Flexural and Impact Behavior of Bamboo-bundle Based Laminated Composites

Haidong Li,[a] Xuejun Xu,[a] Yunxing Zhang,[a] Feifei Zhai,[a,]* Ge Wang,[b,]* Dandan Ma [c]

The objective of this study was to test the effect of four different staking sequences on the mechanical properties and the low viscosity impact behavior of bamboo bundle-based composites. Two different laminate staking structures were used to make the bamboo bundle veneers. The samples were labeled A through D. The density and mechanical properties of the samples, including the modulus of elasticity (MOE), the modulus of rupture (MOR), and the impact bending strength (IBS), were studied under parallel and perpendicular loading to the glue line. Three different impact energies of 50, 95, and 145 J were used to examine the impact response and failure mechanisms of the samples under low-velocity impact. The MOE and MOR values of the type A and type D laminates under both perpendicular and parallel loading to the glue line were found to be insignificant. The IBS values of the type A laminate under perpendicular and parallel loading to the glue line were higher than the values of the other composites. Among the configurations that were investigated in this study, the type D composite exhibited the best impact response and its total energy absorbed was much higher than the other samples.

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Keywords: Bamboo-bundle based composites; Mechanical properties; Stacking sequence; Impact behavior

*Contact information: a: School of Architectural and Artistic Design, Henan Polytechnic University, Jiaozuo, Henan, 454000, P.R. China; b: International Centre For Bamboo And Rattan, 8 FuTong Eastern Avenue, Wangjing Area, Chaoyang District, Beijing 100102, P.R. China; c: Jiyang College of Zhejiang A&F University; *Corresponding author: lkyzff@163.com; Bamboo_Wood@163.com*

INTRODUCTION

Bamboo-based composites have been widely used in residential buildings due to their excellent physical and mechanical properties coupled with the renewable nature of bamboo (Jiang *et al.* 2013; Chen *et al.* 2014; Xiao *et al.* 2014). Various forms of structural bamboo-based composite materials have emerged in the past decades, including plybamboo, bamboo scrimber, glue-laminated bamboo, bamboo laminated lumber, and bamboo-bundle laminated veneer lumber (BLVL) (Li *et al.* 2014). Throughout its service life, a material or structure is subjected to various forces that will reduce its structural integrity over time until failure occurs (Como and Mahmoud *et al.* 2013; Sarasini *et al.* 2014). Impact damage is a serious problem for laminate composite structures, which comprises multiple failure mechanisms such as intralaminar matrix cracking (plasticity), interlaminar delamination, fiber-matrix interface debonding, and fiber fracture (González *et al.* 2011). These failures can be highly significant and may lead to the unexpected collapse of structures. The implications of a disaster such as a structural collapse have led to the growing area of research of low-velocity impact damage of bamboo-based composites, since structural collapse happens at these low velocities.

Bamboo fiber bundles are a new type of material used for manufacturing bamboo-based composites. Bamboo fiber bundles have been successfully commercialized and have seen rapid application throughout China. Advancements in bamboo manufacturing technologies have allowed for the utilization of 90% of bamboo material during processing (Jiang 2007; Li *et al.* 2014). These raw materials are mainly used to prepare bamboo scrimber and BLVL (Yu *et al.* 2014; Deng *et al.* 2015). Bamboo-bundle laminated veneer lumber is an engineered composite made from parallel bamboo fiber bundle veneers. Bamboo fiber bundle veneers are prepared by a process that links fibrillated bamboo bundles together (Zhou *et al.* 2019). A series of bamboo bundle veneer composites has been developed and applied as outdoor wall materials, floor panels, roof sheathing, and other sheathing planks.

Many studies have focused on the effects of parallel and perpendicular loading on the physical and mechanical performance (dimensional stability, tensile, flexure, and impact bending) of glue line bamboo-based composites (Aslan *et al.* 2003; Yu *et al.* 2014; Deng *et al.* 2015; Zhou *et al.* 2019). There have been numerous studies on the low velocity impact responses of composite materials (Dorigato and Pegoretti 2013; Sathishkumar *et al.* 2014; Simeoli *et al.* 2014), but there are only a few references are available on the impact behavior of natural fiber reinforced composites (Zhang *et al.* 2000; Kushwaha and Kumar 2009; Yu *et al.* 2012; Chen *et al.* 2014). A lack of data on bamboo bundle-based composites have prevented its wider implementation, so further research is needed on the use of bamboo bundle-based composites. The objective of this study was to investigate the low-velocity impact behavior of bamboo bundle-based composites by considering the effect of different stacking sequences. The first objective of the study was to design four types of layups for bamboo bundle-based composites and investigate their physical (air-dry density) and mechanical properties (bending and impact bending behavior) under parallel and perpendicular loading to the glue line. The second objective was to compare the impact response (peak impact force and energy absorbed) of the composites from three different impact energy tests.

EXPERIMENTAL

Materials

Cizhu bamboo (*Neosinocalamus affinis*) was used to make the bamboo bundle veneers. The Cizhu bamboo was allowed to grow for three to four years before it was harvested from Changning, Yibin, Sichuan Province, China. The bamboo tubes were first split longitudinally into four pieces of approximately the same size. Thereafter, the bamboo strips were fluffed and rolled into a loosely laminated reticulate sheet using an untwining machine to create net-structured bamboo bundles (Chen *et al.* 2014; Li *et al.* 2014; Zhou *et al.* 2019). Then, a sewing machine was used to connect the bamboo bundles along the width, linking separate bamboo bundles into a uniform one-piece veneer. The untwisting machine and sewing machine are of the authors' own design. The formed bamboo bundle veneer maintained the original fiber arrangement of the bamboo and had a uniform thickness between 4 and 5 mm. The bamboo bundles veneers were air-dried to a moisture content (MC) between 8 and 12%. The poplar (*Populus ussuriensis* Kom.) and Moso bamboo (*Phyllostachys pubescens*), which were used to make the core material for samples C and D (Fig. 2), were supplied by Heqichang Bamboo Co., Ltd. (Fujian, China). The poplar was processed into poplar veneers, and the Moso bamboo was made into Moso bamboo curtains. A sample of the raw materials is shown in Fig.1. The poplar veneers were 2 to 2.5 mm thick and dried to a MC of 8 to 12%. The Moso bamboo curtain had a MC of 8 to 12% and a thickness of 2.2 to 2.5 mm. The phenol formaldehyde (PF) resin was supplied by Beijing Dynea Chemical Industry Co. (Beijing, China). The PF resin had a solids content of 45.59%, a pH of 10.5, and a viscosity of 38 mPa•s.

Fig. 1. The sample of raw materials

Preparation of the Bamboo-bundle Based Composites

In order to obtain a uniform adhesive spread, the PF resin was diluted with water to a solids content of 15%. The bamboo bundle veneer, the wood veneer, and the bamboo curtain went through a resin bath for 7 min and then air-dried to a MC between 8 and 12%. Two different composite layup structures were used to make four different samples of bamboo-bundle based laminated composites (BLC's), as can be seen in Fig. 2. The first layup structure was comprised of five layers in parallel and only used to make sample A. The ply orientation was represented by (0). A five ply, three-layer structure with the third ply in the core of the material was placed perpendicular to the other plies. This structure was used for the second layup, and the orientation of the center layer of the BLC was denoted with (90). The second layup was used to make three samples, a bamboo bundle veneer (sample B), a core of bamboo curtain (sample C), and a core of poplar veneer (sample D). The BLC samples were hot-pressed at a temperature of 150 °C for 15 min, and the hot-press pressure was 3.5 MPa. The dimensions of the finished BLC samples were 2,440 mm × 1,220 mm×12 mm (length × width × thickness). The manufacturing process of the BLC is presented in Fig. 2. Each layup of the BLC was comprised of three samples for a total of 12 BLC samples. Each BLC sample was then analyzed.

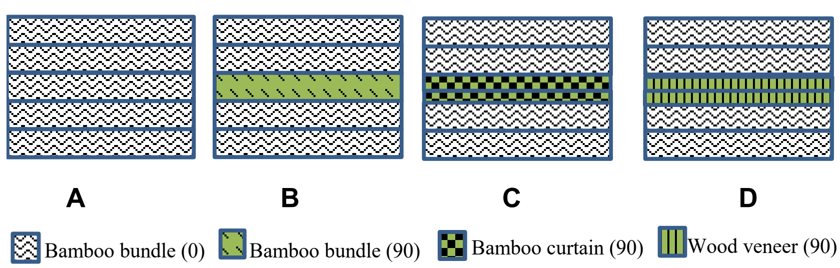

Fig. 2. The schematic illustrations of the bamboo/wood sheet laminate composites

Physical and Mechanical Properties Testing

Four types of BLC structures were tested for their air-dry density and mechanical properties. The BLC mechanical properties that were tested were the modulus of elasticity (MOE), the modulus of rupture (MOR), and the impact bending strength (IBS) under parallel and perpendicular loading to the glue line (Fig. 3). The MOE, MOR, and IBS tests were conducted according to GB/T standards 1936.2 (2009), 1936.1 (2009), and 1940 (2009) and the ASTM standard D143-14 (2014). A minimum of 12 samples for each structural layup of BLC were tested. A total of 288 samples with 300 mm × 20 mm × 12 mm dimensions (length × width × thickness) were prepared for the mechanical testing.

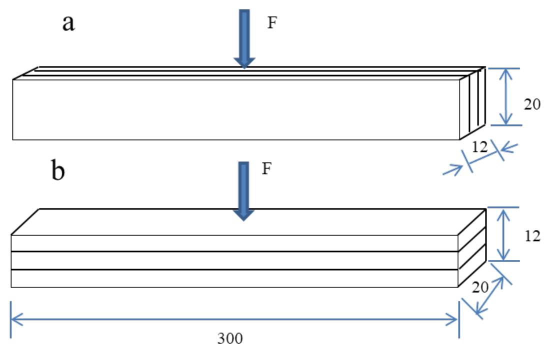

Fig. 3. Schematic of two loading directions (The direction of a is parallel to glue line, b is perpendicular to glue line.)

Five 100 mm × 100 mm × 12 mm replicates of each type of BLC structure were tested for their impact properties. The impact testing was performed using a falling dart impact testing machine (Dynatup 9250HV; Instron, Norwood, MA, USA). The samples were tested at three different drop heights (0.1 m, 0.2 m, and 0.3 m) with an indenter with a hemispherical steel cup insert with a diameter of 12.7 mm and a mass of 48.58 kg. The data from the test were recorded by the dart impact testing machine as the test was performed. The impact test data included the peak impact force, the energy absorbed, the impact time, the impact velocity, and the deformation. The calculation of impact energy formula was detailed in the Chen’s paper (2014).

RESULTS AND DISCUSSION

The Basic Physical and Mechanical Properties of the Bamboo-Bundle Based Composites

The air dry density, the MOE, the MOR, and the IBS values of the four BLC samples were measured, as seen in Table. 1.

The MOE and MOR values of the perpendicular loading tests were higher than the values of the parallel loading tests for all the BLC samples. The IBS testing had an opposite result in that the perpendicular MOE and MOR values were lower than those of the parallel values. Significant variations in the MOR and MOE values were detected during the perpendicular loading to the glue line of the BLC ($p < 0.05$). There was insignificant variation in the loading parallel to the glue line. The data collected from the samples revealed that the MOR and MOE values for loading perpendicular to the glue line went from A > D > C > B when describing the material strength. The layup pattern used to make the BLC sample A was similar to the assembly of laminated veneer lumber, which generally has high MOE and MOR values (Deng *et al.* 2014; 2015). The strong properties of the type A laminate structure allow it to be used for structural elements such as beams, doors, and window frames.

Table 1. Summary of the Physical and Mechanical Properties for the BLC's Corresponding to Different Loading Direction and Lay-up Types

Assembly Types	Air-dry Density (g/cm^3)	MOR (MPa)		MOE (GPa)		Impact Bending Strength (kJ/m^2)	
		Perpendicular	Parallel	Perpendicular	Parallel	Perpendicular	Parallel
A	0.89 (3.37)	191.18a (11.19)	139.55a (17.86)	20.31ab (3.79)	15.74a (8.45)	110.71a (6.68)	117.01a (16.24)
B	0.88 (5.68)	77.25b (29.04)	136.36a (28.70)	16.36b (14.49)	15.19a (17.98)	18.58c (27.50)	79.99b (22.83)
C	0.88 (4.55)	123.95b (23.34)	105.08a (22.05)	17.55b (10.26)	12.77a (13.78)	27.55c (39.89)	62.45b (21.62)
D	0.90 (4.44)	190.05a (18.43)	146.41a (14.28)	21.60a (12.13)	14.26a (7.71)	77.66b (17.56)	81.37b (16.36)

Note: The values in parenthesis are coefficient of variation (%), and the lowercase letters represent significant differences of the effect of the loading way (perpendicular and parallel to the glue line) on the mechanical properties at a significance level of 0.05.

The Effect of Stacking Sequence and Impact Energy on the Impact Behavior

As the BLC samples were subjected to impact, each of the sample types developed its own damage pattern as the impact energies increased. The degree of damage on the composites increased within the range of the energy studied as the impact energy increased.

Figures 4, 5, and 6 show the different damage patterns and structural responses of the laminates tested at increasing impact energies. In the about 50 J drop weight impact test, the impact damage was observed mainly on the front surface (a dent appeared on the front of the sample) and partly at the backside primarily in the form of a ring (Fig. 4). At a drop weight impact test about 95 J, fiber damage appeared on both sides, and sample type A was completely destroyed (transverse cracking) (Fig. 5). In the about 145 J drop weight impact test on the four composite types, the dart penetrated through their thickness and caused splitting on the back side of each sample (Fig. 6).

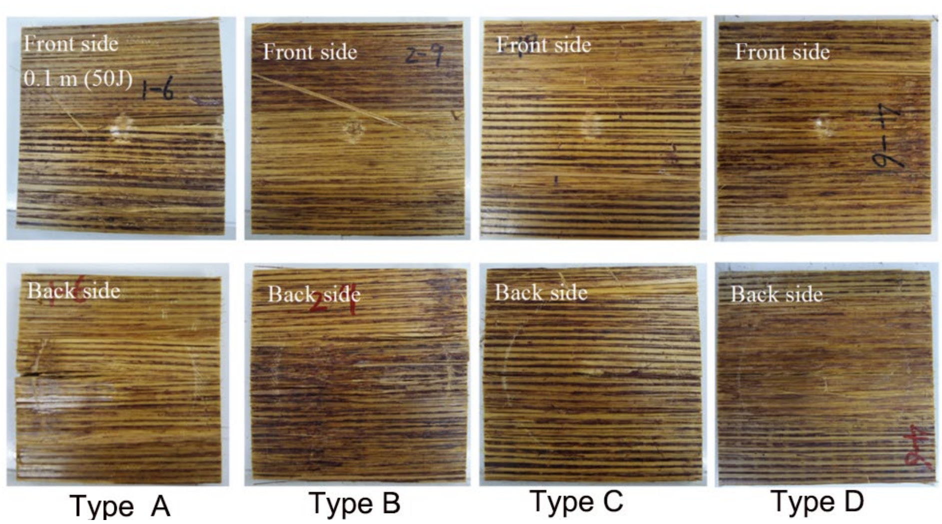

Fig. 4. Representative photos of damage progression on the front and back sides of the four types of bamboo bundle composite panels impacted at 0.1 m (approximately 50 J)

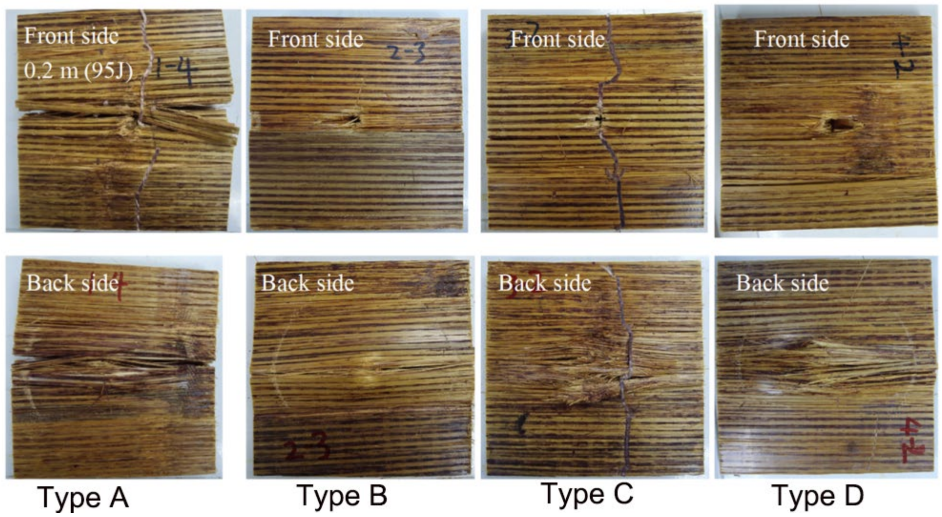

Fig. 5. Representative photos of the damage progression on the front and back sides of the four types of bamboo bundle composite panels impacted at 0.2 m (approximately 95 J)

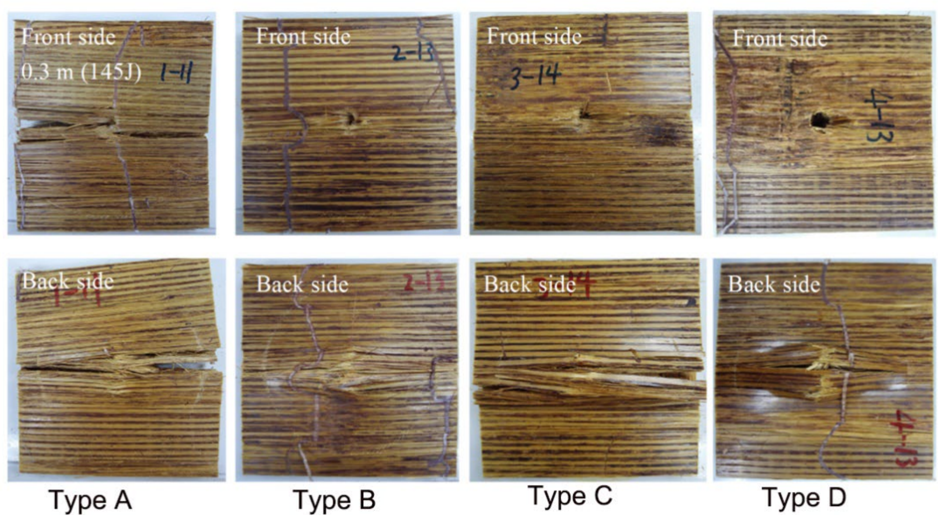

Fig. 6. Representative photos of the damage progression on the front and back sides of the four types of bamboo bundle composite panels impacted at 0.3 m (approximately 145 J)

The drop weight impact test at 145 J on the type A composites samples exhibited matrix transverse cracking on both the front side and back side of each sample, due to their parallel stacking structure. In the same impact condition, multiple fiber ruptures (*i.e.*, hemispherical indentation) and debonding occurred in the front side of the type D samples, and cross-shaped splitting occurred on the back. As can be seen in Fig. 6, the damaged area of fiber breakage for the type D sample was larger than that of the others. This suggested that the type D sample can absorb more energy, because of the fiber breakage needs more energy than matrix cracks along the fiber direction. The failure that occurred in the type B and C samples was a combination of the failure types that occurred in sample types A and D. The type B sample exhibited an impact behavior similar to that of the type D samples, while the type C sample exhibited an impact behavior similar to that of the type A sample. This is because the pavement structure of the cross-laminated type increased the fracture toughness of the board. Compared to type A, the type D was strengthened via internal toughening mechanisms and external toughening mechanisms. The internal toughening comprised fiber bridging of the surface bamboo and plastic deformation of the core wood. And for the type B and C, The fibers could achieve balance at the 0° and 90° directions and could bear impact stresses, which could increase the fracture toughness of the board, to a certain extent. Compared to bamboo bundle veneer *vs.* wood veneer, the strength of cementation between longitudinal and transverse of the bamboo curtain *vs.* bamboo bundle veneer and bamboo bundle veneer *vs.* bamboo bundle veneer was relatively weak (Han *et al.* 2021). Therefore, the type D exhibited the best impact response and its total energy absorbed was much higher than the other samples.

As the sample types underwent impact testing, the data were recorded and plotted to show the curve of the impact load compared to the absorption energy (Figs. 7, 8, and 9).

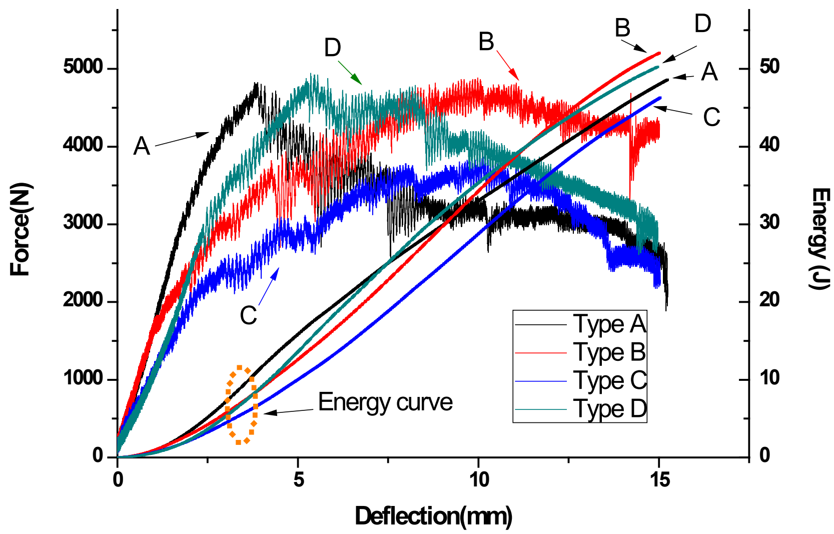

Fig. 7. The typical force *vs.* the displacement response for the 0.1 m test (approximately 50 J) impact response on the four types of bamboo bundle-based composites

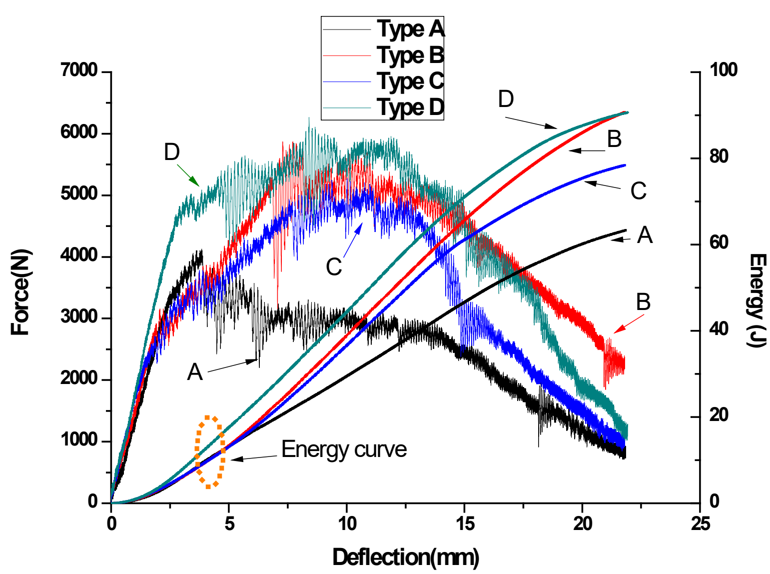

Fig. 8. The typical force *vs.* the displacement response for the 0.2 m test (approximately 95 J) impact response on the four types of bamboo bundle-based composites

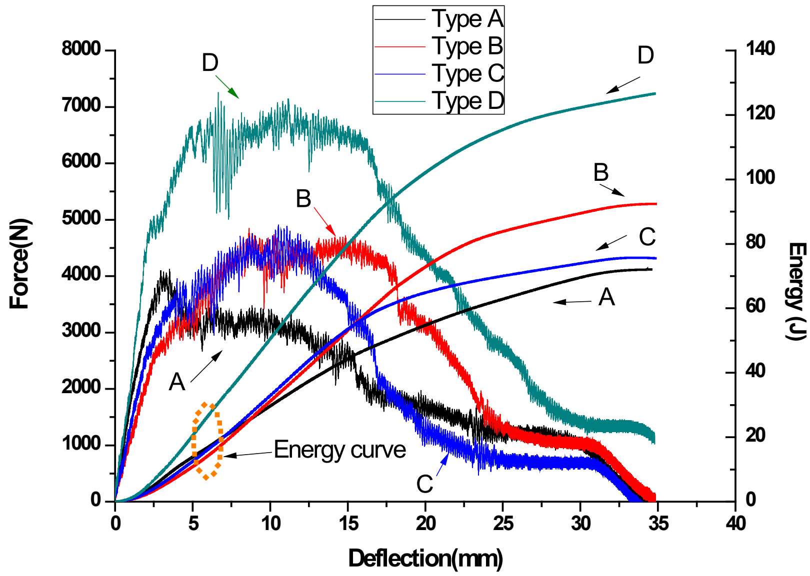

Fig. 9. The typical force *vs.* the displacement response for the 0.3 m test (approximately 145 J) impact response on the four types of bamboo bundle-based composites

The key impact parameters studied for each sample type were the peak load, the total energy, the energy at peak load, the energy at fracture load, and the total impact time (Table 2). The total energy is the sum of the absorption energy of the impact failure and the impact machine, the energy at peak is the absorption energy of the specimen at the peak of loading, and the energy at fracture represents the absorption energy of the specimen at fracture.

The peak load increased as the incident kinetic energy increased, which indicated a greater load bearing ability of the laminates at higher energy levels (Sarasini *et al.* 2014). From Fig. 6 and Table 2, it is evident that the type A sample was not able to absorb high impact energy because of its layup structure and catastrophic damage mechanism. It is clear from Table 2 that the type D sample showed the highest impact strength by means of the peak load and the absorbed energy in the 0.3 m (approximately 145 J) drop weight impact test. Comparing with others, the impact duration of type D was longer, which suggests that it could absorb more impact energy and resist greater impact loads.

As the impact height changed from 0.1 m (approximately 50 J) to 0.2 m (approximately 95 J) to 0.3 m (approximately 145 J), as shown in Figs. 7, 8, and 9, respectively, the amount of energy absorbed by the sample types increased dramatically. The data collected from the sample types was graphed, and the curves of the impact load versus the displacement behaviors of the cross-laminated panels were divided into three phases. These three phases were an approximate linear loading, a plateau or slight unloading, and a nonlinear unloading path. The first impact test results at 0.1 m show how the sample types responded to the impact forces (Fig. 7). The type B sample had the highest absorption energy of the tested sample types. As the samples were subjected to a drop height of 0.2 m, the results were similar to those from the drop height of 0.1 m, but there was much larger plateau from the 0.2 m impact test (Fig. 8). The impact load and absorption energy values from the 0.3 m impact test for the cross-laminated sample types (types B, C, and D) were higher than those for the uniaxial laminated panels (type A) (Fig. 9).

Table 2. Summary of the Experimental Conditions and Results of the Impact Tests on the Bamboo Bundle Based Composites

Specimen	Total Energy (J)	Peak Load (N)	Energy at Peak Load (J)	Energy at Fracture (J)	Fracture Load (N)	Total Time (ms)
Energy: 0.1 m (approximately 50 J)						
A	48.72 (3.33)	5530.06 (17.10)	12.54 (15.55)	——	——	16.13 (1.92)
B	51.91 (3.31)	5210.66 (12.04)	37.50 (23.39)	——	——	16.31 (1.16)
C	46.89 (10.87)	4309.14 (22.71)	25.11 (33.01)	——	——	16.17 (0.74)
D	49.97 (5.56)	6149.02 (24.90)	32.62 (20.57)	——	——	16.12 (1.24)
Energy: 0.2 m (about 95 J)						
A	67.13 (8.03)	4896.55 (22.17)	10.12 (11.96)	63.96 (4.03)	966.00 (21.17)	17.37 (1.32)
B	89.31 (6.47)	5561.77 (6.01)	41.13 (47.50)	——	——	17.23 (1.10)
C	78.29 (17.49)	5732.17 (12.54)	30.50 (17.83)	——	——	17.06 (0.47)
D	91.58 (5.10)	6404.80 (7.22)	31.26 (37.36)	——	——	17.38 (1.09)
Energy: 0.3 m (approximately 145 J)						
A	71.87 (7.37)	4915.92 (13.89)	10.35 (20.37)	65.51 (6.95)	967.22 (12.64)	16.91 (3.90)
B	97.82 (19.96)	5771.14 (20.32)	32.12 (28.83)	90.97 (24.55)	1137.40 (20.96)	17.95 (2.17)
C	80.50 (5.64)	5081.20 (3.48)	28.11 (24.05)	72.20 (8.39)	996.32 (2.63)	17.23 (0.75)
D	115.28 (7.23)	7786.86 (15.38)	34.64 (27.42)	105.13 (10.52)	1517.58 (17.73)	18.27 (1.31)
Note: The values in parenthesis are the coefficient of variation (%)						

The curve of the uniaxial laminated panels (type A) showed only two stages of linear loading and nonlinear unloading. The other sample types performed better than the type A sample because of the 0/90° plied sandwich structure that was used to make the other samples. The 0/90° stacking structure was able to bear the impact stresses by using its weaving and cross-laminated structure to reduce the transverse cracking of the matrix (Chen *et al.* 2014).

At a drop height of 0.3 m (approximately 145 J), the type D sample exhibited significantly higher levels of impact energy absorption compared to the other sample types. The type A sample had the lowest impact energy absorption because the composite was unable to bear the lateral force. The damage mechanism of the type A sample was found to be abrupt and catastrophic. These results further confirmed that uniaxial laminated panels (type A) should not be used in structures subjected to low-velocity impact. The type D sample was able to effectively disperse the stress and absorb high impact energy, so this composite type can be used in cases where low-velocity impact damage is prevalent.

CONCLUSIONS

1. The stacking structure along with the material type had a direct effect on the modulus of elasticity (MOE), the modulus of rupture (MOR), the internal bond strength (IBS) values, and the low velocity impact behaviour of the bamboo-bundle based composites that were used in this study.
2. The type A sample had the highest MOE, MOR, and IBS values, but it suffered from poor impact behavior due to its parallel stacking structure. The use of the 0/90° stacking structure in the type B, C, and D samples helped to improve impact behavior of the bamboo-bundle laminate composites (BLC). The type D sample exhibited the best impact response of the four BLC's, but its MOE, MOR, and IBS values were second to that of the type A sample.
3. Under low-velocity impact load, the curves of the impact load *vs.* displacement behaviors of cross-laminated panels (type B, C and D) could be divided into three phases, while the uniaxial-laminated panels only showed two phases (type-A).
4. Type A BLC which presented the most favourable flexural behaviour was suitable for structural elements such as beams, while the type D BLC was suitable for cases with low-velocity impact damage.

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