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Mechanical properties of bamboo reinforced epoxy sandwich structure composites

S.A.H. Roslan[1], M.Z. Hassan[2*], Z.A. Rasid[1], S.A. Zaki[1], Y. Daud[2], S. Aziz[2], S. Sarip[2] and Z. Ismail[3]

[1]Malaysia-Japan International Institute of Technology,
Universiti Teknologi Malaysia, 54100 Kuala Lumpur, Malaysia
[2]UTM Razak School of Engineering and Advanced Technology,
Universiti Teknologi Malaysia, 54100 Kuala Lumpur, Malaysia
[3]Universiti Sains Islam Malaysia Level 15, Tower B, Persiaran MPAJ,
Jalan Pandan Utama, 55100, Kuala Lumpur, MALAYSIA
*Email: mzaki.kl@utm.my
Phone: +60149684631; Fax: +60321805380

ABSTRACT

In the composite industry, natural fibres have great potential to replace synthetic fibres like carbon and glass, due to their low cost and environmentally friendly materials. Bamboo is emerging as a versatile reinforcing fibre candidate because this woody plant has a number of advantages, such as being naturally strong, biodegradable and abundantly available. In this study, a compression test with a crosshead displacement rate of 1 mm/min was conducted on square and triangular honeycomb core structures based on bamboo-epoxy composites so as to study their specific energy absorption. Both square and triangular honeycomb structures were manufactured by the slotting technique. Initially, a tensile test with the same crosshead displacement rate was conducted to study the tensile strength of unidirectional bamboo-epoxy composites with 0°, 45° and 90° fibre orientations. Bamboo-epoxy composite laminates were fabricated by applying a hand lay-up technique. The experimental data showed that the unidirectional bamboo-epoxy composite with 0° orientation offered the highest tensile strength. This indicates that the bamboo is stronger when parallel to the tensile axis. Meanwhile, the triangular honeycomb bamboo-epoxy structure offered about 10% more energy absorption than the square honeycomb structure, which indicates that the smaller cell size of honeycomb is able to absorb more energy than the bigger one.

Keywords: Bamboo; epoxy; honeycomb structure; mechanical testing.

INTRODUCTION

The introduction of natural fibres such as kenaf, jute, hemp, flax, oil palm and bamboo into fibre reinforced composites has been well accepted by many industries nowadays. The implementation of these natural fibres in such composites is beginning to increase rapidly, especially in the automotive, building construction and marine industries [1-4]. Hence, a number of studies on natural fibre reinforced composites have been accomplished in order to study their mechanical properties and eventually apply them in engineering applications, replacing synthetic fibres [5-7]. This is because most natural fibres require less energy and lower handling costs, besides possessing excellent strength and stiffness as well as desirable environmental values like being renewable, biodegradable and sustainable compared to glass and carbon fibres [8-11]. Bamboo, which is one of the natural fibres, is starting to attract much interest as a potential reinforcing fibre due to its excellent natural strength. Phong et al. [12] mentioned that bamboo tends to be stronger in the longitudinal direction because of the strong fibre bundles that perforate its body from the bottom to the top, even though the pulp is less than 2 mm. They also mentioned that if the string-like bamboo fibre bundles can be extracted, they can be used as a replacement for jute and kenaf fibres. Besides that, the facts that bamboo is able to grow rapidly in diverse climates and does not require replanting as much as other natural fibres make it a versatile material, in a good position to replace synthetic fibres [3, 13]. Bamboo has mainly been exploited fully by six Asian countries: China, India, Indonesia, Philippines, Myanmar and Vietnam [14]. China is in the lead, as the development of more technological innovations based on bamboo products is being encouraged there. Thus, China is becoming the main bamboo consumer among these countries. By contrast, Malaysia is still lagging behind these countries in terms of developing bamboo in engineering materials, especially in fibre reinforced composite, even though this woody plant grows extensively here.

Studies on the mechanical strength of bamboo fibre reinforced epoxy resin have been widely explored by researchers for several years and still continue today. One of the factors that influences the mechanical properties of natural fibre reinforced composite, besides the type of fibre, is the fibre orientation[15, 16]. Malaiah et al. [17] investigated the effect of fibre orientation between jute and bamboo reinforced epoxy composites. Both the jute and bamboo fibres used were plain woven mat 2-D fabric type with 0°/90° and 45°/45° orientations. From the tensile test conducted, both of the composites with 0°/90° fibre orientation outperformed the 45°/45° fibre orientation. However, the tensile strength of jute/epoxy composite in the 0°/90° orientation was much higher than bamboo-epoxy composite with the same orientation due to the compatibility factor. On the other hand, Chandrasekhar et al. [18] conducted tensile tests to investigate the effect of unidirectional bamboo/epoxy. The fibre orientations tested were 30°, 45°, 60°, and 90°. The maximum strength was at 30° fibre orientation as this degree inclines more to 0°, which is parallel to the tensile axis. Kumar [19] conducted some mechanical studies on randomly oriented chemically treated bamboo reinforced with epoxy. From the tensile, flexure and hardness tests done, he concluded that all these mechanical properties are highest at the fibre content of 25%.

Composite sandwich structures offer a high buckling strength and specific bending stiffness to weight ratio under applied load. The light weight of the sandwich structure makes it desirable in high-tech applications, such as aircraft and satellites. Mallaiah et al. [20] conducted fatigue and flexural experimental studies on PU foam-cored sandwich structures with jute, bamboo and hybrid bamboo/glass fibres as reinforcement. They found that the bamboo/glass hybrid structure outperformed the other structures in terms of bending and shear strengths. The energy absorption properties were affected not only by the type of honeycomb material and the thickness of the cell wall but also by the topology of the honeycomb cell. Dharmasena et al. [21] studied the compressive response of five core designs made up of steel sheet and demonstrated that the square honeycomb has a higher resistance strength than the triangular structure and other core designs. Earlier, Yamashita et al. [22] conducted quasi-static compression tests on aluminium alloy honeycomb in order to investigate the effect of the cell shape and the thickness of the wall on the crush behaviour. Based on the numerical result, the buckling failure mainly occurred during cyclic loading and the maximum crush strength was attained with decrease of the cell wall angles but increasing cell wall thickness. The same point was made by Hazizan et al. [23], who stated that the partitioning of energy is strongly influenced by the configuration of the sandwich structure and that the materials they used during the experiment were not rate-dependent.

In this experimental study, a compression test with a crosshead rate of 1 mm/min was conducted on square and triangular honeycomb bamboo-epoxy core structures to determine their specific energy absorption and make a comparison between them. The honeycomb core structures were fabricated through a simple slotting technique. Prior to that, a tensile test with the same crosshead rate was conducted to identify the effect of fibre orientation on the tensile strength of unidirectional bamboo-epoxy composites. The fibre orientations tested were 0°, 45° and 90°. The samples for the tensile test were fabricated using the hand lay-up technique and tested on a Shimadzu Universal Testing Machine.

EXPERIMENTAL SETUP

Specimen Preparation for Tensile Test

First, a bundle of cylinder bamboo sticks with a diameter of 3 mm and length of 250 mm were arranged in order on a sheet of metal. The bamboo material tested was taken from 5 m above the bamboo trunk, which was of the variety Gigantochloa apus and aged about 3–4 years. The polymeric matrix, which is epoxy resin, was poured on the aligned bamboo sticks. The hand lay-up technique was then applied to ensure that the epoxy filled every corner of the arranged bamboo sticks. A sheet of metal of the same size was put on top of the laminate and pressure was applied. Then, the specimen was left overnight for the curing process. Prior to the test, fibre directions of 0°, 45° and 90° were cut using a laser cutter according to ASTM D638 [24]. A constant rectangular specimen with dimensions 150 mm x 25 mm was sectioned as shown in Figure 1.

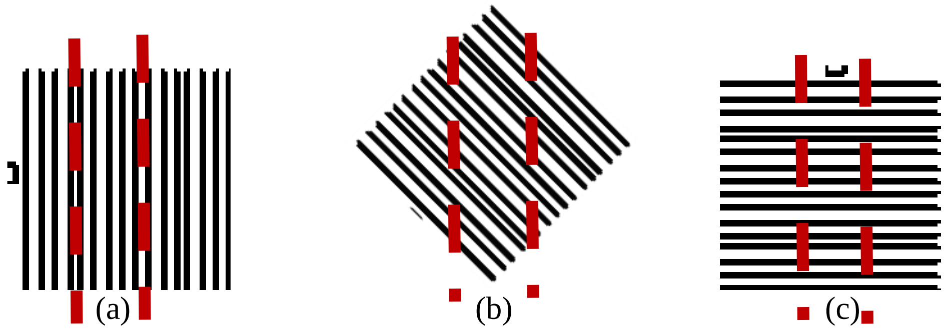


Figure 1. Illustration of how the unidirectional bamboo-epoxy was sectioned according to ASTM D638 with determined fibre directions (a) 0°, (b) 45° and (c) 90°.

Square and Triangular Honeycomb Structure Fabrication

Both the square and triangular honeycomb structures were fabricated via a simple slotting technique [21, 25, 26]. Here, the plates of bamboo-epoxy composites manufactured previously were cut into 70 mm x 20 mm strips using a laser cutter. Each strip was machined with 10 mm deep slots placed 20 mm apart. Then, the strips were slotted together to form square and triangular honeycomb structures as shown in Figure 2.

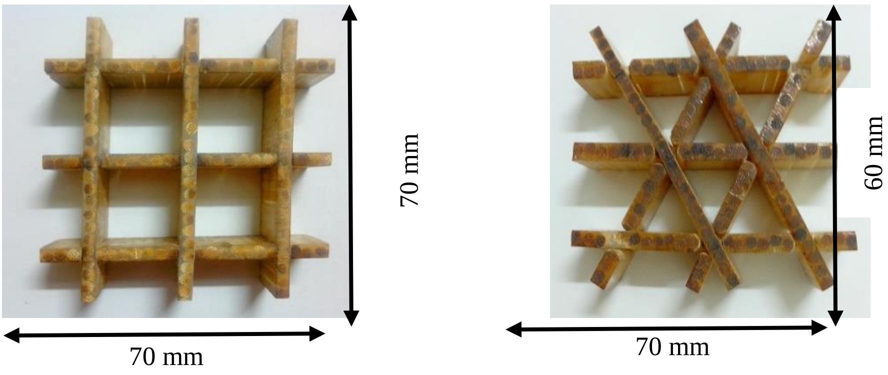


Figure 2. Photos of (a) square and (b) triangular honeycomb core structures.

The sizes of the square and triangular cores are different due to the angles formed to produce the core shapes required, where the angle of the triangular core is smaller than the square core. Lastly, the skins were bonded to the core by using epoxy resin adhesive.

Experimental Procedure

Both tensile and compression tests were carried out using a Shimadzu universal testing machine with 50 kN of load cell at a crosshead speed of 1 mm/min. In the tensile test, the test is stopped when the specimen breaks off. Then, stress–strain curves were plotted for each fibre orientation to determine its tensile properties. In the compression test, the test followed ASTM C365 [27]. It was stopped when the specimen was totally crushed and the force suddenly started to rise. The energy absorption can be determined by calculating the area under the force–displacement curve.

Figure 3. Photos of (a) laser cutting process to produce bamboo-epoxy composite strip (b) tensile test undertaken at Shimadzu Universal Testing Machine.

RESULTS AND DISCUSSION

The Effect of Fibre Orientation

The mechanical properties obtained from the tensile test of bamboo-epoxy composites with 0°, 45° and 90° orientations are tabulated in Table 1. The 0° fibre orientation of bamboo-epoxy composites has the highest tensile strength, which is 138.88 MPa, followed by 45°, which is about 80% lower than 0°. The 90° fibre orientation has the lowest tensile strength of all. The same pattern can be seen for the elongation at break, ε, and elastic modulus, E, for each fibre orientation. Figure 4 compares the stress–strain curves for the 0°, 45° and 90° fibre orientations of bamboo-epoxy composites. The curves are constructed based on the force–displacement data obtained from the tensile test conducted. Clearly, the stress–strain curve for the 0° fibre orientation outperformed the 45° and 90° fibre orientations. This is because the fibres in the 0° orientation are parallel to the tensile load applied and the resistance of the bamboo fibre towards the pull force at this orientation is the greatest. In contrast, the bamboo fibres in the 45° and 90° orientations incline away from the acting tensile load axis. Thus, the resistance is less.

Table 1. The mechanical properties of bamboo-epoxy composites with different fibre orientations.

Angle of fibre orientation (°)	Tensile strength, σ (MPa)	Elongation at break, ε (%)	Elastic modulus, E (GPa)
0	138.88	2.70	4.96
45	8.42	0.62	1.37
90	5.89	0.54	1.09

The failure of aligned fibre composites is often related to fibre fracture since the geometry of loading results in an equal-strain condition [28]. However, increasing the orientation of the fibre in composites away from the acting tensile load axis can cause matrix tensile failure. When the fibre in composites is at θ = 90°, the condition is said to be in equal stress. Here, the fibre does carry the load, but not as effectively as in the equal-strain condition. Matrix or transverse failure can be the main cause of the fracture mode for θ < 90° [28].

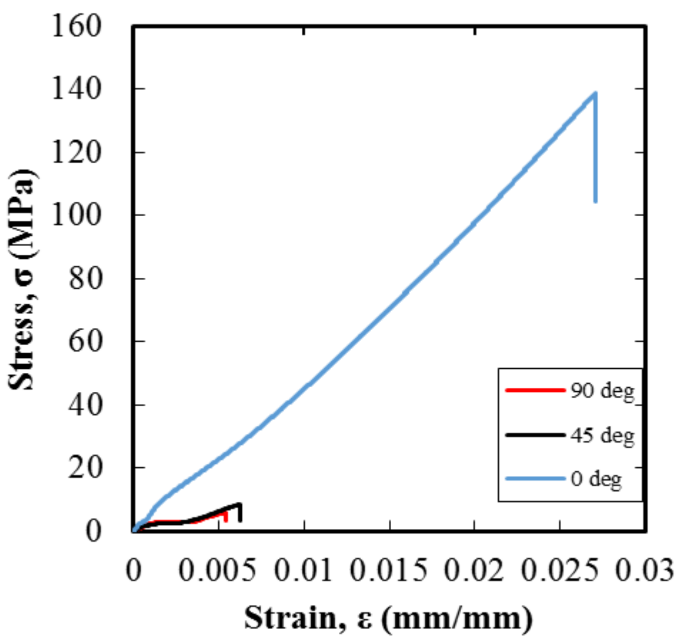
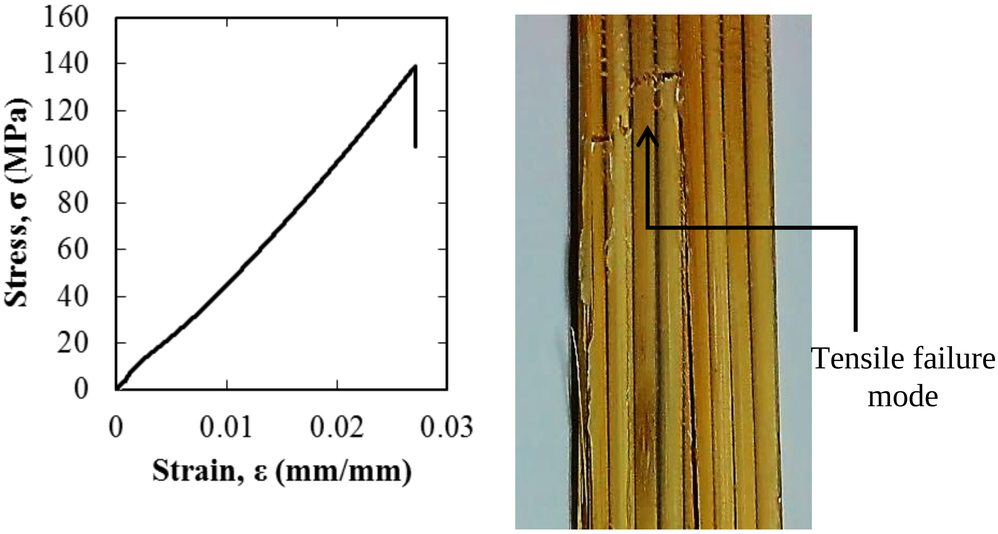


Figure 4. The stress–strain curves of tensile test for 0°, 45° and 90° orientations.

Figure 5(a) shows the stress–strain curve of the 0° fibre orientation. The curve shows that the ultimate strength and the breaking strength are similar due to the brittle properties of composites [29]. The tensile failure mode can be seen in Figure 5(b).



(a) (b)

Figure 5. (a) Typical stress–strain curve of 0° fibre orientation, (b) the tensile failure mode of bamboo-epoxy composites.

The Compressive Properties of Honeycomb Structures

The load–displacement curves for the square and triangular core honeycomb structures are shown in Figure 6. In stage I, both the square and triangular core honeycomb structures initially demonstrated an elastic property until they reached the peak load at stage II. At this point, the peak load for the triangular bamboo-epoxy core honeycomb structure is slightly higher than the square bamboo-epoxy core honeycomb structure. This could be explained by the differences in relative density of the square and triangular cores [30]. The relative density of each core is measured by dividing the density of the honeycomb structure by the density of the bamboo fibre. From the calculation, the relative density of the triangular core honeycomb is 10% higher than the relative density of the square core honeycomb. Thus, it can be concluded that the higher relative density of a honeycomb structure will require a higher compressive strength to deform it. Besides that, the cell size of the honeycomb structure influences the strength of the cores. In the composites industry, the price of larger cell size honeycomb cores is higher than smaller cells [31]. However, larger cells are always layered with thicker skins, which causes telegraphing, a 'dimple' or the condition where the outer surface of the sandwich is sucked in. Therefore, the small cell size cores give an improved surface appearance and provide a greater bonding area [31]. The triangular core has a smaller cell size than the square core. This could be the reason why the maximum compressive load required by the triangular core honeycomb structure is much larger than for the square core. After yielding, the force loading decreased slightly (stage III). Here, both the honeycomb structures started to buckle as continuous compression was applied. The compression force decreases by almost half of the maximum load for both honeycomb structures. Then, they reached the steady state (stage IV). After that, the compressive load starts to increase, until the core is completely crushed and there is no longer any resistance to load (stage V).

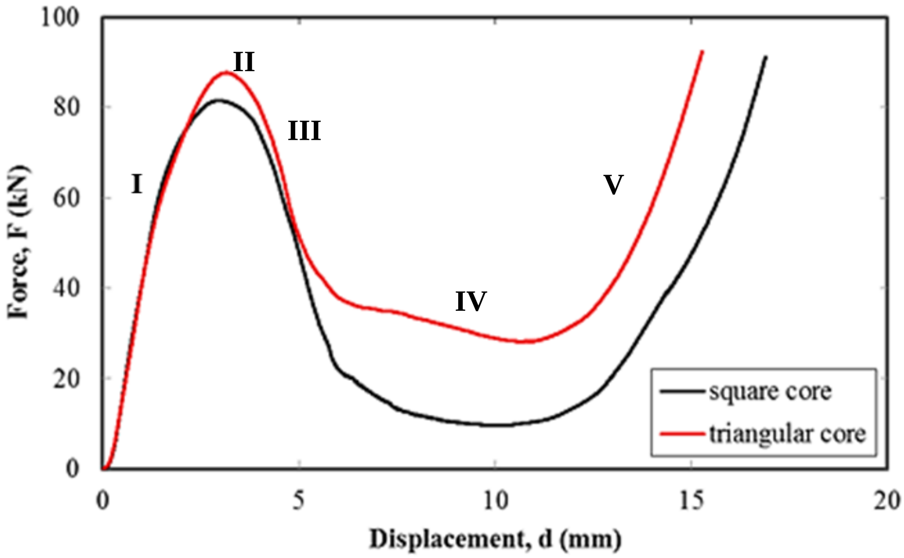


Figure 6. Typical force–displacement curves of square and triangular core honeycomb structures.

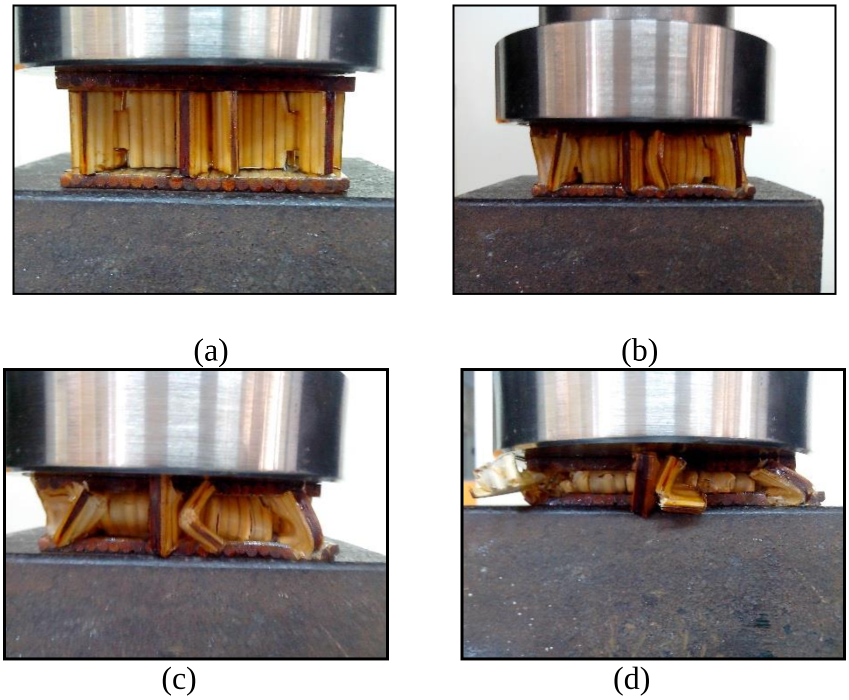
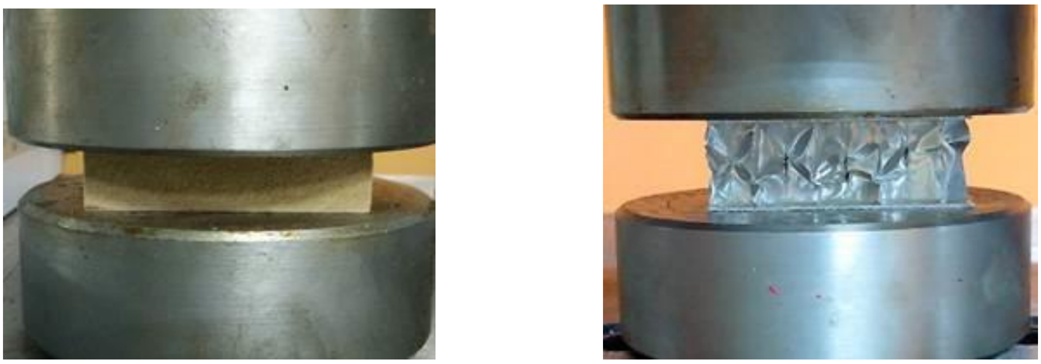


Figure 7. Photos of failure sequences exhibited by square and triangular cores during compressive testing: (a) early stage of compressive test where the specimen was still in a preloading stage; (b) the specimen started to buckle as the compressive load increased; (c) the core started to break; (d) the specimen was completely crushed.

Figure 7 shows the failure mode sequence exhibited by both the triangular and square honeycomb structures. In this work, the compressive test was also performed on other cores of the same specimen size but with different core designs, as depicted in Figure 8. They were a wood-based material, medium density fibreboard (MDF), and an aluminium hexagon honeycomb sandwich structure. Here, the energy-absorbing characteristics were investigated. The specific energy was calculated from the load–displacement curve over the mass of the specimen. Based on this experiment, the thickness of the wall and the angle of the core structure influence the energy absorption, where the highest energy will be obtained with the decrease of the cell wall angles but increase of the cell wall thickness. The thickness of the aluminium core is the least of all, while the triangular bamboo-epoxy core structure has a small angle configuration. Hence, the triangular core gives the highest energy, and the aluminium core gives the lowest energy. This has been proved in studies by previous authors [21-23, 26].



(a) (b)

Figure 8. Photos of (a) medium density fibreboard (MDF) and (b) aluminium sandwich structure subjected to compressive load.

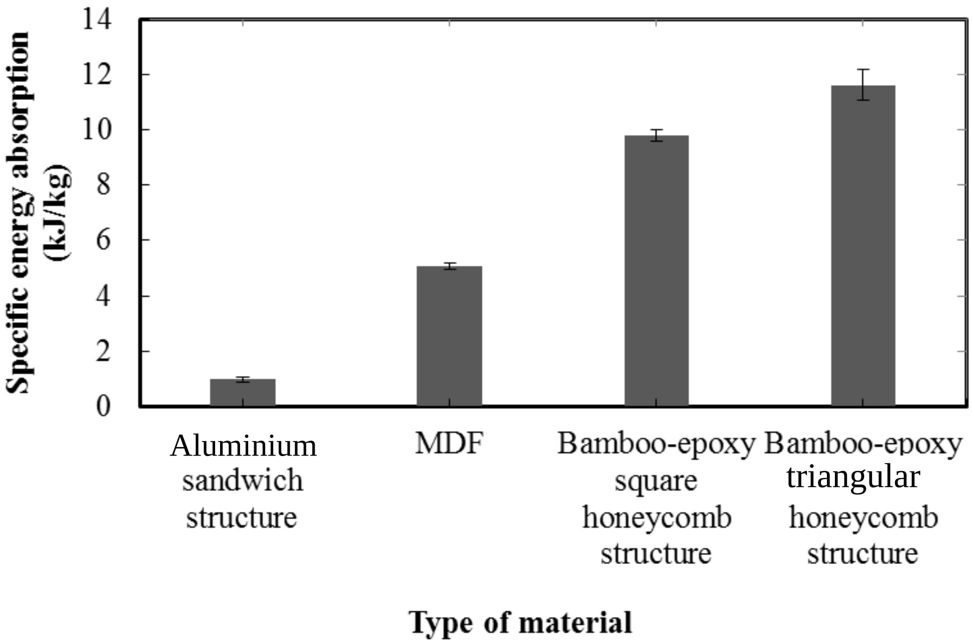


Figure 9. The specific energy absorption of four types of honeycomb structures.

CONCLUSIONS

Both tensile and compression tests were carried out to investigate various configurations of honeycomb sandwich structures. Initially, the unidirectional bamboo-epoxy composites were tested with the tensile test to determine the effect of fibre orientation on the tensile strength. The result showed that the 0° fibre orientation exhibited the highest tensile strength compared to the 45° and 90° orientations. This could be explained by the properties of the fibre reinforced composites, which tend to be stronger when the fibre is parallel to the load applied. On the other hand, compressive tests showed that the triangular core was superior to the square core. Also, a higher energy-absorption capability was found in the triangular core than in the square core. Therefore, the triangular core design can certainly be used in honeycomb applications that require higher strength and stability.

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