Research Article

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Investigation of structural performance subjected to impact loading using finite element approach: case of ship-container collision

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Abstract: Transporting mass products from one country to others is essential activities in industrial cycle. Ships are selected as reliable carriers for this objective considering traveling time and operational cost. During its operational, accidental events such as storm, high tide and bad weather may cause the products which are usually packed in freight containers fall into sea, and impacts the ship structure. In this situation, casualties on both involved structures can be detrimental. This work analyzes a series of ship-container collision in maritime territory in order to investigate resulting structural phenomena. The finite element approach is selected to solve the designed collision cases where the discussion is directed to selected crashworthiness criteria. Impact speed between ship and container structures is chosen as the main parameter in the designed scenario by judging whether this parameter is a good representative of sea state. Overall results indicate that the indication for container rebounding after impact was high. It was followed by a significant increment of the internal energy after higher velocity, which was more than $5 \text{ m}\cdot\text{s}^{-1}$, had been applied to the scenario. Quantification of specific structural performance suggests that approximately more than 80% of the damage occurs on the contacted area of the container structure.

Keywords: impact loading, ship structure, freight container, internal energy, displacement tendency

1 Introduction

Trading activities increase significantly in recent days as barriers between countries are implicitly removed by various bilateral and multilateral market agreements. Countries with abundant natural resources can exchange raw materials for developed technological instruments from countries which are already advanced in technology sectors but lack of natural resources. This fundamental form of market activities requires a transportation mode which is reliable and acceptable in terms of travel period and fuel cost for designated destinations. Ships and other marine carriers are chosen as a medium for this task. Ships such as general cargo vessel, container carrier, oil/chemical carrier and liquefied natural gas carrier, are specifically designed for different cargo and safety demand, where the more dangerous the cargo is, the higher the operational cost is expected [1–5]. In case of general cargo forms for international trading (export-import), container ship is preferred, since the outer protection of the cargo is provided again by the container structures. The positioning of the containers on the carrier is also regulated so that lighter containers will not be damaged or crushed by other heavier containers, in which the weight limit per container is also included in regulation.

The use of the container carrier in transporting export/import commodities is also superior to general cargo vessel as influenced by fast trans-shipment operations and low terminal turn-around time, which are considered vital to calculate transfer time from port to final warehouse [6–10]. Nevertheless, maritime operational is subjected to natural hazard, such as bad weather, which directly affects the traveling process. In this situation, container is possibly fall to open-water area, and due to high wave state, contacts with carrier's hull may damage both structures. Concern to indentation on side hull may lead to flooding as sea water breaches the hull, while in same situation, cargo inside the container can be released to the sea, and it can cause environmental pollution on both sea and coastal area (see actual phenomena in [11–13]). Considering the

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Single-hull structure

If the hull is penetrated in case of collision or grounding, cargo will spill directly into the ocean

Double-hull structure

If the outer hull is penetrated in case of collision or grounding, the inner hull containing the cargo may remain intact

Figure 1: Comparison of the single and double-hull structures against grounding.

possibility of this problem to happen, high consequences after the container collides with ship, and scarce research which directed its focus in this case, there is a need to investigate structural performance under ship-container collision in order to estimate the damage extent on both parties.

This work is conducted to assess the structural performance of a ship and a container during the time these objects create a contact between each other and form an impact loading on both structures. Crashworthiness criteria are taken into account in this work as an observation parameter and performance level of the structures subjected to impact. Finite element approach using explicit methodology is used for nonlinear phenomenon calculation which involves two deformable bodies. Discussion is directed to quantify significance of the collision event to the involved parties, including the cargo inside the container.

2 Hull structure and freight container

Considering safety demand from society regarding maritime operations, ship structure is developed to be more robust during accidental situations, such as under impact loading. Double hull structures [14–17] are proposed to be implemented, especially for dangerous carriers. The structures are initially intended for tanker ship. Side structures are given hulls with double layers of the watertight hull surface. The inner and outer layers of the hull are on the bottom as well as the sides of the tanker ships. The

double-layer construction helps in reducing the risks of marine pollution during a collision, grounding, and any other form of ship's hull damage. It also saves the ship from water ingress or flooding if the outer layer fails. The safety trends now affect structural improvement of other ship types including merchant ships, *i.e.* passenger ship, container carrier, and bulk carrier, to provide more protection from maritime accidents. Compared to the developed double-hull (see Figure 1), the traditional single-hull indeed has bigger load capacity for same hull size as the double-hull requires space to place the second/inner hull. However, risk of after accident events, such as capsizing due to stability loss and oil spill through damaged hull, can be pushed to low level on the double hull structure. This estimation is concluded since in the case of stability loss, the flooding to main cargo tank is unlikely and sea water can only enter to the space between two hulls. On the other hand, the oil spill also can be reduced as the second/inner hull is still intact and protects the cargo and maritime environment at same time.

Besides ship structures, protection for cargo is also improved since the first merchant ship type was introduced. The ship is typically in the form of general cargo ship in which every cargo is piled up and then they are placed on a cargo hatch/hold. This type of ship is later examined, and it indicates that the cargo is prone to be damaged by sea water if the ship structure is breached or capsized. Therefore, cargo container is introduced in the form of large box to put the various cargoes in it. The container is aimed to protect the cargo when it is going to fall to the sea under accidental circumstances. The size and specification of the container in various shipping industries are designed according to the international standard. The Hapag-Lloyd

Table 1: High cube general purpose container 45'

Wooden floor								
Inside dimensions			Door openings		Weights		Capacity	
Length	Width	Height	Width	Height	Max. gross	Tare	Max. payload	
mm	mm	mm	mm	mm	kg	kg	kg	m ³
ft	ft	ft	ft	ft	lbs	lbs	lbs	ft ³
13556	2352	2700	2340	2597	32500	4700	27800	86.0
44' 5.625"	7' 8.625"	8' 10.25"	7' 8.125"	8' 6.25"	71650	10362	61288	3.037
						5050	27450	
						11133	60517	

Table 2: High cube general purpose container 40'

Wooden floor								
Inside dimensions			Door openings		Weights		Capacity	
Length	Width	Height	Width	Height	Max. gross	Tare	Max. payload	
mm	mm	mm	mm	mm	kg	kg	kg	m ³
ft	ft	ft	ft	ft	lbs	lbs	lbs	ft ³
12032	2432	2700	2340	2597	32500	3850	28650	76.3
39' 5.625"	7' 11.75"	8' 10.25"	7' 8.125"	8' 6.25"	71650	8488	63162	2695
	2352					3900	28600	
	7' 8.625"					8598	63052	
	2342							
	7' 8.125"							

Steel floor								
Inside dimensions			Door openings		Weights		Capacity	
Length	Width	Height	Width	Height	Max. gross	Tare	Max. payload	
mm	mm	mm	mm	mm	kg	kg	kg	m ³
ft	ft	ft	ft	ft	lbs	lbs	lbs	ft ³
12032	2325	2700	2340	2597	32500	4300	28200	76.4
39' 5.625"	7' 8.625"	7' 10.25"	8' 10.125"	8' 6.25"	71650	9480	62170	2698
	2342	2395				3950	28550	76.3
	7' 8.125"	7' 10.25"				8708	63603	2695
						3830	28670	
						8444	63206	

[18] container data for shipping purpose is presented in Tables 1 to 3, where the data is classified according to size, cargo type and port handling.

3 Impact phenomena in water territory

During their operations, ships are subject of various types of loads, including working load from human and engine, wave load, vibration load etc. These loads have been considered in structural design phase with a series of simulation and test are followed to confirm reliability and safety of the design. Besides these, ships are also possibly en-

Table 3: General purpose container 20'

Wooden floor								
Inside dimensions			Door openings		Weights			Capacity
Length	Width	Height	Width	Height	Max. gross	Tare	Max. payload	
mm	mm	mm	mm	mm	kg	kg	kg	m ³
ft	ft	ft	ft	ft	lbs	lbs	lbs	ft ³
5900	2325	2393	2340	2292	32500	2300	30200	33.2
19' 4.25"	7' 8.625"	7' 10.25"	7' 8.125"	7' 6.25"	71650	5071	66579	1172
		2395				2350	30150	
		7' 10.25"				5181	66469	
5898		2393		2280	30480	2300	28180	33.0
19' 4.125"		7' 10.25"		7' 5.75"	67196	5071	62126	1165
Steel floor								
Inside dimensions			Door openings		Weights			Capacity
Length	Width	Height	Width	Height	Max. gross	Tare	Max. payload	
mm	mm	mm	mm	mm	kg	kg	kg	m ³
ft	ft	ft	ft	ft	lbs	lbs	lbs	ft ³
5900	2325	2393	2340	2292	32500	2250	30200	33.2
19' 4.25"	7' 8.625"	7' 10.25"	7' 8.125"	7' 6.25"	71650	4960	66690	1172
		2395				2570	29930	
		7' 10.25"				5666	65984	
						2300	30200	
						5071	66579	

counter other forms of loading, which occur during accidental circumstances. Recorded data of maritime accident by Allianz [19] concludes that accidents mostly occur in the form of impact loading, including collision, grounding and explosion (see illustration in Figure 2). Each of these forms has been the focus of previous scholars as numbers of root scenario need sustainable analysis and assessments. In terms of collision, ship-ship collision is particular case to be investigated [20–22], which is followed by ship-bridge and ship-platform interactions [23–25]. As for the grounding, root scenario is divided into raking and stranding [26–32] with variation of seabed geometry is also considered. Explosion on maritime environment is investigated mostly to understand structural behavior which is located below waterline. Effect of such impact to global response, *e.g.* seakeeping and stability is given attention as expected casualties. These impact loadings are analyzed due to horrible track-record on history of merchant ship across the globe. Fundamental revolutions in maritime industry including safety regulation in shipping are initiated due to massive consequences as after effect of impact loading. Taking ice-ship collision of the Titanic in 1912 [32] for instance, more than half of total passenger lost their lives

due to the ship sunk after the collision. Other form of the impact occurs in the form of grounding which contributes to massive oil spill in two large-scale accident and oil spill disaster, *i.e.* the Exxon Valdez in 1989 and the Sea Empress in 1996 [33, 34]. Due to size of environmental casualties, several faunas were stated as extinct, and rehabilitations of sea habitat for animals and vegetation has still been under monitor up to the latest decade. In the case of explosion, infamous case of the Halifax is the best representative. In this maritime disaster, the loss of approximately thousands of lives are concluded as initial casualties which is followed by larger number of injured people [35].

4 Analysis preparation

The models involved in this work are divided into the ship structure and the freight container. The first structure was modelled based on partial of 85 m ship structures (see Figure 3). Finite element model for this entity was designed based on a thin-walled structure where shell element was

Figure 2: Impact loading in maritime environment: (a) collision, (b) grounding and (c) explosion

Figure 3: Numerical model of the hull structures. Modelling is focused on the side structures

used to idealize side shell, frame, deck and other structural components. Deformation due to interaction with container in collision was assessed in discussion which deformable material characteristic is applied in geometry

model. Steel material with properties as presented in Table 4 was applied for the double hull structures with the assumption of kinematic-hardening material model presented in mathematical expression in Equation 1 [36].

The second entity was the freight container which was modelled after a size 40" container. The applied material with the same applied material model is given in Table 5. This table refers to JIS SPA-H Corten steel [37], which is a part of modelling of the deformable structure. To model the load of the container, several drums were set inside the container. The geometry of the described container model is presented in Figure 4. As explicit and nonlinear deformations on the double hull and container were expected during and after collision, failure criterion needed to be defined. In this work, criterion introduced by Peschman and Lehmann [38] was applied (see Equation 2 and Table 6) with fine mesh style so that deformation pattern and contour in the end collision could be captured well.

$$\sigma_Y = \left[1 + \left(\frac{\dot{\epsilon}}{C} \right)^{\frac{1}{p}} \right] \left(\sigma_0 + \beta E_p \epsilon_p^{eff} \right) \quad (1)$$

$$\Delta l_k = \epsilon_g l + \epsilon_m \left(\frac{x_e}{t} \right) t \quad (2)$$

Table 4: Material properties of the hull structure

Parameter	Symbol - Unit	Value
Density	($\rho - \text{kg}\cdot\text{m}^{-3}$)	7850
Elastic modulus	($E - \text{MPa}$)	210000
Poisson's ratio	($\nu -$)	0.3
Yield strength	($\sigma_Y - \text{MPa}$)	315
Hardening number	($n -$)	0
Cowper Symonds parameter 1	($C - \text{s}^{-1}$)	3200
Cowper Symonds parameter 2	(P)	5

Table 5: Material properties of the hull structure

Parameter	Symbol - Unit	Value
Density	($\rho - \text{kg}\cdot\text{m}^{-3}$)	7850
Elastic modulus	($E - \text{MPa}$)	200000
Poisson's ratio	($\nu -$)	0.3
Yield strength	($\sigma_Y - \text{MPa}$)	345

Table 6: Result of the thickness measurement for Peschmann-Lehman criterion

Measurement	ϵ_g (%)	ϵ_m (%)	x_e/t (-)	$(\epsilon_m)x_e/t$ (-)
Collision model	14.66	47.53	1.68	0.7985

Figure 4: Container design for the collision analysis

σ_Y is the initial yield stress, $\dot{\epsilon}$ is the strain rate, C and P are the Cowper-Symonds strain rate parameters, ϵ_p^{eff} is the effective plastic strain, E_p is the plastic hardening modulus, ϵ_g is the uniform strain, ϵ_m is the strain during maximum neck, x_e is the length of necking, t is the element thickness.

The simulation in this work was set as such so that the container impacted the double hull structure as illustrated in Figure 5 with a variety of speed ranging from 1

to $7 \text{ m}\cdot\text{s}^{-1}$. This range was taken by considering the sea state where the rougher the wave was, the higher the impact speed would be. During the impact, the hull structures were set on the initial position with axial displacement being restrained and placed on deck girder, bottom girder and transverse frame. Rotational constrain was also placed to fix the structure. Similar configuration was applied to the freight container by placing constraint on the

Figure 5: Boundary scheme on the hull and container during collision

edge of the container. Displacement on the transverse direction (y axis) was removed so that the container was allowed to move to impact the target structure. Several structural parameters, e.g. energy, velocity and displacement were assessed to understand the behaviors on both entities during and at the end of collision. Performance of the hull and container subjected of impact loading was quantified in order to estimate damage extent.

5 Global performance under ship-container collision

Discussion of the structural performance was initiated by observing the internal energy. This energy type is representative of physical energy which is allocated to plastically deform (material experience excessive strain, and exceeds yield point) of all entities during collision. Results presented in Figure 6 indicated that proportion energy is equal to the increase of the impact speed. The interesting point of this graph is its difference compared to typical energy form under collision in previous publications, such as Ozguc *et al.* [39] and Haris and Amdahl [40]. The peak point of the typical energy is usually located at the end of collision, which is the same as that at the end of the impact time. In this observed collision cases, the peak occurred within the range of 0.0 – 0.10 s after initial simulation had been initiated, and it experienced reduction until it entered constant state. This tendency implicitly indicates that maximum damage occurs on the mentioned time period, and reduction takes place because the moving container bounces back after impacting the target ship. Fur-

Figure 6: Internal energy of a variety collision speed. The energy indicated an amount to plastically deform both entities in collision

Figure 7: Kinetic energy of the system. Due to the moving object was only the container, this energy represents movement tendency of the container

thermore, the period of the bouncing back phenomenon is observed to be faster when faster impact speed is applied in simulation. Clearer evidence of this phenomenon is seen in the summary of the kinetic energy (Figure 7) which is an explicit representation of the container movement as described in boundary scheme, however, only the container was allowed to move in the system. After the interaction of the two entities occurred, significant reduction of the kinetic energy was recorded. The lowest speed, $1 \text{ m}\cdot\text{s}^{-1}$ was the only designed scenario where it almost reached the zero energy, or where the container fully stopped after bouncing back. Higher speeds indicate that the container continued to move to opposite direction of the coming direction in impact. Interference of the sea state was

Figure 8: Total energy occurred during the container's collision with the ship

predicted further to influence distance of the moving container.

Difference in total energy was assessed as a follow-up of the previous discussion related to the internal energy and kinetic energy. As given in Figure 8, it can be seen that the energy occurs during the impact subjected to the speed variety experiences a nonlinear increment. In the lowest speed, average energy during impact is below 5000 J, and application of the $3 \text{ m}\cdot\text{s}^{-1}$ speed produces approximately 15000 J. Higher speeds of 5 and $7 \text{ m}\cdot\text{s}^{-1}$ produces a total energy of 40000 and 80000 J consecutively, in which initial increment changes from 10000 J to 25000 J, and finally to 40000 J. It can be concluded that the significant influence of speed to crashworthiness criteria, i.e. energy, needs to be the critical concern in developing better container designs, especially for high-risk compound which is expected to cause massive marine pollutions during accident. Besides energy criteria, behavior of the involved structures in the idealized system can be predicted through velocity assessment. This criterion is representative of structural movement during the collision takes place, where the magnitude in three different axes according to Cartesian coordinate system are discussed. Presented result in Figure 9 represents velocity magnitude and tendency on the longitudinal direction (x-axis). Intensive fluctuations occur due to rapid response during the time the the container impacts the structure. The faster the speed is applied on the container, the earlier the movement response is produced. It is also worth noting that based on this result, the lowest applied speed results in the fluctuation with the largest gap and explicit approach to zero state in the process. It indicates that the speed is slow enough so that the bounce back phenomenon does

Figure 9: Global system velocity in impact: longitudinal direction (x-axis)

Figure 10: Global system velocity in impact: transverse direction (y-axis)

not clearly take place, and response, including damage expansion is very low. This statement is supported by tendency of structural movement in transverse direction (y-axis) which is the coming direction of the striking container (see boundary condition in previous section). It is presented in Figure 10 that fluctuation of the $1 \text{ m}\cdot\text{s}^{-1}$ speed is suddenly reduced to near zero state right after collision occurs in impact time $T = 0.075 \text{ s}$.

Compared to this speed, speeds in the range of $3\text{--}7 \text{ m}\cdot\text{s}^{-1}$ are not directly experiencing reduction to near zero state area, where a peak still occurs after the collision. This phenomenon can be observed in speed $V = 3 \text{ m}\cdot\text{s}^{-1}$ in time range of 0.05–0.10 s. Velocity magnitude in this axis is the highest as the vertical direction (z-axis) produces similar magnitude and fluctuation tendency as that on the longitudinal direction (see Figure 11). Nevertheless, the gap be-

Figure 11: Global system velocity in impact: vertical direction (z-axis)

Figure 12: Internal energy of the ship structure during impact

Figure 13: Tendency of the container energy shows similarity to the global energy

Figure 14: Internal energy of the idealized drum inside the container

tween a peak point to others on the vertical direction is wider which indicates that the simultaneous responses on the structures during impact does not occur.

6 Tendency of individual entities

The discussion in this section is aimed at assessing the structural criteria on specific entities during ship-container collision. In terms of the internal energy, results (see Figures 12 to 14) indicate that the most damage is experienced by the container with the highest magnitude of approximately 60000 J. Comparison of each deployed impact velocity points to the timing when the damage occurs on the respective entities, including the drum inside the container. Similarity in time is found match for the hull structure and the freight container, where they interact at the same time, and lead to the same time for damage occurrences. Interesting phenomenon is recorded in terms of the drum in Figure 14 where damage occurs near the end of the impact period. This case concludes that the cargo inside the container is not directly affected by collision between the ship and container, which is essentially influenced as a chain reaction of the initial impact. The faster the impact speed is, the faster the damage on the drum inside the container occurs. Investigation in terms of energy magnitude also indicates that most impact only affects the container, and it keeps the drum as a cargo safe. However, further assumption needs to be developed to idealize the situation if the container cargo is full. Expected response in this scenario is that the impact distribution will be directly transferred to the cargo in faster magnitude. Based on the current solution of the drum response, faster magni-

Figure 15: Displacement extent on the longitudinal direction (x-axis) of the container

Figure 16: Container displacement on the transverse direction (y-axis) in impact

tude causes earlier damage occurrence on the cargo, which also equally perpendicular to the damage extent under impact loading. In terms of structural strength, ship hull (Figure 12) is concluded as the strongest structure where the magnitude of the internal energy experiences the most significant reduction after peak point is reached. It means that most elements of the hull structure on the target point have not permanently deformed due to the final damage extent is equal to energy in constant period.

Verification of the bounce back phenomenon of the container is presented in this part which discuss the overall container displacement. In terms of the magnitude, displacement on the longitudinal direction (Figure 15) is observed as having more fluctuating response than the transverse direction (Figure 16) and vertical direction (Figure 17) do. On the contrary, displacement magnitude of this direction is the lowest which indicates that geometry of the displaced element on the container under impact rapidly changes but in very low magnitude. This result is predicted since the axial restraint on the vertical direction, which is placed on the container, makes overall container displacement in the direction very low.

Similar effect is shared on the vertical direction (Figure 17), where the magnitude of the overall displacement is very low, and with direct observation (not based on data), it is explicit that no displacement is expected. However, the fluctuation of the vertical direction is significantly smaller than the longitudinal direction. On the other hand, gradual displacement changes are observed on the transverse direction (y-axis) where the maximum displacement is reached during direct impact with the hull structure. The period of the peak on displacement is found similar to the peak period of internal energy, which leads to the predic-

Figure 17: Displacement tendency of the container on the vertical direction (z-axis)

tion that the changes in container displacement is representative of the bounce-back phenomenon.

7 Conclusions

A series of finite element analysis is conducted in this work to investigate the global and local responses during the ship-container collision case. The condition of the involved entities, *i.e.* ship (represented by hull structure), freight container and container cargo is assessed based on calculation results. Global tendency indicates a good correlation between the structural parameters under impact loading. The highest internal energy is found at the highest applied speed with an increment of more than 100% by increasing 2 m.s^{-1} to the striking container. The most

explicit result which leads to this conclusion is presented in terms of the total energy. Kinetic energy of the lowest applied speed of $1 \text{ m}\cdot\text{s}^{-1}$ is concluded to deliver very minor damage to both the structures and the container cargo as the kinetic energy magnitude is fully zero (container is fully stopped by structure) during the interaction with the hull structure. The behavior of the structural velocity on the transverse direction is equally perpendicular to the summarized kinetic energy where all speeds tend to approach zero state at the end of the impact. A more specific investigation is addressed to the involved entities during collision, which leads to a prediction that the damage on the ship structure at the peak state is very different from that at the end of collision based on the internal energy criterion. The elements of the impacted structure does not receive enough impact to cause permanent damage on it, while the container and the drum (cargo) experience similar damage at the end collision to the peak state.

The displacement criterion on the container as an essential instrument to protect environment contamination due to spilled cargo, corresponds to the internal energy for occurrence period of the peak state, which also validates the bounces back phenomenon after the impact. Interference of the sea state makes the repetition of impact possible, and more damages occur on the container and cargo. Consideration to cargo volume inside the container is also a critical point as the current result indicates the more volume inside the container, the faster the influence on the cargo due to impact is expected. Further work is suggested to develop a container design where the impact (in the form of collision or grounding) cannot cause direct contact and damage to the cargo. Special considerations of the parameters are encouraged to be applied to dangerous compounds which can possibly contaminate marine environment when they are spilled to the open water.

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