

## **QUASI-STATIC RESPONSE OF A 19,000 TEU CLASS ULTRA LARGE CONTAINER SHIP WITH A NOVEL MOBILE DECKHOUSE FOR MAXIMIZING CARGO CAPACITY**

### **Summary**

Modern sea transportation is characterized by ever larger container ships, which require direct calculation procedures and numerical tools to achieve their reliable structural design. There are different attempts to increase the ship loading capacity, as for instance a container ship with a novel mobile deckhouse enabling her to carry additional number of containers, and at the same time changing basic structural properties of the ship. This paper is related to structural design evaluation of a 19,000 TEU ultra large container ship with novel mobile deckhouse for maximizing cargo capacity, particularly relying on quasi-static approach. The ship structural design is evaluated both for fatigue and extreme loads, where conventional container ship of same particulars is used as a reference. Independent analyses of new and conventional design indicate that conventional container ship shows somewhat better performance from viewpoint of fatigue, while global extreme loading is at the same level.

*Key words:*      *Container ship, Spectral fatigue, Extreme response, Quasi-static approach.*

### **1. Introduction**

The trend in modern sea transportation is building ever larger Container Ships (CS); there are already several vessels in service with a maximum capacity of over 19,000 TEU. A specific characteristic of Ultra Large Container Ships (ULCS), compared with the other ship types, is that they are more likely to experience the hydroelastic type of structural responses called springing and whipping [1], [2], [3], [4], [5], [6], [7]. That is caused by their large dimensions leading to higher structure flexibility, a relatively high service speed, and large bow flare. Apart from that, there are different attempts to improve ship design and to increase the ship's loading capacity; one of them is an ULCS with a mobile deckhouse and an open hold below [8], [9], [10]. The mobile deckhouse enables the ship to carry additional number of containers, but at the same time it slightly changes the original structural design, with additional hatch openings making the vessel more vulnerable to warping deformation, compared with the conventional CS design.

The existing rules of classification societies cover only a limited size and types of structures, and are mainly based on a quasi-static approach, while high frequency hydroelastic contributions are either neglected or included only empirically [11]. Due to the above mentioned reasons, such solutions do not seem to be entirely appropriate for ULCSs; therefore, direct calculations are needed to ensure their safe and rational design. In this sense, some classification societies have developed guidelines (rule notes) for the inclusion of hydroelastic effects into the overall design procedure [11], [12], [13], [14], associated with the application of relevant hydro-structure software offered around the world. Usually, these tools have different numerical schemes incorporated, but mainly rely on the same theoretical principles. However, there are some difficulties in the application of hydro-structure software, because its validity domain is not fully clear, and maybe, more important, the methodologies of different classification societies are not completely harmonized in the selection of realistic operational profile and statistical post-processing of the signals, both for fatigue and extreme loads.

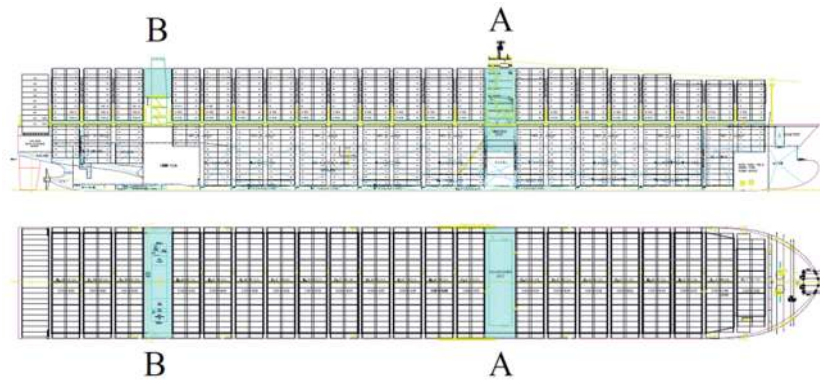
This paper deals with the evaluation of structural design of a 19,000 TEU ULCS having a novel open hold under a mobile deckhouse. The paper illustrates the application of direct calculation methodologies in the design of ULCSs, concerning only the quasi-static structural response. Two container ships are analysed, i.e. the above mentioned ULCS with a mobile deckhouse and a conventional ULCS having the same main dimensions. Fatigue damage obtained by spectral approach and long-term extreme vertical bending moment (VBM) are selected as relevant quantities for comparison.

The analysis was performed by means of a general hydro-structure tool, HOMER [1], [15], where the general FE code NASTRAN [16] and the potential flow code Hydrostar [17] are used as the structural and the hydrodynamic solver, respectively. It is necessary to mention that the relative importance of hydroelasticity is considered in another paper [18] where the BV Rule Note 583 [13] was followed. The calculation setups for quasi-static calculations and for hydroelastic calculations, [18], are the same; direct comparisons of the relevant quantities and an accurate assessment of the hydroelastic effects are made possible by both setups.

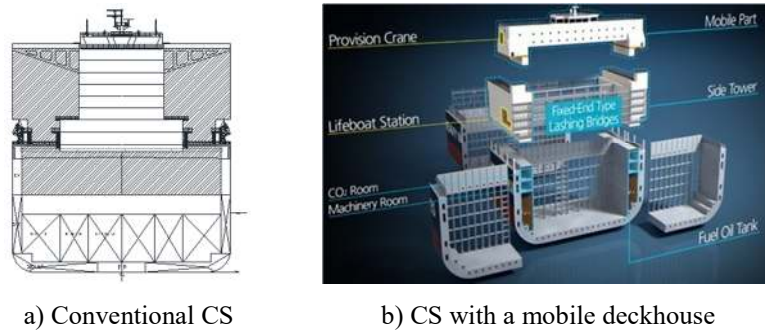
## 2. Mobile deckhouse concept and ship particulars

ULCSs with a capacity of over 10,000 TEU normally adopt the 2-island type superstructure in which a deckhouse structure for accommodation is located in the ship's mid body and is separated from the other funnel and engine casing structure, Figure 1, [8], [9], [10]. Figure 2a shows an arrangement of compartments and spaces around the accommodation in the conventional container ship design. The shaded areas between the upper deck and bridge wings are generally unused spaces and can be considered for extra loading. The space under the upper deck, except the parts for fuel oil tanks and the operation of machinery and facilities, is also available for additional loading. These facts motivated the development of a ship with a mobile deckhouse with the arrangement of compartments shown in Figure 2b. The bench-shaped structure located in the uppermost position shows a mobile part of accommodation, Figure 3. The two structures on both sides used to support the mobile part are named as side towers. Side towers share the function of accommodation together with the mobile part. To arrange a cargo space for an additional 40ft-bay inside the hull structure, the fuel oil tanks with the size of about 40ft in length, which are located under the accommodation, are rearranged and separated into two parts. Each of the tanks has two 40ft-bays in length and is higher than those in the traditional design to ensure the equivalent tank volume. This concept features a bridge and three upper decks mounted on rails, having a capability to move longitudinally. By using the void beneath the sliding block for additional

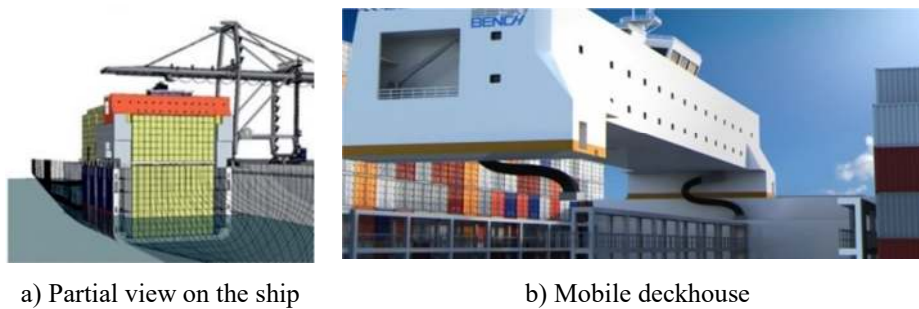
storage, as well as by resizing and repositioning fuel tanks, room is created for an additional two 20ft container bays. Finally, this concept gives an extended loading capacity of around 270, 350, and 450 TEU in 11,000, 14,000, and 19,000 TEU class CSs, respectively, compared with the conventional CS design. The main particulars of the analysed 19,000 TEU container ships are presented in Table 1.



**Fig. 1** General arrangement of a 2-island type container carrier [8]



**Fig. 2** Arrangement of compartments in the conventional CS design and in the ship with a mobile deckhouse



**Fig. 3** Illustration of the mobile deckhouse concept with additional holds

**Table 1** Main particulars of the analysed container ships

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, $\Delta_F$ [t]	212913
Service speed, $v_s$ [kn]	23.0

### 3. Description of the assessment procedure

Reference is made to the newly introduced BV Rule Note NR 583 [13] and to the paper of Malenica and Derbanne [3]. In these documents, the basic assumptions on the numerical methods and the corresponding methodologies are described and are strictly applied in this study. In order to identify the most critical aspects of the approach, we recall below the main assumptions and the calculation steps. For that purpose, different aspects of the hydro-structure interactions are summarized in Table 2.

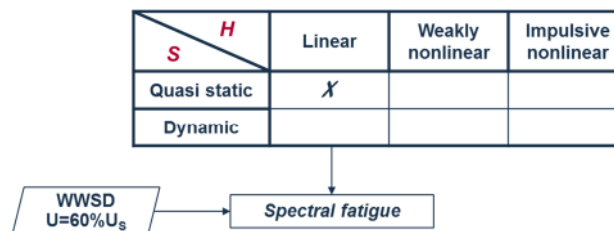
**Table 2** Different hydro-structural issues (H – hydrodynamics, S – structure)

<b>S</b> \ <b>H</b>	Linear	Weakly nonlinear	Impulsive nonlinear
Quasi static	X	X	X
Dynamic	X	X	X

In order to clear up any misunderstanding in the definition of the quasi-static and dynamic (or hydroelastic) structural responses, we point out here that the quasi-static response is defined as the response in which the ship structural vibrations are not taken into account. Basically, this means that the structural loading comes exclusively from the dynamic pressure associated with the rigid body motions. This hydrodynamic pressure is counter balanced by the ship rigid body inertia which allows for a proper definition of the final quasi-static loading cases.

#### 3.1 Fatigue assessment

A classical Palmgren Miner summation approach is adopted. Due to the linearity assumptions, calculations are performed in the frequency domain and the spectral approach is used, which allows for a very low computational cost. The overall computational scheme is shown in Figure 4.



**Fig. 4** Spectral fatigue within the quasi-static approach  
 (WWSD – World Wide Scatter Diagram, U – Ship speed, U<sub>s</sub> – Ship service speed)

##### 3.1.1 Linear quasi static hydro-structure interaction model in the frequency domain

According to the quasi-static assumptions, the hydrodynamic and structural calculations can be performed separately. This means that the ship motions are first calculated and they are then used to produce the consistent loading on the FE model. The ship motion equation looks as follows:

$$\{-\omega^2([\mathbf{M}] + [\mathbf{A}(\omega)]) - i\omega[\mathbf{B}(\omega)] + [\mathbf{C}]\}\{\xi\} = \{\mathbf{F}^{DI}(\omega)\} \quad (1)$$

where:

- $[\mathbf{M}]$  genuine mass matrix of the body
- $[\mathbf{A}(\omega)]$  hydrodynamic added mass matrix
- $[\mathbf{B}(\omega)]$  hydrodynamic damping matrix

$[C]$  hydrostatic restoring matrix  
 $\{F^{DI}(\omega)\}$  hydrodynamic excitation vector  
 $\{\xi\}$  body motions vector (with respect to the ship's centre of gravity ( $X_G, Y_G, Z_G$ ))

Once the ship motions are calculated, the final loading case of the FE model is composed of 3 parts: rigid body inertial loading ( $-\omega^2 m_i \xi_i$ ), pressure loading ( $p^{hs1} + p^{hd}$ ), and gravity term ( $-m_i g \Omega \times k$ ).

The last part of the loading comes from the fact that the hydrodynamic and structural calculations are not performed in the same coordinate system (structure in the body fixed and hydrodynamics in the initial earth fixed coordinate system). Thus, a consistent linearization procedure implies the occurrence of the term without which the FE model would not be properly balanced.

The pressure component of the loading is composed of two relatively distinct parts. The first part of the pressure loading is related to the variation of the hydrostatic pressure due to ship motions; it can be written in the following form:

$$p^{hs1} = -\rho g [\xi_3 + \xi_4(Y - Y_G) + \xi_5(X - X_G)] \quad (2)$$

where ( $X_G, Y_G$ ) are the coordinates of the ship centre of gravity. The second part of the pressure is related to the wave body interactions; it is composed of 8 distinct components (incident, diffracted, and six radiated components):

$$p^{hd} = p_I + p_D - i\omega \sum_{j=1}^6 \xi_j p_{Rj} \quad (3)$$

These pressure components are calculated using the potential flow seakeeping theory where the pressure is calculated using the Bernoulli equation which relates the hydrodynamic pressure to the velocity potential. The velocity potential is calculated using the Boundary Integral Equation Method (BIEM). In addition, the general numerical hydrodynamic code Hydrostar is employed in the present study [17].

It is important to notice that, due to the fact that the hydrodynamic and structural calculations are performed separately using different meshes, the final loading case for the FE structural model might experience significant misbalance if the pressure transfer is not done properly. Special attention should be paid to this issue and the way in which this was done in the hydro-structure tool HOMER is described in [3]. Meanwhile, in order to evaluate the local stress concentration in the particular structural detail, the so called top-down analysis should be used [19]. This means that the global structural response is first calculated on a full coarse mesh ship model and the resulting information (deformations, pressure, inertia...) are transferred to the local structural model which is finally solved using the same numerical FE method as the one used for the global response.

### 3.1.2 Spectral fatigue

The stress response amplitude operators (RAO) for all possible combinations of the frequencies and headings should be calculated for spectral fatigue analysis. In practice, 60 frequencies and 36 headings (every 10 degrees) are used. According to the rules, the ship speed is taken to be 60% of the nominal speed. Once the RAOs are evaluated, they should be combined with the probability of occurrence of different sea states for a given scatter diagram. According to the BV Rules, the scatter diagram which should be used is the so called World Wide Scatter Diagram (WWSD).

### 3.2 Extreme structural response within the quasi-static approach

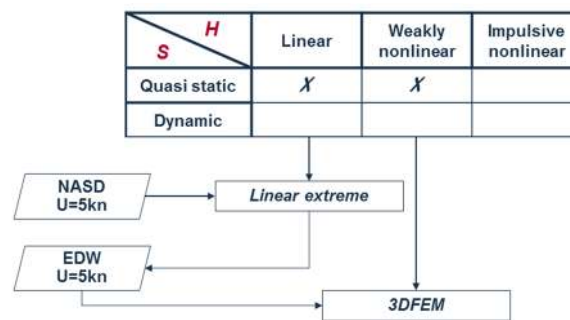
Within the verification process for extreme conditions, there are two types of verifications which should be done:

- Yielding & buckling
- Ultimate strength

#### 3.2.1 Yielding and buckling

In the case of yielding and buckling, the procedure requires the determination of several design load cases which are applied on the 3D FE model; for each of them, the yielding and the buckling check is performed.

The computational scheme for the assessment of the extreme structural response within the quasi static approach is shown in Figure 5.



**Fig. 5** Extreme structural response within the quasi-static approach  
 (NASD – North Atlantic Scatter Diagram, EDW – Equivalent Design Wave)

The procedure starts by the evaluation of the linear long term values of different Dominant Loading Parameters (DLP) such as vertical bending moment, torsional moment, shear forces, etc. Once the long term value of a particular DLP has been evaluated, it is possible to define the corresponding Equivalent Design Wave (EDW). There are different possibilities to define the EDW, starting from a very simple regular wave and ending with relatively complex irregular response conditioned waves. In the simplest case of the regular unidirectional design wave, the frequency and the wave heading are defined as the ones where the RAO of the considered DLP reaches its maximum and the corresponding design wave amplitude is obtained by dividing the linear long term value by the same RAO. In the case of the irregular response conditioned wave, which is recommended to be used, [20], because it accounts better for the nonlinear hydrodynamic loading, the wave is defined in the form of the design wave spectra with different amplitudes and phases chosen to produce the maximum long term value of the DLP at one particular time instant. We do not go here into the details of the procedure and we refer the reader to [20]. Once the equivalent design wave is determined, it should be applied on the structural FE model of the ship, in a weakly nonlinear sense.

There are different types of the weakly nonlinear models and the one which is used within the Bureau Veritas is the hydro-structure tool HOMER [1]. The method is based on using the linear frequency domain results and transferring them into the time domain where the nonlinear hydrodynamic loading is added at each time step. The time domain motion equation is written in the following form:

$$\begin{aligned}
 & ([\mathbf{m}] + [\mathbf{A}^\infty])\{\ddot{\xi}(t)\} + ([\mathbf{k}] + [\mathbf{C}])\{\dot{\xi}(t)\} + [\mathbf{b}]\{\xi(t)\} + \int_0^t [\mathbf{K}(t - \tau)]\{\dot{\xi}(\tau)\}d\tau \\
 & = \{\mathbf{F}(t)\} + \{\mathbf{Q}(t)\}
 \end{aligned} \quad (4)$$

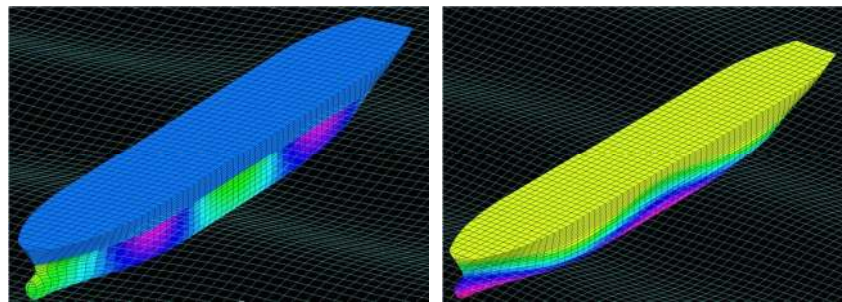
where  $[\mathbf{m}]$  represents the modal mass matrix,  $[\mathbf{A}^\infty]$  is the infinite frequency modal added mass matrix,  $[\mathbf{k}]$  is the structural stiffness matrix,  $[\mathbf{C}]$  represents the hydrostatic restoring matrix,  $[\mathbf{b}]$  is the structural damping matrix,  $[\mathbf{K}(t - \tau)]$  is the impulse response (memory) functions matrix, while  $\{\mathbf{F}(t)\}$ ,  $\{\mathbf{Q}(t)\}$  and  $\{\boldsymbol{\xi}(t)\}$  represent the linear excitation force vector, the nonlinear excitation force vector, and the body motions/deformations vector, respectively.

It can be shown that the impulse response functions can be calculated from the linear frequency dependent damping coefficients using the following relation:

$$\mathbf{K}(t) = \frac{2}{\pi} \int_0^\infty \mathbf{B}(\omega) \sin \omega t \, d\omega \quad (5)$$

where  $B(\omega)$  are the frequency domain damping coefficients, Eq. (1).

Once the impulse response function matrix  $[\mathbf{K}(t)]$  is calculated, the motion equation (4) is integrated in time and the nonlinear forces are added at each time step to the vector  $\{\mathbf{Q}(t)\}$ . There are various types of non-linearities which have to be included in the hydrodynamic model and it is not practically possible to account for all of them. Within the present weakly non-linear hydrodynamic model, the main nonlinearities which are included are related to the so-called Froude Krylov nonlinear loading which accounts for large body motions. In order to illustrate the difference between the linear and the weakly nonlinear hydrodynamic model, the instantaneous pressure distributions on the ship hull for both cases are shown in Figure 6. As it can be seen, the linear pressure “stops” at the mean waterline  $Z=0$ , while the non-linear pressure extends up to the wave surface.



**Fig. 6** Hydrodynamic pressure correction close to the waterline (Froude Krylov approximation) and the difference between the linear (left) and the nonlinear (right) pressure distribution.

### 3.2.2 Ultimate strength

According to the current rules, the verification of the ultimate strength requirements is made by comparing the life time maximum bending moment with the structural capacity of each ship section [20]. For the time being, the life time maximum of the vertical bending moment is prescribed by the rules so that there is no need for direct calculations. Since the main objective was to compare the structural response of two ship types within the direct calculation approach, no detailed ultimate strength check was made for this quasi-static part of the analysis and the comparisons were made for WhiSp2 notation only [18].

## 4. Results and discussion

### 4.1 Numerical model

The ship speed is set at 5.0 kn and 13.8 kn (60% of the design speed) for the extreme and the fatigue response assessment, respectively, [13]. The values of the wave heading angle are considered uniformly distributed from  $0^\circ$  to  $350^\circ$  with steps of  $10.0^\circ$ . The analysis is performed by means of a general hydro-structure code which requires the definition of the structural and the hydrodynamic model, as well as the integration mesh aimed for pressure

transfer from the hydrodynamic to the structural mesh. 3D FE models of the CS with a mobile deckhouse and of the conventional one are shown in Figure 7, together with indicated fine mesh positions for the fatigue life/damage evaluation. For each of the considered ships, 12 structural details of interest, having the same position along the ship, are chosen for the fatigue damage assessment. The hydrodynamic mesh with nearly 6,000 elements and the integration mesh are the same for both ships; they are presented in Figures 8 and 9, respectively.

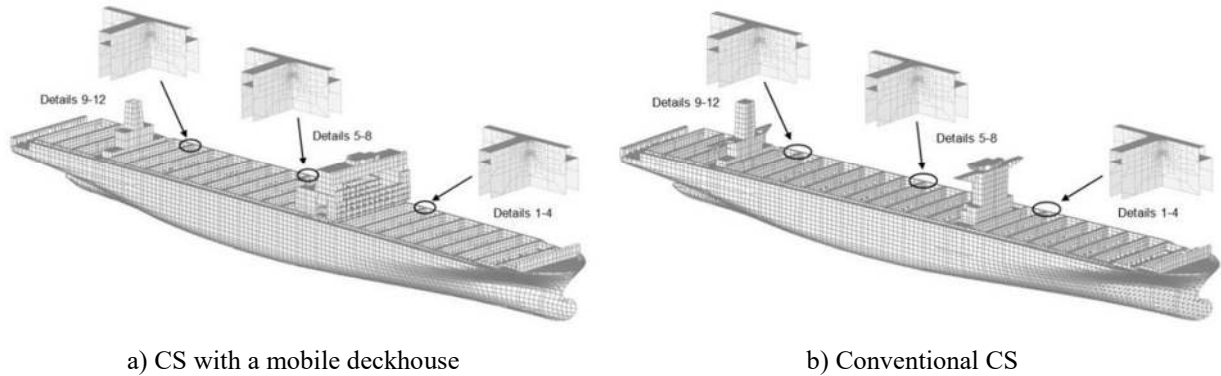


Fig. 7 3D FE models of the analysed container ships with local fine mesh models

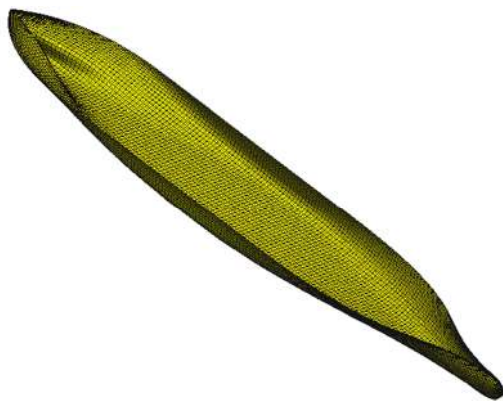


Fig. 8 Hydrodynamic mesh

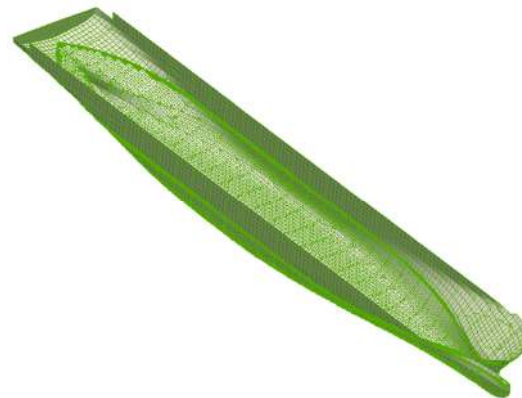


Fig. 9 Integration mesh

In hydro-structure analysis, it is to be checked that the structural model is adequately balanced; this is done by comparing sectional forces and moments with those listed in the loading manual, Fig. 10, where good agreement can be noticed.

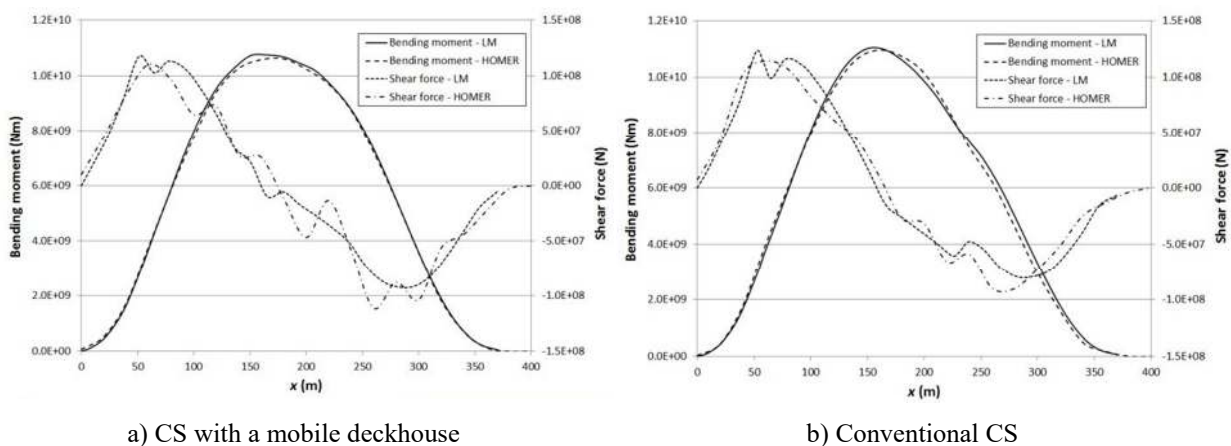
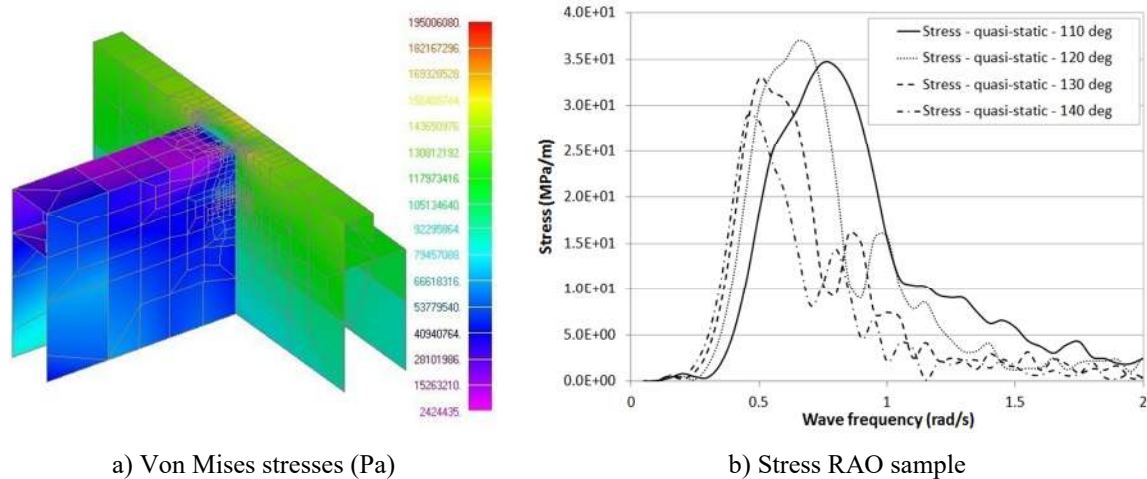


Fig. 10 Still water bending moment and shear forces



## 4.2 Spectral fatigue

Within the top-down approach, the global response is calculated by coarse mesh 3D FE models, Figure 7, and in the second step, the obtained global response is imposed at the boundaries of fine mesh models to calculate the local stress RAOs, with a typical case shown in Figure 11.



**Fig. 11** Typical case of von Mises stresses in the fine mesh model and the stress RAO of the container ship with a mobile deckhouse

Stress RAOs are used as input for the 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 damage ratios of the selected structural details are presented in Table 3. The results are obtained for a sailing factor equal to 0.85 and the mean stress effect is taken into account.

Generally, the conventional CS shows somewhat better performance from the viewpoint of fatigue. This is most probably due to the "softer" hull girder characteristics in torsion of the new design, which leads to a slight increase in the local stress concentration close to the critical structural locations. The greatest fatigue damages are obtained for the hatch corners in the vicinity of the engine room area, which is actually typical of CSs.

**Table 3** Fatigue damage ratio of the selected structural details obtained by the quasi-static approach

Detail Position	Damage ratio Conventional CS/Mobile deckhouse CS
1	1.46
2	0.60
3	1.25
4	0.76
5	1.00
6	0.87
7	0.86
8	0.63
9	0.84
10	0.58
11	0.74
12	0.96

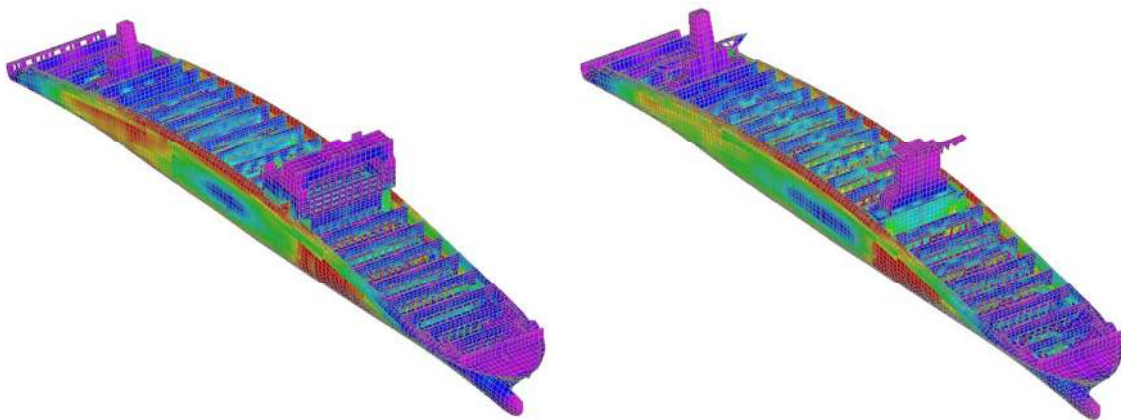
### 4.3 Extreme structural response: yielding and buckling

Within the present approach only the regular EDWs were evaluated. The different values of these EDWs for the vertical bending moment (VBM), the horizontal bending moment (HBM), and the torsional moments (TM) are given in Table 4 for both ships. As one can see, the values for both ships are quite close as expected because the approach is purely quasi-static.

The structural verifications for yielding and buckling were performed for both ships and no critical parts of the structure were identified. This means that both ships are safe from that point of view. Atypical snapshot of structural stresses is shown in Figure 12 for the EDW of the VBM.

**Table 4** Values of EDW for the container ship with a mobile deckhouse and the conventional container ship

Loading parameter	Equivalent Design Wave					
	CS with a mobile deckhouse			Conventional CS		
	Amplitude (m)	Heading (deg)	Frequency (rad/s)	Amplitude (m)	Heading (deg)	Frequency (rad/s)
VBM amidships	9.54	180.0	0.45	9.63	180.0	0.45
HBM amidships	6.49	120.0	0.65	6.44	120.0	0.65
TM at 0.25L	6.38	240.0	0.65	6.29	240.0	0.65
TM at 0.75 L	8.16	290.0	0.65	7.64	300.0	0.65



**Fig. 12** A typical snapshot of the structural stresses of the container ship with a mobile deckhouse and the conventional container ship for the EDW of the VBM in hogging conditions.

## 5. Conclusions

In order to evaluate the structural design of a newly developed container ship with an open hold under the mobile deckhouse, an analysis of the two container ships of the same principal dimensions is done using the quasi-static approach. The BV Rule Note NR 625 is followed in the definition of the calculation setup [20], and the general hydro-structure code HOMER is applied. Effect of structural modification on the ship performance in waves is checked by comparing the fatigue damage of several structural details and the long term vertical bending moment value of both ships. Fatigue is assessed by the linear spectral analysis, where the top-down procedure is applied. The obtained results indicate that two ships are safe from both fatigue and extreme response points of view. Both ships have similar safety levels in the case of extreme response, while, in the case of fatigue, the conventional

container ship shows slightly better performance; this is most likely due to an increase in the stress concentration because of the softer torsional behaviour of the hull girder in the case of the new design. However, a more detailed analysis with hydroelastic effects (springing and whipping) included is necessary for a more realistic comparison of two structural designs, which is the subject of future research.

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Hong-Il Im  
Hyundai Heavy Industries Co., Ltd.  
Ulsan, Korea  
okil@hhi.co.kr  
Nikola Vladimir  
University of Zagreb, Faculty of  
Mechanical Engineering and Naval  
Architecture  
I. Lučića 5, 10000 Zagreb, Croatia  
nikola.vladimir@fsb.hr  
Šime Malenica  
Bureau Veritas, Research Department  
67/71 Boulevard du Château,  
92200 Neuilly-sur-Seine, France  
sime.malenica@bureauveritas.com  
Dae Seung Cho  
Pusan National University, Dept. of Naval  
Architecture and Ocean Engineering  
Busan, Korea  
daecho@pusan.ac.kr