Research Article

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Crashworthiness performance of stiffened bottom tank structure subjected to impact loading conditions: Ship-rock interaction

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Abstract: Shipping time, cargo handling and quality as well as operational cost are main aspects of success in trading and shipping, which leads to high demand for ship safety. During freight shipping is conducted for various cargoes, the ship structure is subjected to numbers of loads, which several of them have been predicted during ship design. Nevertheless, incidental type in form of impact load can deliver massive blow to ship safety and cause immense loss. This phenomenon may be worse than initial condition if structure of chemical-oil carrier experiences impact, which possibly evokes environmental damage to maritime territory. This work is addressed to assess crashworthiness performance of structural part, *i.e.* bottom tank of chemical carrier. This part is one of center point of oil spill during occurrence of the impact load. The loading conditions are defined as configuration of interaction between ship structure and rock when the ship is stranded on shallow water. A series of data observations produced by finite element analysis (FEA) provide a prediction regarding local member's motions during the rock breaches lower parts of the bottom tank. Consequences of the plate towards failure are quantified to obtain effect of the selected impact loading conditions to directly involved (main) member and other affected local member.

1 Introduction

Global-scale trading regulation has been engaged in form of free market policy. Export-import activity is increasing rapidly which leads to incremental tendency of sea traffic. This phenomenon takes place as ship and other water-mode transportations have been designated as one of the most preferred distributor. Developments in terms of navigational instrument, port and industrial handling as well as expansion of international shipping route, make more ships and carriers are demanded by market, and involved investment in shipbuilding industry becomes more global and steadily rising [1]. Despite of this positive trademark, during its operation, the ships tend to experience challenge which comes from environment, *e.g.* sea state, bad weather, and other incidental factors. The recorded history in shipbuilding proves that these factors, which appear as impact loading, produce high possibility to risk ship safety. In several famous cases, such as the *Titanic* in 1912 and the *Exxon Valdez* in 1989, immense number of human casualties and large scale of marine pollution follow impact phenomena on ships. This evidence is supported by facts based on the recent compiled data by Allianz [2] that impact involving ship structure and seabed in form of stranding is the most contributing accident to the ship casualties together with foundering and collision.

Due to this concerning phenomenon, sustainable analysis is needed to assess structural crashworthiness under impact loading in maritime environment. This work is addressed to perform structural analysis on a stiffened bottom tank of chemical carrier, which is subject of high-risk oil spill under impact loading. The loading condition is determined as interaction between the ship and seabed which the crashworthiness criteria, including structural behavior of local member are calculated to provide adequate calculation data to estimate expected consequences in further analysis.

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Figure 1: Typical compartment design on ship hull.

Figure 2: Illustrations of the hull design for naval structures: conventional single hull.

2 Ship structure and historical development

In its design, ship structure is divided into main hull and superstructure. The main hull is where the accommodation, machinery and cargo are located. This part directly contacted with water during its operation and several compartments are designated for specific objectives, such as cargo space, fuel oil, lubrication, waste, ballast, machinery room etc. The illustration of ship compartment is presented in Figure 1. More compartment will be designed on special purpose or dangerous cargo carrier, such pump room on oil carrier [3], and safety space between reactor and working space for officers on nuclear carrier [4]. The main hull will be arranged by certain framing system to support outer shell as skeleton in human body. For a small ship under 90 m, application of transverse framing is preferred as it is relative cheap and longitudinal strength of ship can be supported mainly by stringer and girder. For a larger ship or above 100 m, the longitudinal or combination style is installed.

During initial industrial revolution, ship is designed as a single hull (see Figure 2) which is applied for almost all ship types, including cargo/frigate ship for trading, and passenger ship for leisure across the globe. Nevertheless, as various accidents occurred on ship, and in the peak

Figure 3: Illustrations of the hull design for naval structures: advance double hull.

point, the 269 m-passenger ship namely the *Titanic* sank with more than a thousand human life casualties, change for international ship regulation especially for safety was called and presented in forms of Safety of Life at Sea (SOLAS). A major change on the ship structure began later, or in the beginning of 90's precisely when large oil tanker – the *Exxon Valdez*, ran aground in Alaska, and caused wide range maritime pollution, destruction of water ecosystem, and this accident was responsible for extinction of several bird and mammal species on Prince William Sound. Oil Pollution Act (OPA), which was in force since August 18, 1990, develops various regulations to minimize effect and destruction of maritime territory due to oil spill, which one of them is double hull system (see Figure 3) [5]. The spaces on the side and bottom parts of ship are designed to avoid direct oil spill from cargo compartment, especially against impact loading in forms of collision (ship-ship interaction etc.) and grounding (ship-rock interaction).

3 Impact loading in maritime environment

Prediction of encountered loadings during ship operation is a key of success in shipbuilding industry and international trading. This aspect affects performance of ship structure and furthermore, safety of passenger, crew, cargo and water environment. However, possibility of the operation goes out of control in times of accident may occur due to internal (crew and navigational instrument) and external (bad weather, waterway topology, etc.) factors. In maritime environment, an accident initiated by impact loading, such as collision and grounding causes significant de-

Figure 4: Assumed target points accounting for vertical direction to baseline and ship draught [6].

velopment in shipping regulation due to size and range of casualties after these events.

Collision which is presented in Figure 4, usually occurs in form of interaction between two ships [8–10], but in other cases, contact between ship structure with offshore platform [11], ice-structure interaction in Arctic region [12, 13] and ship subjected to bridge impact [14] are possible to occur in various waterways and routes. On the other hand, the grounding is defined as interaction between ship structure on the bottom parts with seabed formation which is frequently rock, shoal or reef [15–17]. This phenomenon is divided into more specific class according to impact direction. The first is the raking [18] which contact between bottom structure and seabed occurs when ship is in longitudinal motion. In this case, ship can escape from the seabed formation by move back with its propulsion capability. The second is the stranding [19] which impact on the bottom structures takes place in vertical direction. Main cause of this event is slamming in bad weather, and the ship has to be evacuated by supporting offshore infrastructures from the stranded location.

4 Geometry and analysis

4.1 Ship design and seabed geometry

The involved parts during impact in this work are defined as a stiffened bottom tanker of chemical carrier, and an idealized seabed rock. The modelled carrier is focused on the double bottom structures, which consist stiffened bottom tanks. The chemical carrier itself has principal dimension as follows: Length $L = 144$ m, Breadth $B = 22.6$ m, Depth $H = 12.5$ m and Draught $T = 9.2$ m, which is defined as shell structures with fully-integrated Belytschko-Tsay (BT) ele-

Table 1: Material properties of the steel material.

Property	Value	Unit
Yield strength (σ_Y)	350	MPa
Tangent modulus (E_T)	694	MPa
Density (ρ)	7850	kg·m ⁻³
Poisson ratio (ν)	0.29	-
Elastic modulus (E)	200000	MPa

Table 2: Material property of the seabed rock.

Property	Value	Unit
Density (ρ)	2690	kg·m ⁻³
Poisson ratio (ν)	0.296	-
Elastic modulus (E)	67450	MPa

ment formulation in the finite element configuration [20]. A high-strength low-alloy (HSLA) steel material AH36 is applied to the structure as plastic-kinematic hardening material [21], which is presented in Table 1. On the other hand, the seabed is modelled in numerical system as a conical geometry, which is implemented by a mineral entity as material input. *Plagioclase feldspar* is taken to be the reference as this mineral is included in oceanic crustal formation, and possibly contacts with the ship structure. The material properties of the plagioclase are presented in Table 2. The modelled entities in impact are deformable structure for the bottom tank, and rigid body for the rock geometry. These configurations lead observation of behavior and crashworthiness performance on structural members of the tank.

4.2 Impact loading conditions

During analysis using finite element codes ANSYS LS-DYNA, large deformation and structural crushing are expected to occur. Therefore, it is necessary to determine failure state of the deformable bottom tank. In this study, the failure state is represented by strain limit of the steel material. It is well applied in pioneer studies [22–24] that typical strain for application in structural impact cases is in range 0.2–0.35 with frequent input value 0.2. However, this assumption is too convenient since we expect that the material performance on the target ship is not as good as new building due to corrosion, fatigue and other factors. Thus, lower strain approximately in range 5%–10% with value $\epsilon = 0.11$ is implemented to the steel material [25–27]. Besides strain, dynamic behavior of material failure is also influenced by Cowper-Symonds parameters, as the material is

Figure 5: Configuration of impact loading and geometries of the involved entities.

strain-rate dependent. Selected constants $C = 3200 \text{ s}^{-1}$ and $P = 5$ are set to the numerical systems. Structural impact in the analysis is defined as the automatic surface-to-surface contact [20], which the rock is applied by uniform velocity $V = 10 \text{ m s}^{-1}$ to approach the designated bottom tank (see Figure 5) with overall time analysis $T = 0.4 \text{ s}$. The typical static coulomb friction coefficient in range 0.2-0.4 is implemented on the contact configuration to define interaction between steel tank and seabed rock. Several local members of the structure involved in impact are modelled, including floor, stiffener, plate, frame and girder.

5 Results and discussion

5.1 Energy behavior

Energy is one of the crashworthiness criteria, which is needed to be assessed, especially in case a structure becomes subject of impact loadings. The first form of the energy appears as the internal energy of the modelled structure. This energy represents amount of energy to plastically deform, tear or even crush the involved deformable entities in impact. As the seabed rock is defined as solid-rigid entity, the deformation and progressive crushing are focused on the structure. The results are divided into two parts according to interacting local members of the structure with the rock. The groups consist of main members, which are directly interacting with the rock, and the other members, which are influenced during ship-rock interaction but not in direct contact. Presented results in Figure 6 indicate that internal energy of the main members, including lower stiffener, transverse floor and bottom plate, produces significant difference than the other members during interaction period. Approximately, the main members are 1000 times higher than the other members which con-

sists transverse frame, upper stiffener, side girder, inner bottom plate and center girder. If it is assumed that only the main members experience clear and actual casualties in forms of the tearing and crushing, then the ultimate energy to make the material and structure experience such casualties is equal with the difference of the lowest internal energy capacity of the main members, and the highest peak of the other members, which is briefly estimated above 390000 J.

The tendency of the kinetic energy is discussed as follow-up of the internal energy. This energy (see Figure 7) represents movement of the structural members during the rock breaches the target tank. Most of the main members present equal perpendicular value compared to the internal energy. Nevertheless, the transverse floor which has significant internal energy compared to all other members, showed similarity with the transverse frame, upper stiffener, side girder, inner bottom plate and center girder, in terms of the kinetic energy. Therefore, it can be expected that the movement or motion of the transverse floor is not very high due to position of this member on the bottom structures. The floor is located on yz plane, which after the rock breaches the floor during impact, practically this member will not experience either major deformation or progressive crushing. Confirmation of this initial prediction is presented later during discussion on the structural contours. The tendency in Figure 7b also provides an indication that center girder and transverse frame, which are not directly interacting with the rock, show very low kinetic value with ratio below 28% compared to the highest value among of all other members.

Correlation of the energy criteria is shown in Figure 8, in which the energy ratio of the idealized members in finite element analysis provides a tendency that the highly deformed and crushed members have very small ratio in the range 0-0.5. On the other hand, the ratio of the minor

(a)

(a)

(b)

Figure 6: Internal energy during ship-rock impact: a) main members, and b) other members.

(b)

Figure 7: Behavior of the kinetic energy under impact: a) main members and b) other members.

affected members are in range 0-4, and mainly on 0.5-2. Behavior of this energy ratio can give a reference data that impact loading, which causes casualties on more local area (indicated by numbers of the directly involved members) tends to produce more significant expected chain events. Based on this theory, it can be assumed that the significant damage on lower stiffener, transverse floor and bottom plate can cause clear opening on the bottom structures (see discussion of effect to geometrical thickness) and lead to oil spill to sea territory. On opposite loading conditions, when more members are involved in impact, which deformation dominates the damage pattern and no actual tearing/opening on the tank, oil spill may only take place in form of minor leakage or does not occur at all. This prediction leads to a statement that sharp or conical geometrical type, which causes more local damage is more ca-

pable in causing maritime pollution than shoal with cylindrical shape on the contacted surface.

Besides effects to physical geometry, the finite element configuration is found to be significantly affecting calculation validity during hourglass evaluation. As presented in Figure 9, hourglass phenomenon is a condition of the structure, which does not deform in realistic ways according to physical theory. This phenomenon usually occurs on dynamic and nonlinear analyses that often involve major destruction on the idealized geometry. Application of the fully-integrated formulation is proven to be much effective to avoid a structure to experience error during and after analysis, which makes validity of the final results to be checked further.

(a)

(b)

Figure 8: Energy ratio of the modeled structures in analysis: a) main members and b) other members.

5.2 Member acceleration

Acceleration of the main members is observed on three different axes to estimate motion intensity when the designated tank is being impacted by the rock. Behavior of the floor as presented in Figure 10a indicates that damage is spreading almost equally on the longitudinal, transverse and vertical directions. It is noted on the longitudinal direction that large increment added after time $T = 0.3$ s. In this situation, the deformation is reaching the second transverse floor that intercostal of stiffener, floor and plate provides high strength to the bottom structure. Similar tendency is shown by behavior of the plate in Figure 10b, and stiffener in Figure 10c. Comparison of three members concludes that the lower stiffener experiences the highest acceleration, which is followed by the bottom plate. And

Figure 9: Effect of element formulation to hourglass energy in non-linear analysis.

from three axes, the longitudinal direction of the geometrical system has the highest peak acceleration especially during crushing process takes place on the second transverse floor. The direction of rock impact, and position of the specific members are two correlated aspects to the acceleration behavior. Both plate and stiffener are located in longitudinal direction, but the stiffener, which is in xz plane produces the highest peak as the z axis or vertical direction of this member makes frontal interaction with the rock intense. Even though the floor is also on the z axis (yz plane), the intensity is not as high as the other main members since interaction with the rock is over when the rock finally breached this member.

Confirmation of the acceleration is presented in form of displacement ratio. The ratio stands for comparison of progressive displacement in longitudinal, transverse and vertical axes with size of length L , Breadth B , and Depth H of the ship, consecutively. Prediction regarding effect of member locations to the acceleration and motion behaviors is successfully validated by displacement ratio of the floor, which is the lowest in longitudinal direction compared to other main members (see Figures 11 to 13 on the longitudinal section). Similarity in terms of longitudinal displacement is achieved by the plate and stiffener, which are located in x axis.

Floor displacement on the transverse direction presented high fluctuation, which indicates that the displacement is not likely since the member is directly flipped to side and back from the floor opening. The rock is breaching the first and second floors noted by high fluctuations after $T = 0.1$ s and 0.3 s in Figure 12. Displacement on the transverse direction for the plate also indicates flap motion but it is not significant as found on the floor. Tendency of

Figure 10: Acceleration on three axes for the main members: a) floor, b) plate and c) stiffener.

Figure 11: Displacement ratio of the floor member during impact loading is applied.

the plate and stiffener show similarity in terms of gradual displacement as deeper the rock penetrates the tank. Displacement behavior of the plate and stiffener on the vertical axis indicates that the residual member parts near the tearing/opening are pushed to and move to upper side. This prediction will be matched by damage contour in the following sections.

Figure 12: Motions of the plate member in three axial directions.

5.3 Effect to geometrical thickness

When failure occurs on the bottom tank, the members experience thickness reduction progressively from their initial state until the members fail. This process is shown in Figure 14, which can be seen as a series of member thickness changes especially in $T = 0.2$ s. The edge of tearing/opening on the bottom plate reduced approximately until 10 mm.

Figure 13: Displacement of the lower stiffener during interaction with the seabed rock.

Similar phenomenon is also clearly experienced by the lower stiffener with direct observation, found in $T = 0.4$ s. It is also noted that the edge of the first and second transverse floors also experience thickness reduction. The applied impact loading conditions in this work are concluded to lead the damage pattern to be more local, and appears as tearing/opening on the bottom plate as observed in $T = 0.2$ - 0.4 s. Residual parts of plate and stiffener, which

get separated from the members after tearing, tend to get pushed as the rock progressively penetrates the structure. The presented results here are a confirmation related to the initial prediction in the structural acceleration and axial displacement of the main members, which show high intensity and quite large motion, consecutively.

Effect of the impact loading to members is summarized briefly in terms of reduction percentage as presented in Figure 15. Local damage on the tank indicates that only the main members (bottom plate, lower stiffener and transverse floor) experience thickness reduction, which lead to structural failure. This criterion also becomes an evidence related to high fluctuation after $T = 0.3$ s on the acceleration that X-intersection of stiffener and floor is exist in the second transverse floor. This intersection is also strengthened by bottom plate, and makes this location is stronger than the first transverse floor and middle part of the stiffened tank.

5.4 Strain limit

As defined in the finite element configuration, structural failure is determined by the strain limit of the applied material. Therefore, confirmation of the internal energy can be found by assessing strain behavior. As presented in Figure 16 that during impact on the tank, elements of the transverse floor and low stiffener on near the first floor are almost reaching the strain limit but do not exceed it. On the other hand, the element of the bottom plate is quite low compared to other main members. This event indicates that the selected element of the plate for stain assessment is not on the center of frontal impact, which tends to get pushed to side as the rock breaches the first floor. In further penetration, the selected element of the stiffener on the second floor reaches the strain limit and enters stagnant state which implies that crushing of the element is fully over and the rock has passed the element. Similar tendency is shown by the transverse floor and bottom plate, which are not damaged until their limit.

Overall strain contours of the members' element is shown in Figure 17, where the green parts indicating the plate and stiffener are significantly affected by the rock impact while strain of the transverse floor is only found on the edge of this member. Highly damaged parts in this illustration validate the high internal energy in the pioneer discussion regarding the main parts. The other parts are observed to experience almost no strain contours. Nevertheless, considering the internal energy, kinetic energy and acceleration show fluctuation for these members, the

Figure 14: Progressive conditions of the member thickness subjected to impact loading.

Figure 15: Reduction contour on the interacted members during impact.

strain actually occurs but in a very low level, approximately 0.011 according to progressive tendency.

5.5 Stress contour

Stress is fluctuating along the involved structures, which are deformed or getting deformed during the impact period. An estimation and confirmation related to structural strength can be estimated by assessing this criterion. As shown in Figure 18a that a high fluctuation of the main members indicates T-intersection of the first transverse floor and lower stiffener has higher structural strength

than the middle of the stiffened tank. Similar pattern is presented on the second floor (Figure 18b) where stress of three members significantly increases in moment the X-intersection begins experiencing deformation and crushing processes. Besides the stress level of local element, overall contours are presented in Figure 19 to observe structural response subjected to the rock impact. It can be quantified that the stress on the deformable structure will reach its maximum when crushing process takes place on the specific member. Middle tier of stress will be spreading to the connected members which along to the impact direction. Since the rock moves on the longitudinal direc-

Figure 16: Material strain on two different locations: a) the first floor and b) the second floor.

Figure 17: Strain contours of the tank members during its interaction with the rock.

Figure 18: Stress contours on two different locations: a) the first floor and b) the second floor.

Figure 19: Effective stress (von-Mises) contours on the impacted tank.

tion, the stress expands to lower stiffener and bottom plate of the stiffened tank. The second floor starts getting influenced by stress when tearing arrives on the middle of the tank. During $T = 0.3-0.4$ s, middle tier stress also expands to both sides (on the transverse direction) of the rock movement, which indicate the two girders are affected by stress but not high enough to cause these members to experience high strain.

6 Conclusions

A series of structural assessment on the stiffened bottom tank of the chemical carrier was conducted by considering selected crashworthiness criteria during applied impact loading. The calculation data was successfully produced by deploying the finite element analysis, which configuration of the numerical system is designed to perform nonlinear-dynamic simulation. The energy criterion was presented in the beginning of the discussion, which the internal energy indicated there are two classes of the involved members in impact, namely main member which

directly interacted with the rock, and other member which were not significantly affected by impact.

Destruction of the main members which on the lower structure was found immense considering explicit difference on the internal energy was also observed on the kinetic energy. Assessment on the tank structure was continued to be more local by estimating their motion response under impact. Structural acceleration provided an initial estimation that the main members were mainly getting pushed on longitudinal direction during the rock breached the stiffened tank, which the tendency was confirmed by the axial displacement. The stiffener and plate were the highly displaced members compared to the transverse floor, which was affected by position of these members. Effect of the impact on the structural behavior towards failure was assessed on the thickness reduction. Results concluded that the edge of tearing/opening experienced the highest reduction. The reduced element to zero state made the member got separated, and led to failure in form of tearing on the bottom plate and stiffener crushing. Strain criterion was discussed to verify behavior of the internal energy, which represented crushing energy. Strain contours indicated that high strain level was found on the tearing and crushed material, and no visible contours on the other members. However, because of other criteria showed values for the other members, it could be estimated that the members were affected by impact but not in significant level to cause certain failure. Stress contours confirmed this statement, which the stress was spreading on the stiffened tank in moment rock penetrated the first transverse floor.

Compact and detail configurations for numerical procedure and finite element setting are recommended to be applied in further assessment of impact loading, such as ship-offshore collision or stranding analysis. Extended study of impact on Arctic environment will be an interesting topic yet challenging as it requires more data and definition to model ice entity. Considering nature of impact loading, which is included in accidental type or can happen in practically limitless scenario, sustainable research in this topic, especially on involving marine structure and offshore construction is seriously acknowledged.

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References

- [1] Hossain, K.A., Zakaria, N.G.M., 2017. A study on global shipbuilding growth, trend and future forecast. *Procedia Engineering*, 194, pp. 247-253.
- [2] Allianz, 2017. Safety and shipping, review 2017. Allianz Global Corporate & Specialty, Munich, Germany.
- [3] DNV, 2009. Part 5 Chapter 3 Oil carriers. Det Norske Veritas, Oslo, Norway.
- [4] DNV, 2011. Part 6 Chapter 10 Nuclear biological and chemical protection. Det Norske Veritas, Oslo, Norway.
- [5] Prabowo, A.R., Bae, D.M., Cho, J.H., Sohn, J.M., 2017. Analysis of structural crashworthiness and estimating safety limit accounting for ship collisions on strait territory. *Latin American Journal of Solids and Structures*, 14, pp. 1594-1613.
- [6] Prabowo, A.R., Muttaqie, T., Sohn, J.M., Bae, D.M., 2018. Non-linear analysis of inter-island RoRo under impact: effects of selected collision's parameters on the crashworthy double-side structures. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 40, article no. 248.
- [7] Liu, B., Zhu, L., Chen, L. 2017. Numerical assessment of the resistance of ship double-hull structures in stranding. *Progress in the Analysis and Design of Marine Structures: The 6th International Conference on Marine Structures (MARSTRUCT)*, Lisbon, Portugal.
- [8] Zhang, S., Villavicencio, R., Zhu, L., Pedersen, P.T., 2019. Ship collision damage assessment and validation with experiments and numerical simulations. *Marine Structures*, 63, pp. 239-256.
- [9] Prabowo, A.R., Sohn, J.M., Bae, D.M., Cho, J.H., 2018. Estimating structure response and progressive failure of a ship hull under side-bow collisions. *Tehnicki Vjesnik*, 25, pp. 1513-1522.
- [10] Prabowo, A.R., Muttaqie, T., Sohn, J.M., Bae, D.M., Setiawan, A., 2018. On the failure behaviour to striking bow penetration of impacted marine-steel structures. *Curved and Layered Structures*, 5, pp. 68-79.
- [11] Moulas, D., Shafiee, M., Mehmanparast, A., 2017. Damage analysis of ship collisions with offshore wind turbine foundations. *Ocean Engineering*, 143, pp. 149-162.
- [12] Zhou, Q., Peng, H., Qiu, W., 2016. Numerical investigations of ship-ice interaction and maneuvering performance in level ice. *Cold Regions Science and Technology*, 122, pp. 36-49.
- [13] Cao, B., Bae, D.M., Sohn, J.M., Prabowo, A.R., Chen, T.H., Li, H., 2016. Numerical analysis for damage characteristics caused by ice collision on side structure. *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering – OMAE*, 8, article no. V008T07A019.
- [14] Wang, L., Yang, L., Huang, D., Zhang, Z., Chen, G., 2008. An impact dynamics analysis on a new crashworthy device against ship-bridge collision. *International Journal of Impact Engineering*, 35, pp. 895-904.
- [15] Prabowo, A.R., Bae, D.M., Cho, J.H., Sohn, J.M., 2018. Characteristic of double bottom responses under powered-hard grounding scenario with idealized rock indenter. *International Journal of Structural Engineering*, 9, pp. 130-144.
- [16] AbuBakar, A., Dow, R.S., 2013. Simulation of ship grounding damage using the finite element method. *International Journal of Solids and Structures*, 50, pp. 623-636.
- [17] Prabowo, A.R., Sohn, J.M., Bae, D.M., Harsritanto, B.I.R., 2018. Crashworthiness assessment of double-hull tanker structures

- under ship grounding actions. *MATEC Web of Conferences*, 195, article no. 04008.
- [18] Prabowo, A.R., Cho, H.J., Lee, S.G., Bae, S.J., Byeon, J.H., Bae, D.M., Sohn, J.M., Harsritanto, B.I.R., 2018. Evaluating structural crashworthiness and progressive failure of double hull tanker under accidental grounding: bottom raking case. *Open Engineering*, 8, pp. 193-204.
- [19] Prabowo, A.R., Bahatmaka, A., Cho, J.H., Sohn, J.M., Bae, D.M., Samuel, S., Cao, B., 2016. Analysis of structural crashworthiness on a non-ice class tanker during stranding accounting for the sailing routes. *Maritime Transportation and Harvesting of Sea Resources*, 1, pp. 645-654.
- [20] ANSYS, 2019. ANSYS Mechanical APDL Element Reference. ANSYS Inc, Pennsylvania, US.
- [21] ANSYS, 2019. ANSYS LS-DYNA user's guide. ANSYS Inc, Pennsylvania, US.
- [22] Ozguc, O., Das, P.K., Barltrop, N., 2005. A comparative study on the structural integrity of single and double side skin bulk carriers under collision damage. *Marine Structures*, 18, pp. 511-547.
- [23] Lehmann, E., Peschmann, J., 2002. Energy absorption by the steel structure of ships in the event of collisions. *Marine Structures*, 15, pp. 429-441.
- [24] Wiśniewski, K., Kołakowski, P., 2003. The effect of selected parameters on ship collision results by dynamic FE simulations. *Finite Elements in Analysis and Design*, 39, pp. 985-1006.
- [25] Amdahl, J., 1995. Side collision. WEGEMT Graduates School, Technical University of Denmark, Denmark.
- [26] Zhang, S., 1999. The mechanics of ship collision. Technical University of Denmark, Lyngby, Denmark.
- [27] Prabowo, A.R., 2018. Crashworthiness assessment of ship structures under collision and grounding. Pukyong National University, Busan, South Korea.