Bamboo Bundle Corrugated Laminated Composites (BCLC). Part II. Damage Analysis under Low Velocity Impact Loading

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The objective of this study was to investigate the deformation behavior and damage model of bamboo bundle corrugated laminated composites under low velocity impact loading. The influence of different stacking sequences, *i.e.*, bamboo bundle parallel to the corrugated waves (type I), cross-ply (type II), and perpendicular to the waves (type III), in laminates was studied in regard to impact loading. A shape parameter, *K,* was developed to quantify the effect of corrugation on impact response. The results of this study indicated that the type I composites displayed the optimum impact performance, followed by types II and III. The total energy absorbed by the type I laminates was 1.3 and 2.2 times as much as types II and III. The values of peak load were type I > type II > type III. The composites deformed and failed in different manners under low velocity impact loading: material failure, delamination and fiber tensile fracture, and structural collapse were the main modes of failure for type I, II, and III, respectively. The effect of the corrugated shape on impact properties of composites was positive for type I, but negative for type II composites.

Keywords: Bamboo; Impact; Stacking sequence; Corrugated structure; Failure model

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INTRODUCTION

Bamboo is a special and important non-wood forest resource due to its ample availability, fast growth rate, high specific strength and stiffness, low cost, low energy consumption in processing, and biodegradability (Jiang *et al.* 2012; Wang *et al.* 2011). A considerable amount of study concerning bamboo fiber-reinforced composites has been dedicated in recent years to develop economical and high-performance composites so they can be applied to load-bearing, non-structural/structural components (Zhang *et al.* 2000; Lee 2012).

Laminated bamboo fibrillated-veneer lumber (LBL) is one of the most effective and efficient approaches that has been extensively applied to the manufacture of high quality bamboo-based composites in China (Yu *et al.* 2011; Meng *et al.* 2011). By controlling the quality of bamboo veneer, the stable properties of LBL products can be guaranteed during the manufacturing process.

Composite performance is not only related to the material properties themselves, but also to the structural design. Corrugated structure has long been considered an excellent engineering design that can be employed in a variety of applications, *e.g.*, aerospace, automobile, marine, and architecture fields, where the weight of the structure is critically important (Briassoulis 1986; Thorpe and Choi 1992; Duong *et al.* 2010). The advantages of a corrugated structure design include: 1) high energy absorption at impact, 2) anisotropic nature, which is flexible in the direction parallel to the corrugation and stiff in the transverse direction, and 3) high strength-to-weight, tailor-ability, and excellent damage tolerance. Therefore, a combination of LBL manufacturing technology and corrugated structure design to produce high-performance bamboo-based composites is proposed here. Bamboo bundle corrugated laminated composites (BCLC) are a novel as well as valuable alternative to conventional planar materials.

However, during their service life, composite materials or structures are known to be susceptible to accidental impact damage from foreign objects such as hail and debris. The impact is a serious and complex phenomenon, because invisible damage of various kinds occurs easily in composites. Four principle types of damage in composite materials generally occur, *i.e.*, matrix cracking, fiber-matrix interface debonding, delamination, and fiber breakage (Soutis and Curtis 1996; González *et al.* 2011). Together these failures can have a deleterious effect on the mechanical and physical properties of the composites. Furthermore, impact behavior depends on many parameters, including structure (shape, thickness, stacking sequence, density, material properties, and boundary conditions), impact (velocity, impact angle, shape, size, and mass), and environment (temperature and relative humidity) (Fu *et al.* 2010; González *et al.* 2011). Hence, a full understanding of the impact damage mechanisms and impact behavior is essential to the design of a novel corrugated structure manufactured using bamboo bundle.

Extensive experimental studies and analytical methods have been performed that have mainly focused on flat and rectangular laminated composite plates by executing the corresponding standardized protocol, *i.e.*, ASTM D 3763-02, and using the finite element analysis (FEA) method with software such as ABAQUS or ANSYS. Naik and Shrirao (2004) studied low velocity impact events and concluded that structural elements can have a full vibrational response due to the stress waves moving outward from the impact point with enough time to reach the edges of the objects. Hu *et al.* (1999) found that a low velocity impact can produce multiple stacked delaminations at an amount of interface through the thickness of the composite laminates.

As observed by Cheng *et al.* (2003), the impact event can be broken down into three sequential stages: 1) punching, 2) fiber breaking, and 3) delamination. Gu (2003) elaborated on refined analysis models to evaluate perforation problems by taking into consideration energy conservation laws and absorbed kinetic energy of the projectile. An accurate progressive damage model simulating the interaction between crack and delamination from low velocity impact was successfully created by de Moura and Gonçalves (2004). Nevertheless, few studies have been aimed at finding the impact properties of bamboo fiber-enhanced laminated composites with a corrugated structure.

The overall goal of this project was to investigate the feasibility of manufacturing bamboo bundle corrugated laminated composites (BCLC) with PF resin and to study the low velocity dynamic response of composite structures as affected by stacking sequences. The specific objectives were: 1) to explore the technical feasibility of manufacturing BCLC, 2) to investigate the impact behavior of BCLC, 3) to develop an empirical shape parameter, *K*, used for impact response that can be used to quantify the corrugated effect.

MATERIALS AND METHODS

Bamboo Bundle

Three-year-old Cizhu bamboo (*Neosinocalamus affinis*) was obtained from Yibin, Sichuan Province, China. The bamboo material had an initial moisture content (MC) of about 65%. For the material preparation, bamboo tubes were first split into four pieces of approximately the same size. The bamboo nodes were removed using a hatchet. An untwining machine was designed for brooming and rolling the bamboo.

During the brooming process, the bamboo chip was first flattened using a larger gap between the upper and lower rollers: 3 to 4 mm for the first roller set, 2.5 to 3.5 mm for the second, 2 to 2.7 mm for the third, and 2 to 2.7 mm for the fourth. For the subsequent brooming process, the gap for the third and fourth roller sets was reduced to 0.75 to 1 mm. After repeating the process five times, the bamboo strips were rolled, kneaded, and flattened into a loosely laminated reticulate sheet. The laminated sheet was cross-linked in the width direction with no fracture along the length direction, and was nearly uniform in thickness, maintaining the original bamboo fiber arrangement. The bamboo bundle sheets were finally cut into pieces 300 mm in length, and then air-dried to a MC between 8 to 12%. This brooming process produces a greater than 90% bamboo yield.

Preparation of BCLC

A commercial phenol formaldehyde (PF) resin obtained from the Taier Corporation (Beijing, China) was used for the composite fabrication. The PF resin was diluted with water to a solids content of 15%. The bamboo bundles were immersed in the PF resin for 8 minutes and then dried to a MC between 10% and 12% in an ambient environment. A 300 mm × 300 mm CARVER Auto M-3895 hot press with a PressMAN control system (Carver Inc., USA) and a custom designed corrugated mold was used to press the BCLC at a platen temperature of 160 °C. The dimensions of the BCLC were 300 mm (length) × 150 mm (width) × 8 mm (thickness). The target density was 0.88 g/cm^3. The hot press time was 30 minutes (10 minutes for press closing, 10 minutes for the pressure maintained at the target thickness, and 10 minutes for press opening). Three types of stacking sequences were designed: bamboo fibers were aligned in the direction of the corrugated waves (type I), bamboo fibers were cross-laminated (type II), and bamboo fibers were aligned perpendicular to the corrugated waves (type III). Type I (undirectional-ply) and type II (cross-ply) laminated bamboo fibrillated veneer lumber (LBL) were manufactured in order to determine the effect of corrugation. Composites with ramie woven fabrics bonded with the MDI resin were also fabricated and used as controls. Three replicates were made for each condition.

Low Energy Impact Tests

The impact tests were performed using a drop weight impact test machine (INSTRON Dynatup 9250HV). The dimensions of the BCLC were 100 mm × 100 mm, with an average thickness of 8 mm. The hydraulic fixture device and square frame jigs were used to clamp the BCLC with square boundary conditions. The impact test machine equipped with a clamping fixture is shown in Fig. 1. A hemispherical steel impactor with 12.7 mm in diameter and a total weight of 3.5441 kg was used for the impact tests. The punch was guided to drop at the corrugated ridge in the center of the window. The impact energy was set to about 140 J so that the specimen could be penetrated completely. The impact velocity was measured just before impact, and the total impact energy (U_0) can be obtained by Equation 1,

$$U_0 = \frac{1}{2} m v_0^{\ 2} \tag{1}$$

where m is the mass of drop punch, and v_0 is the instantaneous speed of the impactor contacting with the specimen. U, *i.e.*, the absorption energy of impact failure, can be obtained from Equation 2, where v_t is the maximum bouncing speed of the impactor, and the expression $\frac{1}{2} m v_t^{\ 2}$ represents the kinetic energy from elastic deformation of specimen.

$$U = \frac{1}{2} m (v_0^{\ 2} - v_t^{\ 2}) \tag{2}$$

The impact load can be obtained from Equation 3, where $V_{(t)}$ is the instantaneous speed during the impact process. Impact displacement can be calculated from Equation 4.

$$F_t = m \frac{\partial V_{(t)}}{\partial t} \tag{3}$$

$$D_t = \int_0^t V_{(t)} dt \tag{4}$$

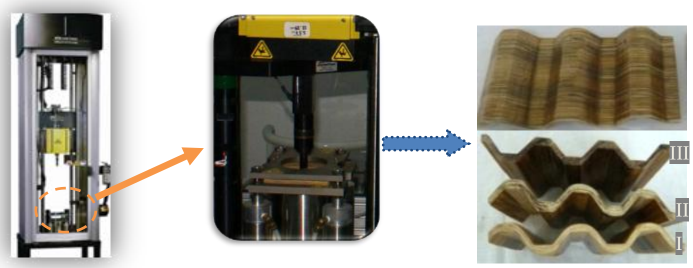

Fig.1. Model HV9520, fixture device, and composite specimens with different stacking sequences

Effect of Corrugated Structure

In order to quantify the effect of corrugation on the different stacking sequences, the shape parameter was determined by the following formulae,

$$K_{type\ I} = (I_{BCLC(type\ I)} - I_{LBL(type\ I)}) / I_{LBL(type\ I)} \times 100\% \tag{5}$$

$$K_{type\ II} = (I_{BCLC(type\ II)} - I_{LBL(type\ II)}) / I_{LBL(type\ II)} \times 100\% \tag{6}$$

where $K_{type\ I}$ and $K_{type\ II}$ are the parameters for type I and type II BCLC, respectively. $I_{BCLC(type\ I)}$, $I_{BCLC(type\ II)}$, $I_{LBL(type\ I)}$, and $I_{LBL(type\ II)}$ are the impact properties (listed in Table 2) of BCLC and LBL.

RESULTS AND DISCUSSION

Impact Response

Figure 2(a)-(d) shows the typical load/time and energy/time curves for the type I, type II, type III, and control specimens. The experimental results of impact properties testing of BCLC with different stacking sequences are summarized in Table 1. It is interesting to note that the force-time curves for all specimens represent rapid fluctuations versus time. When the puncture force began to act on the specimens, the specimens also rebound on the impact puncture and this interaction between the impact force and specimen generated simultaneously. Therefore, this effect brought about shock waves during the process of the superposition of signals.

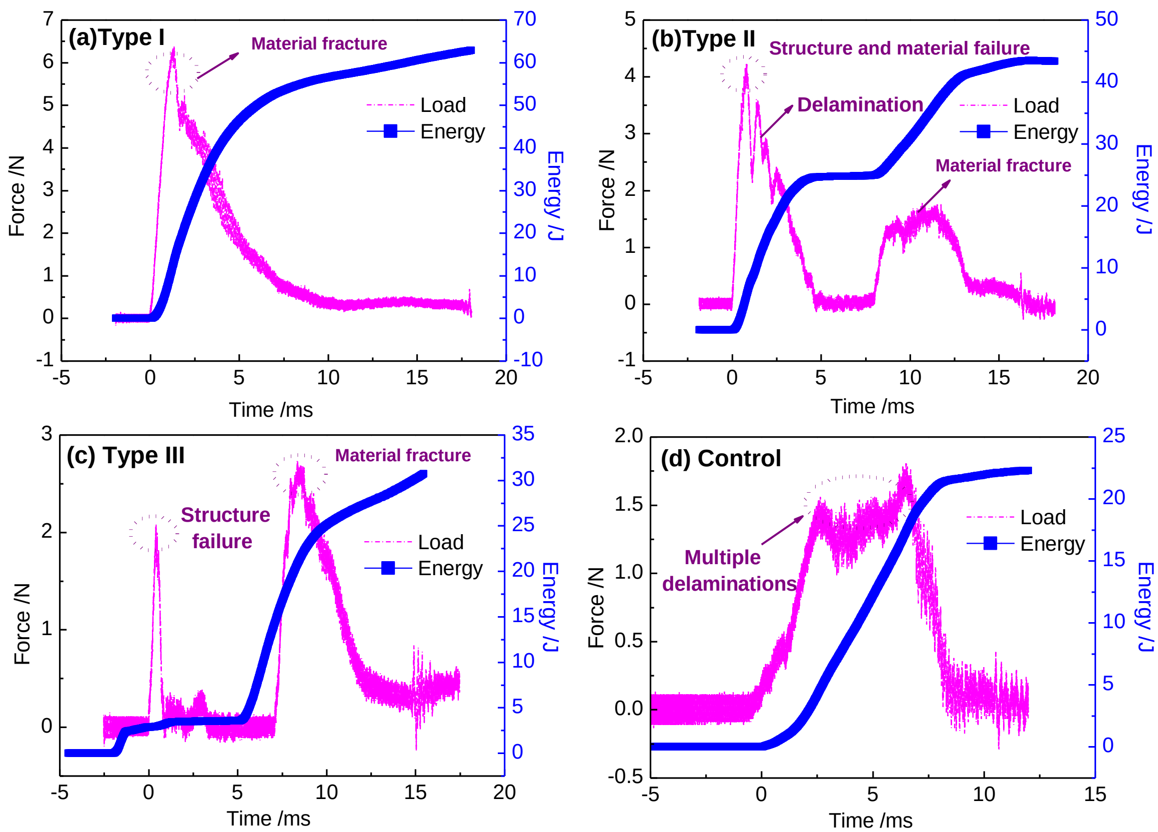

Fig. 2. Impact curves of load/time and energy/time with different stacking sequences

As can be seen, the characteristics of the energy/time curves were dissimilar for each type of composite tested, as illustrated in Fig. 2. The initial rising slope of the curves was almost identical for type I and II before 5 ms. Then, the slope ratio for type I gently increased until the impactor punctured through the lamination (Fig. 2(a)). In contrast, type II had a pustza stage of about 5 to 7 ms, as shown in Fig. 2(b), followed by the curve continuing to linearly increase until 12.5 ms. After the resistance load quickly dropped to zero, the energy/time curve of type II gradually began to level off. However, the energy curve records for type III between 0 and 5 ms were almost equal to zero. After, it presented a similar increasing trend to type I. Because the impact energy, impact speed, and clamped boundary conditions were the same, the only explanation for this behavior is the stacking sequence of BCLC. Part of the explanation of this phenomenon could be that under low velocity impact loading, the resin matrix subjected to compression would have more potential for stress concentration. Delamination, generated from the interface layer where the carrying ability of resin was relatively low, will result in a variety of microfissures. Accompanied by crack propagation parallel to the fiber or between adjacent layers, the composites with fibrous reinforcement in the direction of corrugation (type I and II) would likely release the impact energy through structural deformation. The stress wave would lead to various types of fracture occurring in fibers, resin matrix, or interface, including compression, shearing, tensile effect, and bending moment. Meanwhile, the laminates without fiber enhancement in the direction of the corrugated waves were prone to structural collapse as a first response to impact, then the damaged structure was subjected to a second stroke.

In addition, the number of rebounds in the force/time plots was the lowest for type I, compared with the type II, III, and control specimens. However, the type I composites possessed the highest impact stiffness and damage tolerance, evidenced by the value of impact parameters that were 6.02 kN peak load, 11.27 J energy to maximum load, and 62.46 J total energy absorption (shown in Table 1). The order for the value of peak load and total energy of laminates was type I > type II > type III. The total energy absorbed by type I was 1.3 and 2.2 higher than type II and III, respectively. Because of the elastic mismatches between the two bamboo bundle layers, the composites made from cross-ply bamboo bundle tended to delaminate. The laminations with bamboo fibers perpendicular to the corrugation were also prone to structural collapse along the corrugated waves, due to a lack of reinforcement in this direction. Therefore, type II and type III were more susceptible to structural deformation than the specimens with unidirectional bamboo bundle layers. A lower resistance force, shown in Fig. 2(b) and (c), was demonstrated in the analysis described above. Also, the deflection at peak load for type I (3.24 mm) was higher than type II (2.08 mm), respectively. A higher value of deflection indicated better impact ductility. Although the displacement of type III was the highest, its impact toughness was the lowest because its corrugated structure had been fractured at the initial injury.

Table 1. Puncture Properties of BCLC with Different Stacking Sequences

Stacking sequence	Peak load (kN)	Deflection at peak load (mm)	Energy to max load (J)	Total energy (J)
Type I	6.02	3.24	11.27	62.46
Type II	5.38	2.08	6.17	49.81
Type III	2.73	23.42	9.34	28.15
Control	1.76	10.50	11.03	16.06

Damage tolerance is not only related to the material but also to the structure of the composite. The absorption energy to maximum load was highest for type I, followed by type III, and the lowest for type II. This is due to the fact that the number of layers for load supporting was lower for type II than for type I. The maximum load of type III appeared at the second peak, in Fig. 2(c), after the failure of the corrugated structure that was located in the first peak. Type III bamboo bundle layers would certainly offer more resistance to impact force than type II, leading to an intermediate value among the three types of composites. In general, the value of peak load and total energy for the control were lowest. The inferior strength of ramie fiber as well as a lower density compared to BCLC contributed to this phenomenon. However, both the deflection at peak load and energy to max load of the woven ramie corrugated composites were higher than BCLC. These results clearly demonstrate that a textile structure can result in improved impact capability for composites.

Failure Modes

A series of impact tests were conducted at the same impact boundary to investigate the failure mode of the BCLC. The appearance of fracture on the front and back sides of composites was recorded and displayed in Fig. 3. It can be found that the delaminated areas in the back surface for all specimens were larger than those on the front. This observation was consistent with previous experiments by Avila *et al.* (2007). Under impact loadings, the front and back sides of the laminates were subjected to compression and tensile stress, respectively. So that the delamination would probably be initiated within the middle layers and then become accelerated on the tensile side of the composites.

(a) Front side

(b) Back side

Fig. 3. Classic morphologies of punctures from different stacking sequences

Additionally, the failure mechanism of composites with different overlay structures was obviously dissimilar under impact loading. Material failure was the main fracture model for the type I composite, accompanied by multiple delamination through the whole thickness. The damage on the front side presented a circular indentation, along with a nonpenetrative crack along corrugated wave direction, illustrating the shape of the impact punch and the delamination effect. The bamboo bundles near the impact position were pulled out, which can be observed in the back surface of type I. A mixed model of interlaminar delamination and intralaminar failure (fiber tensile fracture) was displayed by type II. Distinct rectangular boundaries ran perpendicular to the direction of the corrugation on the front side, and a deep flaw could be clearly observed from the back surface. The principal failure model for type III was structural collapse, the evidence for which was three independent parts. The breaking part in the middle position was a bent fracture along the corrugated wave; it could be noticeably detected from the back surface of type III. However, in contrast with the phenomena seen above, no cracks or flaws were observed on the front side of the control specimen. Fabrics in the control specimen were in a torn state accompanied by delamination in the back surface. These results are mainly attributed to the woven fabric structure with interweaved yarns between warp and weft.

Effect of Shape

As mentioned in the previous section, the corrugated shape has a crucial effect on the impact properties of composites with different stacking sequences. The degree of the effect made by the shape (the corrugated structure) could be quantitatively characterized by the ratio of impact difference to the value of impact properties of BLB. The impact difference can be defined by subtracting the value of impact index obtained from BCLC (with both material and structural effect) from that of BLB (only material effect). Due to a certain difference in density between BLB and BCLC, the calculation for the effect of shape was based on the adjusted mean value, using relative density as the covariant (Ahmad and Kamke 2011).

Table 2. Adjusted Value of Puncture Properties for Bamboo Bundle Composites

Specimen	Peak load (kN)	Deflection at peak load (mm)	Energy to max load (J)	Total energy (J)
LBL (type I)	6.08	3.21	11.85	66.39
LBL (type II)	9.12	8.83	50.53	130.56
BCLC (type I)	6.86	3.69	12.85	71.22
BCLC (type II)	6.10	2.36	7.00	56.47

NOTE: Average density for LBL and BCLC was 0.94 and 0.88, respectively. Relative density was used in the property adjustment.

Table 2 shows that the impact index for LBL (type II) was significantly higher than type I. The total energy absorbed by type II LBL was nearly twice as much as type I LBL. As expected, the cross-ply fiber reinforced compound slab had better impact ductility than that of uniaxial-ply (Zhang 2000). By contrast, the puncture properties of corrugated type II(cross-ply) were noticeably lower than that of type I (uniaxial-ply). Under impact loading, bulking and delamination occurred in the cross-ply corrugated structure, which chiefly explains the reduction of impact properties of BCLC (type II).

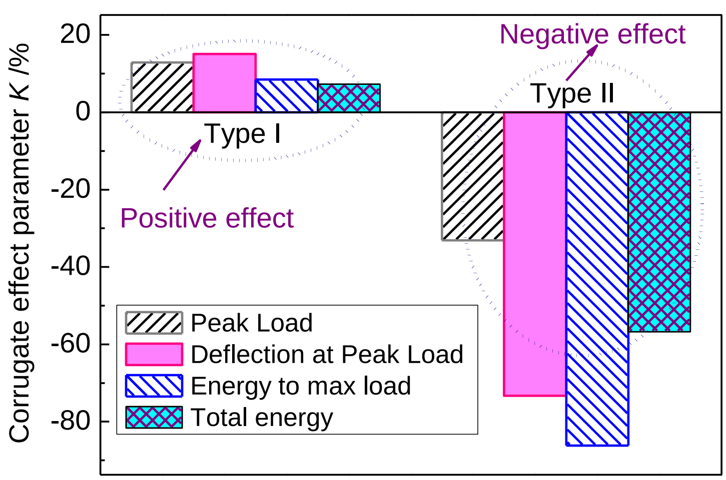

Fig. 4. Corrugated effect parameter with different stacking sequences

Figure 4 displays the shape parameter *K*. The values of *K* in peak load, deflection at peak load, energy to max load, and total energy were 0.129, 0.151, 0.084, and 0.073 for type I and -0.331, -0.733, -0.862, and -0.741 for type II, respectively. The value of *K* was positive for type I, but negative for type II. This clearly indicated that the corrugated structure has a positive effect on the BCLC with unidirectional bamboo bundle layers, *versus* a negative effect in the case of cross-ply bamboo bundle composites.

CONCLUSIONS

1. A novel type of corrugated structural composite using bamboo bundle was successfully fabricated, and its mechanical behavior subjected to low velocity impact loading was studied. Three types of stacking sequences for composites were designed and compared under impact loading. A shape parameter, *K*, was developed to quantify the effect of corrugation on the impact performance.
2. It was found that the composites with unidirectional bamboo bundle layer running parallel to the corrugation (type I) has optimized impact properties, followed by cross-ply composites (type II). The composites with bamboo bundle perpendicular to the corrugated wave (type III) showed the weakest performance.
3. Material failure, interlaminar delamination with fiber tensile fracture, and corrugated structural collapse were the key failure models for type I, II, and III, respectively.
4. The corrugated structure had a positive effect on the type I composite, which can improve impact capability, but a negative effect on type II.

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