THE INVESTIGATION OF THE TENSILE AND QUASI-STATIC INDENTATION PROPERTIES OF PINEAPPLE LEAF / KEVLAR FIBRE REINFORCED HYBRID COMPOSITES

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ABSTRACT

Fibre reinforced polymers are the contemporary advanced materials that possess high specific properties when compared to metallic alloys. They have been widely explored since the past few decades. This research study intends to investigate the quasi-static indentation behaviour of non-hybrid and hybrid pineapple leaf / Kevlar fibre reinforced composites with various stacking configurations. Four fibre stacking configurations were fixed in the composite laminates. The composite panels were fabricated through hot moulding compression process. Quasi-static tensile and indentation test were then conducted to measure the tensile properties, energy absorption, maximum indentation force and specific energy absorption of the non-hybrid and hybrid composites. The front and rear fracture surface of the non-hybrid and hybrid composites were analysed after the indentation test. The findings evidenced that the hybrid pineapple leaf / Kevlar fibre reinforced composites showed a positive hybrid effect where the tensile properties, maximum indentation force and energy absorption were drastically improved after partial incorporation of Kevlar fibre in the composites. However, the hybrid composites with the outermost Kevlar fibre and middle pineapple leaf fibre showed comparable tensile and indentation properties to the non-hybrid Kevlar fibre reinforced composites. The results demonstrated the high potential of hybrid pineapple leaf / Kevlar fibre reinforced composites in the replacement of non-hybrid Kevlar fibre reinforced composites.

Keyword: *Hybrid composites; pineapple leaf fibre; Kevlar fibre; indentation properties; energy absorption*

1. INTRODUCTION

A continuous effort has been given to the exploration of the environmental friendly materials with high specific properties. Fibre reinforced polymers (FRPs) are regarded as lightweight materials that possess high specific properties when compared to metallic alloys (Feng *et al*., 2018). However, current FRPs applied in the industrial applications are mainly dominated by synthetic fibres and thermoset matrix. Kevlar fibres are among the high strength synthetic fibres which encompass high impact resistance, stiffness and toughness (Johnson & Venkatesan, 2018). Due to their high impact resistance, Kevlar fibres are commonly employed for military and defence applications such as bulletproof vests, body armours and combat helmets. Despite the contemporary FRPs have high specific properties but such materials have led to the negative impacts on the environment and human health (Mostafa, 2019). One of the possible techniques to resolve the problem is by using natural fibre based composites instead of synthetic fibre based composites in industrial applications.

To date, natural fibre based composites have been employed in aerospace, automotive, electrical and household applications (Sanjay *et al*., 2018). Due to the increasing demand for lightweight composite materials, it is indispensable to continuously explore the potential of natural fibre based composites. The shift of synthetic fibre towards natural fibre based composites is expected as they can improve renewability, biodegradability, environmental friendliness, and reducing the cost and density of the materials (Afzaluddin *et al*., 2019). Indeed, the natural fibres have offered innumerable virtues such as carbon dioxide neutral, less abrasive, low energy consumption, low cost, biodegradability and lightweight properties (Arthanarieswaran *et al*., 2014; Paul *et al*., 2015; Karahan & Karahan, 2015; Vieira *et al*., 2017; Feng & Malingam, 2019). On this token, pineapple leaf fibre (PALF) has shown a great potential in which PALF possesses a relatively high mechanical strength compared to other natural fibres due to its high cellulose content. Furthermore, PALF is considered as an agricultural waste as their plant is mainly grown for the fruit rather than the fibres. As a result, the incorporation of PALF in the composite materials is beneficial to the environment and the mechanical properties of the composites.

In spite of several attractive features in natural fibres, they also exhibit various shortcomings such as batch-to-batch variation, lack of thermal stability, weak impact resistance, susceptible to strength degradation and high moisture sensitivity (Santulli, 2007; Sgriccia *et al*., 2008; Adekunle *et al*., 2011; Asgarinia *et al*., 2015). The high moisture uptake of the natural fibres eventually leads to poor interfacial bonding with hydrophobic polymer matrices (Kushwaha & Kumar, 2010). Such impediments of natural fibres have retarded their use in structural applications. In fact, the demerits of natural fibres can be resolved using several techniques. Chemical treatments such as silane and alkali treatments are among the most commonly applied techniques to resolve the demerits of natural fibres. Silane treatment provides a siloxane bridge across the fibre-matrix interface, thereby improving the compatibility between fibre and matrix, resulting in the improvement in the mechanical properties. In contrast, alkali treatment alters the fibre surface structure, which removes a certain amount of hemicellulose, lignin and pectin, increasing the number of reactive hydroxyl groups on the fibre surface (Suardana *et al*., 2011; Sullins *et al*., 2017). Thus, the alkali treatment results in the improvement in the aspect ratio of the fibres, leading to the enhancement in the mechanical properties of natural fibre based composites. However, a more efficient and direct method to remedy the shortcomings of natural fibres is via the hybridisation with synthetic fibres (Feng *et al*., 2019a).

Hybrid composites are regarded as the materials that are formed through blending of more than one type of fibres within the polymer matrix. The hybrid composites allow the freedom of tailoring the mechanical properties in accordance with certain industrial applications. Hybrid composites can be grouped into three major classes which are synthetic / synthetic, synthetic / cellulosic and cellulosic / cellulosic fibre based hybrid composites. However, the synthetic / cellulosic fibre reinforced hybrid composites are the most widely explored composite materials. The mechanical properties of synthetic / cellulosic fibre reinforced hybrid composites have been reported in the literature and the findings demonstrated that the partial incorporation of synthetic fibre in the natural fibre based composites improved the mechanical properties (Shahzad, 2011; Ng *et al*., 2017; Kureemun *et al*., 2018; Feng *et al*., 2019b). Through hybridisation of high strength synthetic fibre with low strength natural fibre, it is believed that the energy absorption as well as the indentation properties can be enhanced as well.

Generally, composite materials are susceptible to the indentation loading during their service life (Zhou *et al*., 2017). Therefore, it is particularly important to investigate the indentation properties of the composite materials. Liu *et al*. (2015) studied the temperature effects on the indentation behaviour of carbon fibre reinforced composites with pyramidal truss cores. The findings revealed that the increase of temperature reduced the maximum indentation load and energy absorption of the composite materials due to the degradation of the polymer matrix and the interfacial bonding. Azwan *et al*. (2014) investigated the quasi-static indentation behaviour of composite sandwich structures with glass fibre reinforced polyester as top and bottom layers and polyurethane foam as the core. The indentation test was conducted with several strain rates on the composite materials. They concluded that the increase in strain rate eventually led to an increase in energy absorption of composite materials. Wagih *et al*. (2016) analysed the quasi-static indentation behaviour of carbon fibre reinforced epoxy composites. They found that the indentation damage can be divided into four stages, elastic deformation with no damage, indentation load drop due to matrix cracking, progressive growth of delamination and finally drastic load drop. A recent research study has been conducted by Bulut & Erkliğ (2018) to investigate the quasi-static indentation behaviour of glass / Kevlar / carbon fibre reinforced epoxy hybrid composites. The results demonstrated that the hybrid composites exhibited the highest indentation force and energy absorption compared to non-hybrid composites. Another recent research study was carried out by Salman *et al*. (2018) to compare the indentation properties of non-hybrid and hybrid kenaf / Kevlar fibre reinforced polyvinyl butyral composite laminates. It was observed that the energy absorption of hybrid composites was superior to those of non-hybrid kenaf fibre reinforced composites. Overall, non-hybrid Kevlar fibre reinforced composites achieved the highest energy absorption. However, it should be emphasised that the energy absorption of hybrid kenaf / Kevlar fibre reinforced composites was comparable to the non-hybrid Kevlar fibre reinforced composites.

Since composite materials are susceptible to the localised impact loading which results in the damage of such materials and thus it is necessary to study the indentation behaviours of the composite materials. The literature studies have shown composite materials exhibited excellent indentation properties and energy absorption. In this case, it is vital to continuously explore the potential of composite materials particularly cellulosic fibre based composites. Thus far, the tensile and indentation properties of thermoplastic based PALF / Kevlar reinforced hybrid composites still remain unexplored. Therefore, this study intends to evaluate the tensile and indentation behaviours of PALF / Kevlar fibre reinforced polypropylene hybrid composites with various fibre stacking configurations. Moreover, the damage properties of the penetrated non-hybrid and hybrid composite laminates are also analysed.

2. METHODOLOGY

2.1 Materials

Woven PALF and Kevlar fabrics as shown in Figure 1(a) and Figure 1(b) were used as reinforcement in the non-hybrid and hybrid composites. PALF fabric with an areal density of 315 g/m^2 was purchased from Mecha Solve Engineering, Malaysia. Kevlar fabric with an areal density of 200 g/m^2 was provided by DuPont Knowledge Center, India. Homopolymer polypropylene (PP) granules were supplied by the Al Waha Petrochemical Company, Saudi Arabia. The properties of PALF and Kevlar fibre are summarised in Table 1.

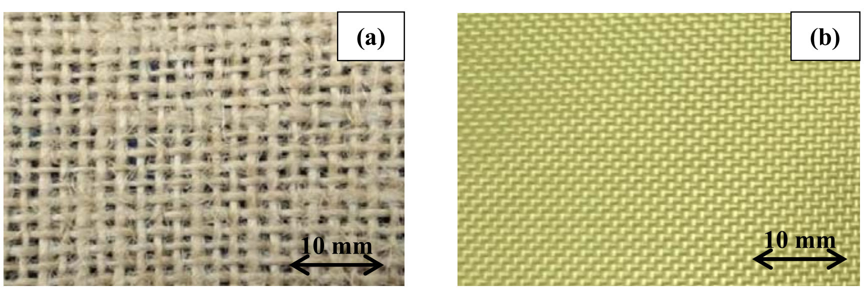


Figure 1: Plain weave woven: (a) PALF (b) Kevlar.

Table 1: Properties of PALF and Kevlar fibre (Ahmad *et al*., 2014; Gurunathan *et al*., 2015).

Properties	PALF	Kevlar fibre
Tensile strength (MPa)	170 – 1627	3000
Tensile modulus (GPa)	60 – 82	124
Strain at break (%)	1 – 3	2.5
Density (g/cm^3)	1.5	1.44

2.2 Fabrication of Composite Laminates

Non-hybrid and hybrid PALF / Kevlar reinforced composite laminates were prepared via hot moulding compression method using Gotech hydraulic hot press machine. Furthermore, film stacking technique was applied to arrange the PALF and Kevlar fabrics as well as PP films before they were compressed in the hot press machine. PP granules were firstly compressed into the form of films prior to the composite fabrication process. Meanwhile, PALF fabric was dried in an oven at a temperature of 80 ºC for 24 hours to eliminate the excessive moisture content to avoid the formation of voids during the composite fabrication. Thereafter, PALF and Kevlar fabrics were stacked alternatively with the PP films in a 3 mm-thick picture frame mould to allow the optimum fibre impregnation. The stack was then subjected to a compression moulding process with a temperature of 175 ºC and pressure of 3.5 MPa. Preheating was applied to the composite laminates before it was fully compressed in order to ensure the heat was evenly distributed throughout the composite laminate. Subsequently, the composite laminate was allowed to cool down until the ambient temperature. Finally, the composite laminate with a nominal thickness of 3 mm was taken out from the hot press machine for visual inspection of any defects.

Non-hybrid and hybrid composites were prepared to study the effects of fibre stacking configurations on the quasi-static tensile and indentation behaviours, including the tensile strength, tensile modulus, maximum indentation load, energy absorbing capacity and specific energy absorption of such materials. Figure 2 depicts the different fibre stacking configurations in the PALF / Kevlar based composite laminates. Each of the non-hybrid and hybrid composite laminates consists of three layers of woven fabric. The non-hybrid PALF and Kevlar fibre reinforced composites are denoted as [PF] and [KV]. When one layer of the middle PALF fabric was replaced with Kevlar fabric in the composite laminate, the hybrid composite is referred to as [H1]. Moreover, the hybrid composite laminate is represented by [H2] when the outermost PALF fabrics were superseded with Kevlar fabrics. The fibre weight and volume fractions along with their respective standard deviations are shown in Table 2. The fibre volume fraction of each composite laminate was calculated with reference to Equation 1.

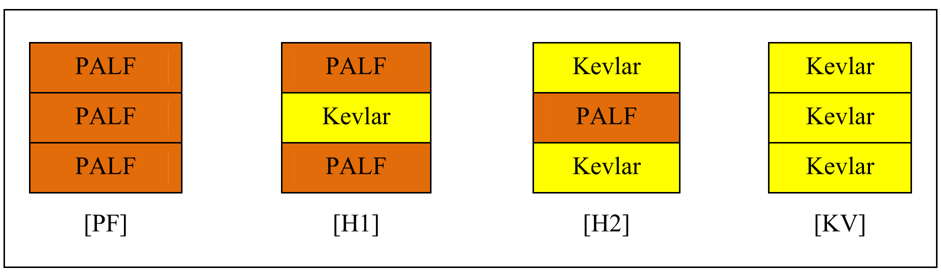


Figure 2: Fibre stacking configurations in composite laminates.

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

Fibre stacking configuration	Fibre weight fraction (%)	Fibre volume fraction (%)		
		PALF	Kevlar	Total
[PF]	31.25 (0.85)	21.62 (0.67)	–	21.62 (0.67)
[H1]	28.21 (1.35)	14.62 (0.79)	4.84 (0.26)	19.46 (1.05)
[H2]	26.94 (1.23)	8.02 (0.41)	10.61 (0.54)	18.63 (0.95)
[KV]	22.58 (1.03)	–	14.81 (0.76)	14.81 (0.76)

$$V_{fibre} = \frac{\frac{w_{PALF}}{\rho_{PALF}} + \frac{w_{Kevlar}}{\rho_{Kevlar}}}{\frac{w_{PALF}}{\rho_{PALF}} + \frac{w_{Kevlar}}{\rho_{Kevlar}} + \frac{w_{pp}}{\rho_{pp}}} \quad (1)$$

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

2.3 Experimental Works

The effects of fibre stacking configurations on the tensile properties of non-hybrid and hybrid PALF / Kevlar based composites were investigated through the quasi-static tensile test. The tensile test was performed with reference to ASTM D3039 at ambient temperature using the Instron model 8872 servo-hydraulic universal testing machine (UTM) with a load cell capacity of 25 kN. A quasi-static cross-head displacement rate of 2 mm/min was fixed throughout the tensile test. Extensometer was equipped on the specimens to monitor the tensile strain. The average tensile strength and modulus were then measured and recorded for further analysis and evaluation.

Quasi-static indentation test was conducted on non-hybrid and hybrid PALF / Kevlar based composites with reference to ASTM D6264 using Instron model 5585 Universal Testing Machine. Maximum indentation force, energy absorption and specific energy absorption were measured during the indentation test. The composite laminates were cut into the dimension of 100 mm x 100 mm and arranged in an edge support configuration as demonstrated in Figure 3. A quasi-static cross-head displacement rate of 1.27 mm/min was fixed throughout the indentation test. Prior to the indentation test, the composite laminate was clamped and tightened between the top and bottom support plates using four screws at the corners to avoid any slippage that affects the accuracy and reliability of the results during the indentation test. An indenter with a 12.7 mm diameter hemispherical tip was used to perform the indentation test. The indentation test was repeated three times for each of the fibre stacking configurations and the average findings were recorded for analysis and evaluation. The results were then represented by force-displacement curves to evaluate the energy absorption and maximum indentation load of the composite laminates. Finally, the damage behaviours of the composite laminates resulted from the indentation force were studied.

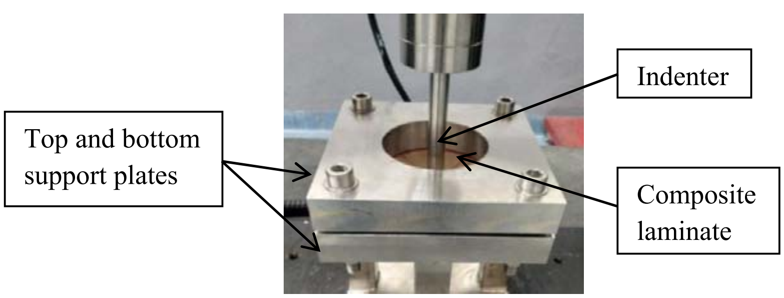


Figure 3: Setup of the quasi-static indentation test.

3. RESULTS AND DISCUSSION

3.1 Tensile Properties

The tensile properties of PALF / Kevlar reinforced composites with different fibre stacking configurations were investigated. The findings obtained from the tensile test were then summarised and recorded as shown in Figure 4. It is undoubtedly that the hybrid PALF / Kevlar composites improved the tensile properties when compared to non-hybrid PALF based composites. On average, the highest tensile properties were noticed in the non-hybrid Kevlar reinforced composites whereas the lowest tensile properties were obtained in non-hybrid PALF based composites. It was shown that the [KV] composite laminates had tensile strength and modulus of 111.73 MPa and 3.56 GPa, which are respectively 281.20 % and 42.97 % higher than [PF] composite laminates. However, improvements of 33.50 % and 9.64 % were observed in the tensile strength and modulus when one middle PALF fabric was superseded with Kevlar fabric in the [H1] hybrid composite laminates. A further improvement was obtained in [H2] composite laminates when two outermost PALF fabrics were replaced with Kevlar fabrics. It can be seen that those [H2] composite laminates exhibited tensile strength and modulus of 100.85 MPa and 3.19 GPa which are 244.08 % and 28.11 % higher than [PF] composite laminates. From Figure 4, the overall findings demonstrated the incorporation of Kevlar fibre in the hybrid composite laminates indeed attested positive hybrid effect on the tensile properties.

Furthermore, it is worth noting that the [H2] composite laminates possessed comparable tensile properties to the [KV] composite laminates. The tensile strength and modulus of [H2] composite laminates are merely 9.74 % and 10.39 % lower than [KV] composite laminates. This trend showed the high potential of employing hybrid PALF / Kevlar composite laminates, [H2], to substitute those of non-hybrid Kevlar based composite laminates [KV]. Apart from the comparable tensile properties of [H2] composite laminates to those of [KV] composite laminates, it can be noticed that [H1] composites had comparable tensile properties to the [PF] composite laminates as well. These behaviours evidenced that the tensile properties of the materials are highly dependent on the outermost layer in the composite laminates. The outermost layers in the composite laminates act as the main load carriers which attract and sustain more loads during the tensile test. Thus, the skin layers have a decisive effect on the tensile properties of composite laminates. Feng *et al*. (2017) obtained similar results in which the hybrid composite laminates with high strength fabrics as the outermost layers exhibited higher tensile properties.

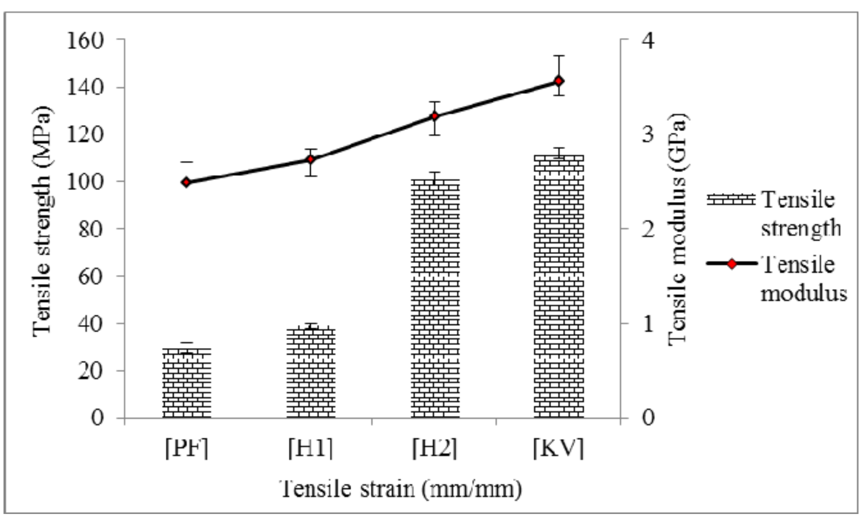


Figure 4: Tensile properties of non-hybrid and hybrid PALF / Kevlar based composites.

3.2 Quasi-Static Indentation Properties

The indentation behaviours of non-hybrid and hybrid PALF / Kevlar fibre reinforced composite laminates were investigated through the quasi-static indentation test. Table 3 records the indentation properties including maximum indentation force, energy absorption and specific energy absorption. The standard deviations of each of the indentation properties are included in the parentheses as well.

Table 3: Indentation properties of non-hybrid and hybrid PALF / Kevlar based composites.

Fibre stacking configurations	Maximum indentation force (N)	Energy absorption (J)	Specific energy absorption (J.m^2/kg)
[PF]	866.13 (40.66)	8.59 (0.86)	2.85 (0.08)
[H1]	2654.95 (140.76)	23.40 (3.37)	7.97 (0.38)
[H2]	4280.06 (206.87)	48.31 (2.47)	18.20 (0.83)
[KV]	5819.00 (135.99)	55.75 (4.19)	20.04 (0.96)

Findings obtained from the quasi-static indentation test are represented by the force-displacement curves as depicted in Figure 5. As can be seen in Figure 5, the force-displacement curves of the non-hybrid and hybrid composite laminates showed a very similar trend irrespective of fibre stacking configurations. The trend demonstrated the increase of indentation force along with the increase of displacement up to a maximum indentation force was reached. In fact, the indentation process of the composite laminates can be divided into three major regions. The load increased at the initial stage up to the peak point where the matrix cracking and initial delamination were noticed. After that, fibre breakage together with the higher extent of delamination occurred that resulted in the reduction in the load-carrying capacity of the composite laminates. Finally, the composite laminates were penetrated, that indicates the complete fracture, leading to the friction between the indenter and the composite laminates. The observation is in agreement with the results obtained by Bulut & Erkliğ (2018) in which the non-hybrid and hybrid Kevlar / glass / carbon fibre reinforced composites evidenced the similar trend during the indentation process.

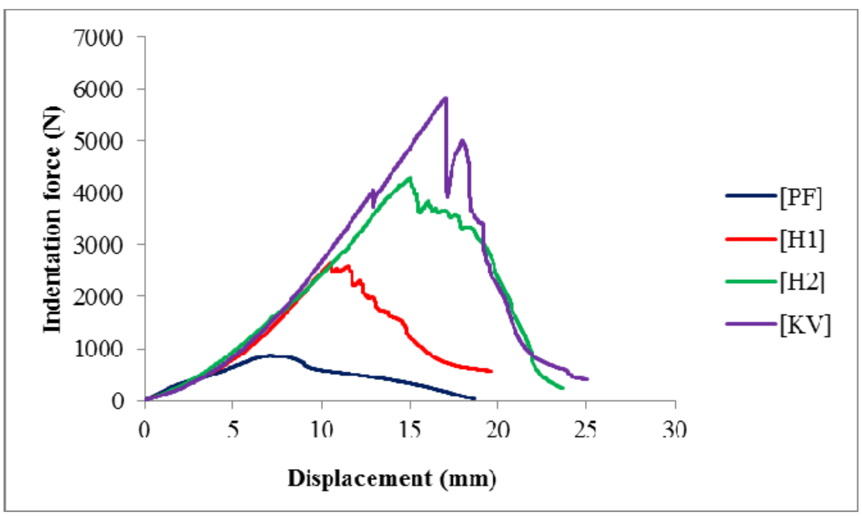


Figure 5: Force-displacement curves of non-hybrid and hybrid PALF / Kevlar based composites.

The energy absorption of the composite laminates was measured by calculating the area under the force-displacement curves. Figure 6 elucidates the maximum indentation force and energy absorption of the non-hybrid and hybrid PALF / Kevlar reinforced composites. Overall, the maximum indentation force and energy absorption were noticed in the non-hybrid Kevlar fibre reinforced composites. On the contrary, the non-hybrid PALF reinforced composites showed the lowest indentation force and energy absorption. The maximum indentation force and energy absorption of non-hybrid Kevlar fibre reinforced composites are 571.84 % and 549.01 % higher than non-hybrid PALF based composites. Nonetheless, the results demonstrated a positive hybrid effect where the maximum indentation force and energy absorption of the composite laminates were significantly improved when Kevlar fibre was partially incorporated. In comparison with the non-hybrid PALF based composites, the improvements in the maximum indentation force and energy absorption are 206.53 % and 172.41 % when one middle layer of PALF was substituted with Kevlar fibre. Moreover, it was shown that the [H2] composite laminates exhibited maximum indentation force and energy absorption of 4280.06 N and 48.31 J which are 394.16 % and 462.40 % higher than [PF] composite laminates. These trends demonstrated the potential of Kevlar fibre in enhancing the indentation resistance and energy absorption of the hybrid composite laminates.

Nevertheless, it is interesting to emphasise that the [KV] composite laminates evidenced the maximum indentation force and energy absorption which are only 35.96 % and 15.40 % higher than [H2] composite laminates, implying that [H2] composite laminates had comparable indentation properties to the [KV] composite laminates. Since the indentation resistance and energy absorption of the composite laminates are highly dependent on the outermost fabric layers, hence the [H2] and [KV] composite laminates had attested superior indentation properties particularly the energy absorption over those of [PF] and [H1] composite laminates. In fact, the indentation resistance of the composite laminates is governed by the bending stiffness of each fabric layer and the outermost fabric layers are the main constituents that have the decisive effect on the indentation properties. Therefore, the placement of the high strength Kevlar fibre as the skin layers is considered as an alternative fibre stacking configuration which contributes to higher indentation properties.

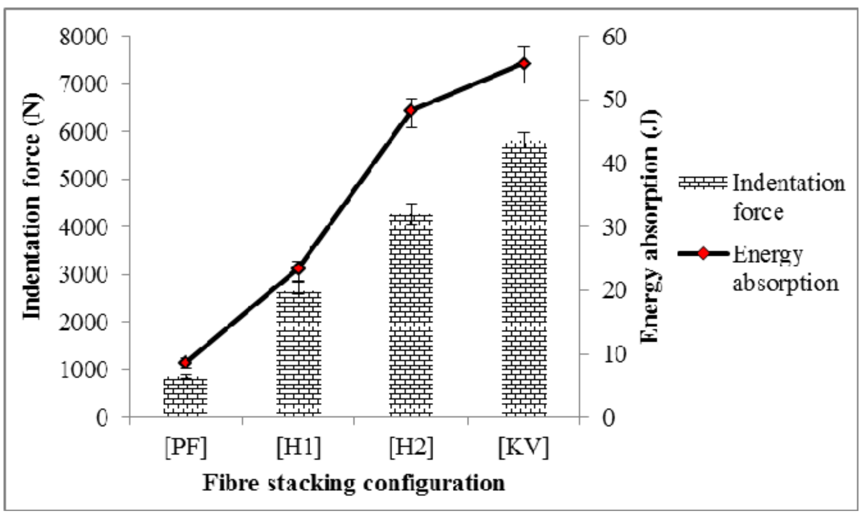


Figure 6: Maximum indentation force and energy absorption of composite laminates under quasi-static indentation.

Lightweight and environmental friendly characteristics are those of criteria which are taken into consideration when searching for an alternative material to supersede synthetic fibre based composites. In this context, it is pivotal to consider the specific properties of non-hybrid and hybrid PALF / Kevlar reinforced composites. Figure 7 shows the specific energy absorption of the composite laminates with different fibre stacking configurations. The specific energy absorption was measured according to the Equation (2) by dividing the total energy absorption by the areal density of the composite laminates.

$$E_{\text{specific}} = \frac{E_{ab\,\text{solute}}}{Areal\ density} \qquad (2)$$

where $E_{ab\,\text{solute}}$ is the total energy absorption.

On average, the trend of the specific energy absorption of the composite laminates as shown in Figure 7 is very similar to the absolute energy absorption. The highest specific energy absorption was noticed in [KV] composite laminates while [PF] composite laminates evidenced the lowest specific energy absorption. The excellent specific energy absorption was still observed in those of composite laminates with the incorporation of high strength Kevlar fabric as the outermost layers. When the areal density of the composite laminates was taken into consideration, [H2] composite laminates still attested the comparable specific energy absorption of 18.20 J.m^2/kg which is only 9.18 % lower than [KV] composite laminates. It is worth noting that the difference in the specific energy absorption of [H2] and [KV] composites was even diminished when compared to their absolute energy absorption. Due to the similar density of PALF and Kevlar fibre, the overall trend of specific energy absorption did not show any significant difference to the absolute energy absorption of PALF / Kevlar based composites.

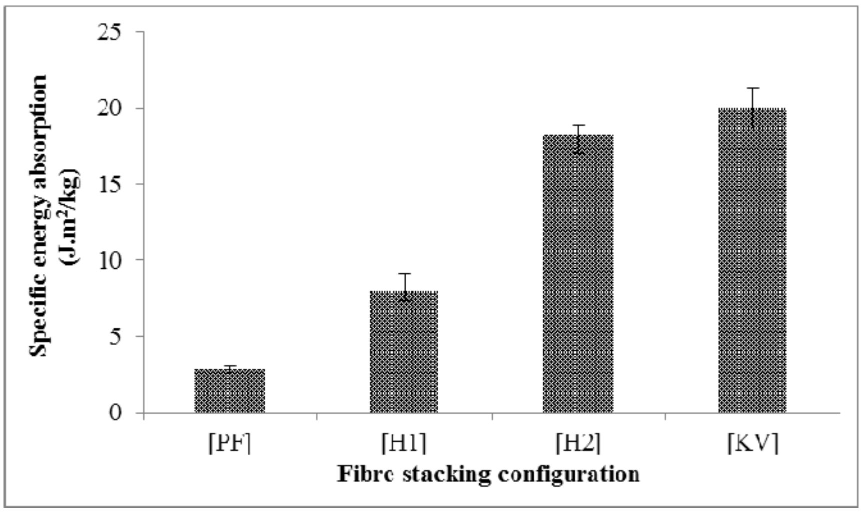


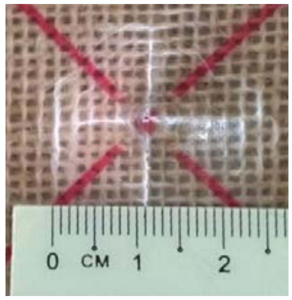
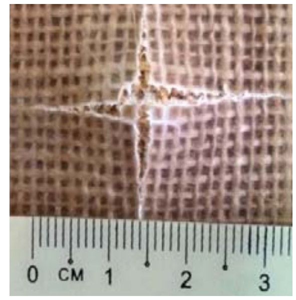
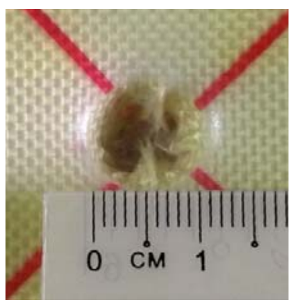
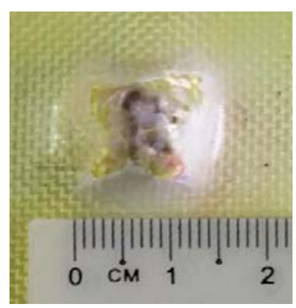
Figure 7: Specific energy absorption of composite laminates subjected to indentation.

3.3 Damage Assessment

The damage assessment of the non-hybrid and hybrid PALF / Kevlar reinforced composites was conducted on the fracture composite laminates to justify the findings obtained from the quasi-static indentation test. The damage behaviours of the non-hybrid and hybrid PALF / Kevlar reinforced composites were evaluated on the front and rear surface of the fracture composite laminates. Table 4 depicts the fracture surface of the front and rear sides of PALF / Kevlar reinforced composites. From Table 4, it was noticed that the damage behaviours of the composite laminates were highly influenced by the fibre types and fibre stacking configurations.

As can be seen in Table 4, the damage was more severe in the PALF based composites in comparison with Kevlar based composites. The crack length of the fracture composite laminate was diminished in both the indented and rear sides when the Kevlar fibre was partially incorporated in the composite laminates. When comparing the damage behaviours of the composite laminates with different fibre stacking configurations, [PF] and [H1] composite laminates exhibited similar damage behaviours while the damage behaviours of [H2] composite laminates were similar to those of [KV] composite laminates. On average, the crack propagation of [H2] and [KV] composite laminates was apparently smaller than the [PF] and [H1] composite laminates. This is attributed to the placement of high strength Kevlar fibre in the outermost layers of the composite laminates, leading to the reduction in the crack propagation of the composite laminates.

Table 4: Fracture surface of PALF / Kevlar reinforced composite laminates.

Composites	Front	Rear
[PF]		
[H1]		
[H2]		
[KV]		

In addition, the composite laminates had evidenced more severe damage on the rear surface instead of the indented surface, implying that the rear surface of the composite laminates was susceptible to higher damage and deformation level during the indentation process. The damage due to the indentation force can be due to the tension-shear and compression-shear. During the indentation test, the damage was initiated with a dent on the indented side, which was then followed by crack initiation and propagation on the rear surface. The crack propagated continuously along with the increase of the indentation displacement until the complete fracture of the composite laminates. Fibre pull-out, fibre-matrix delamination and fibre breakage were observed in the composite laminates as well, which were shown in Table 4. However, the fibre-matrix delamination was more significant in Kevlar based composites compared to PALF based composites, indicating that PALF based composites encompassed better fibre-matrix adhesion. Nonetheless, it should be emphasised that the incorporation of Kevlar fibre indeed resulted in the global deformation of the composite laminates after subjected to indentation force, resulting in an increase in the energy absorbing capacity.

4. CONCLUSION

This research study intends to investigate the quasi-static tensile and indentation properties of non-hybrid and hybrid PALF / Kevlar reinforced composites with various fibre stacking configurations. According to the findings obtained from the quasi-static indentation test, several conclusions have been drawn:

1. The average findings evidenced the high potential of hybrid composites especially [H2] composite laminates in terms of tensile properties. The results showed the partial replacement of PALF with Kevlar fabrics had undoubtedly improved the tensile properties of the composite laminates, indicating the positive hybrid effect towards the enhanced tensile properties. Moreover, it should be noted that the [H2] composite laminates had shown comparable tensile properties to the [KV] composite laminates. The tensile strength and modulus of [KV] composite laminates are only 10.79 % and 11.60 % higher than [H2] composite laminates. Therefore, [H2] composite laminates had evidenced a high potential to substitute the non-hybrid [KV] laminates.

2. The partial addition of Kevlar fibre in the composite laminates had led to the positive hybrid effect in the indentation properties. The improvement in the indentation properties was noticed when the Kevlar fibre was partially incorporated in the composite laminates. However, the highest indentation force and energy absorption were observed in the [KV] composite laminates whereas [PF] composite laminates showed the lowest indentation properties. Moreover, [H2] hybrid composite laminates had demonstrated a comparable indentation resistance and energy absorption to the [KV] composite laminates. The [H2] composite laminates evidenced the indentation force and energy absorption of 4280.06 N and 48.31 J which are only 26.45 % and 13.35 % lower than [KV] composite laminates.

3. In the context of energy absorption, a similar trend to the indentation force was observed. The partial substitution of PALF with Kevlar had improved the energy absorbing capacity of the composite laminates. When one middle layer of PALF was replaced with Kevlar fibre, the energy absorption was enhanced by 172.41 % while the improvement of 462.40 % was noticed when the outermost layers of PALF were substituted with Kevlar fibre. When comparing the energy absorption of composite laminates with different fibre stacking configurations, composite laminates with Kevlar in the outermost layers attested higher potential in the energy absorbing capacity in comparison with the composite laminates with PALF as the skin layers.

4. Since the specific properties and the environmental friendliness are the main concerns in searching for alternative materials to supersede the synthetic based composites, the specific energy absorption of PALF / Kevlar reinforced composites was measured. In accordance with the results obtained, hybrid composites [H2] still demonstrated a high potential in the energy absorbing capacity to replace those of non-hybrid [KV] composite laminates. [H2] composite laminates still showed comparable energy absorption of 18.20 $J.m^2/kg$ which is merely 9.18 % lower than [KV] composite laminates. The trend of the specific energy absorption is very similar to the absolute energy absorption since the PALF and Kevlar have a similar density. The overall results have concluded the high potential of employing PALF in the hybrid composite laminates in order to achieve the balance in environmental friendliness and the indentation properties.

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