

Overview on Bending and Rolling Shear Properties of Cross-Laminated Timber (CLT) as Engineered Sustainable Construction Materials



W. C. Lum, M. B. Norshariza, M. S. Nordin, and Z. Ahmad

Abstract Cross-laminated timber (CLT) is one of the preferred engineered timber products (ETP) used in the construction and building industry. CLT is an orthogonal and laminar structure that can be used as full-size load-bearing structural elements such as wall, floor element as well as a linear timber member. The timber pieces are visually graded before being manufactured into CLT panels. As a result, CLT is able to provide enhanced stability and performance compared with its solid timber counterparts. In order to use CLT products in the construction of timber structures, characteristic bending and shear properties are important values in design. Thus, this chapter provides an overview of the bending and shear properties of CLT made from different timber species with various densities including timbers such as softwood, temperate hardwood as well as tropical hardwood. The factors influencing their properties are summarized and discussed. Their respective failure modes are also reported and discussed. This chapter also covers the general manufacturing process and the applications of CLT in the construction and building sector. Limitations, challenges dealing with the applications of CLT in the construction industries and the future of CLT are also discussed.

Keywords Engineered timber products · Cross-laminated timber · Sustainable construction materials · Bending properties · Rolling shear properties · Failure modes

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1 Introduction

Cross-laminated timber (CLT) is an engineered timber product (ETP) produced from sawn timber planks bonded together by the appropriate adhesive. CLT panels for construction consist of at least three layers of lamella made from either softwood or hardwood. Each timber lamination is arranged 90° (crosswise oriented) to each other. CLT is considered as a relatively new green construction material and was first developed in Switzerland and then further improved in Austria at the starting of twentieth century as an alternative building material to the conventional materials such as concrete, steel, masonry as well as solid timber (Zhou et al. 2014). Due to its orthogonal and laminar nature, CLT can be used as full-size load-bearing structural elements such as walls, floor structures, roofs elements as well as a linear timber member in a large number of innovative residential and commercial buildings (Wang et al. 2015).

There are many advantages in using CLT as preferred construction materials. Some notable advantages are summarized by Santoni et al. (2017). As summarized by the authors, CLT panels are commonly known to have high structural strength and can provide decent structural stability. CLT panels can be manufactured to fulfil specific safety requirements needed with cost-competitive to conventional building materials such as concrete, masonry and steel. Furthermore, the various construction elements can be prefabricated using CLT panels and are more time and labour efficient during onsite assembly. Recently, CLT is gaining traction worldwide as it is proven to be an environmentally friendly and sustainable engineered timber product. The CLT panel used in construction stores CO_2 in the timber in a process known as bio-sequestration. Another benefit mentioned is the ability to convert lower grade or lower class timber into a higher grade CLT panel. The lower grade timber can be used in the neutral axis or the transverse layer where the effect of the tension and compression is minimal.

Until recently, the manufacturing and applications of CLT are mostly confined to its region of origin in Central Europe. In the early twenty-first century, the applications of CLT as structural elements became widespread in Austria, Germany, Norway, Sweden, Switzerland and the United Kingdom (Crespell and Gagnon 2010). However, CLT is rapidly gaining traction outside these regions. Countries like the United States of America, Australia and New Zealand are starting to realize the potentials and benefits of CLT. CLT panels have excellent strength and stiffness as well as improved dimensional stability, which allow it to be used as a wide range of structural elements in various types of buildings. Buildings constructed using CLT are structurally simple and yet provide better design versatility at the same time. Other benefits of the incorporation of CLT in the construction industry are fast installation, decreased waste, less carbon emission, improved thermal performance and high seismic performance (Liao et al. 2017; Viguier et al. 2015).

It is necessary to understand the various properties of CLT products, as well as the entire building system incorporating CLT panels as structural elements for better standardization. In order to better introduce CLT products in the construction of

timber structures, characteristic bending and rolling shear properties are important values in design. Therefore, this chapter covers an overview of the bending and rolling shear properties of CLT made from different timber species and also factors affecting the bending and rolling shear properties. The bending and rolling shear failure modes are also reported and discussed. The manufacturing process of CLT is briefly outlined as well.

2 Manufacturing Process Of CLT

CLT panels are generally manufactured in three or more layers with the same thicknesses of laminations. The layers are arranged in a 90 degree of traverse pattern. The manufacturing process of CLT panels, which generally involves the following steps, is illustrated in Fig. 1:

- (i) Lamella selection, grading and classification
- (ii) Lamella finger jointing
- (iii) Lamella cutting to length and planning
- (iv) Panel lay-up
- (v) Adhesive application
- (vi) Assembly pressing
- (vii) CLT online quality control, machining and cutting
- (viii) Product marking, packaging and shipping.

The effectiveness of the CLT manufacturing process depends on the consistency of the timber quality and the control of the parameters that affect the quality of adhesive bond.

3 Bending Properties Of CLT

Bending properties such as modulus of rupture (MOR) and modulus of elasticity (MOE) of CLT are normally determined using a four-point bending test. EN 408 and EN 16,351 are generally referred in the determination of bending properties, especially in Europe. In the literatures given below, some modified testing methods were also been used based on the specimens and specified criteria being studied and determined. The bending properties from various literatures are summarized in Table 1.

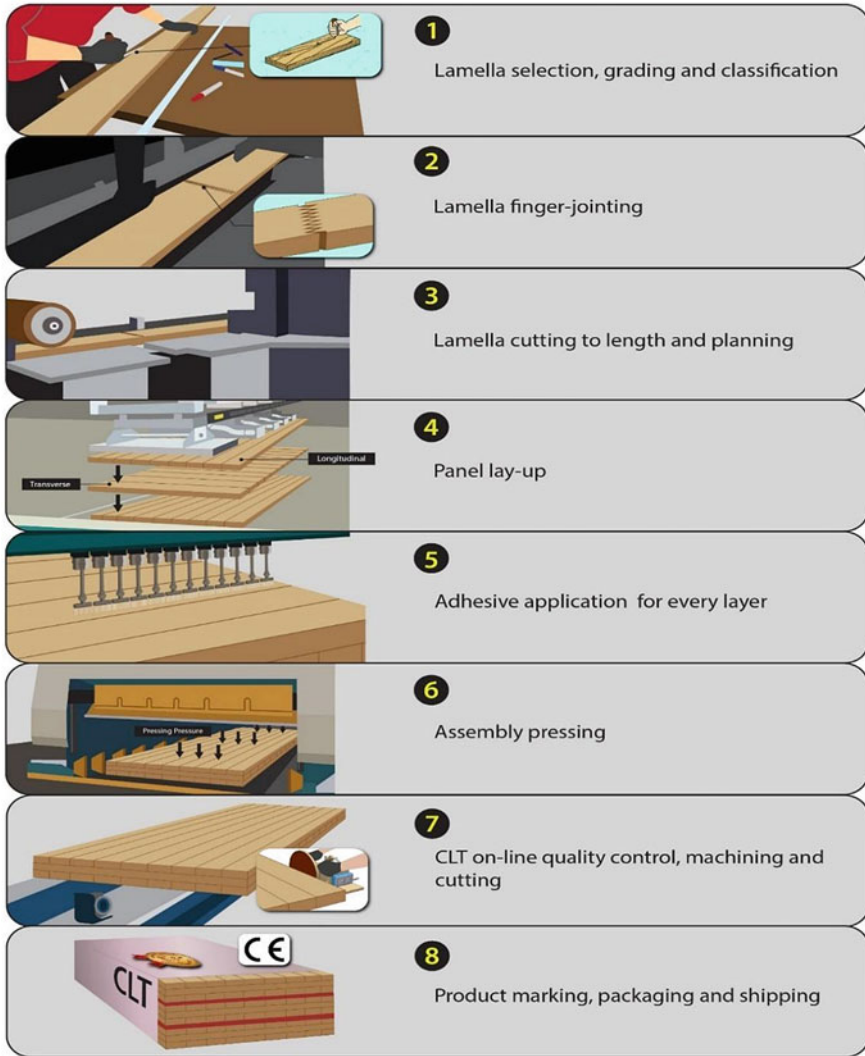


Fig. 1 Schematic diagram for typical CLT manufacturing processes

3.1 Factors Affecting Bending Properties

3.1.1 Timber Species and Density

Several researchers have studied the effects of timber species and density on the bending properties of CLT panels. In the study carried out by Franke (2016), beech (*Fagus spp.*) CLT showed better bending properties than spruce (*Picea spp.*) CLT. The result was expected as Beech (690 kg/m^3) having a higher density than spruce

Table 1 Bending properties of CLT panels correspond to the timber species used, testing methods and other related parameters

Timber species	Parameters	Testing method/comments	MOR (N/mm ²)	MOE (N/mm ²)	Reference
<i>Eucalyptus urograndis</i> , <i>Pinus taeda</i>	Species	Three-point bending	–	11,740 5461	Pereira and Calil (2019)
<i>Eucalyptus nitens</i> , <i>Eucalyptus globulus</i>	Species	Four-point bending	34.58–55.50 52.01–64.16	8900–12,100 11,000–13,700	Pangh et al. (2019)
<i>Acacia mangium</i>	Species, Type of adhesive	Four-point bending	27.78–36.55	10,740–12,693	Yusof et al. (2019)
Irish Sitka spruce (<i>Picea sitchensis</i>)	Species, thickness of panel	Four-point bending – 60 mm – 100 mm	35.71–35.98 34.08–34.43	7319–9552 6310–8404	O’Ceallaigh et al. (2018)
European Norway spruce (<i>Picea abies</i>)	Layer configuration	Four-point bending – CLT 90° – CLT 45°	35.2 47.5	8243 9517	Buck et al. (2016)
Beech (<i>Fagus</i> sp.)	Species	Four-point bending	43.8	12,306	Franke (2016)
Sesenduk (<i>Endospermum malaccense</i>)	Species	Four-point bending	47.14	13,069	Hamdan et al. (2016)
Irish Sitka spruce (<i>Picea sitchensis</i>)	Species, lamella thickness	Four-point bending – 40 mm	24.56–37.67	–	Sikora et al. (2016)

(470 kg/m³). The result was in agreement with the results obtained by Pereira and Calil (2019). Pereira and Calil (2019) tested CLT panels made from *Eucalyptus* timber and *Pinus* timber for bending properties. Their results showed that CLT panels produced from *Eucalyptus* timber exhibited higher strength and stiffness values compared to the panel made from *Pinus* timber. This result was well anticipated as the *Eucalyptus* panels produced in the study had a higher density than the *Pinus* panels. It is worth noting that *Eucalyptus* specimens showed higher drying defects after manufacturing and testing, however, the specimens did not show cracking. On the other hand, *Pinus* specimens include more natural growth defects, such as large knots, which may have reduced MOE of the *Pinus* specimens.

The study by Pangh et al. (2019) showed that two fibre managed plantation species, i.e., *Eucalyptus nitens* and *Eucalyptus globulus* displayed higher flexural performance than other eucalyptus species reported in the literature. They also reported that the MOE and MOR of the CLT panels made from both species are positively correlated

to the stiffness of the timber planks used in the top and bottom layers of the CLT specimens. It is generally known that, under flexural test, the top and bottom surfaces are subjected to compression and tensile load, respectively, and the middle layer acts as the neutral axis. This phenomenon is especially true in CLT panels where the middle layer is perpendicular to the top and bottom layers. This also explains the low rolling shear values in the middle layer during the bending test. Rolling shear properties of CLT will be further discussed in Sect. 4 of this chapter.

3.1.2 Type of Adhesives

The types of adhesives used also have an influence on the bending properties of CLT panels, as shown by the study of Yusof et al. (2019). The researchers studied the bending properties of CLT panels made from *Acacia mangium* bonded using two types of adhesives, namely, phenol-resorcinol-formaldehyde adhesive (PRF) and Polyurethane reactive adhesives (PUR). As demonstrated by their research, the mean MOE of the PRF-bonded panels was 12,639 N/mm², while the mean MOE of PUR bonded panels was 10,740 N/mm². The PRF-bonded panels showed better MOE properties, which was an 8% increment compared with PUR-bonded panels. The MOR of both types of panels also showed a similar trend. The mean MOR values of PRF-bonded panels (36.55 N/mm²) were 14% higher than those of PUR-bonded panels (27.78 N/mm²). It should be noted that the CLT panels produced in this study exhibited higher MOE but lower MOR compared with the results from the literatures.

3.1.3 Lamella Thickness and Layers Configuration

Other factors that influence the bending properties of CLT include Lamella thickness, size effect and layers configuration. Sikora et al. (2016) designed an experiment to determine the MOR, MOE and failure mode for CLT panels made from Irish Sitka Spruce (*Picea sitchensis*). Different thickness of lamella was set as the parameters in the study. In the study, the mean MOE results for each group of specimens tested were calculated per meter width. The researchers reported that there-ply CLT panels with the thickest lamella of 40 mm exhibited the highest MOE values. They also found out that increasing the thickness of the lamella from 20 to 40 mm increased the MOE values as much as 687–698%.

Buck et al. (2016) conducted a study to determine the effect of layer configuration on the bending properties of CLT panels. CLT panels with 45° or 90° alternating transverse layers were produced in the study. Four-point bending was used to determine the desired bending properties. They reported that CLT panels with 45° transverse layers performed better in bending tests when compared with conventional 90° transverse layers. The MOR of CLT with the 45° transverse layer increased by 35% while the MOE increased by 16% when compared with the CLT panels made with transverse layers arranged at 90°.

Results from past studies suggested that the MOE of CLT significantly depends on its lamella thickness. The higher the lamella thickness the higher the MOE. However, the MOR was statistically unfaceted by the lamella thickness of CLT specimens. Also, the orientation degree of the transverse layer has a significant effect on the MOR and MOE. The 45° arranged transverse layer shows both higher MOR and MOE.

3.2 Failures Modes of Bending Test

Generally, three modes of failure were observed in all CLT panels in the literatures, i.e. tension failure (Fig. 2), rolling shear failure (Fig. 3) and combined tension and rolling shear failure (Fig. 4). These failures were often accompanied by glue line failure. Pangh et al. (2019) reported that *Eucalyptus niten* CLT panel made with utility-grade timber failed on the tensile side. On the other hand, the CLT panels



Fig. 2 Tension failure

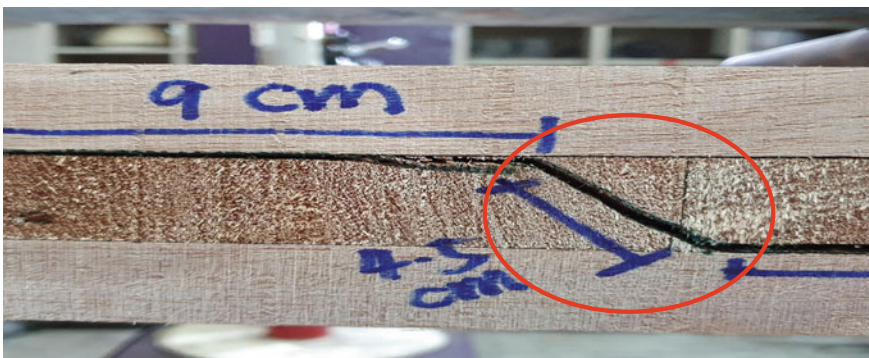


Fig. 3 Rolling shear failure

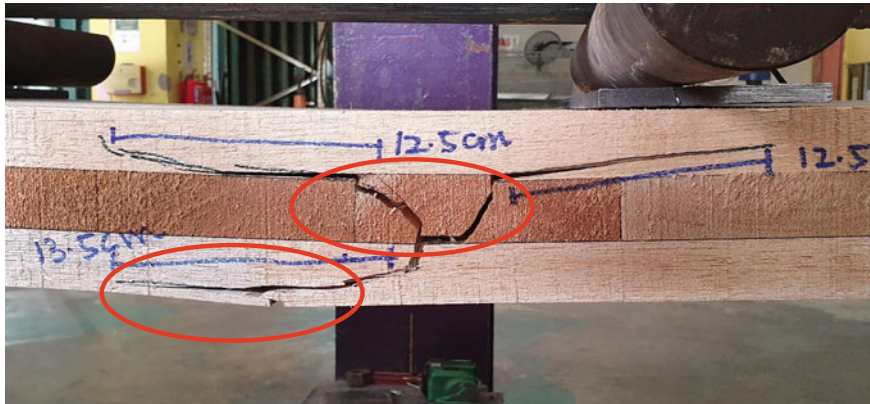


Fig. 4 Combined tension and rolling shear and failure

made with higher grade timber failed by rolling shear. Some degree of splitting was also observed in panels made with higher grade planks along with pure shear failure at the cross-section. However, CLT panels made from *Eucalyptus globulus* using higher grade planks failed under combined tension and rolling shear. The research also suggested that CLT panels produced from higher grade planks generally failed in the transverse layer due to rolling shear associated with splitting of the glue line. Based on the failure mode that occurred, the researcher concluded that the rolling shear strength of the CLT panels in the transverse layer together with the adhesion properties governs the overall bending performance of CLT panels.

Yusof et al. (2019) also found out that the CLT specimens they tested displayed similar modes of failure. The first type of failure mode is failure due to rolling shear stress in the transverse layer. This failure mode is more prevalent in PRF-bonded CLT than PUR-bonded CLT. The second failure mode occurred in the glue line, when the adhesive failed to sustain the subjected load. This type of failure mode was more commonly found on PUR-bonded CLT. The third failure mode is tension failure. This failure mode mostly happened in the tension zone of the lowest outer layer. Only PRF-bonded CLT showed this kind of failure mode. Sousa et al. (2013) also reported similar findings. The CLT specimens tested have mostly failed in the tension zone in the outermost layer and glue line failure in the middle layer. This finding is in agreement with the finding by Mohamad et al. (2011), which reported that the initial failure of the tested specimens often occurs in the glue line rather than in woods. Because of the existence of finger joint and adhesive in the CLT panels, most specimens tested exhibited brittle failure mode when compared with solid timber without finger joint and adhesive (Sikora et al. 2016).

Lim et al. (2020) reported that CLT panels treated and untreated with preservatives generally showed the same shear failure mode under four-point bending test setup. The load–deflection curves of the both CLT specimens were linear up to approximately 70% of their maximum loads. Then, the curves became nonlinear as shear cracks formed in the core layers at inclined angles. The nonlinearity became more

severe as the shear cracks propagated towards the glue lines. Eventually, the wood fibres surrounding the cracks fractured in a brittle manner, which caused the load to abruptly drop.

4 Rolling Shear Properties of CLT

Rolling shear (RS) stress in CLT panel is defined as the shear stress acting on the radial–tangential plane perpendicular to grain, in other words, the shear stress of the cross-layers or transverse layers in CLT (Fellmoser and Blaß 2004). Rolling shear property of CLT panels is the decisive factor influencing the other mechanical properties of the panels such as MOR and MOE (Aicher et al. 2016). RS values of timber are rather low, normally in the range of 1.33–6 N/mm² (Table 2) when compared with its longitudinal shear values. As a result, precisely measuring the cross-layer’s rolling shear properties is critical for CLT product design and application (Zhou et al. 2014). Rolling shear properties of CLT panels correspond to the timber species used, testing methods and other related parameters are summarized in Table 2. Typical rolling shear failure is shown in Fig. 5.

Rolling shear properties of CLT panels are determined by using either bending test method or two-plate shear test method. EN 408 and EN 16,351 are commonly used. However, it was commonly regarded that the two-plate shear test was a more appropriate test method for assessing the rolling shear modulus of a cross-layer in CLT. On the other hand, the bending test is more appropriate to determine the shear strength of CLT. It is because the bending test method could produce a failure mode more similar to that when CLT panels are subjected to bending load, which is a common loading configuration in the construction of building that produces rolling shear failure.

4.1 Factors Affecting Rolling Shear Properties

4.1.1 Influence of Species, Density and Sawing Pattern

According to Aicher et al. (2016), the rolling shear modulus of the tested CLT specimens was weakly correlated to their corresponding density regardless of the sawing pattern of the timber planks. However, when comparing CLT panels made with flat-sawn and pith boards, the difference in rolling shear modulus was about 20%, which was rather significant. The researchers also reported that, among the flat-sawn, quarter-sawn and semi-quarter-sawn specimens, semi-quarter-sawn specimens exhibited the highest rolling shear values. It can be concluded from the research that sawing pattern exerts more influence on the rolling shear modulus than the board density. Another study by Franke (2016) compared the rolling shear strength of CLT made of spruce and beech, respectively. The researcher found out that the rolling

Table 2 Rolling shear properties of CLT panels correspond to the timber species used, testing methods and other related parameters

Timber Species	Parameters	Testing method/comments	Rolling shear strength (N/mm ²)	Rolling shear modulus (N/mm ²)	Reference
United States grown southern yellow pine (<i>Pinus</i> spp.)	Species, Chemical treatment (micronized copper azole type C)	Four-point bending test (untreated) Four-point bending test (treated)	1.70–2.79 1.33–2.51	100–181 94–260	Lim et al. (2020)
Southern yellow pine (<i>Pinus</i> spp.)	Species, Presence of knots	Two-plate shear tests -No knot -With knot Short span bending test -No knot -With knot	1.95–2.05 2.33–2.62 1.77 1.86–1.92	–	Cao et al. (2019)
Irish Sitka spruce (<i>Picea sitchensis</i>)	Thickness of panel	Four-point bending -60 mm -100 mm	2.14–2.22 1.39–1.40	–	O’Ceallaigh et al. (2018)
New Zealand Radiata pine (<i>Pinus radiata</i>)	Species, Testing method	Short-span bending tests Modified planar shear tests	1.97–2.45 1.99–2.33	–	Li (2017)
European beech wood (<i>Fagus sylvatica</i>)	Species, The presence of pith	Two-plate shear tests -with pith -without pith	4.5 6.0	370 370	Aicher et al. (2016)
Beech (<i>Fagus</i> sp.)	Species	Short-span bending tests	3.8	–	Franke (2016)
Irish Sitka spruce (<i>Picea sitchensis</i>)	Species	Four-point bending	1.09–2.09	–	Sikora et al. (2016)
Black spruce (<i>Picea mariana</i>)	Species, testing method	-Two-plate shear tests -Variable span bending test	2.57–2.84 2.02–2.13	31.55–38.12 46.27–88.53	Zhou et al. (2014)

shear strength beech CLT is more than two times higher than spruce CLT. This was owing to the fact that beech wood has a higher density than spruce wood.

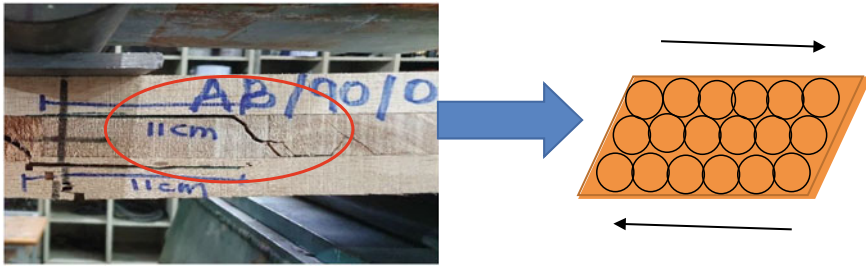


Fig. 5 Rolling shear phenomenon in CLT panels

4.1.2 Knots, Piths and Defects of Timber

In a study done by Cao et al. (2019), the RS strength of CLT specimens composed of cross-laminations with three knot conditions (without knot, intergrown sound knot and encased decayed knot) was determined. Surprisingly, the CLT panels made from the lamellae that contain knots exhibited better RS strength. The results obtained from this research suggest that the presence of knots in CLT panels did not adversely influence the RS strength properties. Furthermore, when comparing CLT panels made of lamellae with pith to CLT panels made of lamellae without pith, it was discovered that there was no substantial difference in RS strength between the two. The researchers also proposed that a two-plate shear test was more appropriate to be used to investigate the effects of particular cross-lamination features or conditions on RS strength. This is because the short span bending test method was more conservative, and the results obtained were not significantly affected by the heterogeneity of the cross-lamellae. Aicher et al. (2016) studied the effect of piths on the rolling shear strength of solid beech wood. However, the results were in contrast with those of Cao et al. (2019). Aicher found out that the pith in the specimens did indeed adversely affect its rolling shear strength. But it is worth noting that the specimens used were solid timber without taking the glue line of typical CLT specimens into consideration.

4.1.3 Lamella and Panel Thickness

Li (2017) studied the effect of lamella thickness (20 mm and 35 mm) on the RS strength properties of CLT panels made from Radiata pine. Short-span bending test and two-plate shear test were used to determine the RS properties. Both testing methods yielded similar results. The RS strength values of 20 mm thick lamella ranged from 2.33–2.45 N/mm². On the other hand, the RS strength values of 35 mm thick lamella ranged from 1.97 to 1.99 N/mm². In the bending tests, due to the short span, relatively high compressive stresses perpendicular to grain may be introduced in cross-layers thus affecting the evaluation of RS strength in cross-layers. In the modified planar shear tests, the specimens were loaded in a relatively “pure shear” mode and the minor compressive stress introduced by the small angle between the

loading direction and the specimen major direction may not significantly affect the RS evaluation. Such a relationship between the lamination thickness and the RS strength can be also explained by the size effect on RS strength of wood. Besides the lamination thickness effect on RS strength, the width-to-thickness of laminations is also believed to affect RS strength evaluations. Sikora et al. (2016) also noted that RS strength was also adversely influenced by increasing CLT thickness. O’Ceallaigh et al. (2018) study the effects of panel thickness or the number of layers on the rolling shear strength of CLT. Two panel thicknesses of 60 mm (three-layered CLT) and 100 mm (five-layered CLT) were investigated. Four-point bending according to EN 408 was used to determine the material properties of CLT specimens. They found out that the rolling shear strength of CLT with 60 mm thickness ranged from 2.14 to 2.22 N/mm². On the other hand, the rolling shear strength of CLT with 100 mm thickness ranged from 1.39 to 1.40 N/mm². Thus, they concluded that rolling shear strength decreases as the panel thickness increases. However, the number of layers shows a negligible effect on the rolling shear strength.

4.1.4 Effects of Chemical Treatment

Lim et al. (2020) study the effect of chemically treated CLT panels on the rolling properties of the specimens. The specimens were subjected to a four-point bending test. From the results yielded, it was clear that preservative-treated CLT specimens had lower RS strength (1.87 N/mm²) than the ones without treatment (2.16 N/mm²). However, the treated CLT specimens showed higher RS modulus (147.72 N/mm²) than the specimens without treatment (132.11 N/mm²). It should be noted that the differences in the RS properties of the untreated and the treated CLT specimens were not statistically significant. Both treated and untreated CLT specimens exhibited rolling shear failure. Only untreated CLT specimens showed secondary bending failure modes near their loading points.

4.2 Failure Modes of Rolling Shear Test

Rolling shear failures from solid timber and CLT are discussed together in this subchapter to give a better understanding of the material properties. These failure modes are resulted from bending test and two-plate rolling shear test. This subchapter focuses on the failure mode of CLT tested using two-plate rolling test. In the two-plate shear tests, the specimens are subjected to a relatively “pure shear” loading. The failure modes of CLT specimens resulted from bending tests are discussed in Sect. 3.2.

In a study by Zhou et al. (2014), RS failure was studied using two-plate shear test and four-point bending test. When subjected to two-plate shear test (Fig. 6), the cracks started within the earlywood zone near the boundary between two growth rings, propagated in a zigzag pattern along growth rings and wood rays and accumulated in the

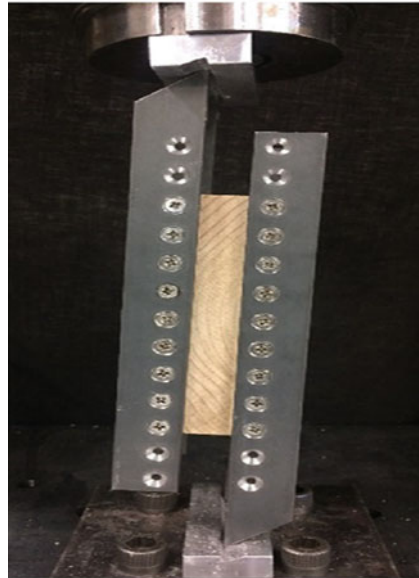


Fig. 6 Two-plate planar rolling shear test setup (Source Li 2017)

bonding area until delamination appeared (Fig. 7). Furthermore, rolling shear failure was observed in several locations along the cross-layer direction, demonstrating that the two-plate shear test was capable of producing nearly pure shear along the specimen. When subjected to four-point bending test, shear failure also initiated as a

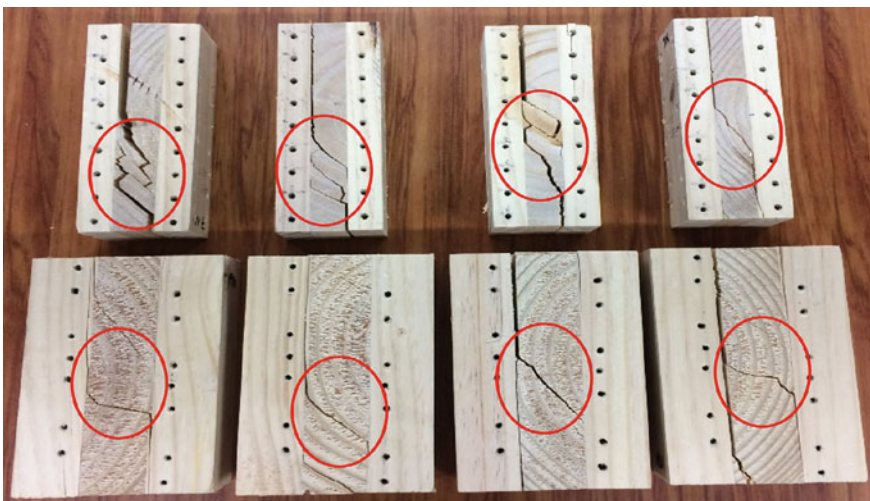


Fig. 7 Typical rolling shear failure of CLT specimens (Source Li 2017)



Fig. 8 Rolling shear failure of beech lamination (Source Aicher et al. 2016)

crack in the earlywood zones of the cross-lamination between the loading point and reaction support, mainly propagated along wood rays and secondly along a growth ring. Finally, specimens failed at the bonding surface or delaminated because of shear.

Lamella thickness and the presence of pith also affect the failure mode of CLT panels. Aicher et al. (2016) reported that solid beech lamination with piths exhibited pre-cracked and significant cracking under shear loading. Figure 8 shows the failure mode of beech lamination with the presence of pith. Cao et al. (2019) also found out that, for CLT made from yellow pine, initial shear cracks appear in the piths or in the earlywood/ decayed zone (brim) of the knots. Cracks propagated along or across the wood grain as shear stress increased, following the decayed knots' border. RS failures were found in all of the tested specimens, with cracks observed in the core layer at inclined angles to the glue lines. The failure patterns of the specimens showed that the sound knots prevented the fibres of cross-laminations to roll over each other, resulting in severe wood failure near the glue lines. The rolling shear failure mode of CLT made from yellow pine is illustrated in Fig. 9.

5 Applications of CLT in the Construction Industry

Structural components made from CLT are used primarily for walls and floor structures, but CLT panels may be used for a wide range of different applications, from small to large scale. Other applications of CLT include lift shafts and stairwells. Figure 10 illustrates the applications of CLT in the construction industry.

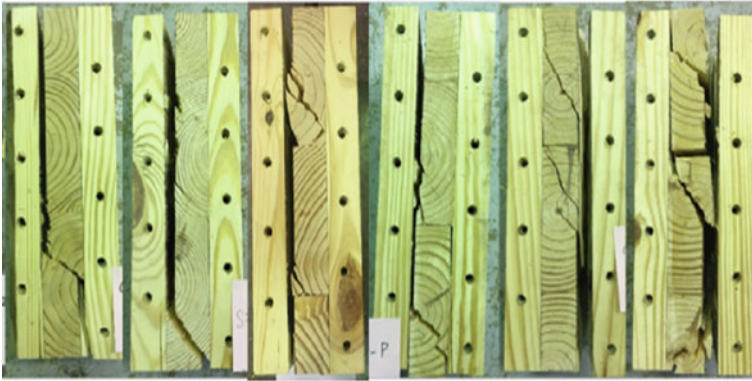


Fig. 9 Rolling shear failure of CLT specimens made with yellow pine (Source Cao et al. 2019)

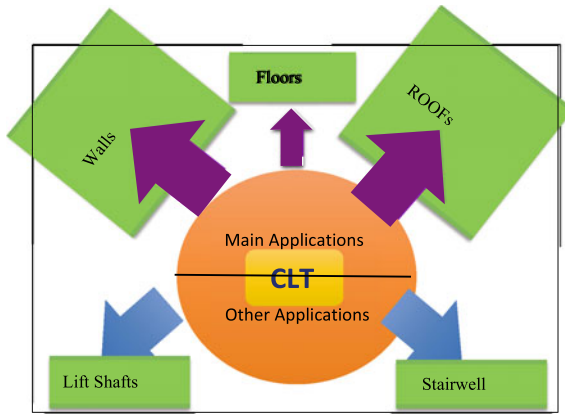


Fig. 10 Applications of CLT as load-bearing structural elements in the construction industry

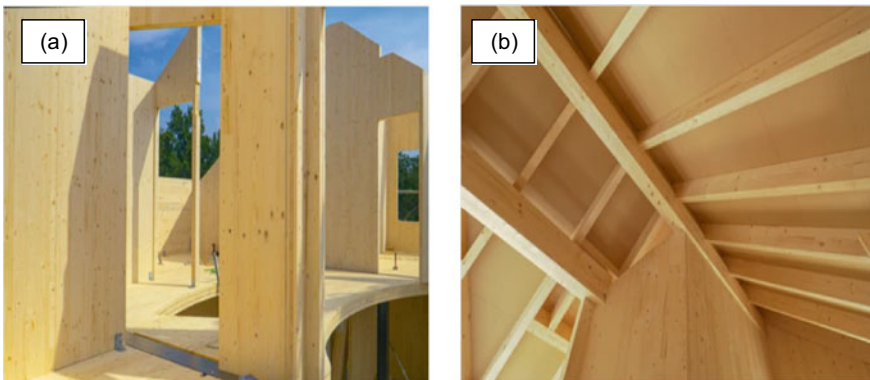


Fig. 11 Structural floor and wall structures (a) and structural roof truss made from CLT panels (b)

5.1 CLT Panels as Floor and Walls Structures

CLT panels can be used as structural floor and wall structures as shown in Fig. 11a. CLT panels can also be utilized as roof trusses of a building Fig. 11b. CLT as a floor structure must transfer vertical loads such as applied load and self-weight to the supports. The floor panel can also handle horizontal loads such as wind load. Panels are set on two supports in the most common form of a CLT structure. Load-bearing CLT panels may be loaded in one or more directions. It can be constructed as a simply supported panel strip if it is load bearing in one direction. It can be classified as a three or four-sided supported panel if it is equipped with two load-bearing directions. The principle for CLT floor structures is that the compression forces are absorbed by the top concrete block, and the majority of the tensile forces are absorbed by the underlying wooden frame in CLT floor structures. Rolling shear fractures can occur in CLT panels used for floor structures. Therefore, it is important that geometry and the quality of the manufactured CLT panels are taken into account when designing timber structure. CLT panels with no edge glueing or tongue and groove and with a width to thickness ratio of less than four are considered to have a bigger risk for shear failures.

Installations are a crucial aspect of a structure's design, and they commonly influence load-bearing component design. When wide holes are drilled in wood structures, reinforcement is often needed to guide forces past the installation holes. However, CLT panels have the advantage of being able to disperse and move forces to adjacent structures without the need for additional reinforcement, even with wide gaps. CLT wall panels usually have a high load-bearing capability. A linear load can be seen as the vertical load in a wall panel, and panels with a thickness of 80 mm can be built to take loads of over 100 kN/m.

Above are some examples of the application of CLT panels. It can be concluded that the mechanical behaviour of the CLT panel used in construction is complex. This is due to the nature of this engineered timber product as lamella of CLT is typically arranged in the perpendicular direction to each other. Besides that, the timber itself is also anisotropy in nature. Christovasilis et al. (2016) pointed out that this complexity of CLT actually works in favour of CLT in construction as that is usually the situations where perpendicular loads to the plane of the panel are applied, e.g., vertical or wind loads on floor or wall panels, loads in the vertical plane.

6 Challenges, Limitations and Future of CLT

The challenges and limitations faced by the CLT players in the construction industry include building regulations, the concern about raw materials and quality, the doubt on the performance of the CLT system, manufacturing technology, logistics and transportation etc. Various researches have been carried out to evaluate the performance of CLT construction against different building codes. The researches all suggested that

CLT structures meet the requirements stipulated, and, in some cases, even outperformed the requirements given (Hindman et al. 2012; Popovski and Gavric 2016). Nevertheless, there is still a concern about the performance of timber structures against fire, decay and earthquake resistance. More efforts and initiatives are needed in order to change the mindset and perspective of the public toward CLT panels and structures. Governments, universities and related industry players need to come together to provide a better information flow on the advantages and performance of CLT structures.

Another concern regarding the CLT panel and its structures is raw material supply and quality. Many consumers have negative feelings towards timber products and timber industry because they view it as the cause of deforestation and adversely impact the ecosystem. However, in order to ensure the feasibility of CLT products, most raw materials are sourced from sustainably managed forest and plantations. The timber industry has a positive effect on human lives, habitats and other natural resources that are interconnected with forests by developing sustainable practices for managing, harvesting and manufacturing forest products (Lippke et al. 2011). To minimize low timber yields, wildfires, water scarcity and severe animal impacts, native forests and plantations must be appropriately managed in all circumstances. Forest certification schemes like the Forest Stewardship Council (FSC) and the Program for the Endorsement of Forest Certification (PEFC) are well known for incentivising the private sector to adopt sustainable forestry practices.

CLT panels are commonly manufactured from softwood. The literatures suggested that most researches done were focused on the mechanical properties of CLT panels fabricated using softwood. Only limited studies on hardwood CLT panels were conducted. The lack of hardwood CLT panels might be due to some challenges faced when using hardwood as the raw materials for CLT. The challenges include longer drying time for hardwood compared to softwood of the same thickness and high shrinkage values of hardwood. Longer drying time will increase the cost of the end products, and high shrinkage value will interfere with the bonding performance of adhesive (Espinoza and Buehlmann 2018). However, in recent years, researchers have shown interest in hardwood CLT panels. This is a welcoming change that will promote and encourage the adoption of hardwood in the manufacturing CLT panels. Engineers and architects prefer hardwoods because they have higher mechanical properties than softwoods, allowing them to work with smaller cross-sections, longer spans and higher loads. Therefore, hardwood CLT has a bright future ahead.

7 Conclusions

CLT panels have great potential in the construction industry. It can be used as a green alternative to conventional materials. CLT panels can also be used to complement conventional building materials. Engineers, architects and designers have better flexibility and choices in selecting the desired building materials based on the required criteria. Nevertheless, despite the numerous benefits of CLT panels, the applications

of CLT panels in the construction industry are still not gaining any desirable traction in developing countries mainly due to lack of exposure and financial constraints. Should CLT structures become a reality in the construction industry one day, such an industry would bring economic benefits to the participants along the CLT value chain and expand markets for underutilized timber species.

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