Investigations on Ultimate Strength for a Container Vessel under Combined Loads

Thomas LINDEMANN[a,1], Patrick KAEDING[a], Alexander WILLSCH[a], Alessandro LA FERLITA[b] and Dario BOOTE[c]
[a] *University of Rostock, Chair of Ship Structures, Rostock, Germany*
[b] *American Bureau of Shipping, ABS Europe Ltd., Hamburg, Germany*
[c] *Department of Electrical, Electronic, Telecommunication Engineering and Naval Architecture University of Genova, Italy*

Abstract. The progressive collapse behavior of a container vessel in pure vertical, horizontal and biaxial bending is determined by nonlinear finite element analyses. A parametric finite element model is used to demonstrate the influence of nonlinear material behavior and welding related imperfections on the ultimate hull girder strength. Convergence for nonlinear static implicit analyses is ensured by using the full Newton-Raphson scheme and the results are validated against Smith's method.

Keywords. Ultimate strength, finite element method, Smith's method, welding residual stress, container vessel, bending

1. Introduction

Ship structures are composed of stiffened plates which bear the whole variety of loads acting on the hull girder during its entire lifetime. To ensure the safety of a ship even under extreme loads, the ultimate strength has to be determined for different loading conditions. Yao and Fujikubo [1] described the buckling behavior and provided different methods to determine the ultimate strength of ships and other ship-like floating structures. Furthermore, Paik [2] proposed approaches for ultimate limit state analyses and design methods of plated structures. In both textbooks the fundamentals of progressive collapse analyses to determine the ultimate hull girder strength are demonstrated.

Smith's method [3] is a well-established incremental iterative approach to perform progressive collapse analyses of hull girders in vertical bending. This approach has been improved to analyze unsymmetric cross sections and ships in biaxial bending [4]. The applicability of Smith's method is demonstrated exemplarily for different intact vessels under pure vertical bending and combined load cases in various ISSC reports [5], [6]. La Ferlita et al. [7] applied Smith's method to determine the residual hull girder strength of a container vessel in pure vertical bending for different damage cases due to grounding. There, Smith's method is used in framework of an advanced salvage method for damaged ships to ensure a short-term decision making process for a save ocean towage.

The Idealized Structural Unit Method (ISUM) is also suitable to perform progressive collapse analyses of hull girders under combined loads with reduced numerical efforts.

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[1] Thomas Lindemann, Book Department, IOS Press, Nieuwe Hemweg 6B, 1013 BG Amsterdam, The Netherlands; E-mail: bookproduction@iospress.nl.

Oksina et al. [8] proposed a review of the current ISUM formulation and results of plates under dynamic loadings. Details of the ISUM formulation and its applicability for ultimate strength analyses of stiffened plate structures are demonstrated exemplarily by Lindemann and Kaeding [9].

The finite element method (FEM) is very well suited to perform progressive collapse analyses of large structures with respect to material and geometrical nonlinearities as well as imperfections due to welding. Lindemann and Kaeding [10] performed nonlinear finite element analyses (FEA) to investigate the influence of shear and lateral loads on the collapse behavior of plate structures under inplane loads. Lindemann et al. [11], [12] also performed ultimate strength tests of box girder specimens in vertical bending experimentally to validate the FE models. The applicability of FEM to perform structural analyses of big yacht superstructures is demonstrated by Boote et al. [13]. Furthermore, thermal load effects on side plates of superyachts are investigated by Boote et al. [14] by FEM. Pais et al. [15], [16] used FEM to perform vibration analyses and the comfort assessment of superyachts numerically. Vergassola et al. [17] performed FEM buckling analyses of stiffened cylindrical structures and validated the results against experimental data. Furthermore, Vergassola and Boote [18] also performed FE vibration analyses and experimental comparison of the dynamic behavior of superyacht structures.

In this paper, nonlinear finite element analyses are performed to determine the ultimate strength of a container vessel under vertical, horizontal and biaxial bending. The implicit ANSYS solver is used for the different load cases. A parametric finite element model is proposed considering the effects of different nonlinear material models for a given model length and mesh size. The results are validated against Smith’s method. For the proposed finite element model initial deflections of plating and stiffeners have been considered. Furthermore, the influence of welding residual stresses on the ultimate hull girder strength is analyzed for all different load cases.

2. Container Vessel

Container ships are characterized by large deck openings to carry maximum number of containers [1]. The torsional stiffness of the hull girder is low and local lateral pressure loads might influence the ultimate hogging moment [19], [20]. Further nonlinear FEA results on dynamic and combined loadings of container vessels are given exemplarily by Yamada et al. [21] as well as by Wang and Wang [22].

2.1. Dimensions and Properties

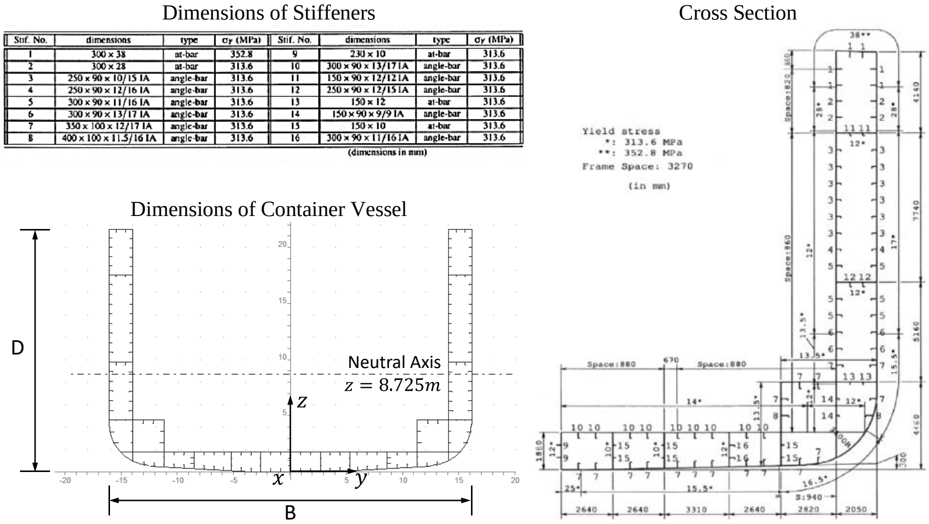
A 3500 TEU (twenty-foot equivalent unit) container vessel proposed within the ISSC reports [5], [6] is investigated for load cases of pure vertical, horizontal and biaxial bending. The principal dimensions and material properties of the container vessel are given in Table 1 and Table 2. Further details about stiffener types, dimensions, yield stress values (σ_Y) and stiffener spacings are shown in Figure 1.

Table 1. Principal Dimensions of Container Vessel [5]

Description	Symbol	Value	Unit
Length	L	230	m
Breadth	B	32.2	m
Depth	D	21.5	m

Table 2. Material Properties of Container Vessel [5]

Description	Symbol	Value	Unit
Young's Modulus	E	210000	MPa
Poison Ratio	ν	0.3	-
Yield Stress *	σ_Y*	313.6	MPa
Yield Stress **	σ_Y**	352.8	MPa



Dimensions of Stiffeners

Stif. No.	dimensions	type	σY (MPa)	Stif. No.	dimensions	type	σY (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)

Cross Section

Dimensions of Container Vessel

Figure 1. Properties of Container Vessel [5]

2.2. Smith's Method based Model

The cross section, modelled with MARS2000 (Bureau Veritas) software, is subdivided into structural elements composed of stiffeners and plates. In Figure 2 the plate thicknesses values and stiffener scantlings are given. Due to symmetry, only a half part is shown. The cross section remains plane during the progressive collapse analysis and there exists no interaction between adjacent elements in the cross section [1].

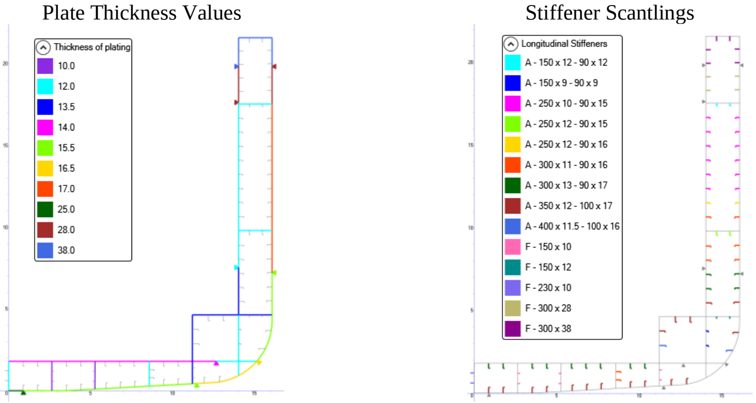


Plate Thickness Values

Stiffener Scantlings

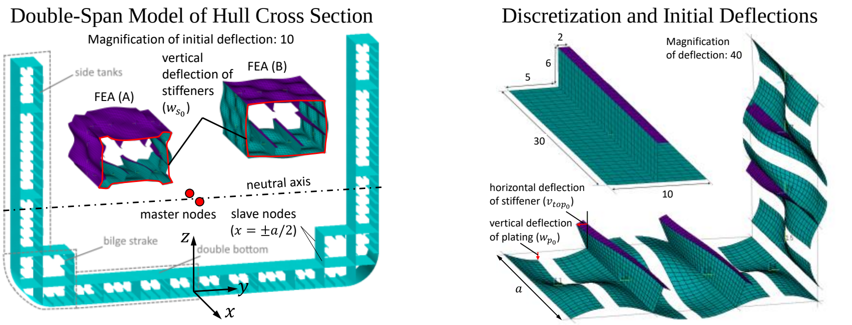
Figure 2. Cross Sectional Elements of Container Vessel

2.3. Finite Element Model

The static implicit ANSYS solver has been used to perform nonlinear finite element analyses. A parametric finite element model of the container vessel is developed. Four-node bilinear shell elements (SHELL181) with six degrees of freedom per node are used with reduced integration. An elastic-perfectly plastic material behavior is assumed by using the material properties given in Table 2. The influence of hardening by using a tangent modulus (T) for an elastic-linear plastic material behavior on the ultimate hull girder strength is also investigated for all different load cases.

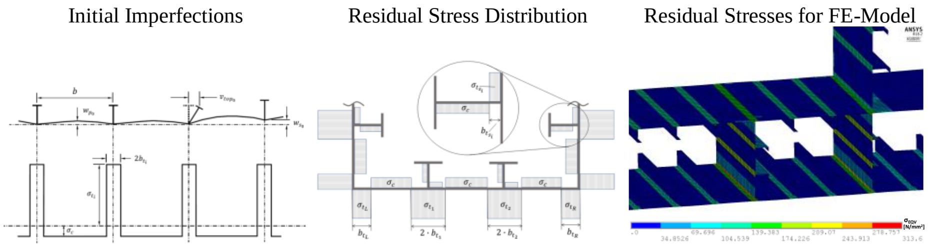
In Figure 3 the double-span model of the entire hull cross section is proposed. Nodal rotations are given incrementally to the master nodes and due to constraint equations inplane displacements of the slave nodes located at the model edges are imposed. Initial deflections due to welding are given to the entire model. For a stiffened plate the initial deflections are composed of the vertical panel deflection as well as the horizontal and vertical deflection of the stiffener. The applied concept is described within the ISSC report [5] and further textbooks [1], [2]. Here, the influence of lateral stiffener deflections is investigated by giving the same amplitude to all stiffeners of a plate panel “FEA (A)” (artificial) respectively using a sine function in transverse direction “FEA (B)” [2].

The influence of welding residual stresses on the hull girder strength is investigated for the container vessel based on the concept proposed by Yao and Fujikubo [1]. The fabrication process of the panels and girders requires fillet and butt welding of different components which cause tensile stresses in the solidified and shrunken heat affected zone [2]. To compensate tension, compression stresses are induced in the adjacent parts (Figure 4). These stresses are adapted to the proposed discretization scheme and applied to the finite element model of the container ship cross section.


Double-Span Model of Hull Cross Section

Discretization and Initial Deflections

Figure 3. Finite Element Model of Container Vessel


Initial Imperfections

Residual Stress Distribution

Residual Stresses for FE-Model

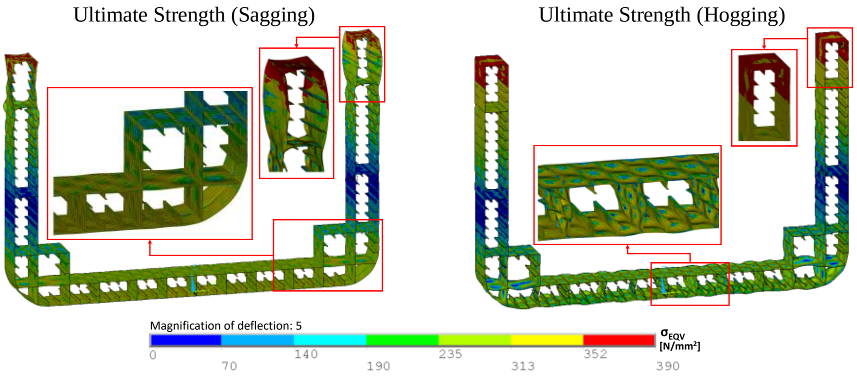
Figure 4. Initial Imperfections due to Welding

3. Vertical Bending

The longitudinal strength is the most fundamental aspect of ship's strength [5]. In Figure 5 the equivalent stress (σ_{EQV}) distribution is shown for the container vessel at ultimate strength in hogging and sagging condition. Here, an elastic-perfectly plastic material model (T = 0) and welding residual stresses (wrs) are applied. The FEA results are validated against Smith's method (T = 0; no wrs) using MARS2000 (BV) and an inhouse code (EXCEL) [7]. The moment-curvature curves are shown in Figure 6.

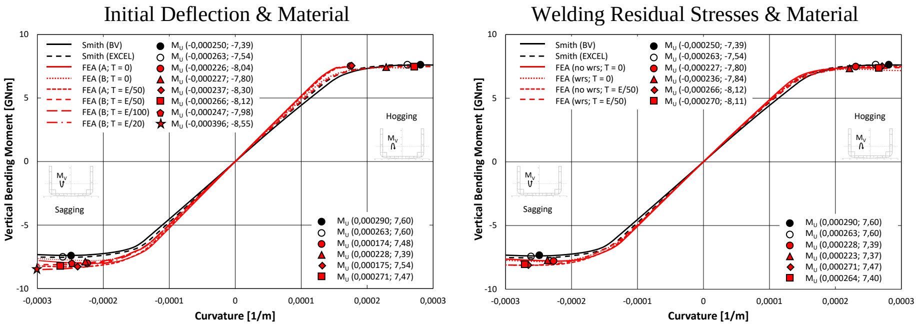
Under hogging condition, the outer bottom plating starts to buckle and spreads over the longitudinal girders. Then yielding starts in the deck and spreads over the shell plating of the upper side tank. Finally, the inner bottom plating starts to buckle and the ultimate strength (M_U) is reached. The influence of welding residual stresses is only marginal but the maximum vertical bending moment increase slightly by using a tangent modulus (T). Convergence difficulties appeared for the initial deflection model "FEA (A)", that only "FEA (B)" is considered for the different material and welding residual stress models.

Under sagging condition, buckling starts at the deck and spreads downwards the side shell and the bottom plating of both top side tanks. Then yielding starts in the deck and spreads over the upper side shell plating until ultimate strength (M_U) is reached. The FE models slightly overestimate the ultimate strength compared to Smith's method results. Higher absolute ultimate strength values are determined for increasing tangent modulus but the influence of welding residual stresses is small.


Ultimate Strength (Sagging)

Ultimate Strength (Hogging)

Figure 5. Finite Element Model (wrs) of Container Vessel in Vertical Bending


Initial Deflection & Material

Welding Residual Stresses & Material

Figure 6. Container Vessel in Vertical Bending

4. Horizontal Bending

To simulate the collapse behavior of the container vessel in horizontal bending, progressive collapse analyses are performed with the FEA (B) model, giving incremental rotations about the vertical axis to both master nodes. In Figure 7 the equivalent stress (σ_{EQV}) distribution is shown exemplarily for the container vessel at ultimate strength produced by a negative horizontal bending moment. Here, an elastic-perfectly plastic material model (T = 0) and welding residual stresses (wrs) are applied. At starboard side, the deck, side shell and bilge structure are under compression. Buckling and yielding already are observed. At portside, the structural components are under tension and yielding starts at the deck. The moment-curvature curves are shown for different FE models and validated against Smith's method results using MARS2000 (BV) software. Except the arrangement of stiffeners at the center girder, the cross section is symmetric. Therefore, the absolute ultimate strength values are nearly identical for the positive respectively the negative horizontal bending moment. The FEA (no wrs; T = 0) model delivers slightly lower ultimate strength values compared to Smith's method. The influence of welding residual stresses (wrs) is very small and under consideration of a tangent modulus (T) the maximum load carrying capacity (M_U) increases slightly.

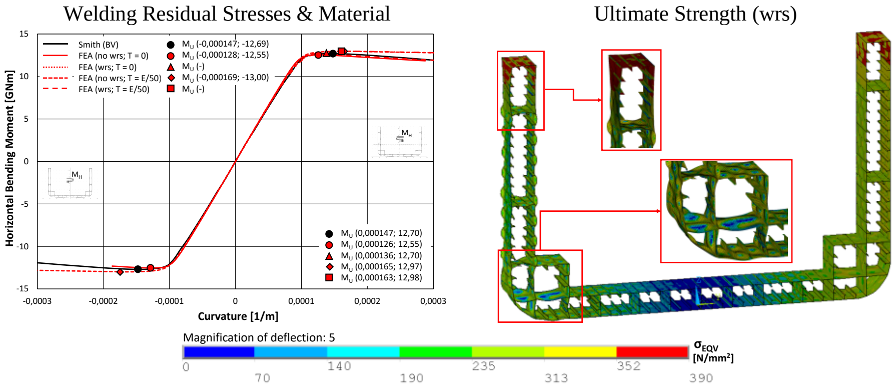


Figure 7. Container Vessel in Horizontal Bending

5. Biaxial Bending

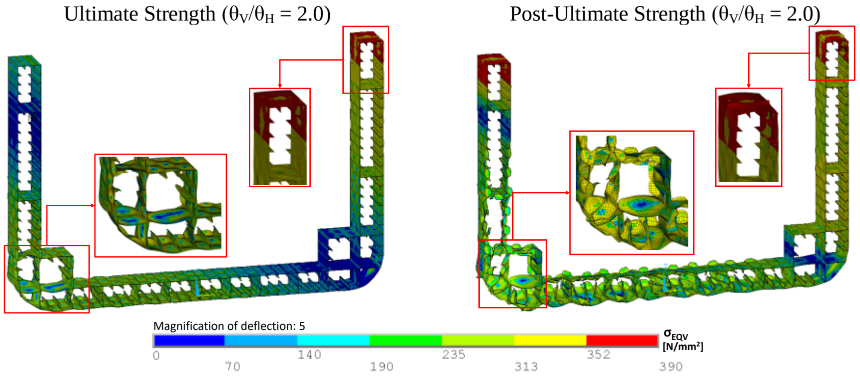
Hull girders are in general exposed to combined vertical and horizontal bending moments, when the ocean going ship is rolling in an oblique sea [1]. Paik [2] performed progressive collapse analyses for different ships using ALPS/HULL intelligent supersized finite element method and he proposed Eq. (1) to approximate the relation between vertical (M_V) and horizontal (M_H) bending moments with respect to the ultimate strength values (M_{VU}; M_{HU}). The results are compared to an ellipse, Eq. (2), a less conservative approach.

$$\left(\frac{M_V}{M_{VU}}\right)^{1.85} + \left(\frac{M_H}{M_{HU}}\right) = 1 \tag{1}$$

$$\left(\frac{M_V}{M_{VU}}\right)^{2} + \left(\frac{M_H}{M_{HU}}\right)^{2} = 1 \tag{2}$$

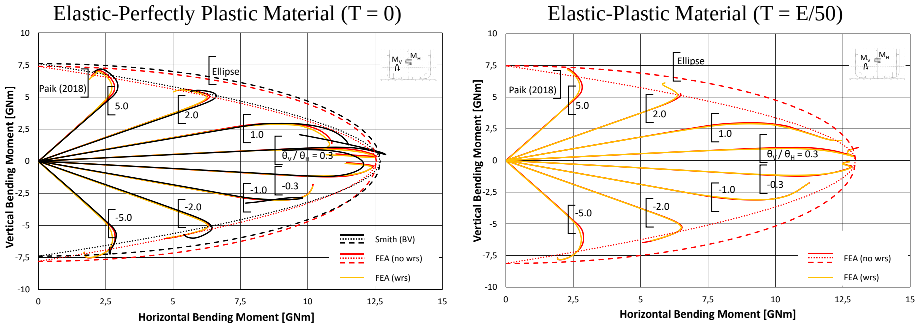
In Figure 8 the collapse behavior is shown for the container vessel in biaxial bending at ultimate strength and at a post-ultimate strength stage, determined by the FEA (B) model including welding residual stresses (wrs) for a fixed ratio of absolute rotation increments of both master nodes due to vertical bending (θ_V) and horizontal bending (θ_H).

In Figure 9 the loading paths are shown for different ratios (θ_V/θ_H) and compared to Smith's method (BV) for an elastic-perfectly plastic material model (T = 0). Due to symmetry only the results for a positive horizontal bending moment are proposed. The FE model delivers slightly more conservative results located close to the approximation curve, Eq. (1), proposed by Paik [2]. The influence of welding residual stresses is very small and the ultimate strength increases slightly by using a tangent modulus (T).


Ultimate Strength ($\theta_V/\theta_H = 2.0$)

Post-Ultimate Strength ($\theta_V/\theta_H = 2.0$)

Figure 8. Finite Element Model (wrs) of Container Vessel in Biaxial Bending


Elastic-Perfectly Plastic Material (T = 0)

Elastic-Plastic Material (T = E/50)

Figure 9. Container Vessel in Biaxial Bending

6. Conclusion

Nonlinear finite element analyses are successfully performed by using a static implicit solver to determine the ultimate strength of a 3500 TEU container vessel under pure vertical, horizontal and biaxial bending. Welding residual stresses only have a very small influence on the collapse behavior. An elastic-perfectly plastic material model delivers more conservative results instead of considering hardening effects. Depending on the initial deflection model good convergence has been reached. The FE results are slightly more conservative compared to Smith's method except in pure sagging condition.

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