SPECTRAL FATIGUE ANALYSIS OF LIQUEFIED NATURAL GAS CARRIER STRUCTURAL DETAIL

N Vladimir and **I Senjanovic,** University of Zagreb, Croatia
S Malenica and **C Ouled Housseine,** Bureau Veritas, France
BK Choi and **HI Im,** Hyundai Heavy Industries, South Korea

SUMMARY

The spectral fatigue analysis of a structural detail of Liquefied Natural Gas (LNG) carrier is presented. The analysis was performed by means of general hydro-structure tool HOMER (BV), where 3D FEM model for the structure and 3D potential flow code for fluid modelling, respectively, is applied. Mode superposition method is used to calculate ship hydroelastic response in waves. Numerical procedure for the fatigue assessment based on the so called top-down procedure is described in details and applied to determine stress concentrations in fine mesh FE model of a selected structural detail. Based on the calculated stress RAOs and taking into account proper S/N curve, the fatigue life of certain structural detail is obtained for a selected operational profile.

1. INTRODUCTION

Natural gas is considered as a cleaner fuel compared to MDO or HFO. In line with increasing environmental care, there is a rising demand for natural gas worldwide and international natural gas markets are continuously growing. One of the most important parts of LNG transportation system are LNG ships, which can be found in service from 1959. A typical LNG carrier is double-hull vessel with four to six tanks located along the centreline, and there are nowadays several containment systems in use, that can be classified into self-supporting ones (also referred to as Moss type) and membrane type ones. Both alternatives are designed, constructed and equipped with sophisticated systems for carrying LNG over long distances at storage temperatures around -162 °C [1]. Recently, the membrane tank system has been adopted widely due maximizing ship load capacity. More details on LNGC cargo containment systems can be found in [1].

IHS Fairplay (IHSF) database [2] includes data on all ships operating worldwide, and here the DWT of ships delivered from 1999 to 2015 (inclusive) is presented in Figure 1, which shows us that largest LNG ships have been built about 10 years ago (several ships with DWT smaller than 60000 t are omitted from the representation). However, it is more interesting to look at the number of delivered ships and number of orders by the end of 2019 (as stated in August 2015), Figure 2. Although there is some slight trend to build larger units, it seems that market of LNG ships is rather unstable, which is a consequence of economic crises.

There are different issues associated with the design (cargo containment system, hydrodynamic aspects, structural aspects, propulsion issues...) and operation (LNG transfer systems, partial filling issues, problem of boil-off…) of LNG ships making them rather complex objects, and this paper is oriented to the structural one, i.e. how to assess fatigue life of a ship structural detail within so-called direct calculation approach.

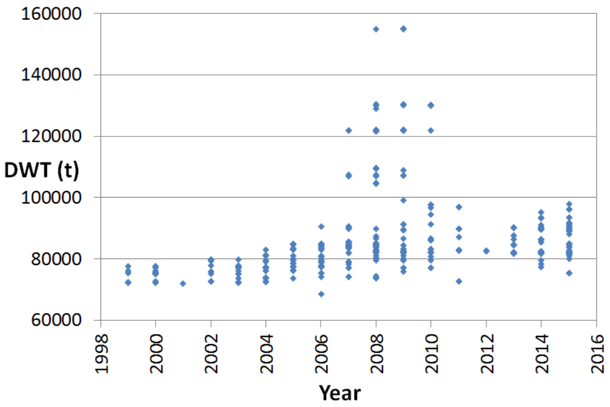


Figure 1 DWT of LNG ships delivered from 1999 to 2015

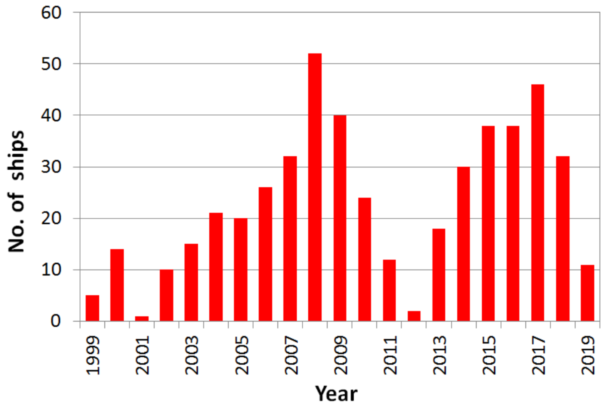


Figure 2 LNG ship fleet and order book

The applied procedure is elaborated in details, as well as the used general hydro-structure tool HOMER [3,4]. More information on the mentioned software is given within the paper, but it is to be noted that it can be applied to any kind of ships and offshore structures in the analysis of both quasi-static and dynamic structural responses, caused by linear, weakly nonlinear or impulsive nonlinear hydrodynamic loading, respectively. Although hydroelastic effects are not expected to be of primary importance in this case (due to relatively high hull girder rigidity and low operational speed), computation of stress RAOs needed for fatigue damage computation is done by hydroelastic model (linear springing included) taking into account also the effect of internal liquid in the cargo tanks, just to illustrate applicability of the software within the complete procedure.

2. DESCRIPTION OF THE ASSESSMENT PROCEDURE

Linear hydroelastic analysis performed here is based on the mode superposition method [5]. Within the modal approach, total displacement of a ship is expressed through a series of modal displacements:

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

where $\boldsymbol{H}\left(x,t\right)$ represents total displacement of one point, $\boldsymbol{h}^{i}\left(x\right)$ is modal displacement (mode shape), $\xi_{i}\left(t\right)$ is modal amplitude, and N represents the total number of modes [4]. Generally, the procedure is very similar to rigid body analysis described in [6] 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 equation of motion is written

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

where **m** is the modal structural mass, **b** is the structural damping, **k** is the structural stiffness, **A** is the hydrodynamic added mass, **B** is the hydrodynamic damping, **C** is the hydrostatic restoring stiffness, while $\mathbf{F}^{DI}$ is the modal hydrodynamic excitation vector.

Once the modal amplitudes have been calculated the total stresses can be obtained, at least theoretically, by summing the individual modal contributions and one can formally write, [6]:

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

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

In order to practically take into account hydroelastic effects on the structural response, dynamic computational scheme is applied, starting with modal analysis in dry condition, Figure 3, [7]. 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.

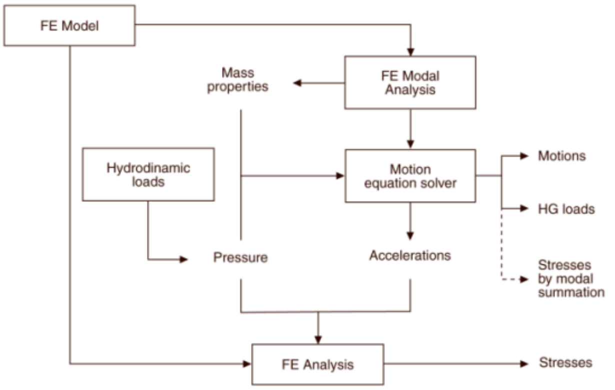


Figure 3 Dynamic analysis computational scheme [7]

In order to cover all types of hydro-structural interactions inherent ships and offshore structures described in [4], the numerical software HOMER is developed in Bureau Veritas Research Department for the direct transfer of the seakeeping loads from the general seakeeping code to a structural FE model, Figure 4, [3,4]. HOMER modules presented in Figure 4 are intended to be used as follows: HMFEM – to compute mass and inertia properties of FE model. Run modal analysis, HMSWB – to analyse still water load case and perform balancing, HMHST – for running hydrodynamic pressures computations using the seakeeping code, HMMCN - solves mechanical problem, HMFEA – to run FE analysis on load cases, HMRAO - to create RAOs and HMTIME – to perform time-domain computations.

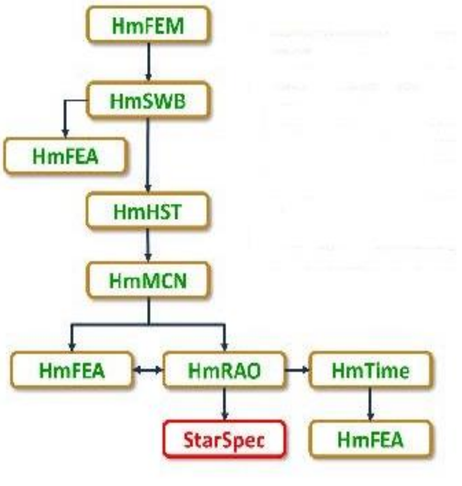


Figure 4 Flowchart of HOMER software application [3]

Three main ideas introduced through HOMER software to obtain the perfect equilibrium of the structural model are the following, [4]:

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 [8] as the hydrodynamic solver, and NASTRAN [9] as the structural solver.

Fatigue assessment of LNG ship structural detail is performed according to the flowchart presented in Figure 5.

For the fatigue life/damage calculation, very local stress concentrations in some particular structural details 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 [10]. In this way the fine mesh FEM calculations are performed in a next 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, defined by loading, wave frequency and heading, and for both real and imaginary part of the loading, resulting in the RAOs of the stresses in each particular structural detail.

A special care is 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 [7], and dynamic part of the response is calculated by summing up the dynamic contribution of each mode.

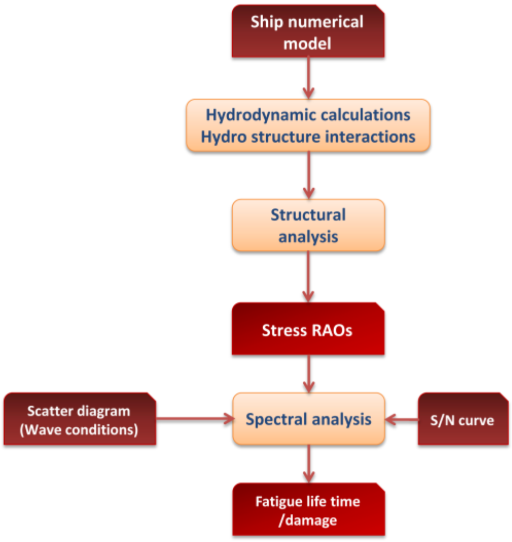


Figure 5 Fatigue analysis flowchart [11]

After obtaining transfer functions of stresses, the spectral analysis is performed and based on the selected S/N curve and wave scatter diagram, fatigue life/damage is calculated [11].

Finally, it is to be noted that the procedure for the fatigue assessment is the same irrespective on calculation of stress RAOs in quasi-static or hydroelastic manner.

3. SHIP DATA, NUMERICAL MODELS

Application of HOMER software to fatigue assessment of ship structural detail is illustrated on 175 KM3 LNG vessel, with tank general arrangement shown in Figure 6. The main ship particulars are the following:

Length between perpendiculars: L_{pp} = 282.0 m
Breadth: B = 46.0 m
Depth: H = 26.0 m
Draught: T = 11.6 m
Displacement, full load: Δ_f = 116973.0 t
Displacement, ballast: Δ_b = 92194.6 t

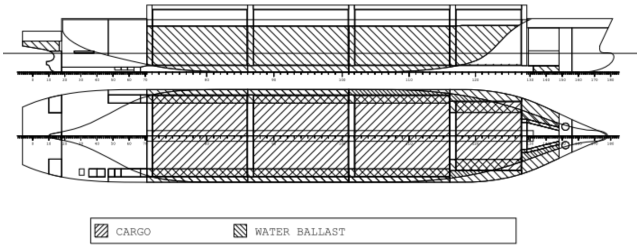


Figure 6 General arrangement of ship cargo tanks

Global FE model of the considered ship, having 427752 elements is used for the calculation, Figure 7. Actually, much coarser mesh can be used for this purpose, but one of the aims of this investigation was software testing at very demanding finite element models.

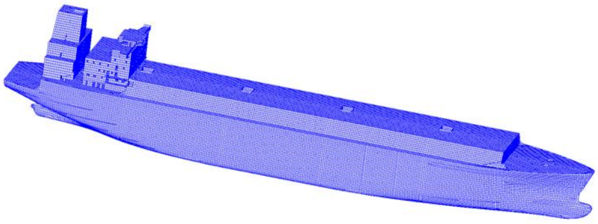


Figure 7 FE model of the analysed ship

Beside global FE model, fine mesh model of a structural detail is required, to be included in the calculation within the top-down scheme, Figure 8.

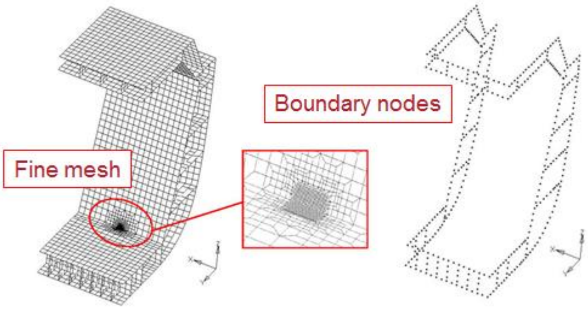


Figure 8 Fine mesh FE model with selected boundary nodes for top-down procedure

The fine mesh model is located in the fore tank, which is for the purpose of this calculation set at 70% of filling capacity, while other 3 tanks are full, Figure 9. It should be noted that this loading condition is not one of the standard ones from loading manual and the ship is not aimed to operate in this way, but it is used here in an academic way for the purpose of investigation.

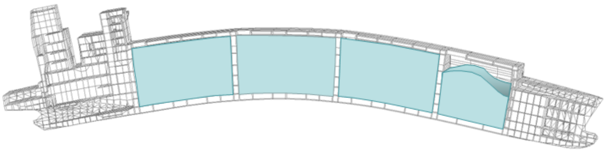


Figure 9 Illustration of the selected loading condition on deformed ship structural model

Beside both FE global and local models of a ship structure, applied procedure also requires generation of the so called integration and hydrodynamic mesh, respectively, Figures 10 and 11. The former is extracted directly from the structural model, and then the latter one, is generated automatically using the existing software routines.

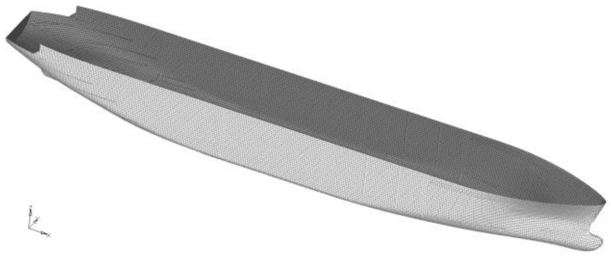


Figure 10 Integration mesh

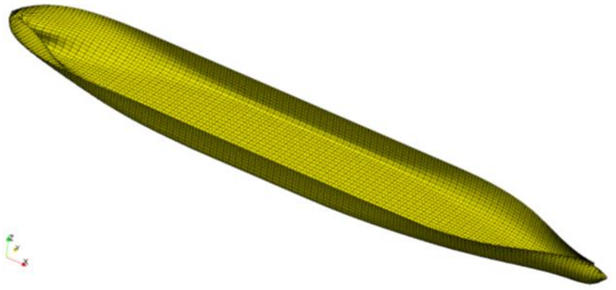


Figure 11 Hydro mesh

The same meshes are required for all cargo tanks containing liquid. Example of tank integration mesh that is also used as a hydro mesh is shown in Figure 12.

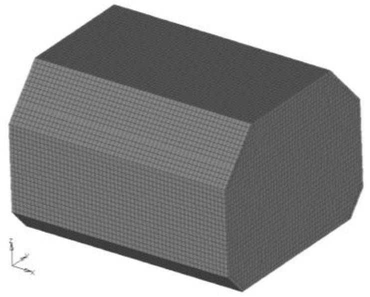


Figure 12 Tank integration and (hydro) mesh

Finally, for the analysed detail, both internal and external integration meshes are needed, Figure 13.

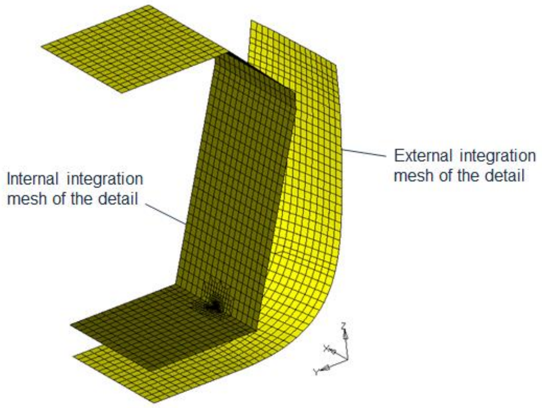
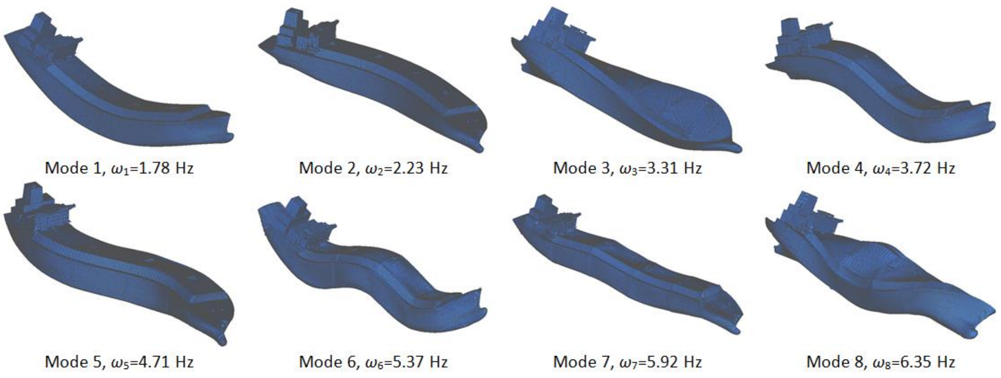


Figure 13 Detail integration meshes

4. RESULTS

Due to reason of simplicity, the analysis was performed for zero forward speed, while wave headings are considered uniformly distributed from 0° to 350° with step of 10.0°. The range of wave frequencies is set from 0.0 to 2.0 rad/s with a step equal to 0.05 rad/s. The first computation step is the modal analysis giving dry natural modes and frequencies, Figure 14, whereas 8 elastic modes are retained for hydroelastic computations.



Mode 1, ω_1=1.78 Hz
Mode 2, ω_2=2.23 Hz
Mode 3, ω_3=3.31 Hz
Mode 4, ω_4=3.72 Hz
Mode 5, ω_5=4.71 Hz
Mode 6, ω_6=5.37 Hz
Mode 7, ω_7=5.92 Hz
Mode 8, ω_8=6.35 Hz

Figure 14 Dry natural modes and frequencies of analysed LNG ship

Prior to running hydrodynamic computations it is very useful to analyze still water case results, that serve as recommended checks of structural and hydrodynamic model consistency, their relative positions in global coordinate system, mass modelling within the structural model and basic calculation setup, respectively, etc. Just for the illustration, here the hydrostatic pressures on ship hull, tank and structural detail are given showing the values accurately reflecting given draught, Figures 15-17.

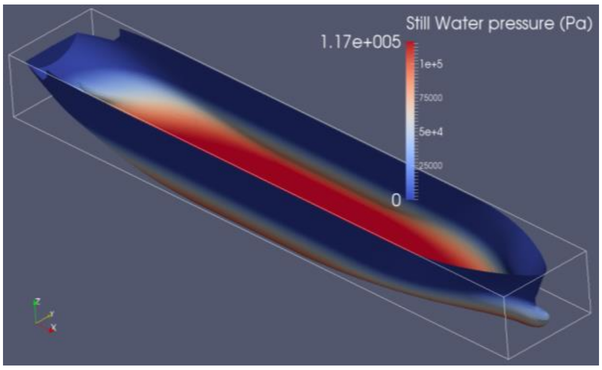


Figure 15 Hydrostatic pressures on hull

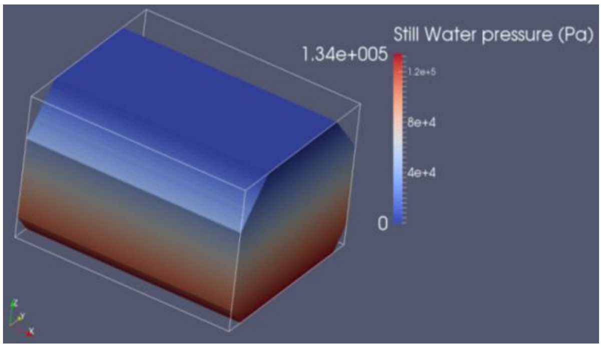


Figure 16 Example of hydrostatic pressures on tank

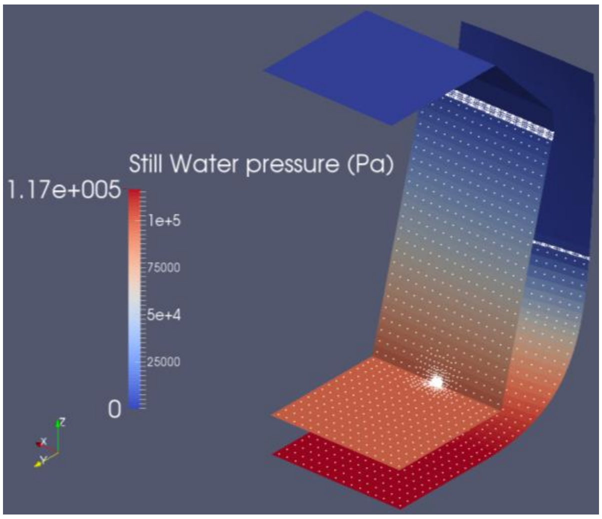


Figure 17 Hydrostatic pressures on detail

Figures 18 and 19 show still water deflections and stresses, where also reasonable numerical values are obtained.

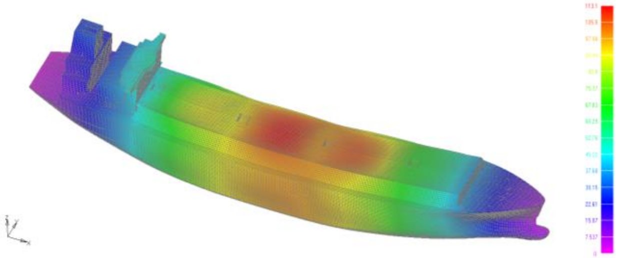


Figure 18 Still water deflections (mm)

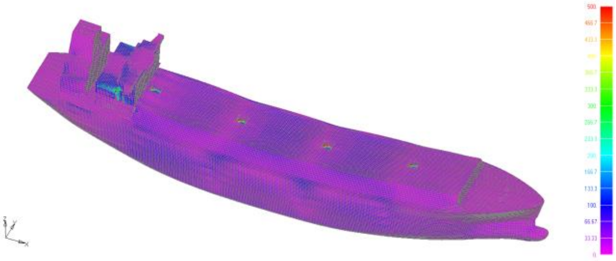


Figure 19 Still water stresses (N/mm^2)

After performing hydrodynamic computations and solving equation of motion, the global hydroelastic response is obtained. The global results are imposed to detail FE model and FE analysis for each combination of ship speed, wave frequency and heading, series of stress RAOs is done. Example of stress pattern in a structural detail is shown in Figure 20, while typical stress RAO is presented in Figure 21.

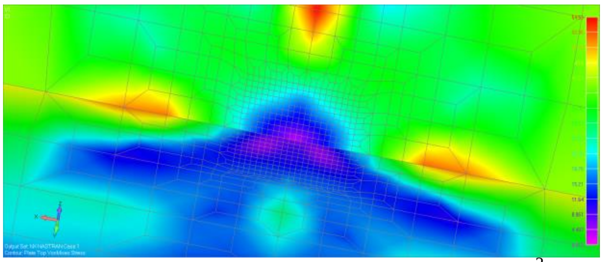


Figure 20 Example of Von Mises stresses (N/mm^2) in a ship structural detail

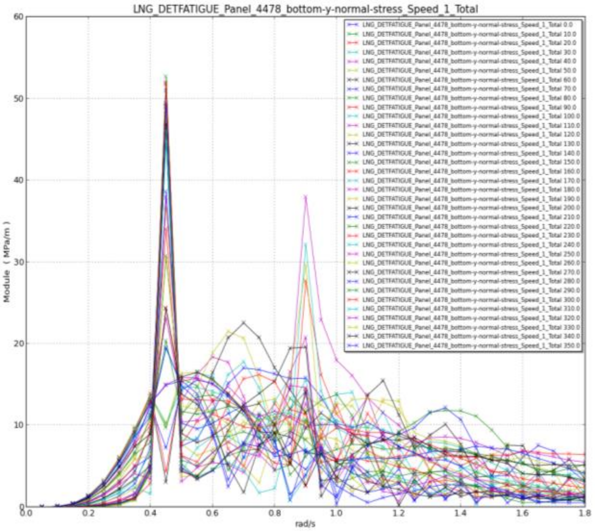


Figure 21 Typical stress RAO

Fatigue lives are computed for all finite elements in the very fine mesh model, and here several ones with the lowest fatigue lives are only identified, Figure 22.

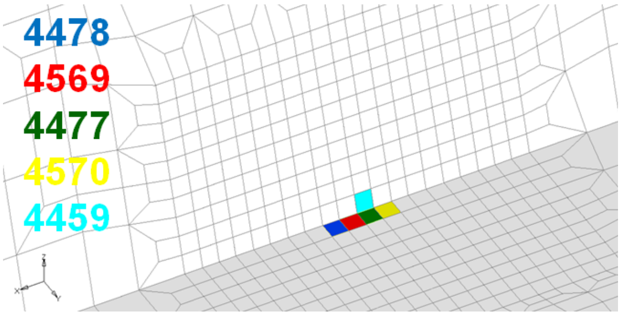


Figure 22 Identification of finite elements with lowest fatigue lives

Fatigue lives for the above finite elements are listed in Table 1, and indicate good fatigue performance of a ship. However, more detailed analysis with realistic ship loading conditions is required to offer final conclusions on her fatigue strength, since this calculation is intentionally performed in a rather academic manner.

Table 1 Fatigue lives of selected finite elements

Element ID	Fatigue life (years)
4478	32.5
4569	33.7
4477	59.0
4570	61.4
4459	81.5

5. CONCLUSIONS

Spectral fatigue assessment procedure by means of general hydro-structure tool 3D FEM structural model and 3D BEM hydro model, respectively, is described in details. All necessary calculation steps and required numerical models are discussed, as well as top-down procedure for the assessment of local stresses, which are further used for the fatigue damage computation. Since fully coupled hydroelastic model is used, ship elastic deformations and her motions in waves are simultaneously taken into account. Fine mesh model of a tank structural detail of LNG carrier, exposed to both internal and external fluid pressure, was used as an application case. The obtained results indicate that the analysed structural detail is well designed from the viewpoint of fatigue, which is in accordance with the fact that analysed ship is in service for several years with no reported damage for the considered detail. Also, the software was found to be user friendly and very robust for application to fatigue assessment of ships and offshore structures, in spite of the very large finite model analysed in this investigation. After these findings, the future work will be oriented to fatigue analysis of the considered ships with forward speed and a set of more realistic loading conditions.

6. ACKNOWLEDGEMENTS

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIP) through GCRC-SOP (Grant No. 2011-0030013) and by University of Zagreb, Croatia within the short-term research grant: “Safety, Energy Efficiency and Environmental Eligibility of Liquefied Natural Gas Carriers”. The first author would also like to acknowledge support of Bureau Veritas for his 3-month visit to their Research Department in Paris. The obtained results and conclusions reflect personal opinions of the authors and do not represent official attitude of their institutions.

7. REFERENCES

1. KIM, H.S., CHUN, M.S., LEE, J.M., KIM, M.H., ‘A comparative evaluation of fatigue and fracture characteristics of structural components of liquefied natural gas carrier insulation system’, *Journal of Pressure Vessel Technology*, Vol. 135, pp. 1-9, 2013.

2. IHS, ‘World Register of Ships – WROS manual’, 2015.

3. SIRETA, F.X., DE LAUZON, J., SURMONT, F., ‘HOMER User guide’, Bureau Veritas, Paris, France, 2013.

4. MALENICA, S., DERBANNE, Q., SIRETA, F.X., BIGOT, F., TIPHINE, E., DE HAUTECLOCQUE, G., CHEN, X.B., ‘HOMER – Integrated hydro-structure interactions tool for naval and offshore applications’, *International Conference on Computers Application in Shipbuilding*, Busan, Korea, 2013.

5. BISHOP, R.E.D., PRICE, G., ‘Hydroelasticity of Ships’, Cambridge University Press, 1979.

6. MALENICA, S., SENJANOVIC, I., VLADIMIR, N., ‘Hydro structural issues in the design of ultra large container ships’, *Brodogradnja*, Vol. 64, No. 3, pp. 323-347, 2013.

7. BUREAU VERITAS, ‘Whipping and Springing Assessment’, Rule Note NR 583 DT R00 E., Paris, France, 2015.

8. BUREAU VERITAS, ‘Hydrostar, User's manual’, Paris, France, 2006.

9. MSC SOFTWARE, ‘MD Nastran 2010 Dynamic analysis user's guide’, Newport Beach, California, USA, 2010.

10. SIRETA, F.X., DERBANNE, Q., BIGOT, F., MALENICA, S., BAUDIN, E., '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, Brazil, 2012.

11. IM, H.I., VLADIMIR, N., MALENICA, S., RYU, H.R., CHO, D.S., 'Fatigue analysis of HHI SkyBench™ 19000 TEU ultra large container ship with springing effect included', *7th International Conference on Hydroelasticity in Marine Technology*, Split, Croatia, 2015.

8. AUTHORS BIOGRAPHY

Nikola Vladimir is Assistant Professor at Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb (UNIZAG), Croatia. He obtained MSc degree in Naval Architecture in 2007 at UNIZAG, and PhD in the field of Hydroealsticity of ship structures in 2011 at the same University. His research interests include vibration of ship structures (hydroelastic – springing & whipping, engine & propeller induced, etc.), vibration phenomena in ship propulsion system (main engine, shafting, propeller…), fatigue, specialized software development and application as well as all other dynamic loading and response issues inherent to ships and offshore units. He published over 100 papers in journals and specialized conference proceedings. Member of Dynamic Response Committee of ISSC.

Ivo Senjanovic, Professor Emeritus of Naval Architecture at the University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, Croatia. Teaching several courses on strength and vibration of ships, offshore structures and submarines. Investigations fields are ship stability, launching, ship strength and vibration, shell theory, design of pressure vessels, non-linear dynamics, ship hydroelasticity, numerical methods, numerical simulations, etc. Books: "Theory of Plates and Shells", "Finite Element Method in Ship Structure Analysis", "Ship Vibrations". Published over 300 papers in scientific journals and conference proceedings. ISSC member acting in Technical Committees on ship strength, vibration, load and response during 10 three-year periods. Fellow of the Croatian Academy of Sciences and Arts.

Sime Malenica graduated in Naval Architecture at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb in 1990. He obtained his PhD degree in 1994, at the University Paris VI, on the problem of nonlinear water wave diffraction. He has published more than 100 papers both in scientific journals and at the specialized conferences. Dr. Malenica is Deputy Director of Bureau Veritas Research Department, leading several national and international research projects. His main fields of research concern the hydro-structural interactions due to the sea waves (linear, nonlinear, frequency domain, time domain, ships and offshore structures…). Actual topics concern the hydroelasticity issues for ships (springing, whipping, slamming, sloshing, green water…). He is a member of editorial board of several respectable journals, Dynamic Response Committee member of ISSC and corresponding member of Croatian Academy of Sciences and Arts.

Charaf Ouled Housseine received MSc degree in Hydrodynamics & Ocean engineering in 2014 from Ecole Centrale de Nantes (ECN), France. Since then, he has been working in Bureau Veritas Marine & Offshore Division, France, as a hydro-structure research engineer. He has been in charge of developing simulation tools and performing advanced studies of ships and offshore unit hydroelastic response. His current research interests include mainly fluid-structure interaction under different approaches: rigid, elastic, linear, nonlinear, etc., as well as other hydrodynamic loads such as Morison forces and linear sloshing.

Byung-Ki Choi, PhD, holds a position of head researcher in the Structure Research Department, Hyundai Heavy Industries. He is responsible for structural assessments of ships and MODU structures. Member of Fatigue and Fracture Committee of ISSC.

Hong-Il Im currently holds a team leader position as a senior engineer in basic hull design department of Hyundai Heavy Industries. Specialized in evaluation of hull girder vibration including offshore, basic hull design of container carriers, tankers, offshore structures and special purpose vessels.