

Crashworthiness and Deformation Pattern Analysis of Single and Double Wall with Addition Infill Structure

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ABSTRACT

Ship collisions are a phenomenon that often occurs in maritime transportation. One part of the ship that often experiences damage is the ship's wall (hull). This research aims to analyze and compare deformation patterns, stress distribution, and energy absorption in three wall models, single wall, double wall, and double wall, with the addition of infill structures. The infill structure used Polylactic Acid (PLA) polymer material because it provided convenience in the manufacturing process, while the walls of the test model used Aluminum 6063 material. The test model was developed by carrying out the design process using CAD software. Furthermore, a simulation test was carried out using software based on the finite element method with an explicit dynamic analysis type. Each test model received an impact load at a speed of 10 m/s that was carried out by the impactor. The results showed that the largest total energy absorption occurred in the double wall model with a filler structure (3643.49 J). In addition, the outward deformation pattern occurs in the double wall without a filler structure, while the inward occurs in the model with the addition of a filler structure. There were three types of stress distribution for single wall, double wall, and double wall with the addition of infill structure, namely concentrated stress, inline uniform stress, and a combination of both concentrated and inline uniform stress, respectively.

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Keywords: Crashworthiness, double walls, impact, auxetic material, PLA

I. Introduction

Fishing boats in Indonesia have been built from generation to generation without adequate construction calculations. Based on studies that have been carried out, small boats (fishing boats) often capsize when operating in waters with high waves. Data from the National Transportation Safety Committee notes that total ship accidents were dominated by fishing boats during 2018–2020 (31%). In accumulation, this number resulted in 342 people being killed or missing during the 2018-2020 period. In addition, it was recorded that 100 people die every year in fishing vessel accidents. Other data also states that 38% of ship accidents were caused by natural factors that caused collisions [1]. Previous research has been investigated to anticipate and reduce the impact of accidents (collisions).

There are three types of accidents that often occur in shipping transportation, namely collision, grounding, and contact [2] (Figure 1). This phenomenon can result in the death of passengers and material and economic losses, and it also has the potential for environmental pollution, such as oil leaks in the ocean. In order to anticipate this incident, the ship's frame



structure must withstand the loads that occur when an accident occurs. One of the frame structures that is important to strengthen when building a ship is the hull (ship body).

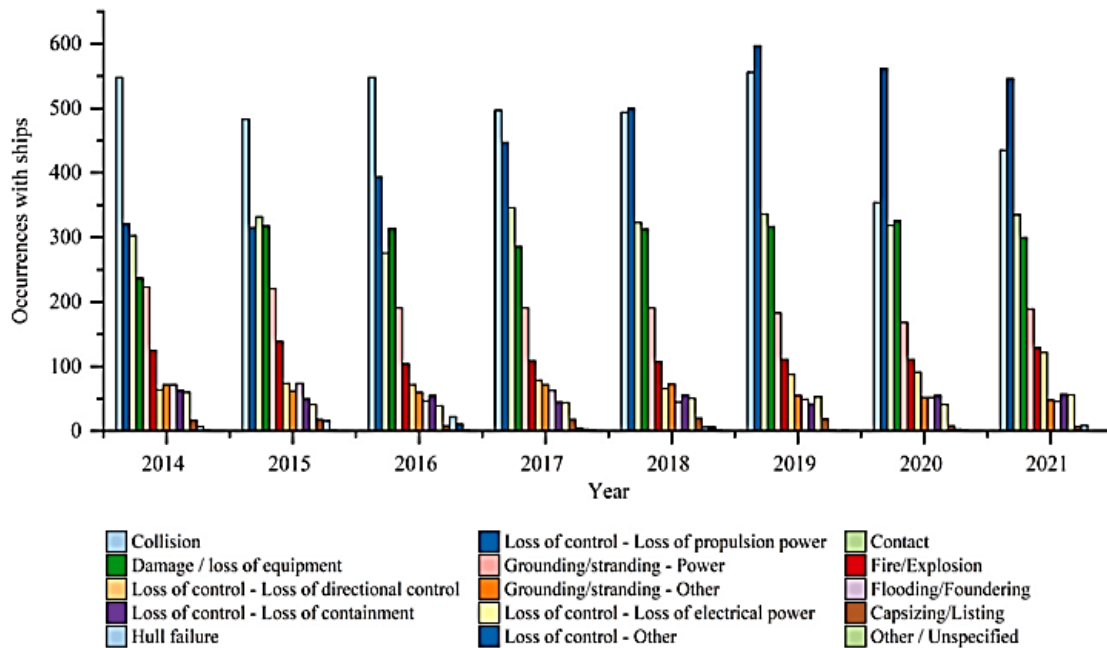


Fig. 1. Ship accidents in 2014 up to 2021 [15]

Double hull is a new structural form that has been developed to improve the mechanical properties of single hull structures [3]. The addition of the new structure aims to improve the stiffness and energy absorption of the ship's side structure such as resistance to projectile loads [4]. Apart from that, the addition of infill structures between layered walls can also increase the stiffness of the structure. Several shapes of filler material have been developed with different characteristics. 3D printing technology is one of manufacturing technology which be used for realize the complex model [5] such the filler structure [6]. Each of parameter set in 3D printing process could influence to the quality of product, such surface roughness [7], mechanical tensile strength or fracture morphology [8]. In addition, each parameter set can also influence the convenience the product modification such as shaping [9]. However, there has been no research that focuses on analyzing deformation patterns, stress distribution and energy absorption with centralized loading models in layered wall models with 3D printed part as a filler structure. This research aims to compare the deformation patterns, reaction forces, and the amount of energy absorption in single wall, layered walls with and without filler material against impact loads.

II. Material and Methods

1. Materials

Three materials were used: Aluminum 6063, Polylactic Acid with aluminum addition (PLA-Al), and structural steel. Aluminum material (Al6063) was a material commonly used in making ship hull, so this material was used as a layered wall material in this research. PLA was a polymer material that was used as a filling material between layered walls. The materials could be printed using 3D printing technology [10] for making it possible to create filler structures with complex shapes [11] by depositing the material layer by layer [12]. Meanwhile, the quality of the printed part, strength [13], or surface quality [14], [15] depend

on the print parameters. Apart from these two materials, structural steel was used as an impactor material in the modeling process. The aim of using this material was so that the impactor was not easily deformed during the impact process. Furthermore, modeling the mechanical properties of aluminum and structural steel materials according to available databases of software the finite element method. However, the mechanical properties of PLA material were obtained by carrying out tensile tests according to ASTM D638-IV standards. This material was designed using CAD software and printed using a Prusa 3D printer. The printed parts were performed tensile tested using a universal tensile machine (UTM). All information on the mechanical properties of materials used in the simulation process is in accordance with Table 1.

Table 1. Mechanical properties of the model

Parameters	Wall (Aluminum 6063)	Filler structure (PLA-Al)	Impactor (structural steel)
Modulus elasticity (MPa)	71000	2270	200000
Poisson's ratio	0.33	0.28	0.3
Yield strength (MPa)	280	18.9	250
Ultimate strength (MPa)	-	-	460
Tangent modulus (MPa)	500	14.45	-
Density (kg/m ³)	2270	1280	7850

2. Methods

In general, the main part of the double wall structure being developed refers to Figure 2. The structure was developed and tested through several stages, namely the design, simulation, and analysis processes. There were three types of wall designs observed in this research, namely single walls (Figure 2a), double walls (Figure 2b) with the addition of stiffeners, and double walls with the addition of infill structures (Figure 2c). The overall length, width, and thickness of the Al6063 plate are designed with sizes of 300 mm, 200 mm, and 5 mm respectively. In addition, the distance between model plates (d) with and without any addition of filler structures was set at 60 mm. The filler structure was designed according to Figure 3, and the number of filler structures was set to three layers, whereas the height (h), length (l), and thickness (t) of the structure were 20 mm, 12 mm, and 1 mm, respectively. Next, the entire model was saved in the form of an ACIS file (.sat) and imported into finite element method-based software as an initial information of shape model test. After that, an explicit dynamic analysis type was chosen to simulate the test model since frontal impact testing must be solved in a certain time period. The type of mesh used was quad for both walls and infill structures with a maximum size of 6 mm (Figure 4). Furthermore, the convergency of mesh quality was tested for all mesh models using Jacobian and Skewness theory. Based on both theories, the average ratio of element shape is close to the range -1 to 1 for Jacobian and between -0 to 0.5 for Skewness theory (Table 2). It indicates that the quality of element is good enough.

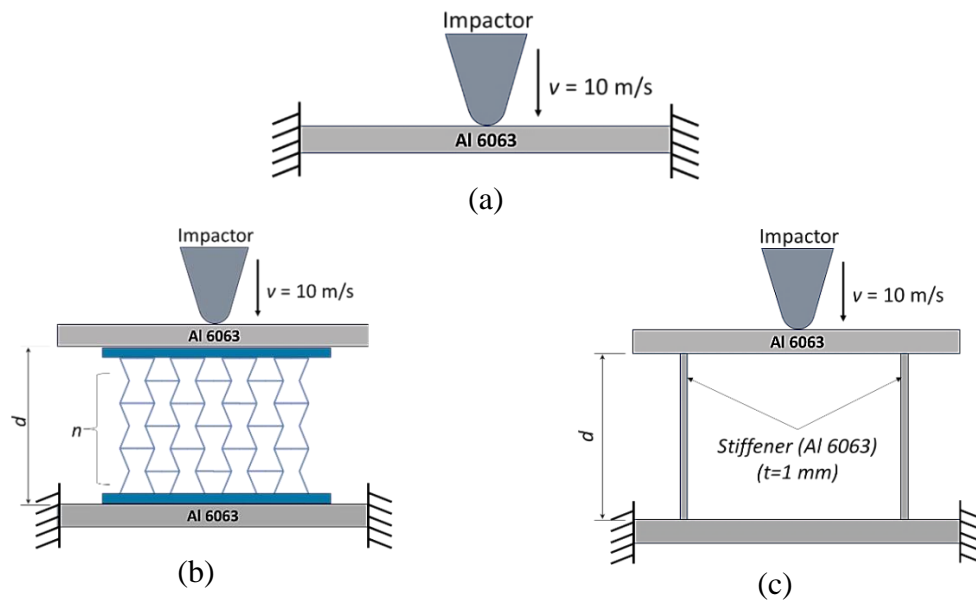


Fig. 2. Layered wall structure design: a) Single plate, b) Double plate and c) Double plate with filler structure

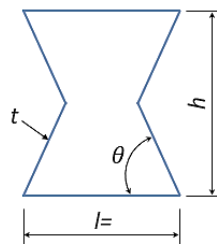


Fig. 3. Dimension of filler structure

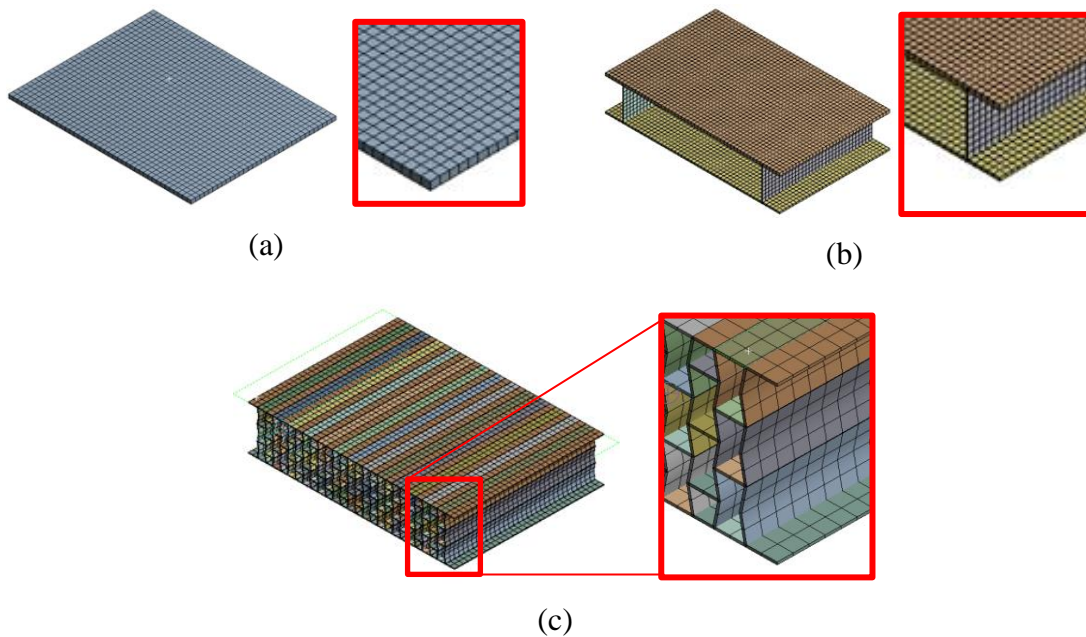


Fig. 4. Meshing setting a) single wall, b) double wall and c) filler structure

Table 2. Convergency result of mesh quality

Convergency of Mesh Quality		Single Wall Model	Double Wall Model	Double Wall with Infill Structure
Jacobian Ratio (std: -1 to 1)	Min	1	1	1
	Max	2.535	2.535	2.843
	Average	1.029	1.0136	1
	Std. Deviation	0.134	8.12×10^{-2}	3.99×10^{-2}
Skewness (std: 0 to 0.5)	Min	1.30×10^{-10}	1.21×10^{-6}	1.30×10^{-10}
	Max	0.66	0.66	0.607
	Average	1.89×10^{-2}	8.97×10^{-3}	4.47×10^{-3}
	Std. Deviation	5.83×10^{-2}	3.56×10^{-2}	1.66×10^{-2}

The entire model receives an impact load from the impactor with a crash speed of 10 m/s [16] (Figure 2). The support locations were placed on the right and left sides of the test model with a fixed support type (Figure 2) since the wall tend to weld in the ship main frame. Apart from that, the type of contact used for the entire model was set to be bounded. In addition, the double wall models with and without any addition of infill structures were arranged in a sandwich structure where each part contact model was arranged using a bounded type. The duration of the impact simulation test was carried out for 0.005 seconds so that the total deformation reached 50 mm. Next, the deformation, reaction force, von-Mises stress and energy absorption of single and layered wall structures were recorded and analyzed to determine the energy absorption performance of each structure. To clarify the flow of the research process, Figure 5 depict the sequence of the entire simulation process.



Fig.5. Sequence of simulation process

III. Result and Discussions

Figure 6 shows the relationship between reaction force and deformation for each model variation. The reaction force of the single wall and double wall models with the addition of infill structures shows a significant increase in changes in model deformation, while the double wall model without any infill structures does not increase significantly. In the deformation range of 1 mm to 10 mm, the reaction force pattern in the three models is almost the same. However, in the range of 10 mm to 50 mm, there is a significant increase in reaction force in the single wall and double wall models with the addition of the filler structure. In this phase, the infill structure begins to deform inward (Figure 7a), causing the structure with the addition of infill structure to become more rigid when the impact load was performing. Horizontal re-entrance structures were chosen and used in this research because these structures can deform inward (Figure 7a) when subjected to compressive loads. This structural model is better at increasing stiffness when compared to the Y and X structural models. The phenomenon is due to the filler structure having a negative Poisson's ratio or known as auxetic material [17]. Auxetic material can shrink if the compressive loads are performed to the material [18]. This is different for common materials, especially for metal;

it tends to experience expansion if compressive loads are applied (positive Poisson's ratio). Its phenomena occur in double wall structures without any addition of filler structures (Figure 7b). In larger deformation range, the reaction force of single wall model is still lower than double wall with addition infill structure, while the lowest reaction force occurs in the double wall model without any infill structure.

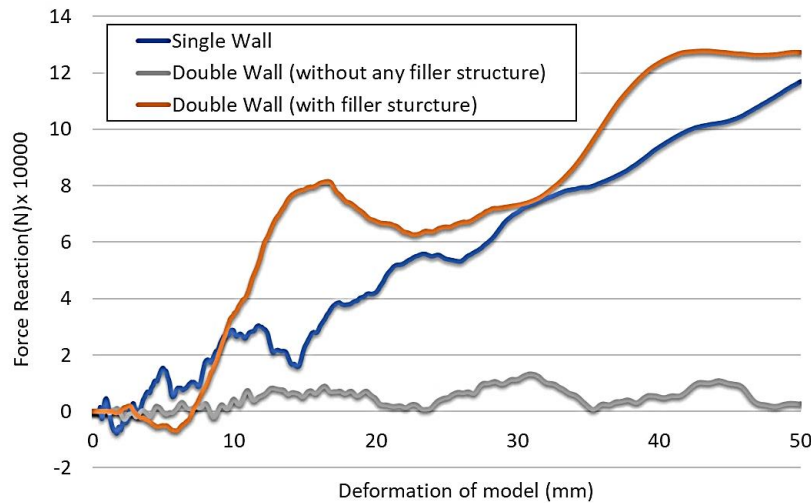


Fig. 6. Reaction force response for three different models

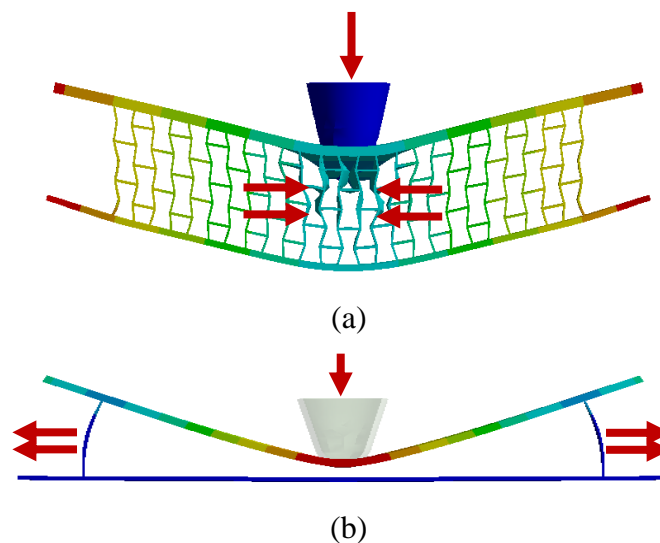


Fig. 7. Deformation pattern of double wall model a) With filler structure and b) Without any filler structure

Calculations of total impact energy absorption were also carried out for the three models. The energy absorption of the structural design was determined using the strain energy equation (Equation (1)) [19], [20]. The energy calculation was determined by the magnitude of the reaction force (F) and the impactor displacement or deformation of the test model (dx). Furthermore, the total energy absorption of the structure was calculated based on the area under the curve of the relationship between reaction force and deformation change. Based on the calculation results of the total energy absorption, the double wall model with the addition of a filler structure has the largest energy absorption (3643.84 J), while the

single wall and double wall models without any filler structures are 2813.49 J and 257.66 J respectively. This phenomenon also occurred by crash box testing using the quasi-static method. The thickness parameter showed an influence on energy absorption. The such parameter could increase the density and stiffness of structure so that the absorption of impact energy could also increase [12].

$$E = \int F. dx \dots\dots\dots(1)$$

Apart from energy absorption, it is also important to analyze the deformation pattern to determine the phenomenon of shape change in the three model variations. Figure 7 depicts three deformation patterns in the three models. Single wall and double wall models with the addition of infill structures tend to experience concentrated loading so that total deformation tends to occur in the middle of the wall. However, a different deformation pattern occurs in the double wall model without any filler structure, namely inline uniform deformation around the contact between impactor tip and the plate. Under these conditions, the deformation pattern of the upper wall is greater compared to the lower wall (Figure 7b). However, it is different phenomena to the double wall with addition infill structure which uniform deformation pattern occur both on upper and lower plate.

The entire model experiences bending loads. The largest stress concentration occurs in the model with a single wall (Figure 8a). It is showed by stress concentration that occurs in the middle area of the wall with a value of 446.62 MPa. Furthermore, stress concentration also occurs in the double wall model with the addition of an infill structure (Figure 8c). However, the stress distribution that occurs is lower than the single wall model with a stress distribution value range of 257.24 MPa to 308.57 MPa (green to yellow bar indicator stress distribution), while the stress concentration that occurs in the middle of the wall area is between 308.57 MPa to 359.91 MPa (yellow to orange bar indicator). That value is lower when compared to the maximum stress of the single wall model. In the double wall model without the addition of an infill structure, the stress distribution tends occur in the upper wall structure so that the maximum stress is lower when compared to other models (Figure 8b). If the maximum stress of model double wall with addition of the infill structure (462.59 MPa) is compared with single wall model (446.62 MPa), the stress value is greater but both stress model is still far above the allowable yield stress value. So that both models experience plastic deformation. In the double wall model without additional infill structures, the maximum stress is much lower (299.81 MPa) when compared to the other two models. That matter because the stress distribution in the model is more uniform. Based on these data, maximum stress, deformation, energy absorption and the stress distribution pattern that occur can be recorded according to Table 3.

Table 3. Stress, deformation, energy absorption, and stress distribution pattern of models

Models	Maximum stress (MPa)	Maximum deformation (mm)	Energy absorption (J)	Stress distribution type
Single wall	446.62	50.11	2813.49	Concentred stress
Double wall without any filler structure	299.81	49.97	257.66	Inline uniform stress
Double wall with filler structure addition	462.59	50.31	3643.84	Concentred and inline uniform stress

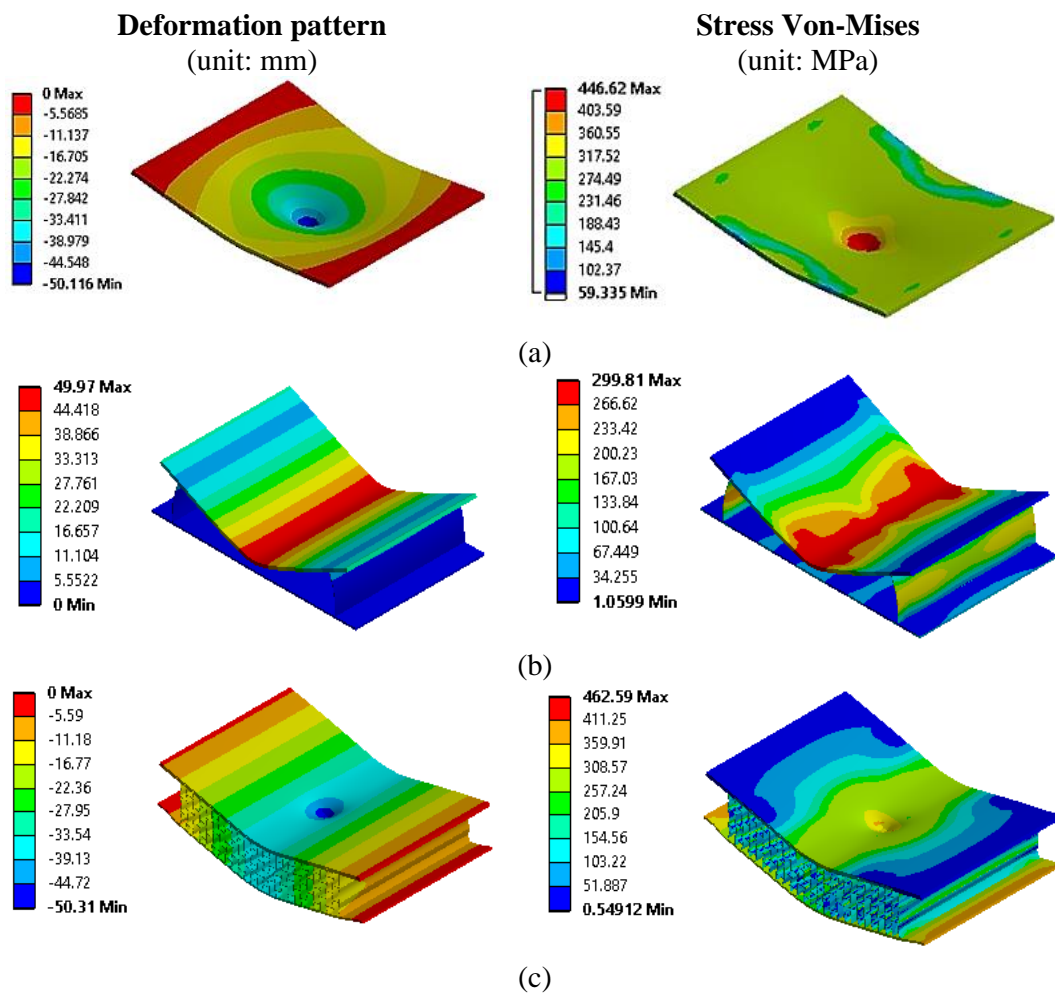


Fig. 8. Deformation pattern and stress characteristic of model a) Single wall, b) Double wall without any filler, and c) Double wall with filler structure

IV. Conclusion

Based on the results of the analysis that has been carried out, adding a filler structure can increase the reaction force and energy absorption. The increasing of energy absorption is due to the auxetic structure which is increase the stiffness of a structure when impact load performing. The maximum energy absorption is experienced by double wall with filler structure addition (3643.83 J). In addition, the addition of infill structure can make uniform pattern deformation on both upper and lower plates. There are three different types of stress distribution in the three models, namely concentrated stress, inline uniform stress, and a combination of both concentrated and inline uniform stress. This research has not considered the influence of reinforcement distance parameters on the model, especially stiffener in the double wall model without any infill structure. Therefore, it is necessary to carry out further research on the influence of these parameters in future research.

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