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A new method for assessing the safety of ships damaged by collisions

Samy A. M. Youssef[a*], Sung Hwan Noh[b] and Jeom Kee Paik[bc]

[a]*Marine Engineering Technology Department, Arab Academy for Science, Technology and Maritime Transport, Alexandria 1029, Egypt*

[b] *The Korea Ship and Offshore Research Institute (The Lloyd's Register Foundation Research Centre of Excellence); Department of Naval Architecture and Ocean Engineering, Pusan National University, Busan 46241, Korea*

[c] *Department of Mechanical Engineering, University College London, London WC1E 7JE, UK*

The longitudinal strength of a ship decreases with the reduction in its bending moment capacity following a collision accident. This decrease may lead to the total loss of the ship in some cases due to its loss of hull girder strength, particularly when large vessels are involved. Therefore, the damaged ship should be able to reach the closest harbour safely without any catastrophic hull girder collapse. This paper aims to develop a method to predict the hull girder residual strength of double-hull oil tankers by considering probabilistic collision damage scenarios. The collision damage index is defined as the reduction ratio of the vertical hull girder moment of inertia, and the residual strength index is characterised as the reduction ratio of the hull girder ultimate bending moment. Four different as-built double-hull oil tankers (Panamax, Aframax, Suezmax and VLCC) were studied to demonstrate the proposed method and to formulate the collision damage index. The relationships between the residual strength index and the collision damage index are identified in the form of diagrams and linear-type regressions. The produced diagrams and regressions represent a first-cut assessment of a ship's safety immediately after taking collision damage.

Keywords: Double hull oil tankers, probabilistic collision damages, intelligent supersize finite element method, residual longitudinal strength, collision damage index.

[*]Corresponding author. Tel.: +201275410420
(E-mail address: samyoussef@aast.edu Samy Youssef).

1. Introduction

As reported in the available accident statistics [1-3], collisions and grounding have become major hazards that increase environmental pollution as both the size and the number of sailing ships grow. Ship hulls damaged by collisions or grounding may collapse if the residual ultimate hull girder strength is less than the applied hull girder loads. This collapse is catastrophic because such a hull girder collapse accident usually leads to sinking. This can occur not only directly after the accident, but also during salvage operations or while the ship is being towed to the nearest repair yard. Hull girder collapse is also of primary concern in association with massive oil spills that can cause environmental pollution if a large oil tanker is involved. Therefore, the assessment and management of a ship's hull collapse after collision or grounding damage is of great importance in association with the safety of ships.

For relevant decision-making associated with following safety measures in collisions or grounding, it is necessary to rapidly assess the residual hull girder strength immediately after the accident. A number of useful studies have been undertaken. Studies of ship collision mechanics have included structural damage prediction, energy absorption capability and hull girder strength [4-16].Concerning innovative methods to assess the structural safety and the risk of hull girder collapse of ships that suffer collision accidents, Paik et al. [17] developed a method for rapid assessment of the possibility of hull collapse following collision and grounding accidents via closed-form formulae of the ultimate hull girder strength and section modulus after damage. Following a similar approach, Wang et al. [18] provided simple equations to correlate residual strength with the extent of damage without performing detailed calculations. Saydam and Frangopol [19] presented a framework for performance assessment of ship hulls that considers grounding and collision accidents as sudden damage. They assessed the longitudinal bending moment capacities of intact and damaged ship hulls based on an optimisation-based version of the incremental curvature method.

Paik et al. [20] developed a new concept which enables to rapidly assess the safety of structures involving in-service damage or accidental damage, where the relationship between the residual strength index versus the premised damage index is established in advance. A limited number of probable scenarios for the target damage event is selected using a sampling technique in which the random variables that affect the damage are probabilistically characterised. A damage index for the corresponding event scenario is defined as a function of the corresponding damage characteristics. The residual strength performance of a structure with the corresponding event scenario is calculated with analytical, numerical or experimental methods. Based on the identification of damages for each of the selected event scenarios, a diagram relating the residual strength performance to the damage index (abbreviated as the R-D diagram) is established. This diagram is very useful for a first-cut assessment of a structure's safety immediately after it has suffered damage. The diagram can also be used to determine acceptance criteria for a structure's safety against damage. An applied example was shown to demonstrate the applicability of the method in terms of the development of a diagram between the ultimate longitudinal strength versus the grounding damage index for four types of double-hull oil tankers (VLCC, Suezmax, Aframax and Panamax) damaged by grounding.

Kim et al. [21] applied the method of Paik et al. [20] for the safety of container ships damaged by grounding, confirming that the concept of Paik et al. [20] is useful. Following risk-based design framework,Youssef et al. [22] introduced a method for assessing the risk of ship hull collapse following collision damage. Using an efficient probabilistic approach, the amount and location of collision damage for selected individual collision scenarios were characterised using a nonlinear finite element method to calculate the ultimate hull girder strength of a hypothetical Suezmax-class double-hull oil tanker.Faisal et al. [23] applied the method of Paik et al. [20] to assess the hull girder bending capacity of ships damaged in collisions by formulating probability density functions that can be used to estimate sets of residual strength indices for damaged double-hull oil tankers in less complicated simulation process and in a shorter time frame.

The aim of this study is to apply the method of Paik et al. [20] to the safety assessment of ships damaged by collision accidents. A set of credible collision damage scenarios are selected by a sampling technique in association with probabilistic characteristics of random variables to represent the ship's impact damage after the collision. The collision damage is then characterised as a form of the collision damage index (CDI). The residual ultimate hull girder strength of ships for each of the collision damage scenarios is computed with the ALPS/HULL program [24] intelligent super-size finite element method [25]. Four types of double-hull oil tankers – VLCC, Suezmax, Aframax and Panamax – are studied to develop a diagram relating the residual hull girder strength performance (i.e., the RSI) to the CDI. The developed diagrams are abbreviated as the RSI-CDI diagram. The use of the developed diagram is presented in terms of rapid assessment of hull girder collapse immediately after the collision accident and the design criteria of ship safety against collisions.

2. Procedure of development of diagrams for RSI versus CDI

The general procedure of development of RSI-CDI diagrams is shown in Figure 1 and consists of three phases: target structure identification, collision damage identification and residual strength calculation. As the first phase, the target ship's structural characteristics, including its principal dimensions, martial properties and scantlings, should first be defined. Intact cross-sections of the candidate structures can then be modelled by considering the previously mentioned characteristics.

Before moving to the second phase, it should be noted that the nature of ship collision impact damage is unclear and involves a variety of influencing parameters that are naturally probabilistic. Therefore, a probabilistic method is used in the first phase to identify more realistic collision damage by considering samples of all possible scenarios based on sets of historical data. The method used to identify the collision damage scenarios was inspired by the innovative method of Paik [20], as discussed in the first section. Each scenario is then defined by a set of influencing parameters of a ship's post-collision impact damage to be dealt with as random variables. The damage parameters are then identified on the basis of a gathered historical ship-ship collision accidental database, to be arranged and statistically analysed using the probabilistic approach, to ascertain the range of possible scenarios. The damage parameter data are then developed into probability density functions to extract sets of randomly selected damage scenarios using a sampling technique. This method is also explained in detail in the literature [23].

Once the collision damage scenarios are obtained, the damaged structures can be modelled. When a ship's structure is damaged in an accident, the damaged structural elements may not contribute to the global ship strength. The damaged elements should thus be eliminated from the strength calculations by removing them from the relevant part of the ship's cross-section. Accordingly, several CDIs to represent damage severity can be obtained in terms of reduction ratios of area, the ratio between the actual damage size and the depth of the ship, and the vertical location of the damage related to the depth of the ship. Moreover, CDI can also be defined in terms of the vertical moment of inertia reduction ratio, as indicated in Eq. (1) of the *i*th accidental scenario, where I_{I_i} and I_{D_i} are the vertical moment of inertia for intact and damaged hull cross sections, respectively.

$$CDI_{i} = \frac{I_{D\_i}}{I_{I\_i}} \quad (1)$$

Figure 1. Procedure for development of RSI-CDI diagrams.

The third phase aims to calculate the RSI for each scenario selected in the second phase. The ultimate longitudinal strength of the target ship's hull for the selected damage scenarios can be calculated with one of the methods discussed in the previous chapter. With the proposed method shown in Figure 1, the ALPS/HULL program [24] can be used for two issues: modelling and calculation of the ultimate longitudinal strength for both intact and damaged target ships' hull cross sections for each damage scenario. In this method, the reduction in the strength capacity of the damaged ship's hull structure is presented in terms of the RSI, which is based on the ultimate longitudinal hull girder strength (i.e., the ultimate bending moment of the damaged hull is compared with that of the intact hull). Equation (2) defines the RSI for the damaged and intact cross sections of the *i*th accidental scenario, where M_{I_i} and M_{D_i} are the ultimate bending moments for the intact and damaged hull cross sections, respectively.

$$RSI_i = \frac{M_{D\_i}}{M_{I\_i}} \quad (2)$$

Once the CDI and the corresponding ultimate RSI are obtained for each of the selected collision scenarios, the RSI-CDI diagrams can be established.

3. Applied examples

3.1. Target structure identification

To demonstrate the applicability of the proposed method, four representative double-hull oil tanker mid-ship sections of different geometry and size – Panamax, Aframax, Suezmax and VLCC – are considered for establishment of the RSI-CDI diagrams. The principal particulars of the examined tanker structures are given in Table 1. The structural condition of the target tankers is as-built scantling (i.e., including corrosion margin values), considering no impairment in the structural thickness. The ALPS/HULL progressive hull girder collapse analysis program, based on the ISFEM, is applied to model the intact cross-sections of the candidate tankers.

Table 1.Principal particulars of target structures.

3.2. Collision damage identification

An investigation of the statistical characteristics of damaged double-hull oil tankers involved in ship-ship collisions performed by Faisal et al. [23] is used in this study. Faisal et al. [23] identified parameters to characterise collision damage scenarios: vertical impact location X_v / D, damage penetration X_b / B, 2D-striking ship's bulbous bow length and height parameters that can affect the damage pattern in the target struck vessels. This 2D-striking bow model's parameters have been defined in a geometric bow portion model introduced by Lützen [26] as a function of the ship's length and bow height.

Using a historical database of ship collision accidents gathered by Faisal et al. [23], each parameter was statistically analysed to estimate the probability of each scenario and to define its range and variability in terms of a histogram to be formulated by a certain probability density function. A sampling method was then used to randomly select 50 damaged ship scenarios, and each was defined as a function of the abovementioned post-collision damage parameters as listed in Table 2. More details of the statistical method can be found in detail [23].By applying the damaged elements removal method discussed in the previous chapter, the damaged cross-sections are modelled in the ALPS/HULL program.

Five damage parameters and reduction properties are considered: the ratio of the transverse extent of the damage to the ship's breadth, the ratio of the vertical extent of the damage to the ship's depth, the vertical impact location with regard to the ship's depth, the area reduction ratio and the vertical moment of inertia reduction ratio. All may be reliable damage indices to predict the residual ultimate strength. However, each is examined with the RSI obtained in the third phase to determine which is the most reliable.

Table 2.Selected post-collision damage scenarios.

3.3. Residual strength calculations

The hull girder ultimate bending capacity of the 50 damaged transverse cross-sections for each vessel type is calculated only by applying hogging and sagging vertical bending loads. For this purpose, 400 numerical simulations are performed using the ALPS/HULL program. The effects of the horizontal bending moment, lateral pressure, shear force and torsion loadings are neglected in this study [15, 19]. Figures 2 and 3 show samples of the analysis results in terms of von Mises stress distributions at the ultimate limit state for cross sections involved in major damaged scenarios, under pure hogging and sagging vertical bending moments, respectively. The moment-curvature curves for a VLCC cross-section in intact, minor and major damage scenarios are shown in Figure 4.

Figure 2. Samples of ALPS/HULL ultimate longitudinal strength predictions in terms of von Mises stress distributions for major damaged cross sections under hogging vertical bending moment. (a) Panamax. (b) Aframax. (c) Suezmax. (d) VLCC.

Figure 3. Samples of ALPS/HULL ultimate longitudinal strength predictions in terms of von Mises stress distributions for major damaged cross sections under sagging vertical bending moment. (a) Panamax. (b) Aframax. (c) Suezmax. (d) VLCC.

Figure 4. Moment-curvature relationships for intact and damage scenarios of VLCC class double-hull oil tanker.

According to the numerical simulation results, the residual hull girder ultimate strength is obtained for each damage case for comparison with the intact hull by applying Eq. (2). The considered CDIs, the ratio of the transverse extent of the damage to the ship’s breadth, the ratio of the vertical extent of the damage to the ship’s depth, the vertical impact location with regard to the ship depth, the area reduction ratio and the vertical moment of inertia reduction ratio are calculated and individually examined with the calculated RSIs. It is found that the reduction ratio of the ultimate strength for all cases studied in this example is best matched with the vertical moment of inertia reduction ratio. Accordingly, the CDI was finally decided to be the vertical moment of inertia reduction ratio (see Eq. (1)) which proved to be a decisive damage index to predict the residual ultimate strength (i.e., the RSI).

3.4. Development of RSI-CDI diagrams

After calculating the CDI and RSI for the 50 damaged transverse cross-sections considered in this study under hogging and sagging vertical loading directions, eight RSI-CDI diagrams are developed for the four double-hull oil tankers under hogging and sagging load directions. A linear regression is performed for each diagram to generate empirical formulations that present the RSI as a function of CDI as follows:

RSI for Panamax-class double-hull oil tanker:

$$RSI = -3.9889 + 9.0535\ CDI - 4.0689\ CDI^2 \qquad \text{in a hogging direction} \qquad (3)$$

$$RSI = 6.5886 - 12.7416\ CDI + 7.1519\ CDI^2 \qquad \text{in a sagging direction} \qquad (4)$$

RSI for Aframax-class double-hull oil tanker:

$$RSI = -0.8625 + 2.6489\ CDI - 0.7877\ CDI^2 \qquad \text{in a hogging direction} \qquad (5)$$

$$RSI = 1.1700 - 1.4924\ CDI + 1.3196\ CDI^2 \qquad \text{in a sagging direction} \qquad (6)$$

RSI for Suezmax-class double-hull oil tanker:

$$RSI = 1.1038 - 1.4070\ CDI + 1.3070\ CDI^2 \qquad \text{in a hogging direction} \qquad (7)$$

$$RSI = -0.4375 + 1.8388\ CDI - 0.4053\ CDI^2 \qquad \text{in a sagging direction} \qquad (8)$$

RSI for VLCC-class double-hull oil tanker:

$$\text{RSI} = 3.5925 - 6.5279\ \text{CDI} + 3.9385\ \text{CDI}^2 \qquad \text{in a hogging direction} \qquad (9)$$

$$\text{RSI} = -0.8874 + 2.5488\ \text{CDI} - 0.6653\ \text{CDI}^2 \qquad \text{in a sagging direction} \qquad (10)$$

Figures 5 and 6 show graphical presentations and the corresponding fitting equations of the developed RSI-CDI diagrams. In addition, the obtained RSI and CDI data are plotted in a single graph to generate a single formula that can represent all of the double-hull tanker classes considered in this study. The obtained general formulas are listed as follows:

$$\text{RSI} = -1.9537 + 5.1973\ \text{CDI} - 2.2463\ \text{CDI}^2 \qquad \text{in a hogging direction} \qquad (11)$$

$$\text{RSI} = -0.7479 + 2.3965\ \text{CDI} - 0.6526\ \text{CDI}^2 \qquad \text{in a sagging direction} \qquad (12)$$

Figure 7 shows the RSI-CDI diagrams plotted with data from four classes of double-hull oil tankers for hogging and sagging.

Figure 5. RSI-CDI diagrams for double-hull oil tankers under hogging vertical bending moment. (a) Panamax. (b) Aframax. (c) Suezmax. (d) VLCC.

Figure 6. RSI-CDI diagrams for double-hull oil tankers under sagging vertical bending moment. (a) Panamax. (b) Aframax. (c) Suezmax. (d) VLCC.

Figure 7. RSI-CDI diagrams for all double-hull oil tankers. (a) Hogging direction. (b) Sagging direction.

3.5. Usage of RSI-CDI diagrams

Generally, the developed RSI-CDI diagrams and the corresponding analytical formulations can be used as a rapid prediction tool of the residual ultimate longitudinal strength performance of a double-hull oil tanker to avoid a post-accident collapse immediately after the occurrence of a collision accident. Once the location and the amount of damage to the struck vessel structure is approximately known, the CDI will be known. Accordingly, the RSI can be determined with the developed diagrams in both hogging and sagging vertical bending moments, as shown in Figure 8 (dash-blue direction). In contrast, such diagrams can also be used to determine the upper limit of the CDI at certain acceptance criteria. For example, the international maritime organisation [27] recommended that the ultimate longitudinal strength of oil tankers and bulk carriers in an intact condition should not exceed 90%. Considering this requirement, the upper limit of the CDI can be known, as shown in Figure 8 (solid-black direction).

Figure 8 Use of RSI-CDI diagram.

4. Conclusions

When a ship is subjected to severe accidental damage, rescue and salvage actions should be taken on the basis of a proper decision that depends mainly on an evaluation of the damage to the ship's safety using the residual strength assessment procedure. The intention of this study is to propose a method to predict the hull girder residual strength of double-hull oil tankers involved in ship-ship collisions. Due to the uncertain nature of ship collision and its influencing parameters, a probabilistic approach is applied to create a relevant set of probabilistic collision damage scenarios based on a historical database of ship collision accidents.

The main target of the proposed method is to relate the residual ultimate longitudinal strength of a damaged ship cross-section (i.e., the RSI) with the corresponding CDI, to be abbreviated as RSI-CDI diagrams. Four classes of double-hull oil tankers – Panamax, Aframax, Suezmax and VLCC – under vertical hogging and sagging bending moments are used to demonstrate the applicability of the proposed method by involving each in 50 randomly selected collision damage scenarios. For simplicity, the effects of the horizontal bending moment, lateral pressure, shear force and torsion loading are neglected in this study. CDI is defined as the vertical moment of inertia reduction ratio after proving its similarity to longitudinal strength reduction (i.e., the RSI). A regression method is then used to generate a simple analytical expression by fitting each plotted curve. The obtained results are then used to develop general analytical formulations for the four tanker classes.

These developed diagrams and the corresponding analytical expressions can be useful for assessment of structural safety in terms of ship hull collapse immediately after a collision, before rescue and salvage operations take place. The allowable collision damage amount in terms of CDI can also be obtained with acceptance criteria for the residual strength performance of damaged structures. In contrast, acceptance criteria for residual strength performance can be developed at a certain amount of collision damage.

It will be valuable to extend the analysis to develop RSI-CDI diagrams for various types and sizes of vessels. In addition, further studies are being carried out to apply the proposed method on aged ships that are subjected to collision damage.

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