The Assessment of the Ultimate Hull Girder Strength of Ro-Ro Ship after Damages

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Abstract. Many accidents of Ro-Ro ships happen in Indonesia such as collision and grounding. When the collision or grounding takes place on the Ro-Ro ship, the ultimate strength of hull structure after damage becomes decrease. Car and passenger decks are critical location since collision and/or grounding occur. In the present study, the assessment of the ultimate hull girder strength is conducted. The cross section of Ro-Ro ship is taken to be analyzed. The collision and grounding damages are assumed to be placed on the side and bottom area, respectively. The damages are created by removing the elements from the side shell and bottom part. Finally, the result obtained is compared with one another.

1. Introduction

Collision or grounding damages may occur on the hull so that the safety of ship and environment would be threatened. Many accidents takes place in Indonesia especially for Ro-Ro ship. In spite of human error, the structural degradation after collision and grounding damages gives impact to the ultimate strength of ship’s hull. This must be stated in the local regulation.

The analysis of the ultimate hull girder strength has been assessed by some researchers particularly for damage cases. Paik [1] 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 damages. Muis Alie [2] presented an incremental formulation of the progressive bending collapse behavior of ship hull girder with damages based on the Smith’s method taking the rotation of the neutral axis into account. The proposed method was applied to the residual strength analysis of bulk carrier and tanker having the collision damage at the side structure. Soares [3] evaluated the ability of simplified structural analysis methods based on the smith’s formulation to predict the ultimate strength of damage ship’s hull. Ohtsubo [4] showed the experimental and numerical work on the ship structural damages due to collision and grounding. This is one of the first attempts to apply explicit finite element method codes such as LS DYNA and DYTRAN to the collision and grounding problems of ships. Muis Alie [5] investigated the influence of superstructure on the longitudinal ultimate strength of a Ro-Ro ship. To investigate the ultimate strength, the Smith’s method was adopted and implemented into the thin-walled beam. The cross section of Ro-Ro ship was taken to be analyzed. Muis Alie [6] analyzed the hull girder ultimate strength of asymmetrically damaged ships using Finite Element Method. The collision damage was modeled by removing the plate and stiffened plate element. The result obtained by FE analysis was compared to the analytical solution and the progressive collapse behavior of ship’s hull was presented. Also, the progressive collapse analysis of ship hull girder based on Smith’s method was developed by [7]. The previous studies showed that the ultimate strength of ship
hull girder was very essential particularly for the assessment of the ultimate strength after damage. The assessment of the ultimate strength must be clear in the local regulation especially for Ro-Ro ship.

In the present study, the assessment of the ultimate hull girder strength is performed. The cross section of Ro-Ro ship is taken and it is quite new to be analyzed for the ultimate strength assessment due to damages in Indonesia. The collision and grounding damages are assumed to be placed in the side shell and bottom area, respectively. The damages are created by removing the element from the side shell and bottom part. The result obtained by analytical formulation both hogging and sagging condition for intact and damages are compared with one another.

2. Analytical Solution

The previous study only consider the collision damage of bulk carrier and tanker taking the rotation of the neutral axis into account (Muis Alie, M.Z. et al 2012) [2]. In the present study, the influence of the rotation of the neutral axis is not considered. The ultimate hull girder strength of Ro-Ro ship is analyzed with collision and grounding damages. It should be noticed that since the collision or grounding takes place at asymmetric position, the assumption of the cross section remained plane may be applied, the axial strain $\varepsilon_i(y, z_i)$ at the $i$-th structural element caused by the horizontal curvature $\phi_H$ and vertical curvature $\phi_V$ can be expressed as

$$\varepsilon_i(y, z_i) = \varepsilon_0 + y\phi_H + z_i\phi_V$$

(1)

where $\varepsilon_0$ is the axial strain at the origin of the bottom keel and the axial stress $\sigma_i$ corresponding to the axial strain $\varepsilon_i$ is given by the average stress-average strain relationship calculated for the individual elements as illustrated in Fig. 1.

To obtain the ultimate strength both hogging and sagging condition, the equilibrium condition must be required, i.e. that the stress where the on neutral axis position is zero and it is a function of the strain. In this regard, the relationship is generally a nonlinear function by considering buckling and yielding and it is expressed as

$$\sigma_i = f_i(\varepsilon)$$

(2)

![Fig.1 Average stress-average strain relationship of a structural element](image)

Where $f_i(\varepsilon) = 0$ and integrating the axial stresses to all the intact part of cross section, the axial force $P$, the vertical bending moment $M_V$, and the horizontal bending moment $M_H$ can be obtained as

$$P = \sum_{i=1}^{N} \sigma_i A_i = 0$$

(3)

$$M_H = \sum_{i=1}^{N} \sigma_i y_i A_i$$

(4)
where \( N \) is the number of intact elements and \( A_i \) is a cross section of the \( i \)-th element.

\[
\Delta \sigma = D_i \Delta \varepsilon \quad \left( D_i = \frac{df}{d\varepsilon} \right) \tag{6}
\]

The relationship of axial force, horizontal and vertical bending moment can be given by

\[
\begin{bmatrix}
\Delta P \\
\Delta M_H \\
\Delta M_V
\end{bmatrix} =
\begin{bmatrix}
\bar{D}_{AA} & \bar{D}_{AH} & \bar{D}_{AV} \\
\bar{D}_{HA} & \bar{D}_{HH} & \bar{D}_{HV} \\
\bar{D}_{VA} & \bar{D}_{VH} & \bar{D}_{VV}
\end{bmatrix}
\begin{bmatrix}
\Delta \varepsilon_0 \\
\Delta \phi_H \\
\Delta \phi_V
\end{bmatrix} \tag{7}
\]

Where

\[
\begin{align*}
\bar{D}_{AA} &= \sum_{i=1}^{N} D_i A_i \\
\bar{D}_{AH} &= \bar{D}_{HA} \\
\bar{D}_{AV} &= \bar{D}_{VA} \\
\bar{D}_{HH} &= \sum_{i=1}^{N} D_i \Delta \varepsilon_i \\
\bar{D}_{HV} &= \sum_{i=1}^{N} D_i \Delta \phi_H \\
\bar{D}_{VV} &= \sum_{i=1}^{N} D_i \Delta \phi_V
\end{align*}
\tag{8}
\]

The stiffness equation, Eq. 8, can be simplified with respect to the variables defined for the instantaneous neutral axes as described in the following.

The expression of the axial force increment \( \Delta P \) of Eq. 8 can be rearranged in the form

\[
\Delta P = \sum_{i=1}^{N} D_i \Delta \varepsilon_i + \bar{D}_{AA} \Delta \varepsilon_0 + \bar{D}_{AH} \Delta \phi_H + \bar{D}_{AV} \Delta \phi_V
\]

\[
= \sum_{i=1}^{N} D_i \left( \Delta \varepsilon_i + \left( y_i - y_G \right) \Delta \phi_H + \left( z_i - z_G \right) \Delta \phi_V \right) A_i
\tag{9}
\]

where

\[
\Delta \varepsilon_0 = \Delta \varepsilon_0 + y_G \Delta \phi_H + z_G \Delta \phi_V
\tag{10}
\]

\( y \) and \( z \) are the coordinates and \( \Delta \varepsilon_0 \) is the axial strain increment at the neutral axis plane caused by \( y \) and \( z \). In this regard, \( y_G \) and \( z_G \) are given by

\[
y_G = \frac{\sum_{i=1}^{N} y_i D_i A_i}{\sum_{i=1}^{N} D_i A_i} \tag{11}
\]

\[
z_G = \frac{\sum_{i=1}^{N} z_i D_i A_i}{\sum_{i=1}^{N} D_i A_i} \tag{12}
\]

And Eq. 9 can be simplified as

\[
\Delta P = \left( \sum_{i=1}^{N} D_i A_i \right) \Delta \varepsilon_G
\tag{13}
\]

Eq. 13, when \( \Delta P = 0 \), there is no axial strain at the neutral axis is produced for any combination of horizontal and vertical curvature increments. Therefore, the relationship becomes
\[
\begin{align*}
\begin{bmatrix}
\Delta P = 0 \\
\Delta M_H \\
\Delta M_V
\end{bmatrix} &=
\begin{bmatrix}
D_{AA} & 0 & 0 \\
0 & D_{HH} & D_{HV} \\
0 & D_{HV} & D_{VV}
\end{bmatrix}
\begin{bmatrix}
\Delta \delta_G \\
\Delta \phi_H \\
\Delta \phi_V
\end{bmatrix} \\
&= 
\begin{bmatrix}
D_{AA} & 0 & 0 \\
0 & D_{HH} & D_{HV} \\
0 & D_{HV} & D_{VV}
\end{bmatrix}
\begin{bmatrix}
\Delta \delta_G \\
\Delta \phi_H \\
\Delta \phi_V
\end{bmatrix}
\end{align*}
\]

(14)

Where

\[
D_{AA} = \sum_{i=1}^{N} D_{i} A_i, \quad D_{HH} = \sum_{i=1}^{N} D_{i} (y_i - y_G) (z_i - z_G) A_i,
\]

\[
D_{HV} = \sum_{i=1}^{N} D_{i} (y_i - y_G) (z_i - z_G) A_i, \quad D_{VV} = \sum_{i=1}^{N} D_{i} (z_i - z_G)^2 A_i
\]

(15)

Using the coefficients of Eq. (15), the relationship of the bending moments and curvatures can be given by

\[
\begin{align*}
\begin{bmatrix}
\Delta M_H \\
\Delta M_V
\end{bmatrix} &=
\begin{bmatrix}
D_{HH} & D_{HV} \\
D_{HV} & D_{VV}
\end{bmatrix}
\begin{bmatrix}
\Delta \phi_H \\
\Delta \phi_V
\end{bmatrix}
\end{align*}
\]

(16)

3. Methodology
The ultimate strength analysis of ship hull girder with collision and grounding damages are performed using analytical formulation. The cross section of Ro-Ro ship is taken to be analyzed. The breadth of ship is 15000 mm and the depth is 10693 mm. The longitudinal direction is represented as one-frame space which has 550 mm in length. The boundary condition is assumed to be simply supported at both sides of the cross section as shown in Fig. 2. The element subdivision consists of plate and stiffener element for Ro-Ro ship is illustrated in Fig. 3.

Fig. 2 Boundary condition

Fig. 3 Element subdivision on Ro-Ro ship
The collision and grounding damages are placed to be located at the side shell and bottom part area, respectively. The collision represented by vertical damage extent and grounding represented by horizontal damage extent. The vertical damage extent is taken as the percentage of ship’s depth, while for horizontal represented by ship’s breadth. Both collision and grounding damages consider two cases; those are 50% and 70%. Additional damage extent is also applied when collision takes place at deck part, that is B/16, and it is constant for 50% and 70% damages. The collision and grounding damages are illustrated in Fig. 4 and Fig. 5.

4. Results and Discussion

The ultimate hull girder strength analysis of Ro-Ro ship is performed using the Smith method implemented into the program code HULLST developed by Yao and Nikolov (1992). Fig. 6 and Fig. 7 show the comparison of the ultimate strength in hogging and sagging condition for 70% and 50% damages between collision and grounding.

Fig. 6 Comparison of ultimate strength for 70% damages
Fig. 7 Comparison of ultimate strength for 50% damages
Table 1 Ultimate strength in hogging

| Damages (m) | Moment (kNm) |
|-------------|--------------|
|             | Collision    | Grounding   |
| 50%         | 6.10         | 6.47        |
| 70%         | 6.05         | 6.42        |

Table 2 Ultimate strength in sagging

| Damages | Moment (kNm) |
|---------|--------------|
|         | Collision    | Grounding   |
| 50%     | 4.10         | 4.22        |
| 70%     | 4.04         | 4.18        |

Fig. 8 Comparison of ultimate strength for collision damages
Fig. 9 Comparison of ultimate strength for grounding damages

The result of the ultimate hull girder strength obtained in Fig. 6 and Fig. 7 are summarized in Table 1 for hogging and Table 2 for sagging conditions. According to Table 1 that the ultimate bending moment capacity of the hull girder in hogging condition for collision and grounding are decreased from 50% to 70% damages. This result is also as expected when compared to Table 2, where the ultimate bending moment capacity of the hull girder in sagging condition reduced due to damage extension from 50% to 70%.

Fig. 8 and Fig. 9 express the comparison of the ultimate strength for collision and grounding damages in hogging and sagging condition. The different of the ultimate bending moment capacity for collision and grounding damages from 50% to 70% is 0.05 or 5% in hogging condition. While, the different of the ultimate bending moment capacity for collision damage from 50% to 70% is 0.06 or 6% and grounding damage from 50% to 70% is 0.04 or 4% in sagging condition. The influence of rotation of neutral axis when the collision or grounding damage is considered is not significant. This may be due to the Ro-Ro ship consists of several decks like main, car, passenger and bridge decks.

This may be also caused by the neutral axis still below the car deck and the maximum collision damage (70%) is still above the car deck. But the different of the ultimate bending moment capacity takes place when it is compared for the damage percentage of ship dimension, according to Fig. 6 and Fig. 9, especially in hogging condition. Probably, this behaviour is influenced by the structural component on the bottom and deck part of Ro-Ro ship, where the cross sectional area is quite different between deck and bottom part measured from the neutral axis up to deck and bottom area. It is observed that the deck part consists of many stiffened plate like car, passenger and bridge deck. On the other hand, plate is only found on the bottom part.
Fig. 10 Stress distribution in hogging condition for 70% collision damage

Fig. 11 Stress distribution in sagging condition for 70% collision damage

Fig. 12 Stress distribution in hogging condition for 70% grounding damage
Fig. 10-13 shows the stress distribution in hogging and sagging condition for 70% collision and grounding damages. The red colour (triangle) indicates collapse elements in tension. The blue one (blue colour) illustrates collapse elements in compression. It is observed that the influence of the rotation of the neutral axis is not significant toward the ultimate strength. It is clear from the stress distribution for the maximum damage (70%).

The stress distribution in hogging condition for 70% collision damage is different compared to grounding one. Yielding (red color) distributed to all members above the neutral axis for grounding with 70% damage. While, for the collision with 70% damage, yielding spreads only on the intact part of side shell, car, passenger and bridge decks. Buckling fully takes place on the bottom part in hogging condition for 70% collision damages. For 70% grounding damage, buckling is not fully distributed on the bottom part.

For sagging condition, buckling fully occurs at both side shell including passenger and bridge decks with 70% grounding damage. But yielding is not fully spread on bottom area. In case of 70% collision damage, buckling is not totally distributed on the member components, but yielding spreads on bottom area.

5. Conclusion
The ultimate hull girder strength analysis of Ro-Ro ship after collision and grounding damages have been performed based on Smith's method. The following conclusions are; the effect of the rotation of neutral axis on the ultimate bending moment capacity of hull girder is not significant. This may be due to the Ro-Ro ship consists of several decks such as car, passenger and bridge decks. But the different ultimate bending moment capacity takes place when it is compared for the damage percentage of ship dimension.

6. References
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