EVALUATING THE PARAMETER INFLUENCE IN THE EVENT OF A SHIP COLLISION BASED ON THE FINITE ELEMENT METHOD APPROACH

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ABSTRACT

The main objective of this paper is to review and examine the effects of the selected collision parameter values on the characteristics of collision energy in several ship collision scenarios. The benchmarking particulars were taken from the ship-to-ship collision case on Sunda Strait in 2014, while the collision process was modeled with non-linear simulations using the finite element (FE) method to determine the predicted damage and internal energy in the collision process. In the first phase, the verified model for the numerical simulation was built based on the benchmarks and other previous findings by researchers. The study of parameters during the collision process was performed in a later stage. The location of the target point in the vertical axis and the effect of the collision angle were the primary main focuses. The characteristics of damage and energy tendencies will be presented. One remarkable findings was that the structure of the car deck showed a better resistance and was more difficult to destroy than the other proposed locations. The angle position between the two objects during the impact process significantly contributed to the damage pattern on the side hull. The final results also indicated that the cross-section of the target point's location influenced the observed parameters.

Keywords: Collision angle; Impact phenomenon; Internal energy; Structural damage; Target point location

1. INTRODUCTION

The impact (short or spontaneous load) phenomenon has become an inseparable aspect of the engineering field, especially in the ship and ocean engineering field. The demand to increase safety on the sea when ships are subjected to impact loads, such as collision and grounding, has been given considerable. Predictions of structures' behaviors are increasingly necessary because each ship has its own configuration that makes the structural responses such as energy and the extent of damage, different in each case. The fundamental concept of this phenomenon has been introduced by previous researchers, including Minorsky (1959), Zhang (1999), and Lützen (2001). More than 50 years ago, Minorsky (1959) introduced and presented the simplified/analytical illustration of a collision analysis and performed a series of observations and studies of collision accidents. Based on these studies, an empirical formula used to assess the energy during the collision process was introduced. As mentioned in several theses of

Zhang (1999) and Lützen (2001), Minorsky's analytical theory and formula showed that the energy released for crushing a structure was mainly determined by several parameters in physical collision phenomena, such as ship velocity and collision angle. The application of these analytical and statistical concepts can be considered a good research opportunity because the rapid development of technology in the 20th century has enabled the development of a virtual calculation method, which is more commonly known as a numerical calculation.

The aim of the present study was to investigate the characteristics of energy and damage patterns based on collision parameters, such as the location of a target point and the collision angle between two ships. Dynamics numerical calculations were performed to obtain the prediction results. The vessel that experienced the impact was a Ro-Ro passenger double-sided skin design that was assumed to be deformable structure, and the vessel that collided with it was a cargo reefer with a rigid body design.

2.   COLLISION PROBLEM

The literature review on ship collision and involved method for assessment are presented in this section. Review on several findings from previous researchers in this field will be discussed to build the comprehensive method for present study.

2.1.   State-of-the-art Experiment and Technology

Ship collision is one of the deadliest accidents on the sea along with grounding based on Lloyd's Register Survey (1995). The damage not only affects the ship; the ship's cargo, the environment, and human lives are also threatened as a result of collisions. Several studies were conducted to develop and increase the safety of ships in the event of a ship collision. Studies and evaluations of real collision accidents were also performed to predict the chronology or scenario of a collision itself; however, predictions based on a real accident are very costly because the calculation of this phenomenon using the finite element method is performed in a full-scale analysis to obtain satisfactory results. Full-scale modelling is preferred the results can be directly compared to physical phenomena, which is more accurate. Nevertheless, as the consequences for using this method, study and evaluation time are too much paid on pre-processing stage, such as compiling the data of real accident, e.g. damage and predicted speed as well as defining these physical data into numerical data or modelling. Full-scale modelling produces accurate results, but too much time and effort are spent in the pre-processing phase. The full-scale modelling process is sometimes unnecessary for predicting or evaluating real phenomena because a numerical analysis is simply an approach rather than an absolute calculation, and the occurred structural damage does not spread on all parts of model.

Bathe (1996) stated that the response of physical problems cannot be precisely predicted because it is impossible to reproduce them, even in the most refined mathematical model. All information that exist in nature and physical problem are too complicated to be perfectly defined in finite element method. The characteristics of a mathematical model are divided into two categories. The first characteristics is *effectiveness*. The most effective mathematical model yields the required response with a sufficient accuracy at lowest cost. The second characteristics is *reliability*, which refers to when the required response is known to be predicted within a selected level of accuracy measured by the response of a comprehensive mathematical model. A full-scale model produces sufficient accuracy, but the cost requirement is not fulfilled. In response to this issue, research performed between year of 2002 and 2015 included simulations that were not full-scale and evaluated the result using other methods. Previous researchers, such as Ozguc et al. (2005) and Haris and Amdahl (2013), performed the evaluation of the structural integrity on a ship's side structure without using a full-scale model and instead used a specific model of a ship's structure that was subjected to collision. To evaluate the results, empirical or

simplified methods were conducted to replace the comparison with physical phenomena or experiments.

In the last two decades, there has been significant technological development, especially in computational technology, which has been applied in various ways, such as in transportation, production and calculation and measurement. In engineering, calculation and measurement play a vital role in the prediction of behaviors and characteristics of observed objects through virtual simulations. The simulations can be considered alternatives in solving engineering problems because the failure probability and cost in some cases of actual experiment cannot be controlled and can be costly. The application of virtual simulations has also been used in naval architecture and marine and ocean engineering to assess physical phenomena. For the collision phenomena, the finite element method (FEM) approach can be considered a powerful calculation method. The implementation of the FEM approach for impact phenomena was also supported by Kitamura in his study in 2002. To obtain good accuracy and practicality, the study must be based on the data of the actual accidents, physical experiments, and/or finite element analysis (FEA) or numerical experiments.

For the present study, a new implementation of the combined structural integrity evaluation procedure was applied by using a specific model of ship. The investigation was performed using the finite element (FE) method approach. Several configurations and parameters from previous research were combined and implemented in the present study. Furthermore, the influence of velocity and angles will be presented to explain the specific effect on the prediction results.

2.2.   Fundamental Characteristics of Ship Collision

Previous authors have presented their research on collisions using the empirical method, experimental method, simplified methods and finite element method. For the empirical method, Minorsky (1959) analyzed 26 collision cases of full-scale ship accidents and developed an empirical formula, as presented in Equation 1 (Zhang, 1999):

$$E = 47.2R_T + 32.7 \tag{1}$$

which $\qquad\qquad R_T = \Sigma \, P_N \, L_N \, t_N + \Sigma \, P_n \, L_n \, t_n$

where E is absorbed energy (MJ), R_T is destroyed material volume for both struck and striking ship/resistance factors (m^3), P_N is damage depth of striking ship (m), L_N is damage length of striking ship (m), t_N is damage thickness of striking ship (m), P_n is damage depth of struck ship (m), L_n is damage length of struck ship (m), and t_n is damage thickness of struck ship (m).

Several experiments on ship collisions have been carried out since the early 1960s. From 1962 to 1976, investigators in Italy, Germany, and Japan conducted a series of model tests. Several authors provided the detailed reviews of these experiments, such as Ellinas and Valsgard (1985), Samuelides and Frieze (1989), and Pedersen et al. (1993). The main purpose of the experiments carried out in Italy, Germany, and Japan was to design nuclear powered ships in which the nuclear reactors were protected from collision damage. A simplified method of ship collision was presented by Zhang (1999) and Lützen (2001) in form of analytical theory of coordinate illustration during collision between two ships. A simplified illustration for a collision case between two ships is presented in Figure 1.

When the bow of a striking ship impacts the parallel side of the struck ship directly, the two ships are assumed as slender beams. To illustrate the assumptions of the method, consider a striking ship *(B)*, which sails at a forward speed of V_{b1} and a speed of V_{b2} in the sway direction. This vessel collides with a struck ship *(A)*, sailing at a forward speed of V_{ax} and a sway speed of

V_{ay}. The theory makes use of three different coordinate systems. A xyz-coordinate system is fixed to the sea bottom. The z-axis points in a direction above the water's surface, the x-axis lies in the symmetry plane of the struck ship pointing towards the bow, and the origin of the xyz-system is placed so that the section amidships is in the yz-plane at the moment t = 0.

The origins of a ξ – axis and η – axis are located at the impact point C. The ξ - direction is normal to the impact surface, the angle between the x-axis and the η-axis is α, and the angle between the x-axis and the 1-axis is β.
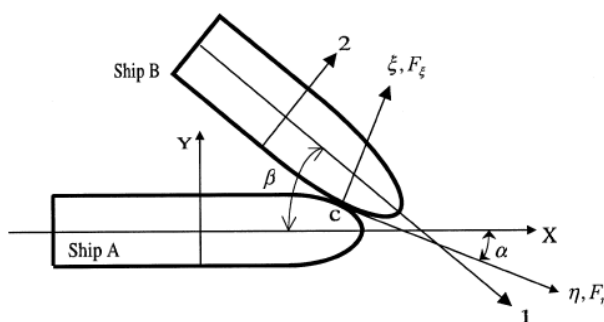

Figure 1 Simplified collision case model involving two ships

3.   IMPACT PHENOMENON MODEL

This section presents the assumed collision model and the setting for conducting numerical simulations. The involved ships, the numerical configuration, and the assumed case will be described. The failure criterion for the analysis will also be discussed. The accident study by Prabowo (2016) was used as the main reference for the present study to satisfy the criteria of comparison between the finite element analysis (FEA) and the actual accident data. Because the empirical method and a material experiment were used, this study satisfied several criteria from Kitamura (2001) regarding the procedure used to obtain accurate results in a collision analysis. To increase the accuracy of verified model, proposed configuration and setting by previous researchers, such as the shell element type, the mesh size, and the failure criterion, were implemented in the numerical simulation process.

3.1.   Configuration and Setting
In the virtual experiment process, the struck ship was considered to be the deformable structure, and the striking ship was considered to be the rigid body. The main dimensions of the ships are presented in Table 1, while the models of the struck ship and the striking ship are presented in Figure 2. Plastic-kinematics materials were considered in the analyses (Krieg & Key, 1976), and the material model for numerical simulations is presented in Table 2.

Table 1 Dimension of involved ships (Prabowo, 2016)

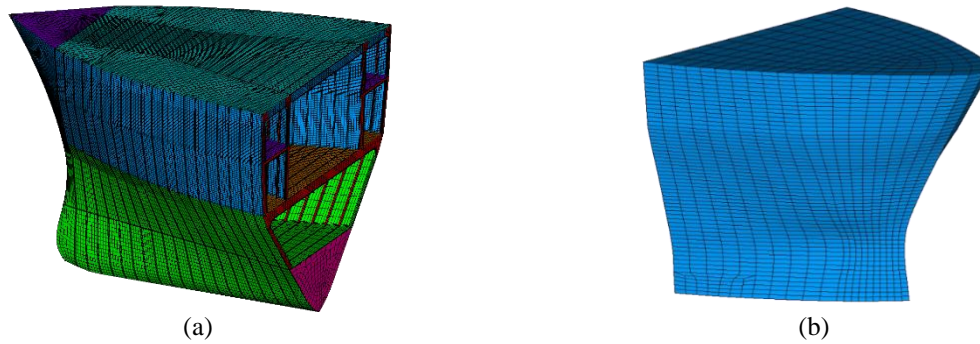| Characteristic	Description	Characteristic	Description
Name of ship	Marisa Nusantara	Name of ship	Qi Hang
Type of ship	Ro-Ro passenger	Type of ship	Reefer
Role	Struck ship	Role	Striking ship
Length over all (m)	85.92	Length over all (m)	144.50
Length between perpendicular (m)	78.00	Breadth moulded (m)	19.80
Breadth moulded (m)	15.00	Design draft (m)	5.60
Design draft (m)	4.30	Depth (m)	10.20
Depth (m)	10.40		

Figure 2 Model of involved ships: (a) struck ship; and (b) striking ship

Table 2 Material models for numerical simulation

Properties		Value	
Density	(ρ)	7850	kg/m^3
Young's Modulus	(EX)	210	GPa
Poisson Ratio	$(NUXY)$	0.30	
Yield Stress	(σ_{ys})	440	MPa
Hardening Parameter		0	
Strain Rate	(C)	3200	$/s$
Strain Rate	(P)	5	
Failure Strain		0.20	

Simonsen (1997) stated that the simplified method is based on the overall deformation mechanism. It is impossible to trace the strain history of material elements on a detailed level. Therefore, several researchers, such as Wang (1995) and Paik and Pedersen (1995), used the maximum strain failure criteria in their studies. When a maximum strain in a structure reaches a critical strain, the structure will experience a rupture. In the present study, the maximum strain failure criteria were also used. Experiments that were conducted by Wen and Jones (1993) as well as Amdahl and Kavlie (1992) showed that the tensile ductility of mild steel is in the range of 0.20 and 0.35. Based on these studies and a recent study by Ozguc et al. (2005), a strain failure with a value of 0.20 was applied for simulation in this study.

The element choice for the present research was the Belytschko-Tsay element. Alsos and Amdahl (2007) as well as Tornqvist and Simonsen (2004) suggested that the element-length-to-thickness (ELT) ratio should be within the range of 5-10 so that the local stress and strain fields can be captured accurately. Fine mesh that was 80 mm in size was applied to the core area of the struck ship, and fine mesh that was 90 mm and 100 mm in size was applied to the transition and the outside area, respectively. The element-length-to-thickness (ELT) ratio for these areas was in the range of 8−10. The area of the striking ship model was divided into two parts. The first area experienced direct contact with the struck ship. A fine mesh that was 340 mm in size was applied. The second was the rest area, and fine mesh that was 680 mm in size was applied.

3.2.   Assumed Collision Scenario

The results of the simulation for this study depended on two main parameters. The first parameter was the target point location in the vertical axis, which refers to different vertical positions of the striking ship to the struck ship, including the car deck, middle deck, and main deck. The second parameter was the collision position, which refers to the collision angle between the two ships. These parameters were applied along with the striking bow, the assumption of the structural state of struck ship, and the material model to create the collision

scenarios. According to Germanischer Lloyd (2003), the formula used to calculate the relevant position of the two ships can be determined based on their drafts, as presented in Equation 2.

$$\Delta T_1 = T_{2\max} - \frac{3.T_{1\min} - T_{1\max}}{4}, \Delta T_2 = T_{2\max} - \frac{3.T_{1\max} + T_{1\min}}{4}$$

$$\Delta T_3 = \frac{T_{2\min} + 3.T_{2\max}}{4} - T_{1\max}, \Delta T_4 = \frac{T_{2\max} + 3.T_{2\min}}{4} - T_{1\max} \tag{2}$$

where T_{1max} is the design draft of the striking ship, and T_{1min} is the ballast draft of the striking ship, while T_{2max} and T_{2min} are the design and ballast draft of the struck ship, respectively.

In terms of the collision angle, which is presented in Figure 1, the angle between the two ships in the collision process was taken into consideration. In the analytical theory illustration, this angle is presented as β. Three collision angles were applied in the simulation, which were 60°, 90° (perpendicular position) and 120°. Fifteen different collision cases were examined using the with non-linear finite element code LS-DYNA. The struck ship was set to be fixed on the center line, while the striking ship was moved to a designated target location with a certain collision angle by using the impact speed 6.17 m/s with a time simulation for the collision process of 0.405 s.

3.3. Failure Criterion

In their work, Ozguc et al. (2005) stated that the failure of a ship's side structure in a collision can be described as the tearing of the side shell plating. Hence, a criterion must be defined for the ultimate strain after which the fracture takes place. The rupture strain of the material is a significant function of the collision energy absorption capability. It would thus be of importance to choose the material that has been welded with good toughens and a large critical rupture strain. In fact, the rupture of a structural component is a complicated process that is influenced by many factors. It is directly related to the material's characteristic parameters, such as the yielding stress, fracture strain, and ultimate tensile stress. It is well-known from numerous practical experiences and theoretical investigations that the failure also depends on the stress states that resulted under complicated loads in the structures. In addition, it is also influenced by the manufacturing quality and production process. The mesh density, element shape, and mesh size also play important roles because the development of a fracture process begins due to the uniform deformation that continues throughout the entire component to a local necking in a very small area in which extreme large strain values occur. To obtain practical failure strain definitions in consideration of several parameters, e.g., element size, stress state, and manufacture influence, several full-scale thickness measurements on prototype-damaged structure components, such as shell plating and stiffeners, have been conducted, and uniform strain in the necking as well as in the necking length have been determined. The definition of a failure strain that is based on the evaluation of the thickness measurements is presented in Equation 3 (GL, 2003).

$$\varepsilon_f(l_e) = \varepsilon_g + \varepsilon_e(t/l_e) \tag{3}$$

where ε_g is the uniform strain, and ε_e is the necking, t and l_e are the plate thickness and an individual element length, respectively.

The values of uniform strain and the necking achieved from the thickness measurements are related to the calculated stress, and they are shown in Table 3.

Table 3 Proposed failure strain-mesh size correlation (GL, 2003)

Stress states	1-D	2-D
ε_g	0.079	0.056
ε_e	0.760	0.540
Element type	Beam-Truss	Shell-Plate

4.   RESULTS AND DISCUSSION

The results of the collision calculation are presented in this section. The observations and evaluations of the target point location and the collision angle effects on the results characteristics, such as energy and structural damage will be discussed.

4.1.   Target Point Location

The results of the target point study showed that the car deck structure had a better resistance than the other locations of the target points. The amount of internal energy indicated the energy level that was needed to destroy the object through an impact load. The resistance extent of the object through an impact load in this subject indicated that the structure component pattern gave influence on the energy. The car deck was built stronger than the other decks to sustain the passenger vehicle as well as to counter the external forces, such as waves, so that in the same time it is required to counter bending moment. The comparisons of the location effect on energy and the structural damage are presented in Figures 3 and 4, respectively.
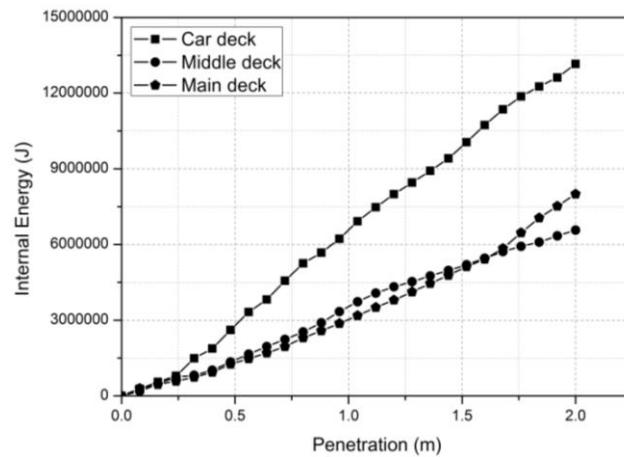

Figure 3 The energy characteristics during the collision process for the three different decks

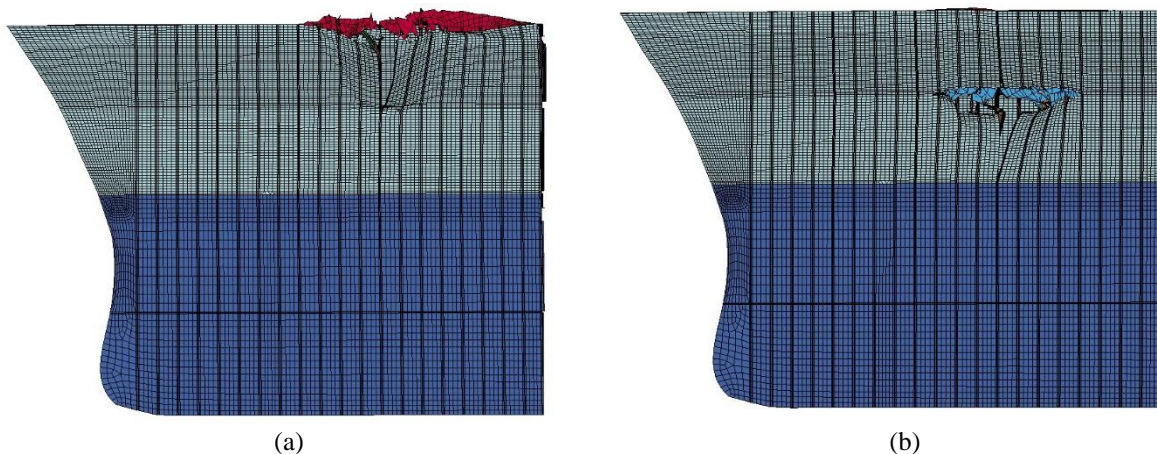(a)   (b)

Figure 4 Structural damage pattern: (a) main deck; and (b) middle deck

The characteristics of energy for each deck had a good correlation with the function of the deck itself. The main deck, which was required to carry the live load and the superstructure, produced a higher resistance, which signaled that this deck was stronger than the middle deck. The middle deck carried several minor loads and acted as an intermediary between the car deck and the main deck, when it was destroyed during the collision process.

4.2. Collision Angle

The internal energy during the collision process indicated that the position of the collision significantly affected the results. At the same structure location, the energy used to destroy the structure in a perpendicular collision was found to be less than the energy used to destroy the structure from a different angles, such as 60° and 120°. This indicates a good correlation with internal energy for various locations, including the deck and side shell.

Table 4 Summary results of all collision cases

No	Location	Angle (deg)	Internal Energy (J)	Tearing Length (mm)	Inner shell displacement (mm)
1	Car deck	60	16464300	6000	0-590.0
2	Middle deck	60	4994450	5400	0-349.8
3	Main deck	60	10066400	5400	0-349.8
4	Side shell car-middle deck	60	13699700	5550	0-349.8
5	Side shell middle-main deck	60	10108500	4200	0-349.8
6	Car deck	90	13157300	4200	0-349.8
7	Middle deck	90	6566510	4500	0-349.8
8	Main deck	90	7997370	4800	0-249.9
9	Side shell car-middle deck	90	7784470	4650	0-716.6
10	Side shell middle-main deck	90	6913440	2400	0-349.8
11	Car deck	120	15526300	4200	0-349.8
12	Middle deck	120	4663740	4800	0-349.8
13	Main deck	120	8339920	4800	0-349.8
14	Side shell car-middle deck	120	8267900	4650	0-349.8
15	Side shell middle-main deck	120	11552100	4200	0-349.8

The impact on the side shell showed that the results for other angles and a perpendicular collision differed in the range between 5%−43% on the side shell between the car and middle decks, while the difference on the side shell between the middle deck and the main deck was estimated to be between 31%−41%; however, an anomaly was found on the middle deck for which the collision energy was the opposite, which the angle 90° produced highest energy than 60° and 120°. The perpendicular collision produced the highest energy with the difference between 23%−29%. Although the differences on middle deck was not as large as other decks, the results for this location were found interesting. In this case, the boundary condition acted as a differentiator that the main deck and car deck had been set to be fixed on the center line formed the tendency which the energy for collision angle 90° is the lowest. In other hand, the end of the middle deck was free that produced tendency which the energy for collision angle 90° is the highest.

During the collision process, the energy was also distributed to displace the position of the middle deck, and the energy used to displace the object was higher for the perpendicular position, as was mentioned by Callister (2007) in Equation 4.

$$\sigma' = \sigma \cos^2 \theta = \sigma\left(\frac{1 + \cos 2\theta}{2}\right) \tag{4}$$

where σ' is the stress on various angle, σ is the stress on perpendicular position and θ is the angle of working stress.

This formula describes the stress that is experienced by the object, which is higher in the perpendicular position. Regardless of the stress state, this formulae can be considered a good representative because the energy and the force have a direct correlation to force and stress in the stress relationship. The structural damage pattern used in this study is presented in Figure 5 a, b, and c for collisions at 60°, 90°, and 120°, respectively, while the summary of simulation results is presented in Table 4.
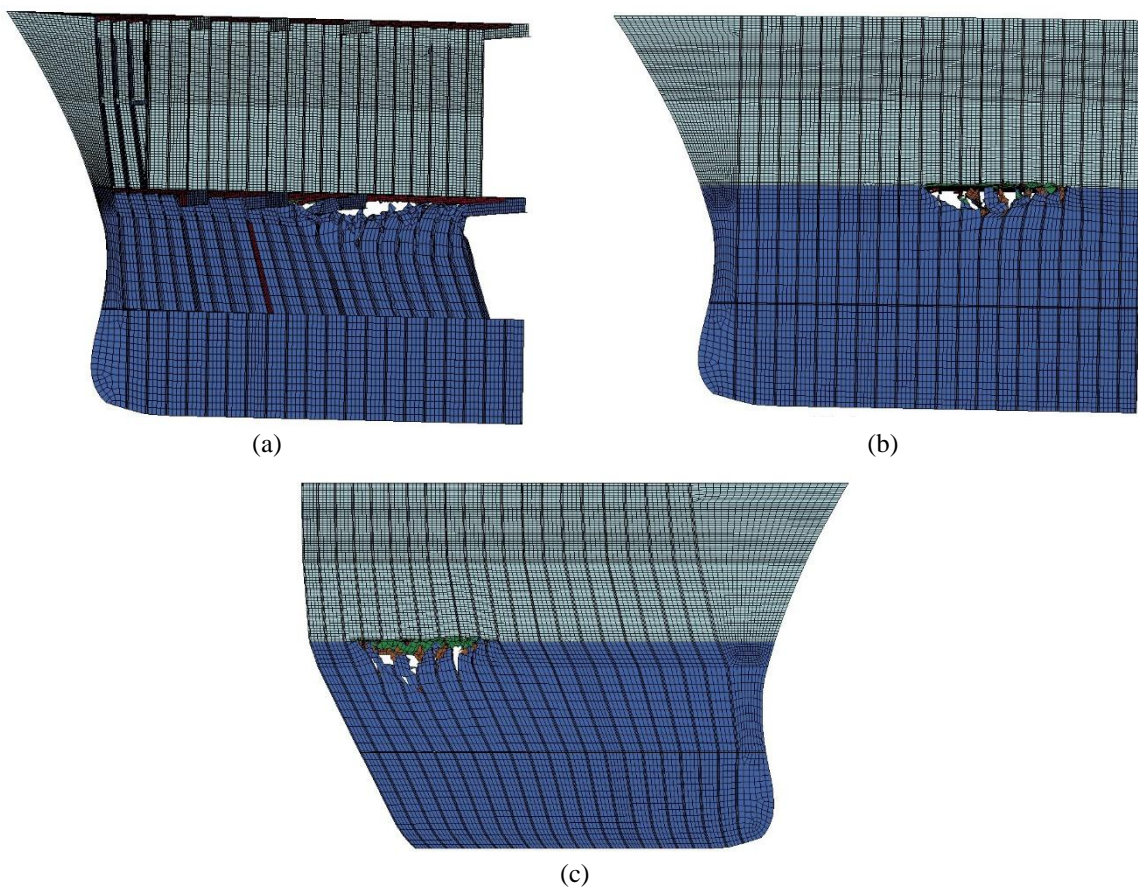
(a)   (b)

(c)

Figure 5 Structural damage on car deck for various angles: (a) 60°; (b) 90°; and (c) 120°

5.   CONCLUSION

In this paper, a study on various scenarios of accidental load phenomena in terms of collisions on side structures is presented. The study was carried out using data of a collision accident at Sunda Strait, Republic of Indonesia in 2014, and several references for collision analyses were reviewed to obtain a verified model for numerical simulations. The study was successfully conducted using the finite element method. The major finding was that the location of a target point in the structure's components influenced the resistance of the structure when it was destroyed by the striking object. The energy and damage represented the strength of the structure subjected to the impact load, and it was proven that the energy and the extent of the damage had a good correlation with the deck roles. In terms of collision angles, the energy at

the end of the collision process for the perpendicular position was less than for the other proposed angles in this study. The applied boundary condition in which the middle deck showed an opposite tendency than the other parts of the structure regarding energy. This phenomenon was verified using the stress formula relationship. Studies that focus on the boundary conditions' effects on ship collision phenomena are recommended for further research.

6.   ACKNOWLEDGEMENT

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