Ultimate strength of typical stiffened panels in container ships with comparison of hull girder bending analysis

Jinju Cui¹,² and Deyu Wang¹,²,*

¹ State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai, China
² Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai Jiao Tong University, Shanghai, China

*E-mail: dywang@sjtu.edu.cn

Abstract. Large container ship’s structural strengths are the major concerns of owners and designers, and local stiffened panels within the mid-ship scope are similar due to the typical arrangements adopted in these ships. In this paper, investigations on longitudinal ultimate strength are made for these typical stiffened panels where considerations of modelling extent, boundary conditions and initial deflections are included. Additionally, the resulting force-load curves and collapse modes are compared with hull girder bending analysis (both hogging and sagging), thus validation are made in the more practical background. The study in this paper can be of reference values to similar container ships.

1. Introduction
Container ships are getting larger and are used extensively due to their high transportation efficiency and large capacity, and their structural strengths are the major concerns of owners and designers, especially after the ‘MOL Comfort’ 8100TEU container ship crash accident in 2013 which broke into two and finally sank in deep sea. As long as hull girder ultimate strengths are concerned, the ultimate strengths of local structures and failure modes also need further investigations to help designers better understand the structural behaviours in specific situations.

The ultimate strength for local stiffened panels is a critical problem in practical structural designs, and many researchers have devoted to these studies, e.g. Fujikubo and Yao [1] studied the elastic buckling strength by introducing torsional rigidity to simulate the interaction between stiffener and plate, and the results have been referenced by classification rules; The ultimate strengths of continuous plates and continuous stiffened panels under combined transverse thrust and lateral pressure are also extensively studied [2, 3]; Tanaka, Yanagihara, Yasuoka, Harada, Okazawa, Fujikubo and Yao [4] studied 720 cases with different numbers, types and sizes of stiffeners using Nonlinear Finite Element Analysis (NFEA), and compared the results with predictions by several existing methods, such as CSR, PULS and FYH; Tekgoz, Garbatov and Guedes Soares [5] analysed the effect of residual stress on the ultimate strength of a thin rectangular stiffened and single plate, and studied the sensitive factor as well as best welding sequence etc.; Cui, Wang and Ma [6] studied ultimate strength of typical stiffened panels in container ships under localized pitting corrosion, and investigated the probabilistic characteristics of ultimate strengths for corroded structures; Kim, Lim, Kim, Hwang and Park [7] proposed an empirical formulation for predicting the ultimate strength of stiffened panels subjected to longitudinal compression, which employs a function of plate slenderness ratio and column slenderness...
ratio with two correction coefficients; Lindemann and Kaeding [8] applied the idealized structural unit method for ultimate strength analyses of stiffened plate structures, and compared the results with Finite Element Methods; Xu, Song, Pan and Soares [9] studied the ultimate strength of continuous stiffened panels under combined longitudinal compressive load and lateral pressure; Zhang [10] made a review and study on ultimate strength analysis methods for steel plates and stiffened panels in axial compression.

In this paper, we studied the ultimate strength of typical stiffened panels for a typical 10000TEU container ship by Nonlinear Finite Element Analysis, and compared with hull girder ultimate strength results in our previous research [11], so the validation can be made for boundary conditions and modelling extent etc. Additionally, the effects of initial deflections are studied. The results are of reference values for similar container ships.

2. Fundamental methods and model description

2.1. Ultimate strength by Nonlinear Finite Element Analysis

Nonlinear Finite Element Analysis (NFEA) is a unified method and can be applied to a wide range of engineering problems especially for complex structures like ships, aero planes and etc. Generally, for ship structures, the ultimate strength problems can be classified as hull girder bending and torsional ultimate strengths, and the local stiffened panels’ (e.g. bottom panels, upper deck panels and etc.) ultimate strengths under uniaxial or bi-axial compression. For container ships, the most critical ultimate strength for hull girder is the hogging case because the loads of static water moment, wave induced moment and cargo loads are combined as the largest according to practical loading manuals, so the corresponding most dangerous local structures are the ones below neutral axis of mid-ship cross section, especially the bottom and inner bottom panels. In this paper, however, we studied both the hogging and sagging cases, and the ultimate strengths of stiffened panels under compression in either case are studied.

The hull girder ultimate strength results for both hogging and sagging results can be found in our previous research [11], and this is used as reference.

To study the ultimate strengths of local stiffened panels, the whole cross section of container ship is divided into several stiffened panels according to typical structural arrangements. Generally, the bottom panel, inner bottom panel, longitudinal girder panel, bilge panel, platform panel, deck panel, longitudinal bulkhead panel and outer shell panel etc. are selected and modelled individually with specific modelling extent and boundary conditions.

2.1.1. Modelling extent and boundary conditions of stiffened panels

The selection of modelling extent of local stiffened panels is according to structural arrangements and mechanics simplifications between connected structures as shown in figure 1. The longitudinal extent is determined by the “1/2+1+1/2 bay” model with periodic boundary conditions at both longitudinal ends, i.e. the displacements except the longitudinal translational ones are the same for paired nodes at the aft and fore ends, thus both symmetric and anti-symmetric longitudinal modes can be captured in the analysis. On the other hand, the transverse or vertical extent of the stiffened panels are determined by their connections with primary support members (PSMs) such as platforms or longitudinal bulkheads etc. Take the bottom panel as an example, the periodic boundary conditions are assigned between edges ‘AF’ and ‘BJ’ while simply supported boundary conditions are assigned at longitudinal girders and transverse frames locations, i.e. ‘KL’, ‘MN’, ‘AB’, ‘CD’, ‘EF’, ‘GH’ and ‘IJ’ while the edges are free to be pulled in to release the normal displacements within the ‘xz’ plane.
2.1.2. Initial deflections
As discussed by Ueda and Yao [12], both initial deflections and residual stresses exist in ship structures; they also investigated the modes and magnitudes of initial deflections according to measured results and actual practice. Thus, initial deflection is a practical consideration associated with manufacturing, and it is also included in the IACS Unified Requirements S11A; however, due to the lack of relevant information in practical cases, we adopted the initial deflections recommended by ISSC [13], and 3 kinds of initial deflections are proposed for structural analysis with Abaqus:

(a) Buckling mode initial deflection of plating:

\[ w_{pl} = A_b \sin \left( \frac{m \pi x}{a} \right) \sin \left( \frac{\pi y}{b} \right) \]  

where \( x \), \( y \) and \( z \) denote the longitudinal, transverse and vertical directions respectively; \( a \) denotes the span between adjacent transverse frames and \( b \) denotes the spacing between adjacent longitudinal stiffeners; \( m \) denotes the buckling mode of plating defined as the minimum integer satisfying \( \frac{a}{b} < \left[ \frac{m(m+1)}{2} \right]^{1/2} \); \( A_b \) denotes the magnitude of the above initial deflection, and is recommended as \( 0.1 \beta t_p \) where \( \beta = \frac{b}{t_p} (\sigma_y / E)^{1/2} \), is the slenderness ratio (\( t_p \) - plate thickness; \( \sigma_y \) - material yield stress; \( E \) - Young’s modulus).

(b) Column type deformation of stiffened panel:

\[ w_c = B_o \sin \left( \frac{\pi x}{a} \right) \sin \left( \frac{\pi y}{B} \right) \]  

where \( B \) denotes the spacing between longitudinal girders and \( B_o \) denotes the magnitude of the column type mode, and is recommended as 0.0015\( a \).

(c) Initial tripping distortion of stiffener:

\[ w_o = C_o \sin \left( \frac{\pi x}{a} \right) \]  

where \( h_o \) denotes the height of the stiffener and \( C_o \) denotes the magnitude of the stiffener tripping mode, and is recommended as 0.0015\( a \).

The above initial deflections are adopted in present study while residual stresses are not considered.

3. Model description
A typical 10000TEU container ship is chosen in this paper, the principle particulars are shown as table 1. The thickness distributions at mid-ship section are shown in figure 2 (left), and we can see that the thicknesses of longitudinal structures range from 9 mm to 70 mm, while high strength steels with different yield strengths (AH32, AH36, EH40, etc.) are adopted.
Table 1. Principle particulars for the 10000TEU container ship.

| Principle particulars          | Values  |
|-------------------------------|---------|
| Overall length: L<sub>OA</sub> | 337.0 m |
| Length between perpendiculars: L<sub>PP</sub> | 320.0 m |
| Moulded breadth: B            | 48.2 m  |
| Moulded depth: D              | 27.2 m  |
| Scantling draft: T<sub>SC</sub>| 15.5 m  |
| Block coefficient: C<sub>b</sub>| 0.642   |

4. Results and discussion

4.1. Results of hull girder ultimate strength
Firstly, the results of hull girder ultimate strength under both hogging and sagging bending moments are introduced as shown in figure 2 (right) according to the authors’ previous research [11]. We can conclude that results of hogging and sagging from both Smith’s method and NFEA are very close with each other, and the results from NFEA are selected for comparison in the following discussions.

Figure 2. Thickness distributions at mid-ship section (left); Bending moment vs. curvature for Smith’s method and Nonlinear Finite Element Analysis method (right).

4.2. Results of local stiffened panels’ ultimate strengths
Based on model setups described before, ultimate strengths of local stiffened panels can be calculated by NFEAs in Abaqus, and the results for individual stiffened panels are shown as table 2.

Table 2. Ultimate strength results of stiffened panels for the 10000TEU container ship.

| Stiffened panel | Stress distribution at ultimate strength | Force-displacement curves |
|-----------------|------------------------------------------|----------------------------|
| Bottom          |                                          |                            |
Inner bottom

Bilge

Longitudinal girder

Step platform

Second deck
4.2.1. **Bottom**

Ultimate strength of bottom panel under longitudinal compression is shown in table 2. Results from adopted stiffened panel are very close with that from hull girder analysis, and collapse modes belong to local collapse between stiffeners. The difference may lie in mesh size effect (different mesh sizes are adopted between stiffened panel and hull girder models, and former mesh is much finer than latter) as described in our previous research [14], boundary condition effect and etc.

4.2.2. **Inner bottom**

Similarly, the results for inner bottom can be found in table 2 which shows local collapse modes and good agreement between stiffened panel and hull girder results.

4.2.3. **Bilge**

Initial deflections are not considered in bilge panel due to the complicated curved surface whose initial deflections are different from the plane panel and have been rarely reported so far. Additionally, the bilge panel covers a certain vertical extent which means the loading are different between top and
bottom in hull girder bending, so we applied both uniform and non-uniform (linear in depth) compression. Apparently, both models overestimate the ultimate strengths, and linear compression is more accurate (5.8% overestimation); linear compression yields smaller ultimate strengths because local collapse happens, develops and expands due to non-uniform loading, i.e. earlier collapse happens rather than sudden overall collapse in uniform compression, and this conclusion can also be applied to other stiffened panels (unless with different thickness distributions).

4.2.4. Longitudinal girder
The #23 longitudinal girder extending from bottom to step platform is chosen, and results are shown in table 2, and we can see that uniform compression yields results of higher agreement with hull girder model, and linear compression yields lower ultimate strengths as analysed before. Additionally, the neutral axis changes rapidly especially after hull girder ultimate bending moments are reached, coinciding with the collapse of #23 girder. However, the linear compression with fixed neutral axis cannot reflect this change, which may cause worse results even than uniform compression.

4.2.5. Step platform
The step platform connecting previous longitudinal girder and side shell is chosen in this study, and the results show local collapse modes and good agreements between two models, and the stiffened panel model slightly underestimates the ultimate strength by hull girder model.

4.2.6. Second deck
The second deck is under compression in sagging bending, and its connections with double shells are not allowed to be pulled in due to double shell’s strong rigidity. The results can be found in table 2, and it’s evident that the stiffened panel model slightly underestimates the rigidity and ultimate strength. Additionally, the collapse mode belongs to local collapse rather than panel collapse.

4.2.7. Longitudinal bulkhead (up)
The results for longitudinal bulkhead locating beneath upper deck are shown in table 2, which shows good agreement between the stiffened panels and hull girder model. Apparently, collapse happens first in thinner plates, and then expands upwards.

4.2.8. Side shell (up)
The results are very similar with previous longitudinal bulkhead, and uniform compression yields results closer to hull girder model results.

4.2.9. Upper deck
The collapse mode immediately at ultimate strength is shown in table 2. Additionally, the stiffened panel model overestimates the ultimate strength by 5.9% than hull girder model.

4.2.10. Hatch coaming
Hatch coaming structures are also studied as shown in table 2. We can see that the collapse happens in the local plate collapse mode, while the ultimate strength by hull girder model lies between the uniform compression and linear compression models, and uniform compression is more accurate which overestimates the ultimate strength by 6.0% than hull girder model.

4.3. Influence of initial deflection on stiffened panel’s ultimate strength
We also considered the effects of initial deflection magnitude on the stiffened panels’ ultimate strengths. A series of NFEAs are calculated by varying the magnitudes and direction of initial deflection, and the results are normalized to unity by the ultimate strength values without initial deflection for more clear comparison between stiffened panels. Also note that bifurcation exists in the
intact structures without initial deflections, so buckling and post-buckling phenomenon cannot be captured in some cases, thus small initial deflections are adopted instead in these cases.

To demonstrate how initial deflection affects ultimate strength, we can take the bottom panel as an example, whose stress distributions immediately at ultimate strength are shown in figure 3 for the cases of zero and 1.5 times magnitude of initial deflection, respectively. Apparently, out-of-plane deformations develops much faster with larger initial deflection, thus the ultimate strength is degraded.

The results for different stiffened panels across the mid-ship cross section are shown in figure 4. Apparently, the ultimate strength decreases almost linearly with increased magnitude of initial deflection while sign or direction is not a sensitive factor for a given type of initial deflection combination, resulting in almost symmetric ‘umbrella shaped’ curves. Additionally, weaker or thinner stiffened panels are more likely influenced by the magnitude of initial deflections, and vice versa.

**Figure 3.** Bottom: stress distribution and deformation shape immediately at ultimate strength (0 x initial deflection, left; 1.5 x initial deflection, right).

**Figure 4.** Influence of initial deflection magnitude on typical stiffened panel’s ultimate strength (normalized).

5. Conclusions
In this paper, we investigated the ultimate strengths of typical stiffened panels in container ships, and compared the results with hull girder analyses. According to the modelling extent with boundary conditions in this paper, the ultimate strength results of typical panels under longitudinal compression matches well with hull girder model (difference within 6.0%), and the collapse modes belong to local collapse between stiffeners, which fulfils design principle that stiffeners should not fail before plates do. Thus the proposed methods are validated, and are supposed to find applications in other container ships or similar double-shelled ships. Additionally, the following conclusions can also be drawn:

(1) Generally, for vertically-spanned stiffened panels with equal thickness distributions, ultimate strengths of linear compression are smaller than uniform compression; however, due to the change of neutral axis in hull girder bending especially after ultimate strengths, the uniform may even yield more reasonable results than the fixed linear compression in specific cases.

(2) In the analysis of weak stiffened panels (e.g. 2nd Deck) between double shells, considering the rigidity of shell structures, it is more reasonable that their connections cannot be pulled in freely.
(3) The ultimate strength decreases almost linearly with increased magnitude of initial deflection while sign or direction of initial deflection is not a sensitive factor for a given type of initial deflection combination. Additionally, weaker or thinner stiffened panels are more likely influenced by the magnitude of initial deflections, and vice versa.

Acknowledgements

This paper is funded by both the Chinese Government Key Research Project KSHIP-II Project (Knowledge-based Ship Design Hyper-Integrated Platform, No.201335) and High-tech Ship Research Projects Sponsored by MIIT(2016-25).

References

[1] M. Fujikubo, and T. Yao, "Elastic local buckling strength of stiffened plate considering plate/stiffener interaction and welding residual stress," Mar. Struct., 12(9), pp.543-64 (1999)

[2] M. Fujikubo, T. Yao, M. R. Khedmati, M. Harada, and D. Yanagihara, "Estimation of ultimate strength of continuous stiffened panel under combined transverse thrust and lateral pressure Part 1: Continuous plate," Mar. Struct., 18(S-5-6), pp. 383-410 (2005)

[3] M. Fujikubo, M. Harada, T. Yao, M. Reza Khedmati, and D. Yanagihara, "Estimation of ultimate strength of continuous stiffened panel under combined transverse thrust and lateral pressure Part 2: Continuous stiffened panel," Mar. Struct., 18(S-5-6), pp. 411-27 (2005)

[4] S. Tanaka, D. Yanagihara, A. Yasuoka, M. Harada, S. Okazawa, M. Fujikubo, and T. Yao, "Evaluation of ultimate strength of stiffened panels under longitudinal thrust," Mar. Struct., 36, pp. 21-50 (2014)

[5] M. Tekgoz, Y. Garbatov, and C. Guedes Soares, "Ultimate strength assessment of welded stiffened plates," Eng. Struct., 84, pp. 325-39 (2015)

[6] J. Cui, D. Wang, and N. Ma, "Ultimate Strength of Typical Stiffened Panels in Container Ships Under Localized Pitting Corrosion," Proc. ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering, American Society of Mechanical Engineers, V003T002A092-V003T002A092 (2016)

[7] D. K. Kim, H. L. Lim, M. S. Kim, O. J. Hwang, and K. S. Park, "An empirical formulation for predicting the ultimate strength of stiffened panels subjected to longitudinal compression," Ocean Eng., 140, pp. 270-80 (2017)

[8] T. Lindemann, and P. Kaeding, "Application of the idealized structural unit method for ultimate strength analyses of stiffened plate structures," Ship Technol Res, 64(1), 15-29 (2017)

[9] M. C. Xu, Z. J. Song, J. Pan, and C. G. Soares, "Ultimate strength assessment of continuous stiffened panels under combined longitudinal compressive load and lateral pressure," Ocean Eng., 139, pp. 39-53 (2017)

[10] S. M. Zhang, "A review and study on ultimate strength of steel plates and stiffened panels in axial compression," Ships Offshore Struct, 11(1), pp. 81-91 (2016)

[11] J. Cui, D. Wang, and N. Ma, "A Study of Key Influencing Factors in Ultimate Strength Analysis for Container Ships," The 27th International Ocean and Polar Engineering Conference, International Society of Offshore and Polar Engineers, San Francisco, California, USA(2017)

[12] Y. Ueda, and T. Yao, "The Influence of Complex Initial Deflection Modes on the Behaviour and Ultimate Strength of Rectangular Plates in Compression," J. Constr. Steel Res., 5(4), 265-302 (1985)

[13] J. Paik, H. Amlashi, B. Boon, K. Branner, P. Caridis, P. Das, M. Fujikubo, C. Huang, L. Josefson, and P. Kaeding, "Ultimate strength-final report of ISSC III. 1," Proc. Germany: International Ship and Offshore Structures Congress (ISSC 2012)

[14] J. Cui, D. Wang, and N. Ma, "A study of container ship structures' ultimate strength under corrosion effects," Ocean Eng., 130, pp. 454-70 (2017)