of the hull girder (the minimum required moment of inertia of the section, the required section modulus).

Moreover, 20 design variable direct constraints (minimum and maximum dimensions of variables) were assumed.

In this version of the program formal constraints connected with the rule control of local instability of structural elements are not considered. However, it does not mean that these requirements are omitted at all. After the preliminary scantling determination satisfying the conditions of local strength (but before starting optimization) the program controls the local stability and, if necessary, increases scantlings for the preliminary assumed (approximate) location of the neutral axis of the hull cross-section. This operation is later repeated after the first optimization run, but for the real location of the neutral axis. When the requirements of local instability are satisfied, the second optimization is performed and afterwards program restarts with the updated values of design variables. After the optimization process is completed the final checking (and eventual correction) of member scantlings in compliance with the requirements for local stability is made.

In this version of the program sectional area of the midship section or mass of a quarter of hold structure (without a transverse bulkhead) is assumed as an objective.

Examples of bulk-carrier structure optimization

A drawing of the midship section of 164,000 t bulk-carrier (of Gdynia Shipyard design) is enclosed as Fig. 3. It was prepared and plotted with use of the ShipC program after the preliminary scantling determination with use of the DWK program. This drawing illustrates capabilities of the SHIPC package: a few tens of figures characterizing the ship's main data, structural loads and topology are entered and as a result a complete drawing of the hull midship section meeting the requirements of the rules is received.

Curves of the midship structure optimization process of the bulk-carrier, i.e. diagram of the objective function (sectional area of the midship section) consisting of the base points generated during the optimization process with use of DWKO are presented in Fig. 2. The figure shows the calculation results of two examples: with consideration of effects of the strength of the double bottom and without consideration of the effects. In the last case the results should be comparable with the received when using the DWK program. The initial structure did not meet the assumed conservative constraints and the program, before beginning the optimization process, modified the assumed thicknesses to meet all the conservative constraints. In Fig. 2 both starting points are marked: initial (not acceptable) and final assumed by the program (acceptable) for the step 0 and 3 respectively.

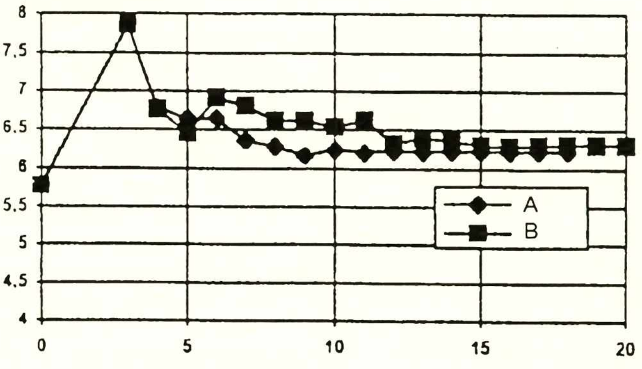

Fig. 2. Process of optimization of 164,000 t bulk-carrier midship section (sectional area in sq m in relation to optimization base step numbers); A - double bottom not accounted for, B - double bottom accounted for.

The presented results are calculated for 3 design variables: inner bottom, outer bottom, and deck plating thicknesses, and 3 behaviour constraints: minimum moment of inertia of the hull section, the required hull section modulus, and the required strength of the double bottom without taking into account stresses from local bending of longitudinals. Run time of a PC 486/33MHz computer was about 30 s.

The midship section structure with scantlings chosen on the basis of the rule requirements for local strength only (option /c in the DWK program) was accepted as the initial structure. However it cannot be used as a basis for estimating the optimum design as it does not meet the general strength requirements (and the strength of the double bottom as well). The acceptable solution assumed by the program (base step 3 in Fig. 2) also is not a realistic basis for comparison as this solution is too heavy. If the solution after the step 6 is accepted as the basis then 9% reduction of the sectional area of the midship section for the first example (with consideration of strength of the bottom) and more than 6% reduction for the second (when the requirements concerning the double bottom strength are not met) is achieved in result of optimization. In the last case, as it should have been expected, the result is almost the same as when using the DWK program for the complete scantling determination (with consideration of the requirements for the hull overall strength).

Further reduction of the structural weight may be obtained through taking into account for optimization bigger number of design variables and constraints. The detail analysis of optimization processes results in conclusion that the smallest set of relations guaranteeing convergence of the optimization process of the midship section of bulk-carriers is: - 6 design variables (cross-section areas of the bottom , inner bottom and deck longitundinals must be additionally introduced as design variables), and - 6 behaviour constraints (constraints for local strength of the bottom,inner bottom and deck longitudinals must be additionally considered).

Conclusions

The DWKO program for hull weight optimization of bulk-carriers developed by CTO (within the purpose project) enables to considerably reduce the cross-section area of the midship section of bulk-carriers (6-9%) fulfilling simultaneously the requirements of the DnV rules of 1992 and accounting for the strength of the double bottom as an orthotropic plate.

Further weight reduction may be achieved by taking into consideration bigger number of design variables and constraints for optimization.

DWKO program is an element of the SHIPC system. Therefore, a few tens of figures characterizing the ship's main data, structural loads and topology are entered and as a result a complete drawing of the midship section structure with optimum design weight and meeting the requirements of the rules as well as accounting for the double bottom strength is received.

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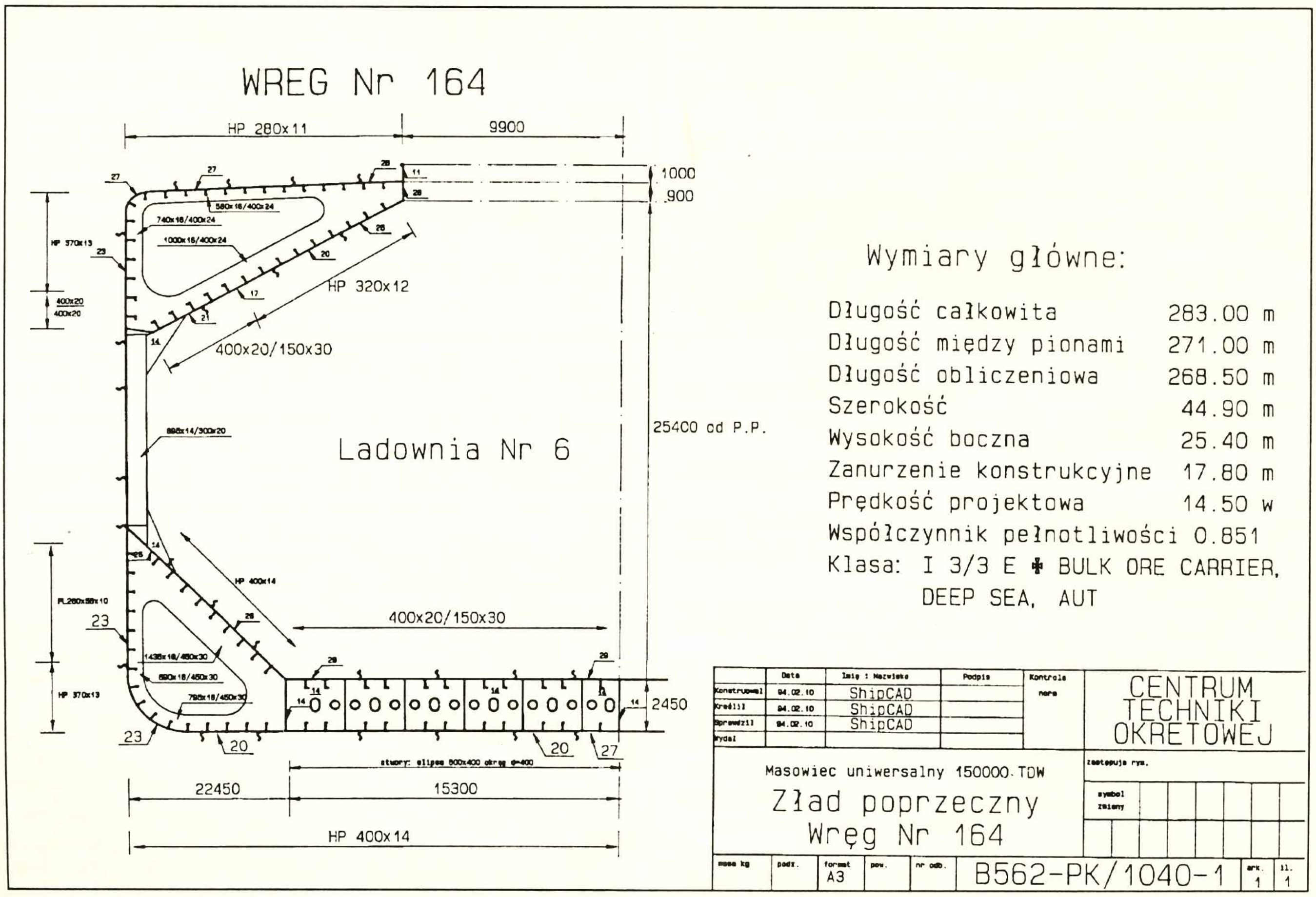

Fig. 3. The midship section drawing.