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Impact Resistance of Bamboo Fabric Reinforced Polypropylene Composites and Their Hybrids

N Z M Zuhudi[1*], K Jayaraman[2], R J T Lin[2], N M Nur[1]

[1]Aerospace Section, Universiti Kuala Lumpur – Malaysian Institute of Aviation Technology (UNIKL MIAT), Lot 2891, Jalan Jenderam Hulu, 43800 Dengkil, Selangor, Malaysia
[2]Center for Advanced Composite Materials (CACM), Department of Mechanical Engineering, The University of Auckland, Private Bag 92019, Auckland, New Zealand

*Corresponding author: zuhairah@unikl.edu.my

Abstract. Bamboo in woven fabric form embedded in the polymer results in easier material handling during production and reduction in the manufacturing cost of the composites. In the current study, the effect of hybridization of bamboo fabric with glass fibres on the impact properties of the composites made from them has been studied. The composites were fabricated using a compression moulding method. Bamboo fibres were in the form of twill-weave fabric. Impact tests were conducted using an instrumented drop weight impact test system. It can be seen that the peak load and energy absorbed increase with the increase in the applied impact energy. For the BPP composites, the applied energy of the impact was increased until penetration was occurred at 55 J. While for the BGPP hybrid composites, they were penetrated at the applied energy of only 35 J. However, The hybrid composites exhibit a greater peak load resistance than the BPP composites. The crack damage in the composites was also reduced with the presence of fabric reinforcement. These preliminary results indicate that bamboo fabric is truly a new contender for developing excellent and balanced properties of composites such as for the interior components.

1. Introduction

1.1. Impact properties of composites and their hybrids

Impact resistance of a structure can be investigated using several test methods such as Charpy, Izod and instrumented falling weight testing. Drop weight impact (DWI) testing can provide more information than Charpy and Izod impact testing. The test output gives more relevant data regarding toughness ability and damage behaviour of composites compared to Charpy and Izod test results. According to Richardson et al. [1], impact can be divided into two categories; high velocity and low velocity impact. High velocity impact response is dominated by stress wave propagation through the materials, in which localised damage occurs rapidly. The impact event is over before the stress waves reached the edge of the structure, so boundary condition effects can be neglected. In contrast, in low velocity impact, boundary conditions are important because the impact duration is long enough for the structure to respond to impact and more energy is absorbed. Most of the impact test work reported in the literature has been conducted using low velocity impact testing in order to be able to observe the damage mode initiation and propagation.

The nature and extent of impact damage is dependent on parameters such as impact velocity, impact angle, shape of the impactor, laminate material (including fibre volume fraction and lay-up), and laminate geometry [2]. It is important to better understand the impact responses of such materials especially hybrid composites, because it has been already proved that incorporation of glass with natural fibres will lead to an enhancement in the mechanical properties of the resulting hybrid composites.

Low velocity impact of glass fibre reinforced composites in thermoset matrices has been the subject of many experimental studies [3,4]. GPP behaviour and damage tolerance under low velocity impact also has been discussed and well-reviewed [5-7]. However, there has not much work on the impact resistance of natural fibre reinforced composites (NFRCs) [8] particularly in PP based matrices for example the work by Bledzki et al. [9]. Interestingly, more researchers are focussing on the effects natural fabric on impact resistance in PP based matrices [10-12]. A few studies have reported the behaviour of NFRCs under drop weight impact testing; however, no such research has been carried out with natural fabric-glass hybrid composites in PP matrices. Most of work on natural fabric hybrid composites used thermoset resin such as polyester [9, 13-14]. For example, Ahmed et al. [2] explored the effects of hybridisation on low velocity impact damage of woven jute fabric reinforced isothalic polyester composites. Their results indicated that jute composites have better impact energy absorption capacity than jute-glass hybrid composites but their damage tolerance capability is lower. Benevolenski et al. [13] performed work on the transverse perforation impact behaviour of flax mat-reinforced PP composites with additional discontinuous cellulose (Lyocell) and discontinuous glass fibre mat at 50 wt.% fibre content. They found the resistance of flax-PP to perforation on impact was strongly improved by the hybridisation with Lyocell and glass fibres. More recently, Pandita et al. [15] carried out drop weight impact tests on jute-glass polyester composites. They found that the impact resistance of their hybrid composites was higher than that of jute woven composites. They concluded that the woven glass at the outer surface of a composite can act as a strong skin.

1.2. Impact behavior study

A typical load-displacement curve derived from drop impact test on the composites is shown in figure 1. The peak load (F_m) is the maximum load that the specimen can sustain on fracture, which indicates the beginning of significant damage. The associated energy absorbed up to this point is symbolized by E_m and it represents the energy to initiate crack. After F_m , the dropping off in force indicates crack propagation and E_p represents the energy absorption in this phase. The total energy absorption is defined as:

$$E_t = E_m + E_p \tag{1}$$

where E_t is the area under the load-deflection curve is [16].

Figure 1 shows the two typical load-displacement curves obtained in an impact event. Shaded areas in the figure represent the energies absorbed by the composites during impact tests resulting in closed and open type curves. A closed type curve as shown in figure 2 (a) shows a rebounding phenomenon happens in the specimen. An open type load-displacement curve has a horizontal section at the very end, a post perforation frictional section. In order to identify the true energy absorption due to damage formation in the specimens, the post-perforation friction section needs to be removed from the curve. For this purpose, the initial part of the descending section of the curve may be extended to the displacement axis, shown as an estimated point in figure 2 (b). The absorbed energy can be determined from the initial kinetic energy minus the rebound kinetic energy using the initial and rebound velocities. The difference between absorbed energies calculated from these curves and that calculated with kinetics energy methods is negligible.

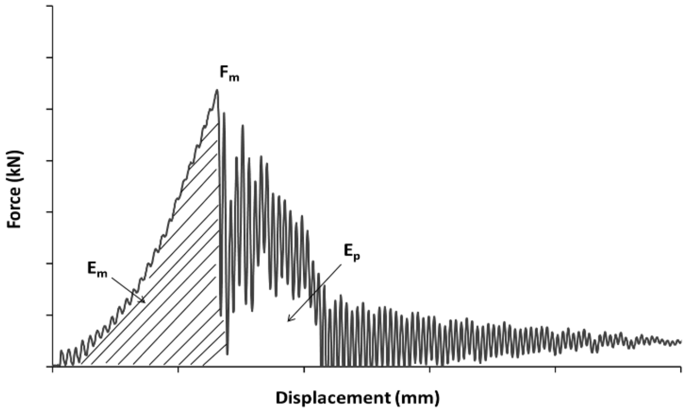

Figure 1. Schematic diagram of force versus displacement from a drop weight impact test showing the area under curve

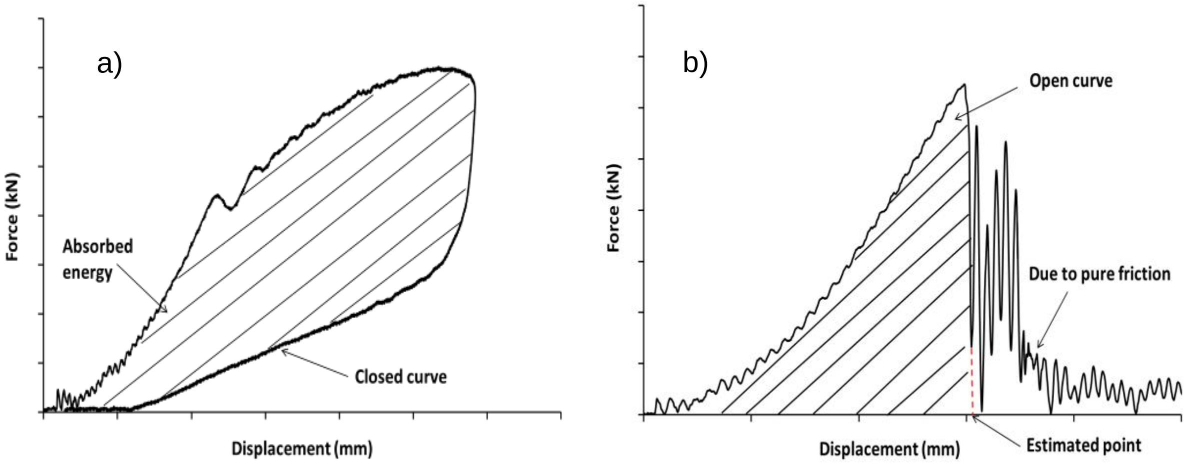

Figure 2. Schematic diagram of force versus displacement from a drop weight impact test for a) non-perforated specimen and b) perforated specimen

The penetration threshold is defined as the impact energy at which the impactor does not rebound from the specimens [16]. The perforation threshold is defined as the absorbed energy when the tup penetrates the specimen. In the case of a thick specimen, the hemispherical nose may completely bury into the specimen, resulting in penetration without reaching perforation, as shown in figure 3 (a). However, it should be noted that it is hard to observe such penetration when the specimen is much thinner than the radius of the impactor nose. The impactor nose used in this study had a hemispherical shape with a radius of 8 mm while the composites were in the range of 1.8 to 3.0 mm nominal thickness. Accordingly, penetration of specimens is generally followed by perforation. Figure 3 (b) shows the impactor at the onset of perforation and figure 3 (c) illustrates the perforation through the specimen.

It is important to study in detail the behaviour of the composite under impact in order to estimate not only the consequences of the energy absorption, but also how the impact damage can be minimized in some way. In this research, the objective of this paper is to carry out a preliminary study of the effect of hybridization of bamboo fabric with glass fibres on the impact behaviour of the composites impacted at different applied energies. The result reported here is associated with the previous results reported elsewhere [17].

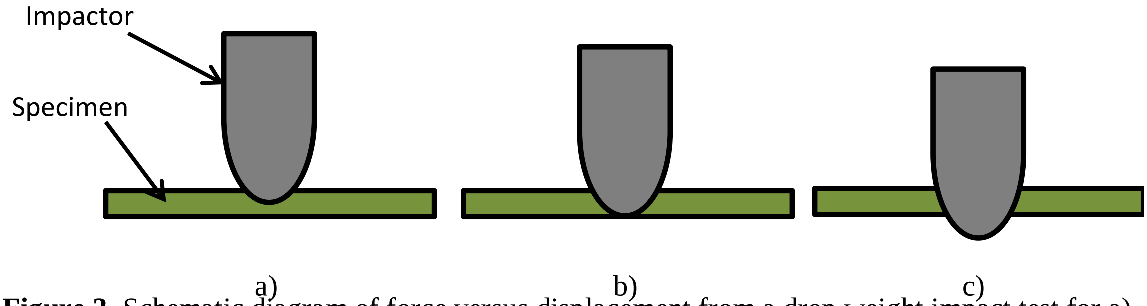

Figure 3. Schematic diagram of force versus displacement from a drop weight impact test for a) penetration, b) impactor is at the onset of perforation and c) perforation [16]

2. Materials and Methods

The raw materials used to fabricate the BPP composites in this work were polypropylene and woven bamboo fabric. The matrix used was polypropylene (PP) random copolymer, Moplen RP241G, manufactured by Lyondell Basell Industries and supplied by Field International Ltd., Auckland, New Zealand. The PP sheets have a nominal thickness of 0.38 and 0.58 mm. 100% bamboo fabric twill-woven was obtained from Xinchang Textiles Co.Ltd., Guangzhou, China. The bamboo fabrics with a width of 1500 mm and weight of 220 gsm were used, having specification of 20*20 tex and 108*58 per square inch for yarn count and density, respectively. The glass pre-preg supplied by Plytron ICI Ltd. UK with nominal glass volume fraction and density of 35% and 1480 kg/m^3 . The nominal thickness and sheet width are 0.47 mm and 240 mm, respectively.

2.1. Methods

2.1.1. Fabrication of composites.

The compression moulding process was used in this research to produce composite laminates. The closed mould was heated until the required temperature of 185°C was reached. The ply stack that had been dried earlier was placed in the mould cavity for pre heating, and the loaded mould was continuously heated for about five minutes without pressure to allow the polypropylene to start melting and percolating through the fibres. At this point, the consolidation pressure of 0.80 MPa was applied and held steady for five minutes. During this impregnation stage, pressure was applied to force the molten polymer into the fabrics while removing the excess air and volatiles. During the cooling period, the pressure applied was maintained until the temperature of the mould cavity dropped down to 40°C or lower when the laminate could be removed from the mould. The bamboo polypropylene (BPP) composites and their bamboo-glass polypropylene (BGPP) hybrid composites were fabricated in the range of about 55-65% fibre weight fraction, all in warp direction. The hybrid composites were fabricated with about 30% of bamboo and 20% of glass fibre weight fraction.

2.1.2. Instrumented drop weight impact test.

Impact test were conducted using an instrumented drop weight impact test system (DYNATUP 8250) on samples size of 150 x 100 mm. The test was performed using a drop weight with a steel (Thyrodur 2550) hemispherical striker tip of 16 mm diameter. Different impact energies of 20, 25, 35, 45 and 55 J were applied to the composites. The energy was obtained by changing the drop height, with constant impactor mass of 9.745 kg. For every type of laminate five specimens were tested. The specimen was tested using a test rig with a toggle clamp at all edges. The impact data was generated by the data system in terms of force-time, energy-time, force-displacement graphs which can be displayed from the output, along with the computed values of input energy, impact velocity, peak load, total energy, maximum energy at peak load, etc.

3. Results and Discussion

3.1. Effects of applied impact energy

A summary of the impact properties computed for the BPP composites for different energy levels when tested using the toggle clamps is shown in table 1. The BPP composite was not penetrated with the applied energy of 25 J. The applied energy of the impact was then increased until penetration was achieved at 55 J. It can be seen that the peak load and energy absorbed increase with the increase in the applied impact energy. Typical impact force versus displacement of BPP composites as a function of applied impact energy is shown in figure 4. A closed-loop type behaviour for applied energy lower than 55 J shows that complete perforation did not take place. The impactor rebounded in such cases. The force increased to a peak before dropping off in several phases. The gradual dropping off led to more displacement before failure and it is associated with higher energy absorption.

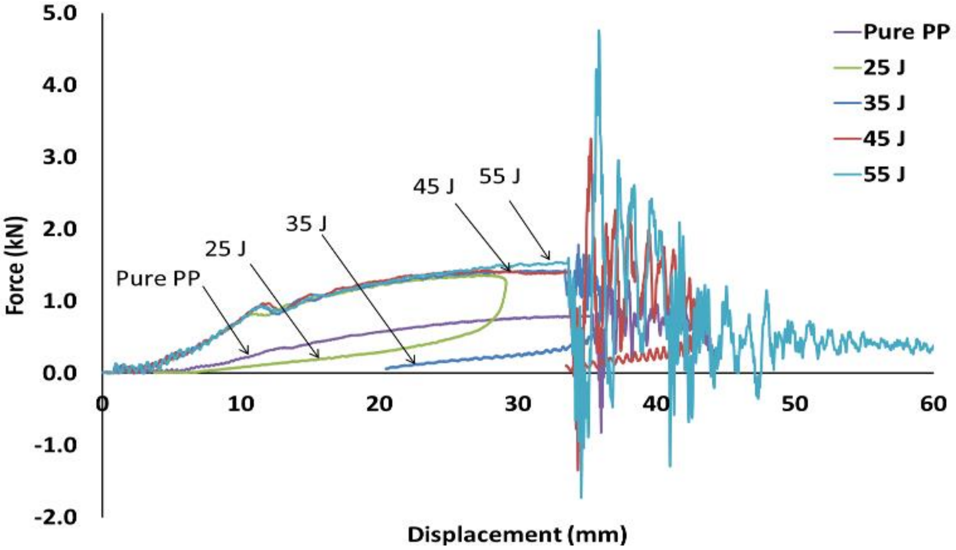

Figure 4. Typical impact force versus displacement of the BPP composites at different applied impact energies

Table 1. Impact properties of the BPP composites at different applied energies

Applied Energy (J)	Peak Load (kN)	Energy absorbed (J)	Displacement to max. load (mm)	Impact responses
25	1.365±0.3	21.93±0.2	27.12±0.8	Indentation
35	1.422±0.2	30.52±0.5	32.89±0.2	Indentation
45	1.452±0.8	32.07±0.8	33.64±1.1	Indentation
55	1.599±0.6	32.40±0.1	33.65±1.5	Perforation

Damage patterns in BPP composites impacted at various applied energies are shown in figure 5. The BPP composites were not penetrated or perforated with impact energies of 25 J, 35 J and 45 J. The impactor bounced back. At 25 J up to 45 J, the damage in the composites was limited to small indentations at the point of impact and became obvious on the other side of composites as the applied energy increased. However, as can be seen, the impact damage at 55 J is more profound at the back surface. Fibre failure and matrix cracks were obvious at the back surface. The damage propagates from the back surface (tension side) to the front surface (compression side) until the maximum force is reached.

The study of these properties using drop weight impact testing provided insight into the capability of the BPP composites in term of impact resistance and energy absorption properties. The force in the BPP composites increased before dropping off. The gradual dropping off indicated crack propagation occurred and energy was then, absorbed by the bamboo fabric. The impactor bounced back at energies lower than 55 J, as indicated by the load-displacement curves for the BPP composites. Damage in the composites impacted at 25 J to 45 J was limited to small indentations at the point of impact. 55 J was required to perforate the specimens. These results indicate the greater impact load carrying ability of the BPP composites. This is because of greater stiffness and load bearing ability in the bamboo fabric compared to the pure PP. A larger damage area was associated with the increase in the applied energy. This is consistent with findings elsewhere in the literature [2].

The higher applied impact energy required to perforate the BPP composite can be explained in terms of the fibre toughness. Woven fabric inhibits the initiation of interlaminar cracks. The fabric composites offer excellent resistance to impact damage through the cross-over points, which act as stress distributors. The impact loading applied on the fabric composites beyond the perforation threshold energy level produces crack initiation within the ply in the fabric composites, which begins to propagate through the thickness, but has to cut through the fibre. Unless the energy available is high enough to fracture the fibre tow, the crack is arrested [18].

It is widely accepted that an improvement in the impact properties of polymer composites with high stiffness reinforcements, such as glass, can be obtained by mixing them with tougher and higher energy absorption reinforcements such as natural fibres. There have been no studies reported in the literature on the impact response of bamboo fabric and glass unidirectional reinforced PP hybrid composites.

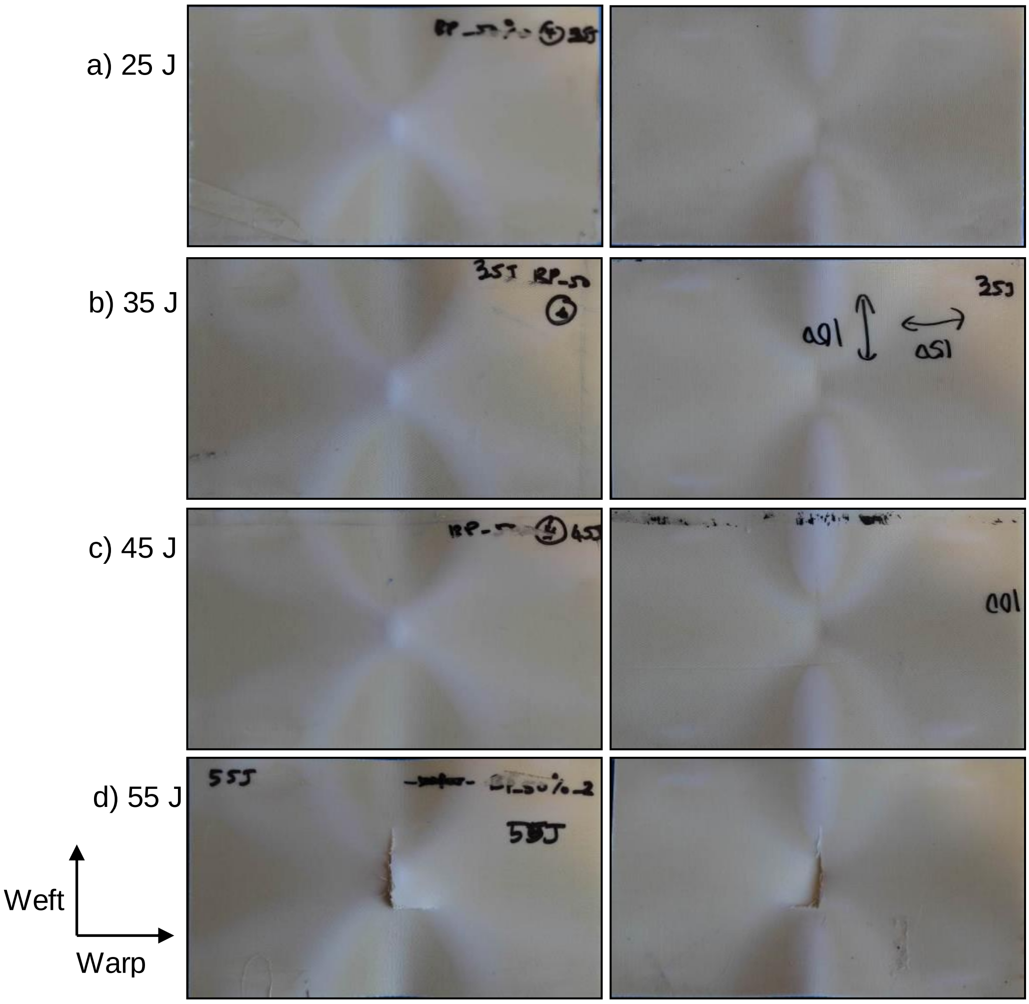

Figure 5. Photos of damage patterns (front and back view) in the BPP composites impacted at different applied energies when tested using the toggle clamp

3.2. *Effect of hybridization*

A summary of the impact properties computed for the BGPP hybrid composites for different energy levels when tested using the toggle clamps is summarised in table 2. The BGPP hybrid composites were not penetrated with the applied energy of 25 J. The hybrid composites started to be penetrated at the impact energy of 35 J. It can be seen that the peak load and energy absorbed increase with the increase in the applied impact energy. Typical impact force versus displacement of the hybrid composites as a function of applied impact energy is shown in figure 6. A higher impact force and energy was absorbed in the composites for higher applied energy. No significant difference observed as the applied energy increased.

Photos of damage patterns in the hybrid composites impacted at different applied energies are shown in Figure 7. It can be seen that perforation of the composites occurred at 35 J. The applied energy was then increased to 45 J and 55 J to observe the damage area. The impact damage in the hybrid composites at 35 J is mainly in the form of delamination, matrix cracking and fibre breakage. There was no difference in the length of cracks and the size of the damage area with the increase in applied energy. The crack was initiated at the bamboo-glass interface.

Table 2. Impact properties of the BGPP hybrid composites at different applied energies

Applied Energy (J)	Peak Load (kN)	Energy absorbed (J)	Displacement to max. load (mm)	Impact responses
35	2.015±0.1	10.08±0.1	33.68±0.5	Perforation
45	2.216±0.2	12.78±0.1	34.78±0.3	Perforation
55	2.366±0.8	13.44±0.2	35.99±0.1	Perforation

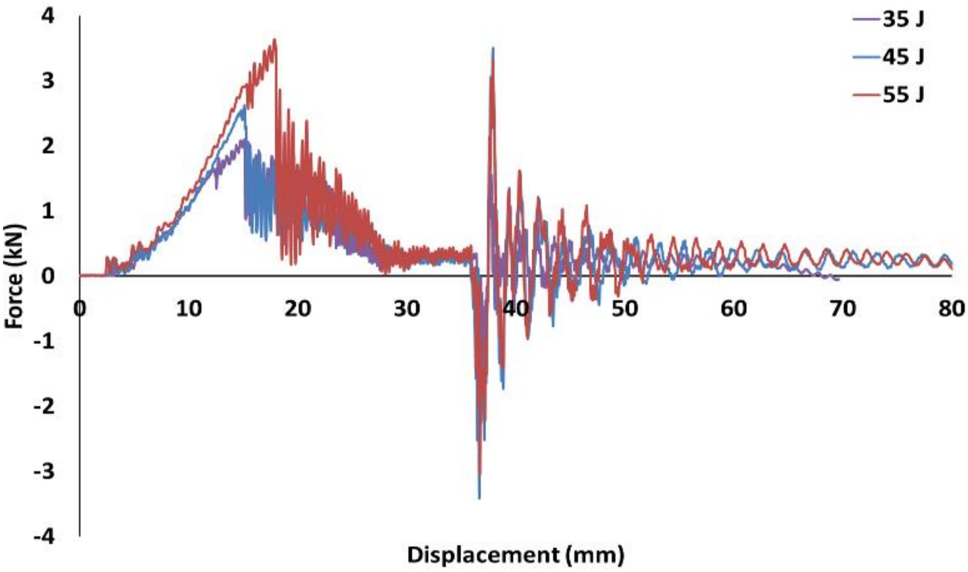

Figure 6. Typical impact force versus displacement of the BGPP hybrid composites at different applied impact energies when tested using the toggle clamps

For the effect of hybridisation, the force versus displacement for the hybrid composites was similar with that observed in the BPP composites. A gradual dropping off of force led to much higher deflection values. The bamboo fabric offers excellent resistance to impact damage. The peak force increased with the increase in the applied impact energy. When compared with BPP composites, the hybrid composites withstand a higher peak force but lower energy absorbed. This increase in peak force is due to the greater stiffness of the glass plies. The higher energy absorbed in the BPP composites than that in the hybrid composites, indicates that the BPP composites have better energy absorption than the hybrid composites. The displacements in the BPP and hybrid composites are comparable and it depends mainly on the stiffness and thickness of the composites and applied impact energy. The hybrid composites were perforated at 35 J applied energy, compared to 55 J for the BPP composites. The damage was greater for the BPP composites, indicating the better damage resistance capability of the hybrid composites. The hybrid composites exhibit a greater peak load resistance than the BPP composites. The pattern of impact damage in the hybrid composites was strongly affected by the mechanical properties of the glass. Because of the fibre alignment in the glass, the delamination tended to occur when the crack and fibre failures were found along the glass fibre direction. The presence of bamboo fabric in the hybrid composites reduced the amount of delamination, although the hybrid composites displayed a lower energy absorbed than the BPP composites. From the results obtained, the hybrid composites give better impact resistance in terms of much higher peak force. The glass layer in the hybrid composites effectively withstood greater impact peak load than the BPP composites. This result is consistent with previous hybridisation work by Ahmed et al. [2] and Sarasini et al. [19].

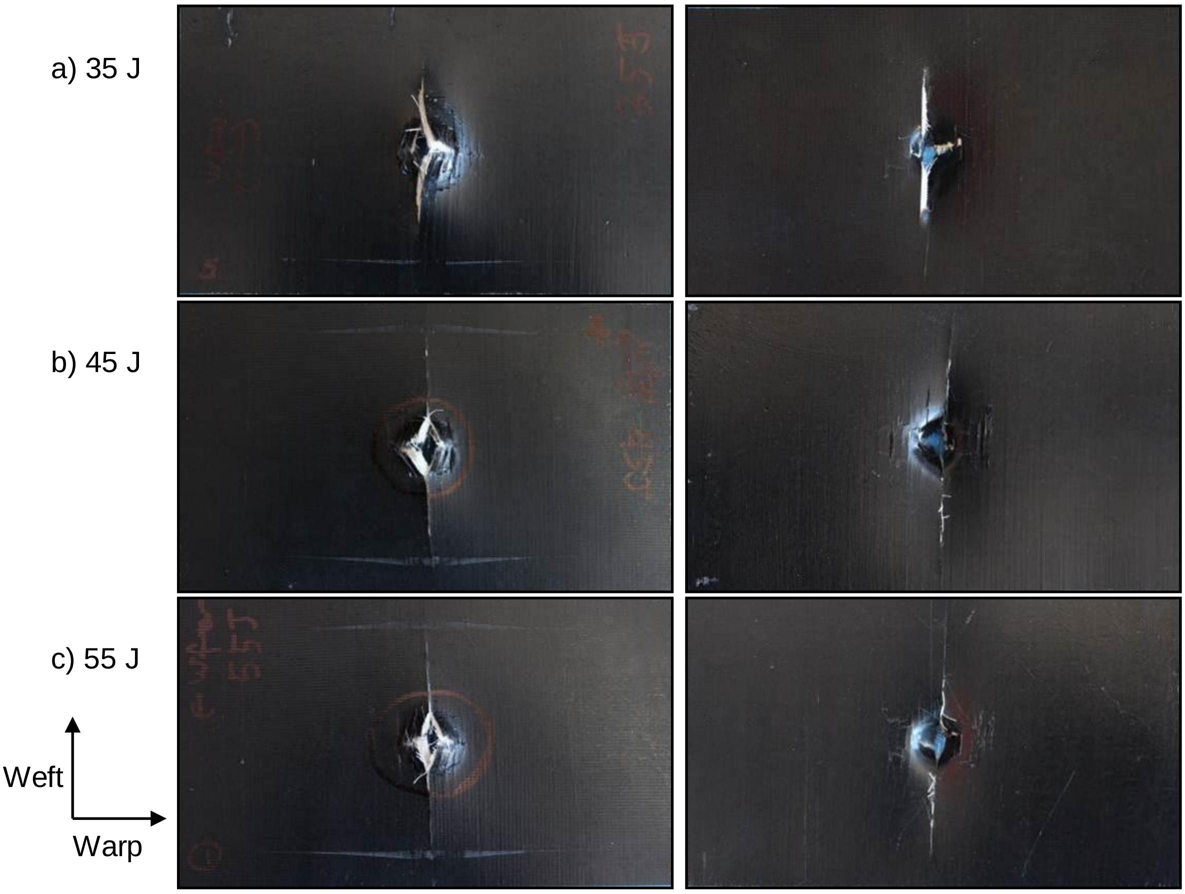

Figure 7. Photos of damage patterns (front and back view) in the hybrid composites impacted at applied energies and tested using the toggle clamps different

Hybridisation of high performance fibres has been reported to be an efficient way to improve the impact performance of composites. According to Santulli et al. [20], a hybrid laminate had much more impact resistance (up to four times for the same laminate thickness) when impacted on the glass side. It was thus suggested that the sandwich configurations with glass fibre in the skin and natural fibre in the core can be considered as the most suitable configuration for high impact resistance. They identified the following factors for development of natural fibre/glass hybrid bio-composites: larger fibre volume fraction, improved effectiveness of the interface in dissipating impact damage, and modification of the configuration to improve impact properties. This phenomenon occurred because the interlaced yarns resulted in an uneven and crimped surface of the woven fabric, which restrained of the growth of delamination caused by mismatching of the bending stiffness. The delamination propagated along the glass fibre direction. According to Acha et al. [21], the radial cracking mechanism is less effective in terms of toughness (at least when the cracks are isolated), however, in this study, the toughness of the bamboo fabric was higher than that of the glass fibres. This may increase the energy absorbed during impact. Another reason which contributed to the higher energy absorption was the deformation mechanism such as fibre pull-out and debonding, which influenced the damage behaviour and led to higher energy absorbed.

4. Conclusion

The study was undertaken to evaluate the effect of hybridisation on impact resistance of the composites. The applied energy of the impact was then increased until penetration was achieved at 55 J for the BPP composite. It can be seen that the peak load and energy absorbed increase with the increase in the applied impact energy. The perforation impact energy was at 55 J for the BPP composite, compared to that of neat PP, at 20 J. For the BGPP hybrid composites, they were not penetrated with the applied energy of 25 J, however, were penetrated at the applied energy of 35 J. The crack damage in the BPP composites was also reduced with the presence of fabric reinforcement. The damage was greater for the BPP composites, indicating the better damage resistance capability of the hybrid composites. The hybrid composites exhibit a greater peak load resistance than the BPP composites. The hybrid composites exhibit a greater peak load resistance than the BPP composites. This evidence suggests that the possibility that hybridisation can provides the potential of achieving a desired combination of properties. This research will serve as a base for future studies and makes several noteworthy contributions to the usage of bamboo fabric composites as alternative natural reinforcement and a more cost-effective usage of synthetic fibres can be produced by replacing the partially with the bamboo fabric.

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