

Low-velocity Impact Performance of Glass Fiber, Kenaf Fiber, and Hybrid Glass/Kenaf Fiber Reinforced Epoxy Composite Laminates

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The goal to decrease global dependency on petroleum-based materials has created a demand for bio-based composites. Composites that are reinforced with natural fibers often display reduced strength compared with those using synthetic reinforcement, and hybridizing both types of reinforcement within a common matrix system offers a possibly useful compromise. This research investigated the low-velocity impact performance of glass, kenaf, and hybrid glass/kenaf reinforced epoxy composite plates. The aim of the study was to determine the low-velocity impact behavior of biocomposite material in assessing its potential for application in the radome structures of aircraft. Natural fibers possess low dielectric constants, which is a primary requirement for radome. However, the structural integrity of the material to impact damage is also a concern. Composite samples were prepared *via* a vacuum infusion method. A drop weight impact test was performed at energy levels of 3 J, 6 J, and 9 J. The Impact tests showed that the impact peak force and displacement increased with the energy level. Hybrid glass/kenaf composites displayed damage modes of circular and biaxial cracking. The former is analogous to the damage observed in glass-reinforced composite, while the latter is unique to woven kenaf reinforced composites. The severity of the damage increased with impact energy and was found to be significant at 3 J.

Keywords: *Low velocity impact; Hybrid; Kenaf fiber; Glass fiber; Composite laminates*

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INTRODUCTION

The implementation of composite materials is widely established in aerospace, automotive, and marine industries. Composite materials can have high specific strength, stiffness properties, and direction of the fiber, and these attributes can be tailored for desired applications and are huge advantages compared with metallic materials.

Current interest in utilizing biodegradable materials for commercial purposes is rising due to such factors as lower density, higher cost efficiency, less harm to the environment than conventional material, and comparable specific strength and stiffness. The utilization of natural resources may reduce the emission of carbon dioxide, as the usage of natural fiber composite can decrease the net contribution to greenhouse gas effects (Mohanty *et al.* 2002; Holbery and Houston 2006; Bogoeva-Gaceva *et al.* 2007; Mohanty *et al.* 2012). Petroleum-based composites also do not decompose and thus pose serious environmental problems. The demand and need for the development of bio-based composites are also partly driven by the depletion of petroleum resources and the pursuit of material sustainability. Policies and regulations are put in place to curb the usage of plastic materials and to promote greener alternatives.

Composite materials, either conventional or biodegradable, are prone to failure as a result of impact loading or damage due to low transverse and interlaminar shear strength. A critical example where this might occur is in aircraft structures, for example: hail impact, runaway debris, tool drop, and maintenance work within the range of 2 to 50 J, which is considered low velocity (Chaves and Birch 2003; Faivre and Morteau 2011). The factors that affect impact resistance or impact damage are due to the different types of fiber, matrix, impactor, stacking sequence, fiber orientation, temperature, volume of fiber/matrix loading, and the geometry of specimen impacted (Cantwell and Morton 1989; Richardson and Wisheart 1996; Reid and Zhou 2000; Gupta and Velmurugany 2002; Abrate 2005; Dhakal *et al.* 2012)

Biocomposites, or natural fibers composites, are defined as two or more dissimilar components used as reinforcement combined with matrix, which can be made from biodegradable materials and produce distinct properties from the individual components. Natural fibers can be categorized as bast fiber, leaf fiber, seed fiber, grass fibers, and straw fibers. Fibers from kenaf (*Hibiscus cannabinus* L.) are classified as bast fibers and are mainly composed of cellulose, hemicellulose, and lignin, with favorable mechanical properties (Ramesh 2016).

The efficiency of reinforcement for the natural fibers composites is influenced by the crystallinity and content of cellulose in the fibers plant. This depends on maturity, location of plant growth, environment of plant location, species of the plant, method of processing for fibers extraction, and size (Liu and Sun 2010; Mohanty *et al.* 2012). D-glucopyranose ($C_6H_{11}O_5$) units joined by β -1,4-glycosidic bonds represent cellulose natural polymer, and it is the main component in lignocellulosic plants. It exists as cellulose fibrils surrounded with lignin matrix that give support to the plant. It is also categorized as hydrophilic due to the presence of three $-OH$ groups per anhydroglucose unit. Many of the $-OH$ groups within the cellulose chain combine intramolecularly with hydrogen bonds inside itself, with other cellulose, or with the air (John and Thomas 2008; Mohanty *et al.* 2012).

Hemicelluloses are comprised of hetero-polysaccharides and sugar units such as glucose, xylose, mannose, and others (John and Thomas 2008; Ren and Sun 2010). Hemicellulose acts as a support matrix for the cellulose fibrils and they are naturally hydrophilic. The fibrils dissolve in alkali and hydrolyzed in acids, with a degree polymerization of 50 to 300; cellulose is insoluble in high alkali and has a higher degree of polymerization. Lignin provides rigidity to the plants and is made up of complex hydrocarbon polymers together with aliphatic and aromatic constituents, which can be categorized in its hydroxyl and methoxyl groups (John and Thomas 2008). Lignin is hydrophobic in nature as compared to cellulose and hemicellulose. The microfibrillar angle is defined as the angle between the microfibrils and fibers axis, and gives influence to the stiffness of fibers (Bogoeva-Gaceva *et al.* 2007; John and Thomas 2008). A low microfibril angle with abundant cellulose content determines high mechanical properties of the natural fibers, the chemical component, and the interior structure of natural fibers as it relates to electrical resistivity, density, ultimate tensile strength, and initial modulus (Bogoeva-Gaceva *et al.* 2007). Naidu *et al.* (2017) presented a comprehensive review of the chemical and physical properties of various natural fiber reinforced composites. The review gives valuable insights into the influence of these properties on the mechanical behaviour of natural fiber reinforced composites.

To utilize biocomposites for a radome structure, its structural integrity after impact needs to be considered. Bledski *et al.* (1999) investigated the effects of fiber

content and voids content towards impact strength of flax and jute reinforced with epoxy foam. They discovered that the impact strength was higher in flax/epoxy than jute/epoxy in higher fiber content. Low void content results in higher fiber content, leading to improved impact strength of the biocomposites. Mazharuddin *et al.* (2015) determined the effect of fiber loading on the impact strength of rose madder and Burmese silk orchid. They found that an increase in the level of the fiber loading increased the impact strength of the biocomposites. Srinivasa and Bharath (2011) investigated the effect of an alkali treatment and fiber loading on the impact strength of areca/epoxy. They concluded that treated fiber and high fiber loading increased the impact strength of the biocomposites. Bax (2008) investigated the impact strength of flax/PLA and Cordenka/PLA together with its tensile properties. At a fiber mass of 25%, Cordenka/PLA had a higher impact strength than flax/PLA due to its adhesion between fiber and matrix. Higher fiber content leads to lower matrix around the fiber therefore less energy was absorbed during the impact. Extensive research has been performed to determine the properties of natural fibers in order to implement them in industrial applications.

To improve its mechanical properties, natural fibers have been combined with synthetic fibers to form hybrid composites. Jawaidd and Khalil (2015) stated that the hybridization between natural and synthetic fibers in a matrix is uncommon, but it can potentially reduce cost and provide positive response towards the environment. Davoodi *et al.* (2010) observed improvement in the mechanical properties of kenaf/glass epoxy composites utilized for car bumper beams. Velmurugan and Manikandan (2005) carried out an investigation on the comparisons between the mechanical properties of palyra fiber waste (pfw) and hybrid of pfw/glass polyester sandwich composites. The results showed an improvement in mechanical properties and impact strength with the increment of glass fiber content in the composites. Jawaidd *et al.* (2011) determined the physical and mechanical properties of hybrid composites of oil palm empty fruit bunch fiber and chopped strand mat glass fiber with polyester. They found that the addition of 30% to 70% glass fiber increased the tensile modulus and impact strength of hybrid composites to levels greater than pure oil palm/polyester composites. Ramesh and Nijanthan (2016) combined continuous kenaf fiber with chopped strand glass fiber with epoxy matrix and evaluated the tensile, impact and flexural properties at 0° and 90° fiber directions. Their work showed 90° having higher tensile properties, whereas the flexural behaviour seemed unaffected by the fiber directions. All studies suggest that the mechanical behaviour of hybrid composites are superior to the pure natural fiber composites, but still lower than their synthetic counterparts. However, the mechanical properties of natural fibers can be improved *via* soaking treatment, processing parameters, or alkali treatment (Mohd Haris *et al.* 2011). In spite of their lower mechanical properties, natural fibers possess a low dielectric constant that reduces signal loss due to reflection during radiowave transmission (Mohd Haris *et al.* 2014). This is a primary requirement for radome material applications. The second important requirement for radome material is the structural integrity of the radome structure. Changes in the geometrical shape of the structure can reduce the transmission efficiency. Among works on low velocity impact of both natural and synthetic fiber reinforced composites were by Hassan *et al.* (2013), Ismail and Hassan (2014), Ismail *et al.* (2018), and Vishwas *et al.* (2017), but none of those considered the combination of kenaf and glass fiber as potential material for aircraft radome application. In this work, a low velocity impact within 3 to 9 J was simulated on composite plate samples with thickness that fulfill the radome's material specification.

EXPERIMENTAL

Materials

Three configurations of reinforced epoxy composites—and fiberglass/epoxy, kenaf/epoxy, and hybrid fiberglass/kenaf—were fabricated with a thickness of 3 mm *via* vacuum infusion. The wall thickness of the radome based on Crone *et al.* (1981), is dictated by a quarter wavelength requirement within the band frequency of 10 GHz. The structural arrangement of the hybrid configuration is composed of 1 layer of woven kenaf fiber bounded by layers of glass fiber, as shown in Fig. 1.



Fig. 1. Structural layout of hybrid glass/kenaf configuration

The chopped strand mat of glass fibers and woven kenaf fiber were made from a commercially available epoxy (EpoXAmite 103, Smooth-On, East Texas, PA, USA), which was combined with a slow hardener to create a longer pot life (curing time) of 55 min. Composites were fabricated by vacuum infusion. Hence, the usage of EpoXAmite helped facilitate resin flow and extend pot life due to its low viscosity, which ensured that the resin was distributed uniformly around the fibers.

Drop Weight Impact Test

The drop weight impact test was used to examine low velocity impact according to ASTM D7136 (2012), using an IMATEK IM10T-15HV instrument (Imatek, Gloucester, UK) to collect displacement and time data. Alternatively, force data was calculated based on height and mass of the impactor. Figure 2 shows the hemispherical tup (falling mass) with a 16 mm diameter.



Fig. 2. Instrumented Drop Weight Impact tester with tup

The dimensions of the impacted specimens were 100 x 150 mm. The drop height was adjusted according to Eq. 1,

$$U = mgh \quad (1)$$

where U is the potential energy, m is the mass (g), g is the acceleration due to gravity (m/s), and h is the drop height (m). For each energy level, the experiment was repeated three times.

RESULTS AND DISCUSSION

Force-time Response

The typical force time response described the impacted force variation against the duration of impact (Fig. 3).

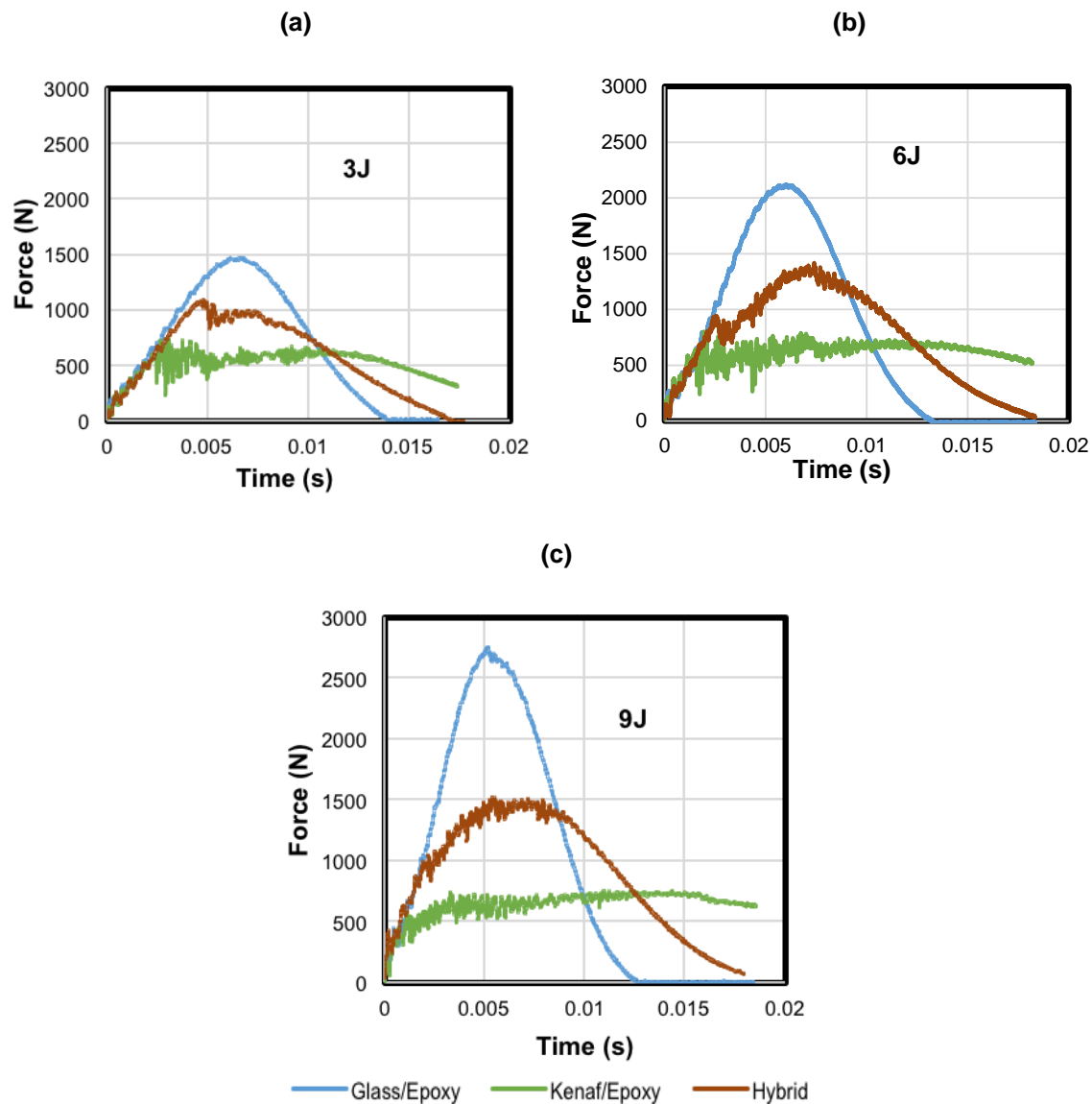


Fig. 3. Force against time for a) 3 J, b) 6 J, and c) 9 J

The glass/epoxy composites formed an almost quadratic curve at all energy levels for both loading and unloading conditions. The force-time curves remained smooth and symmetrical in shape between the fracture initiation region and the fracture propagation region, which indicates that the damage is undersized (Hosur *et al.* 2005; Sutherland and Soares 2005a; Cantwell 2007).

The fracture initiation region was indicated prior to the peak load, and the fracture propagation region was indicated beyond the peak load. The loading curve increased proportionately for the kenaf/epoxy composites until a sawtooth like curve was formed at peak force before unloading took place. The sawtooth curve represented oscillatory behaviour of the contact force, which revealed vibrational motions between the impactor and the impacted surface. The change of the curved slope for the kenaf/epoxy and hybrid composites beyond the first peak force dropped due to the reduction of material stiffness, in reference to the second region of the force-time curve. The first load drop in the force time curve refers to Hertzian failure, indicating first material damage (Belingardi and Vadori 2002; Sutherland and Soares 2005a; Evci and Gülgeç 2012). The curve generated by the hybrid composites appeared as a combination of the curves produced by the glass/epoxy and kenaf/epoxy composites. The loading part increased linearly from the initial point until the first drop of impact force. A sawtooth like curve was observed with increased loading and transitioned to a smooth curve beyond the unloading part. The first drop in force showed the first internal damage initiation, which is the onset of delamination between fiber and matrix and usually does not affect the load carrying ability of the laminate. According to Agarwal *et al.* (2018), the load-time response produces two fracture initiation regions. The first region refers to the range between the initial point and the peak load; meanwhile the second portion refers to the fracture propagation region. In the first region, the material behaves elastically with minor failures such as microbuckling. The second region however shows major failure relating to interlaminar shear strength. Thus, severe damage occurred to the kenaf/epoxy samples compared to the glass/epoxy and hybrid composites samples.

The increment in energy level increased the loading rate and significantly increased the peak force in proportion to the energy level. Higher peak loads indicated a higher load carrying ability for the laminate. The trend of force against time for the kenaf/epoxy sample did not intersect with the x-axis point. With a higher impact energy on the kenaf/epoxy composites, a higher peak load was generated. The decreased stiffness of the kenaf/epoxy sample allowed it to absorb higher levels of impact energy than the glass/epoxy sample, which exhibited low peak force. When comparing the force time response of all three configurations, it was obvious that the glass/epoxy laminate had the highest peak force, followed by the hybrid and the kenaf/epoxy laminates for all energy levels. Except for the glass/epoxy sample, the configurations showed failure initiation and damage progression.

Figure 4 presents the average peak force at each impact energy for the glass/epoxy, kenaf/epoxy, and hybrid composites. There was an increment of peak force and impact energy increased for the glass/epoxy at about 48.2%, and for the hybrid composites at about 15.8% from 3 to 6 J. However, there was a slight decrease in impact energy for the kenaf/epoxy of about 0.823%. When impact energy increased from 6 to 9 J, the peak force increased by 26.8% for glass/epoxy, 12.1% for kenaf/epoxy, and 11.50% for hybrid composites. Standard deviation for glass/epoxy is less than 5% but upon incorporation of kenaf fiber, the standard deviations increased up to 10% for both kenaf/epoxy and hybrid composites, mainly caused by the variability of quality of kenaf

fiber.

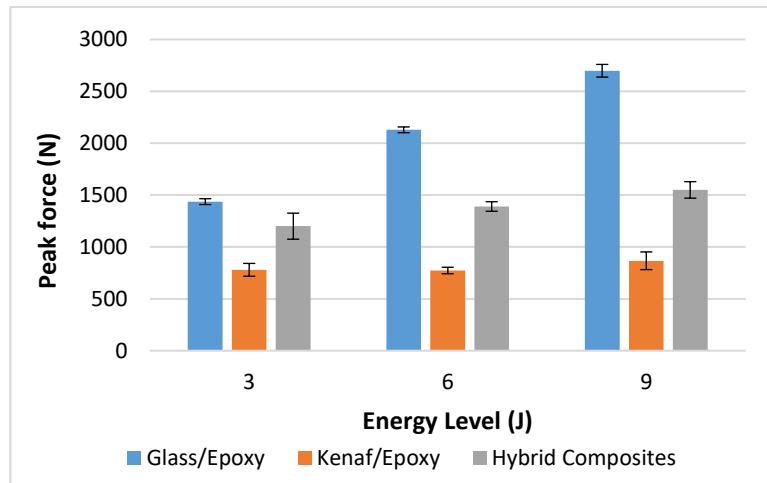


Fig. 4. Peak force against impact energy

The impact damage tolerance is the remaining strength possessed by the laminate after the impact event, and it usually requires a measure of the residual compressive strength. This can be a difficult task, as impact damaged specimens may require additional support for testing due to the change of the fiber curvature. Zhou (1998) proposed a force ratio (threshold impact force corresponding to first fracture initiation of the material to the maximum peak force) to be used as an indicator for the changes in the residual strength of impacted laminates. There was a direct correlation between the residual strength and the force ratio. Therefore, an increasing force ratio increases the residual compressive strength. The glass/epoxy laminates did not portray the onset of failure, indicating that the force ratio was equivalent to 1 and the residual strength was retained. Figure 5 illustrates the ratio of force to impact energy on the kenaf/epoxy and hybrid composites. However, this technique is irrelevant in cases where the fracture initiation will also lead to final failure.

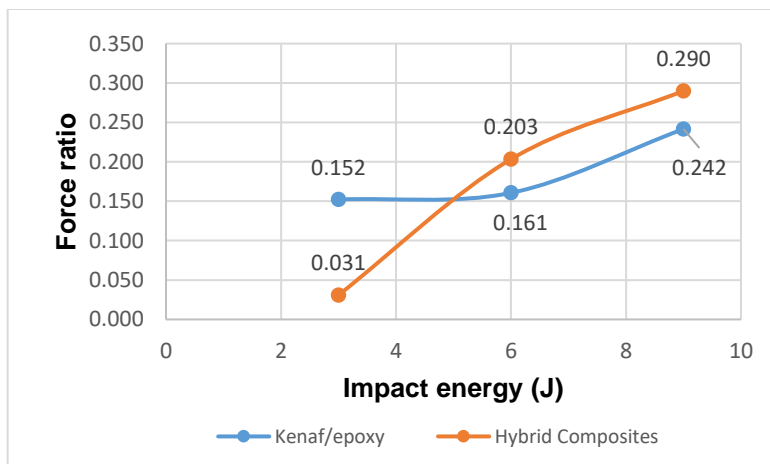


Fig. 5. Force ratio against impact energy

Force-displacement Response

In this section, the comparison of force-displacement curves for all three types of composites laminates at all energy levels are presented in Fig. 6. The glass/epoxy composites generated a closed-loop curve that started by loading the material until it reached a peak force, then the curve returned to the initial point. This indicated the rebounding of the impactor due to deformation energy (area under the curve), which promoted energy transformation. This energy transformation moved from the impactor to the plate, and then back to the rebounding impactor while the area under the closed loop represents impact energy absorbed during the impact (Belingardi and Vadori 2002; Sutherland and Soares 2005b; Evci and Gülgeç 2012).

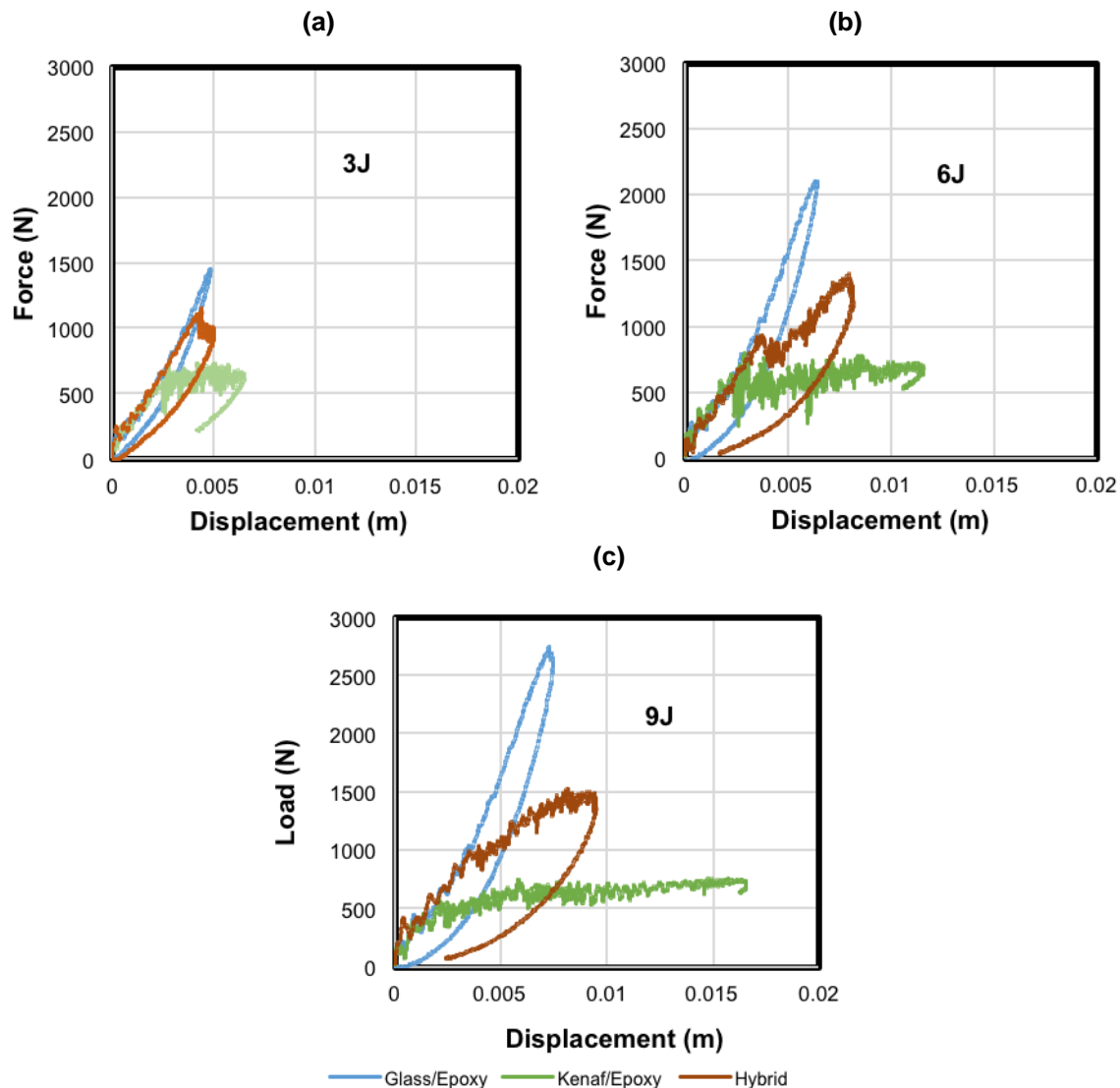


Fig. 6. Force against displacement for a) 3 J, b) 6 J, and c) 9 J

The response of the kenaf/epoxy composites under the force displacement curves possess an increment of force from initial showed a proportional trend until reaching peak force. However, beyond the peak force, the trend of the curves showed an increase in displacement with a slight increase of force until it was terminated at certain

displacement. At a lower impact energy, the curves returned to the initial point; and as the impact energy increased, the curves terminated away from the initial point. Hybrid composites that showed an increase in force and displacement from the initial point until they reached the peak force that indicated the fracture initiation region. At a lower impact energy of 3 J, beyond the peak force the curves showed a sharp drop, and continue to elongate at lower impact force until they reached a second impact force that was lower than the first impact force. The termination of the curves occurred without returning to initial state. Meanwhile at an impact energy of 6 J, after a sharp drop at the first peak force, the curve continued to increase until it reached a second peak force. Then the curves terminate in reduction of displacement. At an impact energy of 9 J, as the first peak force was reached, there was a sharp drop then the curve continued to elongate and increase in impact force. The second peak force terminated the curve by decreasing the displacement. Both kenaf/epoxy and hybrid composites experienced permanent damage (indentation) which was indicated by the sawtooth curve where fiber starts to become damaged (Sutherland and Soares 2005a; Evci and Gülgeç 2012).

Figure 7 describes the maximum displacement achieved at different impact energy levels for the three types of composites materials: glass/epoxy, kenaf/epoxy, and hybrid composites. There were increases in displacement as impact energy increased at all impact energy. The percentage of increment for glass/epoxy, kenaf/epoxy, and hybrid composites from 3 to 6 J were 31.9%, 76.8%, and 51.6%, respectively. The increment in percentage for glass/epoxy, kenaf /epoxy, and hybrid composites from 6 to 9 J were 14.8%, 30.8%, and 27.0%, respectively. Standard deviations for all configurations were less than 5%. This data concluded that the increase of impact energy influenced the displacement of the impacted specimen.

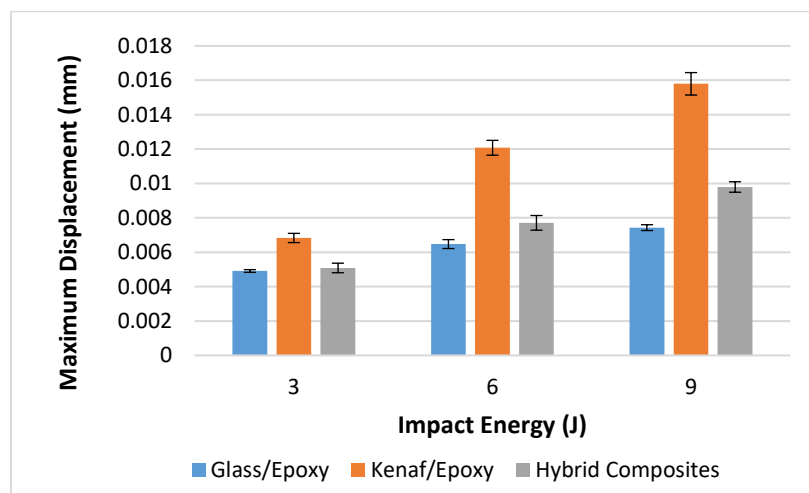


Fig. 7. Maximum displacement against impact energy

Damage Characterization

Damage characterization was carried out under visual inspection of the impacted side (front) and non-impacted side (rear) of the impact test specimens (Fig. 8) and measurement of the size of damage (Table 1).

The main type of damage was in the form of matrix cracking. The development of the cracks on the glass/epoxy followed the fiber type, which was chopped strand mat. The direction of the glass fibers were arranged randomly, which caused the damage to expand

radially from the impact point and create a circular shaped damage. Different types of fiber arrangement produced different damage propagation, especially for woven fiber which can be observed in the kenaf/epoxy composites. For kenaf/epoxy, the cracking occurred along the fiber directions whereas for the hybrid, a combination of radial and directional cracking was observed. One way to quantify the extent of damage is by measuring the size of the visible damage. Therefore, the size of damage is evaluated either by the damage area for circular crack or by the measurement of the crack length along the major (horizontal) and minor (vertical) axes and these results are tabulated in Table 1. Referring to table 1, the circular damage area of glass/epoxy laminate was measured and found to increase by 27% from 3 to 6 J, an increment of 73.6% from 6 to 9 J, and an increment of 120.4% from 3 to 9 J of impact energy. The damaged area was significantly affected by the increase of impact energy and had more than double the size from 3 to 9 J of impact energy.

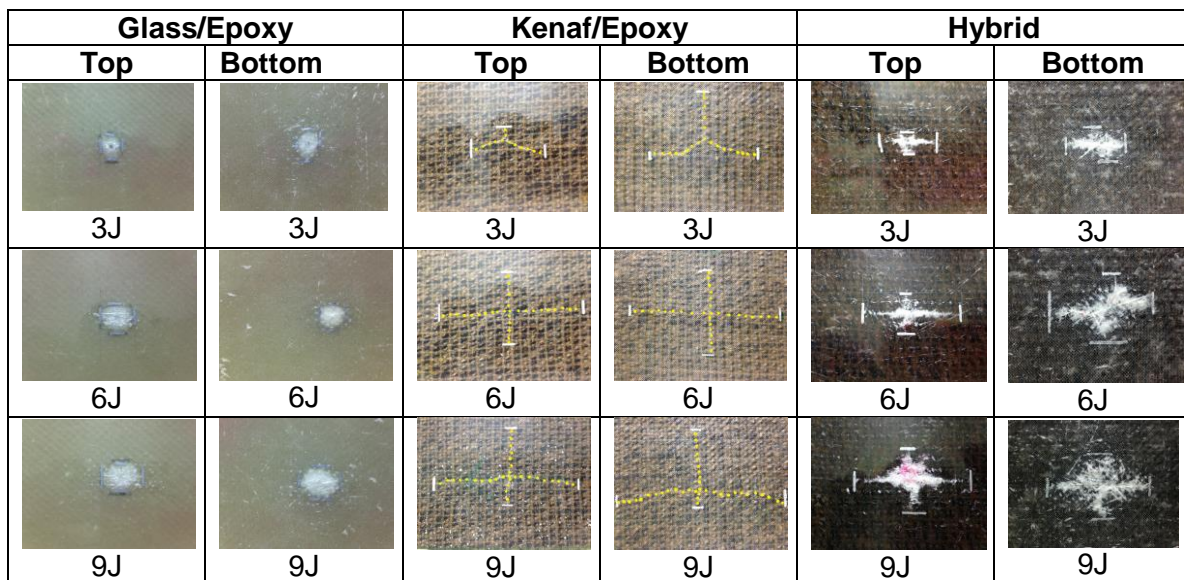


Fig. 8. Visual inspection of impacted surface at 3, 6, and 9 J

Table 1. Analysis of Damage

| Impact Energy | Glass/Epoxy | | Kenaf/Epoxy | | Hybrid | |
|---------------|-----------------------|--------------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| | Radius of Damage (mm) | Damage Area (mm ²) | Major Crack Length (mm) | Minor Crack Length (mm) | Major Crack Length (mm) | Minor Crack Length (mm) |
| 3 J | 10.79 | 365.76 | 47.72 | 4.34 | 25.57 | 11.40 |
| 6 J | 12.16 | 464.53 | 82.58 | 45.51 | 45.39 | 26.05 |
| 9 J | 16.02 | 806.26 | 100.61 | 56.92 | 52.92 | 32.80 |

The kenaf/epoxy damage propagation as seen in Fig. 8 showed crack propagation according to the direction of the warp and weft of the fiber. According to Hosur *et al.* (2005), the crack of the adjacent ply can only happen if the fiber tow of the first ply completely fractures, and the fracture of the adjacent ply will be terminated unless sufficient energy has been exerted. This behavior is beneficial in enhancing the applications of woven fiber in structures on resisting impact. An analysis of the crack length (Table 1) showed that the crack length had more than double in the major axis and

increased 14 times in the minor axis when the impact energy increased from 3 to 9 J. Percentage-wise, the length of the crack from 3 J to 6 J was about 76.8% for the major axis, and higher than 100% for the minor axis. The percentage of the length of the crack from 6 J to 9 J was about 21.8% for the major axis, and 25.1% for the minor axis. The percentage of the length of the crack from 3 J to 9 J for the major axis was doubled, and the percentage of the length of the crack for the minor axis was higher than major axis due to low fiber strength in the transverse direction, as compared to longitudinal direction. An increase in energy level largely influenced the extent of cracks. Although there was no perforation, the observation of the damaged samples showed that a significant warping (depth) occurred due to the impacted force. At a lower impact energy of 3 J, the damage was significant. At an impact energy of 6 and 9 J, the damage was dominantly caused by fiber breakage which created indentations in the laminates.

A similar observation was noted on the hybrid composites. The increment of impact energy affected the length of crack of hybrid composites specimens. The percentage of increment on the length of the crack propagation from 3 J to 6 J was about 77.5% for the major axis and about double the increment based on the initial value. The percentage of increment on the length of the crack propagation from 6 J to 9 J was 16.6% for the major axis and 25.9% for the minor axis. The damage formed on this type of fiber which was a combination of non-woven and woven fiber can be observed in Fig. 8. The damage on the glass/epoxy follows the direction of the fiber tow of the kenaf/epoxy specimens, since the kenaf/epoxy is in the middle layer, in between the glass/epoxy. The non-impacted face showed more severe damage than the impacted face due to the effect of fiber layups. Although the kenaf /epoxy utilized woven fiber and higher mechanical properties than the glass/epoxy, the impact properties exhibited by the glass/epoxy were better than kenaf/epoxy. In this instance, no warpage was observed. In terms of crack length, it was significantly reduced as compared to the kenaf/epoxy laminate.

At a low energy of 3 J, the significant damage of matrix cracking was seen. At higher impact energies of 6 J and 9 J, the fibers started to break and caused indentation to occur. Therefore, significant damage was also found under hybrid composites laminates at the lowest impact energy, which was 3 J.

CONCLUSIONS

1. Experimental low velocity impact was investigated for glass/epoxy, kenaf/epoxy, and hybrid glass/kenaf/epoxy 3-mm laminated plates, with impact energy ranging from 3 J to 9 J.
2. Glass/epoxy showed highest peak load with the least displacement, while a kenaf/epoxy sample displayed the opposite response.
3. Force-displacement response showed the glass/epoxy sample as having a closed-loop curve, indicating full rebounding, while the other two displayed partial perforation.
4. The main mode of damage in all laminate types was matrix cracking. However, in kenaf/epoxy and hybrid composites, woven kenaf fibers acted as a stopping mechanism to the propagation of the matrix cracking and limited the propagation along the warp and weft direction as opposed to a radial crack propagation.
5. Kenaf/epoxy composite displayed lower resistance to impact damage. Hence,

hybridizing with glass/epoxy can enhance its load-carrying capacity under impact loading. However, as damage was relatively significant even at 3 J, it is recommended that the thickness of the laminate to be increased within the allowable specification and/or to replace the CSM glass fiber with woven glass fiber that may provide better impact resistance.

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