THE INFLUENCE OF FIBRE STACKING CONFIGURATIONS ON THE INDENTATION BEHAVIOUR OF PINEAPPLE LEAF / GLASS FIBRE REINFORCED HYBRID COMPOSITES

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ABSTRACT

Composite materials have gained wide acceptance among industries since the past decades. They have been widely employed in a wide variety of engineering applications. In this research, the influences of fibre stacking configurations on the indentation behaviour of pineapple leaf/glass fibres reinforced polypropylene hybrid composites were investigated. The indentation behaviours of hybrid composites were then compared to non-hybrid composites. Composites were fabricated through the hot press moulding compression technique using hydraulic hot press machine. The indentation behaviours of composites were presented in terms of maximum indentation force, energy absorption and specific energy absorption. The damage mechanism of composites was also studied after the indentation test. From the findings, it was concluded that the partial incorporation of glass fibre in the composite laminates improved the indentation resistance and energy absorption. In overall, non-hybrid glass fibre reinforced composite laminates showed the highest indentation resistance and energy absorption. However, the hybrid composites with the substitution of middle glass fibre with pineapple leaf fibre had a comparable indentation resistance and energy absorption to the non-hybrid glass fibre based composites. Therefore, these results have evidenced the potential of hybrid composites to supersede non-hybrid glass fibre based composites.

Keyword: *Hybrid composites; pineapple leaf fibre; fibre stacking configuration; indentation behaviour; energy absorption.*

1. INTRODUCTION

Metallic alloys are contemporary materials being widely employed in structural applications. However, the material requirements in the engineering applications have inclined towards lightweight and high specific properties. Therefore, effort has been given to search for alternative materials with high specific properties. It was evidenced that composite materials have demonstrated excellent specific properties over metallic alloys (Feng *et al*., 2018). Thus, composite materials have received great attention for engineering applications due to their excellent specific properties. It is undeniable that the increasing exploration of natural fibres is because of the awareness on increasing product performance by employing lightweight components (Arpitha *et al*., 2017). Apart from the high specific properties in composite materials, the substitution of metallic alloys to composite materials could offer the flexibility to tailor the materials properties by the specific industrial applications. Currently, composite materials have been the well-known materials that are widely used in outdoor and load-bearing applications such as automotive, aerospace, sports equipment and marine structures (Sivakumar *et al*., 2016; Pickering *et al*., 2016; Habibi *et al*., 2018). In spite of various advantages by using composite materials, they have arisen several environmental issues since the main reinforcement used is dominated by glass fibres owing to their high mechanical strength and they are inexpensive. In the military application, glass fibres are widely used to make military mine hunters (Chawla, 2006). The extensive use of glass fibre could lead to severe occupational health issues (Le Duigou *et al*., 2010). Due to the shortcomings of synthetic fibre based composites, several attempts have been provoked to explore alternative materials to resolve such problems (Yang *et al*., 2011; Feng *et al*., 2017; Ng *et al*., 2017).

To rectify the drawbacks of synthetic fibre based composites, the use of natural resources as the reinforcement is indispensable. Renewability, recyclability and biodegradable are those desired properties for alternative environmental friendly materials. Most of the natural fibres are abundant, low cost, lightweight and encompass relatively good mechanical properties and thus shows a high potential to be used in composite materials. Besides, natural fibres are insensitive to fatigue loading, non-abrasive, carbon dioxide neutral, consuming less energy and having high specific properties (Asgarinia *et al*., 2015; Feng & Malingam, 2019). Owing to their advantages, natural fibres have recently received the interest among technologist and scientists particularly for military applications (Alam *et al*., 2014). In this context, pineapple leaf fibre (PALF) is among the potential cellulosic fibre which possesses high mechanical strength relative to other natural fibres while having a lower density than glass fibres. PALF is considered as a secondary fibre crop as the plants are mainly grown for its fruit rather than their fibres. Owing to the high availability and good mechanical strength, PALF has shown a great potential to replace the glass fibres. Nonetheless, PALF is similar to other natural fibres which are susceptible to high moisture sensitivity due to their intrinsic hydrophilic behaviour. The high moisture sensitivity eventually retards the use of natural fibres in industrial applications. Therefore, hybridisation of natural fibres with synthetic fibres represents a great alternative technique in this context.

Recently, there is a growing interest in exploring the mechanical properties of hybrid composites. Hybrid composites are formed through the blending of two or more types of fibres into a single polymer matrix. There are three distinct types of hybrid composites, namely, synthetic/synthetic, synthetic/natural and natural/natural hybrid composites. However, the most commonly studied hybrid composites are based on synthetic/natural fibres. Previous works have concluded hybrid composites offer many benefits compared to non-hybrid composites such as reduction in the moisture uptake and improvement in the mechanical properties (Karahan & Karahan, 2015; Malingam *et al*., 2018). The hybridisation of two different types of fibres within a single matrix could lead to positive hybrid effect in which the advantage of one fibre could compensate for the shortcomings of other fibres. Thus, balance properties such as lightweight, high mechanical strength, modulus and toughness could be achieved. Although the environmental friendliness of the composites could be reduced, this is compensated with the improvement in the mechanical properties and a reduction in the moisture sensitivity.

In general, composite materials have been subjected to localised impact load through the solid objects during their service (Zhou *et al*., 2017). This localised load eventually leads to damage to the structures, which is known as indentation behaviour. Furthermore, it is stated that the indentation resistance of the composite materials also indicates the energy dissipating characteristic of the structures under out-of-plane loading without the consideration of rate effects. To date, several research studies have been conducted on the indentation behaviour of composite materials at the quasi-static rate. Bulut & Erklig (2018) investigated the quasi-static indentation behaviour of laminated composite plates based on carbon, glass and Kevlar fabrics with different stacking sequences. They concluded non-hybrid carbon fibre reinforced epoxy composites showed higher energy absorption compared to glass and Kevlar reinforced composites. In overall, hybrid composite laminates demonstrated the highest indentation force and absorbed energy in comparison with non-hybrid composites. Mohamad *et al*. (2017) studied the quasi-static indentation of sandwich panels based on polyurethane and kenaf foam. The fibre content was in the range of 0 % to 30 % while the thickness of the foam was fixed at 15 mm, 30 mm and 45 mm. The findings showed fibre content of 20 % and foam thickness at 45 mm evidenced the highest indentation resistance. Salman *et al*. (2018) conducted an indentation test at a quasi-static rate on the kenaf/Kevlar fibre reinforced polyvinyl butyral hybrid composite laminates. They revealed that the hybrid composites had higher energy absorption compared to non-hybrid kenaf reinforced composites. Furthermore, hybrid composites showed a comparable energy absorption to those of non-hybrid aramid fibre reinforced composites. Yahaya *et al.* (2014) studied the effect of hybridisation on the quasi-static indentation behaviour of woven kenaf/aramid reinforced epoxy composite laminates. They found the hybrid composites absorbed more energy than non-hybrid kenaf and aramid fibre reinforced composites. Erkendirci & Haque (2012) compared the indentation behaviour of S-2 glass and E-glass fibres based composites using different types of polymer matrices. The results showed high density polyethene based composites exhibited lower indentation properties than epoxy based composites.

Majority of the energy absorbed during low velocity, high velocity and even ballistic is due to the static deformation (Lin & Fatt, 2006). Thus, quasi-static indentation behaviour of composite materials is vital in determining the impact characteristics of such materials. The aforementioned studies have shown the potential of thermoset based hybrid composites in terms of indentation resistance and energy absorption. Nevertheless, there are still very limited studies that focus on the thermoplastic based hybrid composites. Moreover, the quasi-static indentation behaviour of PALF/glass fibre reinforced polypropylene still remains unexplored. Therefore, this study aims at exploring the influence of fibre stacking configurations on the quasi-static indentation behaviour in terms of maximum indentation force, energy absorption, specific energy absorption and the associated damage mechanism.

2. METHODOLOGY

2.1 Materials

Plain weave PALF and glass fabrics as shown in Figure 1 (a) and (b) were employed as reinforcement in this study. Woven glass fabric with an areal weight of 600 g/m^2 was supplied by ZKK Sdn. Bhd, Malaysia. Woven PALF fabric with an areal weight of 315 g/m^2 was provided by Mecha Solve Engineering, Malaysia. Polypropylene (PP) granules with a density of 0.91 g/cm^3 were purchased from Al Waha Petrochemical Company, Saudi Arabia. The tensile properties of PALF and glass fibre are shown in Table 1.

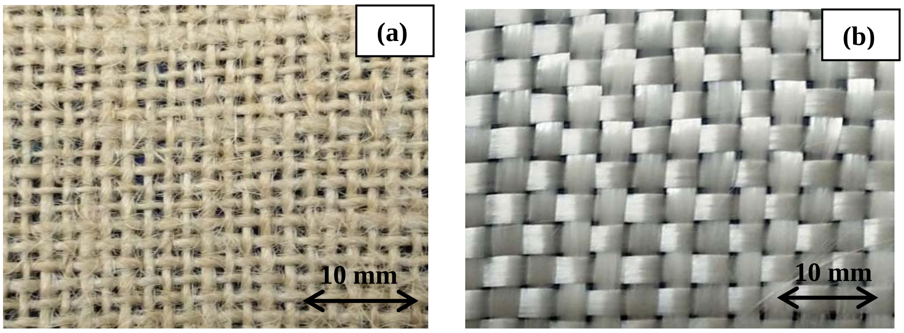


Figure 1: Plain weave woven: (a) PALF (b) glass.

Table 1: Tensile properties of PALF and glass fibre (Gurunathan *et al.*, 2015; Dittenber & GangaRao, 2012).

Properties	PALF	Glass fibre
Tensile strength (MPa)	170 – 1627	2000 – 3500
Tensile modulus (GPa)	60 – 82	70 – 76
Strain at break (%)	1 – 3	1.8 – 4.8
Density (g/cm^3)	1.5	2.5

2.2 Composite Preparation

PP granules were mixed with 3 % of Maleic Anhydride Polypropylene (MAPP) before the composite fabrication. According to Beg & Pickering (2008), optimum fibre-matrix adhesion could be achieved by the introduction of 3 - 5 % of MAPP in the composites. The mixing process of PP granules with MAPP was conducted using an internal mixer (Haake Rheomix OS) at a temperature of 175 ºC. The mixture was then pelletized and compressed to form PP films. Non-hybrid and hybrid composite laminates were then formed through hot press moulding compression technique using hydraulic hot press machine.

Non-hybrid and hybrid composite laminates with a nominal thickness of 3 mm were fabricated by stacking the woven fabrics and PP films alternatively to allow optimum fibre impregnation. The stack was arranged in the picture frame mould with a dimension of (250 mm X 250 mm X 3 mm). After that, the stack was subjected to the heat compression moulding at a temperature of 175 ºC and pressure of 3.5 MPa. Preheating for 2 minutes was conducted prior to the heat compression moulding process to ensure the heat was evenly distributed throughout the composite laminates. Subsequent cooling process was performed on the composite laminates until room temperature before it was taken out from the hot press machine.

A total number of four fibre stacking configurations were fixed in the composite laminates. Non-hybrid PALF and glass fibre reinforced PP composite laminates consist of three layers of woven PALF and glass fibre, which are referred as [P/P/P] and [G/G/G]. One of the hybrid composites was arranged by replacing the outermost skin layers of woven glass fibre with woven PALF, which is represented as [P/G/P]. Another hybrid composite laminate, [G/P/G], was fabricated by substituting the middle woven glass fibre with woven PALF. Figure 2 shows the fibre stacking configurations in composite laminates. The fibre weight and volume fraction of non-hybrid and hybrid composite laminates are summarised in Table 2. The standard deviations of the fibre weight and volume fraction are included in the parentheses. The fibre volume fraction of was determined in accordance with Equation 1.

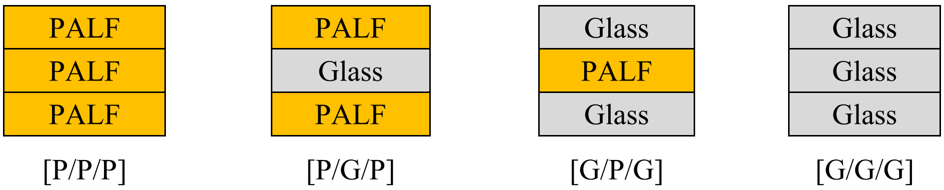


Figure 2: Fibre stacking configurations in composite laminates.

Table 2: Fibre weight and volume fraction in composite laminates.

Fibre layup	Fibre weight fraction (%)	Fibre volume fraction (%)		
		PALF	Glass	Total
[P/P/P]	31.07 (2.65)	21.09 (0.15)	–	21.09 (0.15)
[P/G/P]	36.08 (0.58)	13.75 (0.27)	7.86 (0.16)	21.61 (0.43)
[G/P/G]	42.56 (1.68)	7.16 (0.37)	16.35 (0.86)	23.51 (1.23)
[G/G/G]	47.08 (1.32)	–	24.47 (0.98)	24.47 (0.98)

$$V_{fibre} = \frac{\frac{w_{PALF}}{\rho_{PALF}} + \frac{w_{Glass}}{\rho_{Glass}}}{\frac{w_{PALF}}{\rho_{PALF}} + \frac{w_{Glass}}{\rho_{Glass}} + \frac{w_{PP}}{\rho_{PP}}} \qquad (1)$$

where w_{PALF} is the weight of PALF, w_{Glass} is the weight of glass fibre, w_{PP} is the weight of PP, ρ_{PALF} is the density of PALF, ρ_{Glass} is the density of glass fibre and ρ_{PP} is the density of PP.

2.3 Experimental Works

The indentation test in edge support configuration was conducted according to ASTM D6264 at room temperature using the universal testing machine, Instron 5585 with 150 kN load cell. Non-hybrid and hybrid composite laminates with various fibre stacking configurations were cut into the dimension of 100 mm X 100 mm (Length X Width) for the indentation test. The quasi-static crosshead displacement rate was fixed at 1.27 mm/min. The specimen was clamped between the top and bottom support plate, which was tightened using four screws to avoid slippage during the test. The setup of the quasi-static indentation test for composite laminates is depicted in Figure 3. A hemispherical tip indenter with a diameter of 12.7 mm was used to perform the indentation. The experiment was repeated three times for each fibre stacking configuration to obtain the average findings. The force-displacement curves from the indentation test were then recorded to evaluate the energy absorption and the maximum indentation load of each composite laminate. The damage mechanism of the front and rear fracture surfaces of each composite was subsequently investigated.

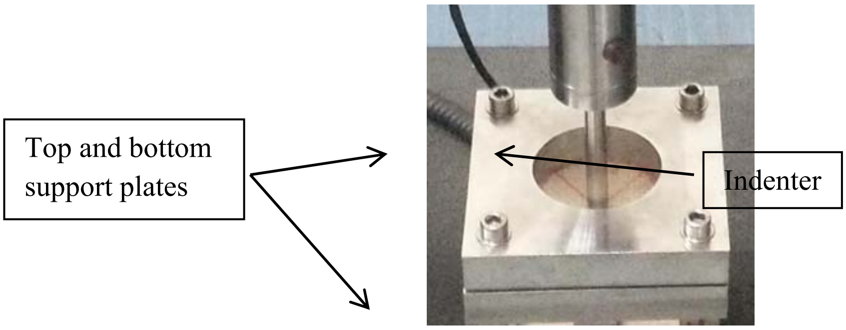


Figure 3: Setup of the quasi-static indentation test.

3. RESULTS AND DISCUSSION

3.1 Quasi-Static Indentation Properties

The quasi-static indentation test was conducted on the non-hybrid and hybrid composite laminates to study the indentation resistance and energy absorption behaviours. The indentation properties in terms of maximum indentation force, energy absorption and specific energy absorption of non-hybrid and hybrid composite laminates are summarised in Table 3.

Table 3: Indentation properties of non-hybrid and hybrid composite laminates.

Fibre stacking configurations	Maximum indentation force (N)	Energy absorption (J)	Specific energy absorption ($J.m^2/kg$)
[P/P/P]	860.76	8.47	2.76
[P/G/P]	939.62	8.92	2.78
[G/P/G]	1372.97	13.43	3.77
[G/G/G]	1474.55	15.10	3.95

The force-displacement curves of the non-hybrid and hybrid composite laminates are represented in Figure 4. The overall trend of the force-displacement curves is similar irrespective of the fibre stacking configurations. The indentation force increased along with the increase of the displacement up to the maximum point where the failure of the composite laminate occurred. As noticed in Figure 4, the indentation force increased at the initial stage until the maximum value, leading to the matrix cracking and initiation of the delamination. Then, it was followed by the penetration and fibre breakage which drastically reduced load carrying capacity of the fibres. Subsequently, the composite laminate was subjected to the perforation that resulted in the friction between the sample and the indenter prior to the final failure. Similar behaviour could be observed in the research study by Abisset *et al*., (2016) who found the indentation force increased initially until the load drop, which was followed by the delamination and finally fibre failure.

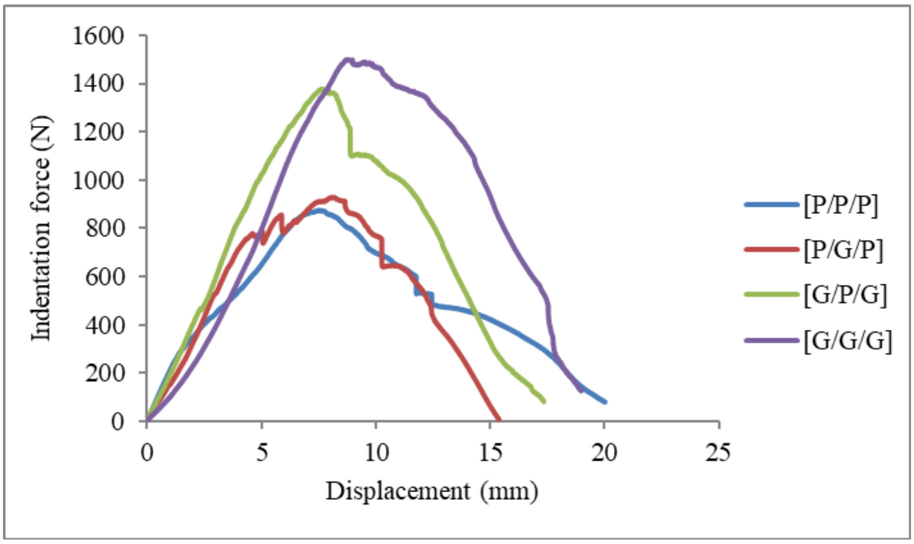


Figure 4: Force-displacement curves of non-hybrid and hybrid composite laminates.

The maximum indentation force and the energy absorption of each non-hybrid and hybrid composite laminate are shown in Figure 5. The energy absorption for each composite laminate was determined by obtaining the area under the force-displacement curves. From the findings, it was evidenced that non-hybrid glass fibre reinforced composites had the highest indentation force and energy absorption compared to other composite laminates. In contrast, non-hybrid PALF reinforced composites demonstrated the lowest indentation force and energy absorption. The maximum indentation force and energy absorption of non-hybrid glass fibre reinforced composites were 1474.55 N and 15.10 J which are 71.31 % and 78.28 % respectively higher than non-hybrid PALF reinforced composites However, the partial incorporation of glass fibre in the PALF based composites resulted in the positive hybrid effect where the overall indentation force and energy absorption were increased. When one middle layer of PALF was replaced by glass fibre, the maximum indentation force and energy absorption were improved by 9.16 % and 5.31 %. Furthermore, the maximum indentation force and energy absorption were enhanced by 59.51 % and 58.56 % when glass fibres substituted the outermost PALF fibre layers.

It is interesting to note that composite laminates with [G/P/G] fibre stacking configuration exhibited comparable maximum indentation force and energy absorption to those of [G/G/G] composite laminates. The maximum indentation force and energy absorption of [G/P/G] composite laminates were merely 6.89 % and 11.06 % lower than [G/G/G] composite laminates. These trends indicate the potential of hybrid composites to replace non-hybrid glass fibre reinforced composites. Besides, it was also noticed that the [P/P/P] composite laminates had comparable indentation properties to those of [P/G/P] composite laminates. It can be observed that the indentation properties of composite laminates are governed by the skin layers instead of the middle fibre layer. The skin layers in the composite laminates are the primary load carrier instead of the intermediate layer. The intermediate fibre layer has a minor contribution to the indentation properties of composite laminates. Besides, the indentation behaviour of composite laminates depends on the bending stiffness of each fibre layer. Therefore, the incorporation of high strength glass fibre as the skin layers could provide higher indentation resistance to the composite laminates.

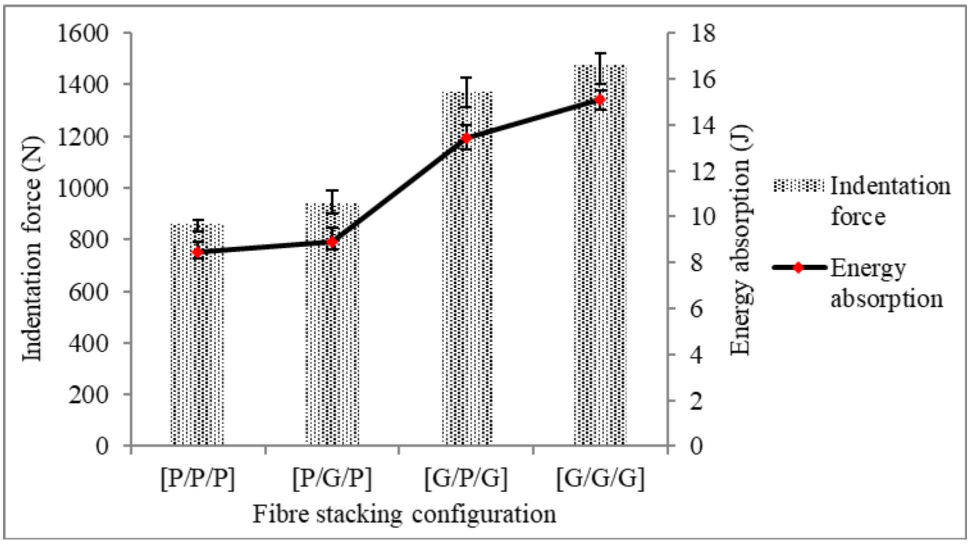


Figure 5: Maximum indentation force and energy absorption of composite laminates under quasi-static indentation.

Since lightweight characteristic is the advantage of natural fibres in comparison to synthetic fibres, thus it is paramount to study the specific indentation behaviour of the PALF based composite laminates. Figure 6 depicts the specific energy absorption of composite laminates subjected to indentation. The specific energy absorption of each composite laminates was obtained by dividing the total energy absorption ($E_{absolute}$) by the areal density, which is attested in Equation 2.

$$E_{specific} = \frac{E_{absolute}}{Areal\ density} \qquad (2)$$

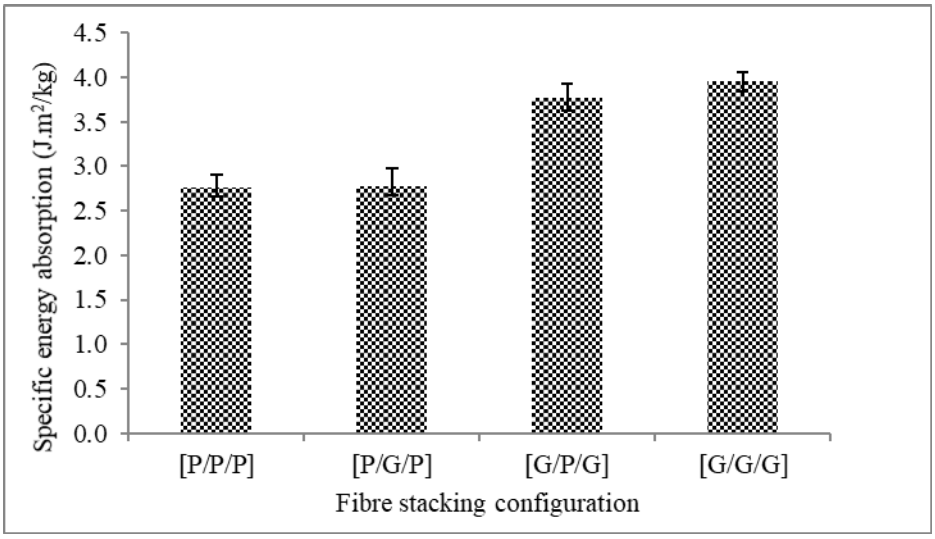


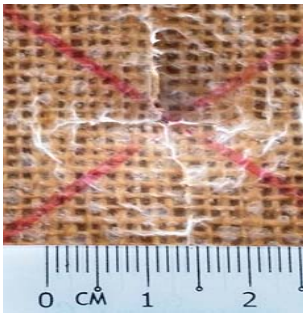
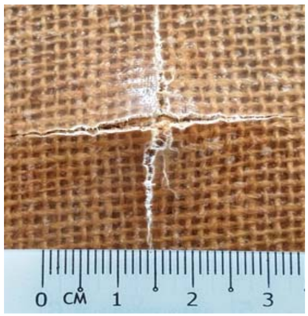
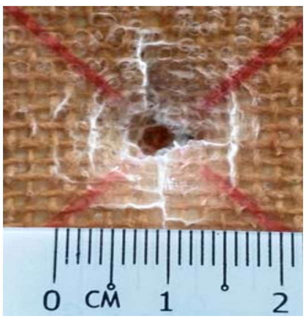
Figure 6: Specific energy absorption of composite laminates subjected to indentation.

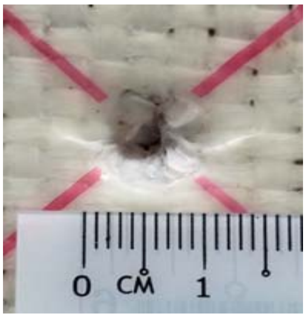
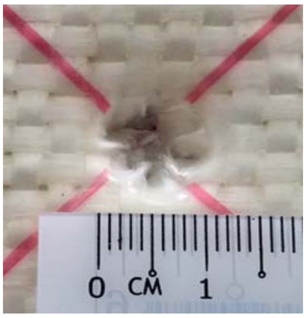
The results indicate the difference in the specific energy absorption of each composite laminate was diminished with an increasing amount of PALF in the composite laminates. In spite of [G/G/G] composite laminates still demonstrated the highest specific energy absorption, however, the difference in the specific energy absorption between non-hybrid [G/G/G] composite laminates and [G/P/G] composite laminates reduced. The specific energy absorption of [G/P/G] composite laminate is only 4.53 % lower than [G/G/G] composite laminates. A similar trend was observed in the [P/P/P] and [P/G/P] composite laminates in which the specific energy absorption of [P/P/P] composite laminates is only 0.49 % lower than [P/G/P] composite laminates. Due to the intrinsic lower density of PALF as compared to glass fibre, therefore the incorporation of PALF in the composite laminates is considered beneficial to the specific properties.

3.2 Damage Assessment

The fracture mechanism of the non-hybrid and hybrid composite laminates was evaluated after the quasi-static indentation test. The fracture surfaces of the indented and rear sides of each composite laminate are shown in Table 4. The overall observation shows the fracture mechanisms of composite laminates are highly dependent on the fibre type in the outermost layers of composite laminates.

Table 4: Fracture surface of composite laminates subjected to quasi-static indentation.

Composites	Front	Rear
[P/P/P]		
[P/G/P]		

[G/P/G]		
[G/G/G]		

From Table 4, it was observed that [P/P/P] and [P/G/P] composite laminates exhibited similar fracture mechanism. Meanwhile, the fracture mechanism of [G/P/G] and [G/G/G] composite laminates was similar. The fracture mechanism of PALF based composite laminates demonstrated larger crack propagation as compared to glass fibre based composite laminates. However, the crack propagation was reduced when one layer of PALF was substituted by glass fibre. In overall, the crack propagation of composite laminates with glass fibre as the skin layers was significantly smaller compared to those composite laminates with PALF as the skin layers, which was evidenced in Table 4. The failures due to the quasi-static indentation are compression-shear and tension-shear which could occur at the indented and rear surface respectively. During the indentation, the failure occurred first at the indented surface with a dent which was followed by the crack initiation and propagation on the rear surface. The crack length on the rear surface increased with the increase of indentation displacement. Moreover, the crack on the rear surface was more severe than the indented surface, implying that rear surface exhibited more damage and deformation during the indentation.

4. CONCLUSION

In this research work, the influence of the fibre stacking configuration on the indentation behaviour of pineapple leaf/glass fibre reinforced PP composite laminates was investigated. The indentation behaviour of hybrid composites was compared to those of non-hybrid composites. From the results obtained, the following conclusions were drawn.

1. The quasi-static indentation behaviour of composite laminates was highly dependent on the fibre stacking configurations. Non-hybrid glass fibre reinforced composite laminates demonstrated the highest indentation force over other composite laminates. On the contrary, the lowest indentation force was noticed in non-hybrid PALF based composite laminates. The indentation force and energy absorption of hybrid composite laminates were in between non-hybrid composite laminates. However, hybrid [G/P/G] composite laminates exhibited a comparable indentation force and energy absorption which was only 6.89 % and 11.06 % lower than the [G/G/G] composite laminates.

2. In terms of the energy absorption, the same trend was observed in which the [G/G/G] composite laminates showed the highest value, which was followed by [G/P/G], [P/G/P] and finally [P/P/P]

composite laminates. The partial incorporation of glass fibre indeed leads to the positive hybrid effect which improved the energy absorption of the PALF based composite laminates. The results evidenced that the energy absorption was enhanced by 5.31 % when one middle PALF layer was replaced by glass fibre. In addition, the replacement of the outermost PALF layers with glass fibre resulted in the improvement up to 58.56 %.

3. When the areal weight of each composite laminate was taken into consideration, the advantage of incorporating PALF in the composite laminate become prominent due to the lower density of PALF compared to the glass fibre. In comparison with the absolute energy absorption, it was shown that the difference in the specific energy absorption of composite laminates was diminished with an increasing amount of PALF. The specific energy absorption of hybrid composite laminates with [G/P/G] fibre stacking configuration was only 4.53 % lower than [G/G/G] composite laminates while the specific energy absorption of [P/P/P] composite laminates was merely 0.49 % lower than [P/G/P] composite laminates. These findings have shown the potential of PALF based hybrid composites as a substitution for the non-hybrid glass fibre based composites.

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