Investigation of impact phenomena on the marine structures: Part I - On the behaviour of thin-walled double bottom tanker during rock-structure interaction

A R Prabowo, H J Cho, J H Byeon, D M Bae, J M Sohn*  
Pukyong National University, Nam-gu, Yongso-ro 45, Busan 48513 – South Korea  
jminz@pknu.ac.kr

Abstract. Predicted loads, such as crew, cargo, and structure have been applied as main inputs during ship design and analysis. However, unexpected events on the sea has high possibility to deliver remarkable losses for ship, industry, and environment. Previous oil spill incident by the Exxon Valdez in Alaska is the perfect example which an environmental damage and industry loss are initiated by an impact phenomenon on the ship, i.e. grounding. Even though hull arrangement has adopted double hull system, grounding may threaten ship safety in various scenarios. This situation pushes society to demand sustainable investigation for impact phenomena on water transportation mode to update understanding in the phenomenon and ensure structural safety during ship operation. This work aimed to study structural behaviour of chemical tanker as a marine structure under impact, namely ship grounding. Bottom raking case was considered to be calculated by virtual experiment. The study was performed using nonlinear finite element (FE) method and an idealised geometry of seabed rock would be deployed to be hard obstruction. Observation on the selected crashworthiness criteria, i.e. internal energy and crushing force indicated that as advanced penetration occurred on the ship structure, the absorbed strain energy continued to increase, while major fluctuation appeared during the initial contact between obstruction and ship happened. Damage extent of several structural members during the crushing process was shown, which concluded that the bottom plating had the largest severity in forms of tearing mode among of all members on the bottom structure.

1. Introduction
International shipping routes have been used for countless export-import operation. Distributions of raw materials and other commodities are expected to take place through these routes. Indonesia as an archipelago country holds important roles as involved parties in this activity and acts as both distributor and host. The host here is given as Indonesia water territory is included in international route, for example, Bali and Sunda straits. In international shipping territory, accident tends to take place with various causes which human error, weather, and navigation are several examples of them [1]. Especially for strait and shallow water territory, crash incident between two objects may happen suddenly, and immense damage occurs on involved parties. Collision and grounding have been observed as the most often cause of water environment pollution since after these events take place, other chain reactions (ship sinking, oil spill, coral damage) occur. In a high-profile accident, such as ship grounding of the Exxon Valdez in Prince William Sound, wide-range damage to maritime environment in form of species extinction occurred in this area. In other location, impact damage on the hull of a passenger liner, Costa Concordia in Off Isola del Giglio, caused remarkable human life losses. The effort to investigate these incidents may be continuously preformed as there is always demand to rise the quality of safety for involved elements in shipping, e.g. passenger, cargo, and structure. Possibility of ship grounding,
collision and other impact phenomena can be determined as countless, which makes this field is always interesting and attracts various researchers to study it. Variety on impact phenomena was presented for example by Alsos and Amdahl in terms of stranding [2], and Prabowo et al. [3-5] for side collision investigation and structural safety on Northern and Southern Sea routes, and Bae et al [6] for their numerical prediction of ice-structure interaction at the Arctic. Even though several aspects have been studied in pioneer researches, impact phenomena always offer opportunity to study other variety in interaction scenarios. Investigation of structural behaviour in ship grounding itself can be conducted by several perspectives, such damage mechanism, seabed characterization and crashworthiness criteria. In the present study, prediction of structural behaviour on the bottom structure would be observed based on crashworthiness criteria and damage extent. Resistance of the ship structure is discussed based on the summarized FE experimental data. Response contours of several bottom members were shown to estimate further failure events.

2. Literature review of ship grounding

The process of ship grounding can be considered as a complicated process. It involves large contact force in short time, which is delivered to the large amount of structural members such as shell plating, longitudinal stiffener, bottom floor, etc. Several works had been conducted in order to assume sea-bottom topology which is considered important in term of damage extent on the ship structure. Many of these works were performed based on remarkable grounding incident Exxon Valdez in 1989. Damage pattern of this incident was adopted and used as a foundation to develop analytical form solution for cutting mechanics [7]. Simonsen also performed a future research to introduce analytical solution of raking problem [8]. In case of grounding phenomenon, there is a similarity with collision problem which is represented by a truncated cone is forced to penetrate hull structure [9]. Based on these literatures, the grounding phenomena is fundamentally classified in two major groups, namely:

1. Grounding on soft seabed, which is called soft grounding. The damage to the hull in terms of crushing at the point of ground contact is limited but the hull girder may fail in a global mode due to shear force and bending moment exceeding the hull girder capacity.
2. Grounding on hard bottom, which is called hard grounding. The main concern here is the local crushing and tearing of the ship bottom due to a cutting by rock.

HARDER project was concluded in 2003 and the damage data was processed further by Lützen and Simonsen [10]. Statistical tendency indicated that if deformations go deep into the hull, the magnitude of structural damage is likely to be local. While in the other hand, if large parts of the ship breadth are damaged, the penetration will be small. In concluded part, it can be said that damage extent on ship structure is highly influenced by shape and size of obstruction or rock on sea-bottom.

3. Ship model and analysis setting

The ship was modeled after 17,000-ton chemical tanker, which its dimensions were given as follows: length \( L_{oa} = 144 \) m, breadth \( B = 22.6 \) m, and height \( H = 12.5 \) m. Cargo tank was divided by five transverse bulkhead, and it had average tank length 14 m. Geometry of the ship model was defined as arrangement of thin-walled plate applied by material formulation plastic-kinematic model embedded in ANSYS LS-DYNA [11]. Plate material for this work considered typical marine steel with density \( \rho = 7850 \) kg/m\(^3\), Young’s modulus \( E = 210000 \) MPa, Poisson’s ratio \( \nu = 0.3 \), and Yield strength \( \sigma_Y = 315 \) MPa. It was important step to define structural failure since remarkable damage could be expected in ship grounding. Failure on the ship was defined as the material surpassed their ultimate strain limit. Failure strain value 0.2 was applied on material model for the ship. Meshing size was considered essential to achieve accurate result in reasonable calculation time. In this study, the ship was built using shell formulation fully integrated Belytschko-Tsay (formulation number = 12) [11] and element with size 100 mm x 100 mm considering element-length-to-thickness ratio [3]. Especially for the shell
formulation, this option was chosen to evaluate weather undesired behaviours, for example, hourglass, could be repressed in simulation. Grounding simulation was performed in raking impact between the center structure of the ship and seabed obstruction. Rock topology used in pioneer work of Prabowo et al. [5] would be used as idealised obstruction. Properties of pyroxene mineral on crustal ocean formation (density \( \rho = 4002 \text{ kg/m}^3 \), Young’s modulus \( E = 147000 \text{ MPa} \), and Poisson’s ratio \( v = 0.281 \)) was inputted to rigid material to complete the involved entities in hard-grounding scenario. In addition to the engineering model, the friction properties were also applied as influenced parameter since contact between two entities is found during ship-rock grounding. Typically, static coulomb friction coefficients (\( \mu_s \)) in the range of 0.2-0.4 are adopted for rock and steel contact. In simulation carried out in the following section, the standard coefficient of 0.3 would be applied in contact configuration.

During interaction process between the ship and obstruction, the ship was restrained on the centerline by boundary condition applied to the edge of inner bottom, bottom and bilge plates. Fixation was given for axial and rational displacement. Meanwhile, the obstruction was embedded by velocity 10 m/s to move in longitudinal direction to the ship. Illustration of the ship grounding is presented in Figure 1. Interaction between two entities was defined as the surface-to-surface contact which the time simulation was assumed to be very short with \( t = 0.5 \text{ s} \) since the grounding was categorized in impact phenomena.

4. Results and discussion
The result of the proposed grounding scenario is presented in this section. In term of damage extent, the lower side of the double-bottom structure experienced major damage as the bottom plate and watertight floor got completely torn off after contacted with the obstruction. Direct contact was also involving the obstruction with the longitudinal girder and bottom stiffeners. In the end of the simulation, it was obtained that the extent of damage was approximately 4.6 m in length (\( l \)) and 1 m in width (\( w \)). Detail of this finding is summarized with the strain-damage contour of the watertight floor in forms of illustrations which are shown in Figure 2. The observation was extended to local deformation of the involved structural members. As already noted from the global results, the bottom plate and stiffener were also damaged in grounding. Specifically presented in Figure 3a, the damage on bottom plate was found massive as clean tearing was observed. This result has good correlation with Alsos and Amdahl [2], as in the grounding, bottom raking is dominated by cutting by indenter and it is found very different with quasi-static crushing processes. Meanwhile illustration in Figure 3b indicated that after grounding process, the bottom stiffener had experienced similar phenomenon with the bottom plate which under thickness reduction on the nearest part to the penetration route. This reduction has similar concept with
necking phenomenon which can be found during a specimen is tested by tensile load. Confirmation in crushing process concluded that the ship structure experienced failure according to good mechanism.

Figure 2. Strain contour and damage extent of the ship structure: (a) global response from lower view, and (b) tearing on watertight floor.

Figure 3. Local damage highlighted by the percentage of thickness reduction contour on the members: (a) bottom plate, and (b) bottom stiffener.

Previous results were verified by concentrated strain energy and critical stress (von Mises) contours as presented in Figures 4 and 5 consecutively. It was found that in grounding process with time estimation under one second and ship velocity 10 m/s, the obstruction was able to breach two intercostal members (girder-floor intersection) which provided the highest resistance on the bottom structure. Condition in the end of simulation indicated that the third intercostal was almost breached, and both strain and stress were concentrated on lower part of the longitudinal girder (this part is pointed by arrow in Figures 4 and 5). If the grounding process was extended, this location was predicted to be the initial fracture before it expanded to the longitudinal direction which was same direction as the penetration.

Besides global and local damages, crashworthiness criteria was also important to be assessed, especially to observe overall process of ship grounding and numerical calculation. Therefore, the internal energy and crushing force graphs are presented in Figure 6a. The internal energy was defined as an amount of energy that is needed to plastically deform the involved objects in impact. During contact between rigid and plastic objects, the energy was completely used to deform the deformable object. The crushing force was the magnitude of the contact force in crushing process of the deformable structure. History of the
internal energy and crushing force indicated that during the initial contact between the double bottom structure and obstruction, the energy increased until approximately in range 0-1 m of the obstruction’s displacement. In same time range, the force fluctuated intensively since interaction between the obstruction and intercostal members (the watertight floor, longitudinal girder, and bottom plate) which possessed the highest resistance on the double-bottom structure was initiated.

![Figure 4](image1.png)  
**Figure 4.** Pressure contour and concentration location on bottom structure.

![Figure 5](image2.png)  
**Figure 5.** Stress characteristic and predicted position of initial fracture in further penetration.

![Figure 6](image3.png)  
**Figure 6.** Energy during the rock impacted the structure: (a) showed internal energy and crushing force, while (b) presented kinetic and hourglass energies.

After these members experienced failure, the force decreased for a moment, and increased again during contact with the second intercostal members (approximately after 3 m displacement). However, since this contact was already started with the destruction of the bottom plating and longitudinal girder, the fluctuation in this part was not as high as the first intercostal. Observation on the kinetic energy was also done as it is presented in Figure 6b. A significant increment was observed during 0.5 m obstruction
displacement. This position was matched with the moment of the obstruction breached the first intercostal members. After this period, the kinetic energy reduced which was similar to the crushing force. The second rising occurred in the crushing process of the second intercostal in 3 m displacement which was also well correlated with the crushing force. Furthermore, the hourglass phenomena was observed, since in the nonlinear phenomena, such as grounding and collision, it affected the structural behaviour and made the members deformed in unphysical process. Application of the fully integrated Belytschko-Tsay was considered well enough to present satisfactory in avoiding hourglass with amount of the hourglass energy in the present work was zero through the end of obstruction displacement.

5. Conclusions
This work presented a study in estimating structural behaviours of the double bottom structure during ship grounding. In terms of the global response, the damage was dominated by the lower structure namely the bottom shell. This results was concluded match with analytical theory of the grounding mechanics. Observation on the local deformation was successfully estimating locations of the strain-stress concentration and expected rupture initiation. Comparison of structural responses, i.e. the internal energy, crushing force, and kinetic energy indicated that the steep increment and high fluctuation represented the structural member, namely the intercostal had exceptionally high structural resistance. Besides physical results, discussion on the numerical definition for complex structure, such as a ship, was also conducted in this study. Implementation of suitable shell formulation, i.e. fully integrated element would be helpful to obtain a good result in acceptable time process.

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