대한조선학회 프로그램

Hydroelastic Analysis of 19000 TEU Ultra Large Container Carrier

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Abstract

The trend in modern sea transportation is building of ever larger container vessels, which require application of different direct calculation methodologies and numerical tools to achieve their reliable structural design. In this paper structural design of 19000 TEU class ultra large container carrier is evaluated both for fatigue and extreme response within so called WhiSp1 and 2 methodologies, respectively. WhiSp1 implies evaluation of fatigue life of selected structural details with linear springing effect included, while within WhiSp2 the ultimate strength check is done considering slamming induced whipping. Mathematical model is based on the application of the 3D potential flow theoretical models coupled with the 3D FEM structural models. The general hydro-structure code HOMER, developed in Bureau Veritas is used. Stress RAOs of selected structural details are obtained for full scatted diagram by the top-down procedure, and further used to assess their fatigue lives. Linear long term analysis is performed to define most contributing sea state to the vertical bending moment (VMB). Whipping response is computed on so called increased design sea state in time domain. Finally, extreme VBM is determined, and ultimate strength check is done. Preliminary results indicate that analyzed ship satisfies both WhiSp1 and 2 criterion, respectively.

Keywords : ULCS, Hydroelasticity, WhiSp, Fatigue, Extreme response, Frequency domain, Time domain simulation

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 (Malenica et al., 2012, 2013a,b; Senjanović et al., 2014a,b). That is mainly caused by their large dimensions leading to higher structure flexibility, relatively high operational speed and large bow flare. 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 and 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™ with particular aim to increase ship capacity (Im et al., 2014a,b). The ship has an additional hatch opening, which could make the vessel relatively vulnerable to warping deformation. Therefore, it was 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 (Bureau Veritas, 2015), and here results related to WhiSp1 and 2 are presented, respectively. It should be mentioned that some of the preliminary results related to WhiSp1 are briefly discussed in (Vladimir et al., 2015). A general hydro-structure tool HOMER (Sireta et al., 2013), where 3D FEM model for the structure and 3D potential flow code for fluid modelling, respectively, is used.

2. Methodology description and outline of the mathematical formulation

From methodology point of view, the Bureau Veritas Rule Note NR583 is applied (Bureau Veritas, 2015). 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 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.

However, 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 appropriate 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 (Bureau Veritas, 2015), 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. Within the investigation presented in this paper, HOMER is used with Hydrostar (Bureau Veritas, 2006) as the hydrodynamic solver, and NASTRAN (MSC Software, 2010) as the structural solver.

Fatigue assessment of selected structural details is performed according to the flowchart presented in Fig. 1. For the fatigue life 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 (Sireta et al., 2012).

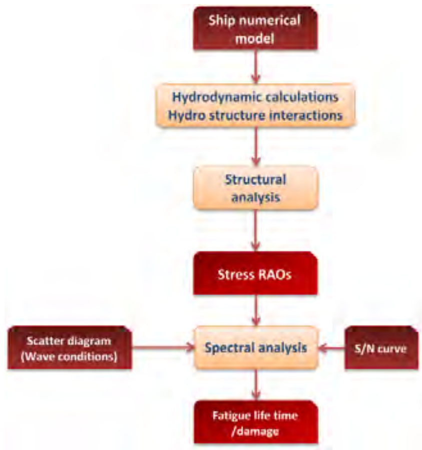

Fig. 1 Fatigue assessment flowchart

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.

Within WhiSp1, fatigue analysis presented in this paper 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 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°.

Linear hydroelastic analysis performed here is based on the mode superposition method (Bishop and Price, 1979). 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. Generally, the procedure is very similar to rigid body analysis described in (Malenica et al., 2013b) 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 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

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

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 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, (Malenica et al., 2013b):

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

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 (Bureau Veritas, 2015). 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.

As mentioned above WhiSp2 calculation implies ultimate strength assessment with additional whipping computation, where ship speed is set at 5.0 kn (Bureau Veritas, 2015). At first, it is necessary to determine the linear long term value of vertical bending moment (VBM) and most contributing sea states to that value, by spectral analysis. After that design sea states for which time domain simulation are needed, should be determined. Then time domain simulations are run on design sea states, and statistical analysis of time signals is performed to obtain the non-linear value of VBM. According to Bureau Veritas (2015) it is to be checked that the hull girder ultimate bending capacity at any cross-section is in compliance with the following formula:

$$M\le\frac{M_U}{\gamma_R} \tag{5}$$

where M_u represents ultimate bending capacity of hull transverse section, M is computed extreme vertical bending moment and γ_R is partial safety factor taken equal to 1.1.

2. Ship particulars and calculation models

Main particulars of the analysed 19000 TEU container ship are presented in Table 1.

Table 1 Main particulars of the considered container ship

Length over all, LOA	400*m*
Length between perpendiculars, LPP	383*m*

Breadth, B	58.6*m*
Depth, H	30.5*m*
Design draught, Td	14.5*m*
Scantling draught, Ts	16.0*m*
Displacement at full load, ΔF	212913*t*
Service speed, vs	23.0*kn*

Global FE model with indicated positions of fine mesh models for fatigue life assessment is presented in Fig. 2. In total 14 structural details of interest are selected. 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, Fig. 3 (Sireta et al., 2013). 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.

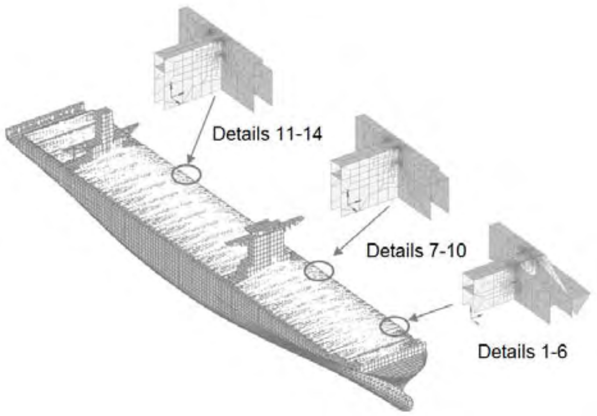

Fig. 2 Finite element model of the analyzed ship with local fine mesh models and their positions along the ship

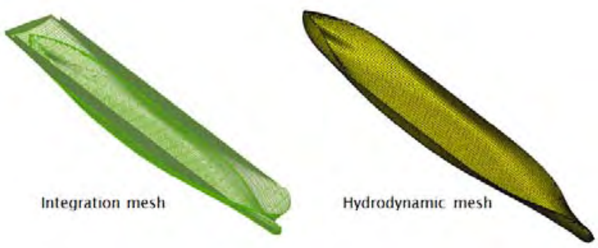

Fig. 3 Integration and hydrodynamic meshes

3. Verification of calculation models

Hydroelastic analysis based on the modal approach requires dry natural vibration analysis as a first step, and in this case 10 global natural modes are retained for the calculation. Before the hydroelastic analysis, it is required to perform some checks, to ensure correct numerical setup, proper interactions between used models and their proper positions in global coordinate system. Therefore, one should:

- verify that calculated still water bending moments and shear forces reasonably agree with those listed 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,
- definition of slamming sections for whipping simulation.

Still water bending moment and shear forces are presented in Fig. 4, where very good agreement between HOMER numerical results and loading manual data is achieved.

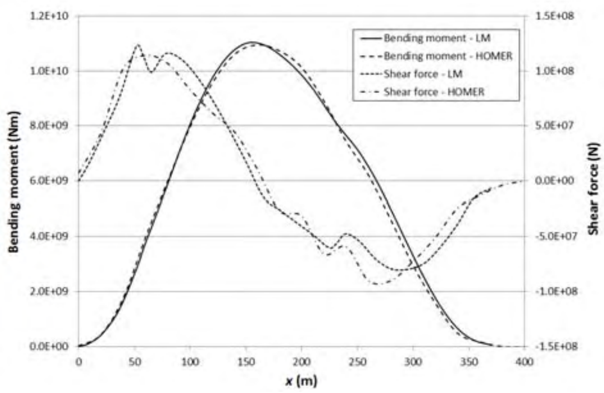

Fig. 4 Still water bending moment and shear force

Realistic values of still water pressures on ship hull, and appropriate positioning of structural, integration and hydrodynamic meshes are evident from Fig. 5, 6, 7 and 8, respectively.

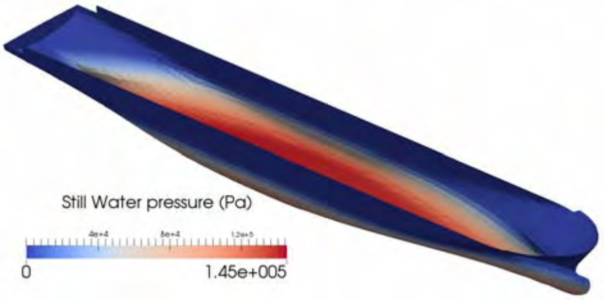

Fig. 5 Hydrostatic pressures on ship hull

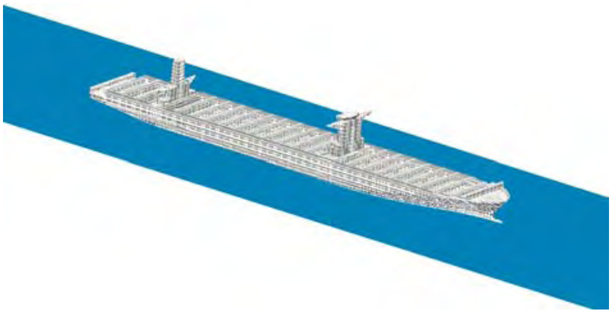

Fig. 6 Position of structural model relative to free surface

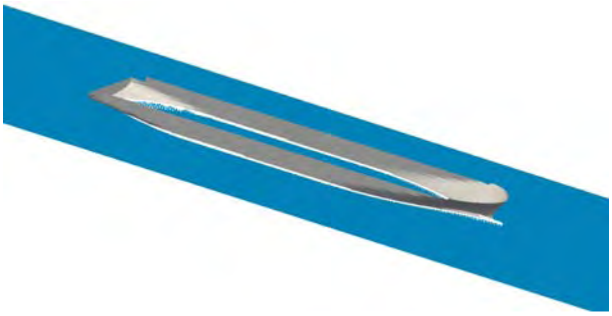

Fig. 7 Position of integration mesh relative to free surface

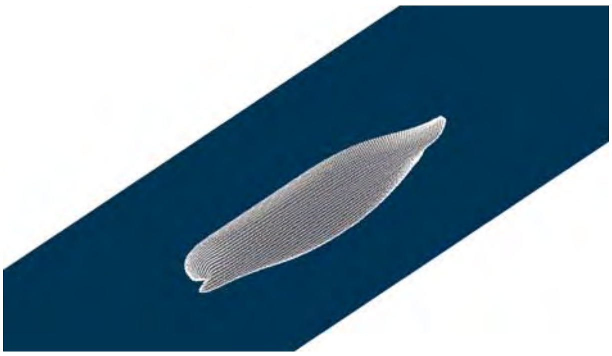

Fig. 8 Position of hydrodynamic mesh relative to free surface

Positions of fine mesh models along the structural finite element model are presented for elastic modes in Fig. 9. Fig. 10 and 11 show still water von Mises stresses of the ship and details 11–14, respectively.

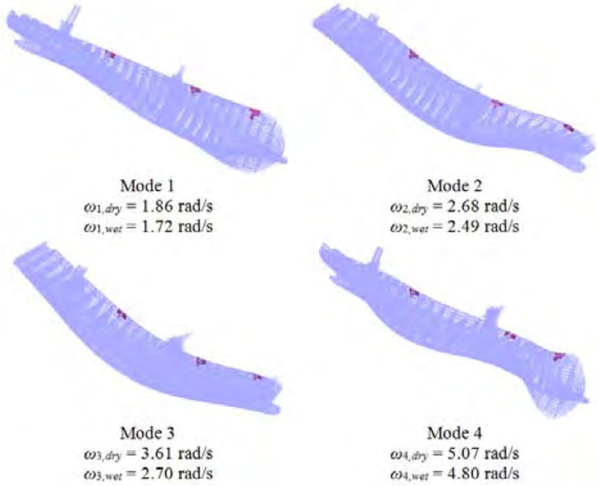

Fig. 9 Wireframe presentation of dry natural modes of container ship with fine mesh models for top-down

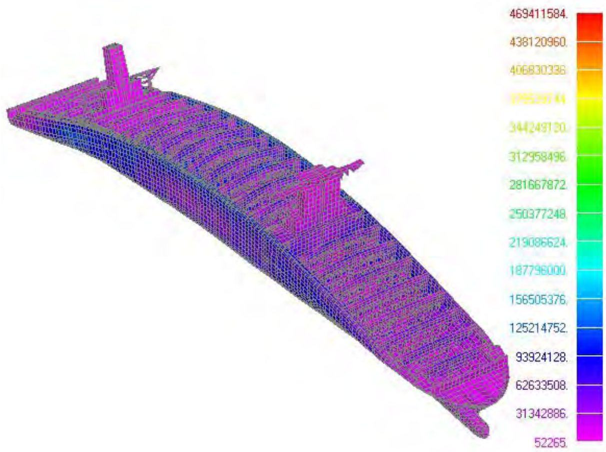

Fig. 10 Presentation of still water von Mises stresses (Pa) on deformed model in hogging condition

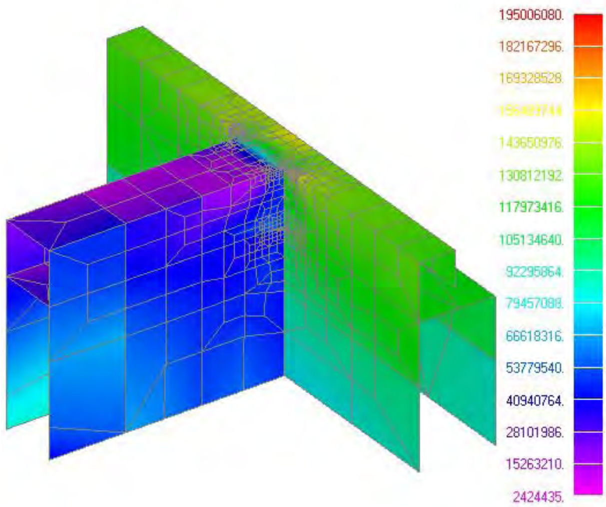

Fig. 11 Still water von Mises stresses in details 11–14 (Pa)

In total 8 slamming sections are created along the front quarter of the ship to perform whipping simulations, Fig. 12.

Fig. 12 Definition of slamming sections for whipping simulations

4. RESULTS

4.1 Global hydroelastic response

Global ship hydroelastic response, i.e. RAOs of vertical bending moments at midship for β=130° and 180°, are presented in Fig. 13. RAOs of torsional moments at 0.25L and 0.75L, and horizontal bending moments at 0.5L are shown in Fig. 14 and 15, respectively.

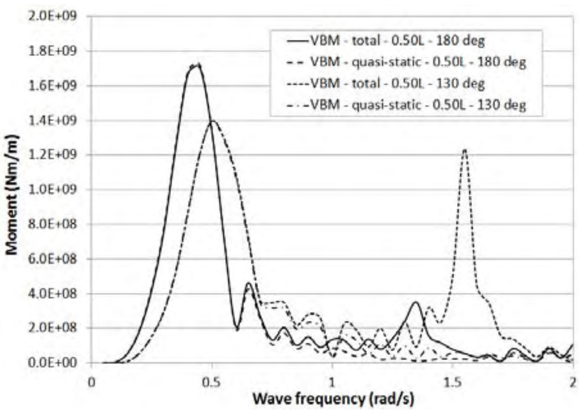

Fig. 13 RAOs of vertical bending moments at midship

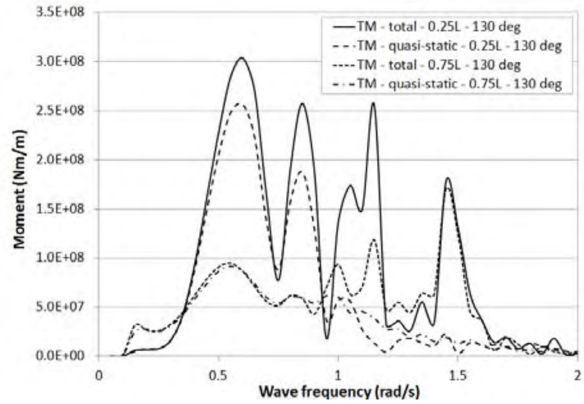

Fig. 14 RAOs of torsional moments

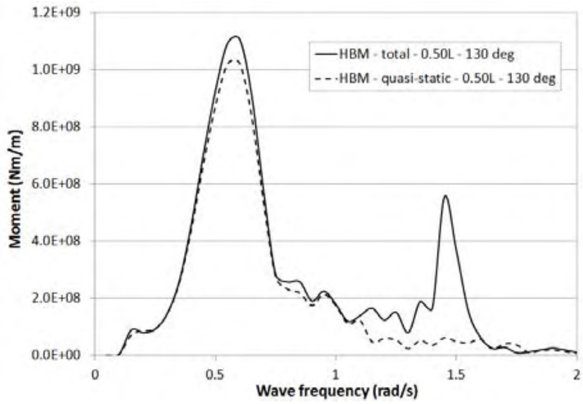

Fig. 15 RAOs of horizontal bending moments at midship

4.2 Local response – stress RAOs

Similarly as in the case of sectional moments, obtained stresses for fatigue computation are also presented as the rigid body component and total quantity, Fig. 16 and 17.

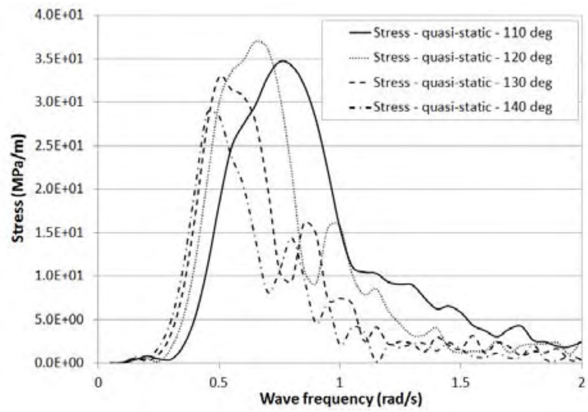

Fig. 16 Quasi–static stress RAOs, detail 13

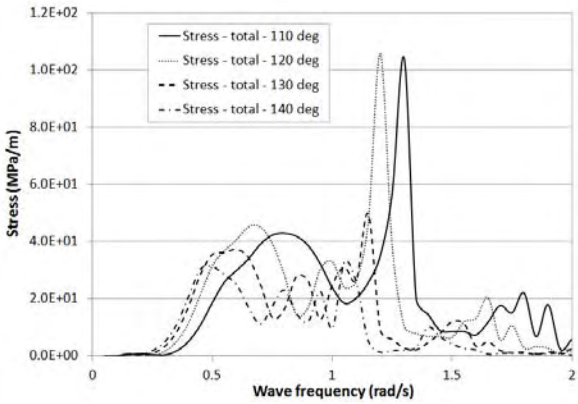

Fig. 17 Total stress RAOs, detail 13

4.3 Whisp1 – fatigue strength check

Stress RAOs are used as input for fatigue calculation. The axial stress in the rod elements at the hatch corner radius free edges of fine mesh FE models is taken into account. 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.

Table 2 Fatigue lives of analyzed structural details

Position	Fatigue life(years)	
	Quasi-static	Total
1	52329411	11144705
2	379764	106494
3	8367058	6382352
4	2082	579.6
5	1216470	276470
6	1073	309.8
7	179.8	124.1
8	468.2	367.9
9	380.6	161.1
10	3576.5	529.8
11	172.0	98.4
12	656.9	208.1
13	102.7	40.2
14	206.9	73.9

Minimum fatigue life is obtained for detail 13 and yields 40.2 years. Therefore, all analysed details satisfy WhiSp1 criterion (28 years if WhiSp3 is not granted and 25 years if WhiSp3 is granted). However, the analysis is planned to 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 13 are presented in Fig. 18 and 19, respectively.

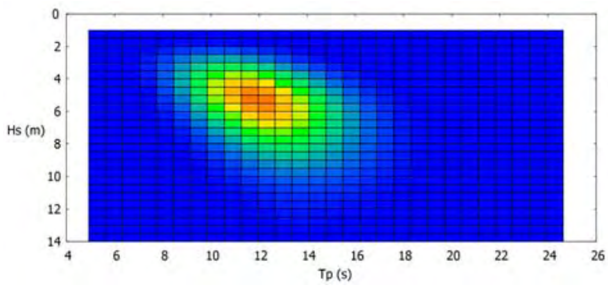

Fig. 18 Contribution of different sea states to total fatigue damage, detail 13

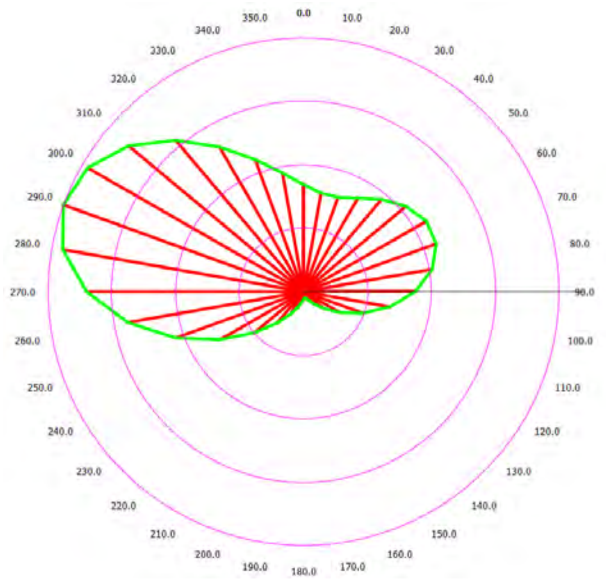

Fig. 19 Azimuth contribution to total damage, detail 13

4.4 WhiSp2 – ultimate strength check

A spectral analysis is performed considering the IACS recommendations with VMB RAO as a loading parameter. The contributions from all the sea states show that the highest contribution to VBM is given by a head sea state, Fig. 20, with the following parameters: Tp=16.19 s, Hs=14.50 m. In order to improve the convergence (to reduce simulation duration) the concept of so called increased design sea state (IDSS) is applied, Fig. 21. It means that the wave height is increased to reduce return period of VBM. Therefore, parameters for whipping simulation are set at Tp=16.19 s and Hs=17.12 m. Simulation time is determined based on the 25-years extreme VBM on IDSS (1097 s) and yields 22000 s (nearly 20 times higher). VBM time histories obtained by linear recomposition and time domain simulations with whipping included are presented in Fig. 22 and 23, respectively.

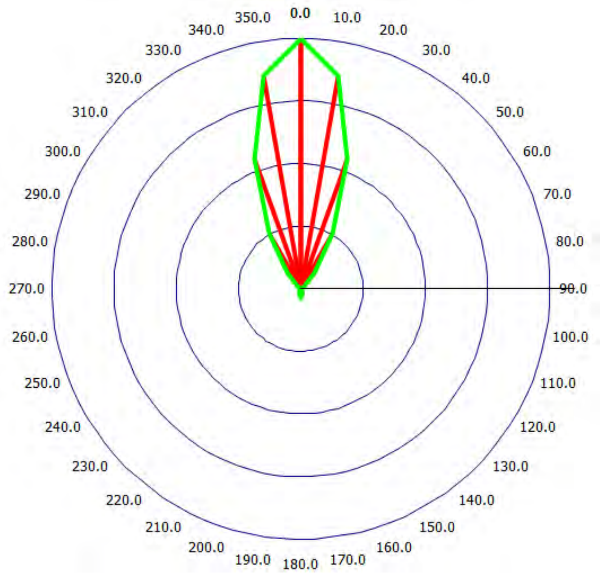

Fig. 20 Azimuth contribution to VBM

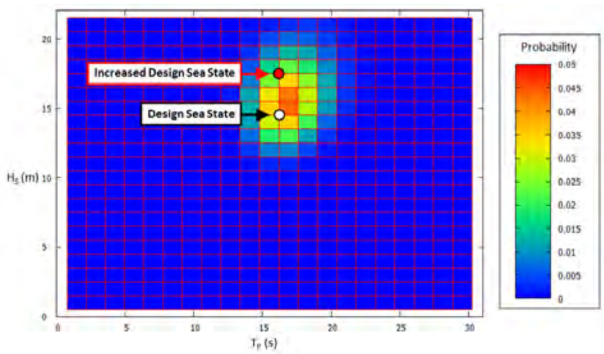

Fig. 21 Increased design sea state concept

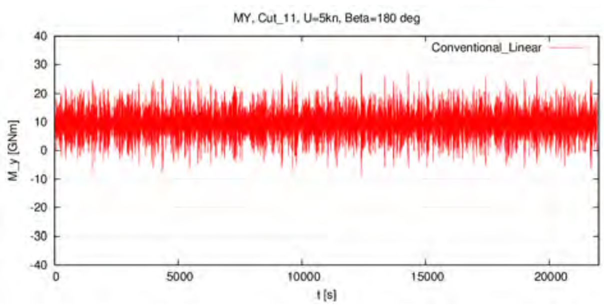

Fig. 22 VBM time history – linear + SWB

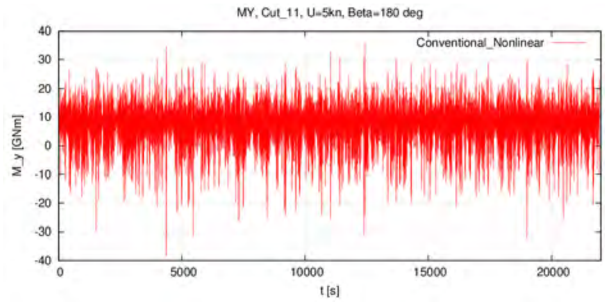

Fig. 23 VBM time history – nonlinear with whipping

Postprocessing of time signal is done to obtain extreme long term values of total bending moments, that yield $2.743 \cdot 10^{10}$ Nm (hogging) and $-2.187 \cdot 10^{10}$ Nm (sagging). Generally, one can see that the maximum bending moment is significantly increased due to whipping.

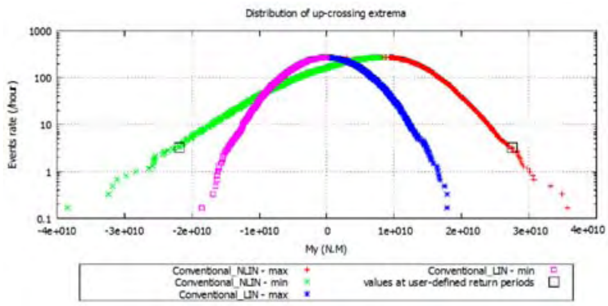

Fig. 24 Long term values of total vertical bending moments

Ultimate bending capacity of the hull girder is determined by nonlinear FE analysis using Abaqus (Dassault Systémes, 2008), and yields $3.918 \cdot 10^{10}$ Nm. By introducing relevant quantities into Eq. (5) one obtains:

$$2.743 \cdot 10^{10} \leq \frac{3.918 \cdot 10^{10}}{1.1}$$

$$2.743 \cdot 10^{10} \leq 3.562 \cdot 10^{10}$$

Since the obtained quantities satisfy Eq. (5), one can confirm that the analyzed container ship fits to WhiSp2 criteria.

5. CONCLUSION

Hydroelastic analysis of 19000 TEU ultra large container ship is performed within new WhiSp methodology. 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. The results indicate that no fatigue cracks are expected before 40.2 years, which implies that WhiSp1 criterion is satisfied. The computed long term VBM is compared with structure ultimate bending capacity, Eq. (5), determined by FEM, and it is found that the ship can withstand imposed load, i.e. WhiSp2 criterion is also satisfied. Both findings are 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 investigation will be oriented to fatigue strength assessment according to WhiSp3, which enables to assess relative influence of hydroelasticity (i.e. slamming and whipping) on the fatigue life. That includes determination of design sea state and azimuth most contributing to the fatigue damage, 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, fatigue damage can be calculated.

Acknowledgments

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