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Effect of Natural Fibers Reinforcement of Honeycomb Sandwich Using Numerical Analysis

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Abstract. The honeycomb sandwich structure has been extensively investigated for its mechanical performance. Modification in improving such mechanical properties is an innovation required for honeycomb sandwiches, especially by adding a random fibers reinforcement inside a sheet panel plate. This study was developed random fiber reinforcement using natural fiber of Oil Palm, Sugar Cane, and Coconut, which constructed by the commercial software code of MATLAB. This investigation analyzed the performance of three-point bending behavior using the finite-element model, which provides four levels of fiber condition to observed: 0, 50, 100, and 150 fiber numbers. Ansys Workbench/Dynamic code was chosen to predict mechanical performance such as stress and displacement analysis. In the fiber development study, a series of numerical simulations were carried out with two types of fiber orientation reinforcement, unidirectional and chopped randomly. The hybrid orientation was also implemented in this research by combining unidirectional and chopped fiber, which was fixed at 150 numbers and then varied in three sets: S50/C100, S100:C50, and S75/C75. As a result, it was confirmed that the fiber reinforcement enhances the stiffness of the structure, which contributed a lot to the promotion of the bending resistance capacity and energy absorption. Especially, unidirectional fiber orientation has shown a significant increase in absorbing stress during testing. The fiber reinforcement sandwich demonstrated better mechanical behavior in the simulation, as reported by the hybrid system, and this was influenced by the unidirectional orientation.

Keywords: Honeycomb sandwich; Hybrid; Nature fiber; Numerical; Sheet plate

1. Introduction

Honeycomb sandwich has shown a remarkable impression on mechanical performance by bringing high the stiffness/weight and strength/weight ratios, which are supported by complicated structure for weight reduction. The target productions were implemented for several applications such as the automotive, naval, and transportation industries (Zinno et al., 2011; Huang et al., 2012; Crupi et al., 2013; Partridge & Choi, 2017). The mechanical performance could be varied based on the structure due to varied size, thickness, and shape, but the main contribution was on an array of hollow cells built between thin vertical walls. It was constructed to allow the reduction of material used with minimal weight and cost. At the same time, the thin-walled aluminum honeycomb structure could be excellent

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in energy-absorbing to allow high deformable barriers from some crash tests to predict the crashworthiness, which requires special applications such as transportation regulations (Zhang et al., 2021; Wei et al., 2021; Zhang et al., 2021).

Several researchers have proposed panel plate materials combined with fiber and proposed-of-the-art composites that have existed in aviation and rockets (Vavilov et al., 2016; Monogarov et al., 2018). In several areas, the honeycomb materials, from packaging in the shape of a paper carton to sports equipment such as skis and snowboards (Mou et al., 2014), were developed with varied tailored hierarchical honeycomb cores (Li et al., 2020). The fiber reinforcement for panel plates had been developed to improve honeycomb strength, one of the most popular things was using Carbon Fiber Reinforced Plastic (CFRP) (Dungani et al., 2012; Pehlivan & Baykasoğlu, 2019; Xiao et al., 2021; Oiwa et al., 2021; Xiao et al., 2018). The CFRP has been shown to help in increasing the dynamic impact of honeycomb sandwiches by different configurations of laminate fibers (Xio et al., 2021). Laminate reinforced fiber-enhanced mechanical performance; phenomena from stacking angle (0 and 90^{o}) performance on the hexagonal honeycomb energy absorption properties increased in the 90°-layered honeycombs (Li et al., 2021). The honeycomb was implemented in motorcycle helmets for head protectors during road traffic accidents involving motorcyclists due to its high energy absorption (Li et al., 2020). From the researcher's side, fibers as substances or materials were required to explore from various resources to fulfill the material industry's performance, reliability, toughness, and resistance

Natural fiber-reinforced honeycomb has shown promising results in increasing honeycomb strength and fascinating mechanical properties (Han et al., 2020; Atiqah et al., 2020; Kumar et al., 2021; Ocieczek et al., 2021; Shieddieque et al., 2021). This was an inspiration to combine biological fiber with environment-friendly materials while improving the mechanical performance of honeycomb. They successfully developed a sandwich honeycomb with basalt fiber and a unidirectional skin sandwich-structural honeycomb to improve flexural and energy absorption (Han et al., 2020). Other studies have found that honeycomb with natural fiber could be a viable replacement for synthetic fiber as a reinforcement in polymer composites due to improvements in hardness testing (Atiqah et al., 2020). Basalts fibers are a commercialized product with higher costs and better physic-mechanical properties than fiberglass. Exploring potential nature fiber in the honeycomb structure was required to observe to meet engineering development needs.

The numerical simulation technology has been used widely in engineering, especially the Finite Element Method, which has the power to design and initial predict in various engineering fields. It has proven reliable and effective for analyzing honeycomb-like sandwiches (Wang et al., 2019; Yanuar et al., 2020; Xiao et al., 2021). The absorption of honeycomb design was required to improve the performance, and it required careful prediction using the finite element. Unfortunately, they considered it as the homogeneous material property to introduce composite materials by avoiding the fibers distribution technique. The efficiency of the construction of a sandwich honeycomb was directly related to the quality and quantity of fibers composite panels within the honeycomb. This research aimed to investigate the effect of using the honeycomb sandwich by the natural fibers distribution technique of panel plate composites which was proposed in this study. This paper introduced a developing model of the natural fibers distribution technique implemented in the panel plates. The concept of the research was to use various natural fibers as filler and condition the Oil Palm, Sugar Cane, and Coconut fiber in two orientation conditions. The first orientation focused on unidirectional random distribution, while the second was the chopped fiber random orientation; then, the honeycomb sandwich was subjected to a three-point bending (TPB) to find the best orientation type of composites.

2. Numerical Model

The process was divided into two stages in this simulation-based investigation. In the first stage, fibers were developed using MATLAB. While the second stage was subjected to the mechanical performance of Three-Point Bending (TPB) using Finite Element analysis. The detailed process is as follows:

2.1. Fibers development

The distribution of fibers was an essential part of this research for investigating the effect of panel plates on honeycomb core. To randomly develop fiber inside a sheet panel plate, the sheet plate was designed based on the required size to develop domain size, which was fiber distributed inside. The sheet panel plate dimension was designed with 76 mm × 221 mm × 1.5 mm based on the three-point bending (TPB) standard of ASTM C-393 (ASTM Standard C393, 2016). This bending test size covered the standard test dimension for honeycomb sandwich because the size was adequate by the following ratio conditions: width/total thickness ratio ≥ 2, Length/width ratio ≥ (1.5+50 mm), and t_{panel}/t_{core} ratio < 0.1. Two types of fiber orientation were developed through different designing methods using MATLAB software.

The random fiber was designed in a radius of 0.1 mm for both unidirectional and chopped fiber orientation. To fulfill nature fiber behavior, the microstructure was generally passed through three stages: a) Generate domain size, b) Determine launch point c) Produce fiber. All stages procedures for unidirectional orientation are explained as follows; the points were launched randomly within the domainand avoided the repeated point selected by the program. The point launched technique was used on the thickness side only. The side selected is considered a longitudinal direction from the beginning to the endpoint of fibers. Each side was implemented to select the point randomly and repeatedly until satisfying the number required. Once the points were selected and saved on the storage as *x*, *y*, and *z*-axis. Chopped fibers were more complex compared to unidirectional fibers. The point launched technique method was implemented directly into the domain with fiber size already determined. Each fiber was performed by random point connection which was distributed inside the domain. It was recommended that one fiber have at least four points of connections to perform a smooth fiber pattern. The distribution and pattern were developed randomly and repeatedly until satisfying the number required. The domain system selected the multi-point number registered in the domain randomly. Point selection was made once to avoid overlapping conditions. Furthermore, the program allowed the construction of several points to perform fiber design of a random chopped shape. The multi-orientation of chopped made it possible to perform several points neighbor position. These neighbor distances were limited by an allowed distance, ($L_{allowed}$), among the first point (P_i). The first points (P_i) selected were considered as the initial point in coordinate fiber position and fixed, while the second-order points selected (P_{i+1}) acted as a neighbor which allowed moving from the origin point. Second-order points (P_{i+1}) were attached as a neighbor by following the Pythagoras concept where the angle θ_i was used to be measured the distance L_i from P_i. Points (P_{i+1}) were attached to P_i by using the same θ_i as a neighbor in $L_{allowanced}$ as distance. In addition, re-selecting point P_{i+1} would re-process if $L_i \leq L_{allowanced}$. The step was repeated until the number point was satisfied for one fiber design and fulfill the model by several fibers' numbers. In the final stage, every single point of a single fiber came out with *x*, *y*, and *z* coordinate information that could be exported into an excel file. Both types of fiber orientations were observed in 3 different quantities: 50, 100, and 150 fibers number. For the hybrid system, the total fibers' unidirectional and curving orientation content was fixed at 150 fibers number. As shown in Figure 1, the number ratios of the hybrid system using unidirectional and curving fiber orientation are varied in three sets: S50/C100, S100:C50, and S75/C75. The number on the left indicates the unidirectional orientation fibers content, while on the right indicates the curving orientation fibers content. Table 1 shows the complete fiber content and orientation types.

Table 1 Fiber orientation code

Fiber code	Definition/fiber content
S50	unidirectional orientation/50 fibers
S100	unidirectional orientation/100 fibers
S150	unidirectional orientation/150 fibers
C50	chopped orientation/50 fibers
C100	chopped orientation/100 fibers
C150	chopped orientation/150 fibers
S50/C100	unidirectional50: chopped100/150 fibers
S100/C50	unidirectional100: chopped 50/150 fibers
S75/C75	unidirectional75: chopped 75/150 fibers

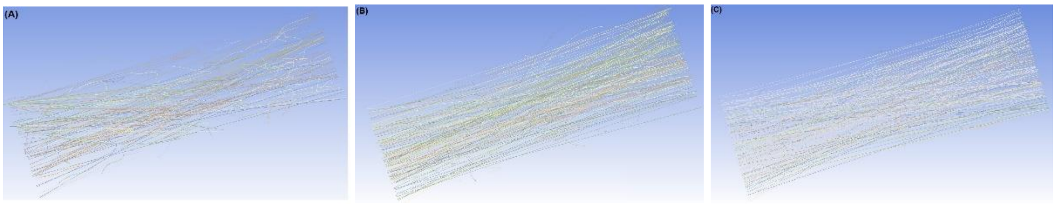
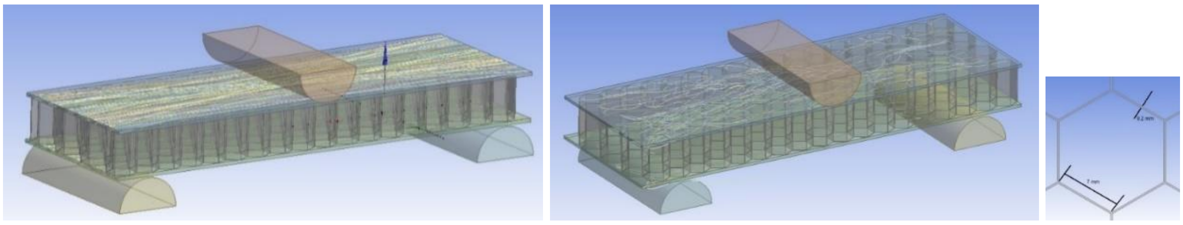


Figure 1 A hybrid system using unidirectional and curving fiber orientation for (A) S50/C100, (B) S75/C75, and (C) S100/C50

2.2. Finite element analysis

A three-dimensional nonlinear elastoplastic finite element model of Three-Point Bending (TPB) was implemented using the commercial software Ansys Workbench Dynamic to investigate the dynamic mechanical behavior of sandwich panels with honeycomb core. The honeycomb sandwich panel under considered here is constituted by the top and bottom sheet plate panel and a regular hexagon aluminum honeycomb core, as illustrated in Figure 2;1(a) is shown for unidirectional orientation fiber while 2(b) is shown for chopped fiber orientation. For both cases, the sheet panel plate polyethylene and aluminum honeycomb core were bonded as a sandwich while the natural fibers were imported from MATLAB software by introducing the coordinate points using a text document file. In this simulation, the sandwich model's geometrical parameters are defined as follows: The thicknesses of the face sheets and aluminum honeycomb core were defined as 23 mm. The wall length and thickness of honeycomb cells were 7.0 mm and 0.2 mm, respectively. The square sandwich panel measured 76 mm, 221 mm in length, and 20 mm in height. The regular hexagon honeycomb core had a side length of 7 mm. Then the specimen was subjected to the three-point bending load from semi-cylinder steel with a diameter and pressure of30 mm and 10GPa, respectively. The Young Modulus of Steel, Polyethylene, and Aluminium presented in 200 GPa, 1.1 GPa, and 71 GPa, respectively. For natural fiber of Oil palm, Sugar cane, and Coconut was 2.7-3.2 GPa, 18-27 GPa, and 4-6 GPa, respectively (Dungani et al., 2012). The fibers reinforcement was embedded in Polyethylene plastic as a sheet panel plate. Further study was focused on meshing size to carry out numerical analysis to meet convergence results without being affected by the element size.



(a) (b)

Figure 2 Ansys Workbench model of honeycomb sandwich panel (a) Straight-line fiber, (b) Curving fiber

2.3. Failure of three-point bending

Core Shear Stress of Single-Point Midspan Load had calculated the core shear stress as follows Equation 1 (ASTM Standard C393, 2016):

$$\tau = \frac{P}{(d+c)b} \tag{1}$$

Where τ, *P, d, c,* and *b* denoted core shear stress, MPa (psi), load, N (lb), sandwich thickness, mm (in), core thickness, mm (in), and sandwich width, mm (in), respectively. While core failure is predicted by shear failure in Equantion (2) as follows:

$$S \leq \frac{2\sigma_{fmax} t}{kF_S} \tag{2}$$

Where S was the distance support span, σfmax was the face sheet estimate ultimate strength, *k* was the core shear strength factor to ensure face sheet failure (0.75 was recommended by the previous researcher (Daniel et al., 2002), and *Fs* was the core shear strength.

2.4. Validation

The modeling honeycomb core using homogeneous orthotropic solid geometries was validated with a plain face sheet honeycomb before further observation using a reinforced face sheet. Failure observation was conducted by using Eq. (2) which was the core crushing of the subject study. Three-point bending with 8000N of the load is reported at 1×10^{-3}s for observation as shown in Figure 3. Through this time, when the failure started with a shear stress of 342 MPa, local indentation failure could be seen in the simulation. This failure mode was also recorded by Eq. (2) which the failure value of the shear stress occurred at 340 MPa. This phenomenon is also captured by plotting graphs of shear stress versus time; as shown in the figure, the shear stress begins disordered from the linear condition at the time of 1×10^{-3}s. It was obvious, that the structure condition starting to destruct as existed in the simulation during the flexural loading. Furthermore, it was observed that the shear strength of the core error earned by using theoretical and finite element analysis was presented at 0.58%.

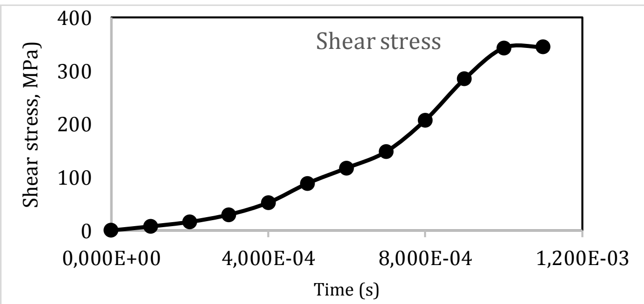


Figure 3 Shear stress of core sandwich

3. Results and Discussions

During the simulation, the barrier of the research was fiber distribution development which was difficult to control such as the fiber curve in the panel sheet. It caused the fibers to curve outside the panel sheet area despite the point coordinate was still inside the panel sheet area. To avoid this constraint, the programming could adjust the point distancing in a small space. At the same time, the point numbers should be added to maintain the fiber length. Unfortunately, this condition influenced to increase in the cost of running time to produce fiber distribution.

In the numerical dynamic calculation process, the total time of the analysis step range was 4×10^{-6} to 2×10^{-5} s. The stress mode in the bending process of the honeycomb sandwich was analyzed using natural fibers material to investigate the details of its bending resistance ability the observation regarding the normal stress simulation resulted in which three conditions of fiber content: 0, 50, 100, and 150 fibers of Oil Palm in each sheet plate. The interaction contact relationship between the load and sandwich panel was observed. The interaction between the face sheet and semi-cylinder load was determined by the high pressure of loading, which meant that the honeycomb sandwich was investigated by destructive testing. The three-point bending load at the whole system absorbed the load better than the honeycomb sandwich, making it simple to investigate the output stress that could be absorbed through the honeycomb sandwich. As the consumption time increased, the permanent deflections of both top and bottom face sheets of damage enlarged gradually. The honeycomb core then compressed slowly and finally reached the failure stage. The integral folds of the honeycomb core increased, and the buckling area steadily enlarged. The normal stress (*z-axis*) that occurred at the composite plate samples was increased by increasing fibers number for unidirectional fiber of Palm Oil, due to the strong tensile absorption in bending loading. It was shown that the normal stresses had been blocked by the panel composite before it was absorbed by the honeycomb core. The orientation of the longitudinal fibers was consistent with the normal stress absorption. The normal stresses received by the honeycomb core were shown to reduce by increasing the fiber number, a random orientation that caused the normal stress (z-axis) output was absorbed by the fibers. The composite plate of Oil Palm with unidirectional orientation successfully reduced normal stress (z-*axis*) in 45%, 70%, and 72% at early 7.02×10^{-6} s of time for fibers content of 50, 100, and 150, respectively. While Sugar Cane and Coconut fiber also showed a similar reduction range from 44% to 72% of normal stress before being received by the core compares to the plain plate. The previous researcher also reported that fiber composites were an effective way to avoid premature failure and improve the mechanical properties of a sandwich structure (Sun et al., 2021).

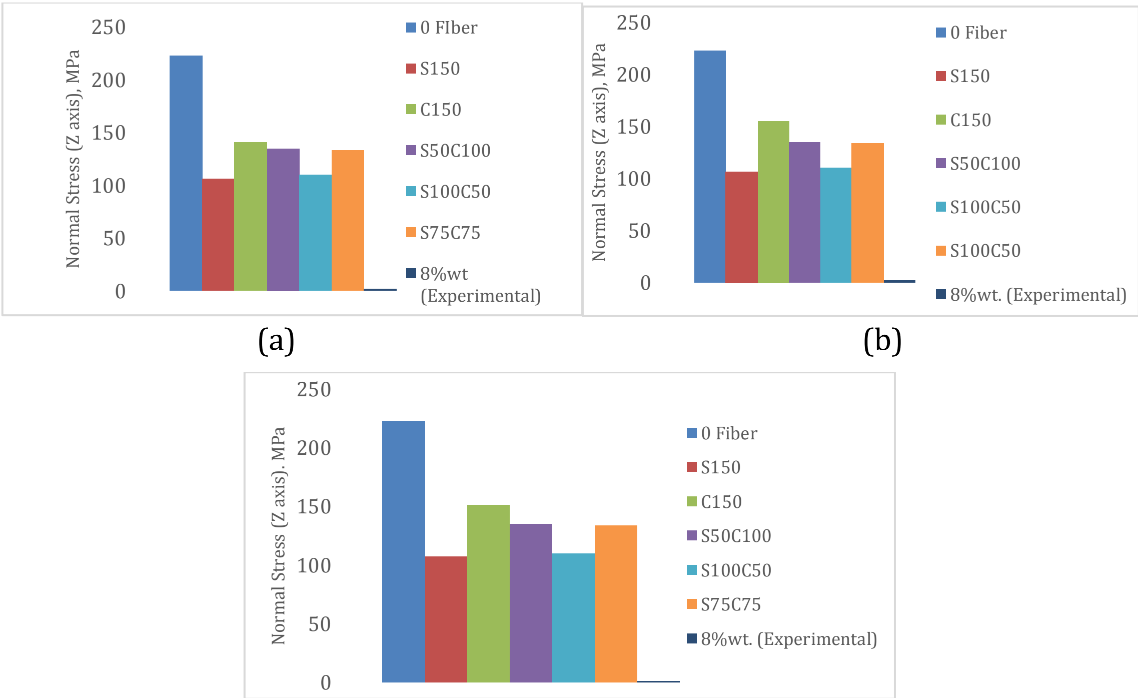
The composite plate's repeated TPB testing and stress absorption properties were performed and investigated to study the effect of the fiber content of chopped orientation on the normal stress behaviors. It was found that with the increase of fibers number of composite plates, the normal stress (z-*axis*) absorption through the plate composite increased in the condition of the condition of the early time loading at 4.4×10^{-6}s. It could be seen that the stress absorption with the random fiber's direction composite was uncertain due to fiber orientation, which influenced the tensile stress absorption. The normal stress absorption performance of chopped orientation during TPB caused non-gradually normal stress absorption to fiber number content. On the other hand, normal stress absorption significantly increased in the composite plate, reducing 43% to 48% stresses compared to the plain plate.

To further investigate the dynamic mechanical behaviors of honeycomb, natural composite under TPB loads was performed. These results showed that the deformation of the unidirectional fiber composite sandwich was obviously could be seen near the two support areas and the middle of the front face sheet plate. It could be observed that the numerical load-deformation was varied by increasing the number of the fibers due to fiber reinforcement increasing resistance to the load. However, fiber distribution very significantly influenced the deformation level. It occurred at 50 fibers number, which was fiber distributed mostly in the center of the plate along the longitudinal direction with close to each other. It helped the plate to absorb the load in a single strength unity. In contrast, the interaction of the honeycomb core could be seen in the curving orientation, which demonstrated a more desirable deformation pattern, providing an increase in stiffness by adding higher fiber content. This could be explained as the increase in the fiber content; the distribution well enough had reached all directions to fulfill the x and y-axis systematically. It gave rise to the benefits of the reinforcement effect of the honeycomb core as well as the global strength and stiffness of the plate. Previous research on the natural fiber of papaya revealed a significant reduction in stiffness and strength when random fiber orientation was compared to longitudinal orientation (Coura et al., 2020). This statement validated the findings concerning flexural phenomena.

A study on the hybrid of unidirectional and curving orientation at 150 fibers numbers is shown in Figure 4. These observations were investigated on honeycomb core at a range time of 0 to 4×10^{-6} s. The normal stresses (z-axis) of these hybrid unidirectional and curving orientations were varied due to the fiber orientation content of the plate composite. Based on the fiber number ratios, the normal stress levels were dominated by the unidirectional orientation fiber. It meant that the unidirectional fiber contributed to the composite's resistance to flexural load. Despite the fact that the S100/C50 hybrid finding received lower normal stress, the S150 still showed higher performance in absorbing the flexural load. Due to the flexural test being dominated by tensile stress conditions, the fiber in the longitudinal direction provides advantages in resistance during testing. Previous researchers had reported the benefit of hybrid fiber of natural fiber composites by introducing banana, Prosopis juliflora plant, and coconut fibers as composite reinforcement (Muthalagu et al., 2021).

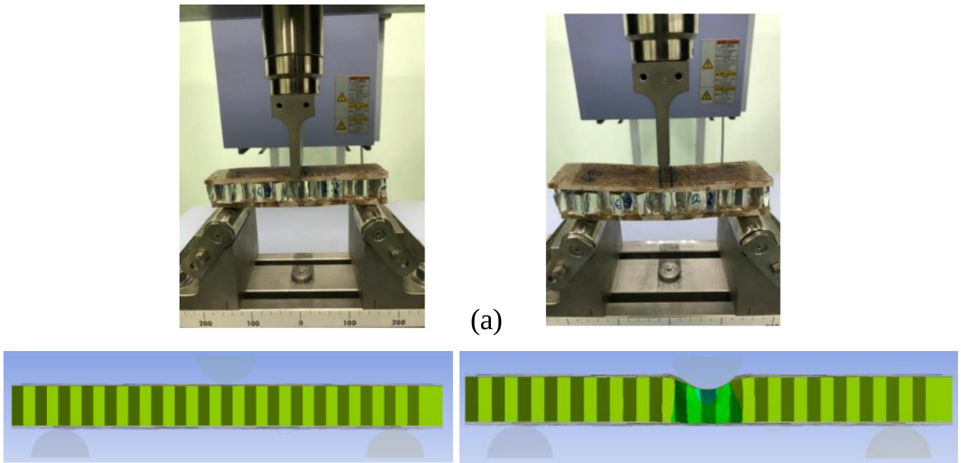
Figure 4 illustrates an irrelevant comparison when the experimental method had a fiber content of 8%wt. This fiber content exceeded the fiber number implemented in the simulation which was 150 fiber number only. The experiment was observed by varying fiber content from2%wt. to 8%wt., it shown signs of incrementing stress absorption by increasing fiber content. The fiber content had shown many contributions to reducing flexural stress and, at the same time, successfully improving tensile stress in honeycomb sandwiches. All nature fiber types presented similar phenomena during flexural testing where fiber helped counter preliminary failure. The fiber was randomly distributed. and the same method was implemented by the hybrid technique that caused strong in any direction.

Figure 5 compares the deformation characteristics of conventional honeycomb sandwiches in experiments to simulation testing for oil palm fiber reinforcement. The deformation characteristics informed the local indentation pattern captured for both experimental and simulation. The deformation was both experimental and simulated from the movement of the loading impactor. The results had shown a good agreement and consistency in three-point bending behavior. The simulation results also show reliable data with the experiment test which was validated using deformation recorded at 5×10^{-6} s as shown in Figure 6. The deformation that occurred for both methods presented insignificant deviation which simulation came out at 1.1974 mm of displacement while 1.134 mm for the experimental result, which confirmed the consistency of the simulation results.



(c)

Figure 4 Normal stress (z-axis) comparison of hybrid orientation for (a) Oil Palm fiber, (b) Sugar Cane fiber, and (c) Coconut fiber



(b)

Figure 5 Deformation patterns of conventional honeycomb sandwich of (a) experimental and (b) numerical stages with oil palm reinforcement

4. Conclusions

Numerical simulations for the aluminum honeycomb sandwich are performed and fiber reinforcement successfully develops reinforcement distribution technique by coding MATLAB software. Based on the results mentioned above and discussions, some significant conclusions can be drawn as the research results. The first conclusion that the reinforcement increase strength and stiffness for the whole honeycomb sandwich. In this way, the bending resistance capacity of reinforcement sandwiches gets substantially compared to the plain plate. This fact is embodied in the load-deflection chopped and different deformation patterns. The second conclusion describes that the numerically calculated results of the TPB dynamic mechanical behaviors of sandwiches show an increase in the stress absorption can be effectively modulated by the reinforcement fibers. And then the third found that the unidirectional fiber orientation achieves a high tensile strength due to the fiber's structure in a longitudinal position on the plate. The last conclusion, mention that the hybrid of unidirectional and chopped orientation, performance was dominated by unidirectional orientation characteristics in stress absorption during flexural testing. The natural fiber of Oil Palm, Sugar Cane, and Coconut was a promising reinforcement for polymeric composites and suitable to be implemented as a facing panel of honeycomb.

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