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Simplified Approach on the Ultimate Hull Girder Strength of Asymmetrically Damaged Ships

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The objective of the present study is to investigate the ultimate hull girder strength of an asymmetrically damaged ship under a sagging condition. Two kinds of ships are taken as the object of analysis. The cross section of the ship is considered and assumed to have remained plane. The simply supported boundary condition is applied to both sides of the cross-section. The ultimate hull girder strength is attained when a plate and/or stiffened plate element at the specified location called "critical element" reach its ultimate strength. To investigate the ultimate hull girder strength, a simplified approach is proposed. The result obtained by the simplified approach is compared with the progressive collapse analysis to determine effectiveness and for validation.

INTRODUCTION

The ability to predict accurately the ultimate strength of ship hull girder when subjected to longitudinal bending is one of the most important aspects of ship structural design. Collision and grounding damage may take place on the ship's hull, which may threaten safety of ships and surrounding environment. In this regard, to enhance the safety of ship's structure and minimize the risks, the International Maritime Organization (IMO, 2009) has required in Goal Based Standard for New Ship Construction (GBS) to consider the residual strength of the hull girder in specified damage conditions as one of the functional requirements for the structural rules for bulk carriers and tankers.

Many studies have been conducted on the analyses of the residual hull girder strength as a result of collision and grounding damages. Pedersen (1994) presented a mathematical model to estimate the contact pressure between the grounded ship and the sea bottom. The grounding contact force was compared with the force that would crush the forward bottom of the ship. The sectional bending moment due to grounding was determined and compared with the ultimate hull girder strengths. The model experiments and full-scale controlled grounding experiments were also performed to validate the mathematical model. Paik et al. (1998) developed a rapid procedure to identify the possibility of hull girder failure after collision and grounding damages based on the closed-form formulae of the ultimate hull girder strength and section modulus after the damages. Guedes Soares et al. (2008) evaluated the ability of simplified structural analysis methods based on Smith's formulation to predict the ultimate strength of damaged ship's hull. Muis Alie et al. (2016) investigated the influence of the superstructure on the ultimate strength of Ro-Ro ship under a vertical bending moment. The cross section was considered to be analyzed. The results obtained by beam theory with and without superstructure were compared with one another. The assessment of the ultimate hull girder strength was conducted by Muis Alie et al. (2017). The cross-section of Ro-Ro ship was taken to be analyzed. The collision and grounding damages were assumed to be located on the side and bottom areas, respectively. The damages were created by removing the element from the side shell and bottom part. Ohtsubo et al. (1994) showed the experimental and numerical works on the ship structural damages due to collision and grounding. This was one of the first attempts to apply the explicit finite element method codes, such as LS-DYNA and MSC Dytran, to the collision and grounding problems of ships. Özgüç et al. (2005) investigated the collision resistance and residual strength of single-skin and double-skin bulk carriers subjected to damages. Notaro et al. (2010) carried out full nonlinear finite element assessments of hull girder capacity in intact and damage conditions. The effects of several influential factors such as model extend and complexity, damage representations, and model imperfections were investigated on the different vessels. It was found that the effect of damage extent in a vertical direction is more critical than in a longitudinal direction, and the damage varies according to the location of the neutral axes including higher stresses in proximity of the damage areas. The various probability levels were considered for the damage extent estimation.

When a hull-girder cross-section is symmetric with respect to the centerline and subjected to pure vertical bending moment, the neutral axis for vertical bending is always horizontal and moves only vertically during the progressive collapse behavior. However, when the cross-section is asymmetrically damaged, for example, because of a collision, the neutral axis rotates. Both rotation and translation need to be taken into account during the progressive collapse behavior even when only a vertical bending moment is applied, and the problem needs to be treated as a biaxial bending problem. Previous studies using the Smith's method on the ultimate strength of hull girders under biaxial thrust (Özgüç and Barltrop, 2008) and the residual strength of damaged hulls (Fang and Das, 2004; Hussein and Guedes Soares, 2009; Choung et al., 2011) consider the rotation and translation of neutral axis in a reasonable way. However, they employ a trial-and-error approach to detect the position of neutral axis. An easier approach to detect the position of neutral axis is suggested.

BASIC ASSUMPTION

The following assumption is made for the prediction of the residual hull girder strength under the sagging condition:

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KEY WORDS: Single hull bulk carrier, double hull oil tanker, cross section, neutral axis, asymmetrically damaged, ultimate strength, simplified approach.

(1) The ultimate sagging strength is attained when a stiffened panel element at the specified location (hereafter called "critical element") reached the ultimate strength.

(2) The hull girder cross-section is elastic until the failure of the critical member.

(3) The ultimate strength of the critical member is predicted from the average axial stress and average axial strain relationship calculated by HULLST (Yao and Nikolov, 1992).

EFFECT OF NEUTRAL AXIS ROTATION ON THE ESTIMATION OF THE ULTIMATE HULL GIRDER STRENGTH

In the elastic cross section, the bending stress at the *i*-th element (see Fig. 1), σ_i, is expressed as

$$\sigma_i = E\{(y_i - y_G)\phi_H + (z_i - z_G)\phi_V\} \tag{1}$$

where E is Young's modulus, y_G and z_G the centroid coordinates, and ϕ_H and ϕ_V the horizontal and vertical curvatures, respectively. y_G and z_G are given by

$$y_G = \frac{\sum_{i=1}^{N} y_i D_i A_i}{\sum_{i=1}^{N} D_i A_i} \tag{2}$$

$$z_G = \frac{\sum_{i=1}^{N} z_i D_i A_i}{\sum_{i=1}^{N} D_i A_i} \tag{3}$$

where D_i, A_i, and (y_i, z_i) are the tangential stiffness obtained as a slope of the average stress-average strain curve, cross-sectional area and the coordinates of the centroid of individual elements, respectively.

For the case of an asymmetrically-damaged cross-section, Eqs. 4 through 8 are used, and for the intact one, the expressions are given in Eqs. 9 and 10. The biaxial moment and curvature relationship is given in the form

$$\begin{Bmatrix} M_H \\ M_V \end{Bmatrix} = \begin{bmatrix} EI_{HH} & EI_{HV} \\ EI_{VH} & EI_{VV} \end{bmatrix} \begin{Bmatrix} \phi_H \\ \phi_V \end{Bmatrix} \tag{4}$$

where

$$\begin{aligned} I_{HV} = I_{VH} &= \sum_{i=1}^{N} (y_i - y_G)(z_i - z_G)A_i, \\ I_{HH} &= \sum_{i=1}^{N} (y_i - y_G)^2 A_i, \\ I_{VV} &= \sum_{i=1}^{N} (z_i - z_G)^2 A_i \end{aligned} \tag{5}$$

where I and M are the moment of inertia and bending moment, respectively. When the vertical bending moment M_V is applied to the cross-section with no constraint on the horizontal curvature (Case 1), the horizontal curvature as well as the vertical curvature is induced under the condition of horizontal bending moment $M_H = 0$. The incremental equation to be solved is

$$\begin{Bmatrix} 0 \\ M_V \end{Bmatrix} = \begin{bmatrix} EI_{HH} & EI_{HV} \\ EI_{VH} & EI_{VV} \end{bmatrix} \begin{Bmatrix} \phi_H \\ \phi_V \end{Bmatrix} \tag{6}$$

Therefore,

$$\begin{Bmatrix} \phi_H \\ \phi_V \end{Bmatrix} = \frac{1}{E(I_{HH}I_{VV} - I_{HV}^2)} \begin{Bmatrix} -I_{HV}M_V \\ I_{HH}M_V \end{Bmatrix} \tag{7}$$

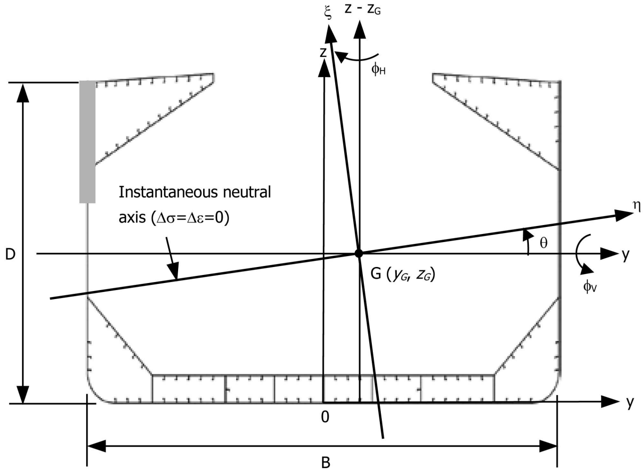


Fig. 1 Neutral axes of the elastic hull girder cross-section with asymmetric damage

Substituting Eq. 7 to Eq. 1, the bending stress σ_i is given by

$$\sigma_i = \frac{-(y_i - y_G)I_{HV} + (z_i - z_G)I_{HH}}{I_{HH}I_{VV} - I_{HV}^2} M_V \tag{8}$$

The terms including the moment of inertia, I_{HV}, represent the effect of the rotation of the neutral axis.

On the other hand, when the vertical bending moment is applied to the cross-section with the horizontal curvature constrained (Case 2), the bending moment is induced under the condition of $\phi_H = 0$, that is,

$$\begin{Bmatrix} M_H \\ M_V \end{Bmatrix} = \begin{bmatrix} EI_{HH} & EI_{HV} \\ EI_{VH} & EI_{VV} \end{bmatrix} \begin{Bmatrix} 0 \\ \phi_V \end{Bmatrix} \tag{9}$$

Therefore,

$$\phi_V = \frac{M_V}{EI_{VV}} \tag{10}$$

Substituting Eq. 10 to Eq. 1, the bending stress σ_i is given by

$$\sigma_i = \frac{z_i - z_G}{I_{VV}} M_V \tag{11}$$

Here, it is assumed that the residual hull girder strength in the sagging condition M_V^u is attained when a critical member at the location of (y_C, z_C) reached its ultimate strength, σ_C^u, namely for Case 1:

$$M_V^u \Big|_{\text{CASE 1}} = \frac{I_{HH}I_{VV} - I_{HH}^2}{-(y_C - y_G)I_{HV} + (z_C - z_G)I_{HH}} \sigma_C^u \tag{12}$$

And for Case 2:

$$M_V^u \Big|_{\text{CASE 2}} = \frac{I_{VV}}{z_C - z_G} \sigma_C^u \tag{13}$$

Therefore, the reduction rate of the residual strength due to the rotation of the neutral axis in the framework of the proposed approximate approach is given by ratio of Eq. 12 to Eq. 13 as

$$\frac{M_V^u|_{\text{CASE 1}}}{M_V^u|_{\text{CASE 2}}} = \frac{I_{HH}I_{VV} - I_{HH}^2}{-(y_C - y_G)I_{HV} + (z_C - z_G)I_{HH}} \frac{z_C - z_G}{I_{VV}} \tag{14}$$

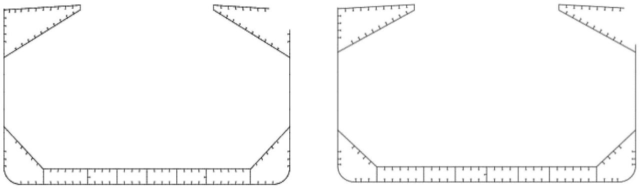
Ship	B1	B2	T2
L (mm)	217,000	219,000	234,000
B (mm)	32,236	32,240	44,000
D (mm)	18,300	19,900	21,200
Design criteria	Pre-IACS UR	IACS CSR-B	IACS CSR-T

Table 1 Subject ships

CASE STUDY

Two single-hull bulk carriers, B1 and B2, and one double-hull oil tanker, T2, are taken as the subject ships as shown in Table 1. Ship B1 is designed according to the International Association of Classification Studies (IACS) Pre-UR (Unified Requirements) rule and built in 1987 and Ship B2 according to Common Structural Rules for Bulk Carriers (CSR-BC), having larger cross-section and scantling sizes. Ship T2 is designed according to Common Structural Rules for Oil Tankers (CSR-OT).

The damage of the upper part of side shell due to collision is assumed. The vertical damage extent is taken as 10%, 20%, 40% and 70% of the depth D for both bulk carriers and tanker. The horizontal damage extent is taken as B/16, and it is kept constant for all damaged cases. The damaged cross-sections of Ship B1 are illustrated in Fig. 2 and those of Ship T2 in Fig. 3. The stiffness of the elements in the damaged area is completely removed. For the double-hull tanker, only outer side shell is assumed to be damaged. The locations of the critical deck element are presented in Fig. 4 for single-hull bulk carrier and double-hull oil tanker, respectively.


(a) 10% damage (b) 20% damage

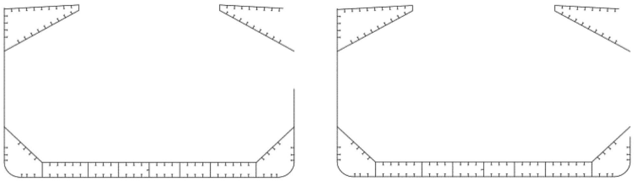
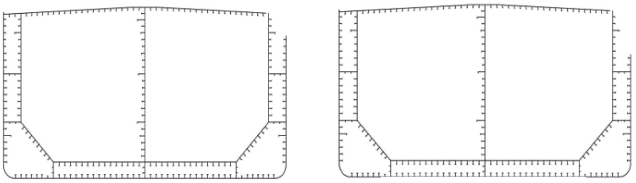

(c) 40% damage (d) 70% damage

Fig. 2 Single-hull bulk carrier (Ship B1)


(a) 10% damage (b) 20% damage

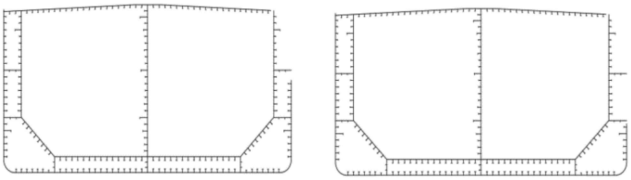
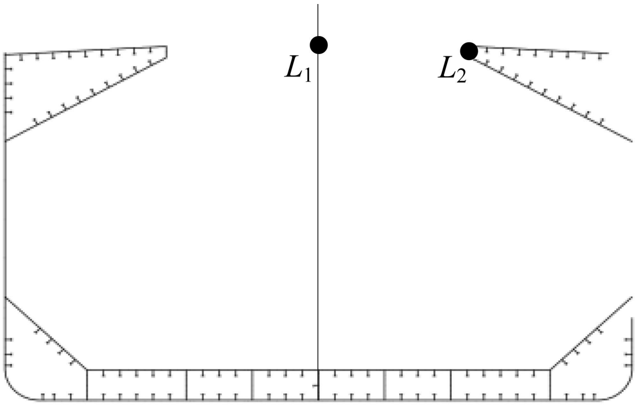
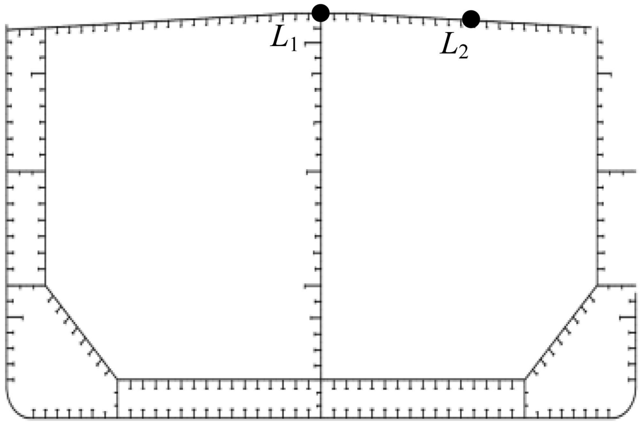

(c) 40% damage (d) 70% damage

Fig. 3 Double-hull oil tanker (Ship T2)



(a) Single-hull bulk carrier



(b) Double-hull oil tanker

Fig. 4 Locations of the critical deck elements

The investigation of the residual hull girder strength under sagging condition is performed by taking two locations of the critical deck elements as shown in Fig. 4. For single-hull bulk carriers (B1 and B2), the locations of the critical element are L_1 and L_2. L_1 is located at the center line and L_2 at the hatch coaming on the damage side. For the case of double-hull oil tanker (T2), L_1 is located at the center line and L_2 at the distance of $B/4$ from the damaged side shell. As for the critical stress, the maximum stress of elements located at points L_1 and/or L is used.

RESULTS AND DISCUSSION

In sagging condition, it is well recognized that the ultimate hull girder strength is almost attained when the primary deck members in longitudinal compression reached their ultimate strength. Because the damage takes place at the asymmetric position, i.e., collision damage is placed at the side shell through to the deck part ($B/16$) and there is no damage located at the bottom part, it is very important to investigate the critical member under sagging condition. In the present study, the ultimate strength is analyzed after damage has taken place. The water ingress is not considered in the analysis.

The results obtained by progressive collapse analysis under sagging condition for 20% and 70% damage are presented in Fig. 5 and Fig. 6, respectively. Case 1 considers the rotation of neutral axis and Case 2 does not. The resultant of bending moment versus curvature is plotted.

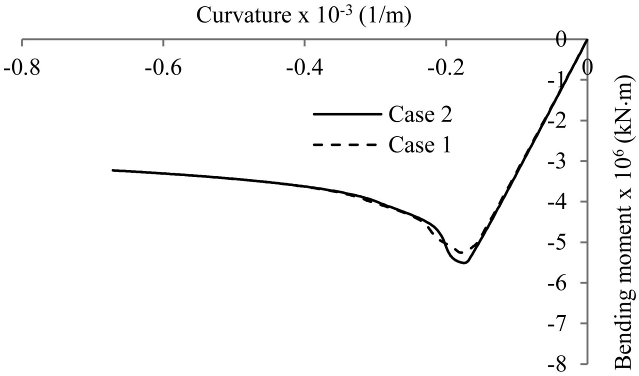


Fig. 5 Single-hull bulk carrier (Ship B1) with 20% damage

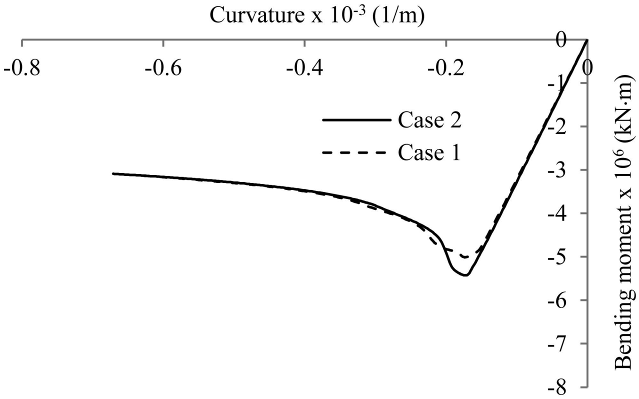


Fig. 6 Single-hull bulk carrier (Ship B1) with 70% damage

Similarly, the resultant bending moment and curvature curve for Ship B2 and Ship T2 with 20% and 70% damage are presented in Figs. 7 through 10.

Figures 7 and 8 show the results of the moment-curvature relationship obtained by progressive collapse analysis for single-hull bulk carrier (B2). It is found that Case 2 generally gives higher ultimate strength than Case 1 because the horizontal curvature is constrained. The ultimate hull girder strength is attained even when the horizontal curvature is constrained because of the horizontal bending moment induced by the incremental equation for horizontal and vertical bending moments, causing the ultimate hull girder strength to increase. The effect of constraint is the largest in Ship B1, and is smaller in Ship B2. For Ship B1, Case 1's strength is 7.3% smaller than Case 2's in the sagging condition. The difference between Ship B1 and Ship B2 may be attributed to that of the depth-to-breadth ratio, member scantlings, etc. Figures 9 and 10 represent the moment-curvature relationship under the sagging condition for a double-hull oil tanker (T2) for 20% and 70% of damages, respectively. According to the result obtained by progressive collapse analysis of a double-hull oil tanker (Ship T2), the effect of rotation of the neutral axis on the ultimate longitudinal bending strength is small when only the outer side shell is damaged.

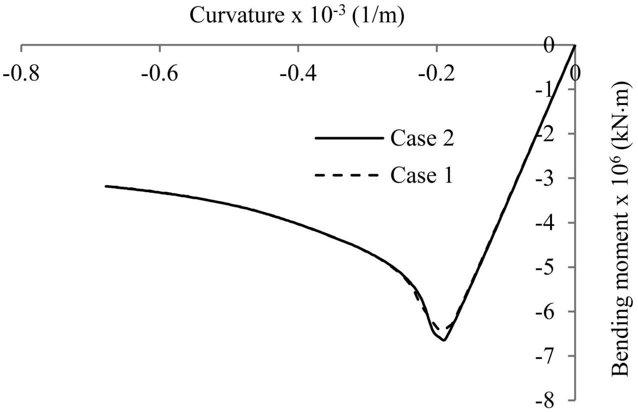


Fig. 7 Single-hull bulk carrier (Ship B2) with 20% damage

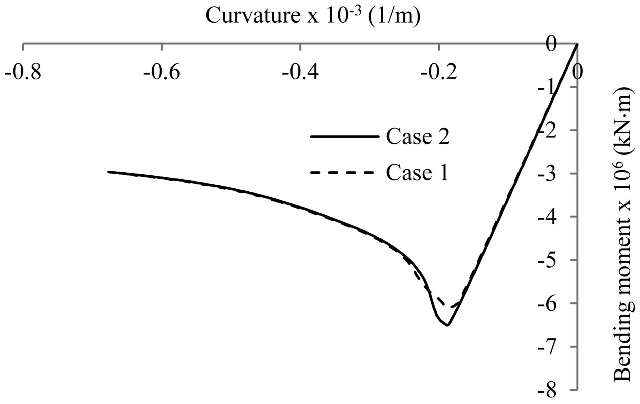


Fig. 8 Single-hull bulk carrier (Ship B2) with 70% damage

The residual strengths of Ships B1, B2, and T2 obtained for the four different damage extents are summarized in Figs. 11 and 12. It is found that Eq. 11 gives an estimate of the residual strength that is in good agreement with the result of the progressive col-

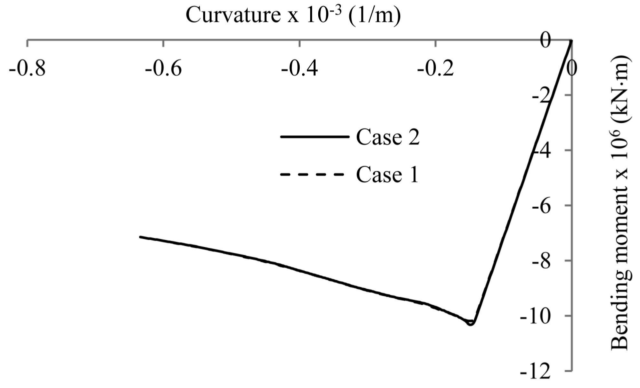


Fig. 9 Double-hull oil tanker (Ship T2) with 20% damage

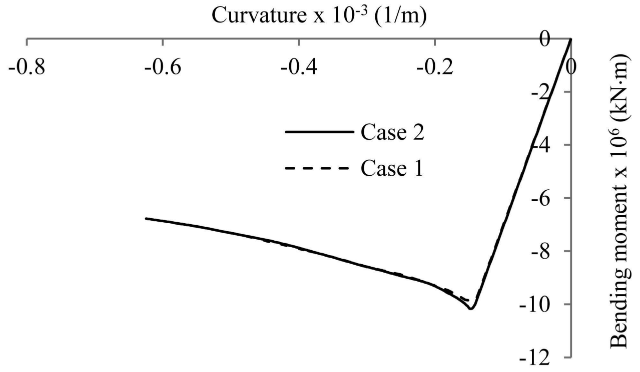
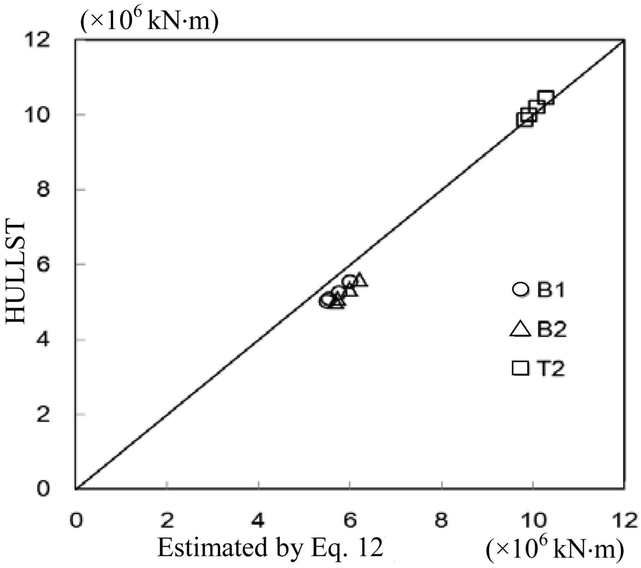
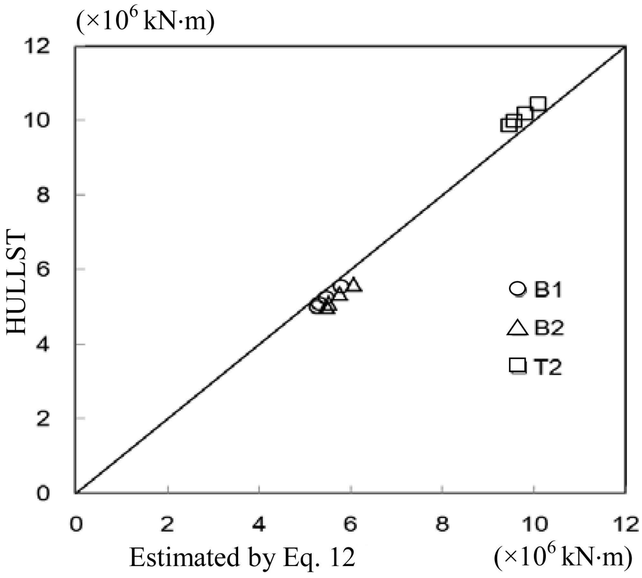


Fig. 10 Double-hull oil tanker (T2) with 70% damage

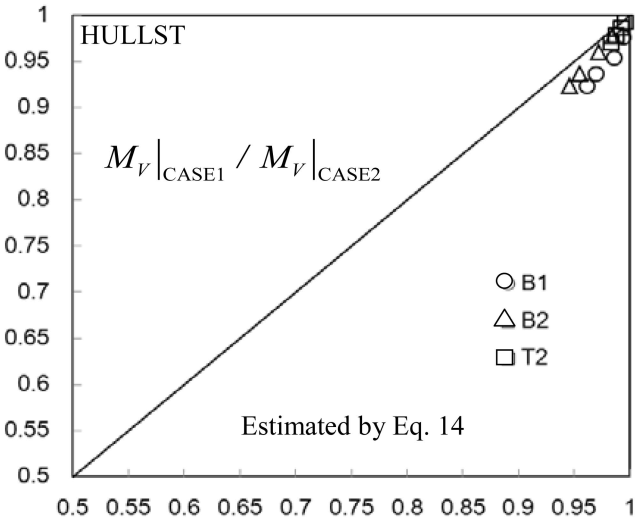


(a) Location L_1

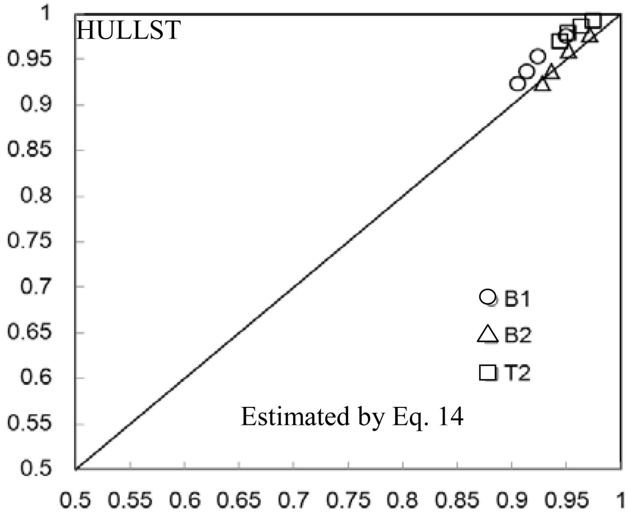


(b) Location L_2

Fig. 11 Comparison of residual hull girder strength M_V between the simplified method and the progressive collapse analysis



(a) Location L_1



(b) Location L_2

Fig. 12 Comparison of reduction ratio of residual hull girder due to rotation of neutral axis between the simplified method and the progressive collapse analysis (Case 1/Case 2)

lapse analysis. For bulk carriers, the critical element at the location L_2 gives a better estimate of the residual strength. For the location L_1 bulk carriers, the ultimate strength of critical element is evaluated by using that of the element at L_2. This is consistent with the observed collapse behavior in which the ultimate strength was attained when topside tank region of the damaged side almost fully failed. In the case of a double-hull tanker, location L_1 gives a better estimate of the residual strength than L_2. This is also consistent with the failure behavior of T2 in which the ultimate strength was attained when the deck part almost fully failed.

CONCLUSIONS

Progressive collapse analysis was performed on two single-hull bulk carriers and a double-hull oil tanker with asymmetrically damaged cross-section. Closed-form formulae of residual strength and that of the reduction ratio of the residual strength considering the rotation of neutral axis are proposed. It is found through a comparison with the results obtained by the progressive collapse analysis that the residual hull girder strength of asymmetrically damaged ships under the sagging bending moment can be predicted by the proposed formulae with reasonable accuracy. The ultimate strength obtained with the horizontal curvature constrained is larger than that without constraint. The effect of the rotation of the neutral axis is the largest for single-hull bulk carrier and almost negligible for the double-hull oil tanker. The difference characteristic for two single-hull bulk carriers may be related to that of the depth-to-breadth ratio, member scantlings, etc.

The resultant of bending moment is induced by the accumulation of the horizontal and vertical bending moments based on the reference coordinate system. Figure 12 shows the comparison of the reduction rates of the residual strength due to rotation of the neutral axis obtained by Eq. 14 and progressive collapse analysis. The influence of the rotation of the neutral axis is larger for a larger damage extent in general. For the case of the subject ships and damages under consideration, the influence is larger in bulk carriers than in tankers. Equation 14 gives a relatively good estimate of the reduction rate. It can be a good basis of a rational expression of the influence of the rotation of the neutral axis on the reserve ultimate hull girder strength, as required in ship structures. More systematic analyses are definitely needed to develop the formula having a larger applicability in ship types and damaged cases.

According to the result obtained by progressive collapse analysis of double-hull oil tanker, the effect of rotation of neutral axis on the ultimate longitudinal bending strength is small when only the outer side shell is damaged.

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