Puncture Impact Performance of Coir-Aramid/Epoxy Hybrid Composite: Effects of Stacking Configurations

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***Abstract*—Hybrid composites allowed the possibility to alter the composite properties for a specific application, improving their manufacturability and reducing the cost by introducing cheaper fibres. Therefore, the hybrid of natural and synthetic fibres in a composite system has attracted interest in research field attributable to environmental consciousness. The focus of the study is to determine whether any improvement in impact response exists as a result of combining high-performance woven Kevlar synthetic fibre and woven coir natural fibre in a specified laminated stacking sequence. Thus, the study was conducted by performing an experiment to differentiate the capabilities of hybrid by comparing the impact responses effect of different stacking configurations. It focused on the impact resistance and penetration behaviour of the hybrid composites, as well as their suitability for modern structural applications. The results from this study showed that the hybrid of coir/Kevlar-epoxy laminated composites revealed an improved in impact response.**

***Index Terms*— epoxy, hybrid composites, puncture impact, woven Coir, woven Kevlar**

I. INTRODUCTION

Synthetic fibres are frequently used and applied in various outstanding applications due to their flexibility and greater mechanical and chemical properties, which have aided the industry in producing mechanical machinery or electrical components. Nowadays, new investment in developing new materials in order to minimize the dramatically increasing of synthetic fibres usage and develop materials that can exceeded the ability of the synthetics fibres. This is in consideration of achievable outcomes, such as low-cost production, high sustainability, low hazard manufacturing, and the presence of renewable resources [1-3].

Implementation of natural fibres as the reinforcement composite has attracted much interest in displacing conventional reinforcement materials. Recently, composites are considered as important engineering materials that are frequently incorporated due to their outstanding physical, mechanical and thermal properties. They include high stiffness and strength to weight ratio, good fatigue, outstanding corrosion resistance, and dimensional stability. These materials are widely applied in many branches of the industry, including the commercial automotive and automation industry [4-5].

A relatively high demand for fabrication of modified laminated composites through tailored microstructures exists since the outcomes are strongly dependent on the characteristics of their constituent materials, distribution, and the interaction among their structures. These composites are built to overcome the weakness of the properties and fulfil the requirements so as to cope with the synthetic fibre properties.

Nevertheless, during the operations of product application, one may encounter an exposure to impact relatively from small, as the low-energy object that can lead to damage laminate structures and consequently a significant reduction of the structure [6-9]. Generally, the effect of low-velocity impact damage is determined through impact velocity and energy absorption in fibrous composites. Therefore, this research aims to explore the potential of natural fibres in working with high-performance Kevlar aramid fibre to absorb energy from penetrative impact and investigate the after-effect of the test. Thus, further investigation is done to determine the performance of coconut coir hybrid composite.

II. LITERATURE REVIEW

Coir fibres suit the requirements as the experimental specimen for several engineering applications [10]. Many researchers have conducted numerous studies on the mechanical properties of coir reinforced composite materials, such as between epoxy/coir fibre composites and coir fibre/sawdust from the utilisation of coir fibre reinforced with epoxy hybrid composites [11]. Coir fibre has also gained scholarly attention due to excellent energy absorption attributes and have become one of the most ductile materials known [12].

Composites that comprehend a strong load-carrying material are known as reinforcement. The position and orientation of the reinforcement are maintained by the

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matrix or binder. It is important to note that if both components are together, the combination of their qualities renders the individual constituents incapable of self-generating and provides the strength and rigidity to support structural load [13].

Impact behaviour of structures made by materials differs inherently due to different material specifications specified for laminated composites structures. However, the damage to metals is observable on the surface, while the damage to composites is hidden inside, especially when subjected to a low-velocity impact. The invisible form may cause a serious decrease in material strength, which can occur during the production, repair, maintenance, and small particle crashes to the composite body [14-15].

III. Methodology

A. Materials

Plain weave Kevlar 29 was supplied from China Beihai Fiberglass Co. Ltd., China in a roll of weaved fabric. The yarn size was 1100 dtex with 200 g/m^2 of fabric weight. The coconut coir yarn with a density within the range of 1.15 g/cm^3 – 1.46 g/cm^3 was used and provided by Btex Engineering Ltd., India. Then, the yarns were weaved manually into the plain woven structure. In addition, epoxy DER 332 was used as the resin matrix to efficiently hold the fibre in place with a density of 1.16 g/mL, alongside Jeffamine D-230 hardener with a density of 0.948g/mL that was used as the curing agent.

B. Sample Preparations

Coir yarns were fabricated into plain woven structures whereby the yarns were weaved in warp and weft direction using a manufactured self-designed handloom. Fig. 1 shows the woven coir mats.

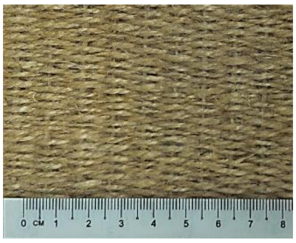

Figure 1. Coir mats

Composite materials were comprised of a combination of two different constituent materials, namely the coir mats structure as the reinforcement and the epoxy resin and hardener as the matrix. Preparation matrix were done in accordance with previous research [16]. Next, the composite was fabricated via compression moulding method. The hybrid composites of coir and Kevlar were prepared with different stacking configurations consisting of three laminate layers. Fig. 2, illustrates the stacking configurations.

The letter “C” refers to the coir ply whereas “K” stands for Kevlar ply. The first letter of each hybrid sample’s coding represents the area of the front face facing the impactor. For instance, CKC sample meant that the coir ply was located at the front and back face while Kevlar was placed in the middle of the stacking.

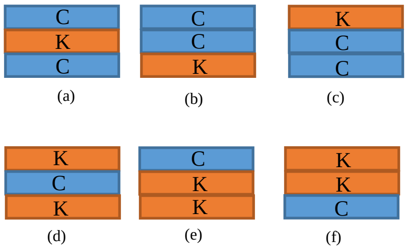

Figure 2. The stacking sequences coir/aramid hybrid, (a) CKC (b) CCK (c) KCC (d) KCK (e) CKK and (f) KKC

C. Testing and Characteristic Analysis

Coir yarn properties were assessed upon receiving the material from the supplier, such as its diameter, linear density, yarn twist type, and direction. Yarn tensile test was performed using Universal Testing Machine (UTM); Lloyd Instrument LR 30K with a gauge length of 200mm and a crosshead speed of 1.3 mm/min to analyse its tensile strength and modulus. Shimadzu Hydroshot Impact Test Machine was used at ambient temperature as the low-velocity impact tests were carried out. A hydraulic system actuator dropped an impactor with a nose tip of about 12.7 mm at various loading rates. The striker was equipped with a load transducer whose output was fed to a data acquisition board installed in a computer. Fig. 3, demonstrates the impact test, whereas Fig. 4 shows the force-stroke curve of the impact event.

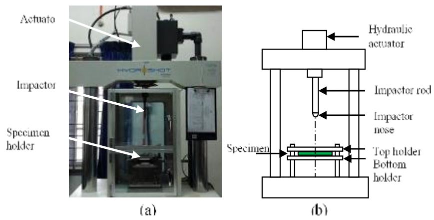

Figure 3. Impact test, (a) actual machine and (b) schematic diagram

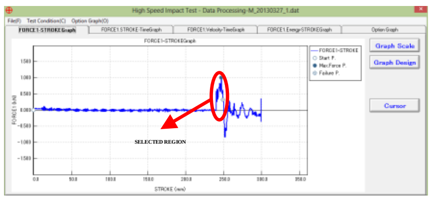

Figure 4. Force-stroke curve of the impact event generated by the data processing impact software

Solely the raw data from the region marked with a circle on Fig. 4 was extracted for further analysis. From the curve, impact responses such as the first material damage, the total displacement (δ), the peak load (P_{peak}), energy absorbed (E_a) and propagation energy (E_p) were obtained and calculated. A new curve using the raw data of the marked region was then plotted using Matlab. Basic curve fitting was conducted to obtain a smoother curve that best fit the original series of data points using the basic fitting tool in Matlab. Fig. 5, presents the curve fitting using Matlab, and Fig. 6 shows the identification of impact response data.

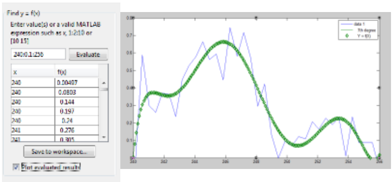

Figure 5. Basic curve fitting with generate gridded curve with function value

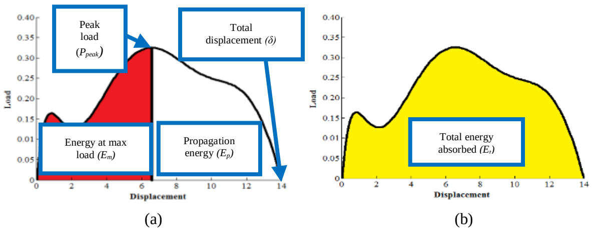

Figure 6. The identification of impact response data; (a) peak load, total displacement, energy at maximum load and propagation energy and (b) total energy absorbed

The energy dissipated after the yield point was defined as E_p (propagation energy), where $E_p = E_t - E_m$. The impact strength or impact toughness value in joule per meter square [J/m^2] can be obtained as per (1).

$$\text{Impact strength} = \frac{E_m}{\pi d^2/4} \tag{1}$$

Where, E_m is the energy value at maximum load point, and d is the striker diameter with a value of 12.7 mm. Damages on composites were evaluated by visual inspection through the cross-section of the composites.

IV. Results and Discussions

A. Yarn Properties

According to the results obtained, it was revealed that the outcomes were favoured to the Kevlar in terms of tensile properties, such as high tensile maximum load, strength at break and modulus of elasticity, except for strain at break in which the coir yarn was higher than Kevlar. Table I indicates the physical and tensile properties of coir and Kevlar yarns.

TABLE I. Physical and Tensile Properties of Coir and Kevlar 29 Yarns

Properties	Coir	Kevlar 29
Diameter (mm)	1.5	0.5
Linear density (Tex)	923	110
Twist type	2-ply spun	-
Twist direction	S	-
Tensile maximum load (N)	84	98
Tensile strength at break (MPa)	47	497
Tensile modulus of elasticity (GPa)	3.3	33.1
Tensile strain at break (%)	3.3	2.3

B. Fabric Characteristics

The result showed that the crimp per cent of the woven fabric structure was low (< 20 crimp %), which was an advantage as a higher crimp would results in the deterioration of mechanical properties. Crimp and areal density were affected by weave density. Table 2 shows the fabrics characteristics for coir and Kevlar. The results were in accordance with the findings obtained by [17], whereby woven fabric density influenced the yarn wavelength. However, in this research wavelength had decreased as the weft density increased, which was due to the inconsistent warp density. Table II shows the fabrics characteristics for coir and Kevlar.

TABLE II. Characteristics of Coir Fabric and Kevlar 29 Fabrics

Characteristic	Woven Coir	Woven Kevlar 29
Thickness, t (mm)	4.0	0.3
Weight (g/m^2)	1039	200
Warp density (warp/10mm)	1	9
Weft density (weft/10mm)	18	9
Crimp percent, k (%)	2	1.25
Weft crimp wavelength, λ (mm)	20	2.5
Inter-yarn fabric porosity, ε	0.35	0

C. Composite Characteristics

Two plies of Kevlar (Group K) in a composite with two plies of coir (Group C) were presented in a 1:2 ratio of their difference in thickness and areal density. All samples represented an open type curve, implying the initiation of a complete perforation. Fig. 7 (a) depicts the load-displacement plots for all six stacking configurations of coir/Kevlar hybrid composite panels, whereas Fig. 7 (b) illustrates the energy absorbed-time curve.

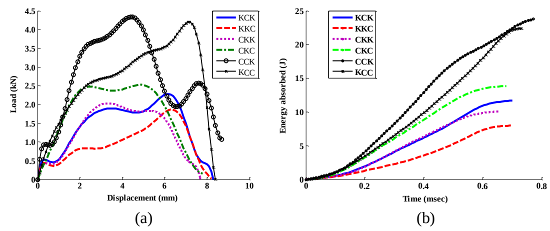

Figure 7. Hybrid composites with different stacking configuration; (a) Load-displacement curve (b) Energy absorbed-time curve

Among the composites tested, it was observed in Fig. 7 (a) that composites group C had recorded the highest load required, which was 4.46kN, from CCK to penetrate the composites. In contrast, composites of group K recorded the lowest load required, which was 2.20kN from KCK. Eventually, coir/epoxy composites were firmer and tougher than Kevlar/epoxy composites, as coir composites distorted less thus carried a higher load.

For Fig. 7 (b), composites group C showed good energy absorption through the time taken off the penetration. This was expected to be due to the bond strength present between the reinforcement and matrix. It was observed that composites of group C and group K both had a large and different levels energy absorption to each other, in which CCK reached until 26.36 J while the highest value for KCK was only 11.47 J.

Composites with a low increase of energy absorption might be due to the low stiffness and large deformation within a short time. Generally, the energy absorbed is affected by the thickness of the layers [18]. Clearly, increasing of impact damage size has resulted in higher absorbed energy [19]. Moreover, enhancing the compressive properties, stiffness, impact resistance and indentation hardness can lead to improvements in energy absorption. More specific impact responses are summarised in Table III and IV.

TABLE III. MEAN SCORE FOR STACKING CONFIGURATION PARAMETER ON IMPACT RESPONSE

Sample type	Peak load (kN)	Displacement at peak load (mm)	Total displacement (mm)	Energy absorbed to peak load (J)	Total energy absorbed (J)
KCK	2.20±0.07	6.23±0.06	8.03±0.38	9.35±0.11	11.47±0.23
KKC	1.82±0.04	6.37±0.12	8.20±0.20	6.01±0.26	7.90±0.34
CKK	2.06±0.03	3.55±0.23	7.66±0.15	3.96±0.24	9.73±1.20
CKC	2.78±0.24	4.20±0.75	7.80±0.30	8.67±2.04	15.29±2.25
CCK	4.46±0.13	4.50±0.17	9.60±0.90	13.57±1.37	26.36±2.25
KCC	4.14±0.78	7.10±0.40	8.73±0.29	18.93±4.68	22.83±4.50

TABLE IV. MEAN SCORES FOR STACKING CONFIGURATION PARAMETER ON PROPAGATION ENERGY, SPECIFIC ENERGY ABSORBED AND IMPACT STRENGTH

Sample type	Propagation energy (J)	Sp. energy absorbed to peak load (J/kg)	Sp. total energy absorbed (J/kg)	Impact strength (kJ/m^2)
KCK	2.14±0.34	2.29±0.03	2.81±0.06	73.61±0.85
KKC	1.89±0.09	1.48±0.06	1.94±0.08	47.35±2.01
CKK	5.78±1.42	0.98±0.06	2.38±0.29	31.18±1.92
CKC	6.62±2.09	1.27±0.29	2.23±0.33	68.31±16.03
CCK	12.8±0.54	1.98±0.20	3.83±0.33	106.86±10.77
KCC	3.91±0.39	2.75±0.68	3.32±0.65	149.04±36.85

Data in Table IV was calculated by the formulation stated in methodology section. Impact strength was clearly dominated by the composite from group C, which was the KCC composite since the impact strength was up to 150kJ/m^2 followed by CCK with 106kJ/m^2.

D. Visual Composite Damage Assessment

The cross-sectional images of the fractured surface in the figure shows a straightforward indication of the damage formation through the failure modes. Fig. 8 portrays the image damage of the composites.

The cone formation was clearly seen in KCK, KKC, CKK and CCK. Meanwhile, the dome was formed as the sample protruded along the rim of circular support, due to the sample being compressed and deflected by the tip of the impactor. Deformation mechanisms such as indentation, deflection and debonding have dissipated a significant amount of impact energy prior to the perforation and penetration of the impacted panels. Fractures hanging were held by Kevlar yarn, which encountered less fibre breakage compared to coir yarn. It was observed that serious crack size on each sample did not unravel much of the Kevlar yarn. CKK and CCK samples also showed that the segmented fracture part of the coir was held by the Kevlar layer due to fewer Kevlar yarn breaks. Other than that, KCC did not appear to be cone-shaped as the high strength of the Kevlar layer when placed on the front face resisted the penetration and avoided to form such cone shape. Therefore, the types of failure depended on the material and geometric properties of the target materials as more severe damage on composite panels is predicted with an increasing impact energy of the impactor [20-21].

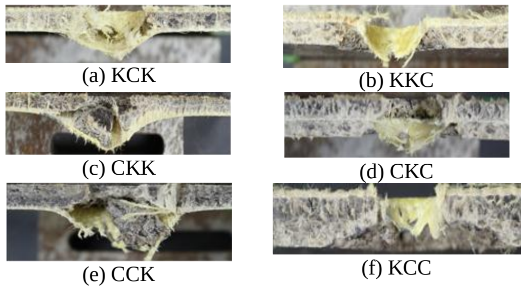

Figure 8. Damage of cross-section surfaces observed for panels impacted at 5m/s (a) KCK (b) KKC (c) CKK (d) CKC (e) CCK (f) KCC

V. CONCLUSIONS

The work presented in this paper provided a substantially new analysis towards the puncture impact performance of coir-aramid/epoxy hybrid composite effects of different stacking configurations. By comparing the impact responses with different stacking configurations, optimal results were presented and the parameter was capable to describing the damaged state of the composites at the end of the test.

Coir were favoured physically due to them being thicker and heavier, while Kevlar was in favour of mechanical characteristics, such as high tensile strength. Major achievements were obtained from the research, which were as follows:

- Woven coir-aramid/epoxy hybrid composite leads to improved impact properties by modifying the structure of composites and using the layering system.
- The stacking configuration provides precise outcomes via a comparison of the composites and is capable of differentiating their differences in a clear manner.

- CCK and KCC were the best stacking configurations as both had equally high impact strength, peak load and energy absorbed. This was due to the two-ply coir structure that helped in resisting the penetration through its excellent mechanical properties and appropriate thickness.
- One ply of Kevlar become the front face as shown in Fig. 8 was highlighted as the best findings, whereby it could reduce the delamination, fibre breakage and matrix cracking due to its high strength, as well as supporting the two-ply coir layers.

Thus, further experimental testing at a various ranges of speed can be undertaken in the future. Moreover, a balanced plain-woven coir structure can be considered in future works to ensure that there will be no extreme differences in the testing results. Lastly, in order to achieve more balanced warp and weft structures, the weaving device needs further improvement.

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