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Letter

Analysis of structural behavior during collision event accounting for bow and side structure interaction

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ABSTRACT

The main goal of this study was to investigate the effects of selected ship collision parameter values on the characteristics of the absorbed energy in several ship collision scenarios. Non-linear simulations were performed using a finite element method (FEM) to obtain virtual experiment data. In the present research, the size of the side damage from a collision phenomenon were measured and used to verify the numerical configuration together with the calculation results using an empirical equation. Parameters in the external dynamics of a ship collision such as the location of the contact point and velocity of the striking ship were taken into consideration. The internal energy and deformation size on the side structure were discussed further in a comparative study. The effects of the selected parameters on several structural behaviors, namely energy, force, and damage extent were also observed and evaluated in this section. Stiffener on side hull was found to contribute significantly into resistance capability of the target ship against penetration of the striking bow. Remarkable force during penetration was observed to occur when inner shell was crushed as certain velocity was applied in the striking bow.

In recent years, the demand of case investigation with objective to minimize the phenomenon of ocean pollution and vessel losses as the casualties of collisions and grounding has risen as the primary necessity. One example is the environmental damage caused by the Exxon Valdez accident, which forced the USA to make The Oil Pollution Act 1990 (OPA-90) into law. The accident of several roll on-roll off ships, such as the Scottish Viking on 2010, the Primula Seaways in 2015, and remarkable accident of collision between the Doña Paz and the MT Vector in 1987 with the casualties of more than 4000 lives, made the related parties perform investigation and evaluation of the safety of passenger ships in many countries. Collisions and groundings contribute significantly to ship structural damage. Based on the statistical data from the International Oil Pollution Compensation Fund in 2006, collisions and groundings were responsible for more than 50% of all environmental damage as cause of oil spill [1]. A collision accident also occurred in the Sunda Strait on May 3, 2014, at around 2:25 am local time, between Sumatra Island and Java Island which are both located in the Republic of Indonesia. The collision occurred between the Ro–Ro passenger ship Marisa Nusantara and the reefer Qi Hang. After the accident, the struck Ro–Ro passenger ship Marisa Nusantara, which carried 75 passengers and 47 vehicles, experienced severe damage at the forepeak hull side, with a tear of 7 m in length and other material losses from passengers.

This paper presents a comparative study on the results of a simulation using several parameter values in collision simulations. Finite element (FE) simulations for several collision case scenarios were conducted to obtain virtual experiment data. This study was focused in assessing structural response as collision load was applied on target structure. Scenario was built based on several physical parameters which were classified as dynamic parameter in ship collision. Comparative analysis was conducted on each parameter category to obtain prediction of side structure behavior after collision event.

The studies by various methods on the object's behavior under collision load were performed by previous researchers and related

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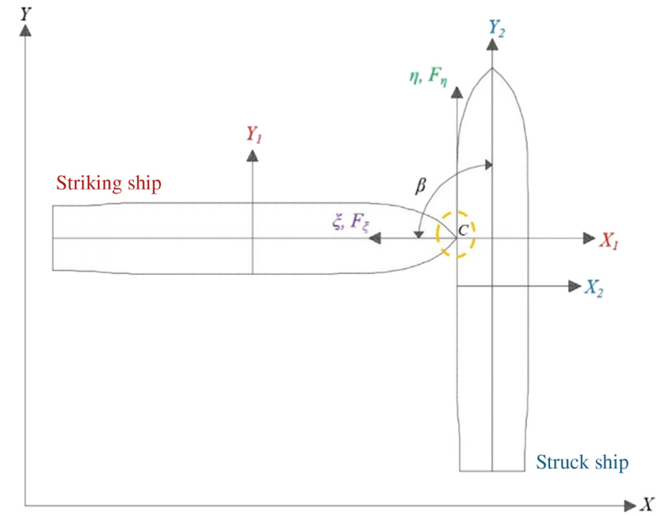

Fig. 1. Illustration of coordinate system.

parties. Research on the collision of tanker with double hulls [2] were performed including a comparative study in terms of structural behavior of hull construction from bulk carriers in collision damage [3], and a finite element method (FEM) to the simulation of impact damage [4]. Other researches on impact technology were also carried out between 2011 until 2014 in terms of mathematical and virtual models [5–7].

The ship collision study by Wiśniewski and Kolakowski [8] described numerical simulation of simplified experiment on the impact phenomenon. Several simulations of ship collisions based on the collision type were studied by Haris and Amdahl [9]. Another reference on this subject is the study of Kitamura [10], in which he stated that in order to obtain good accuracy and practicality, the study must be based on several data, including from finite element analyses (numerical experiments), physical experiments, and actual accidents.

When a collision between ships occurs, the involved ships are classified as the "*struck*" and "*striking*" ship. The struck ship is the ship that has part of its body penetrated by the other ship. The striking ship is the ship that penetrates into the other ship. Collisions can occur in many possible scenarios, for an instance is side collision. In this phenomenon, the side part or hull of the struck ship is crashed into by the striking objects which can be ship, rigid log, etc. Simplified coordinate system used in the collision process is presented in Fig. 1.

Collision analysis itself has experienced continuous improvements since it was first introduced by some researchers. The methods used in collision analysis can be divided into four categories: empirical methods, simplified methods, experimental methods, and FEM. Empirical methods have been introduced and developed by many researches. Minorsky [11], Woisin [12], and Zhang [13] were considered in the present study.

Improvement on the methods of both Minorsky and Woisin was presented by Zhang [13]. The proposed formula by Zhang [13] represents the damage in crushing, folding, and tearing categories. An FE approach is introduced these days for performing the analysis and simulation of complicated cases in physics and mathematics. The approach basically consists two different analysis concepts. The non-linear concept is performed to calculate the structural response, such as stresses and deformations during general loading and non-linear material conditions are defined in phenomenon model. The non-linear analysis generally involves complex model, in which high non-linearity is involved, but most of complicated phenomenon, namely contact mechanics was successfully observed using this method.

Table 1
Configurations of struck ship.

Characteristic	Value
Length over all (m)	85.92
Length between perpendicular (m)	78.00
Breadth molded (m)	15.00
Design draft (m)	4.30
Depth (m)	10.40
Frame spacing (m)	0.60

Table 2
Configurations of striking ship.

Characteristic	Value
Length over all (m)	144.50
Breadth molded (m)	19.80
Design draft (m)	5.60
Depth (m)	10.20

The implementation of a non-linear analysis was considered to be the most suitable for the present study. In this research, a non-linear FE analysis was conducted using the LS-DYNA FE codes to produce virtual experiment data. The algorithm in this code is characterized as given in Eqs. (1) and (2).

$$\{a_t\} = \{M\}^{-1}\left(\left\{F_t^{\text{ext}}\right\} - \left\{F_t^{\text{int}}\right\}\right), \tag{1}$$

$$F^{\text{int}} = \sum\left(\int_{\Omega} B^{\text{T}}\sigma_n \text{d}\Omega + F^{\text{hg}}\right) + F^{\text{contact}}, \tag{2}$$

where $\{a_t\}$ is the acceleration at time t, $\{M\}$ is the mass matrix, $\left\{F_t^{\text{ext}}\right\}$ is the applied external and body force vector, $\left\{F_t^{\text{int}}\right\}$ is the internal force vector given by Eq. (4), F^{hg} is the hourglass resistance force, and F^{contact} is the contact force.

In this algorithm, the velocities and displacements are then evaluated as presented in Eqs. (3)–(6).

$$\left\{V_{t+\Delta t/2}\right\} = \left\{V_{t-\Delta t/2}\right\} + \{a_t\}\,\Delta t_t, \tag{3}$$

$$\{u_{t+\Delta t}\} = \{u_t\} + \left\{V_{t+\Delta t/2}\right\}\Delta t_{t+\Delta t/2}, \tag{4}$$

$$\Delta t_{t+\Delta t/2} = \frac{1}{2}\left(\Delta t_t + \Delta t_{t+\Delta t}\right), \tag{5}$$

$$\Delta t_{t-\Delta t/2} = \frac{1}{2}\left(\Delta t_t - \Delta t_{t+\Delta t}\right). \tag{6}$$

The model is progressing by adding the updated displacement variable to the initial model $\{x_0\}$, as presented in Eqs. (7) and (8).

$$\{x_{t+\Delta t}\} = \{x_0\} + \{u_{t+\Delta t}\}, \tag{7}$$

$$\lambda_{i+1} = \lambda_i + K_{\text{cont}}\Delta x_{\text{penetr}}. \tag{8}$$

A collision occurred on May 3, 2014, between Sumatra and Java Island, specifically in the Sunda Strait, 5 km from Bakauheni Port (Lampung Province). Marisa Nusantara, a Ro–Ro passenger ship was severely damaged after Qi Hang, a reefer ship struck its hull. Qi Hang ran with a velocity approximately 6 m/s into the starboard side of the Ro–Ro passenger ship. As a result, a rip formed with a length approximately 7 m and width 5 m. An illustration of the damage can be seen in Fig. 2. The penetration depth was 2 m between the main deck and middle deck [14].

The configurations and main dimensions of these ships are presented in Tables 1 and 2, respectively. The struck ship is the ship that has its body penetrated by the other ship, whereas the striking ship is the ship that crashes into the other ship.

In the FE experiment, the plastic-kinematic characteristic was implemented in the analyses, and material model for virtual experiment is given in Table 3. The numerical models of the both of involved ships are presented in Fig. 3. Some researchers such as Kitamura explained that the strain failure is not constant but varies