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ORIGINAL

Impact performance of two bamboo-based laminated composites

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Abstract The present work aims to determine the impact performance of two bamboo-based laminated composites [bamboo/poplar laminated composite (BPLC) and bamboo/glass fiber laminated composite (BGFLC)] using low-velocity impact tests by a drop tower. In addition, fracture characteristics were evaluated using computed tomography (CT). Results showed that BPLC presented better impact properties in both directions than BGFLC. Three stages are noted in impact load–deflection curves. The load–deflection curve characteristics of two composites are different in different stages. Matrix cracking, fiber-matrix interface debonding and delamination, and fiber breakage are the three main fracture mechanisms of two composites. Structural characteristics of the components and bonding strength are the important factors for impact properties and fracture mechanism of both bamboo-based laminated composites.

1 Introduction

Bamboo is a natural bio-composite. It has been used in a wide range of applications in engineering and in civil construction since ancient times, not only for its lightness, renewability, and fast growth, but also because it has remarkable mechanical properties.

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Full culm bamboo construction is not extensively practiced around the world, with primary uses of traditional bamboo construction found in Asia, Latin America and East Africa (Ramage et al. 2015). In Colombia, Trujillo et al. (2013) noted five types of bamboo structures: traditional construction, social housing, luxury housing, long-span buildings and footbridges. Additionally, vehicle bridges have been constructed in Colombia (Stamm 2002) and in China (Xiao et al. 2010, 2013). In Ethiopia, the structural use of bamboo is part of traditional construction methods and is used in the form of full culm and split bamboo with other materials (Kibwage et al. 2011). Other traditional structural uses of full culm bamboo include scaffolding in India, China and Hong Kong (Chung and Yu 2002; Muthukaruppan 2008; Yu et al. 2003; 2005). Bamboo is a potential biomaterial, while lack of bamboo engineering data and building codes hindered bamboo utilization in construction (Harries et al. 2012; Gatoo et al. 2014). Bamboo oriented strand board was developed by the layering of bamboo flakes in the tangential or substantially tangential direction perpendicular to the radius of a bamboo stalk for use in furniture and container floor (Zhang and Zhang 2013). Laminated bamboo sliver lumber (Lin et al. 2012) and laminated bamboo strip lumber (LSBL) (Jiang et al. 2006) were developed for wind blades. Parallel randomly stacked, stranded, laminated bamboo boards and bamboo fiber composites have been used in packing and shipping shell (Plaehn 1996; Tanaka et al. 2007). Corradi et al. (2009) manufactured bamboo laminates from bamboo strips. The overall mechanical characteristics of bamboo fibres reinforced composites and sandwich for general marine applications were analysed. As applications, a hull panel and a spinnaker pole have been realised and tested for impact and for axial compression load. Manik (2002) found bamboo as a good alternative composite material for ship shell.

Bamboo-based composites are being increasingly used in engineering because of their lightness and high mechanical properties compared to metallic materials. Physical and mechanical properties of bamboo and bamboo-based composites have been studied in static tests (Jiang 2002; Sharma et al. 2015; Sinha et al. 2014; Sulastiningsih and Nurwati 2009; Liu et al. 2014a, b) and it was concluded that bamboo exhibited excellent mechanical properties and toughness due to its composite and graded structure. Crupi et al. (2014, 2015a, b) investigated different types of composites subjected to low-velocity impact tests and analysed their collapse modes using three-dimensional (3D) computed tomography and IR thermography as well as finite element (FE). The damage mechanism observed for laminated wood after impact tests was local crushing due to indentation and global fiber debonding due to bending. However, there are few studies on the performance and damage involved in dynamic tests which are important for effective design and use of bamboo components.

The low-velocity impact damage is often internal and invisible, but can significantly reduce the stiffness, strength and fatigue life of the structure (Bull et al. 2015). The fracture characteristics have been investigated by an X-ray computed tomography (CT) system, which demonstrated that the CT system can detect the damage and internal flaws, including delamination and micro cracking, in fiber-reinforced polymeric matrix composites. The complex internal damage architecture of laminated composites due to impact loading was visualized and investigated by using micro-computed tomography that was able to show detailed through-thickness matrix cracks distribution and 3D delamination damage pattern (Schilling et al. 2005; Fidan et al. 2012; Bull et al. 2015; Crupi et al. 2015a, b). However, there are few studies on the impact properties of bamboo-based laminated composites but without CT system (Zeng et al. 1995; Yu et al. 2012).

In order to enlarge the applications of bamboo-based composites in engineering, a better understanding of the impact response of the composites is required. This study investigated the impact properties of two bamboo-based laminated composites under low-velocity impact conditions. In addition, the impact response and fracture modes were analyzed by impact curves and CT images.

2 Materials and methods

2.1 Materials

Two kinds of bamboo-based laminated composites were manufactured in the laboratory. One was bamboo/poplar laminated composite (BPLC) which was made of bamboo sheets and poplar veneers. The other was bamboo/glass fiber laminated composite (BGFLC), which was made of bamboo sheets and bi-directional woven glass fiber cloth.

Moso bamboo (*Phyllostachys pubescens* Mazei ex H. de Lebaie) culms (4 years old) were obtained from Fuyang bamboo plantation in Zhejiang province, China. Culms diameter at breast height was 100–120 mm, and average thickness of culm walls ranged from 10–12 mm. The culms were split to strips with dimensions of 2 m in the longitudinal direction, 7.5 mm in the tangential direction, and 3 mm in the radial direction. The strips were placed in parallel to form sheets using a hot-melt adhesive lace (Fig. 1).

Poplar (*Populus spp.*) veneers were peeled with a thickness of 0.5 mm. The length and width of the poplar veneer were determined by the size of the lay-up mat.

Glass fiber lattice cloth had a thickness of 0.5 mm and was purchased from Taishan fiber glass Inc. (China). The cloth was knitted by glass fiber with the lattice square being 5 mm × 5 mm.

A mixture of epoxy resin adhesive (WSR618 (E-51)) with acetone and phenol formaldehyde resin (PF) was used to glue bamboo sheets, poplar veneer and cloth together for bamboo-based laminated composites. Acetone was the dissolvent of epoxy resin adhesive, and PF was an additive. The weight proportion of epoxy to acetone to PF was 3:2:2. All chemicals were purchased from Dynea Guangdong Co., Ltd. (China).

2.2 Bamboo-based composite manufacturing process

Firstly, bamboo sheets, poplar veneers, and glass fiber cloth were immersed in adhesive for 1, 2, and 1 h, respectively. After drying to below 10% moisture content in air, five

Fig. 1 Schematic of bamboo veneer

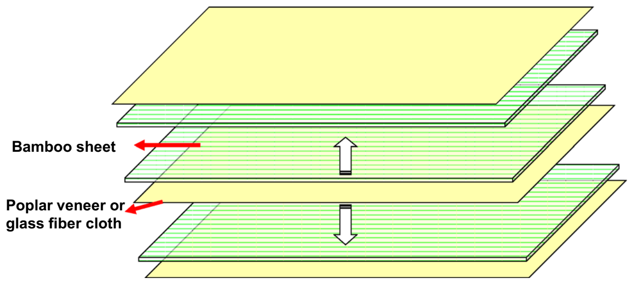

Fig. 2 Schematic of lay-up process

layers of bamboo sheets and seven layers of poplar or glass fiber cloth were laid up by hand in the longitudinal direction (Fig. 2) in a pressing mold. The outer layer was veneer or cloth. Layered mats were pressed to compression percent of 10% and fixed. After that mats within the mold were placed in a kiln (130 °C) for 16 h. The mechanical and physical properties of two bamboo-based composites are presented in Table 1.

2.3 Low-velocity impact tests

Low-velocity impact tests were performed using an Instron Dynatup 9250 impact test machine (Instron Corp., MA, USA). The machine was capable of impacting samples at maximum gravity mode velocity up to 5.0 m/s at the maximum physical drop height of 1.25 m and maximum spring assisted high velocity up to 20 m/s at the simulated drop height up to 20.4 m. Standard weight crosshead range was 4.7–23.7 kg, and impact energy range of 4.6–945 J. According to ASTM D143-94 (2000), impact toughness tests were conducted in three-point bending with a span of 710 mm (Fig. 3).

The two impact directions were in radial direction (R) and in tangential direction (T) (Fig. 4). A force transducer having a capacity of 45 kN was mounted on the front end of the impactor rod and encapsulated by a hemispherical nose. The impactor was set at a dropping height of 1.3 or 1.1 m to give impact velocity of 5 m/s and 4.6 m/s for the tests (Table 2). At least 6 specimens were used for each type of impact test (BPLC-R, BPLC-T, BGFLC-R, BGFLC-T).

The principle of impact testing is the determination of the energy absorbed to break a test specimen under impact conditions (impulsive load). Falling weight

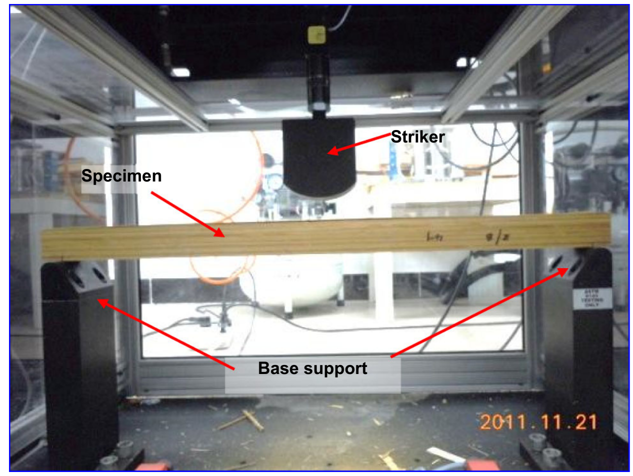

Fig. 3 Schematic of three-point bending impact with a span of 710 mm

impact testing principle is that a dart releases and falls down by gravity, or accelerated by springs or pneumatic/ hydraulic actuator. It can be loaded with additional weights. There is a tup on the striker which could record the force in impact process, and there is a sensor which could record the velocity of striker from the first time contacting the specimen. The corresponding velocity history of the impactor could then be calculated. Subsequently, the corresponding deflection history of the impactor could be calculated from integrating the velocity history. The load–deflection curves are recorded by impact system and are not filtered.

The parameters in impact testing were calculated as follows:

The impulse of striker was calculated by Eq. 1.

$$I(\mathrm{t}) = \int_0^t F(t)dt \quad (1)$$

Impact velocity was calculated by Eq. 2.

$$\mathrm{v}(\mathrm{t}) = v_0 - \frac{1}{m} \times I(t) \quad (2)$$

The deflection of striker was calculated by Eq. 3.

$$\mathrm{u}(\mathrm{t}) = v_0 \times t - \frac{1}{m} \times I(t) \quad (3)$$

Table 1 Physical properties of bamboo-based composites

Material	Thickness (mm and loading direction)	Density (g cm^{-3})	Moisture content (%)	Modulus of elasticity (MOE) (GPa)	Modulus of rupture (MOR) (MPa)
BPLC	45 (R)	0.869	5.5	16.83	182.04
	45 (T)			15.94	182.02
BGFLC	45 (R)	0.886	5.5	15.10	155.60
	45 (T)			15.53	168.95

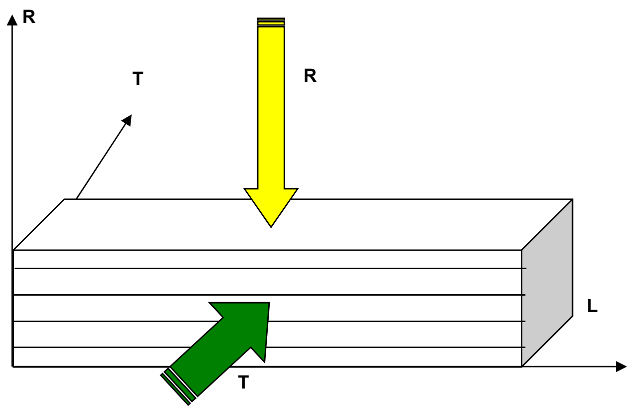

Fig. 4 Schematic of two impact directions (in radial direction and in tangential direction)

Table 2 Impact test conditions

Material	Thickness (mm)	Span (mm)	Impact direction	Weight of impactor (kg)	Height of impactor (m)
BPLC	45	710	R, T	49	1.3
BGFLC	45	710	R, T	49	1.1

Energy lost by the striker was calculated by Eq. 4.

$$\Delta \mathrm{E(t)} = v_0 \times I(t) - \frac{I(t)^2}{2m} \quad (4)$$

Impact toughness was defined as the impact energy per cross area of the specimens, α_k (J/cm^2).

$$\alpha_k = \frac{E}{b \times h} \quad (5)$$

where: t = impact time (s), v_0 = the velocity at the first contact with specimen (m/s), b = width of the sample (mm) and h = height of the sample (mm).

2.4 Computed tomography imaging

Computed tomography imaging was performed on a bright speed excel 4-layer helical (also known as spiral) CT system (General Electric, USA). The scans were conducted with a "small field" and the thickness of the scan layer and interlayer spacing of two scan layers were the same (1.25 mm). Parameters of the tomographic investigation are presented in Table 3.

Table 3 Parameters of the tomographic investigation

Scanning parameters	Values
Voltage	120 kV
Current	160 mA
Focal spot size	0.4 mm^2
Integration time	≤0.8 s/3600
Voxel size	1.25 mm
Reconstruction algorithm	Bone+
Image size (pixel)	512 × 512

3 Results and discussion

3.1 Impact properties

Several representative parameters are essential to describe the impact properties of both laminated composites (Table 4). Peak load is the threshold for the main break of bamboo-based laminated composites. The impact performances are globally described in terms of impact toughness and impact deflection at peak load. Table 3 shows that BPLC has higher peak load and higher energy to max load and with smaller deflection than the BGFLC in both impact directions.

Energy-deflection curves in Fig. 5 show that impact energy of both composites in both impact directions increased continually with deflection. However, impact velocity is decreasing in the process (Fig. 6). Higher impact load and faster velocity decreasing in impact process would absorb more energy and present better impact performance. The absorbed energy of BPLC in both directions is higher than that of BGFLC (Table 4), which presents better impact performance. Impact performance is due to the components of two bamboo-based laminated composites. Because of the different properties of two main components, there would be shear stress in the interfaces. Therefore, the bonding strength in the laminate plays a crucial role in impact strength.

Both laminated composites are composed of bamboo sheets and poplar veneers or glass fiber cloth. The structure of the components decided their function in impact process. Bamboo is a typical graded fiber-reinforced bio-composite (Ray et al. 2005). It exhibits remarkable properties and toughness because of its graded and hierarchical structure (Shigeyasu et al. 1996, Ghavami et al. 2003). Especially, the gradient of fiber volume in radial direction of bamboo culm provides graded bamboo mechanical properties and remarkable toughness in radial direction, which demonstrated a large amount of deformation without breaking. But bamboo suffers poor bonding performance because of its dense tissues and siliceous chemical components on the surface (Jiang 2002) however, poplar veneers improve the bonding strength of BPLC for their porous structure. So the impact properties of BPLC are better than those of BGFLC. According to the static bending properties of the composites in Table 2, impact toughness at peak load varies concomitant with their properties in static bending tests.

Table 4 Impact properties of bamboo-based composites

	BPLC		BGFLC	
	R	T	R	T
Number of valid specimens	7	8	8	9
Peak load (kN)	24.46 (5.55)	24.63 (5.08)	19.69 (7.88)	20.65 (9.68)
Deflection at peak load-1 (mm)	23.94 (11.26)	23.51 (3.73)	24.71 (25.09)	25.91 (24.88)
Energy to max load-1 (J)	233.26 (20.27)	214.52 (5.26)	187.08 (35.30)	198.74 (35.56)
Impact toughness to max load(J cm^{-2})	10.75 (20.39)	9.88 (5.91)	9.51 (35.19)	10.13 (33.54)

Number in brackets is coefficient of variation

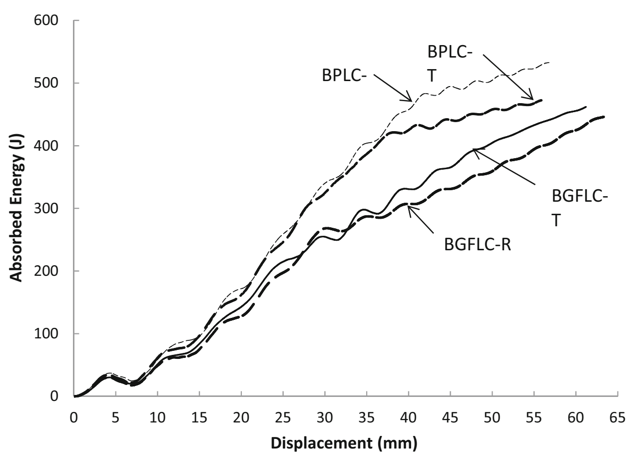

Fig. 5 Absorbed energy-deflection curves

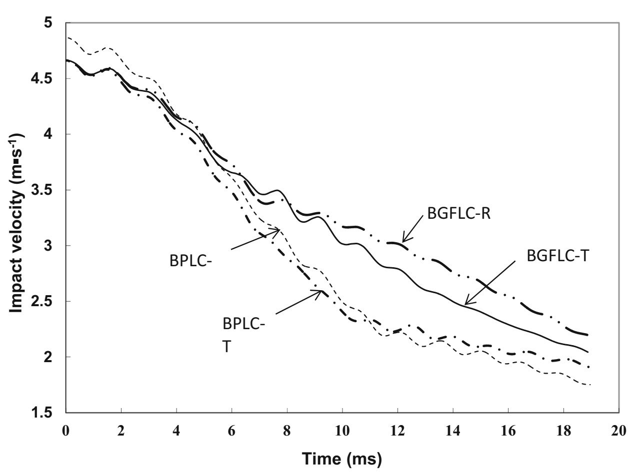

Fig. 6 Impact velocity–time curves

3.2 The responses of bamboo-based composites in impact process

The response of bamboo-based composites under impact loading was analysed in load–deflection curves. The representative load–deflection plots for BPLC and BGFLC in radical and tangential direction are shown in Fig. 7, which could be separated into three stages which are noted by dotted line. The load–deflection responses of two bamboo-based laminated composites are different in amplitudes, especially after the peak load.

In the first stage, the impact load increases from zero to the peak load. Four load–deflection curves at the first stage are similar in shape, the load increases to peak load at the fourth wave crest and at deflection about 22.5 mm (Fig. 7). Delamination and matrix cracks happened in this process of bending. A substantial break of bamboo strips at the bottom of the specimens happened at the peak load.

Then the second stage is a fracture period from the peak load to the threshold load in curves. The characteristics of the curves in this stage are obviously different. The deflection from peak load to threshold load of BPLC (> 15 mm) is larger than that of BGFLC (< 8 mm). The impact load changes in wave which is corresponding to the progressive collapsing of layers. For the better bonding strength of BPLC, BPLC absorbed more energy in this process accompanied by the larger impact velocity decrease (Fig. 6). Moreover, the main fracture (bamboo sheet break, matrix crack, interface debonding, etc.) of BPLC happened in this stage.

In the third stage, fatal fracture happened with a load drop to minus at the critical load in load–deflection curves. Contact load increased and caused the matrix crack and progressive fiber break at the bottom of piles due to the tensile force. Interface delamination and matrix cracks and sub-fractures happened in this process. Due to the laminated structure of specimens, the load–deflection curves are in smaller amplitudes (Fig. 7). The third stage is the main period for BGFLC, the amplitude and impact time and deflection of BGFLC are larger and longer than BPLC. For the poor bonding strength of BGFLC, debonding is the main failure mode of BGFLC.

The characteristics of load–deflection response are different in two impact directions. For BPLC, the response of load is obviously different in the second stage in two impact directions (Fig. 7a, b). The amplitude of curve and deflection in R direction impact is larger than in T

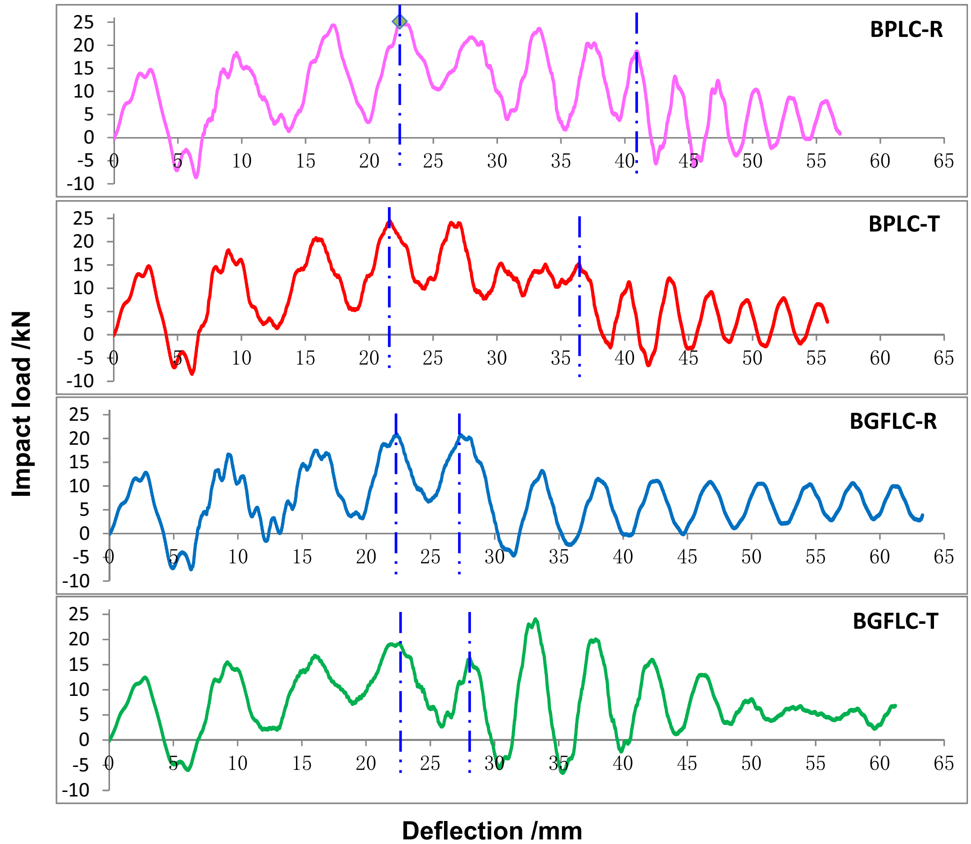

Fig. 7 Impact load–deflection curves

direction. In R direction, the bamboo sheet at the base of specimens fractured at the peak load, however, the fracture enlarged from bottom to top layer by layer, so there are more and larger amplitude waves load–deflection curves (Fig. 7a). However, all the bamboo sheets in specimen fractured at the peak load in T direction, corresponding to the interlinear debonding and shearing with smaller amplitude in curve. For BGFLC, the different response of load–deflection in two impact directions is significant in the third stage (Fig. 7c, d). In R direction, the waves are similar and uniform after the threshold (Fig. 7c) but in larger amplitude than in T direction (Fig. 7d). In R direction, the load transmits from surface to inner layer by layer, so the waves are almost uniform. But in T direction, all of the bamboo sheets carry the load and fractured at the peak load, so the load decreased fast.

3.3 CT Impact damage characteristics and mechanisms

In this study, the impact tests were conducted under same impact condition (same impact energy, and impact one time), which is different from the literature (tested at several impact energy levels and impact repeatedly) (Bull et al. 2015, Fidan et al. 2016). The failure mode and the internal damage of the impacted composites have been investigated using three-dimensional (3D) computed tomography (Fig. 8).

The detailed characteristics of damage were observed in CT images, and three main fracture mechanisms were found. The first type of damage characteristic of the composites is bamboo sheets breakages and fractures at the base of specimen (Fig. 8(2), (6), (10)) corresponding to a sharp drop at the peak load (Fig. 7). The second damage mechanism is delamination which is mainly in the second stage (Fig. 8(1), (3), (4), (5)). Delaminations in two bamboo-based laminated composites are a major concern because there is significant loss of stiffness. The third damage mechanism is matrix cracks (Fig. 8(8)). The matrix crack tips act as initiation point for delamination and fiber breaks that can dramatically change the local or global stiffness of the composite and affect the force–deflection curves. Bull et al. (2015) reported that the response of particle-toughened carbon-fiber composite materials to low velocity impact was: matrix cracks initiated first, with increasing deflection delaminations were observed initiating at previously formed matrix cracks; in this case ligaments consisting of interconnected regions of material bridging the two ply interfaces. Different from the result of Bull's study, delaminations of interface happened in the

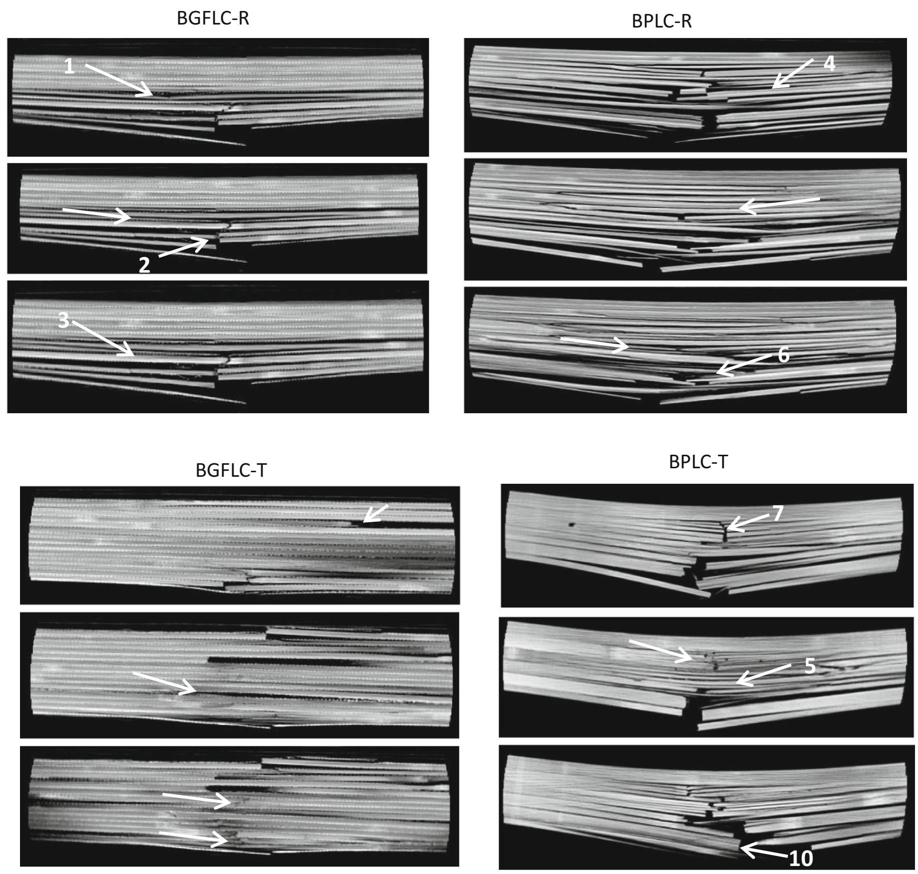

Fig. 8 Representative fracture behavior of composites in two impact directions: (*1*) Main debonding in middle plane, (*2*) Bamboo strips break at bottom, (*3*) Delamination between plies and interlaminar cracks, (*4*) Delamination extent to both sides, (*5*) Delamination with bridging ligaments, (*6*) Bamboo strips break from bottom to top layer by layer, (*7*) Flat fracture surface of bamboo strips, (*8*) Matrix crack, (*9*) Unbroken part, (*10*) Initial and substantial fiber fracture

whole process of two bamboo-based composite. However, ligaments also exited and consisted of interconnected regions of matrix, which acted as bridging in two ply interfaces (Fig. 8(5)).

Experimental evidence shows that impact damage is directly related to the structure of impact behavior, which, in turn, is controlled by the governing parameters. Under drop-weight impact loading, the damage process of laminated composites starts with interfacial debondings and delamination. Damage results from the nature of composites, such as interaction between various failure mechanisms (matrix cracking, fiber-matrix interface debonding, delamination, and fiber breakage), and also depends on the lay-up manner because of the anisotropic properties of bamboo. The fracture mechanisms of delamination and breaking layer by layer in the R direction of BPLC could absorb more energy in impact process and improve the impact properties.

4 Conclusion

1. The energy absorbed by BPLC in both directions is higher than that of BGFLC. Poplar veneers enhanced the bonding strength and improve the impact properties of BPLC.
2. Three stages are noted in impact load–deflection curves. Peak load is the turning point of the impact waves. The load–deflection curve characteristics of two composites are different, the second stage is the main fracture period for BPLC, and the third is the main one for BGFLC.
3. Matrix cracking, fiber-matrix interface debonding and delamination, and fiber breakage are the three main fracture mechanisms of the two composites. The main fracture features of BPLC and BGFLC are fracture in bending and debonding, respectively. Structural characteristics of the components and bonding strength are the important factors for impact properties and fracture mechanism of both bamboo-based laminated composites.

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