Investigation of impact phenomena on the marine structures: Part II - Internal energy of the steel structure applied by selected materials in the ship-ship collision incidents

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Abstract. Phenomena of impact loads on the marine structures has attracted attention to be predicted regarding its influences to structural damage. This part demands sustainable analysis and observation as tendency may vary from one to others since impact involves various scenario models and the structure itself experiences continuous development. Investigation of the damage extent can be conducted by observation on the energy behaviour during two entities involve in a contact. This study aimed to perform numerical investigation to predict structural damage by assessing absorbed strain energy represented by the internal energy during a series of ship collisions. The collision target in ship-ship interactions were determined on the single and double hulls part of a passenger ship. Tendency of the internal energy by the steel structures was summarized, and verification was presented by several crashworthiness criteria. It was found that steel structures applied by the material grades A and B produced different tendencies compared to the material grades D and E. Effect of the structural arrangement to structural responses in terms of strain and stress indicated that the single hull presented contour expansion mainly on the longitudinal directions.

1. Introduction
Distribution of large mass products is conducted mainly by the water transportation mode these days. Consideration in terms of delivery time and packing cost make ships as the vital member in international trading. However, challenges rise as the ship may be a subject to impact phenomena. The concern on this matters require adequate attention from several involved parties in the trading industry, since the further casualties for structure, crew/passenger, and environment in several cases has already evidenced unaffordable. In the end of the 19th century, more than 400 life losses were recorded during the Salem Express was struck on a reef, sank within ten minutes. More casualties were found on maritime disaster of the MV Doña Paz after colliding with the MT Vector. Approximately human casualties were 4000 lives which made this accident to be the deadliest ferry history in history during non-war period. Before life losses occurs, the impact phenomena produce structural damage on ships. Countermeasure to avoid remarkable casualties can be started by conducting assessment of structural resistance and damage contour on the ship. Fundamentally during any contact, the involved entities have their resistance which the weaker entity will experience larger deformation. Resistance level can be vary according to several influences on the ship structure. Based on the previous work by Prabowo et al. [1], material type to be a reasonable method to increase the structural strength against impact, for both operated ships on the Southern and Northern Sea Routes. International regulation [2] is established to keep the structural strength on the track and meet the safety requirement. Several material grades are denoted to be options for applied material on ship hulls, especially side hull and double bottom which frequently to be the targets for collision and grounding consecutively.

The present work was addressed to estimate effect of the applied materials on the collision resistance and damage extent during ship collision incident. Crashworthiness criteria were evaluated to present
influence level of the selected materials which were taken based on the international requirement for marine steel structures. Internal mechanics in crushing process were estimated by observation on the response contour on the target. In the result’s discussion, comparison in terms of the influence level between applied materials would be presented.

2. Literature review of impact engineering and marine structures

2.1. Impact assessment

Development of modern technology leads engineering analysis to be conducted by various methodologies, or even combinations of them. Structural assessments for accidental collision phenomena were performed using numerical method, finite element (FE) analysis by Bae et al. on the strait region in forms of ship-ship collision [3], and Arctic environment by simulating ice-structure interaction [4]. Description for offshore design was also compiled by Storheim and Amdahl [5] who possibility of considered ship-platform interaction. Various factors in collision make this field is interesting and continuously requires sustainable analysis to provide broad references regarding phenomena, both in the external dynamics and internal mechanics on the ship collisions [6,7]. Other research group also paid their attention to special cases, in forms of explosion to offshore installation [8] and torpedo impact on submarine hull [9]. Results of the mentioned studies in this section can be possibly expanded to safety design and navigation development areas.

2.2. Material requirement

Material is an inseparable part for every entities in engineering theory and practice. Implementation of various material types in shipbuilding has a main objective to provide better safety and operability. In event of accidental collision, steel material and structure work to provide resistance against penetration by other entity, such as ship. Global standard to guarantee material quality for designated steel structures is established by International Association of Classification Society (IACS) as international organization which consists of several main ship classification societies. The summary of the materials’ composition and strength is given in Tables 1 and 2. This standard provides detail requirements, including material treatments and composition percentage to achieve adequate material strength.

| Grade | A | B | D | E |
|-------|---|---|---|---|
| Deoxidation practice | For $t \leq 50$ mm | For $t \leq 50$ mm | For $t \leq 25$ mm | Killed and fine grain treated |
| | Any method except rimmed steel | Any method except rimmed steel | Killed | |
| | For $t > 50$ mm | Killed | For $t > 25$ mm | Killed and fine grain treated |
| | Killed | Killed | fine grain treated | |

| Grade | Chemical composition | Mechanical properties |
|-------|---------------------|-----------------------|
| | C max. (%) | Mn min. (%) | Si max. (%) | P max. (%) | S max. (%) | Al min. (%) | Yield strength min. (MPa) | Ultimate strength range (MPa) |
| A | 0.21 | 2.5 * C | 0.5 | 0.035 | 0.035 | - | 235 | 400-520 |
| B | 0.21 | 0.8 | 0.35 | 0.035 | 0.035 | - | 235 | 400-520 |
| D | 0.21 | 0.6 | 0.35 | 0.035 | 0.035 | 0.015 | 235 | 400-520 |
| E | 0.18 | 0.7 | 0.35 | 0.035 | 0.035 | 0.015 | 235 | 400-520 |
3. Preparation and procedure

3.1. Numerical geometry and configuration

Ship geometries were defined based on role of the involved entities in collision process. During side collision impact, the striking ship was addressed to a 144 m cargo reefer which performed a penetration to selected target on the 85 m passenger vessel. This vessel was denoted as the struck ship as penetration would take place on the side of this ship. Selected target location on the struck ship (Figure 1) was determined on two different parts, namely single and double hull structures which the numerical geometry of this part was modelled according to actual dimension. The striking ship was defined as the rigid characteristic (non-deformable), and side structures of the struck ship were given the plastic-kinematic material model [10]. It was assumed that all energy in contact was absorbed by the struck ship possessed deformable structures. All geometries were built by shell element formulation the Belytschko-Tsay with element formulation (EF) = 0, and embedded automatic surface-to-surface contact in ANSYS LS-DYNA [10] was used to define ship-ship interaction in collision. Considering simulation time was essential in nonlinear analysis, the explicit methodology with the determined time process $t_s = 0.486$ s was suitable to load type of ship collision and grounding [11]. Variation of structural strength was presented using different material type according to IACS requirements [2]. There were four normal steels to be applied on the geometries with following details: density $\rho_{A,D,E} = 7.870$ kg/m$^3$; $\rho_{B} = 7.858$ kg/m$^3$; Poisson’s ratio $\nu = 0.29$; yield strength $\sigma_{Y-A} = 370$ MPa; $\sigma_{Y-B} = 395$ MPa; $\sigma_{Y-D} = 340$ MPa; and $\sigma_{Y-E} = 325$ MPa. On the struck ship, fixations for axial and rotational displacement were applied on connection between shell and frame. Meanwhile, the striking ship was given a constant velocity, and displacement was only allowed in the transverse direction.

![Figure 1. The geometries of the selected targets during ship collision: (a) AP section-single hull, and (b) midsection-double hull.](image)

3.2. Dynamic collision scenario

The scenario for this study considered accidental side collision (Figure 2), which the striking was coming from transverse direction, and contact with the side hull of the struck ship. Applied velocity according to the average speed of the cargo reefer $v_a = 12$ knots, or approximately 6.17 m/s was given to the striking ship. Crashworthiness criteria, namely the absorbed energy and crushing force would be assessed to evaluate material influence on the struck ship. Furthermore, response contours of the plastic strain and thickness reduction and critical stress (von Mises) would be summarized to verify the structure criteria.

4. Results and discussion

The results in this study would observe structural responses of the struck ship during and after penetration by the striking ship. Firstly, the internal energy was discussed. This energy is defined as the amount of energy magnitude that is needed to plastically deform the involved entities in any contact form. Beside the internal energy, the collision force of all materials is also presented in Figures 2 and 3.
This response describes the force level that is experienced by the struck ship during ship-ship collision. As described in the basic formulae of mechanical work, the experienced energy and force for same entity will be perpendicularly equivalent. In terms of the midsection-double hull structures, the initial rupture was predicted during tendency of the collision force was escalating in displacement range 0.5 - 1 m. The energy on the displacement 1 m was found reduce in 1.25 m which could be estimated as the initial rupture of the outer shell. Meanwhile, after passing this displacement range, the force reduced as for a moment the target (outer hull of the struck ship) had passed its ultimate point. It is a nature of the steel material which after passing the yield and ultimate strengths, it experiences rupture/failure together with reduction of the stress. A simple version of this phenomenon can be seen in the tensile strength test.

When approaching the end of collision process (approximately displacement = 2.75 m), the striking ship was successfully penetrating the inner shell of the struck ship. However, this penetration was considered minor without significant transversal tearing on the shell. After discussion regarding structural criteria, an observation on the applied materials was also addressed. Yield strengths of the material grades A and B differed by 25 MPa or the A was 5% stronger than the B. If it was compared to collision scenario using the grades D and E (see detail explanation in Section 3), distinction between the grades A-B was...
higher than the grades D-E. Related to this comparison, it was concluded in terms of the internal energy that grades A-B presented higher distinction than D-E, which equally perpendicular with difference of the yield strength. These results could be used as a useful reference in future works, especially in structural assessment to quantify polar-class material failure on complex structures and nonlinear loads. Furthermore, satisfactory was also achieved from these results, as material grade with higher yield strength produced higher energy and force levels. However, it should be noted that low level hourglass energy (Figures 2 and 3) occurred during the displacements surpassed 1 m or in other words, after initial failure. Even though it was not significant, the authors encourage to deploy the fully integrated shell element formulations for impact analyses, including collision, grounding and explosion.

![Figure 4](image_url1)  
**Figure 4.** The plastic strain contour on the struck ship: (a) AP section and (b) midsection.

![Figure 5](image_url2)  
**Figure 5.** The plane stress contour on the struck ship: (a) AP section and (b) midsection.
An expanded observation on the structural arrangement was conducted and it was indicated from the results that significant difference in terms of the deformation pattern and response contour were obtained when the AP section and midsection were compared. The AP section which was strengthened by a stringer and possess no inner hull, produced strain contour mainly in longitudinal direction or in same direction as the stringer (see Figure 4a). In other hand, illustration in Figure 4b indicated that damage on the midsection occurred mostly on the vertical direction as the structure was dominated by transverse frames. Confirmations of these results were presented in forms of the plane stress (Figure 5) which contour expansion of the stress was recorded on the longitudinal direction for the AP section, and the maximum plane stress on the midsection was shown on the vertical direction.

5. Conclusions
The present work described a series of collision analyses that involved material strength and structural type as the main parameters. It was concluded from the results that the double hull structure provided the best resistance against side collision when it was combined with the steel Grade B. In further discussion, progressive structural failure was successfully estimated based on the crashworthiness criteria. Special treatment by applying suitable element type for geometry model in nonlinear analysis was required to avoid hourglass phenomenon in crushing process. Contour of the plastic strain and plane stress were evaluated, and the correlation in terms of the expansion tendency was judge well enough.

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