



Numerical Simulation of Damage in Sandwich Composite Panels Due to Hydrodynamic Impact

Satrio Wicaksono^{1*}, Nur Ridhwan Muharram¹, Hermawan Judawisastra¹ & Tatacipta Dirgantara¹

Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung,
Jalan Ganesha 10, Bandung 41032, Indonesia

*E-mail: satriowicaksono@ftmd.itb.ac.id

Highlights:

- Development of a numerical model implementing the Coupled Eulerian-Lagrangian (CEL) method that is capable of predicting the hydrodynamic damage mechanism of sandwich composite panels.
- The effect of the hydrodynamic impact velocity on the damage of the sandwich composite panels.
- The hydrodynamic force is affected significantly by the deflection of the sandwich composite panels, which is also affected by the damage mechanism.

Abstract. The float and hull are vital parts of amphibious planes and boats, respectively, as both have to absorb hydrodynamic impact due to interaction with water. Sandwich composite panels are commonly used for such applications and other impact-absorbing structures. Unfortunately, the failure mechanism of sandwich composite panels under hydrodynamic impact is very complicated, as it may consist of composite skin failure, core failure, and non-uniform delamination. Hence, a numerical study on the damage of sandwich composite panels under hydrodynamic load is necessary. In this study, numerical simulation implementing the Coupled Eulerian-Lagrangian (CEL) method was performed to observe the damage mechanism of sandwich composite panels. The CEL method combines the Lagrangian and Eulerian frames into one model. Thus, analysis of structure deformation and fluid motion can be performed simultaneously. The result of the current numerical simulation shows a fair agreement with the experimental results in the literature, which shows that the current methodology can represent the sandwich composite panel response in real-life conditions, especially before shear core failure initiates.

Keywords: *Coupled Eulerian-Lagrangian method; damage mechanism; explicit dynamics; finite element analysis; hydrodynamic impact; sandwich composite.*

1 Introduction

The use of composite sandwich panels has increased significantly nowadays due to their high flexural strength to weight ratio, especially in applications where

high flexural strength and light weight are important [1]. Some of its applications are boat hulls and amphibious plane floats, where composite sandwich panels are often exposed to hydrodynamic impact [2,3]. Both components are vital, as both have to withstand hydrodynamic impact due to interaction with water. Failure to both components may result in grave accidents, possibly with many casualties and fatalities. Unfortunately, the failure mechanism of sandwich composite panels under hydrodynamic impact is very complicated [4], as it may involve composite skin failure, core failure, and delamination. Thus, it is crucial to thoroughly understand the failure behavior of sandwich composite panels when exposed to hydrodynamic impact.

One of the ways to study the failure behavior of sandwich composite panels under hydrodynamic impact is by performing experimental testing. Charca and Safiq [5,6] have experimentally studied the damage in sandwich composite panels due to single and multiple hydrodynamic impacts. They found that higher impact energy and smaller deadrise angle create more damage to the composite sandwich panels [5], where the greatest damage was found in the vicinity of the chine [6]. Allen and Battley [3,7] developed a servo-hydraulic system to control the water impact velocity to test marine sandwich panels. From the experiment that was performed on a flexible sandwich panel, it was found that a large local strain appeared in the vicinity of the chine [7]. Huera-Huerte, *et al.* [8] have performed experimental tests to study the hydrodynamic impact on sandwich panels, especially at the water entry phase. They observed that at a deadrise angle of less than 5° , the impact was cushioned significantly by air that was trapped between the panel and the water [8]. Another study on water slamming into a composite sandwich hull was performed by Qin and Batra [2], who proposed an analytical model to predict the deflection of sandwich composite hulls. The deflection result from the developed analytical model matched very well with the numerical validation result [2]. A numerical study on panel hydrodynamic impact has also been performed by Panciroli, *et al.* [9], who developed a 2D plane strain finite element model, where the water was modeled as smoothed particle hydrodynamics (SPH). The developed numerical model was able to accurately predict the elastic response of the panel, with the condition of no trapped air between the panel and the water [9]. Additionally, it was also observed that the trapped air phenomenon occurred at an impact speed of 20 m/s or higher for a 15° deadrise angle [9]. From the previous discussion, it is clear that numerical studies on the failure behavior of sandwich composite panels under hydrodynamic loads are still very limited and not well established yet. Thus, further study on how to accurately model sandwich composite panels under hydrodynamic load is still needed.

In this study, numerical simulations were performed to observe the damage mechanism of sandwich composite panels under hydrodynamic load. The effect

of the hydrodynamic impact velocity on the damage in composite sandwich panels was also studied. The newly established model implements the Coupled Eulerian-Lagrangian (CEL) method, which combines the Lagrangian and Eulerian frames into one model. The Lagrangian frame is used to observe the structure's deformation, while the Eulerian frame is used to observe the fluid motion. Thus, analysis of the structure deformation and fluid motion can be performed simultaneously.

2 Finite Element Modeling

In the current study, a numerical model was developed to predict the damage mechanism of sandwich composite panels under hydrodynamic load, with variation of impact velocity. The modeling was performed using Abaqus 2019 software. A 3D explicit finite-element model was created based on the experimental set-up shown in Figure 1, where the sandwich plates are clamped at the keel and chine. The velocity was kept constant for the whole simulation, with four different velocity magnitudes of 4 m/s, 6 m/s, 8 m/s, and 10 m/s were attempted to see the effect of impact velocity on sandwich composite panel damage.

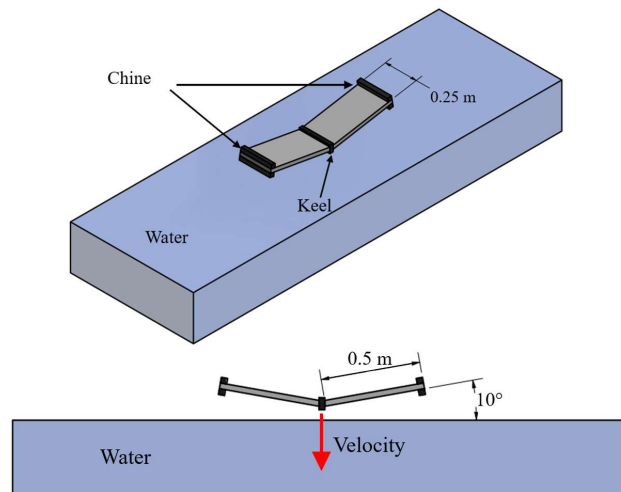


Figure 1 The scheme of the test set-up [4].

In order to reduce the computational time and realizing that the set-up had two symmetrical axes, a quarter model was used in the current study instead of a full model. The quarter model was believed to be able to give good accuracy in the current case, providing the boundary conditions were defined with care. A schematic of the quarter model is shown in Figure 2. The developed model, as

explained previously, is divided into two frames: Lagrangian and Eulerian. The Lagrangian frame consists of a sandwich composite panel model, while the Eulerian frame consists of water and void.

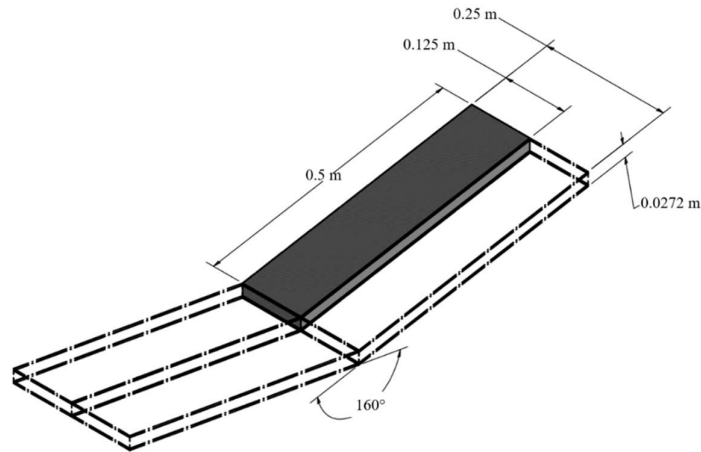


Figure 2 The quarter model schematic.

2.1 Lagrangian Model

The modeled sandwich composite panel consisted of identical top and bottom skins made of a glass fiber-polyester matrix, a Divinycell H80 foam core in the middle, and a polyvinyl ester interface between the core and the skins, with dimensions as shown in Figure 3. The interface between skin and core was modeled as a cohesive layer with a thickness of 0.1 mm. The composite skin properties, as shown in Table 1, were taken from the literature [4].

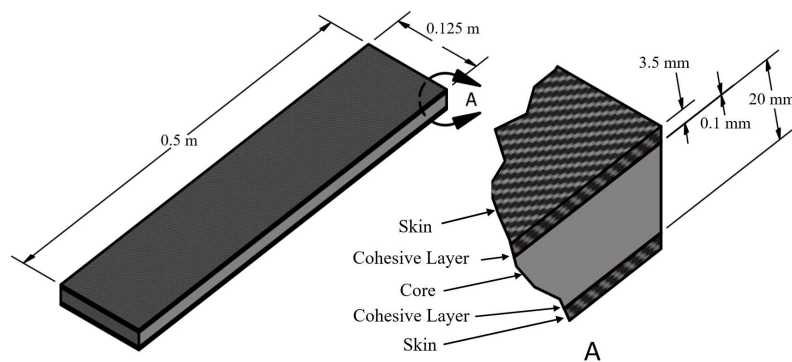


Figure 3 Schematic and dimensions of the sandwich composite panel quarter model.

Table 1 Physical and mechanical properties of the skin [4].

Material Properties	Values
Density	1960 kg/m ³
E ₁₁	48.16 GPa
E ₂₂ and E ₃₃	11.21 GPa
v ₁₂ and v ₁₃	0.274
v ₂₃	0.096
G ₁₂ and G ₁₃	4.42 GPa
G ₂₃	9 GPa
Longitudinal Tensile Strength (X _T)	1021 MPa
Longitudinal Compressive Strength (X _C)	978 MPa
Transverse Tensile Strength (Y _T)	29.5 MPa
Transverse Compressive Strength (Y _C)	171.8 MPa
Longitudinal Shear Strength (S _L)	70 MPa
Transverse Shear Strength (S _T)	30 MPa

From previous research it is understood that the failure of a composite skin due to impact load can be quite complex and can consist of multiple damage modes [10]. In order to capture the failure mode accurately, Hashin criteria were employed in the model of the composite skins as formulated in Eqs. (1) to (4), for fiber tensile, fiber compression, matrix tensile, and matrix compression damages, respectively. Linear damage evolution was also applied, which means that the stress-strain response after the damage initiated followed the graph shown in Figure 4.

$$F_T^F = \left(\frac{\sigma_{11}}{X_T} \right)^2 \geq 1 \quad (1)$$

$$F_C^F = \left(\frac{\sigma_{11}}{X_C} \right)^2 \geq 1 \quad (2)$$

$$F_T^M = \left(\frac{\sigma_{22}}{Y_T} \right)^2 + \left(\frac{\tau_{12}}{S_L} \right)^2 \geq 1 \quad (3)$$

$$F_C^M = \left(\frac{\sigma_{22}}{2S_T} \right)^2 + \left[\left(\frac{Y_C}{2S_T} \right)^2 - 1 \right] \frac{\sigma_{22}}{Y_C} + \left(\frac{\tau_{12}}{S_L} \right)^2 \geq 1 \quad (4)$$

The Divinycell H80 core had a density, elastic modulus, and Poisson's ratio of 80 kg/m³, 77 MPa, and 0.3, respectively. The core was modeled to have an elastic-perfectly plastic bi-linear response, with a yield strength of 1.4 MPa. In order to ensure the validity of the core model, the compressive response of the core model was then compared with experimental result from the literature [11], and the result showed good agreement, as shown in Figure 5.

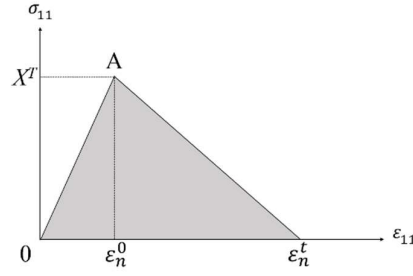


Figure 4 The linear damage evolution response.

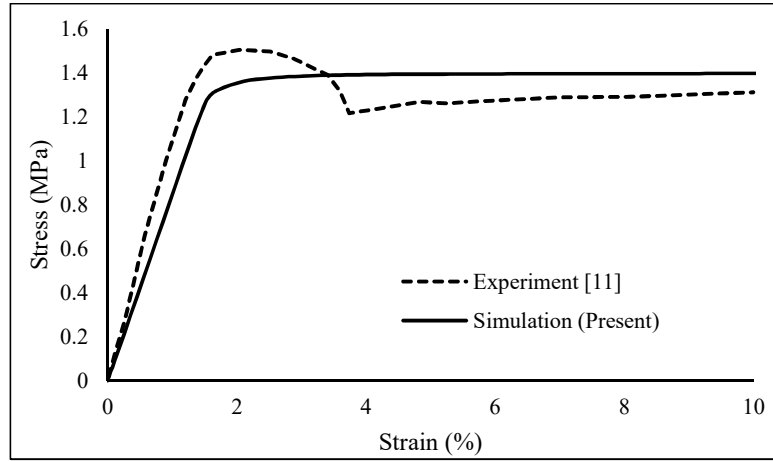


Figure 5 Compressive response of the core from the current simulation result and experiment results from the literature [11].

The cohesive layer interface is the part that connects the core with the top and bottom skins. It is very important to model this part in order to see the delamination behavior of the composite sandwich panel. The quadratic separation criterion was used to model the delamination damage. The damage was initiated when a quadratic interaction function, as shown in Eq. (5), reached a value of one.

$$\left(\frac{t_n}{t_n^o}\right)^2 + \left(\frac{t_s}{t_s^o}\right)^2 + \left(\frac{t_t}{t_t^o}\right)^2 \geq 1 \quad (5)$$

where t_n^o , t_s^o and t_t^o are the peak values of the contact separation in the pure normal, shearing, and tearing directions, respectively. Once the first damage occurs, the cohesive stiffness degrades linearly, and in mixed-mode loading, the delamination propagations follow the Benzeggagh-Kenane formulation as shown in Eq. (6).

$$G_T^c = G_n^c + (G_s^c - G_n^c) \left(\frac{G_s - G_t}{G_T} \right)^\varphi \quad (6)$$

where G_T^c , G_n^c , G_s^c and G_t^c are the mixed-mode, normal, shearing, and tearing direction critical energy release rates, respectively. G_T , G_s and G_t are the mixed-mode, shearing, and tearing energy release rate, and φ is a cohesive property parameter. The values of the material properties used in the cohesive layer model were taken from the literature [4] and are shown in Table 2.

Table 2 Material properties of the cohesive layer interface [4].

Material Properties	Values
Density	1590 kg/m ³
E	2 GPa
t_n^o	2.5 MPa
t_s^o and t_t^o	5 MPa
G_n^c	484 N/m
G_s^c and G_t^c	296 N/m
φ	1.45

2.2 Eulerian Model and Final Assembly

In order to accurately predict the fluid motion effect on the sandwich composite panel damage, the Eulerian frame must be appropriately modeled. To be able to do that, the basic concept of the Eulerian frame must be understood. While the elements in the Lagrangian frame deform with the material, in the Eulerian frame, the elements retain the initial shape and do not deform with the material, which means the material can flow through the elements [12]. Thus, the Eulerian frame is useful for very large deformation cases [12], which includes the analysis of fluid flow. The current Eulerian frame consists of two parts: water and void. The water was modeled as an incompressible fluid with a density of 1000 kg/m³ and a viscosity of 0.001 Pa.s.

The Lagrangian frame was then assembled inside the Eulerian frame. As the Lagrangian frame and the Eulerian material (in this case, water) cannot occupy the same area, in the current model the Lagrangian frame was initially placed inside the void, on top of the water. The schematic assembly is shown in Figure 6. A gravitational field of 9.81 m/s² was defined in the final assembly model. The two symmetries explained above were modeled as symmetric boundary conditions to the Lagrangian frame, while all faces of the Eulerian frame were defined to have non-reflecting boundary conditions to exclude the effect of wave reflection.

The interaction between the Lagrangian frame (sandwich composite panel) and the Eulerian material (water) was defined as hard contact. The sandwich

composite Lagrangian model was fixed at the keel and chine. The loading was given by defining a constant velocity to the whole sandwich composite panel until the keel touched the water. After the keel touched the water, the velocity was only kept constant at the keel and chine regions, while the velocities of the other composite sandwich panel regions were not defined to mimic the actual loading conditions.

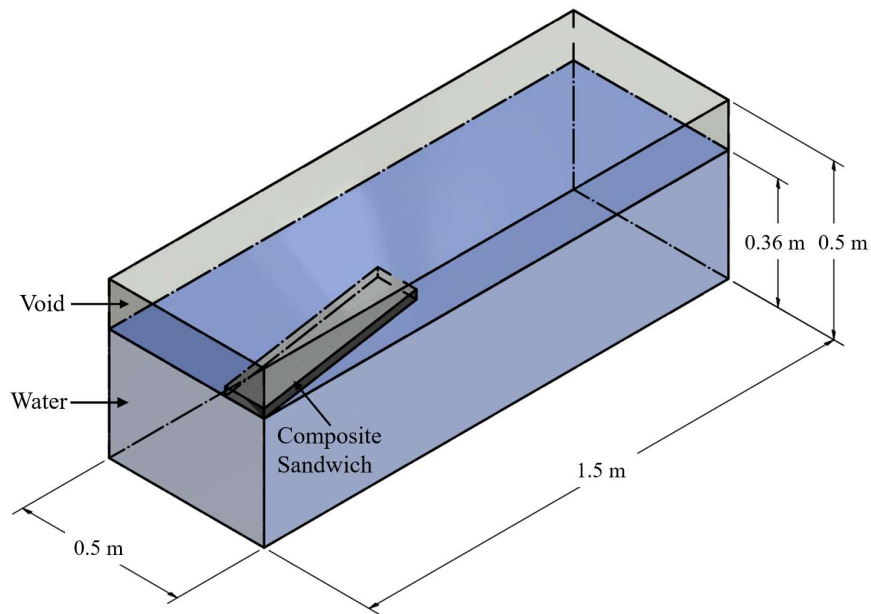


Figure 6 The schematic assembly of the Eulerian and Lagrangian frames.

The mesh size used for the skins and the core was made consistent at 2.5 mm with a total of 5,148 elements and 80,000 elements for the skins and the core, respectively. The type of element used for the skin was an 8-node continuum shell element with reduced integration (SC8R), while the type of element used for the core was an 8-node 3D linear brick element with reduced integration (C3D8R). The cohesive part was set to have a mesh size of 1 mm, with a total of 62,500 COH3D8 elements (8-node 3D cohesive element). The final mesh of the Lagrangian model is shown in Figure 7. Additionally, to reduce the computational time, varying mesh from a size of 44 mm at a location far from the impact to a size of 5.5 mm at a location near to the impact were used for the void and water, with a total of 469,560 elements.

The element type used for the void and water was an 8-node 3D linear hexahedral Eulerian element with reduced integration (EC3D8R). The final meshed model is

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shown in Figure 8. Four simulations with four different velocity magnitudes of 4 m/s, 6 m/s, 8 m/s, and 10 m/s were performed.

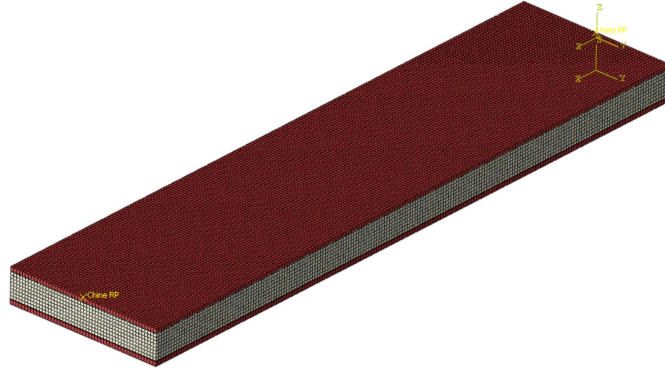


Figure 7 The final mesh of the Lagrangian model.

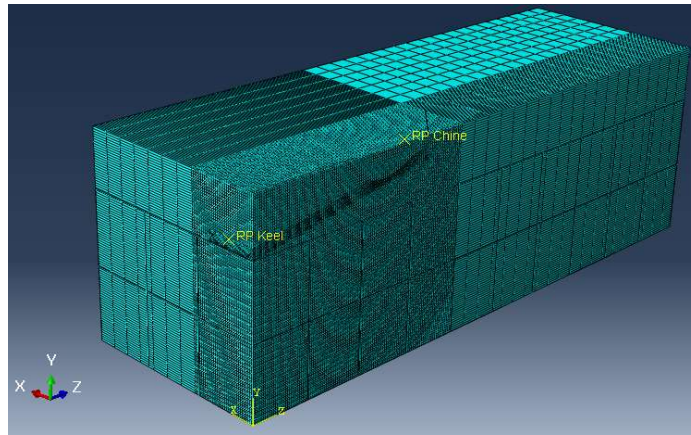


Figure 8 The final mesh of the whole model.

3 Results and Discussions

From the simulations that were performed, the total hydrodynamic force suffered by the sandwich composite panels could be obtained by adding together the reaction forces at the keel and the chine. The resulting hydrodynamic forces were then compared to the experimental results, which was performed by Hassoon [4], as shown in Figure 9(a), (b), (c), and (d) for constant velocities of 4 m/s, 6 m/s, 8 m/s, and 10 m/s, respectively. It can be seen that at lower velocity (4 m/s and 6 m/s), the simulation results matched very well with the experimental results almost over the whole duration. On the other hand, at higher velocity (8 m/s and

10 m/s), the hydrodynamic force agreed reasonably well with the experimental results at the beginning of the simulation but drifted away at the end of the simulation. The similarity between the hydrodynamic force results from the simulation and experiment at lower velocity (4 m/s and 6 m/s) and the early stage of higher velocity (8 m/s and 10 m/s) confirm the validity of the boundary conditions used in the current model. To confirm the reason behind the difference in the hydrodynamic force at the later stage of higher velocity simulation, detailed observation and analysis on the composite sandwich panel deformation and failure needed to be performed.

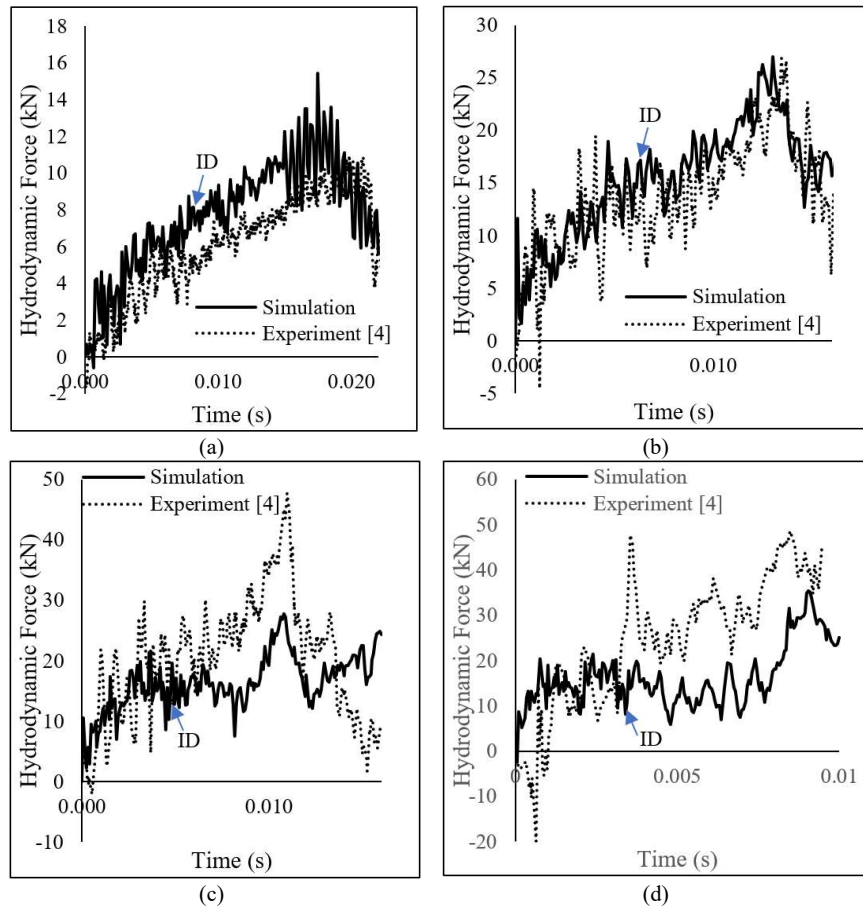


Figure 9 Hydrodynamic force from the current simulation results and experimental results from the literature [4] at a velocity of: (a) 4 m/s, (b) 6 m/s, (c) 8 m/s, and (d) 10 m/s (ID indicates the occurrence of initial delamination).

Figure 10 shows the sandwich panel's deformed shape from the current simulation in comparison to the experiment performed by Hassoon [4] at the same time frame for a velocity of 10 m/s. It can be seen that the panel deflection from the experimental test was slightly larger than the simulation result. Based on the experimental observation by Hassoon [4], the delamination initiated almost at the same time as the occurrence of core shear failure.

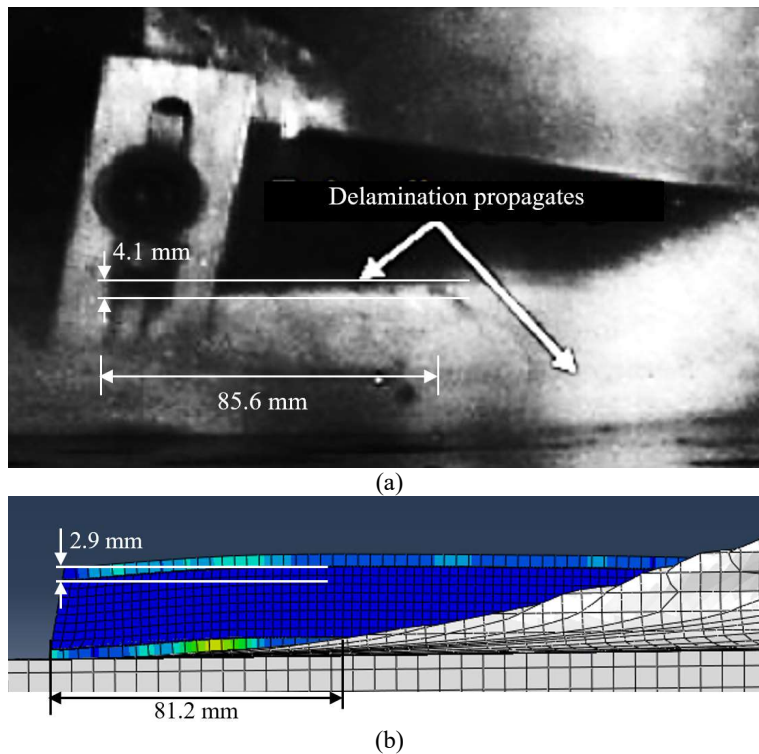


Figure 10 Composite sandwich panel deformation at a velocity of 10 m/s: (a) experimental result from the literature [4] and (b) current simulation result.

The existence of core shear failure will reduce the flexural stiffness of the sandwich panel, which increases its deflection and subsequently increases the drag coefficient and the hydrodynamic force. Unfortunately, due to limited data, the core shear failure was not modeled in the current simulation. Thus, the panel deflection from the simulation was slightly lower than that from the experimental result. The omission of the core shear failure was also the reason behind the difference in the hydrodynamic force results at the later stage of higher velocity. It can be seen from Figure 9 that the difference in the hydrodynamic force results

between the current simulations and the experiments started to get larger when delamination was initiated, especially at higher velocity.

The core shear failure was initiated almost simultaneously with the initial delamination [4]. Thus, the sandwich panel in the simulation after the initial delamination was slightly stiffer than in the experiment, which resulted in a lower hydrodynamic force due to a lower coefficient of drag. At lower velocity, on the other hand, the core shear failure most likely was not as pronounced as at higher velocity. Hence, the hydrodynamic force results still matched quite well with the experimental results.

Further delamination analysis was performed to better understand the response of composite sandwich panels under hydrodynamic load. In the current research, the delamination profile in the cohesive zone between the bottom skin and the core was examined in detail. Figure 11(a) shows the delamination profile at a velocity of 10 m/s obtained from the simulation. The delamination area in the simulation results is represented by a grey color. The result was compared to the experimental result from literature [4], as shown in Figure 11(b).

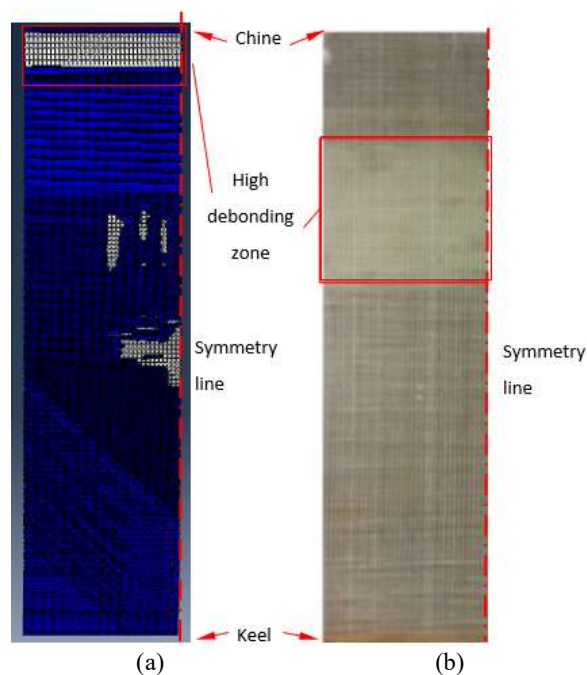


Figure 11 Delamination results at velocity of 10 m/s: (a) the current simulation and (b) experiment from literature [4].

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The delamination area of the simulation results was concentrated in the chine area. The chine is the last part to touch the water and receives higher water pressure than the other parts, which causes damage and delamination concentration at the chine [6,7,13]. There was a difference in the location of the delaminated area between the simulation and the experimental results caused by the difference in failure at the panel's core. In the experimental result [4], the failure was initiated at the bottom cohesive layer and the core, which then propagated further at the bottom and top cohesive layers. In the simulation result, on the other hand, shear failure was not modeled due to limited data, and delamination was initiated at the chine due to higher water pressure at that location. Although the high debonding zone was not in exactly the same location as in the experimental result, the delamination profile was still quite representative, as it also showed small delamination in the same area as the experimental results.

The delamination results at velocities of 4 m/s, 6 m/s, and 8 m/s were also analyzed, as shown in Figure 12(a), (b), and (c), where the delamination area is represented by a grey color. It can be seen that the delamination area got larger as the velocity increased. The results for all velocities were also consistent, as the delamination was concentrated in the area near the chine and the area in the middle of the chine and the keel.

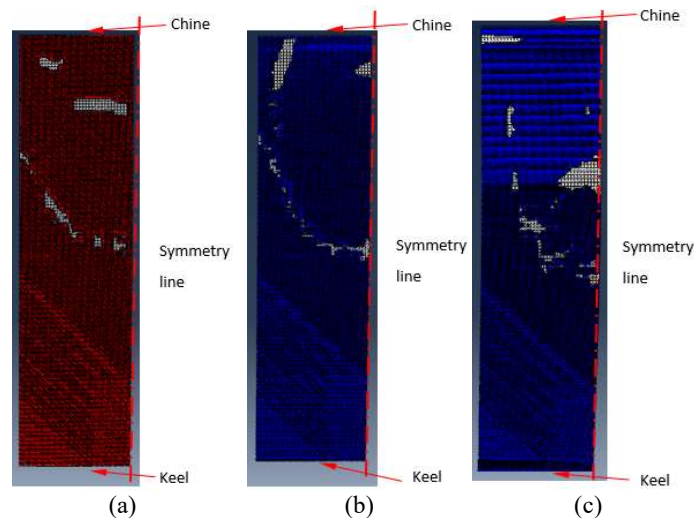


Figure 12 Delamination results at velocities of (a) 4 m/s, (b) 6 m/s, and (c) 8 m/s.

In order to further understand the response of sandwich composite panels under hydrodynamic load, a damage analysis was also performed on the bottom skin.

As explained earlier, the Hashin criteria were employed to model the damage of the skins, which includes four different damage modes: fiber tension, fiber compression, matrix tension, and matrix compression damages. No fiber tension, fiber compression, or matrix compression damage was indicated in the simulation results. On the other hand, significant matrix tension damage was found at the bottom skin, as shown in Figure 13.

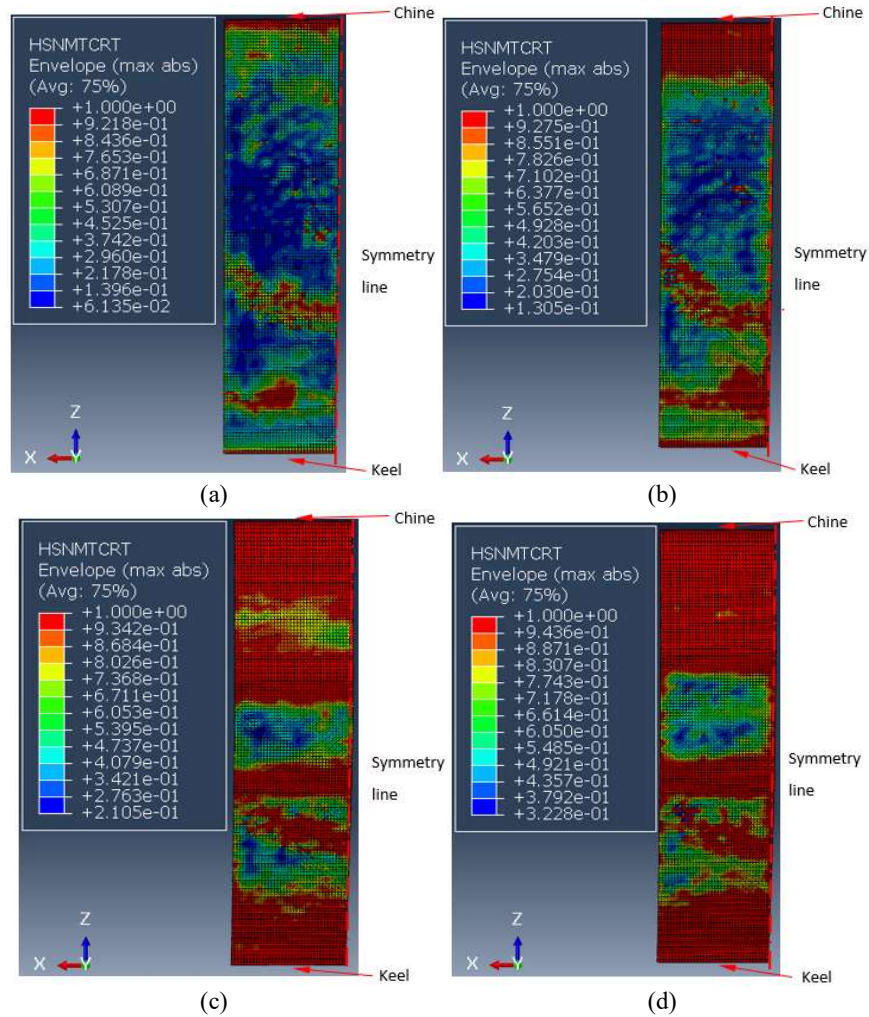


Figure 13 Bottom skin matrix tension damage at a velocity of: (a) 4 m/s, (b) 6 m/s, (c) 8 m/s, and (d) 10 m/s.

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It was shown that the matrix tension damage (red color in Figure 13) got more prominent as the velocity increased, which is logical, as the impact energy is proportional to the velocity and consistent with the delamination results discussed above. It was also shown that the worst matrix tensile damage happened in the chine area.

4 Conclusions

A finite-element model capable of predicting sandwich composite panel damage due to hydrodynamic load was successfully developed. The developed model has the capability to predict the resulting hydrodynamic force and deflection of water-impacted sandwich panels with fair agreement when compared with experimental results from the literature. The developed model was able to predict the response of composite sandwich panels accurately at lower impact velocities (4 m/s and 6 m/s) as well as at higher impact velocities (8 m/s and 10 m/s) before delamination and core shear failure were initiated.

The accuracy was less after the delamination was initiated, especially at higher impact velocities, due to the omission of core shear failure in the model. No fiber tension, fiber compression, and matrix compression damages were indicated in the simulation results. On the other hand, significant matrix tension damage at the bottom skin and delamination between the bottom skin and the core were found, which got more prominent as the impact velocity increased. Additionally, the predicted delamination location at a velocity of 10 m/s was slightly off compared to the experimental results from the literature, which was also caused by the difference in core shear failure.

The current research is an initial step to achieve a better prediction of the response of sandwich composite panels under hydrodynamic impact and was performed numerically with only secondary data. In the near future, coupon testing to get all the necessary properties will be performed, and shear failure of the foam will be modeled in order to get a better prediction of the sandwich composite panel's damage mechanism.

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