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The Effect of Torsion to the Longitudinal Strength on Container Ship

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Abstract

The large deck openings of ultra-large container ships greatly reduce their torsional stiffness, and hydroelastic analysis is a must for reliable structural design. In the initial design stage, the beam model is a rational choice. This study aims to investigate torsion's effect on container ships' strength using a numerical approach based on fatigue boundary conditions and ultimate boundary conditions in the midship region. Regarding fatigue boundary conditions, the dimensional influence of the container ship is obtained at the connection between the longitudinal side shell stiffeners and the transverse web frame for nine structural details, which refer to different arrangements of reinforcing elements. The structural influence on the local stress distribution was assessed along the longitudinal plates between the regular stiffeners bounding the perimeter of the torsion box by calculating the hull girder stresses.

Keywords: Container Ships, Cross Section, Torsion, Longitudinal Strength

1. INTRODUCTION

Container ships are key to the world economy due to their importance in the transportation logistics chain, based on economies of scale. This phenomenon states that the unit cost per container transported will decrease as the carrying capacity of container ships increases, leading to a rapid growth in the size of these ships [1]. This increase in capacity is related to two phenomena: on the one hand, an increase in the main dimensions and, on the other hand, an increase in the loads and stresses suffered by the structure during its operational life [2]. The ship has a unique and exclusive general arrangement, making it very effective in container loading and unloading operations at ports. Therefore, its cross-section is an open profile with small torsional stiffness and is quite susceptible to this phenomenon, resulting in high loads and stresses on board [3]. The stresses on board are very high, combined with the bending moments of the vertical waves caused by the low cross-sectional modulus on the deck, with its conception and properties [4].

Container ships have a distinctive structure (thin-walled girders and large hatches) that allows them to be faster at port stowage operations. Still, at the same time, they are more sensitive to stresses originating from a combination of global bending and moment torsion. Koh et al. [5] studied the failure mechanism due to the torsion of ships with large hatches from the establishment of numerical models and experimental tests in the process of structural collapse, obtaining the main failure mode in the warping phenomenon, which also has a direct influence on the main torsional strength, reducing it significantly while Ostapeko et al [6] designed two different models to reflect and compare the failure modes due to torsional loads. Other variables influence the structural assessment of ship strength; Pedersen [7] developed beam theory to analyze the torsional buckling response of ship hulls. After years of development, structural model testing and nonlinear finite element methods have become the main research methods, but the complex FSI (Fluid-Structure Interaction) effects have not been considered.

Tanaka et al. [8] conducted ultimate strength tests on three 1/13-scale hull models under combined vertical bending and torsion, showing that torsion can significantly reduce the ultimate hull girder bending capacity. Wang et al. [9] found a comparable scale model to evaluate the ultimate strength of very large container ships. They conducted a comprehensive analysis of the longitudinal and torsional buckling limits and proposed a similar theory, designing a scale model that accurately represents the gradual collapse behavior observed on real ships during ultimate strength model testing. Zhang et al. [10] investigated the ultimate

strength of a sandwich-box girder under vertical bending and torsion. They validated the accuracy of the numerical model by comparing the test results with the simulation results. Lee et al. [11] examined the ultimate strength characteristics of the hull structure built on a very large container ship. The researchers used the intelligent finite element method to analyze the ultimate strength of hull beams on very large ships, considering the coupling of bending moment and torsional moment. Hu et al. [12] conducted a numerical study on the residual ultimate strength of box girders with crack damage due to torsional and flexural loads applied separately or in combination. The effects of crack length, location, and orientation angle on the residual ultimate strength of the box girder were analyzed using the nonlinear finite element method. [13]
The main problem associated with the beam model of container ships is fulfilling warping compatibility at the connection of the closed engine room structure with the open hatch cross-section a sophisticated solution, assuming that the discontinuity of the cross-section is compensated by induced horizontal bending. The solution is realistic for hull-length open and closed segment joints. However, in the case of short engine room structures, the FEM analysis shows that the discontinuity at the joint with an open hatch is compensated by cross-sectional distortion. This study aims to determine torsion's effect on container ships' strength. [14]

2. METHODS

The thin-walled girder torsion theory assumes that the structure behaves as a membrane and there is no cross-sectional distortion. In the more advanced torsion beam theory, the influence of shear on torsion is taken into account in the same way as in the bending beam theory [15]. Therefore, the torsional angle consists of a pure torsional angle and a shear contribution

$$\psi = \psi_1 - \psi_s$$

where the latter depends on the former

$$\psi_s = -\frac{EI_w d^2\psi_t}{GI_s dx^2}$$

E and G are Young's modulus and shear modulus, respectively, and I_w and I_s are the bending modulus and shear moment of inertia of the cross-section, respectively. The cross-sectional forces include the torsion T, which consists of the pure torsion Tt and the bending contribution T_w, and the moment B_w, due to the primary and secondary shear stress fields, and the normal stress due to the restrained curvature [16].

$$T = T_t + T_w, T_t = GI_t \frac{d\psi_t}{dx}$$

$$T_w = GI_s \frac{d\psi_s}{dx} = -EI_w \frac{d^3\psi_t}{dx^3}$$

$$B_w = EI_w \frac{d^2\psi_t}{dx^2}$$

where I_t is the torsional modulus. The governing differential equation resulting from balancing the total cross-sectional torque with the distributed external torsional load, $dT = -\mu_x d_x$, Figure 1.

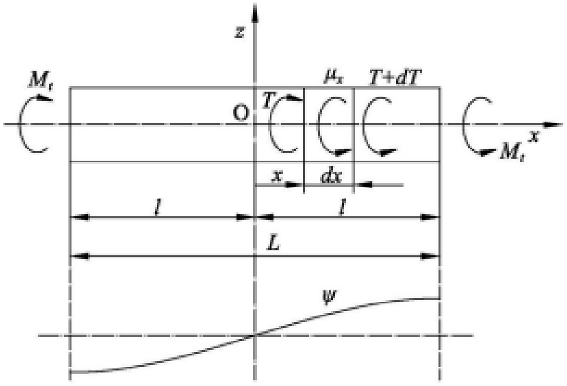


Figure 1. Beam Torsion

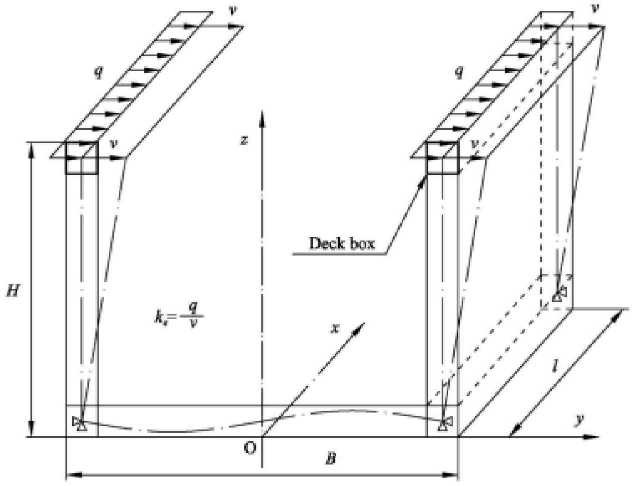
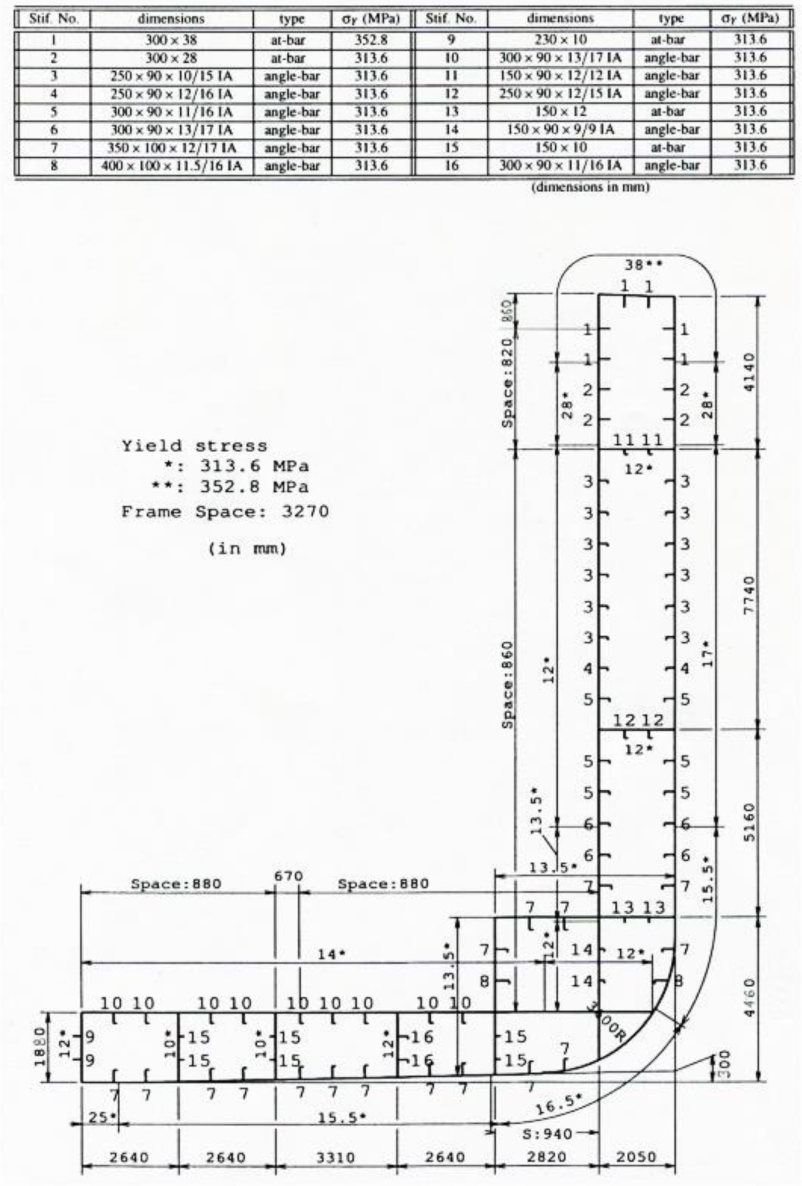


Figure 2. Definition of Deck Box Support Stifennes.

In this study, Non-Linear Finite Element Analysis is used with ANSYS code. The cross-section and material properties of the container ship are shown in Figure 3.



Stif. No.	dimensions	type	σ_Y (MPa)	Stif. No.	dimensions	type	σ_Y (MPa)
1	300 × 38	flat-bar	352.8	9	230 × 10	flat-bar	313.6
2	300 × 28	flat-bar	313.6	10	300 × 90 × 13/17 IA	angle-bar	313.6
3	250 × 90 × 10/15 IA	angle-bar	313.6	11	150 × 90 × 12/12 IA	angle-bar	313.6
4	250 × 90 × 12/16 IA	angle-bar	313.6	12	250 × 90 × 12/15 IA	angle-bar	313.6
5	300 × 90 × 11/16 IA	angle-bar	313.6	13	150 × 12	flat-bar	313.6
6	300 × 90 × 13/17 IA	angle-bar	313.6	14	150 × 90 × 9/9 IA	angle-bar	313.6
7	350 × 100 × 12/17 IA	angle-bar	313.6	15	150 × 10	flat-bar	313.6
8	400 × 100 × 11.5/16 IA	angle-bar	313.6	16	300 × 90 × 11/16 IA	angle-bar	313.6

(dimensions in mm)

Yield stress
*: 313.6 MPa
**: 352.8 MPa
Frame Space: 3270
(in mm)

Figure 3. Container ship cross section

The 3D finite element model was created using shell element type 181 with the configuration and material specifications for each element, as shown in Figure 5. The mesh size used was 300 mm and was used for the entire model.

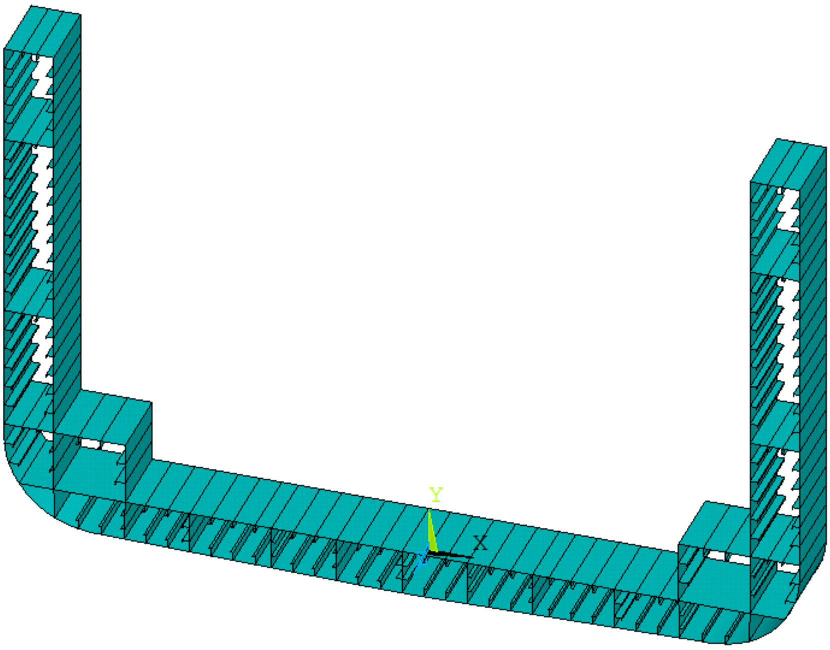


Figure 4. Container ship cross-section in Ansys

Non-Linear Finite Element Analysis (NLFEA) uses static analysis with the arc length method to obtain the ultimate buckling and post-buckling values of the structure. The ultimate buckling strength was then evaluated and compared with previous studies.

3. RESULTS AND DISCUSSION

The load conditions correspond to a typical arrangement of static and dynamic loads resulting from global and local load contributions (static pressure and waves) that induce shear forces and bending moments in the longitudinal stiffeners of the side shells as a single beam (between each web frame). The boundary conditions respond to fixed supports at the ends of the plates referring to the side shells. Joints between elements are generated by welding, which is simulated in the program by assuming a single element. The load conditions corresponding to the contribution of static pressure and external waves on the longitudinal side shells are generated in the tilted ship condition, which occurs when the ship encounters waves that generate ship motions in the XY and YZ planes; there is an unsymmetrical relative motion of the seawater line on the ship side that generates the hull girder loads mentioned in the previous section.

On the other hand, the same previous case devoted to the longitudinal stiffeners of the main deck occurs in the upright ship condition when the ship encounters waves that produce ship motions in the X-Z plane. The torsional deformation of the container ship can be seen in figure 5.

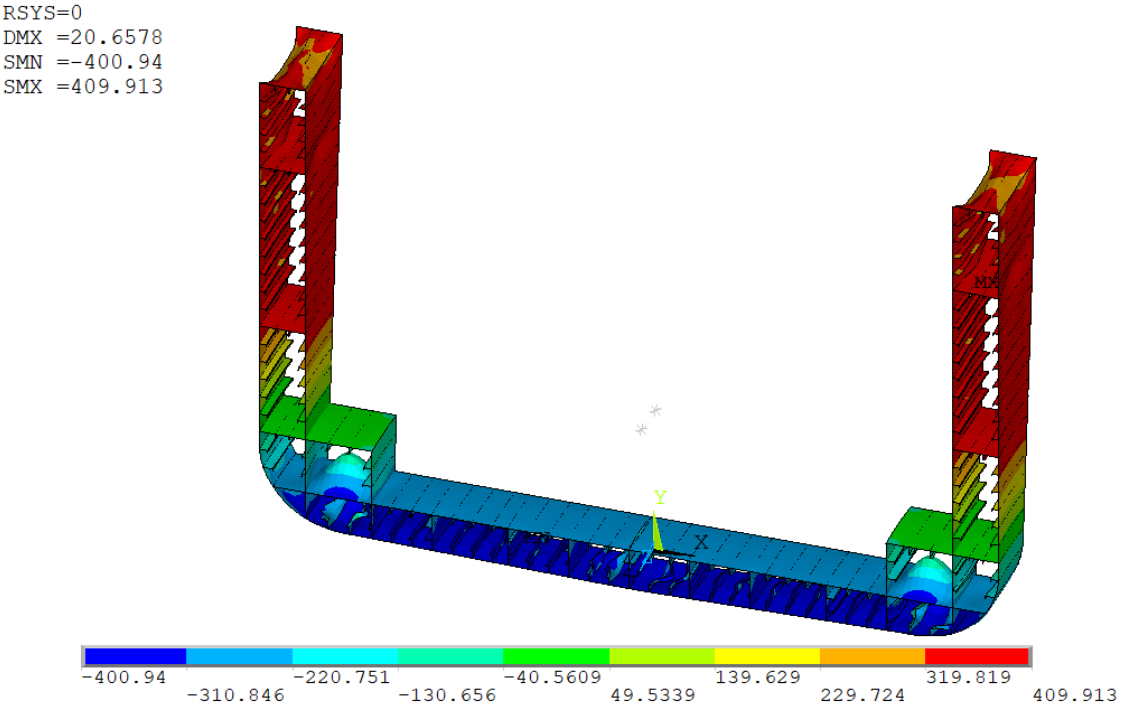


Figure 5. Deformation of the hull girder limit strength due to hogging

In the figure above, the working stress value that occurs in the container ship structure when experiencing torque on the structure during hogging conditions is - 400.94 N/mm^2 at the bottom, and the most significant stress occurs on the deck with a stress value of 409.913 N/mm^2 while at the time of sagging can be seen in the following image.

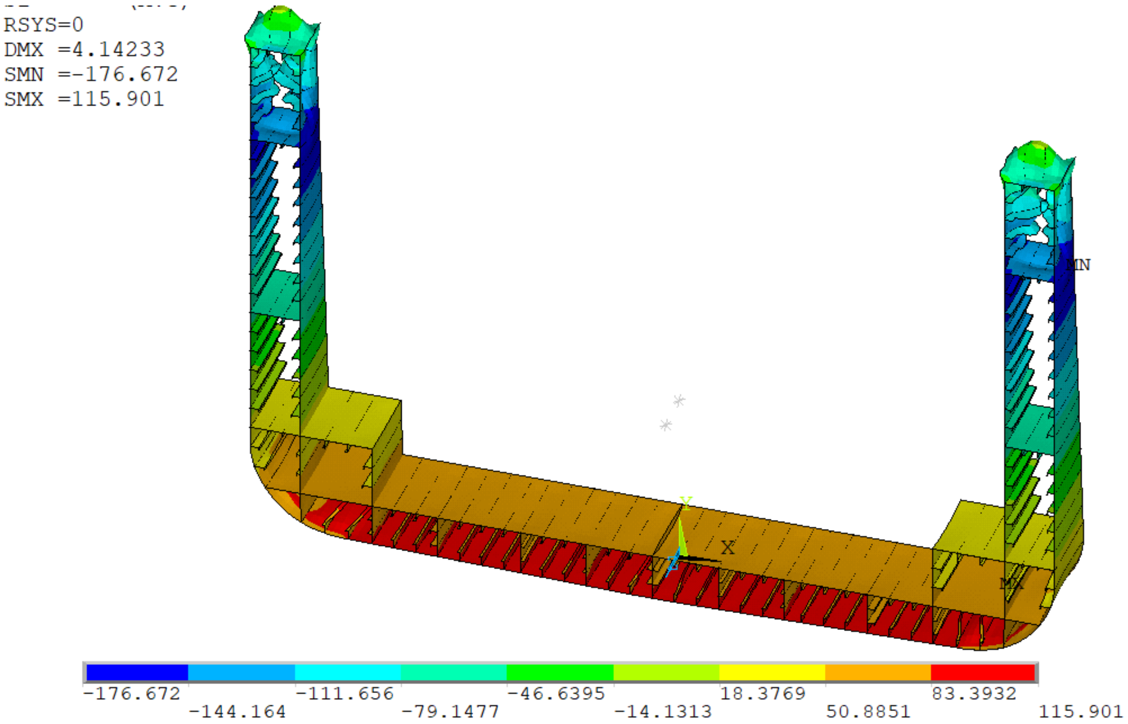


Figure 6. Deformation of the hull girder limits strength due to sagging

In the figure above, the working stress value that occurs in the container ship structure when experiencing torque on the structure during hogging conditions is 115.901 N/mm^2 at the bottom, and there is a deck stress with a stress value of -176.672 N/mm^2.

Table 1 shows the ultimate torsion strength results calculated under slack and hogging conditions using NLFEA.

Table 1. Ultimate torsion strength results

Kondisi	Metode NLFEA
$M_{u\ Hogging}$ x 10^{13}	1.39
$M_{u\ Sagging}$ x 10^{13}	-1.17

Based on the table above, the limit strength of the container ship due to torque when hogging is 1.39 × 10^{13} Nmm, and when sagging is - 1.17 × 10^{13} Nmm. The relationship between the moment of curvature and the rotation of the container ship using the NLFEA method in Ansys can be seen in the following Figure 7.

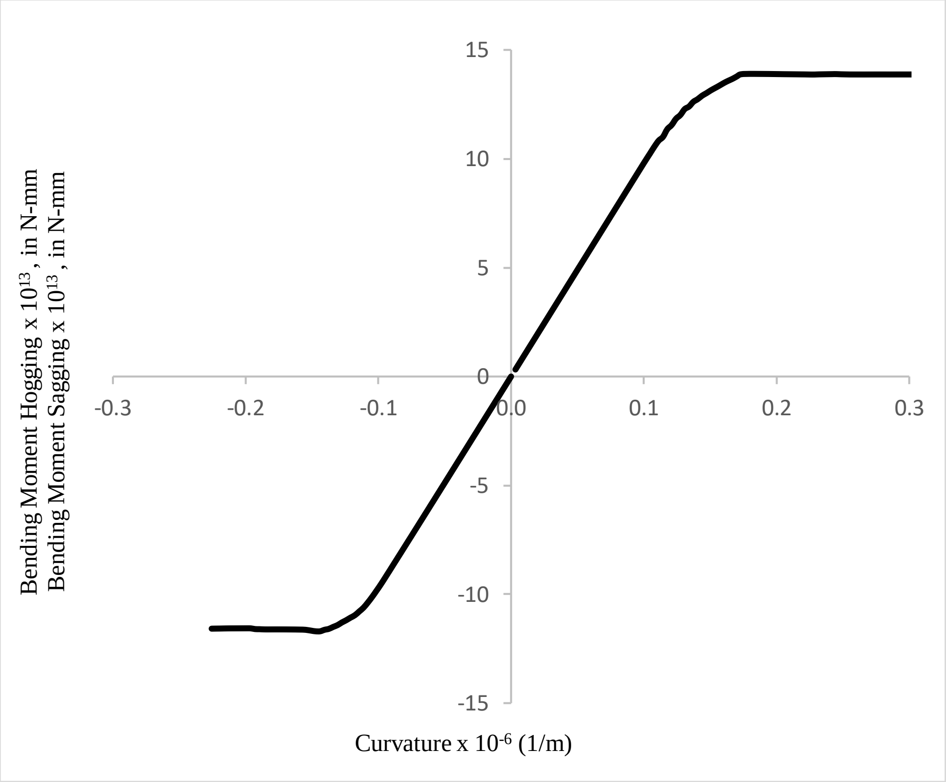


Figure 7. Moment-curvature relationship

The figure above shows that the container ship, when sagging, the strength of the ship's limit is faster to make the ship damaged than experiencing hogging. This can be seen from the magnitude of the vertical limit moment experienced by the third sagging ship is smaller than when hogging.

In this investigation, structural design criteria for container ships were obtained. The degree of influence of the upper wing torsion box characteristics (height and width) has been shown on the global and local structural assessment of the behavioral relationship between geometric variables, onboard stress, and fatigue strength assessment of various structural details located on the side shell.

4. CONCLUSION

Large container ships are elastic and sensitive to torsion due to large deck openings. Transverse bulkheads increase the torsional stiffness of the hull but not sufficiently. For the hydroelastic analysis required in the early design stage, the use of a hull girder beam model is preferred. From the results of the analysis, it can be further considered to analyze the cross-section of container ships in one or more loading spaces to obtain maximum results. Elemental method analysis is highly recommended for the analysis of numerical vessels in the present and future.

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