ISSN 0554-6397
PREGLEDNI RAD
(*Review*)

Nikola Vladimir
E-mail: nikola.vladimir@fsb.hr
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, Croatia
Šime Malenica, Jérôme De Lauzon
Bureau Veritas, Research Department, Paris, France
Ivo Senjanović
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, Croatia
Hongil Im, Byung-Ki Choi
Hyundai Heavy Industries Co., Ltd., Ulsan, South Korea
Dae Seung Cho
Pusan National University, Busan, South Korea

Structural Design of Ultra Large Ships Based on Direct Calculation Approach

Abstract

The trend in modern sea transportation is building of ever larger ships, which require application of different direct calculation methodologies and numerical tools to achieve their reliable structural design. This is particularly emphasized in case of ultra large container ships (ULCS), but also other ship types like bulk carriers or large LNG ships belong to this category. In this context some classification societies have developed guidelines for performing direct calculations and for that purpose there are several hydro-structure tools available around the world, mainly relying on the same theoretical assumptions, but having incorporated different numerical procedures. Such tools are mostly based on the application of the 3D potential flow theoretical models coupled with the 3D FEM structural models. This paper illustrates application of general hydro-structure tool HOMER (BV) in the assessment of ship structural response in waves. An outline of the numerical procedure based on the modal approach is given together with basic software description. Application case is 19000 TEU ULCS built in South Korean shipyard Hyundai Heavy Industries. Extensive hydroelastic analyses of the ship are performed, and here some representative results for fatigue response with linear springing influence are listed.

Keywords: HOMER, Ultra Large Container Ships, hydroelasticity, fatigue, linear springing

1. Introduction

Specific characteristic of Ultra Large Container Ships (ULCS), compared to the other ship types, is that they are more likely to experience the hydroelastic type of structural response called springing and whipping [1,2,3,4]. That is mainly caused by their large dimensions leading to lower structure rigidity, relatively high operational speed and large bow flare. The evaluation of the hydroelastic response and its inclusion into the overall design procedure is significantly more complex problem than the calculation of quasi-static structural response [2]. The Rules of classification societies are not directly applicable to ULCSs, and therefore direct calculations are necessary for their safe and rational design. In this context some classification societies have developed guidelines (rule notes) for inclusion of hydroleastic effects into overall design procedure. Moreover, for that purpose there are several hydro-structure software available around the world, mainly relying on the same theoretical assumptions, but having incorporated different numerical procedures. Such tools are mostly based on the application of the 3D potential flow theoretical models for fluid flow coupled with the 3D FEM structural models.

In this paper, some aspects of application of direct calculations in the design of ultra large ships are discussed, whereas preliminary results of hydroelastic analysis of 19000 TEU container ship designed by Hyundai Heavy Industries (HHI) are presented. The paper is motivated with the development of new container ship type called HHI SkyBench^{TM} with particular aim to increase ship capacity. Details of new HHI SkyBench^{TM} CS design are presented in [5,6,7]. The ship has an additional hatch opening, which could make the vessel relatively vulnerable to warping deformation. Therefore, it is necessary to investigate its springing and whipping performance and compare it with the performance of conventional container ship. The whole analysis is done at so called WhiSp1, 2 and 3 levels, and here preliminary results related to WhiSp1 are presented [8].

A general hydro-structure tool HOMER [9,10], where 3D FEM model for the structure and 3D potential flow code for fluid modelling, respectively, is used.

The paper is structured into 7 sections. In the second one, WhiSp methodology proposed by Bureau Veritas (BV) is given. An outline of the numerical procedure based on the modal approach and stress concentration calculation by HOMER is presented in the third section. The fourth section is related to ship particulars and used calculation models while some specific results inherent to unique balancing procedure available within the used software and verification of calculation models are presented in the fifth section. In the sixth section, both global and local ship responses are demonstrated, and calculated fatigue characteristics of the selected structural details are listed. In order to assess the relative influence of hydroelasticity quasi-static contribution is clearly separated from the total response. Finally, preliminary conclusions are drawn and guidelines for further investigation are given.

2. Outline of the applied methodology

From methodology point of view, the Bureau Veritas Rule Note NR583 is applied [8]. Generally, it deals with the part of structural analysis which aims at performing ultimate strength and fatigue assessment based on direct hydro-structure calculations including whipping and springing response. Application of BV Rule Note 583 includes:

- recommendations for springing and whipping assessment,
- methodology for long-term direct hydro-structure calculations including springing and whipping response,
- definition of additional service features and class notations WhiSp.
- Additional service features or additional class notation WhiSp are defined as follows:
- WhiSp1 notation covers the effect of linear springing in the fatigue damage assessment, but whipping is not considered neither for fatigue nor for ultimate strength,
- WhiSp2 notation corresponds to WhiSp1 notation with additional whipping computation for ultimate strength assessment,
- WhiSp3 notation corresponds to WhiSp2 notation with additional whipping computation for fatigue assessment.

It should be mentioned that there is not a single methodology to compute the extreme response or the total fatigue damage, so the above mentioned Rule Note 583 includes a list of methods and tools. Depending on what is to be simulated, a given long-term methodology is to be used in conjunction with a specific hydro-structure model.

In order to cover all types of hydro-structural interactions inherent ships and offshore structures described in [8], the numerical software HOMER is developed in BV Research Department for the direct transfer of the seakeeping loads from the general seakeeping code to a structural FE model, [9,10].

Three main ideas introduced through HOMER software to obtain the perfect equilibrium of the structural model are the following, [10]:

1. Recalculation of the pressure at the structural points (instead of interpolation),
2. Separate transfer of the different pressure components, and calculation of the different hydrodynamic coefficients by integration over the structural FE mesh,
3. Solution of the motion equation using the above calculated hydrodynamic coefficients and inertia properties of the FE model. This point ensures the perfect equilibrium of the FE load case because of calculation of all the coefficients of the motion the FEM model.

Within the investigation presented in this paper, HOMER is used with Hydrostar [11] as the hydrodynamic solver, and NASTRAN [12] as the structural solver.

Fatigue assessment of selected structural details is performed according to the flowchart presented in Figure 1. For the fatigue life/damage calculation, very local stress concentrations are needed, and generally they can be calculated by refining the global coarse mesh or using the so called top-down approach. The former approach seems to be impractical leading to excessive number of finite elements, and therefore here, the latter one is used, which implies solving the global coarse mesh FEM problem at first, and applying the coarse mesh displacements at the boundaries of the local fine mesh later [13]. In this way the fine mesh FEM calculations are performed in a second step with the load cases defined by the prescribed displacements from the coarse mesh and by the local pressures and inertia of the fine mesh. The above procedure should be performed for each operating condition (combination of ship loading condition, wave frequency and heading) and for both real and imaginary part of the wave loading, resulting in the RAOs of the stresses in each particular structural detail. A special care should be given to the separation of the quasi-static and dynamic parts of the response to ensure a proper convergence of the results. The quasi-static part of the response is calculated using the so called quasi-static method as described in [8], and dynamic part of the response is calculated by summing up the dynamic contribution of each mode. After transfer functions of stresses are obtained, spectral analysis is performed and based on the selected S/N curve and wave scatter diagram, fatigue life/damage is calculated.

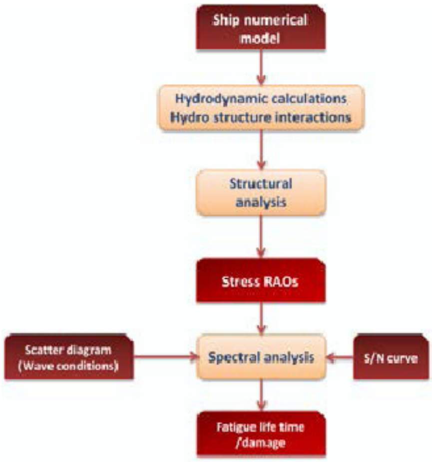

Figure 1. Fatigue assessment flowchart.

Within WhiSp1, which is considered in this paper, and in accordance with [8], fatigue analysis is carried out for a single loading condition, selected so as to maximise the still water bending moment in hogging. The sea states are modelled by a well-known Pierson-Moskowitz spectrum and "cos *n*" spreading function, with n=2. Worldwide scatter diagram is used. The ship speed is taken to be as 60% of the ship design speed in all sea states, while values of the wave heading angle are considered uniformly distributed from 0° to 350° with step of 10.0°.

3. Outline of the mathematical model

Linear hydroelastic analysis performed here is based on the mode superposition method [14]. Within the modal approach, total displacement of a ship is expressed through a series of modal displacements:

$$\boldsymbol{H}(x,t)=\sum_{i=1}^{N}\xi_i(t)\boldsymbol{h}^{i}(x) \tag{1}$$

where $\boldsymbol{H}(x,t)$ represents vector of total displacement of one point, $\boldsymbol{h}^{i}(x)$ is vector of modal displacement (mode shape), $\xi_i(t)$ is modal amplitude, and N represents the total number of modes [10]. Generally, the procedure is very similar to rigid body analysis described in [2] except that the number of degrees of freedom is extended from 6 to 6 plus a certain number of elastic modes. The used modal approach implies the definition of supplementary radiation potentials with the following body boundary condition:

$$\frac{\partial \varphi_{Rj}}{\partial n}=\boldsymbol{h}^{j}\boldsymbol{n} \tag{2}$$

where $\boldsymbol{n}$ is unit normal vector. After solving the different boundary value problems for the potentials, the corresponding forces are calculated and the matrix motion equation is written

$$\left\{-\omega^2\left(\mathbf{m}+\mathbf{A}\right)-i\omega(\mathbf{B}+\mathbf{b})+(\mathbf{k}+\mathbf{C})\right\}\xi=\mathbf{F}^{DI} \tag{3}$$

where **m** is matrix of the modal structural mass, **b** is matrix of the structural damping, **k** is matrix of the structural stiffness, **A** is the hydrodynamic added mass, **B** is the hydrodynamic damping matrix, **C** is the hydrostatic restoring stiffness matrix, and $\mathbf{F}^{DI}$ is the modal hydrodynamic excitation vector. Once the modal amplitude vector ξ has been calculated the total stresses can be obtained, at least theoretically, by summing the individual modal contributions and one can formally write, [2]:

$$\Sigma(x,\omega)=\sum_{i=1}^{N}\xi_i(\omega)\sigma^{i}(x) \tag{4}$$

where $\Sigma(x,\omega)$ is the total stress and $\sigma^{i}(x)$ is the spatial distribution of modal stresses.

In order to practically take into account hydroelastic effects on the structural response, dynamic analysis computational scheme is applied, starting with modal analysis in dry condition, [8]. Once the dry modes are obtained, the modal displacements are transferred from the structural model to the hydrodynamic one, and corresponding hydrodynamic problem is formulated. After that, fully coupled dynamic equation is solved, giving the modal amplitudes.

4. Ship particulars and calculation models

A HHI 19000 TEU ULCS with main particulars given in Table 1 is analysed.

Table 1. Main particulars of a HHI 19000 TEU container ship

Length over all, L_{OA} [m]	400
Length between perpendiculars, L_{PP} [m]	383
Breadth, B [m]	58.6
Depth, H [m]	30.5
Design draught, T_d [m]	14.5
Scantling draught, T_s [m]	16.0
Displacement at full load, Δ_F [t]	212913
Service speed, v_s [kn]	23.0

Global FE model of the considered ship, having 91076 finite elements and 30050 nodes, with indicated position and fine mesh models for fatigue life assessment, is presented in Figure 2. In total 14 positions of interest are defined. Beside both FE global and local (fine mesh) models of a ship structure, applied procedure and used numerical code also require generation of the so called integration mesh and hydrodynamic mesh, respectively, Figure 3. The former is extracted directly from the structural model, and then the latter one, having 5984 wetted panels on hull, is generated automatically using the existing software routines and slightly adapted for the sake of smooth computations. The loading and operating conditions, i.e. calculation setup established according to [8] and presented in the second section are used for numerical computations.

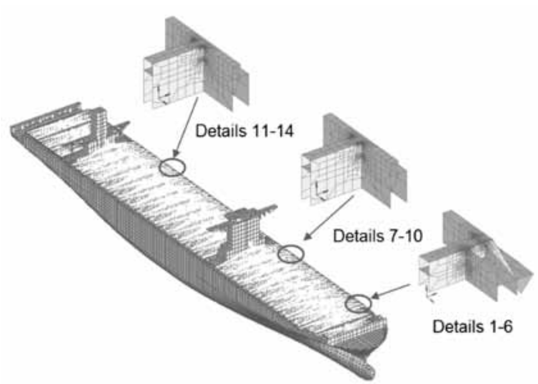

Figure 2. Finite element model of the analysed ship with local fine mesh models and their positions along the ship.

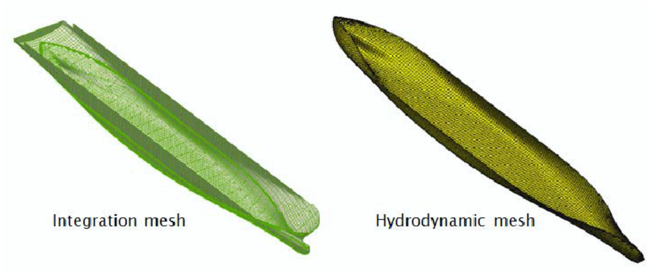

Figure 3. Integration and hydrodynamic meshes.

5. Verification of calculation models

Hydroelastic analysis based on the modal approach requires dry natural vibration analysis as a first step. In this case 10 global modes is retained for the analysis, and for illustration the first 6 modes and corresponding frequencies are shown in Figure 4.

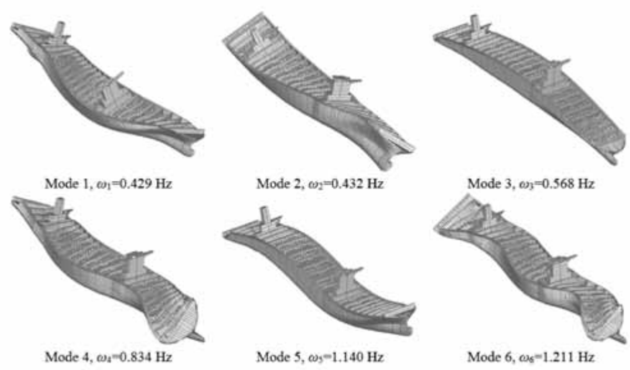

Figure 4. Mode shapes and dry natural frequencies of 19000 TEU container ship.

Prior to proceeding to the hydroelastic analysis, it is required to perform several checks, to ensure correct numerical setup, proper interactions between used models and their proper positions in global coordinate system. Therefore, it is necessary to:

- compare still calculated still water bending moments and shear forces with those given in loading manual,
- check still water pressures on ship hull,
- check position of structural model, integration mesh and hydrodynamic mesh relative to free surface,
- verify positions of local models to which Top-down is applied along the ship global FE model on elastic modes,
- check still water deflections and stresses both for global FE model and fine mesh models.

Still water bending moment and shear forces are presented in Figure 5, where very good agreement between HOMER numerical results and loading manual data is achieved.

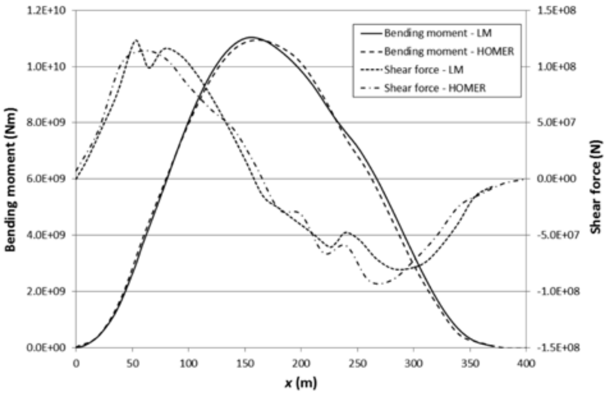

Figure 5. Still water bending moment and shear force.

Realistic values of still water pressures on ship hull, and appropriate positioning of structural, integration and hydrodynamic meshes are evident from Figures 6, 7, 8 and 9, respectively.

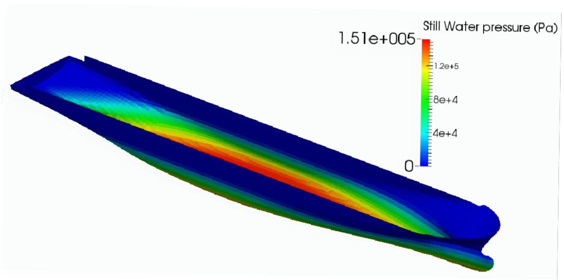

Figure 6. Hydrostatic pressures on ship hull.

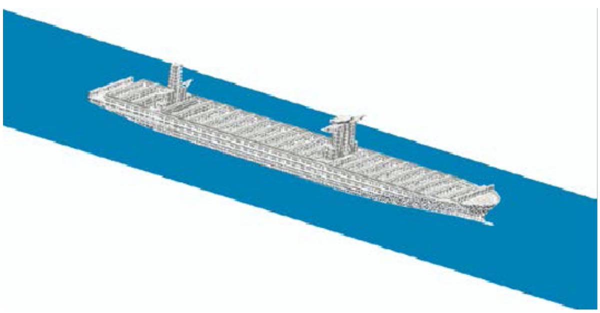

Figure 7. Position of structural model relative to free surface.

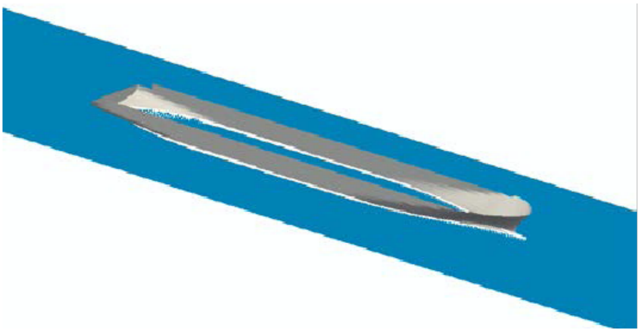

Figure 8. Position of integration mesh relative to free surface.

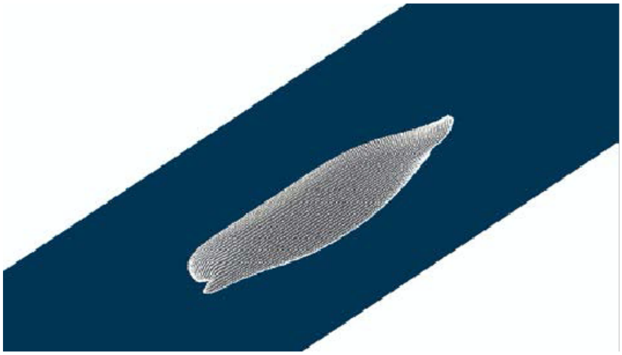

Figure 9. Position of hydrodynamic mesh relative to free surface.

Positions of fine mesh models along the structural finite element model are presented for elastic modes in Figure 10. Figure 11 and 12 show still water deflections and still water stresses of a ship respectively. In addition, von Mises stresses for details 11-14 are shown in Figure 13.

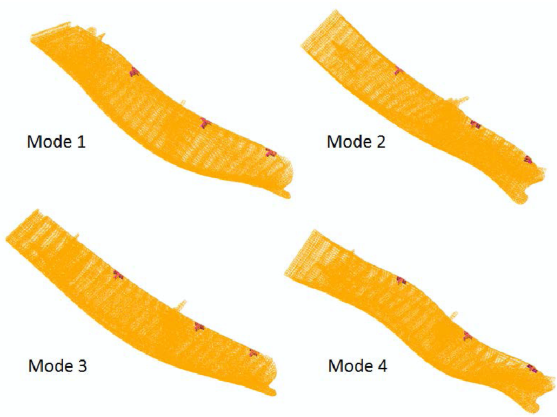

Figure 10. Positions of fine mesh models along the ship on elastic modes.

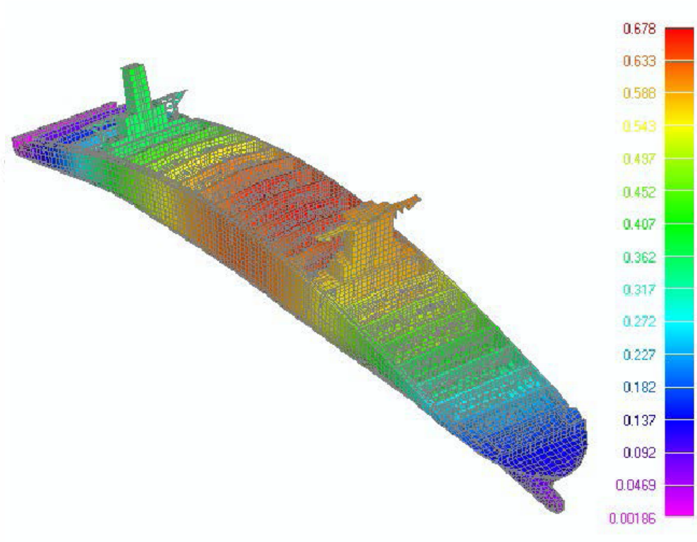

Figure 11. Still water deflection.

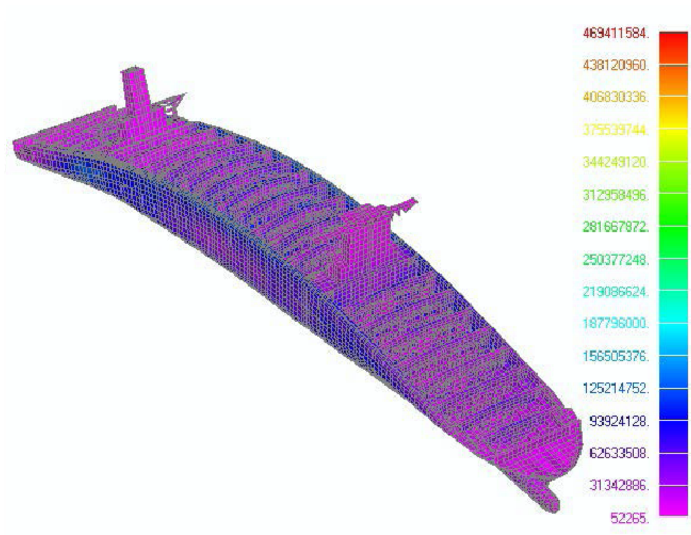

Figure 12. Still water von Mises stresses (Pa).

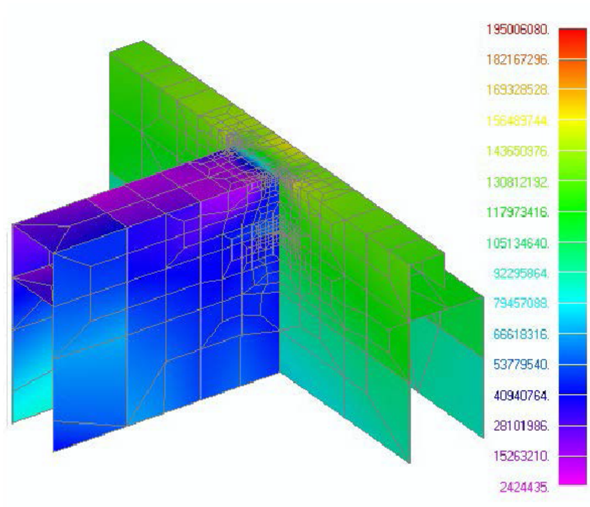

Figure 13. Still water von Mises stresses in details 11-14 (Pa).

6. Results of hydroelastic analysis

Global ship hydroelastic response, i.e. RAOs of vertical bending moments at midship for β=130° and 180°, is presented in Figure 14. RAOs of torsional moments at 0.25L and 0.75L, and horizontal bending moments at 0.5L are shown in Figures 15 and 16, respectively.

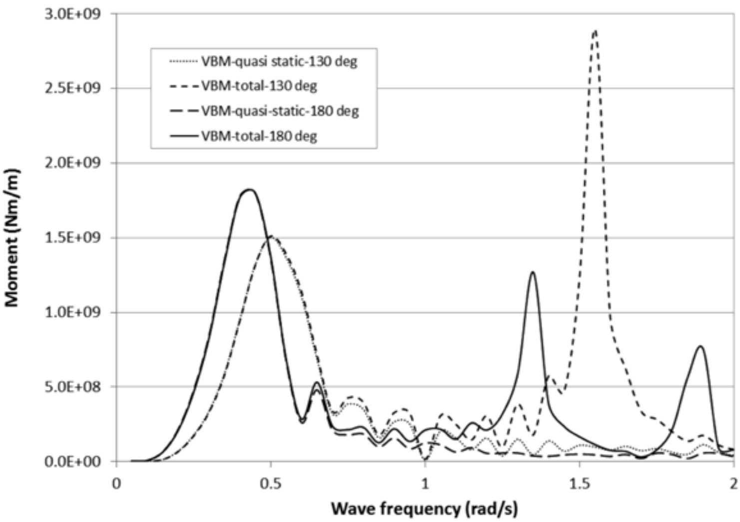

Figure 14. RAOs of vertical bending moments at midship.

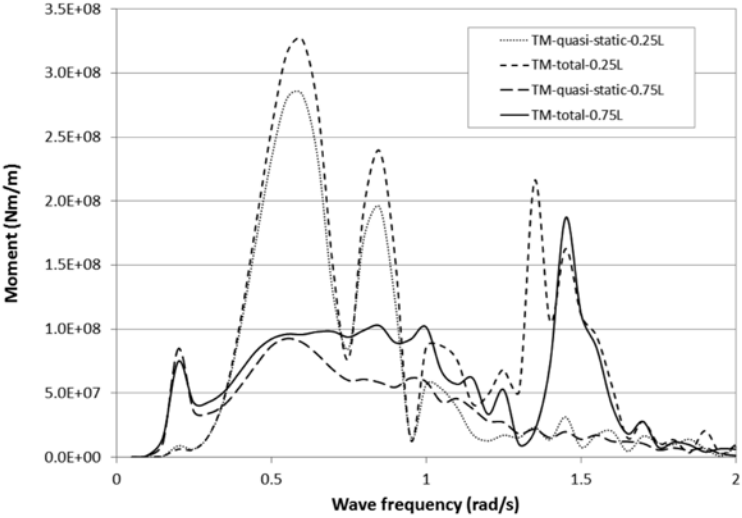

Figure 15. RAOs of torsional moments, β=130°.

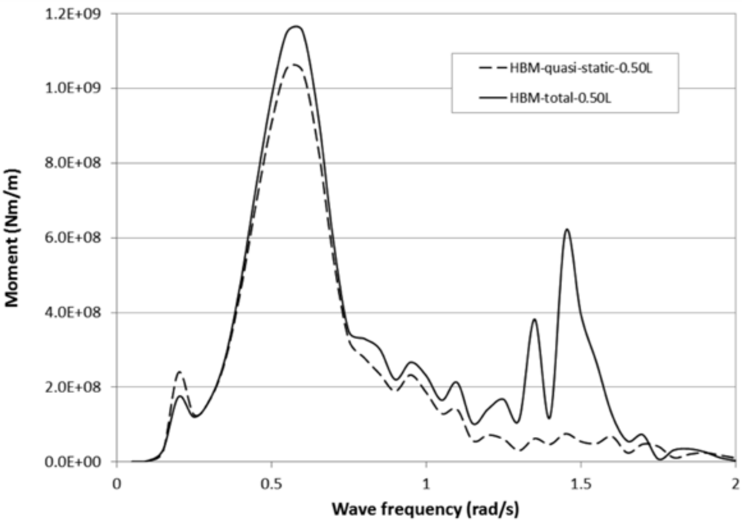

Figure 16. RAOs of horizontal bending moments at midship, β=130°.

Similarly as in the case of sectional moments, obtained stresses for fatigue computation are also presented as the rigid body component and total quantity, Figures 17 and 18.

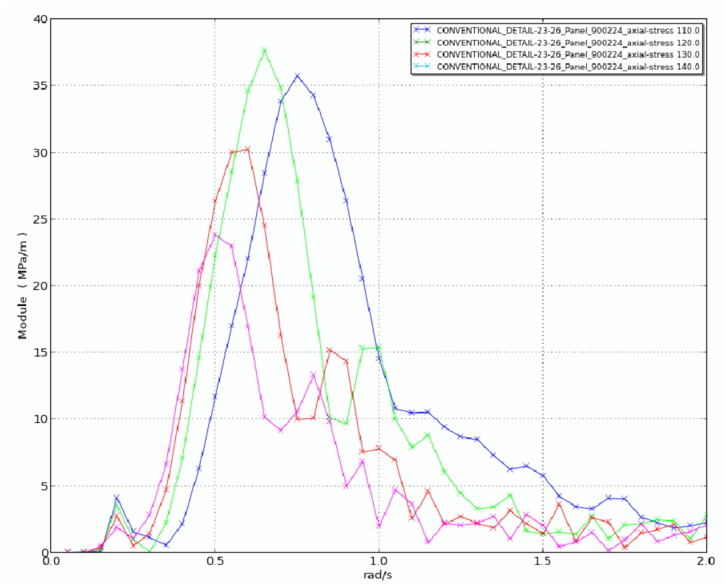

Figure 17. Quasi-static stress RAOs, detail 13.

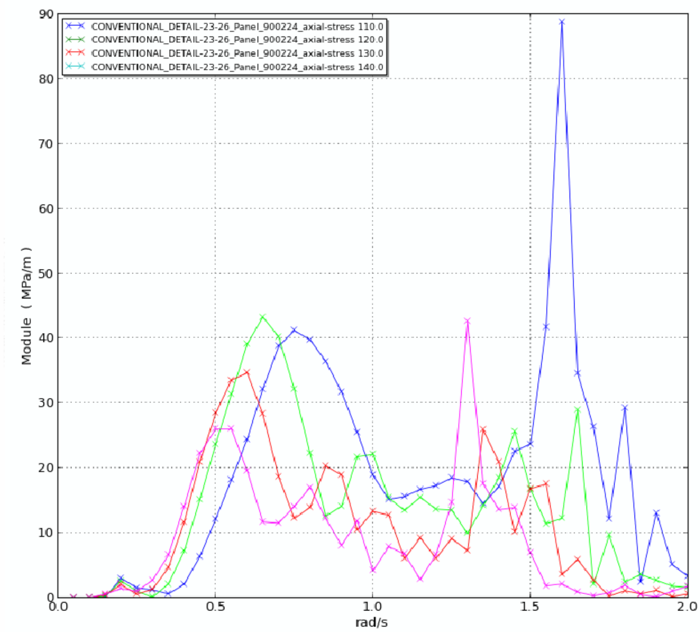

Figure 18. Total stress RAOs, detail 13.

Stress RAOs are used as input data for fatigue calculation. As the representative one, the axial stress in the rod elements at the hatch corner radius free edges of fine mesh FE models is used. Fatigue lives of selected structural details are presented in Table 2. The results are obtained for sailing factor equal to 0.85 and mean stress effect is taken into account.

The all analysed details satisfy WhiSp1 criterion (28 years if WhiSp3 is not granted and 25 years if WhiSp3 is granted). However, the analysis should be further extended to cover more structural details of the considered ship. For each of the analysed detail influence of sea states and azimuth can be analysed. Based on these parameters, representative input for time domain simulations for WhiSp3 assessment is to be selected. For illustration, contribution of different sea states and azimuth for detail 14 are presented in Figures 19 and 20, respectively.

Table 2. Fatigue lives of analysed structural details

Position	Fatigue life (years)		Position	Fatigue life (years)	
	Quasi-static	Total		Quasi-static	Total
1	64588235	35717647	8	235.53	192.82
2	458000	257882	9	538.00	406.12
3	67247058	45000000	10	463.41	374.94
4	2544	1490	11	165.53	129.65
5	632705	368000	12	196.47	152.00
6	1215	716.94	13	126.82	68.85
7	224.35	175.06	14	189.29	91.49

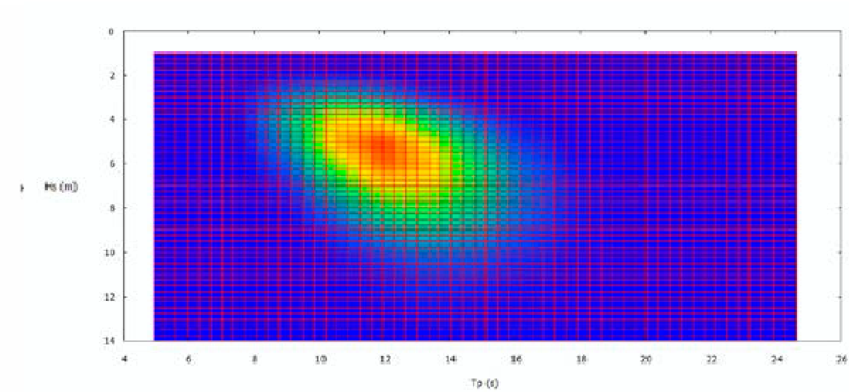

Figure 19. Contribution of different sea states to total fatigue damage, detail 13.

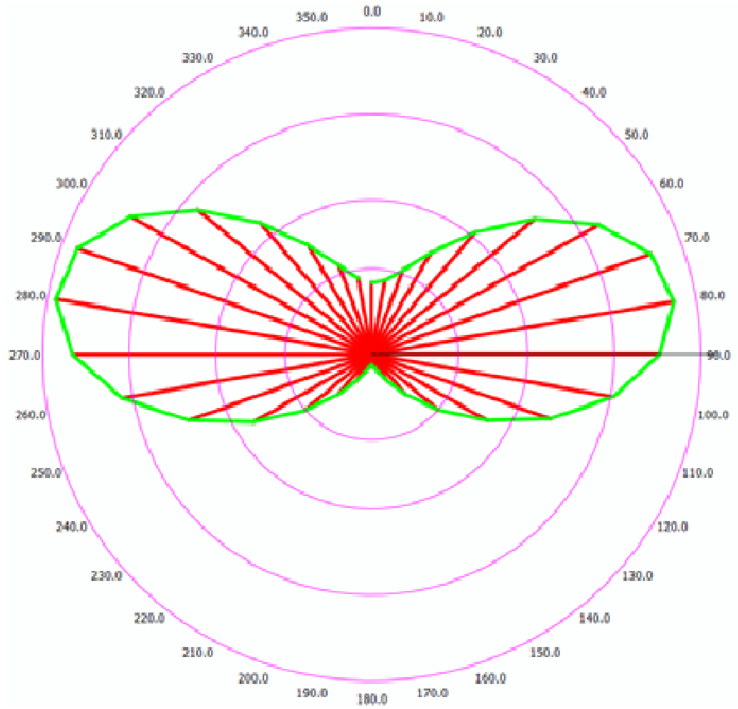

Figure 20. Azimuth contribution to total damage, detail 13.

7. Conclusion

Application of direct calculation methodologies and general hydro-structure numerical tool HOMER (BV) in the structural design of ultra large ships is illustrated. The application case was the HHI 19000 TEU ultra large container ship. Modal approach is employed for the determination of global ship hydroelastic response, and top-down procedure is applied to determine stress concentrations using the fine mesh models of selected structural details. Preliminary results indicate that no fatigue cracks are expected before 68.85 years. That is in line with the fact that the analysed ship was built several years ago, and safely operates worldwide, without any fatigue damage registered for the time being.

Future work will be related to ultimate strength and fatigue performance check according to WhiSp2 and 3, respectively. For WhiSp3 which includes whipping influence on fatigue, for each structural detail the design sea state and azimuth, most contributing to the fatigue damage are required, based on the linear long term analysis. For those sea states, time domain simulations will be done to obtain stress time histories, and after performing rainflow counting, relative influence of hydroelasticity for each particular detail can be determined.

Acknowledgments

This investigation was done within the Joint Research Project (JRP) "A Study on Springing and Whipping of Hyundai SkyBench™ Container Carrier". Authors are grateful to Quentin Derbanne and Maximilien Basquin from Bureau Veritas, Paris, for valuable discussions related to WhiSp methodology application. Also, the support of the Korean Government (MSIP) and National Research Foundation of Korea (NRF) through GCRC-SOP (Grant No. 2011-0030013) is greatly acknowledged.

References

1. Š. Malenica, N. Vladimir and I. Senjanović. *Proceedings of the 2nd International Workshop on Springing and Whipping of Ships*. Split, Croatia, 2012.
2. Š. Malenica, I. Senjanović and N. Vladimir. Hydro structural issues in the design of Ultra Large Container Ships. *Brodogradnja*, 64(3):323-347, 2013.
3. I. Senjanović, N. Vladimir, M. Tomić, N. Hadžić, Š. Malenica. Global hydroelastic analysis of ultra large ships by improved beam structural model. *International Journal of Naval Architecture and Ocean Engineering*, 6(4):1041-1063, 2014.
4. I. Senjanović, N. Vladimir, M. Tomić, N. Hadžić, Š. Malenica. Some aspects of structural modelling and restoring stiffness in hydroelastic analysis of large container ships. *Ships and Offshore Structures*, 9(2):199-217, 2014.
5. H.I. Im, D.S. Cho, T.J. Kim, B.K. Choi, H.R. Ryu and B.R. Lee., A new design of container carrier for maximizing cargo capacity. *The Royal Institution of Naval Architects: Design & Operation of Container Ships*, 53-60, London, UK, 2014.
6. H.I. Im, D.S. Cho, G.H. Hwang, D.H. Lee, B.K. Choi and B.R. Lee. SkyBench™ container carriers for maximizing cargo capacity. *28th Asia Pacific Technical Exchange and Advisory Meeting on Marine Structures-TEAM*, 508-513, Istanbul, Turkey, 2014.
7. H.I. Im, N. Vladimir, Š. Malenica, H.R. Ryu, D.S. Cho. Fatigue analysis of HHI SkyBench™ 19000 TEU ultra large container ship with springing effect included, *Proceedings of the 7th International Conference on Hydroelasticity in Marine Technology*, Split, Croatia, 2015., 561-574.
8. Bureau Veritas. *Whipping and Springing Assessment, Rule Note NR 583 DT R00 E*. Bureau Veritas, Paris, July 2015.
9. F.X. Sireta, J. De-Lauzon and F. Surmont. *HOMER User guide*. Paris, France, 2013.
10. Š. Malenica, Q. Derbanne, F.X. Sireta, F. Bigot, E. Tiphine, G. De Hauteclocque and X.B. Chen. HOMER – Integrated hydro-structure interactions tool for naval and offshore applications. *International Conference on Computers Application in Shipbuilding*, Busan, Korea, 2013.
11. Bureau Veritas. *Hydrostar, User's manual*, Paris, 2006.
12. MSC. *MD Nastran 2010 Dynamic analysis user's guide*. Newport Beach, California, USA: MSC Software; 2010.
13. F.X. Sireta, Q. Derbanne, F. Bigot, Š. Malenica and E. Baudin. Hydroelastic response of a ship structural detail to seakeeping loads using a top-down scheme. *31st International Conference on Ocean, Offshore and Arctic Engineering - OMAE*, ASME, Brasil, 2012.
14. R.E.D. Bishop and G. Price. *Hydroelasticity of Ships*. Cambridge University Press, 1979.

Nikola Vladimir, Šime Malenica, Jérôme De Lauzon, Ivo Senjanović, Hongil Im, Byung-Ki Choi, Dae Seung Cho

Osnivanje konstrukcije ultra velikih brodova na temelju direktnih proračuna

Sažetak

U suvremenom pomorskom prijevozu trend je gradnja sve većih brodova, koji zahtijevaju primjenu različitih postupaka i računalnih programa za direktne proračune, kako bi se osigurala pouzanost njihove konstrukcije. To je posebice izraženo u slučaju ultra velikih kontejnerskih brodova, ali i kod drugih tipova brodova, kao što su primjerice brodovi za prijevoz rasutog tereta ili veliki brodovi za prijevoz ukapljenog plina. U tom smislu određena klasifikacijska društva razvila su smjernice za direktne proračune, za što diljem svijeta postoji nekoliko suvremenih programskih paketa uglavnom temeljenih na istim teorijskim osnovama, s različitim numeričkim postupcima. Takvi alati najčešće su utemeljeni na primjeni paketa 3D modela potencijalnog strujanja spregnutim s 3D FEM strukturnim modelima. U ovom članku ilustrirana je primjena općeg programskog paketa HOMER (BV) za analizu strukturnog odziva broda na valovima. Ukratko su opisana metodologija, numerički postupak i programski paket, te je razmotrena njegova praktična primjena na ultra veliki kontejnerski brod nosivosti 19000 TEU izgrađen u južnokorejskom brodogradilištu Hyundai Heavy Industries. Provedene su opsežne hidroelastične analize, a u radu su prikazani rezultati reprezentativni za zamor odabranih strukturnih detalja broda s utjecajem linearnog pruženja.

Ključne riječi: HOMER, ultra veliki kontejnerski brod, hidroelastičnost, zamor, linearno pruženje