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Cross-Laminated Timber: A Review on Its Characteristics and an Introduction to Chinese Practices

Zhiqiang Wang and Tianxiao Yin

Abstract

Cross-laminated timber (CLT) is a popular engineering wood product in recent years. It has some characteristics of configuration and mechanical properties, which makes it an excellent building material for floor, roof and other places. In Europe and North America, lots of middle and high-rise buildings have adopted CLT as their main structural component. CLT has recently been used to construct public buildings in China. As a building material, the lower rolling shear properties of CLT has always been a concern. To overcome this shortcoming of CLT, the structural composite lumber and bamboo have been employed to develop hybrid CLT. This chapter also presents the latest development and advances of CLT in China.

Keywords: Cross-laminated timber, Configuration characteristics, Rolling shear, Hybrid cross-laminated timber, Development in China

1. Introduction

1.1 Background

Cross-laminated timber (CLT) is an engineered wood product (EWP) that was originally developed in Europe in the 1990s, which has been gaining worldwide popularity in helping define a new class of structural timber products known as massive or “mass” timber. It is an engineered wood-based solution that complements the existing light frame and heavy timber options and is a suitable candidate for some applications that currently use concrete, masonry, and steel systems [1].

CLT is a kind of prefabricated engineering wood made of layers of lumbers stacked crosswise (typically at 90 degrees) and glued together on their wide faces and, sometimes, on their narrow faces as well, by structural adhesive. In some specific structural requirements, the lumbers of adjacent layers can be laminated in non-90 degrees groups. Usually, CLT consists of an odd number of layers, such as 3, 5, and 7 layers, and in some cases more. CLT products are usually 0.6 m, 1.2 m, 2.4 m and 3 m in width, up to 18 m in length and up to 508 mm in thickness.

At present, CLT is usually used in buildings as floor, wall and other structural components. CLT used for prefabricated wall and floor assemblies offers many advantages, and the ‘reinforcement’ effect provided by the cross-lamination in

CLT also considerably increase the splitting resistance of CLT for certain types of connection systems.

1.2 Development of CLT in China

The Chinese researchers and manufacturers began to develop and produce CLT materials and buildings around 2010. A number of research teams have carried out researches on the physical and mechanical properties and connection properties of CLT. Domestic fast-growing wood species such as poplar, eucalyptus and Japanese larch, and wood-based panels, such as construction OSB (COSB) boards, have been developed to produce CLT and hybrid CLT (HCLT) [2–4]. At the same time, the researchers also studied the embedment performance of CLT, the mechanical properties of the CLT joints connected by self-tapping screws (STS) and the mechanical properties of the new tongue-and-groove CLT joints [5–8]. In terms of the standard, the Standard for Design of Timber Structures (GB 50005–2017) and the Technical Standard for Multi-story and High-rise Timber Building (GB /T 51226–2017) have the corresponding provisions on CLT materials and CLT structure height. For example, for the structural system of pure timber structure, the maximum number of floors allowed for the CLT timber shear wall structure is 12. For the concrete core timber structure, the maximum number of floors allowed for the CLT shear wall structure is 18. The industry standard Cross-laminated Timber (LY/T 3039–2018) was officially implemented in May 2019.

China's domestic CLT manufacturers have also started from scratch, and now there are 4 CLT factories located in Hebei, Shandong, Zhejiang and Jiangsu provinces. Among them, Jiangsu Global CLT Co., Ltd. was established in 2017, with an annual capacity of 60,000 m³ of CLT panels, as shown in **Figure 1**.

CLT buildings have been also developed in China. In 2019, Ningbo Sino-Canada Low-carbon Technology Research Institute Co., Ltd. built a 2-storey CLT public



Figure 1. Jiangsu global CLT Co., ltd. and internal CLT production equipment (source: Photo obtained from Jiangsu global CLT Co., ltd).

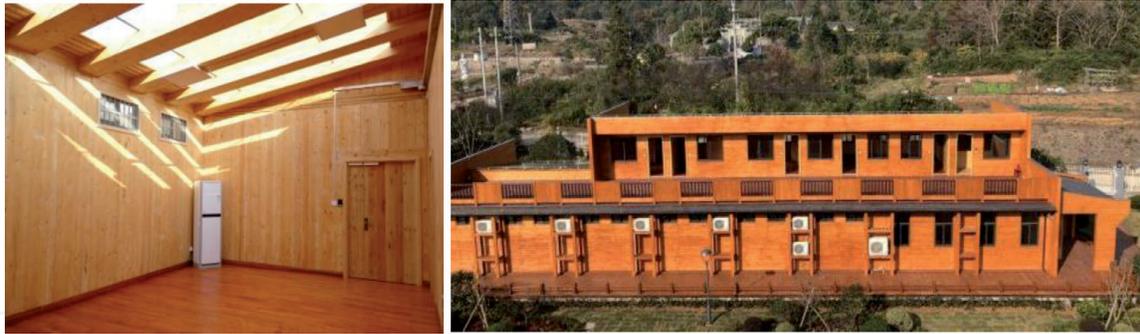


Figure 2.
CLT public residential building in China (source: Picture obtained from https://www.sohu.com/a/391796450_100108650).



Figure 3.
6-story timber structure research and development center in China (source: Photo obtained from Shandong DENCHWOOD CLT Co., ltd).



Figure 4.
CLT office building in China (source: Photo obtained from Jiangsu global CLT Co., ltd).

residential building, with a total area of nearly 1,500 m², as shown in **Figure 2**. CLT are used as floor, wall and roof panels of this building, and the amount of CLT used is 215 m³. In 2020, the first six-story pure timber structure building in China -- Shandong DENCHWOOD CLT Research and Development (R&D) Center project has been completed, as shown in **Figure 3**. The construction area of this building is 4771.96 m². The whole building employed glulam frame-shear wall structure as the main structure, and the elevator shaft and stairwell adopt 160 mm thick CLT as shear wall. In 2021, Jiangsu Global CLT Co., Ltd. completed a two-story, 1600 m² CLT office building, as shown in **Figure 4**. In this CLT building, CLT is used as floor panels (thickness 155 mm), wall panels (thickness 105 mm) and roof panels (thickness 105 mm), respectively, and the amount of CLT and glulam used are 406 m³ and 82 m³, respectively.



Figure 5.
CLT press (source: Photo obtained from Yantai Bohai woodworking machinery Co., Ltd).

Besides, the development of CLT equipment is also under way in China. In 2015, Yantai Bohai Woodworking Machinery Co., Ltd. developed China's first automatic CLT assembly/glue-pouring/feeding/pressing production line. The press is shown in **Figure 5**, and it was put into use in Shandong Zhongyi Senke Wood Structure Co., Ltd. The maximum size of pressing CLT products is 24 m long and 3.5 m wide.

2. Characteristics of CLT

Generic CLT products consist of odd number of layers of lumber or structural composite panel stacked crosswise by applying structural adhesives, such as phenol-resorcinol formaldehyde (PRF), emulsion polymer isocyanate (EPI), melamine formaldehyde (MF), one-component polyurethane (PUR), etc. In some CLT product standards, lumber is required to be 6–45 mm thick, 40–300 mm wide, and width- thickness ratio greater than 4. For three-layer CLT, the thickness of the transverse layer ranges from 6 to 60 mm [9], as shown in **Figure 6**. Structural composite panels used as layer in CLT include laminated veneer lumber (LVL), laminated strand lumber (LSL), oriented strand board (OSB) and so on.

On some special cases, the adjacent layers of CLT can be assembled in the same direction. For example, the outermost layers of a 5-layer CLT can be successively set with two parallel layers [9], as shown in **Figure 7**. In addition, some CLT layers are glued at an angle of 45 degrees between adjacent layers [10], as shown in **Figure 8**. Some researchers have developed a box-based CLT system used in floor applications for more diverse structural performance [11], as shown in **Figure 9**.

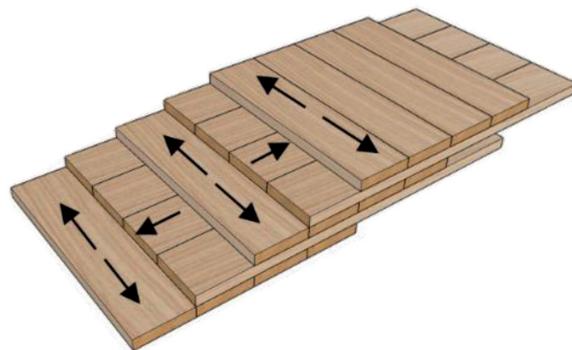


Figure 6.
Generic CLT configuration.

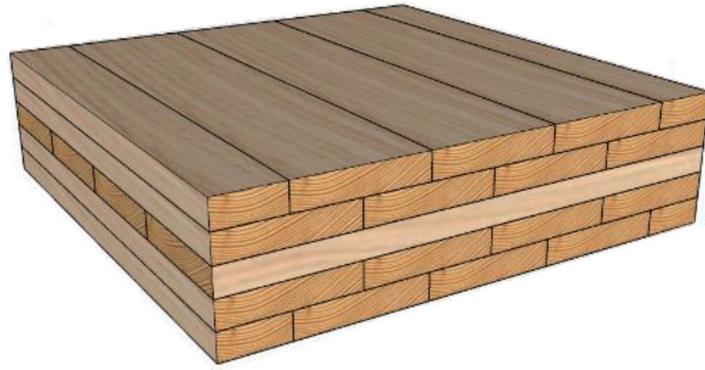


Figure 7.
CLT panel layup with two parallel layers in outermost layers.

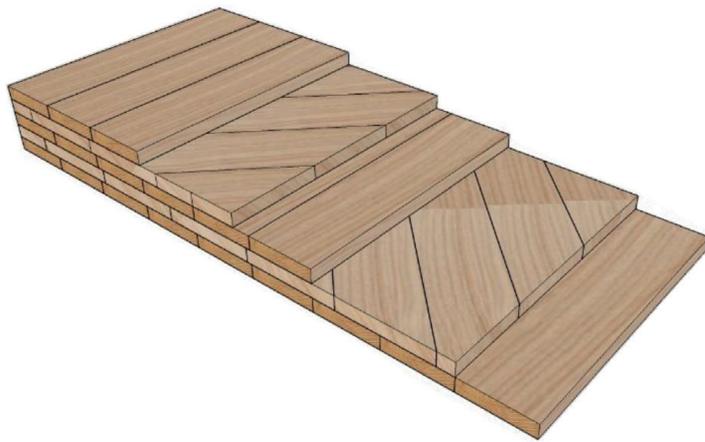


Figure 8.
CLT panel layup with $\pm 45^\circ$ alternating transverse layer configuration (adapted from Buck et al. [10]).



Figure 9.
CLT panel layup with box-based configuration (adapted from Chen [11]).

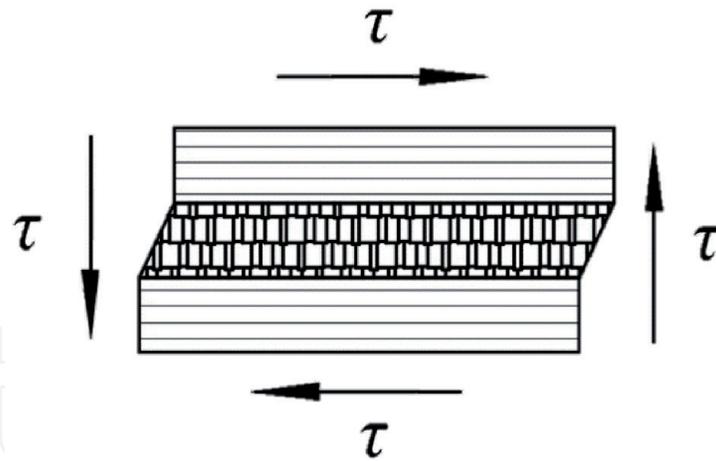


Figure 10.
Rolling shear of CLT.

In consideration of cost and the transverse deformation of the lumber, CLT may not apply adhesive between edges of the laminations at the same layer. If no adhesive is applied, the gap width between the laminations should not exceed 6 mm [9]. In addition, the vacuum pressurized CLT has stress relief to release the stress and reduce the warpage deformation of the CLT panel. However, the existence of gaps has adverse effects on CLT's mechanical properties (such as rolling shear properties), building physical properties (sound insulation, fire protection and thermal insulation properties), connection properties and product appearance, etc.

The orthogonality of CLT also makes the rolling shear failure of the transverse layers which is the key and main failure mode when CLT element is loaded with out-of-plane loads. Rolling shear, or called planar shear, usually refers to the behavior of shear strain occurring in the transvers layers, as shown in **Figure 10**. The cracks will initiate and propagate along the weak zones in the radial-tangential (RT) plane of wood transverse layer, resulting to low bending and shear strength properties. These weak zones include the earlywood/latewood boundary and wood rays. The rolling shear properties of wood are lower than those parallel to the grain of wood. For general wood or wood group used in CLT, such as spruce-pine-fir (SPF), Douglas Fir-L and Hem-Fir lumber, the assuming value of rolling shear modulus is only 50 MPa. The rolling shear properties is very important in the design of CLT products, which is the key factor in the design of CLT floor and roof panels [12].

3. Rolling shear properties of CLT

In recent years, researchers have mainly studied the rolling shear properties of CLT in two aspects: the evaluation method and influence factors of rolling shear properties of CLT. The employed testing methods for the rolling shear performance are mainly divided into two categories: compression shear and bending shear testing approaches. The influence factors of rolling shear properties of CLT include: the types of layer material (softwood, hardwood, and wood-based panels, etc.), macroscopic characteristics of lumber (growth ring orientation, and earlywood or latewood, etc.), processing technology (pressure and edge-gluing, etc.) and geometric characteristics of CLT, etc.

3.1 Factors influencing rolling shear properties

3.1.1 Types of layer materials

At present, CLT are mainly made of softwood, such as SPF, Norway spruce and other softwood. However, due to the low rolling shear modulus and strength of softwood, the development and utilization of hardwood and structural wood composite panels with high rolling shear properties to produce CLT has become one of the main research focus of CLT. Studies have shown that the rolling shear properties of some hardwood are higher than those of generic softwood. Aicher et al. [13, 14] studied the feasibility of using European beech wood (*Fagus sylvatica*) as transverse layer in CLT. They tested the rolling shear properties of European beech wood by compression shear method and found the rolling shear strength and modulus of European beech wood exceed the respective characteristic value for softwood by roughly factors of 5 and 7. In addition, a hybrid softwood-hardwood CLT build-up with outer layers of European spruce (*Picea abies*) and a center cross-layer of European beech (*Fagus sylvatica*) has been investigated with regard to out-of-plane bending. The novel investigations reveal the great potential of mixed softwood-hardwood CLT build-ups for structural elements in the building sector. Gong et al. [15] evaluated the rolling shear properties of cross hardwood lumber in HCLT. The tested wood species were spruce (*Picea mariana*), aspen (*Populus tremuloides*), white birch (*Betula papyrifera*) and yellow birch (*Betula alleghaniensis*). Based on their experimental results, it was found that the hardwoods (aspen and birches) exhibited a larger resistance to rolling shear stresses than that of softwoods (spruce). Ehrhart et al. [16] studied the rolling shear properties of some hardwoods and softwoods. They also found the hardwoods, such as birch (*Betula pendula* Roth), beech (*Fagus sylvatica* L.), poplar (*Populus spp.*), ash (*Fraxinus excelsior* L.), had higher rolling shear properties than that of softwood. In addition, some researchers have also studied the rolling shear properties of local wood, fast-growing wood and wood-based panels to evaluate the potential application of these materials in CLT. Wang et al. [17, 18] evaluated the rolling shear properties of normal and modified fast-growing poplar (*Populus tomentosa* Carr) modified by compression perpendicular to grain and impregnated with phenol-formaldehyde (PF) resin. Results showed that the characteristic value of rolling shear modulus and strength of normal fast-growing poplar were 177 MPa and 2.24 MPa, respectively, which are much higher than the properties of SPF, indicating the fast-growing poplar can be used as transverse layer in CLT.

3.1.2 Macroscopic characteristics of lumber

The influences of macroscopic characteristics, such as growth ring orientation and pith, on the rolling shear properties of lumber were studied. Zhou et al. [19] investigated the influence of growth ring orientation and laminate thickness on the rolling shear properties of wood cross layer (WCL). They found that the growth ring orientation had a significant effect on the rolling shear modulus of WCL but did not on the rolling shear strength. And when the growth ring orientation was 45°, the maximum rolling shear modulus and strength could be obtained. Aicher et al. [13] tested the rolling shear properties of specimens with different growth ring orientation and pith board. It was found that the semi-quarter-sawn boards revealed the highest shear moduli whereas the quarter-sawn boards showed roughly 30% lower values. Wang et al. [2] used the compression shear test method

of EN 408 to study the influence of macroscopic characteristics of fast-growing poplar sawn timber on the rolling shear properties. It was found the presence of pith had significant influence on the rolling shear properties of poplar board. Distance to pith and annual ring orientation both had effects on the rolling shear properties jointly. The rolling shear properties increase with the increase of distance to pith.

3.1.3 Manufacture technology of CLT

Yawalata et al. [20] studied the influence of different pressure on the rolling shear strength. When the pressure was 0.4 MPa and 0.1 MPa, the rolling shear strength of CLT was 2.22 MPa and 1.85 MPa respectively, and higher production pressure could improve the rolling shear performance of CLT. On the other hand, in order to prevent product deformation and save the cost of adhesives, the edge-gluing between laminations in the same layer are not applied in some manufacturers, resulting gaps between laminations. A study showed that the average width of the gaps in the transverse layers reaches 2 mm [21]. The maximum gap width allowed in the European CLT product standard EN 16351 is 6 mm. The existence of these gaps will have an impact on the rolling shear properties of CLT transverse layers. Gardner et al. [22] explored the effect of gaps between boards in transverse layers of CLT on shear strength. Five-ply specimens with gaps of 0, 6, 89 and 178 mm were subjected to short-span three-point bending tests. The digital imaging correlation (DIC) technique was used to quantify strains and displacements in transverse layers. It was found that panel shear capacity met the requirements of the PRG 320 standard for performance-rated CLT for the gap sizes tested, suggesting that small gaps did not reduce shear strength enough to warrant consideration in design. Wang et al. [23] evaluated the influence of edge-gluing and gap width (0 mm, 2 mm, 4 mm and 6 mm) between the transverse layers on the rolling shear properties. It was found that edge-gluing and gap size had a significant influence on measuring rolling shear strength rather than apparent rolling shear modulus by the modified rolling shear test method. With the gap size larger than 2 mm, its influence on measuring rolling shear strength became negligible.

3.1.4 Geometric characteristics of CLT

The research of effect of geometrical characteristics on rolling shear properties mainly focus on the thickness and the width-thickness ratio (γ) of layer. Sikora et al. [24] studied the influence of layer thickness on rolling shear properties. With the increase of the thickness of layers, the rolling shear properties tended to decrease, and the average rolling shear strength ranged from 1.0 MPa to 2.0 MPa. Li [25] used 35 mm and 20 mm thick layer to evaluate the influence of layer thickness on the rolling shear strength of CLT. It was found that the thickness had a significant effect on the rolling shear strength of CLT. Ehrhart et al. [16] tested CLT specimens with a constant thickness of 30 mm and different widths (60 mm, 120 mm and 180 mm), and found that the width-thickness ratio had a significant effect on the rolling shear strength and modulus. Gui et al. [26] studied the rolling shear properties of fast-growing eucalyptus lumbers with different width-thickness ratio ($\gamma = 2, 4$ and 6), and used the DIC technique to record and evaluate the rolling shear strain distribution during rolling shear tests. The result showed that the mean values of rolling shear modulus and strength of eucalyptus layer were 260.3% and 88.2% higher than those of SPF layer with the same width-thickness ratio of 4, respectively. The rolling shear properties of eucalyptus layers increased as the width-thickness ratio increased. The high shear strain regions were primarily found around the gaps

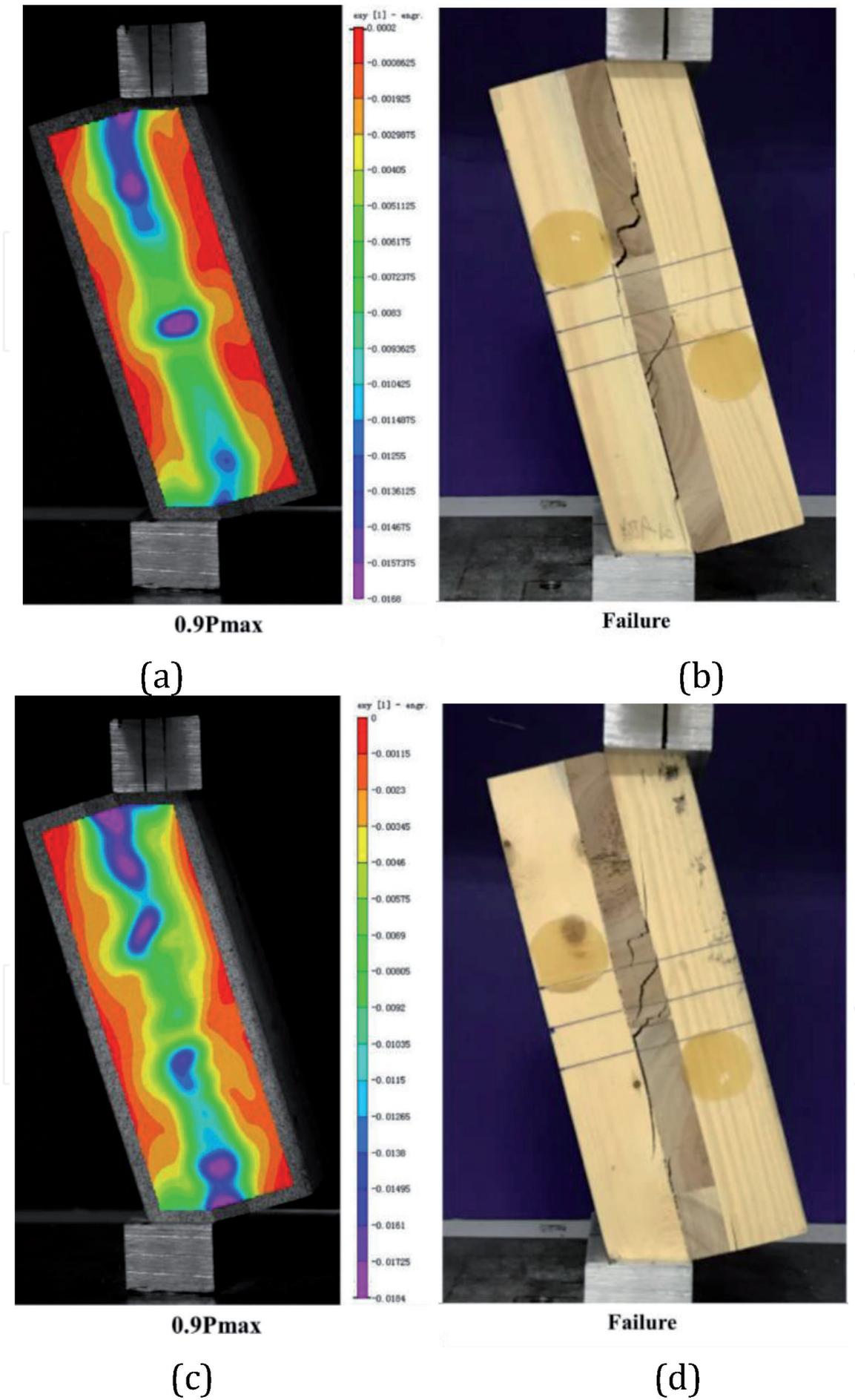


Figure 11. Strain distribution and failure of eucalyptus CLT specimens under rolling shear: (a) and (b) width-thickness ratio (γ) = 4, and (c) and (d) γ = 6 (adapted from Gui et al. [26]).

between segments of transverse layer. The quantity of high shear strain regions increased as the width-thickness ratio of layer decreased, as shown in **Figure 11**.

3.2 Failure mechanism of CLT caused by rolling shear stress

The rolling shear failure mode of lumber is closely related to its macroscopic characteristics. Wang et al. [27] found that the rolling shear failure of SPF dimension lumber mainly happened at the weak macroscopic characteristics in the radial-tangential (RT) section of lumber, such as the junction of earlywood and latewood and wood rays, as shown in **Figure 12**. On the other hand, Yang [28] used the acoustic emission (AE) technique to monitor the changes of AE parameters during the rolling shear failure process of CLT. By clustering analysis of AE signals of different wood species, the relationship between AE signals and the mechanism of the rolling shear damage of CLT was established, as shown in **Figure 13**. There are two kinds of AE events in CLT specimens during rolling shear failure process: the main AE events with middle amplitude and the secondary AE signal with high amplitude.

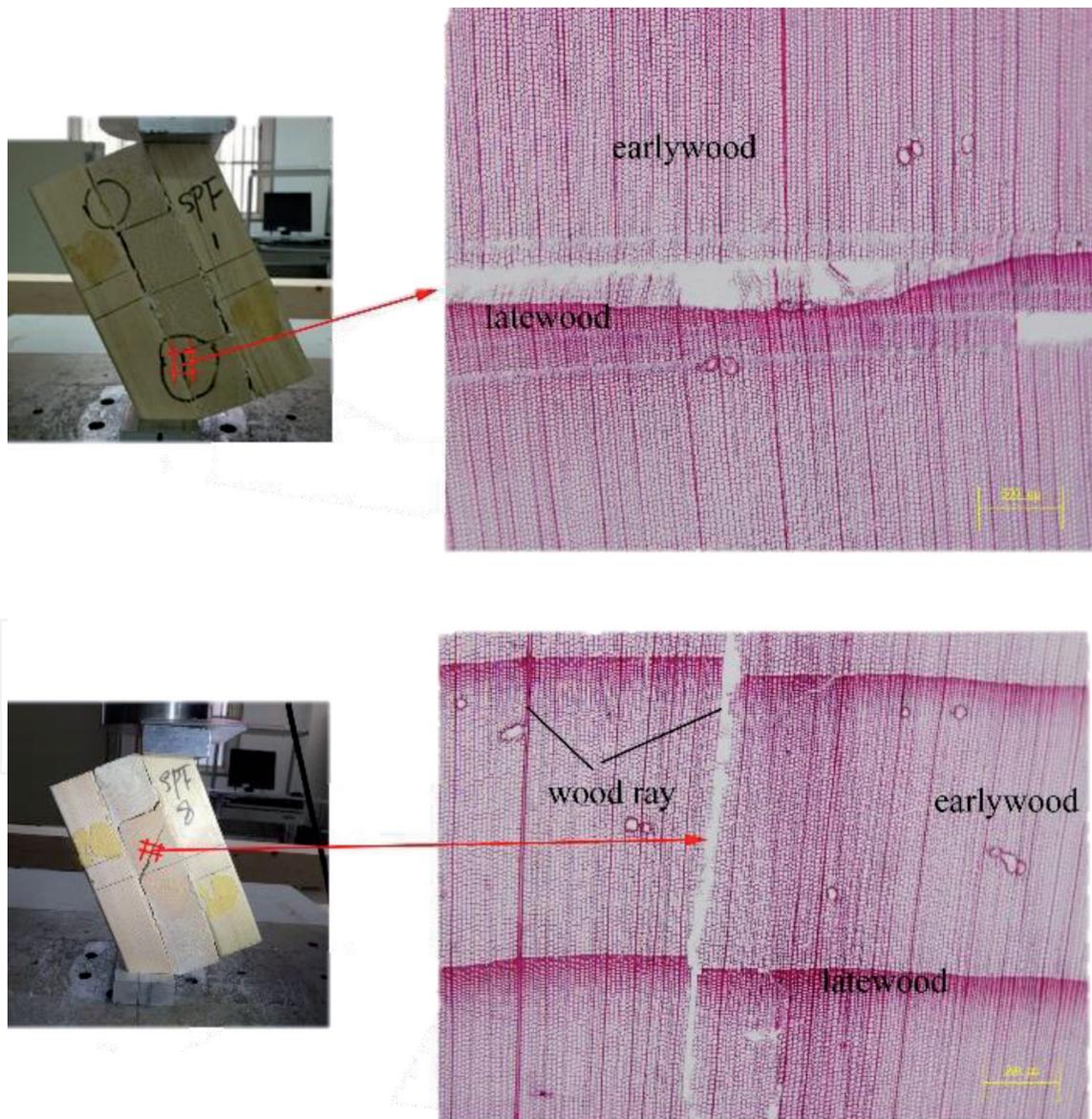


Figure 12. Microscopic images of failure modes of rolling shear of SPF CLT (adapted from Wang et al. [27]).

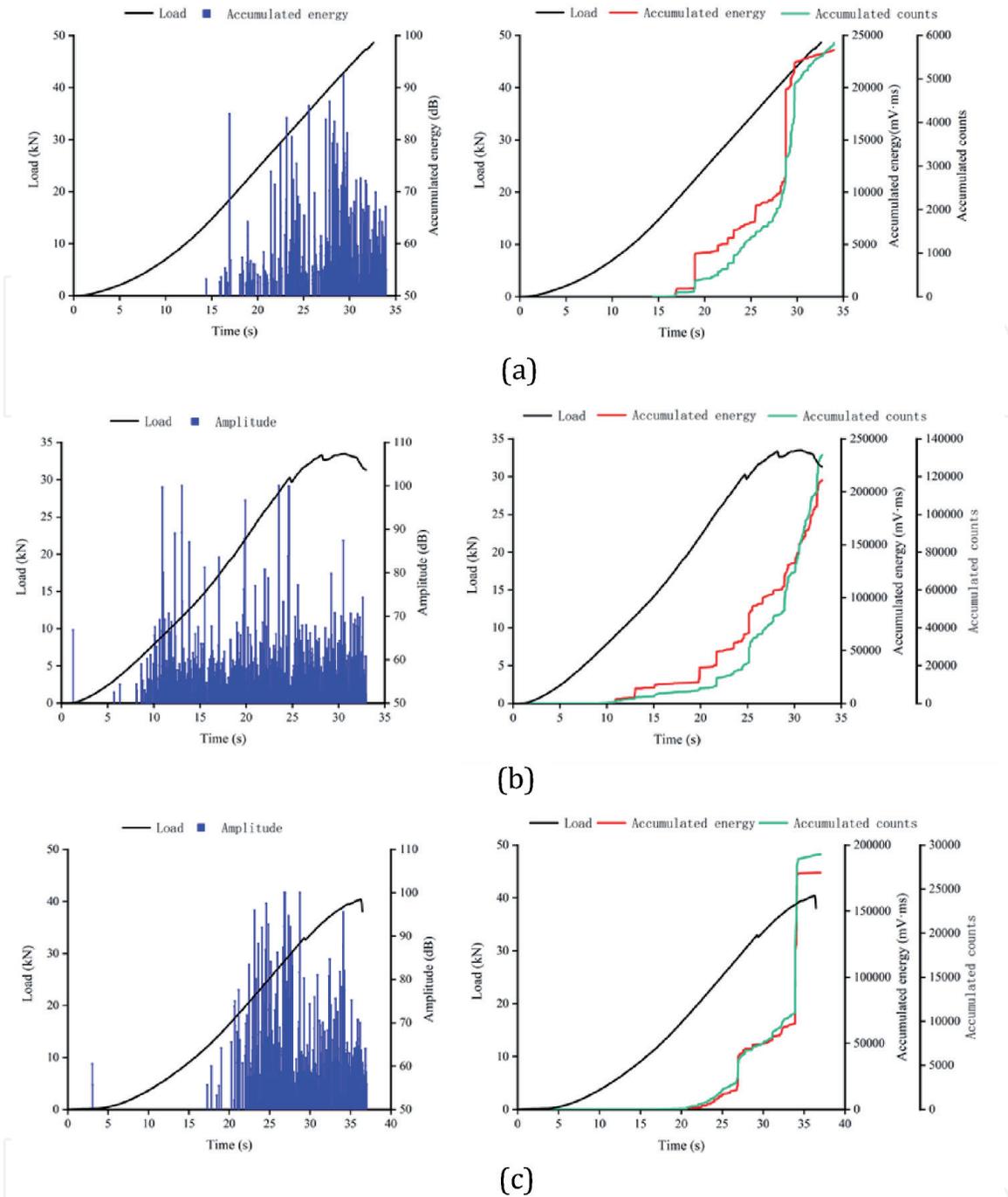


Figure 13. AE activity for 3 groups of CLT specimens during rolling shear failure, (a) SSS-4, (b) SHS-2, and (c) SZS-3 (adapted from Yang et al. [28]).

| Specimen | Main AE events | | | Secondary AE events | | |
|----------|----------------|----------------|--------------|---------------------|----------------|--------------|
| | Percentage (%) | Amplitude (dB) | Duration (s) | Percentage (%) | Amplitude (dB) | Duration (s) |
| SSS-4 | 88 | 52–68 | 14–34 | 12 | 67–91 | 17–34 |
| SHS-2 | 70 | 52–65 | 6–33 | 29 | 52–100 | 9–33 |
| SZS-3 | 80 | 52–70 | 17–37 | 19 | 52–100 | 19–35 |

Table 1. Statistical analysis of clustering features.

The duration of two kinds of AE events covered the whole process of rolling shear failure, while the duration of secondary AE events was slightly shorter than that of main AE events. The main AE events accounted for a high proportion, with AE amplitude within 70 dB, while the secondary AE events mainly distributed in the medium and high amplitude range, as shown in **Table 1**. Combined with rolling shear failure process of CLT, the main AE events might come from the accumulation of internal damage in the transverse layer. As the crack propagation, the accumulated energy was released continuously, thus producing the secondary AE events.

4. Research progress of hybrid CLT

In order to expand the source of CLT raw materials and improve the mechanical properties of CLT, the HCLT, i.e., CLT composed of laminations of different wood species, or composed of solid sawn wood and structural composite panels, has been developed. Compared with sawn timber, structural composite lumber (SCL) or structural wood-based panels have better mechanical properties and more sources of raw materials. Some studies have been conducted on the HCLT fabricated with sawn timber and SCL/ wood-based panels. The SCL/ wood-based panels employed in these studies included LVL, LSL, oriented strand lumber (OSL), COSB and plywood [27–35]. Wang et al. [29] fabricated the HCLT by mixing SPF and LSL, and when LSL was used as the outer layer (longitudinal layer), the modulus of elastic (MOE) and modulus of rupture (MOR) of HCLT increased by 19% and 36%, respectively, compared with the generic lumber CLT. When LSL was used as the cross layer (transverse layer), the MOE and MOR of HCLT were increased by 13% and 24%, respectively. Davids et al. [34] also obtained a similar research conclusion that the use of LSL hybrid structure could improve the bending performance of CLT, mainly because LSL had better mechanical properties (rolling shear properties and tensile properties) and more homogeneous mechanical properties than solid wood. Wang et al. [27] studied the mixing of SPF and LVL according to different layouts and formed three kinds of HCLT. It was found that due to the low rolling shear properties of LVL, the bending mechanical properties of CLT could be greatly improved only when LVL was placed in the outer layer. Other researchers studied the bending properties of HCLT mixed with Korean larch plywood (*Larix kaempferi Carr.*) and North American Douglas fir (*Pseudotsuga menziesii Franco*). When larch plywood was placed in the transverse layer of CLT, the experimental results showed that the MOE and MOR of CLT were improved with the increase of the number and thickness of larch plywood [35].

Furthermore, layers with different wood species have been studied to fabricate HCLT. Wang et al. [18] studied the mechanical properties of CLT mixed with different wood species. The results showed that the MOE, MOR and shear strength of HCLT formed by placing poplar lumber in the cross layer and Douglas fir lumber in the outer layer could be improved to some degree. Ukyo et al. [36] investigated the out-of-plane shear strength of HCLT with outer layers of hinoki (hinoki cypress, *Chamaecyparis obtusa*) and inner layers of sugi (Japanese cedar, *Cryptomeria japonica*). The influence from rolling shear properties of transverse layers on the shear strength of CLT, stress analysis was conducted using the shear analogy method. Pang et al. [37] analyzed swelling (S_w) and shrinkage (S_h) behaviors of CLT made of different species and various layer thickness and combinations. Compared to S_w and S_h of CLT made of larch, S_w and S_h of CLT made of pine showed lower values.

Bamboo has been extensively applied in composite industries due to its faster growth, higher specific strength and rigidity, and a relatively lower water swelling ratio compared with wood. The potential of using bamboo as CLT lamination has

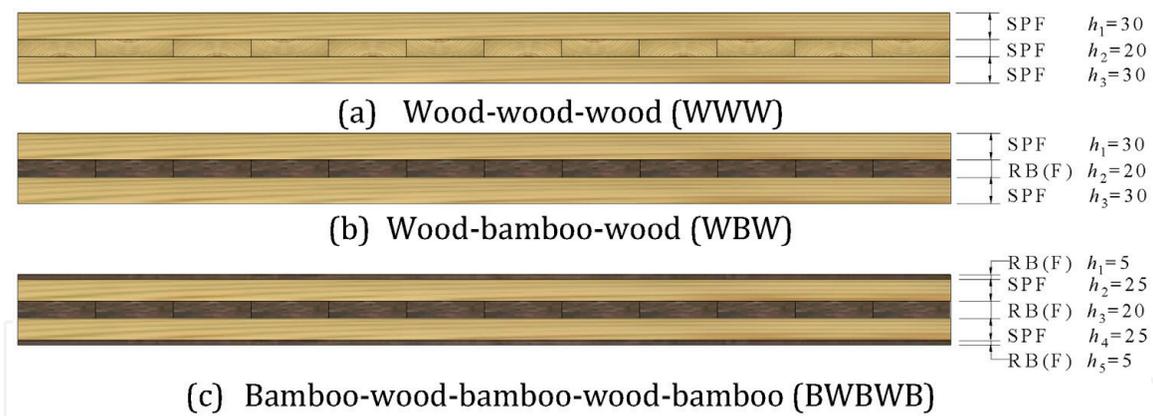


Figure 14. Configuration of bending specimen of CLT and CLTB (unit: mm). (a) Wood-wood-wood (WWW), (b) wood-bamboo-wood (WBW), (c) bamboo-wood-bamboo-wood-bamboo (BWBWB) (adapted from dong, [46]).

got attention in recent years with the development of CLT. So far, there are not many studies on composite cross-laminated timber-bamboo (CLTB). Wei et al. [38] investigated the feasibility of manufacturing composite cross-laminated timber (CCLT) from bamboo parallel strand lumber and hem-fir lumber. They found the rolling shear strength of CCLT was first governed by the low strength of hem-fir lumber, particularly in the direction perpendicular-to-grain. Munis et al. [39] added strips of *Dendrocalamus asper* bamboo species on the outer layers of generic wood CLT as reinforcement, and found a significant increase in the parallel compression-to-grain in the configuration of the CLT reinforced with bamboo in the longitudinal direction. Barreto et al. [40] evaluated the structural performance of CLTB produced from wood (*Pinus spp.*) and bamboo strips (*Dendrocalamus giganteus*). Their results showed a good potential of this composite CLTB for structural uses.

Bamboo resources are abundant in China. To make good use of bamboo, several engineered bamboo products (EBPs), such as bamboo scrimber, bamboo glulam and bamboo plywood, have been developed and utilized [41, 42]. Bamboo scrimber is a new engineering material made of bamboo via defibring and compositing technology that utilizes up to 90% raw materials [43]. Many studies have been carried out on the mechanical properties, e. g. tension and bending properties, of EBPs [41–45], however there are few studies on the rolling shear properties of them.

Dong [46] evaluated the rolling shear properties of two bamboo scrimbers and one bamboo plywood and the bending properties of CLTB. The configuration of the CLTB is shown in **Figure 14**. The results indicated that the rolling shear modulus and strength of bamboo scrimber were 92.65% and 98.53%, 337.89% and 120.31% higher than those of bamboo plywood and SPF dimension lumber, respectively. The bending properties of CLT can be improved by using bamboo scrimber as transverse or longitudinal layers, or a combination of the two layers. Compared with the generic SPF CLT, the apparent bending modulus of CLTB specimen having bamboo scrimber as transverse layer, increased by 3.54%; furthermore, the apparent bending modulus and strength of CLTB specimen, having bamboo scrimber both as transverse layer and the outermost longitudinal layer, increased by 23.69% and 60.43%, respectively.

5. Conclusions

Compared with other engineered wood products, CLT has unique structural and mechanical properties, which makes CLT widely used in medium and high-rise timber construction. In addition to Europe, other countries and regions in the

world are also paying attention to the development of CLT material and buildings. Hardwood, fast-growing wood, wood-based panels, bamboo, and local wood will be widely used in CLT materials.

In general, due to the orthogonal structure of CLT and the orthotropy of wood, the rolling shear properties have a significant effect on the mechanical properties of CLT. On the other hand, the layer material, the assembly structure, the fabricate process and the test method all affect the rolling shear properties of CLT. The mixing of different layer materials can effectively improve the rolling shear properties of CLT, and AE technology is helpful to evaluate the process and mechanism of rolling shear failure of CLT.

In China, product standards of CLT have been gradually established and improved, meanwhile, production and construction of CLT are in the stage of development. The development and production of HCLT using fast-growing wood, bamboo or wood-based panels, which are abundant in China, will greatly promote the development and application of CLT in China.

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