Research Article

Aditya Rio Prabowo, Teguh Muttaqie, Jung Min Sohn*, Dong Myung Bae, and Agus Setiyawan

On the failure behaviour to striking bow penetration of impacted marine-steel structures

https://doi.org/10.1515/cls-2018-0006
Received Jan 21, 2018; accepted Mar 07, 2018

Abstract: Demands for water transportation modes are continuously increasing as rapid economic and industrial growths in the recent decade. Ship as representative of the water transportation is generally needed to carry various products from one location to another. Besides as product carrier, ship also acts as public facility to transport human across islands for number of reasons, such as tourism and vehicle. Considering its importance, structural damage due to accidental loads or so-called impact can cause unacceptable casualties which threat ship passenger, shipping industry and maritime environment in same time. The most frequent impact phenomena occur in forms of collision and grounding, which are targeting side structure and double bottom consecutively. However, since responses of the impacts on structure are highly nonlinear and vary due to development of ship structures, sustainable analysis as an update of pioneer calculation can be beneficial as rational reference for improving safety and navigational instruments. This work aims to assess failures of the side structures subjected to penetration of striking bow in ship-ship collision scenario. Locations of impact are idealized to happen on after-end, midsection and fore-end to provide complete assessment. Striking bow is to be deployed by varying input velocity to observe significance of the fractures on the side structure. This configuration is implemented on the designed collision scenario, and later calculated using nonlinear finite element method (NLFEM). Summary of the solution indicated that the midsection produced the highest resistance against side collision. Breaching of the inner shell was successfully avoided on the fore-end, but the critical damage to the cargo was observed during bow penetration to the after-end region. This location was recommended to be added by longitudinal framing to increase its resistance against ship collision.

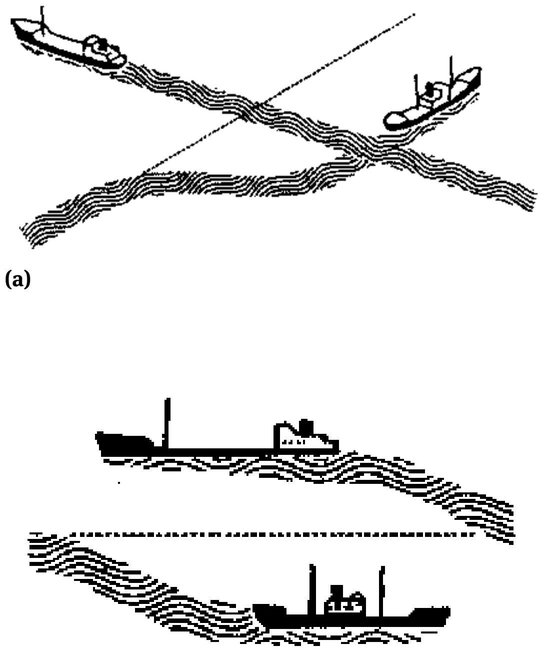
Keywords: Ship collision, single and double hulls, nonlinear finite element method (NLFEM), material sensitivity, crashworthiness criteria, progressive structural failure

***Corresponding Author: Jung Min Sohn:** Interdisciplinary Program of Marine Convergence Design, Pukyong National University, South Korea; Department of Naval Architecture and Marine Systems Engineering, Pukyong National University, South Korea; Email: jminz@pknu.ac.kr; Tel. +82 (0) 516296618; Fax. +82 (0) 516296608
Aditya Rio Prabowo: Interdisciplinary Program of Marine Convergence Design, Pukyong National University, South Korea; Department of Naval Architecture, Diponegoro University, Indonesia
Teguh Muttaqie: Department of Naval Architecture and Marine Systems Engineering, Pukyong National University, South Korea; Agency for the Assessment and Application of Technology, Indonesia
Dong Myung Bae: Department of Naval Architecture and Marine Systems Engineering, Pukyong National University, South Korea
Agus Setiyawan: Center for Fisheries Research, Ministry of Marine Affairs and Fisheries, Indonesia; Department of Environmental Science and Management, University of Rhode Island, United States

1 Introduction

Transportation role in society has been expanded into several modes to satisfy daily activities of human. Cargo carrier and public vehicle are the most fundamental categories in terms of the transported object. For archipelago countries, ship role as public facility is also vital, especially to support connection of tourism spots with main islands. In this case, water transportation mode is chosen, and ship is preferred to fulfil such objective. During its operation, ship sails on designated routes according to selected destination which strait is one possible route in inter-island operations. This location can be a critical point for manoeuvring (Figure 1) during two ships encounter, such as crossing and head-on situations [1, 2]. Due to numerous causes, such as bad weathers, storm, local-geographical disaster, traffic management and human-navigation error, impact on the participating ships occurs so-called collision, and structural failures can take place, regardless the sizes (see influence of the waterway systems on the probability of collision [3]).

For straits located in international shipping routes, crossing situation is frequently happens as inter-island and international routes meet in one point. Side collision is the most general possibility considering this situation,



(a)

(b)

Figure 1: Close-quarters situations for ship manoeuvring: (a) crossing situation, and (b) head-on situation [1].

which damage on struck ship due to penetration of striking bow can be fatal. Furthermore, safety of passenger and environment is threatened, and may possibly cause immense chain disaster. Aim to ensure the safety can be fundamentally divided into two main classes, *i.e.* active and passive methods. In the active methods, the navigational equipment is developed, crew requirement is set to be capable and has proficiency in dealing with accidental situation, and improvement on traffic management can also be considered in this method. However, scholars realize that despite of such efforts, collision may always occur and cause accidental failures [4–7]. Its characteristics as nonlinear phenomena allow it to appear in various scenarios. Therefore, the second method, such as development of structural crashworthiness is taken into account. Large numbers of ship in voyage across the globe, make sustainable analysis in this subject is required with purpose to estimate possible collision scenarios and minimise the experienced casualties in further accidents.

This work is addressed to conduct assessment on ship structure due to collision with other participating ship, which side collision scenario in effect of crossing situation is considered as main reference in designing the scenarios. The numerical methodology for analysing nonlinear phenomena is performed to calculate the scenarios, and the solutions are summarized so that can be used as references of assessment. Behaviours of structural failure will be focussed on the struck ship as impacted-steel structures, and structural estimation is conducted based on tendency of the selected crashworthiness criteria in collision process.

2 Structural modelling and analysis technique using NLFEM

Ship structures consist numbers of arranged steel members, such as plating and framing. The shell plating forms the watertight and hull skins of the ship and at the same time in merchant ship construction, contributes to the longitudinal strength, and resists vertical shear forces. Internal strengthening in forms of framing systems on the shell plating may be both installed in transverse and longitudinal systems according to the designated objective and route. Generally, they are designed to prevent collapse of the plating against various loads, including impact loads in maritime operations. As advance improvement of computational instrument and rising demand of quantitative assessment on shipbuilding, application of finite element method (FEM) is considered to idealise geometry of steel structures. The most common technique to conduct such modelling is by assuming the ship as thin-walled object (see Figure 2). In this case, the ship is defined in FE using shell element formulations in two dimensional geometry, and thickness is inputted by adjusting real constant value. Numbers of researches adopted this method by implementing the Belytschko-Tsay element on shell structures [8–10]. This element type is described as the fastest of the explicit dynamics shells. Transverse shear is taken in calculation by inputting the Mindlin-Reissner assumption as fundamental assumption of this element. It should be noted that constraint of the technique using thin-walled concept structural geometry is not recommended to be meshed in coarse discrete models [11].

Characterization of impact phenomena is vital to select suitable analysis methodology so that numerical simulation can be completed in reasonable time process, and acceptable accuracy is acquired. Ship collision is considered as a highly nonlinear phenomenon, which it happens accidentally in forms of large level loads but within very short time process. Considering possibility of structural damages, steel material may experience beyond yield limit and surpasses the ultimate fracture, which make the ship collision is included in the dynamic class [14].

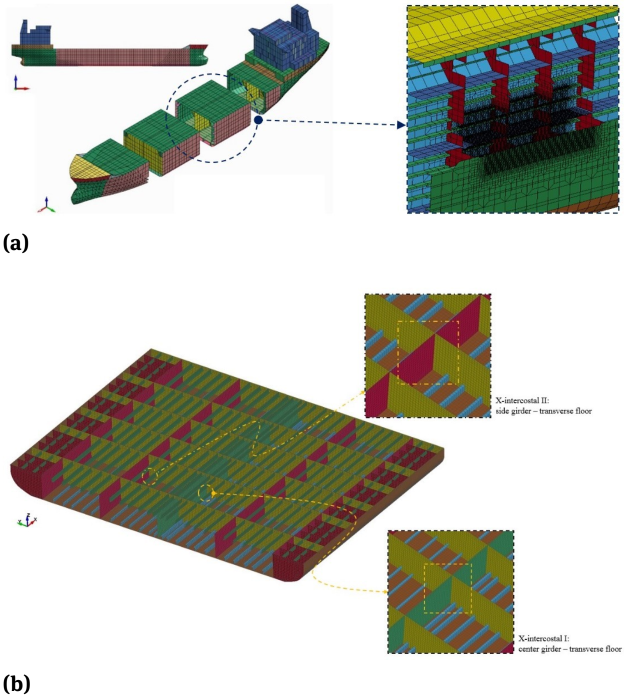


Figure 2: Examples of thin-walled geometries based on actual ship structure: (a) intersections of trans. webs and long. stiffener on the side hull [12], and (b) floor-girder intersection on the bottom structures [13].

$$\{a_t\} = [M]^{-1}\left(\left\{F_t^{ext}\right\} - \left\{F_t^{\text{int}}\right\}\right) \quad (1)$$

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

$$\left\{v_{t+\Delta t/2}\right\} = \left\{v_{t-\Delta t/2}\right\} + \{a_t\}\,\Delta t_t \quad (3)$$

$$\left\{u_{t+\Delta t/2}\right\} = \{u_t\} + \left\{v_{t-\Delta t/2}\right\}\Delta t_{t+\Delta t/2} \quad (4)$$

$$\{x_{t+\Delta t}\} = \{x_0\} + \{u_{t+\Delta t}\} \quad (5)$$

where $[M]$is the mass matrix; $\left\{F_t^{ext}\right\}$ is the applied external and body force vector; $\left\{F_t^{\text{int}}\right\}$ is the internal force vector; $\{a_t\}$ is the acceleration at time t; F^{hg} is the hourglass resistance force, $F^{contact}$ is the contact force; B^T is the body force, σ_n is the internal stress; Ω is the solid volume; $\{v_t\}$ is the velocity at time t; $\{u_t\}$ is the displacement at time t; $\{x_0\}$ is the initial geometry; $\{x_t\}$ is the updated geometry at time t; Δt_t is the difference in time of at time t compared to the initial/selected condition.

Based on these descriptions, nonlinear finite element method (NLFEM) will be selected to solve numerical model of ship collision. Specifically, explicit strategy is adopted in calculation using ANSYS LS-DYNA [15]. This strategy is judged similar with characteristic of collision action. Comparing to the implicit, nonlinear problem is solved by performing no inversion of the stiffened matrix which this phase is computationally expensive and required in the implicit strategy. Other characteristics of the explicit are a lumped mass matrix is required for simple inversion, the equations (see Equations 1 to 5) is uncoupled and can be solved directly, and convergence checks are not required since the equations are uncoupled. However, designer and engineer have to be cautious related to stability limit of the explicit. Time step size is required to be smaller than the critical time step size.

3 Sensitivity of steel material and structural fracture

Effect of material aspect to the results of any structural analysis is significance in fields of ship structure since most of merchant vessels these days are built using steel. Previous research by Jones [16] concluded that yield stress of mild steel is very sensitive to the strain rate, which is not found on aluminium. The strain-rate effect is reported in form of mathematical equation by Cowper and Symonds [17] as presented Equation 6. Other experimental test on reduced scale medium tanker panel, also used this expression to scale yield stress to obtain a simplified estimation of the total strain rate effect [18]. Cowper and Symonds described rate parameters for C and m are 40.4 s^{-1} and 5 consecutively, which often used as assumption for the mild steel. However, large damage extent and deformation contour are expected during various impact phenomena, such as collision and grounding. In this case, greater values of C (than 40.4 s^{-1}) are often preferred [19]. Applications of this approach had been considered in penetration test using rigid indenter with C = 4000 s^{-1} [18], and performance assessment of double hull by applying C = 3200 s^{-1} [20]. Concept of strain rate effect is also embedded in FE methods, which variables of the Cowper and Symonds expression are often denoted in different form, such as m is represented as P in the plastic-kinematic material model.

$$\frac{\sigma_{eq}^D}{\sigma_{eq}} = 1 + \left(\frac{\dot{\varepsilon}_{eq}}{C}\right)^{\frac{1}{m}} \quad (6)$$

where σ_{eq} is the quasi-static equivalent flow stress; σ_{eq}^D is the dynamic flow stress; $\dot{\varepsilon}_{eq}$ is the equivalent strain rate; and C, m are the Cowper and Symonds parameters.

When structures are subjected to load actions, it will experience deformation. Eventually, the deformation expands on the structures and causes structural ruptures. In this condition, structure is exposed to failure, and risk of large scale structural collapse is exist. Predictions of structural rupture are complex objectives as different loads may produce different failure modes. Jones and Wierzbicki discussed several failure criteria based on metal beam behaviours against large dynamic loads [21]. The first criterion is the *tensile tearing failure* which is reached when ultimate strain equals with critical rupture/failure strain of the material (see Equations 7). The second criterion is described as *transverse shear failure* due to occurrence of large transverse shear deformation on very short region equals a critical value as shown in Equation 8. The third criterion is the *energy density failure* which appears during critical value Θ_c is same with the absorption of plastic work per unit volume (Equation 9). Based on these criteria, structural assessment is generally conducted by considering the *tensile tearing failure*, and considers the structure is embedded by strain-dependent material. Therefore, it is vital objective to select appropriate failure strain to properly define structural ruptures. Experimental test performed by Amdahl and Kavlie [22] as well as Wen and Jones [23] showed that tensile ductility of steel in range 0.2-0.35. Based on this concluding remark, failure strain value 0.2 is to be applied in analysis configuration with assumption that when material reaches the failure strain due to impact loads, structural rupture takes place.

$$\varepsilon_{\max} = \varepsilon_c \quad (7)$$

$$W_s = kH \quad (8)$$

$$\Theta = \Theta_c \quad (9)$$

where $\varepsilon_{\max}$ is the maximum strain of material; ε_c is the experienced/critical strain; W_s is the transverse shear displacement; k is the constant in range $0 < k \leq 1.0$; H is the beam thickness which kH is the critical value; Θ is the absorption of plastic work per unit volume; and Θ_c is the critical value of energy density.

4 Ship collision analysis

4.1 Participating ship and embedded material

Structural data of a passenger ship is to be idealised as the *struck ship* which to be penetrated by a reefer carrier under collision action. The penetrating ship is later denoted as the *striking ship*. In the current study, the dimension of the struck ship is shown as follows: Length L = 85.92 m; Breadth B = 15 m; Draft T = 4.3 m; and Depth H = 10.4 m. Relative to this ship, larger striking ship is selected with the following principal data: Length L = 144.5 m; Breadth B = 19.8 m; Draft T = 5.6 m; and Depth H = 10.2 m. Selected targets are designated on different regions of the struck ship's side hull, namely after-end, midsection and fore-end as shown in Figure 3. Numerical approach is considered in this study, which the explicit codes ANSYS LS-DYNA [15] is used as nonlinear finite element method (NLFEM) to model the involved ships and calculate the designed collision scenarios. Specifically in terms of the ship model, structures are idealised using the *thin-walled concept* so that structural members are designed as shell geometry in the FE. Shell element formulation (EF) Belytschko-Tsay is applied on all ship models. Application of the meshing size on the deformable ship is following the element-length-to-thickness ratio in range 5-10 as widely used in numerical calculation for automobile industry. This method is considered more adequate and reasonable than selection of arbitral very small mesh size which can be intensively time consuming during meshing process and simulation running using average computational instrument.

Collision in this study is defined as interaction of deformable side hull of the struck ship, and rigid upper bow of the striking ship. Therefore, two material models are necessary to be defined on these ships. The deformable structures is to be applied by inelastic-kinematic hardening with strain-dependent characteristic [24]. Mathematical expression for this material model is given in Equation

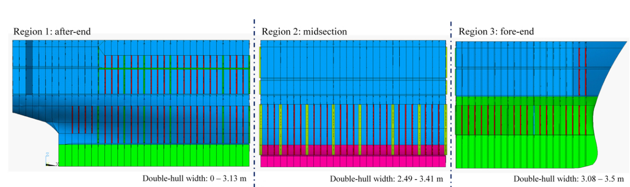


Figure 3: The denoted regions on the full-scale model of the struck ship. Size of double hull on each region is highlighted on lower part of the side hull.

10. A typical carbon steel for naval-used industry is collaborated with the selected material, with details are given as follows: Density ρ = 7850 kg·m^{-3}; Elastic modulus E = 210000 MPa; Poisson's ratio v = 0.3; Yield stress σ_Y = 440 MPa; Cowper-Symonds parameters C = 3200 s^{-1} and P (m in Equation 6) = 5; and Hardening exponent/parameter β = 0.

$$\sigma_Y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}}\right]\left(\sigma_0 + \beta E_P \varepsilon_P{}^{eff}\right) \tag{10}$$

where σ_Y is the yield stress; $\dot{\varepsilon}$ is the strain rate; C and P is the Cowper-Symonds strain rate parameters; σ_0 is the initial yield stress; β is the hardening parameter; E_p is the plastic hardening modulus; and ϵ_p^{eff} is the effective plastic strain.

4.2 Configuration of side-bow interactions

Collision scenario is built based on two parameters included in the external dynamics of ship collision, namely location and velocity. As mentioned earlier in ship model, the location of target point is selected on three regions of the struck ship, namely after-end, midsection and fore-end. The striking ship will be given by another parameter, *i.e.* velocity to move to the selected targets on the struck ship. The velocity is varied in ranges of 5-15 kts or approximately 2.5-7.7 m·s^{-1} using international unit, and to be applied in uniform type. Position during ship collision is designed to stay under side contact condition which involves side hull of the struck ship and upper bow of the striking ship. The boundary conditions are applied on the edge of model in longitudinal and transversal parts, such as main deck, middle deck, car deck and tank top. Vertical members, namely the side frame is also restrained from any displacement. The constraints are implemented to idealise the worst possible damage rather than realistic situation. In the current work, it is assumed that striking ship is approaching the target in 90° (perpendicular collision), and the struck ship is standstill against the bow penetration. Therefore, all axial and rotational displacements are fixed on the both models. As illustrated in Figure 4, only transversal displacement of the striking ship is excluded in boundary definitions. Typical friction coefficient for steel-to-steel contact with the kinematic and static values are applied as μ_k = 0.57 and μ_s = 0.74 consecutively. Automatic surface-to-surface contact formulation is chosen in preparation, with time simulation is set to be very short, which $t_{simulation}$ = 0.405 s is embedded on the nonlinear FE analysis.

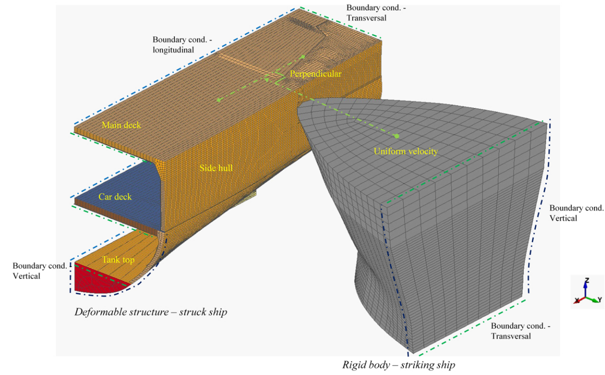


Figure 4: Configurations of the collision scenario for the FE analysis. It is highlighted that a perpendicular-side collision is set during interaction of the struck ship's hull and the striking ship's bow.

5 Results and discussion

5.1 Progressive failure on the crushing force

Assessment on the impacted structures is conducted by evaluating crashworthiness criteria and failure tendencies for each designed scenario. The first assessment is addressed to the energy level in the end of collision, which is assumed as accumulative experienced absorbed strain energy during the struck ship was resisting penetration of the striking ship. As summarized in Table 1, the energy gradually increases which is equal to increment of the applied velocity. Percentage of the increment was observed significant during the lowest velocity 5 kts was changed to 10 kts with specific range 77-82%. This range is considered higher than the energy increment from applied velocity 10 to 15 kts, which increased by 52.7%, 58.59% and 49.33% for the after-end, midsection and fore-end regions consecutively. This phenomenon is expected since in the velocity 5 kts, only minor damage and insignificant indentation took place on the side hull while these tendencies were remarkably changed when the velocity 10 kts caused massive indentation on the outer shell and side frame. Correlation with longitudinal strength of ship hull is also reaching satisfactory by observing the midsection was superior to all observed regions. As described in fundamental of structure behaviours, a ship tends to experience maximum bending loads during its operation due to sagging and hogging phenomena. This reason makes the midsection of ship is designed to be stronger than after-end and fore-end regions to withstand these loads. It is interesting research opportunity to conduct further collision-response assessment using fundamental approach by considering nature of a ship design itself.

Table 1: Summary of energy and stress criteria after collision occurred on the side hull.

Location	Velocity	Energy		Stress		
		Internal (J)	Hourglass (J)	X 10^8 (Pa)	Y 10^8 (Pa)	Z 10^8 (Pa)
After-end	5	1231450	16599	5.041-6.302	4.218-5.371	6.026-7.336
	10	5584170	161731	6.393-7.764	5.142-6.439	6.056-7.407
	15	11805200	526451	5.125-6.362	5.531-6.837	5.787-7.207
Midsection	5	1157930	25301	5.426-6.674	4.182-5.253	5.353-6.573
	10	6506660	219709	5.347-6.589	6.137-7.506	6.067-7.456
	15	15714500	500633	5.545-6.871	6.031-7.496	6.100-7.602
Fore-end	5	1054380	9369	5.446-6.778	4.666-5.849	5.966-7.302
	10	5412600	146138	5.902-7.268	4.666-5.926	5.702-7.017
	15	10683000	507463	6.721-8.135	6.261-7.761	6.222-7.650

Besides physical energy, numerical aspect of the collision simulation is presented in this discussion, in forms of the hourglass energy. Magnitude of this response represents error level of the structural model in experiencing massive deformation. According to the guidelines [15], this criterion is also possible to be used as reliability control of the FE solution in structural analysis. Same with the internal energy, the hourglass rose as higher striking velocity was applied, and the tendency was perpendicular to expected final damage state (higher energy is predicted during occurrence of more significant damage). Comparing to the internal energy, the hourglass value indicated very low state in the end of the collision. The significance percentage of the hourglass energy against the internal energy is only varying in range 0.88-4.75%. This result indicated that the performed FE analysis reached satisfactory considering the error value is very low and below 5%. After energy, the stress criterion is assessed according to three-dimensional directions in the Cartesian coordinate system. Tendency of this criterion concluded that linearity of the structural stress during side collision with energy criteria is shown by transversal or Y direction. Occurrence of this result may be highly influenced by the crushing process of the side hull due to penetration of the striking bow took place from side direction. However, stress state is highly affected by condition of member's failure in the penetration, which lower stress value of a higher striking velocity (for example see Z stress of the after-end in 5-15 kts) may occur due to impacted members reached the ultimate strength, or the members simply had not reached the failure state and stress continued to increase. Uncertainty in this aspect leads the assessment to the crushing force criterion which progressive failure for each scenario is quantified.

Tendency of the crushing force criterion is presented based on target location of the struck ship, *i.e.* after-end in Figures 5 to 7, midsection in Figure 8 to 10, and fore-end in Figure 11-13. The force level is found satisfy the relation with the striking velocity which higher force was produced during faster movement of the striking ship in simulation. Significance of structural crashworthiness on the transversal direction is also confirmed by the force fluctuation of the Y direction is dominating in every designed collision scenario. Based on this criterion, the critical point during certain failure or event takes place can be predicted. Summary of the progressive failure in 5 kts is only minor damage occurred on the side hull until the end of collision. Compared to other velocity, time to reached the target of the 5 kts in all regions is considered the longest which was approximately half of overall time simulation. In this applied velocity, the initial indention appeared on the outer shell. For the after-end, damaging on the single structural member were observed which deflection of the side stringer began to take place. On the midsection and fore-end which are covered with full-double hull design, damage on the outer hull was already appeared by indentation on shell and frame. Condition of the inner shell on these region was evaluated same with the after-end which any damage was not yet found.

On the higher velocity 10 kts, the striking was faster in approaching the target with time approximation 0.1 s. Failure was begun by initial indentation on the outer shell and followed by tearing on the frame. It was also noted that, in this velocity, the observed shell indentation in 5 kts was expanding. It made a web frame got completely torn and the middle deck was damaged on the edge part by the striking ship. Structural failure in this velocity presented a remarkable event on the double hull part of the midsection and fore-end, which the inner shell was dis-

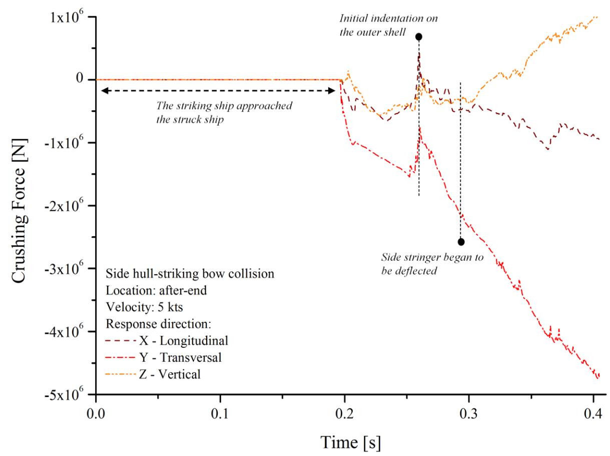


Figure 5: Patterns of crushing force, and sequences of progressive failure: after-end impacted by velocity 5 kts.

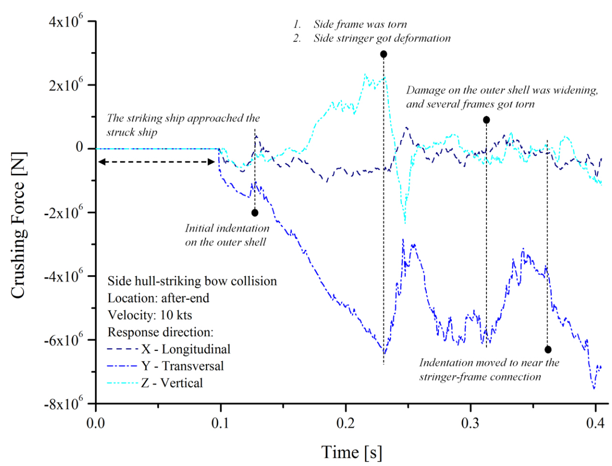


Figure 6: Patterns of crushing force, and sequences of progressive failure: after-end impacted by velocity 10 kts.

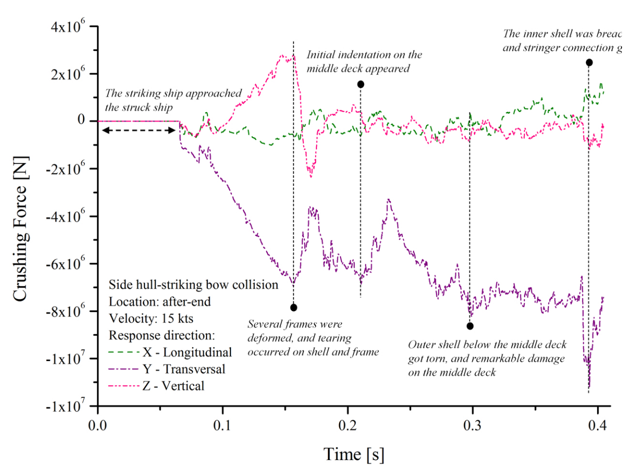


Figure 7: Patterns of crushing force, and sequences of progressive failure: after-end impacted by velocity 15 kts.

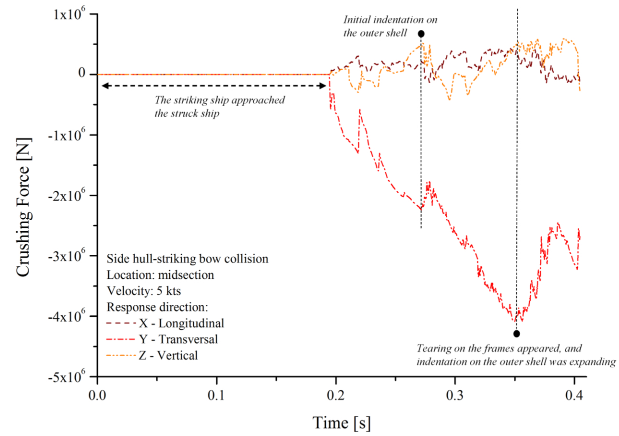


Figure 8: Force criterion and behaviour of the failure on the side hull: midsection impacted by velocity 5 kts.

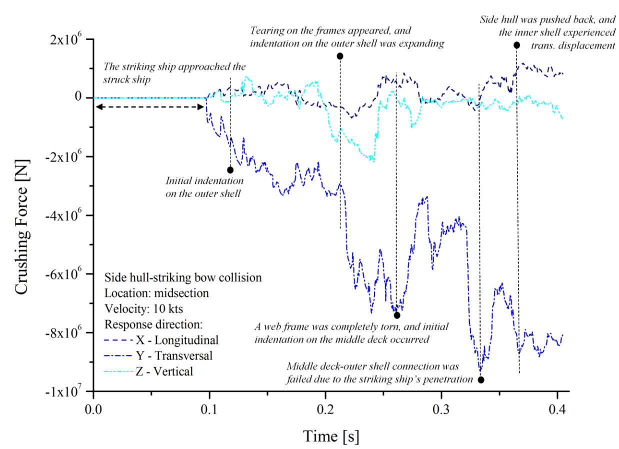


Figure 9: Force criterion and behaviour of the failure on the side hull: midsection impacted by velocity 10 kts.

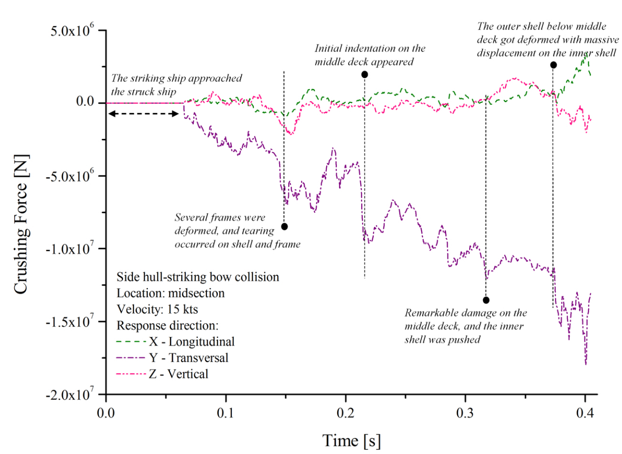


Figure 10: Force criterion and behaviour of the failure on the side hull: midsection impacted by velocity 15 kts.

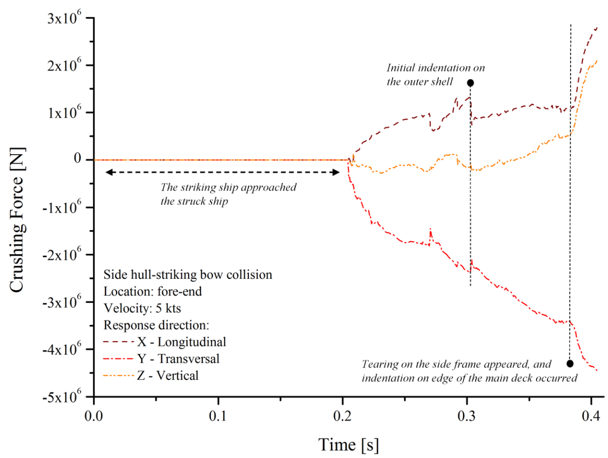


Figure 11: Structural responses of the struck ship – fore-end against collision with velocity 5 kts.

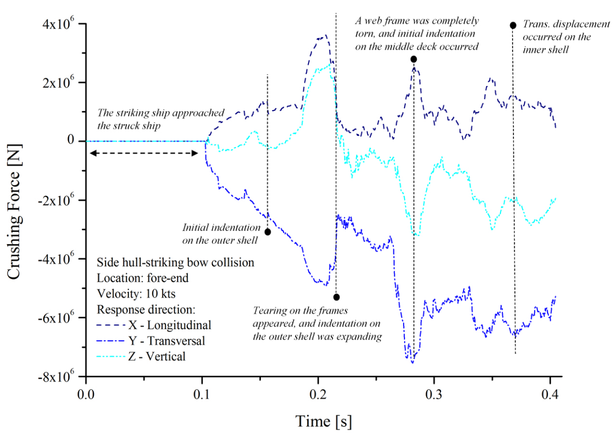


Figure 12: Structural responses of the struck ship – fore-end against collision with velocity 10 kts.

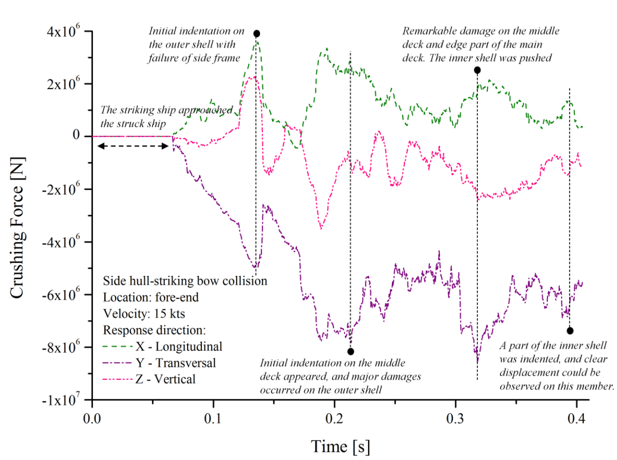


Figure 13: Structural responses of the struck ship – fore-end against collision with velocity 15 kts.

placed from its initial position after the middle deck-side shell connection was severed. As for the after-end, damage had not reached the double hull part, and side stringer which was on the single hull part was almost failed due to the penetration. In the highest velocity 15 kts, the double hull part of the after-end was finally influenced by side impact that caused remarkable damage on the middle deck. The inner shell was also breached after 0.38 s since initial movement of the striking ship. Crushing on the single hull part was considered major on the side hull-stringer. Wide tearing appeared on the outer shell and side stringer got torn. Conditions of the double hull on the midsection and fore-end region were found similar with the after-end but penetration on the inner shell was non-existent. However, axial displacements on the inner shell was significant, and it can damage cargo on the car deck.

5.2 Damage extent on the side structures

To provide complete investigation, damage extent on the struck ship is necessary to be assessed to understand the experienced failure by hull members. The damage is presented per collision region for all velocities so that severity of the side hull's damage can be evidenced. As shown in Figure 14, damage on the lowest velocity was minor with small indentation on the outer shell and range of the critical stress (von-Mises stress) expansion limited on the upper side hull of the after-end. Clear indentation in forms of tearing on the side shell and frame was spotted in the selected velocity 10 kts. Stress started to expand to lower hull part, and reached inner shell of the double hull structure. Remarkable damage as caused by the highest velocity produced complete tearing on the side stringer, and high critical stress was observed on the inner shell near the single hull part. Similar damage pattern was shared on the midsection (Figure 15) which focussed on the side hull, including the outer and inner shells. In comparison with the after-end, the inner shell of the midsection had been influenced by the critical stress since the lowest velocity was selected. This phenomenon occurred due to side hull was full covered by inner shell.

This expansion pattern was also affecting the stress contours in 10 kts which the inner parts were covered with the stress, especially middle deck. It was also indicated from the outer view that crushing damage almost reached the middle deck in the end of collision. The highest velocity 15 kts produced remarkable damage on the side hull which the outer shell lower than the middle deck was seriously deformed. Stress intensity indicated the car deck was also affected due to collision with high veloc-

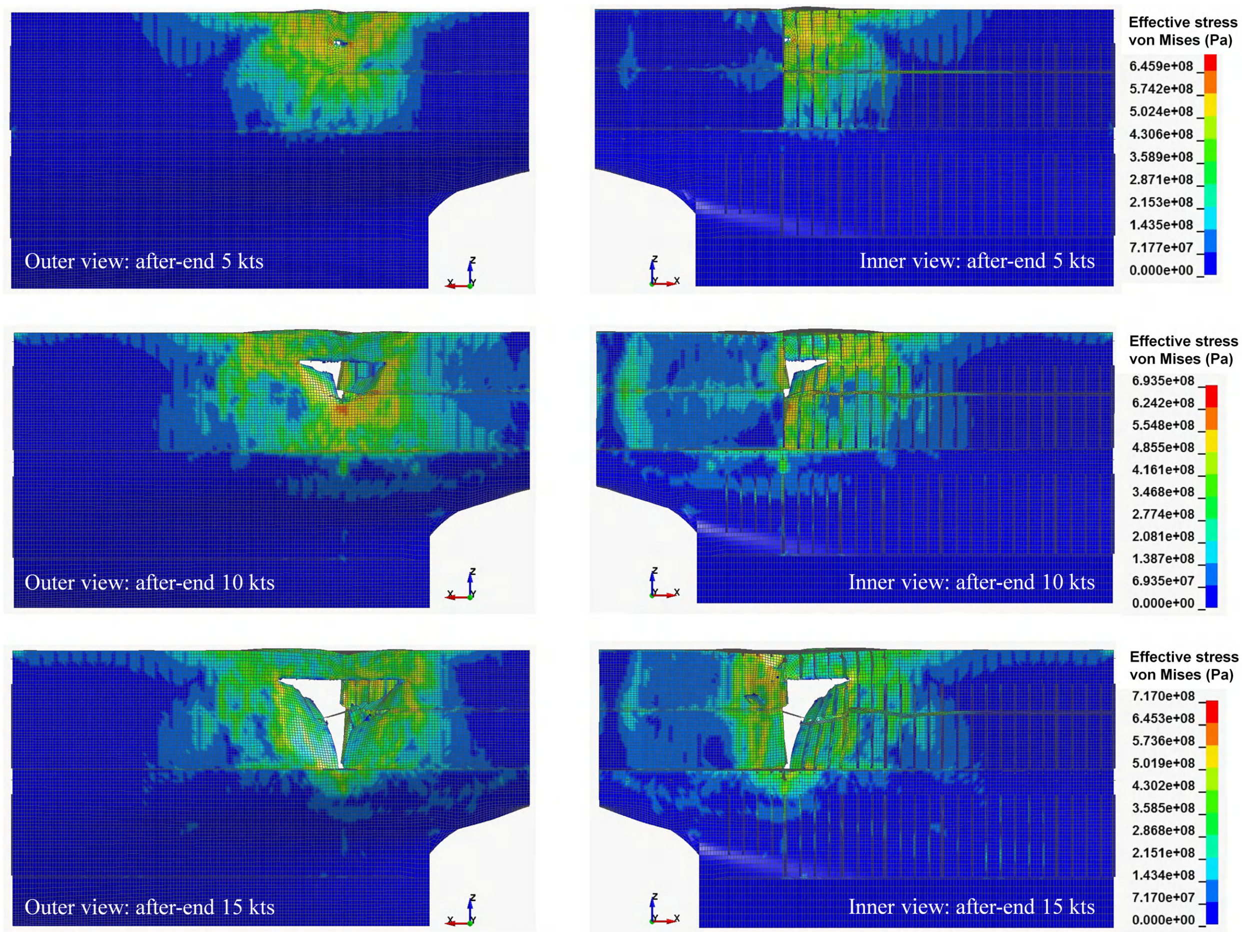


Figure 14: Damage extent and stress contours on the after-end impacted by the selected striking velocity.

ity. However, breaching of the inner shell was unlikely found in this structural region. In terms of the indentation and stress in early collision (velocity 5 kts), the fore-end was similar with the midsection. Difference began to occur since 10 kts which the main deck was severely deformed due to advance penetration of the striking ship in following tearing damages on side shell and frame. On the other hand, stress expansion on the inner shell was more clearly observed with the center of this contour was spotted on the middle deck. In the highest applied velocity, the outer shell was breached, and tearing damage formed a hole while intensity of the critical stress expanded in line with geometrical characteristic of the middle deck. Therefore, it could be concluded according characteristic of double hull structure on all regions that the displacement of the inner hull was maximum on the transversal direction near the middle deck.

6 Conclusions

This work was addressed to investigate structural response of the marine-steel structures against impact loads in various conditions. Numerical analysis was successfully performed using the finite element codes for nonlinear phenomena, namely ship collision. Criteria of crashworthy ship structures were assessed as representative of the responses in process of side collisions. Observation was initially directed to energy criterion which accumulative internal energy indicated higher magnitudes as increment of striking velocity increments. Effect of the impact location in ship collision was considered unlikely during low-velocity impact (applied velocity 5 kts) with significance in range of 6-34-8.94%. However, the similarity was lost starting from 10 kts since the midsection appeared as the region which produced the highest internal energy. Superiority of this region indicated structural arrangement was successfully providing better resistance against side collision than the after-end and fore-end. Reliability of the numerical so-

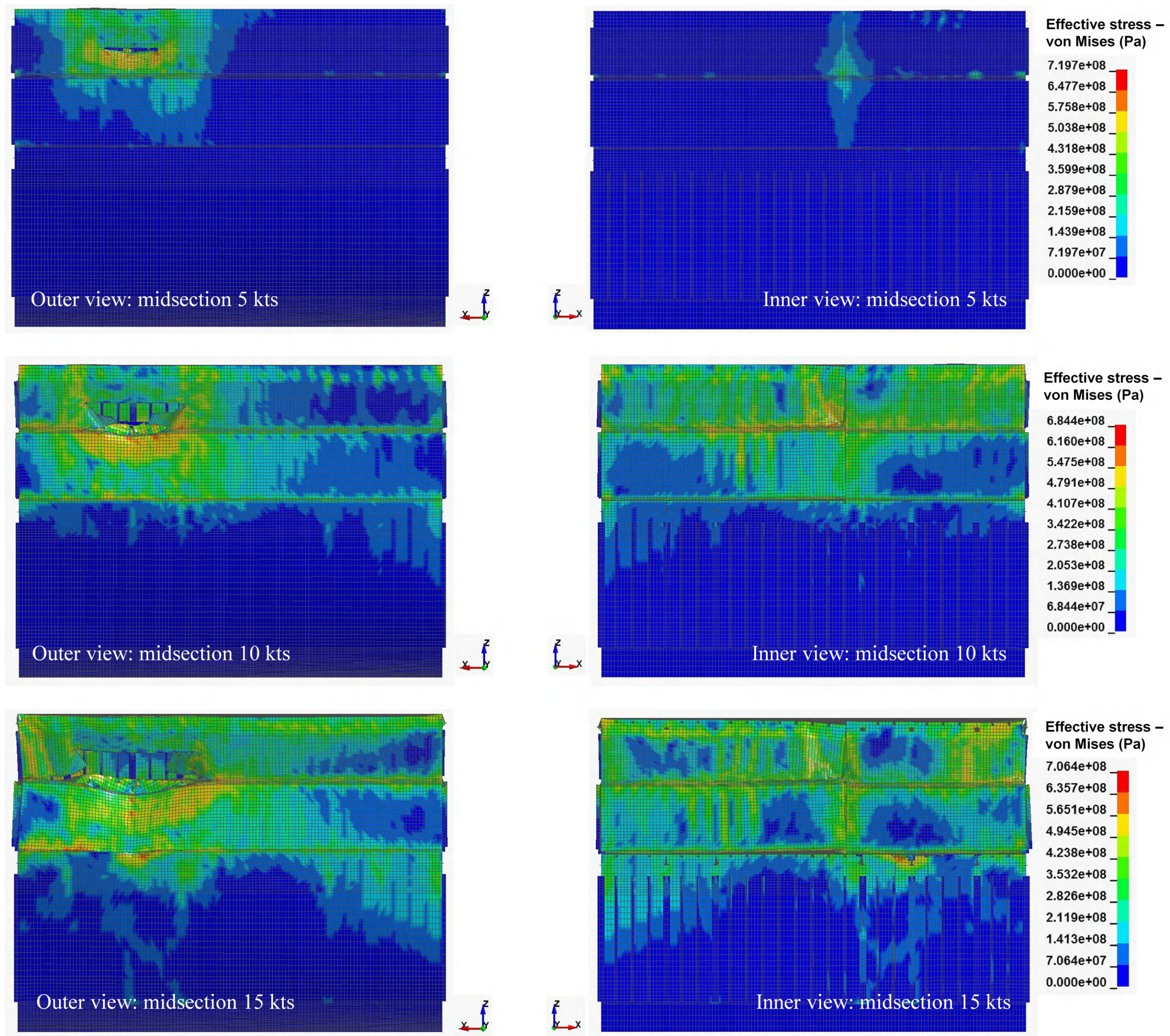


Figure 15: Damage extent and stress contours on the midsection impacted by the selected striking velocity.

lution was assessed to present adequate clarification. Very small hourglass energy with percentage against the internal energy under 5% was formed for all designed scenarios. This tendency indicated that satisfactory in terms of the numerical configuration and methodology in impact analysis was successfully achieved. Details of the current work can be used as rational reference for further work in accidental load analysis of marine structures.

After the energy, the stress criterion concluded that the most crushing process took place in line of the approaching direction of the striking ship (in this work was the transversal direction). Attention was focussed to behaviour of progressive structural failure to observe detail of affected members on the struck ship. Failure events per applied velocity were successfully quantified, with notable remark was given since 10 kts as the inner shell began to be displaced. The highest velocity selected in this work was evidenced high enough to provide remarkable damage, especially on the after-end. Collaboration of the single and double hulls on this region should be addressed by serious consideration for side impact scenario above the maximum waterline. To strengthen the single hull part, longitudinal stiffener and high-strength material can be applied as alternative of the inner hull's construction. Further works in fields of marine structural assessment considering failure sequences of the struck ship in several penetration angle can be good opportunity to validate safety of the single hull passenger ship in ship-ship collision.

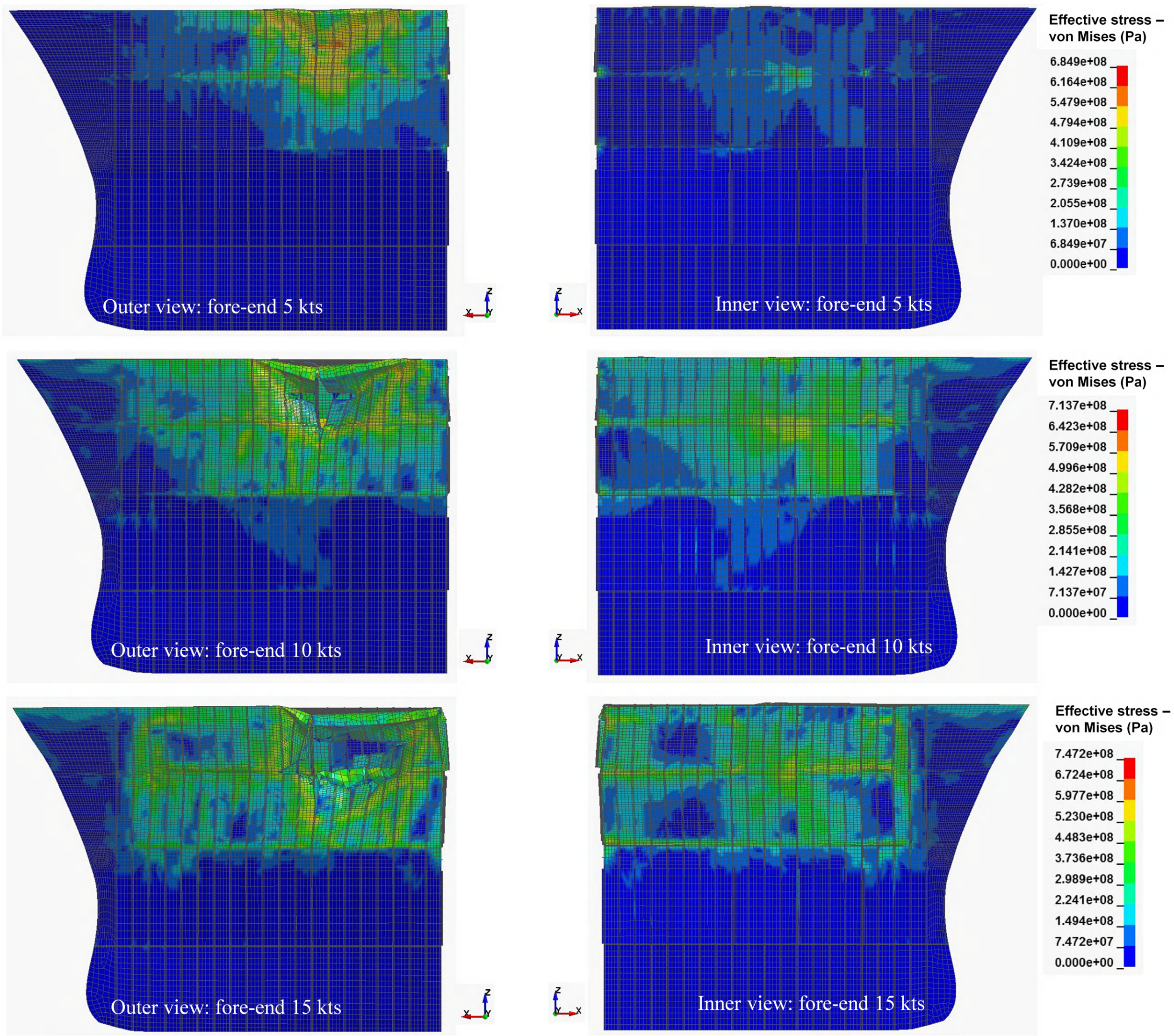


Figure 16: Damage extent and stress contours on the fore-end impacted by the selected striking velocity.

Acknowledgement: This study is successfully presented and published with the support from BK21 plus MADEC Human Research Development Group, Republic of Korea. The gratitude is addressed to Laboratory of Ship Structure and Vibration Analysis, Pukyong National University that provided a full-support for authors during experiment, observation, and manuscript writing.

References

[1] IMO, International Regulations for Preventing Collisions at Sea 1972 – as amended by Resolutions A464(XII), A626(15), A678(16) and A736(18), International Maritime Organization, London, UK: Part A General 1-3, 1989.

[2] LR, COLREGS - International Regulations for Preventing Collisions at Sea, Lloyd's Register, London, UK, 2005.

[3] M. Lützen, Ship Collision Damage, Ph. D. Thesis, Department of Mechanical Engineering, Technical University of Denmark, Lyngby, Denmark, 2001.

[4] J.K. Paik, Practical techniques for finite element modeling to simulate structural crashworthiness in ship collisions and grounding (Part I: Theory), Ships and Offshore Struct. 2 (2007) 69-80.

[5] K. Tabri, J. Broekhuijsen, J. Matusiak, P. Varsta, Analytical modelling of ship collision based on full-scale experiments, Mar. Struct. 22 (2009) 42-61.

[6] A.R. Prabowo, D.M. Bae, J.M. Sohn, B. Cao, Energy behavior on side structure in event of ship collision subjected to external parameters, Heliyon 2 (2016) e00192.

[7] A.R. Prabowo, D.M. Bae, J.M. Sohn, A.F. Zakki, B. Cao, J.H. Cho, Effects of the rebounding of a striking ship on structural crashworthiness during ship-ship collision, Thin-Walled Struct. 115

(2017) 225-239.
[8] S. Haris, J. Amdahl, Analysis of ship–ship collision damage accounting for bow and side deformation interaction, Mar. Struct. 32 (2013) 18-48.
[9] A. Zhang, K. Suzuki, Numerical simulation the bottoms structures grounding test by LS-DYNA, The 5^{th} European LS-DYNA Users Conference, Birmingham, UK: Methods and Techniques (3), 2005.
[10] A.R. Prabowo, S.J. Baek, H.J. Cho, J.H. Byeon, D.M. Bae, J.M. Sohn, The effectiveness of thin-walled hull structures against collision impact, Lat. Am. J. Sol. Struct. 14 (2017) 1345-1360.
[11] ANSYS, ANSYS Mechanical APDL Element Reference, ANSYS, Inc., Pennsylvania, US, 2017.
[12] D.M. Bae, A.R. Prabowo, B. Cao, J.M. Sohn, A.F. Zakki, Q. Wang, Numerical simulation for the collision between side structure and level ice in event of side impact scenario, Lat. Am. J. Sol. Struct. 13 (2016) 2991-3004.
[13] A.R. Prabowo, B. Cao, D.M. Bae, S.Y. Bae, A.F. Zakki, J.M. Sohn, Structural analysis of the double bottom structure during ship grounding by finite element approach, Lat. Am. J. Sol. Struct. 14 (2017) 1-18.
[14] D.M. Bae, A.R. Prabowo, B. Cao, A.F. Zakki, G.D Haryadi, Study on collision between two ships using selected parameters in collision simulation, J. Mar. Sci. Appl. 15 (2016) 63-72.
[15] ANSYS, ANSYS LS-DYNA User's Guide, ANSYS, Inc., Pennsylvania, US, 2017.
[16] N. Jones, Structural Impact, Cambridge University Press, Cambridge, UK, 1989.
[17] G.R. Cowper, P.S. Symonds, Strain Hardening and Strain Rate Effects in the Impact Loading of Cantilever Beams. Technical Report No.28, Brown University, Providence, US, 1957.
[18] H.S. Alsos, J. Amdahl, On the resistance to penetration of stiffened plates, Part I – Experiments, Int. J. Impact Eng. 36 (2009) 799-807.
[19] R. Törnqvist, Design of Crashworthy Ship Structures, Department of Mechanical Engineering, Technical University of Denmark, Lyngby, Denmark, 2003.
[20] A.R. Prabowo, J.M. Sohn, D.M. Bae, J.H. Cho, Performance assessment on a variety of double side structure during collision interaction with other ship, Curved and Layered Stuct. 4 (2017) 255-271.
[21] N. Jones, T. Wierzbicki, Structural Crashworthiness and Failure, Taylor and Francis, Oxon, UK, 2010.
[22] J. Amdahl, D. Kavlie, Experimental and Numerical Simulation of Double Hull Stranding, DNV-MIT Work Shop on Mechanics of Ship Collision and Grounding, Oslo, Norway, 1992.
[23] H.M. Wen, N. Jones, Experimental investigation of the scaling laws for metal plates struck by large masses, Int. J. Impact Eng. 13 (1993) 485-505.
[24] R.D. Krieg, S.W. Key, Implementation of a time dependent plasticity theory into structural computer program, constitutive equation in viscoplasticity: computational and engineering aspects, Am. Soc. Mech. Eng. 20 (1976) 125-137.