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Effect of Natural Fibers Reinforcement of Honeycomb Sandwich Using Numerical Analysis

Muhammad Zulkarnain[1], Khairul Amri Tofrowaih[1], Silvi Ariyanti[2]

[1] Fakulti Teknologi Kejuruteraan Mekanikal dan Pembuatan, Universiti Teknikal Malaysia Melaka (UTeM), 75450 Ayer Keroh, Malacca, Malaysia

[2]Department of Industrial Engineering, Engineering Faculty, University of Mercubuana, Jakarta, Indonesia.

Abstract. The honeycomb sandwich structure has been extensively investigated for its mechanical performance. Modification in improving such mechanical properties is an innovation required of honeycomb sandwich, especially with 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 commercial software code of MATLAB. This investigation was analyzed the performance of three-point bending behavior by using the finite-element model which provides four levels 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 fiber development study, a series of numerical simulations were carried out with 2 types of fiber orientation as reinforcement, unidirectional and chopped randomly. The hybrid orientation also implemented in this research by combined unidirectional and chopped fiber which was fixed at 150 numbers 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 contributes a lot to the promotion of the bending resistance capacity and energy absorption. Especially on unidirectional fiber orientation shown a significant increase in absorbing stress during testing. It was similar which reported by the hybrid system, the fiber reinforcement sandwich showed better mechanical behavior in the simulation, and it was influenced by the unidirectional orientation.

Keywords: Nature Fiber; Honeycomb sandwich; Hybrid; numerical, sheet plate

1. Introduction

Honeycomb sandwich has shown impressed regarding on mechanical performance with bringing high the stiffness/weight and strength/weight ratios which 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 et al., 2017). The mechanical performance can be varied based on the structure due to varied size, thickness and shape, but the main contribution is 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 in energy-absorbing to allow high deformable barriers from some crash tests to predict the crashworthiness which needed special application such as transportation regulations (Zhang et al., 2021; Weiet al., 2021; Zhang et al., 2021).

Several researchers have proposed panel plate materials combine with fiber and proposed-of-the-art composites that have been present in aviation and rockets (Vavilov e 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). Regarding on fiber reinforcement for panel plate have been developed to improve honeycomb strength one of the most famous was using Carbon Fiber Reinforced Plastic (CFRP) (Dungani et al., 2012; Pehlivan and 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 has the benefit to mechanical performance, phenomena from stacking angle (0 and 90^{o}) performance on the hexagonal honeycomb energy absorption properties increase in the 90°-layered honeycombs (Li et al., 2021). Regarding high energy absorption, the honeycomb was implemented in motorcycle helmets for head protectors during road traffic accidents involving motorcyclists (Li et al., 2021). From the researcher's side, fibers as substances or materials are required to explore from various resources to fulfill the performance, reliability, toughness, resistance of the material industry.

Natural fiber-reinforced has been promising in increasing honeycomb strength and shows fascinating mechanical properties (Han et al, 2020; Atiqah et al., 2020; Sathees Kumar et al., 2021; Aneta O. et al., 2021; Apang D S. et al., 2021). This is an inspiration to meet biological fiber with environment friendly during in improving the mechanical performance of honeycomb. They successfully developed a sandwich honeycomb with basalt fiber with unidirectional skin sandwich-structural honeycomb to improve flexural and energy absorption (Han et al., 2020). Other research reported that honeycomb with natural fiber can be a potential candidate to replace the synthetic fiber as a reinforcement in polymer composites due to improvements in hardness testing (Atiqah et al., 2020). Basalts fibers are a commercialized product that becomes high cost and has better physic-mechanical properties than fiberglass. Exploring potential nature fiber in the honeycomb structure require to observe to meet engineering development needs.

The numerical simulation technology has been used widely in engineering, especially the Finite Element Method has powerful to design and initial predicting in various engineering fields, which it has proofed and regarded as a reliable and effective to analyze honeycomb-like sandwiches (Wang et al. 2019; Yanuar et al., 2020; Xiao et al., 2021). The absorption of honeycomb design is required to improve the performance and it needs careful predicting by 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 is directly related to the quality and quantity of fibers composite panels within the honeycomb. The aim of this research is to investigate the effect of using the honeycomb sandwich by natural fibers distribution technique of panel plate composites which is proposed in this study. This paper introduces a developing model of the natural fibers distribution technique implemented in the panel plates. The concept of the research is to use various natural fibers as filler and conditioned the Oil Palm, Sugar Cane and Coconut fiber in two orientation conditions. The first orientation focuses on unidirectional random distribution while the second is the chopped fiber random orientation, then the honeycomb sandwich is subjected to a three-point bending (TPB) in order to finally find the best orientation type of composites.

2. Numerical model

In our investigation by using simulation, the process is dividing into two stages. The process was involving fibers development using MATLAB conducted in the first stage. While the second stage was subjected to the mechanical performance of Three-Point Bending (TPB) using Finite Element analysis. The detailed process is explained below:

2.1 Fibers development

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

The random fiber is designed in a radius of 0.1 mm for both unidirectional and chopped fiber orientation. Generally, the microstructure was passed through three stages to fulfil nature fiber behaviour: a) Generate domain size, b) Launch point c) Generate fiber. For unidirectional orientation all the stages procedures are explained as follows. The points were launched inside the domain randomly and avoid the repeated point selected by the program. The point launched technique was used on the thickness side only. The side selected which consider as a longitudinal direction from 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 save on the storage as *x*, *y* and *z*-axis. While chopped fibers, 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 to fulfil one fiber not less than 4 points connections to perform smooth fiber pattern. For both distribution and pattern were developed randomly and repeatedly until satisfying the number required. In the domain system, the multi-points number registered in the domain is selected randomly. Point selection is done once to avoid overlapping conditions. Furthermore, the program allows constructing several points in order to perform fiber design of a random chopped shape. The multi orientation of chopped makes 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 are considered as the initial point in coordinate fiber position and fixed, while the second-order points selected (P_{i+1}) acts as a neighbor which allows moving from the origin point. Second-order points

(P_{i+1}) are attached as a neighbor by following the Pythagoras concept where the angle θ_i is used to measuring the distance L_i from P_i. Points (P_{i+1}) are 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} will re-process if $L_i \le L_{allowanced}$. The step is repeated until the number point is satisfied for one fiber design and fulfil the model by several fibers' numbers. In the final stage, every single point of a single fiber come out with x, y and z coordinate information that can be exported into an excel file. For both types of fiber orientations were observed by 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. The number ratios of the hybrid system using unidirectional and curving fiber orientation were varied in three sets: S50/C100, S100:C50, and S75/C75 as shown in Figure 1. The number on the left indicates the unidirectional orientation fibers content, while on the right indicates the curving orientation fibers content. For complete fiber content and orientation types are presented in Table 1.

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

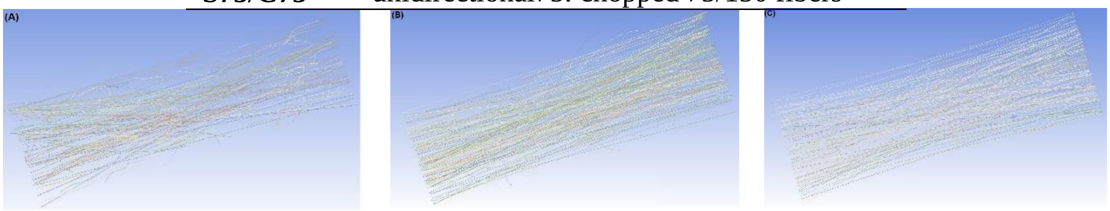
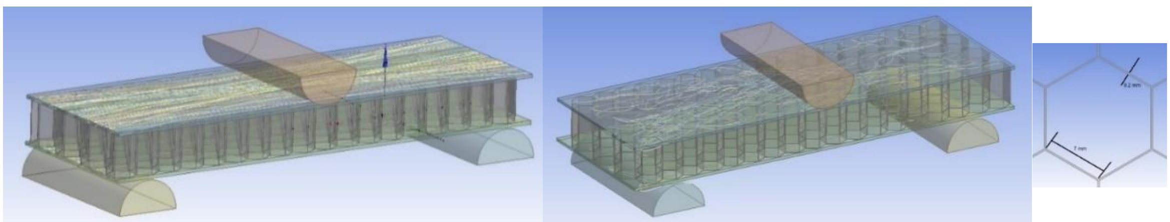


Figure 1. Hybrid system using unidirectional and curving fiber orientation for (A) S50/C100, (B) S75/C75 and (C) S100/C50

2.2 Finite element analysis

To investigate the dynamic mechanical behavior of sandwich panels with honeycomb core, a three-dimensional nonlinear elastoplastic finite element model of Three-Point Bending (TPB) was implemented by using the commercial software Ansys Workbench Dynamic. The honeycomb sandwich panel considered here is constituted by the top and bottom sheet plate panel as well as regular hexagon aluminium honeycomb core as shown in Figure 2. 1(a) was shown for unidirectional orientation fiber while 2(b) shown for chopped fiber orientation. For both cases, the sheet panel plate polyethylene and aluminium honeycomb core are bonded as sandwich while the natural fibers are 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 aluminium honeycomb core are defined as 23 mm. The wall length and thickness of honeycomb cells are 7.0 mm and 0.2 mm, respectively. The dimension of the square sandwich panel is 76 mm × 221 mm with 20 mm of the height. The side length of the regular hexagon honeycomb core was 7 mm. Then the specimen was subjected to the three-point bending load from a semi-cylinder steel which has 30 mm and 10GPa for diameter and pressure, 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 is 2.7-3.2 GPa, 18-27 GPa, and 4-6 GPa, respectively (Dungani et al., 2012). The fibers reinforcement were imbedded in Polyethylene plastic as sheet panel plate. Further study was focused on meshing size to carry out numerical analysis to meet convergence results without effected 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 was calculated the core shear stress as follows (ASTM Standard C393):

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

Where τ, P, d, c, and b denote to 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 predicted by shear failure in Eq. (2) as follow:

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

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

2.4. Validation

The modelling 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 is the core crushing as the subject study. Three-point bending with 8000N of the load was reported at $1 \times 10^{-}$

^{3}s for observation as shown in Figure 3. Local indentation failure can be seen in simulation by this time which failure have been starting by the shear stress of 342 MPa. This mode of failure was also recorded by Eq. (2) which the failure value of the shear stress occurs at 340 MPa. This phenomenon was also captured by plotting graphs between the shear stress versus time, the shear stress began disordered from the linear condition at the time of 1×10^{-3}s as shown in figure. It was obvious, the structure condition starting destructive as present 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%.

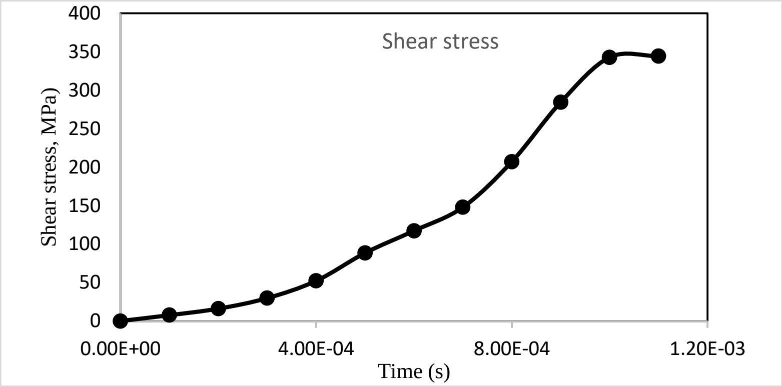


Figure 3 Shear stress of core sandwich

3. Results and discussions

The research constraints during the simulation were found that fiber distribution development was difficult to control such as fiber curve in the panel sheet. It caused the fibers to perform curving outside the panel sheet area even though the point coordinate was still inside the panel sheet area. The programming can adjust the point distancing in a small space to avoid this constraint. At the same time, the point numbers should be added to maintain the fiber length. Unfortunately, this condition influence to increase the cost of running time to produce fiber distribution.

In the numerical dynamic calculation process, the total time of the analysis step range is 4×10^{-6} to 2×10^{-5}s. To investigate the details of the bending resistance ability of the honeycomb sandwich, its stress mode in the bending process is analyzed based on natural fibers material. The observation regarding the normal stress simulation results in which of 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 has been observed. The interaction between the face sheet and semi-cylinder load is determined by the high pressure of loading, which means that the honeycomb sandwich was investigated by destructive testing. The three-point bending load at the whole system exceeds the honeycomb sandwich to absorb the load, which makes it easy to investigate the output stress that can absorb through the honeycomb sandwich. As the increase of consuming time, the permanent deflections of both top and bottom face sheets of damage enlarge gradually, the honeycomb core compresses gradually and finally reach the failure stage, the integral folds of the honeycomb core increase and the buckling area gradually enlarges. Obviously, clear the normal stress (*z-axis*) that occurred at the composite plate samples were increasing 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 have been blocking by panel composite before absorbing 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 shown to reduce by increasing the fiber number, randomly orientation causes the normal stress (z-axis) output was absorbed by the fibers. The composite plate of Oil Palm with unidirectional orientation successful reducing 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 shown a similar reducing range starting from 44% until to 72% of normal stress before being received by the core compares to the plain plate. This phenomenon was also reported by the previous researcher that fiber composite was an effective way to avoid premature failure and improving the mechanical properties of a sandwich structure (Sun et al., 2021).

In order to study the effect of fibers content of chopped orientation on the normal stress behaviors, the repeated TPB testing, and stress absorption properties of composite plate are performed and investigated. It can be found that with the increase of fibers number of composite plates, the normal stress (z-*axis*) absorption through the plate composite increases in the condition of the early time loading at 4.4×10^{-6}s. It can seem that with the random fiber's direction composite, the stress absorption shown an uncertain level due to fiber orientation influences the tensile stress absorption. The normal stress absorption performance of chopped orientation during TPB causes non-gradually normal stress absorption to fiber number content. However, normal stress absorption significantly increases in the composite plate by reducing 43% until 48% stresses compared to the plain plate.

To further investigate the dynamic mechanical behaviors of honeycomb natural composite under TPB loads were performed. These results shown that the deformation of unidirectional fiber composite sandwich was obviously can be seen near the two supports area and the middle of the front face sheet plate. It can be observed that the numerical load deformation was varied by increasing the fibers number due to fiber reinforcement increasing resistance to the load. However, fiber distribution very significant influence on the deformation level. It occurred at 50 fibers number which is fiber distributed mostly in the center of the plate along the longitudinal direction with close each other. It is helping the plate to absorb the load in one strength unity. By contrast, the interaction of the honeycomb core can be seen in the curving orientation, which clearly demonstrates a more desirable deformation pattern, providing the increase with the stiffness by adding higher fiber content. This could be explained that as the increase of the fiber content, the distribution well enough has reached all directions to fulfil the *x* and *y*-axis systematically. It gives rise to the advantages of the reinforcement effect of the honeycomb core as well as the global strength and stiffness of the plate. The previous finding on the natural fiber of papaya has been reported that a massive reduction in stiffness and strength is observed on random fiber orientation compared to longitudinal orientation (Courca et al., 2020). This statement has supported the results obtained regarding flexural phenomena.

A study on the hybrid of unidirectional and curving orientation was conducted at 150 fibers numbers have 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 means that unidirectional fiber brings the composite resistance to the flexural load. Even though the S100/C50 hybrid finding has received lower in normal stress, the S150 still showed higher performance in absorbing the flexural load. Due to the flexural test was dominated by tensile stress condition, the fiber in longitudinal direction brings advantages in resistance during the testing. The benefit hybrid fiber of natural fiber composites has been reported by previous researchers by introducing banana, Prosopis juliflora plant, and coconut fibers as composite reinforcement (Muthalagu R. et al., 2021).

An irrelevant comparison has been shown in Figure 4 when the experimental method was at 8%wt. of fiber content. This fiber content much exceeds the fiber number implemented in the simulation which was 150 fiber number only. The experiment was observed by varied fiber content in the range of 2%wt. until 8%wt., it has shown signs in the increment of stress absorption by increasing fiber content. The fiber content has shown much contributions to reducing flexural stress and same time successfully improving tensile stress in honeycomb sandwiches. All nature fiber types presented similar phenomena during flexural testing where fiber much helped to counter preliminary failure. The fiber is randomly distributed and the same method is implemented by the hybrid technique that causes strong in any direction.

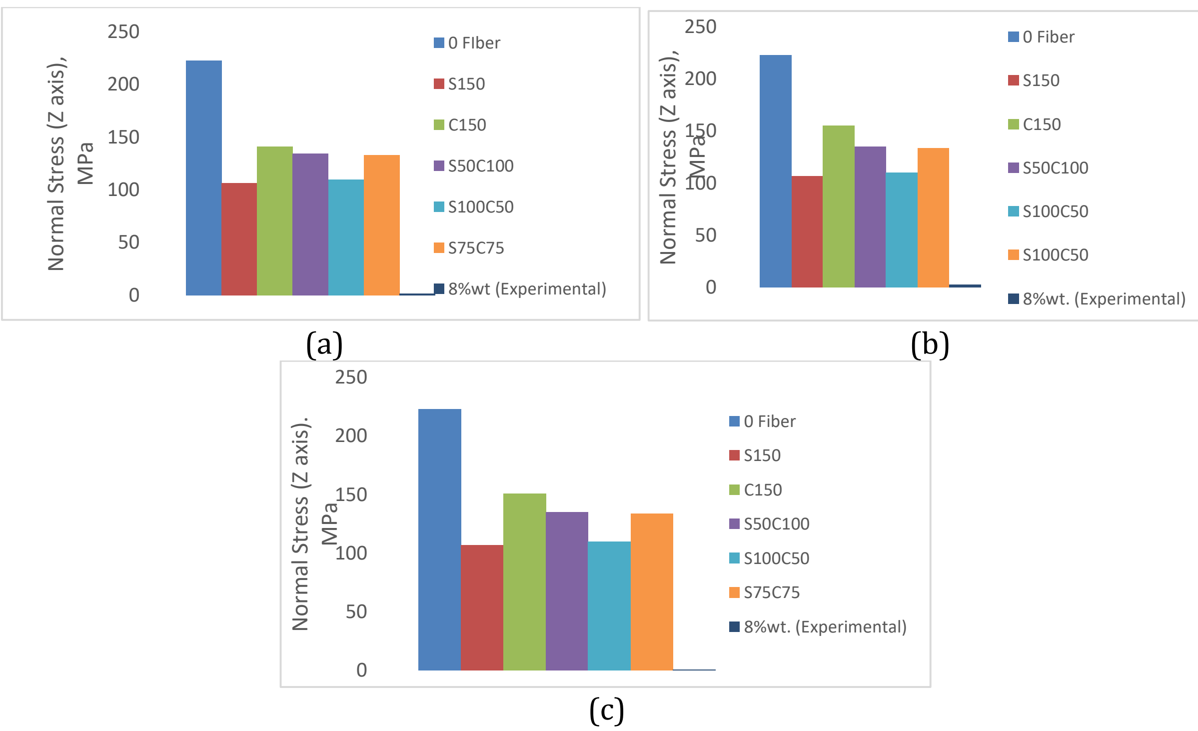
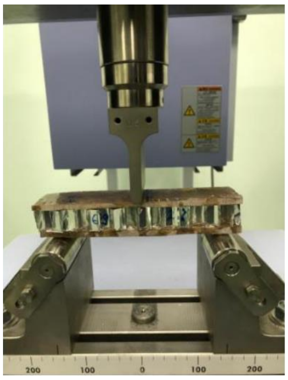
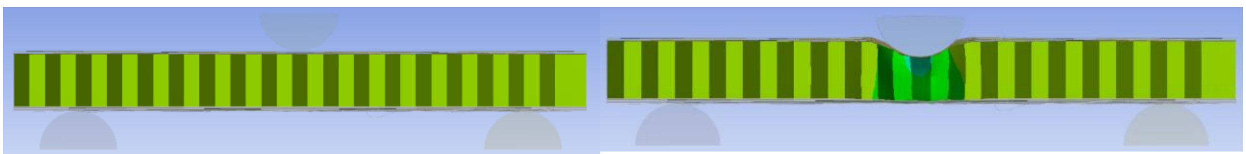


Figure 4 Normal stress (z axis) comparison of hybrid orientation for: (a) Oil Palm fiber, (b) Sugar Cane fiber and (c) Coconut fiber.

Figure 5 shows deformation characteristics of conventional honeycomb sandwich in experiments compare to simulation testing for oil palm fiber reinforcement. The deformation characteristics inform that local indentation pattern capture for both experimental and simulation. The deformation is both experimental and simulated from the movement of the loading impactor. The results have shown a good agreement and consistency in three-point bending behavior. The simulation results also showed reliable data with the experiment test which validate using deformation recorded at 5×10^{-6} s as shown in Figure 6. The deformation that occurs for both methods presents insignificant deviation which simulation comes out at 1.1974 mm of displacement while 1.134 mm for experimental result, which confirms the consistency of the simulation results.

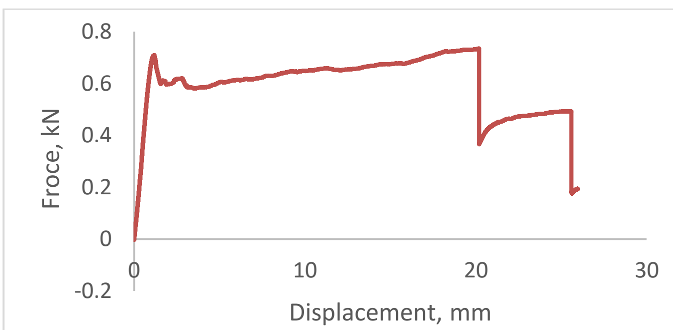


(a)

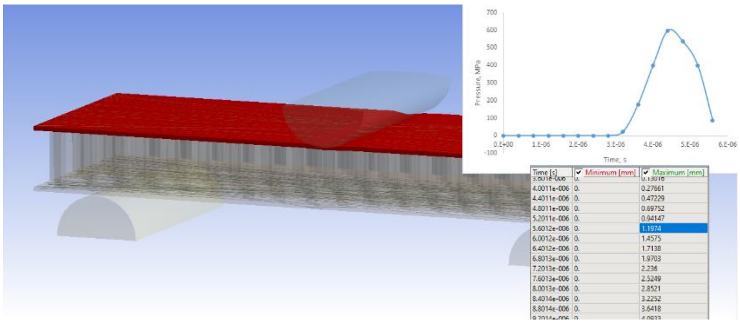


(b)

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



(a)



(b)

Figure 6. The deflection phenomenon during composite panel failure of (a) Experimental Method and (b) Simulation Method.

4. Conclusions

Numerical simulations were carried out for the aluminum honeycomb sandwich and fibers reinforcement was successful to develop reinforcement distribution technique by coding software of MATLAB. Based on the above-mentioned results and discussions, some significant conclusions can be drawn as follows:

a. The reinforcement clearly brings an increase in strength and stiffness for the whole honeycomb sandwich. In this way, the bending resistance capacity of reinforcement sandwiches gets substantial promotion accordingly comparing with the plain plate. This fact is embodied in the load-deflection chopped and different deformation patterns.
b. The numerically calculated results of the TPB dynamic mechanical behaviors of sandwiches show an increase of the stress absorption can be effectively modulated by the reinforcement fibers.
c. The unidirectional fiber orientation achieving a high tensile strength due to structure fiber in longitudinal position in the plate.
d. The hybrid of unidirectional and chopped orientation performance was dominated by unidirectional orientation characteristics in stress absorption during flexural testing.
e. The natural fiber of Oil Palm, Sugar Cane and Coconut was a promising reinforcement for polymeric composites and suitable to be implemented as facing panel of honeycomb.

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