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Fatigue strength assessment of a 2700 TEU container ship

SUMMARY

This paper is a continuation of the previous one [1] which contains a procedure for fatigue strength assessment of container ships structures. The procedure takes into account two different levels of fatigue strength assessment: approximate one - based on rules and recommendations of classification societies, and the direct approach based on the long term prediction of wave loads. Both methods are compared with the use of 2700 TEU cellular container ship as an example.

The fatigue strength assessment is based on the generalized Wöhler curves (S-N curves) for welded and not welded details in corrosive and non-corrosive environment, as well as on the hypothesis of linear fatigue damage summation. The basic S-N curves should be used for the nominal stresses multiplied by the stress concentration factor K.

INTRODUCTION

The degree of exposure to fatigue damages depends on ship type and category of hull structural members. Fatigue strength depends particularly on dynamic stress amplitudes, corrosion activity of the environment, stress concentration factors of the structural details. The importance of possible fatigue failures depends on number of the points where such failures may happen and their effect upon the safety of ship and people. The areas particularly exposed to fatigue fractures in container carriers are shown in Tab.1 (acc. to [2]).

Tab.1. The areas particularly exposed to fatigue fractures in container carriers

Structural members	Structural details	Type of loads
Bottom and side longitudinals	Butt welds, attachment to transverse webs, transverse bulkheads and inserted longitudinals	Hull girder bending and torsion, lateral load of longitudinals due to pressure and support deformation
Upper deck	Butt welds of plates and longitudinals, hatch corner brackets and supporting structures for containers and hatch covers	Normal stresses generated by hull bending and torsion

Considerable warping stresses may also appear in bilge region, due to restrained hull girder torsion, within the sections from the forward bulkhead of engine room to 1/4 of ship length measured aft from the forward perpendicular.

In assessing the upper deck fatigue strength the combined effect of vertical and horizontal bending of the hull and restrained warping torsion effect should be taken into consideration. For hatch opening corners additional stresses due to local bending of transverse and longitudinal strips of deck plating, generated by torsion of the entire hull, should be accounted for.

The assessment of fatigue strength for variable load amplitudes is based , as earlier stated in [1], on generalized results of fatigue tests of samples at constant amplitude (i.e. on S-N curves), as well as on Palmgren-Miner's linear damage cumulation hypothesis to account for variable amplitudes. According to the hypothesis the total structural damage may be represented by a sum of damages occurring at each load cycle at various stress levels, irrespective of their sequence.

The life time of ship (in respect to fatigue strength) is generally assumed not less than 20 years. The acceptable level of the dimensionless fatigue damage sum D, expressed by the so called usage factor (damage ratio) η, should not exceed 1.0.

A linear theoretical model may be assumed for determination of wave generated loads. Ship response to irregular waves may be obtained by using the superposition method. Due to this approach the analysis may be limited to the frequency domain. The resulting stresses are the sum of stresses caused by individual wave loads. The most frequent ship loading conditions should be taken into consideration for computing the fatigue strength (usually the ballast and full load conditions only). The service speed should be assumed for both cases of computation.

The long term stress probability distribution applicable to fatigue strength computation can be selected from North Atlantic wave statistics in the form of distribution of significant wave height H_S and mean zero crossing period T_Z (Tab.5.1 in [2]) or in the form of H_s and T_Z distributions for unrestricted area of navigation (Tab.5.2 in [2]).

EXAMPLE OF FATIGUE ASSESSMENT

Within the scope of this work SANKO2 software system [3] was completed and modified to make the fatigue strength assessment on the basis of the procedure described in [1] possible. In this way a new version of the program SANKO3 was developed which enables to compute the dimensionless sum of fatigue damages D, time T after which fatigue fractures may appear, as well as the shape coefficient h of long-term stress Weibull distribution, and the total number of cycles of wave generated stresses N for two selected loading conditions simultaneously (generally for full load and ballast condition), for the same input data as required for SANKO2 program but supplemented by the number of load conditions (1 or 2), and indicator of navigation area (0 - unrestricted area, 1 - North Atlantic).

Computation was performed for PK 6101 container carrier (designed by Gdańsk Shipyard S.A.). The ship has double hull and transverse bulkheads subdividing the hull into five holds. The engine room is located aft.

Ship's main characteristics

Length overall	L_{OA} = *205.90 m*
Length between perpendiculars	L_{PP} = *190.00 m*
Length on waterline	L_{WL} = *194.18 m*
Breadth	*B = 32.20 m*
Depth to upper deck	*H = 18.75 m*
Design draught	*T = 12.00 m*
Block coefficient	C_B = *0.632*
Displacement	*D = 35 000 t*
Container capacity	*2700 TEU*
Speed	*V = 20.9 knots*
Design aft perpendicular	*frame 3* $^{+100\,mm}$
Design forward perpendicular	*frame 252* $^{+40\,mm}$
Cargo weight	*CC = 2700 × 14 t = 37 800 t*
Maximum length of open deck	*d = 139.1 m*
Maximum still water bending moment	M_{SW}= *1 611 789 kNm.*

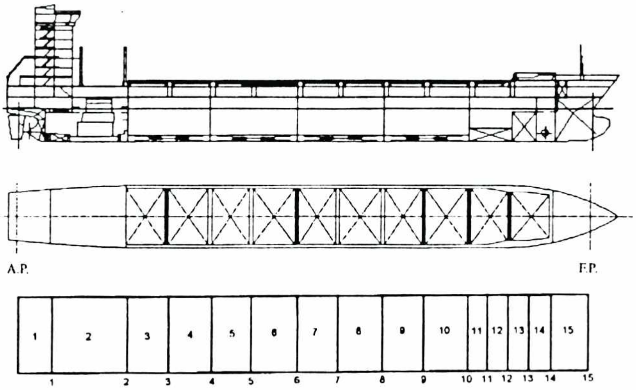

Fig.1. Thin-wall beam idealization of PK-6101 container ship

The ship hull is considered as a thin-walled beam with variable cross sections represented by 15 segments (11 different frame section shapes). Fig.1 shows the hull subdivision into segments, including the segment numbers. Geometrical characteristics of eleven representative hull sections located at frames 6, 40, 60, 80, 124, 178, 200, 210, 219, 228, 242 (determined by using WOKA program [5]) are given in [4]. Some representative results of computation (selected from [6]) are shown in Fig.2 to 4.

Fig.2 shows deformation of hatch openings (for the exceedance probability $Q = 10^{-8}$) computed with the use of SANKO2 program, i.e. with application of Walden's wave statistics for North Atlantic. Two following measures of hatch deformation are shown in the figure : the relative longitudinal displacement of longitudinal coamings Δu (equal to double warping deformation of cross-section) and relative deformation of hatch opening diagonal $\Delta l/l$ as the mean and envelope values for all wave headings. Intermediate hatch deformations may actually occur because the ship master may avoid the heading which causes considerable rolling in heavy seas. Δu values according to GL rules are also presented for comparison. The latter considerably exceed the maximum values obtained from SANKO2 program.

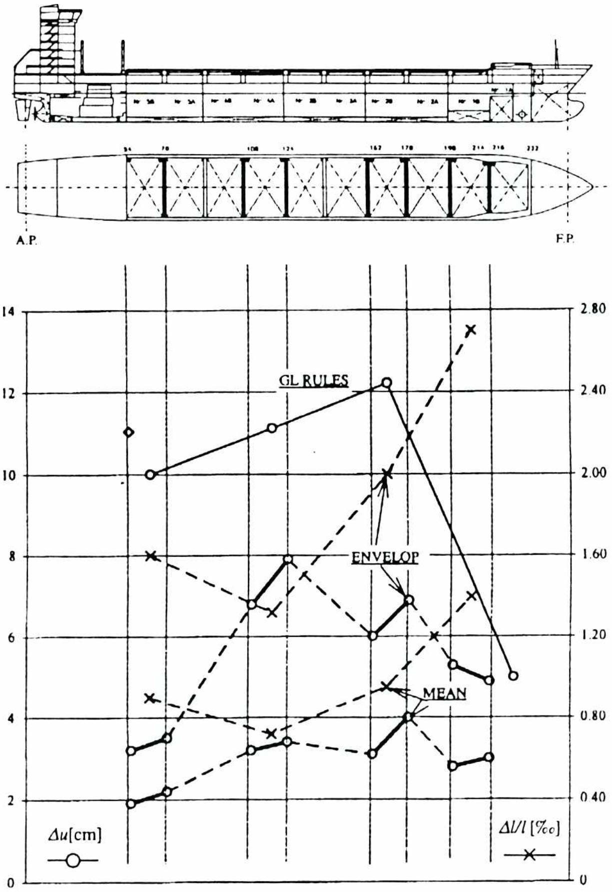

Fig.2. Comparison of hatch deformations (explanation in the text)

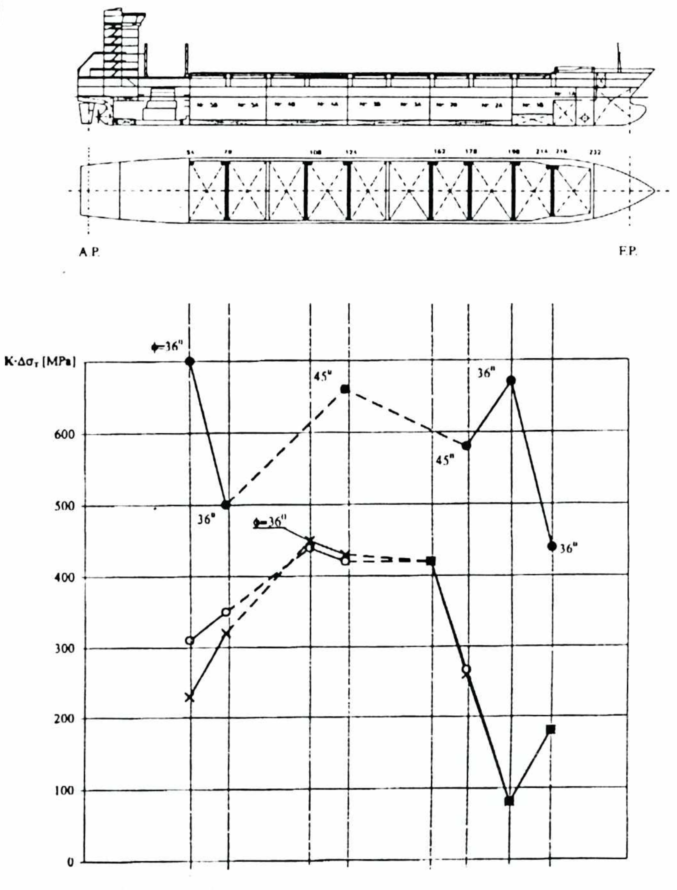

Fig.3. Comparison of local stress ranges at hatch corners (explanation in the text)
K - stress concentration factor

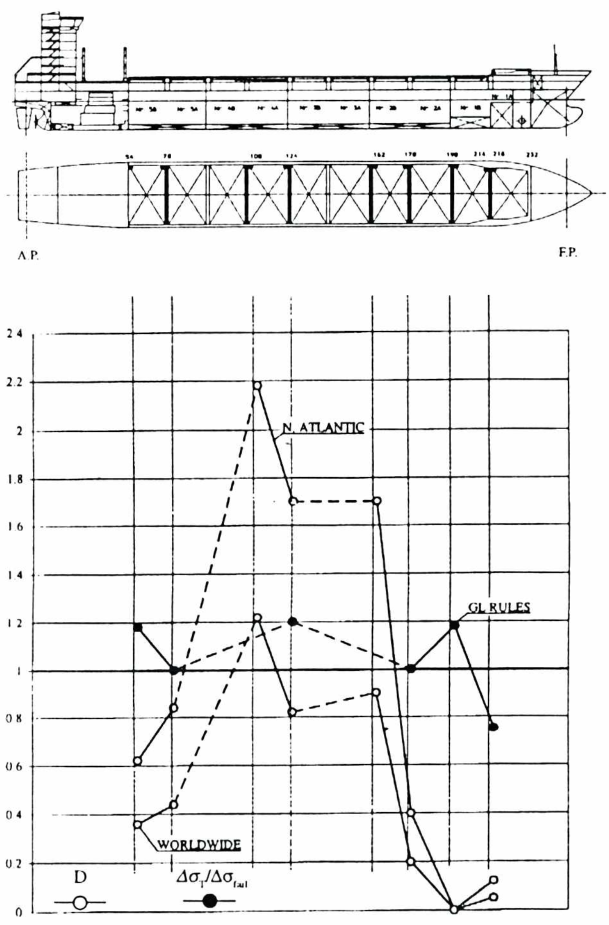

Fig.4. Comparison of fatigue strength of hatch corners (explanation in the text)

Fig.3 shows ranges (double amplitudes) of the wave generated, combined (total) stresses, $\Delta\sigma_T$, in hatch corners, computed with the use of SANKO3 program, taking into account K-factors obtained from DECKFRAME program [7], for the full load (circle-marked line) and ballast (cross-marked line) conditions, presented as mean values for all headings in respect to wave direction. In the figure the angles ϕ which define location of the maximum stress occurring at hatch corner cut-out edge (in other cases the angle is equal to 27^o) are also included. Comparative values obtained from GL rules are also indicated (by black filled circles). Everywhere the latter values are greater that those obtained from SANKO3 program, particularly near the ends of the open part of the hull. This results from much greater stresses caused by local bending of the deck strips (due to ship torsion) assumed by GL.

Fig.4 shows results of fatigue strength computations for hatch corners (taking into account respective K-factors) in the form of the dimensionless sum of fatigue damages D (circle-marked line) in the case of North Atlantic and worldwide wave statistics. Comparative values of the stress range $\Delta\sigma_T$ to allowable-fatigue-stress $\Delta\sigma_{fail}$ ratio obtained on the basis of GL rules (black-filled circle marked line) are also included. In spite of considerable differences in stress ranges (see Fig.3), the results are similar within the middle part of the ship in the case when worldwide wave statistics is accounted for in SANKO3 calculations.

COMPARISON BETWEEN CALCULATION RESULTS BASED ON THIN-WALL BEAM THEORY AND GLOBAL FEM ANALYSIS

Fatigue strength assessment of a structure is strongly influenced by accuracy of stress range determination. Results based on the thin-wall beam theory were compared with the coarse-mesh global FE analysis of PK6101 container ship by using MAESTRO computer program described in [10]. Hull subdivision into finite elements, modules and substructures is shown in Fig.5 according to [8]. FE model contained about 28 000 degrees of freedom altogether.

Though FEM calculations were realized only for two conventional, torsion-horizontal bending wave loads, acc. to DNV [9], called further LC1 and LC2, conclusions are valid also for the direct method of wave load long-term prediction. Results selected from [4], are described beneath.

Warping deformations of longitudinal coaming due to ship torsion, determined by using different methods for LC1 load case, are shown in Fig.6.

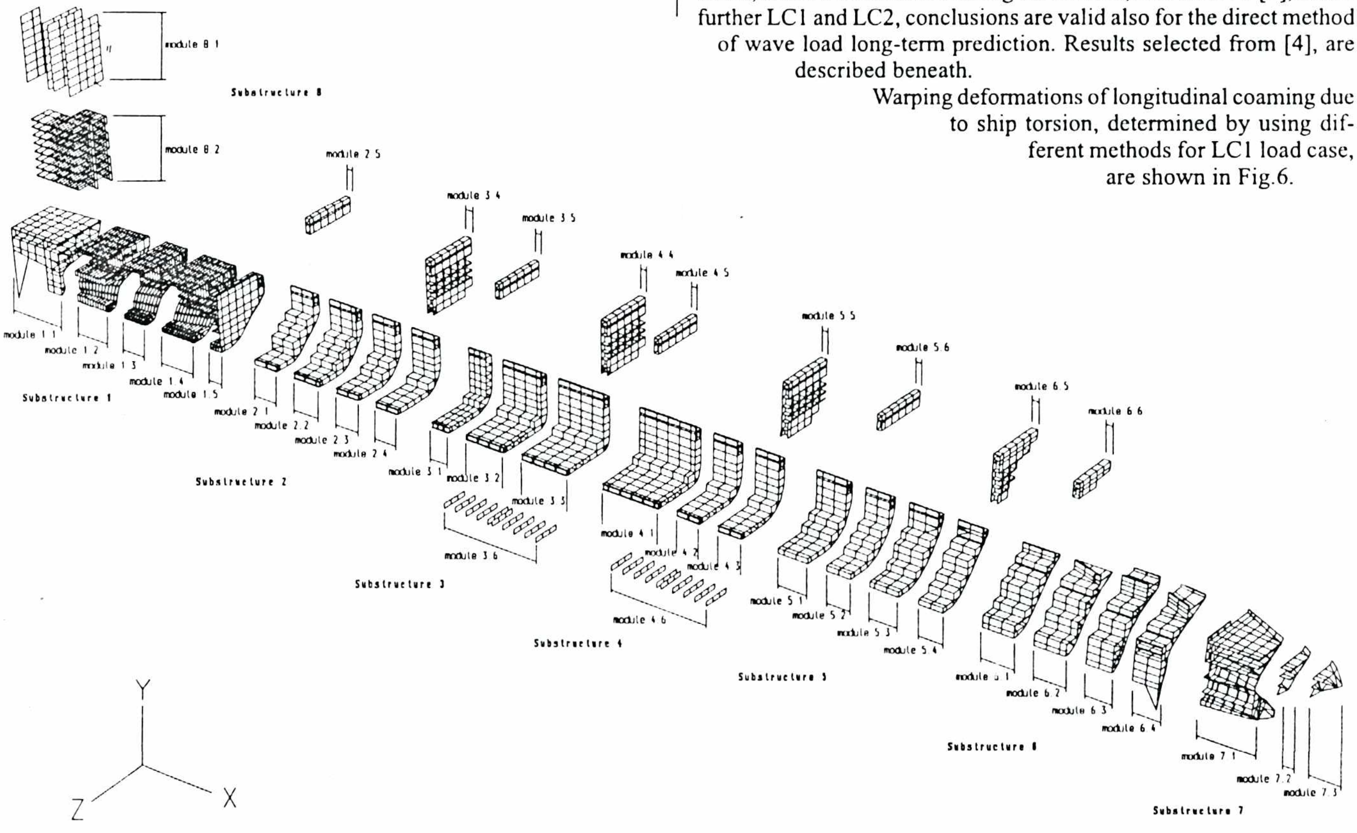

Fig.5. MAESTRO idealization of PK6101 container ship

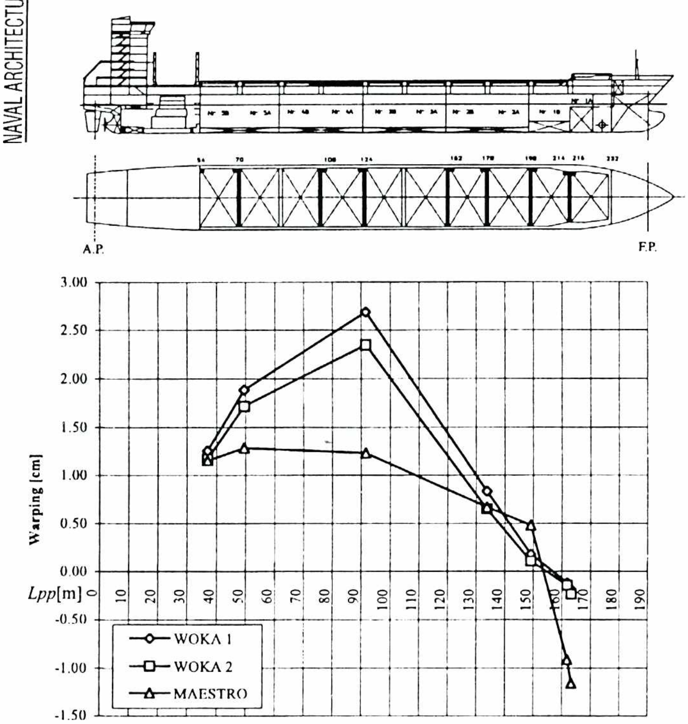

Fig.6. Warping deformation of hatch longitudinal coaming

Here WOKA1 and WOKA2 stand for results obtained by using WOKA program [5] based on the thin-wall beam theory, while MAESTRO means FEM analysis results by using MAESTRO program [10].

Nominal stresses in longitudinal coaming caused by restrained warping torsion are shown for LC1 load case in Fig.7.

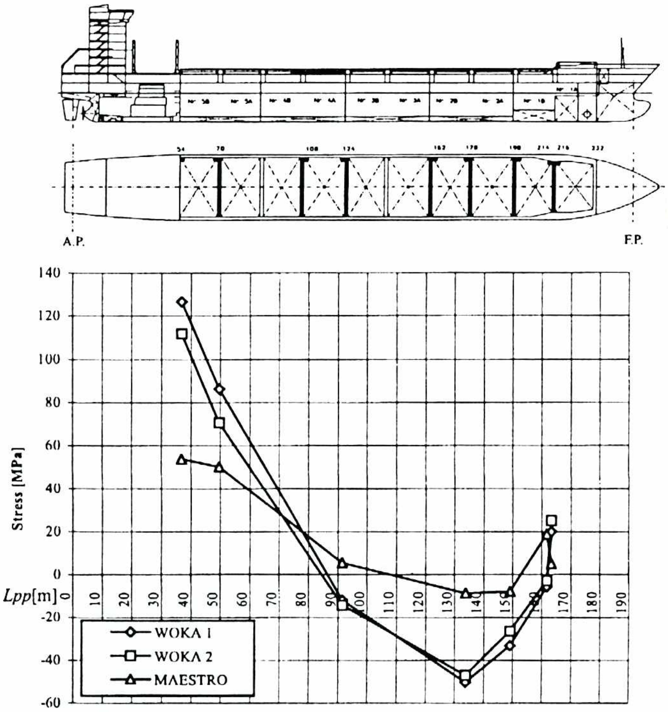

Fig.7. Warping stresses in hatch longitudinal coaming

Though stress and deformation distributions along the ship, determined by using both methods are very similar, MAESTRO based results are, as a rule, of much lower magnitudes than those obtained by using WOKA program. The difference between WOKA1 (transverse deck strips idealized as isolated beams) and WOKA2 (full deck plane frame) based results is of a low, if any, importance in comparison with errors inherent in applying the thin-wall beam theory to ship torsion analysis, at least when a slender hull, typical of the cellular container ships, is concerned.

CONCLUSIONS

The following conclusions may be deduced from the performed computations :

- Wave statistics data for the unrestricted area of navigation should be used in SANKO3 program as default values instead of those for North Atlantic used in the present version of the program. This will provide a more realistic fatigue strength assessment of the ships not designed exclusively for North Atlantic service.
- Effect of local bending of longitudinals for fatigue strength should be assessed by means of a direct method. For this purpose a new version of the program should be developed with the effect of local pressures induced by waves and of accelerations taken into account to predict long-term total stresses in longitudinals.
- Bow flare slamming effect should be taken into account in prediction of total stresses to improve accuracy of the total hull girder stress prediction in forward deck region.
- The thin-wall beam theory is of little value as far as torsion analysis of slender body, cellular container ship is concerned. The coarse-mesh global FE analysis should be used instead to determine nominal total stress level. The fatigue stress assessment approach described in [1] is still valid, however the component stresses due to unit load distributions, needed in the total stress approach [11], should be determined on the basis of the coarse-mesh global analysis rather than by means of the thin-wall beam model.

Appraised by Janusz Kolenda, Prof.,D.Sc.,M.E.

BIBLIOGRAPHY

1. Baczyński A., Konieczny L., Latuszek P, Walczyk M.: „Fatigue Strength Assessment of Container Ships", Polish Maritime Research, No. 2, June 1997
2. Det Norske Veritas: „Fatigue Assessment of Ship Structures". DNV Report No. 93-0432, 95-01-31
3. CTO: „System Analizy Kadłubów Otwartych SANKO II (TAW12J,THD27J, THD28J). Instrukcja użytkowania programu ". Oprac. nr RK-85/U-133, Gdańsk, 1985
4. Baczyński A., Latuszek P.: „Testowanie wymagań przepisowych zawartych w projekcie Publikacji PRS nr 24/P". Raport Techniczny CTO nr RK-95/T-143, Gdańsk, 1995
5. CTO: „WOKA: Obliczanie wytrzymałości ogólnej kadłuba. Instrukcja użytkowania programu". Oprac. nr RK-89/U-071, Gdańsk, 1989
6. Baczyński A., Konieczny L., Walczyk M.: „Ocena wytrzymałości zmęczeniowej kontenerowców". Raport Techniczny CTO nr RK-95/T-68, Gdańsk, 1995
7. Fricke W.: „Example for the calculation of deformation and stresses in ships having a high deck opening ratio according to GL Rules 1992". Rev. August 1994
8. Latuszek P.: „Analiza wytrzymałości ogólnej oraz optymalizacja rozwiązania konstrukcyjnego przedstawionego w projekcie PA6101". Raport Techniczny CTO Nr RK-95/T-64, Gdańsk, 1995
9. Det Norske Veritas: „Strength Analysis of Container Ship Structure" Draft Classification Note, January 1994
10. Hughes O. F.: „Ship Structural Design, A Rationally Based, Computer Aided Optimization Approach". SNAME, 1988
11. Baczyński A., Konieczny L., Walczyk M.: „Application of Total Stress Approach to Open Hull Strength Prediction". First International Conference on Marine Technology ODRA'97. Szczecin, September 1995