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Original Article

Research Trends in Hybrid Cross-Laminated Timber (CLT) to Enhance the Rolling Shear Strength of CLT[1]

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ABSTRACT

In this study, hybrid CLT research and development trends were analyzed to improve the low rolling shear strength of CLT, a large wooden panel used in high-rise wooden buildings. Through this, basic data that can be used in research and development directions for localization of CLT were prepared. As a way to improve the low rolling shear strength, the use of hardwood lamina, the change of the lamina arrangement angle, and the use of structural composite materials are mainly used. Rolling shear strength and shear modulus of hardwood lamina are more than twice as high as softwood lamina. It confirmed that hardwoods can be used and unused species can be used. Rolling shear strength 1.5 times, shear modulus 8.3 times, bending stiffness 4.1 times improved according to the change of the layer arrangement angle, and the CLT strength was confirmed by reducing the layer arrangement angle. Structural wood-based materials have been improved by up to 1.35 times MOR, 1.5 times MOE, and 1.59 times rolling shear strength when used as laminas. Block shear strength between the layer materials was also secured by 7.0 N/mm^2,which is the standard for block shear strength. Through the results of previous studies, it was confirmed that the strength performance was improved when a structural wood based materials having a flexural performance of MOE 7.0 GPa and MOR 40.0 MPa or more was used. This was determined based on the strength of layered materials in structural wood-based materials.

The optimal method for improving rolling shear strength is judged to be the most advantageous application of structural wood based materials with strength values according to existing specifications. However, additional research is needed on the orientation of CLT lamina arrangement according to the fiber arrangement of structural wood-based materials, and the block shear strength between lamina materials.

Keywords: cross laminated timber, rolling shear strength, hybrid cross laminated timber, structural wood based materials, lamina, mid-layer angle

1. INTRODUCTION

When reinforced-concrete structures were developed in Europe in the early 20th century, it received attention as an economical material for building construction, and traditional timber structural began to be replaced by those constructed with mineral-based concrete and brick (Hong *et al.*, 2015). At that time, the market share of wood compared with other building materials was 10% or less, and it was mainly used

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for timber light-weight constructions, such as residential buildings, nonresidential buildings and exhibition halls. Since then, wooden building construction and the market share of wood have increased as wood has replaced concrete in the construction of residential buildings, offices, schools, and other areas of construction. In addition, interest in wooden buildings has increased in countries where wood was not previously used. This is not only due to the development and adoption of engineered wood, such as glulam and laminated veneer lumber (LVL), but also the development of cross-laminated timber (CLT) panels in Austria in the early 1990s, which popularized the use of wood for medium-rise buildings (Antonio *et al*., 2021).

Subsequently, CLT (Fig. 1) began to be developed in the sawmill industry to look for its higher-value usage than in sideboards (Guttmann, 2008) and to utilize scrap wood (Sander, 2011), wood with low-machine grades, and waste wood (Cameron, 2013). CLT is a large wooden panel consisting of odd-numbered (3, 5, 7, 9) layers of semi-rigid composites or engineered wood boards where the cross-laminated layers are arranged at the 90° angle so that it can withstand both in-plane and out-of-plane loading (Ehrhart and Brander, 2018; Karacabeylli *et al*., 2013).

CLT, initially known by the German term *Brettsperrholz* (BSP), was classified as a sub-product of laminar-laminated timber product in terms of its shells, grid shells, and spatial 3D shells, and it later earned the designation "cross-laminated timber" (Schickhofer and Hasewend, 2000). The first residential building using CLT was constructed by Moser in 1995. In 1990, research was conducted in Central Europe, including Austria, Germany, and Switzerland, primarily by Graz University of Technology, which led to international research projects (Brandner *et al*., 2016). This research led to the development of CLT, and small- scale production facilities were built to begin its production in Europe in the early 2000s. Since then, production facilities have been built outside of Europe in countries such as Canada, the United States, Japan, China, and New Zealand, where production, R&D, and standardization activities are being actively carried out.

Research on CLT has led to an increase in the number of high-rise wooden buildings. This includes the construction of the following: *Stadthaus*, a wooden 9-floor apartment building in London, UK, in 2009 (Xiong *et al*., 2016); *Forté*, a wooden 10-floor apartment building (Li *et al.*, 2019) in Melbourne, Australia, in 2012; *Treet*, a 14-floor apartment building in Bergen, Norway, in 2014 (Malo *et al.*, 2016); and *Brock Commons*, an 18-floor wooden dormitory building at the University of British Columbia in Vancouver, Canada, in 2017 (Fast *et al.*, 2016) (Fig. 2).

The increase in the construction of high-rise wooden buildings has led to the growth of the CLT market; annual CLT production in European was 25,000,

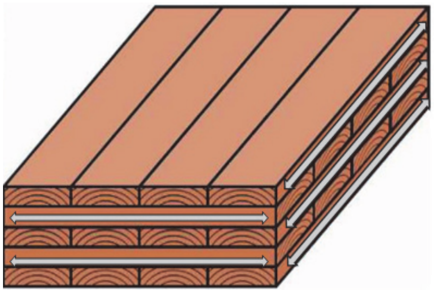


Fig. 1. Cross Laminated timber (Karacabeyli *et al*., 2013).

9 floor Stadthaus in London (2009)

10 floor Forté in Melbourne (2012)

14 floor Treet in Norway (2014)

18 floor *Brock Commons* in Canada (2017)

Fig. 2. CLT buildings (Xiong *et al*., 2016; Li *et al*., 2019; Malo *et al*., 2016; Fast *et al*., 2016).

340,000, 650,000 m³ in 1996, 2010, and 2015, respectively. Production continues to grow rapidly and was forecast to have increased to 1.2 million m³ by 2020 (Brandner *et al.*, 2016). In addition to the production increase in Europe, annual CLT production is also increasing in the United States, Canada, Australia, Japan, and New Zealand (Ipbal, 2018; Pei *et al.*, 2016; Goto *et al.*, 2018).

Along with the rapidly growing CLT market, research on CLT is being conducted globally due to the interest in this large wooden panel and its increasing use as a material for the construction of high-rise buildings. Various studies on CLT as a building material are being conducted to assess its material characteristics, such as its shear-wall structural performance, thermal characteristics, fire-resistance, performance at the joints, and sound-absorption (Jang and Lee, 2019; Kang *et al*., 2019; Choi *et al*., 2018; Ahn *et al*., 2021; Park *et al*., 2020). In particular, research is expanding on the development of CLT with enhanced strength characteristics and performance based on main species to each country's forest environment. This research is mainly focused on improving CLT's relatively low block shear strength. The block shear strength varies depending on the layer arrangement. As an example, when the red pine species was for layers, the resulting glulam showed a strength of 10 N/mm² or higher, and CLT had a strength of 3.5 N/mm² (35% of the value for glulam) or higher (Kim *et al.*, 2013). To improve this strength, the optimal quantity of applied adhesive and resulting shear adhesion strength were evaluated using Pine (*Pinus koraiensis*) while adjusting the pressure. The maximum shear adhesion strength was obtained when the quantity of applied adhesive was 250 g/㎡ the pressure was 0.8 MPa. This resulted in a maximum block shear strength of 6.07 N/mm², which not reach 7.0 N/mm² of the specified block shear strength in glulam standard (Park *et al*., 2017). The block shear strength increases with the increase in the ring angle of the cross-laminated layer.

However, as for the failure mode for block shear strength, the shear strength applied to the CLT layers reached the annual rings before the cross-laminated layer, unlike in glulam, and the resulting failure mode showed the rolling shear failure mode along the annual rings (Kim *et al*., 2013; Song and Hong, 2016). It has been reported that rolling shear failure indicates a low block shear strength, explaining the low rolling shear strength of CLT.

Therefore, based on established CLT standard, this study intends to identify the current status of research on CLT strength according to the species used for the layers and hybrid CLT with the aim of improving rolling shear strength of CLT and to produce base data that can be utilized in the R&D on the localization of CLT.

2. MATERIALS and METHODS

CLT, which is mainly used as an structural member in buildings, has very important quality performance and relevant specifications and standards. CLT quality standards are specified in ISO 16696-1:2019, and different countries in Europe and North America along with Japan have their own definitions. For example, Europe enacted the "Timber Structure-Cross-Laminated Timber-Requirements" (BS EN 16351:2015) specification in 2008 (Brandiner *et al*., 2016), while in 2012, the United States and Canada adopted the "Standard for Performance-Rated Cross-Laminated Timber" (ANSI/APA PRG 320) (Kaboli *et al*., 2020). In 2013, Japan enacted and promulgated the Japanese agricultural standard for CLT (JAS 3079, 2013) (Fujimoto *et al*., 2021). In 2020, Republic of Korea prepared a Korean Industrial Standard for structural CLT to provide a definition and quality standard for CLT products and to set performance standards and provide guidance on inspections. This standard is currently under review.

The CLT standards in each country provide strength values according to the fiber direction of each machine-graded class of layers, and the species used in the layered material vary depending on the forest environment of each country. In Austria, where CLT was first developed, C24, C18, and C16 strength grade Norway spruce (*Picea abise*) are mainly used (Brandner *et al*., 2016), although White fir (*Abies alba*), Scots pine (*Pinus sylvestris*), European larch (*Larix decidua*), Douglas fir (*Pseudotsuga menziesii*), and Swiss stone pine (*Pinus cembra*) are also used (Fink *et al*., 2018). In Australia and Canada, species such as Spruce (*Picea spp*.), Lodgepole pine (*Pinus contorta*), and Douglas fir (*Pseudotsuga menziesii*) are used for CLT production (Zhou *et al*., 2014), while in the U.S., CLT specification states that spruce- pine-fir (SPF) lumber, Douglas fir, Larch, Eastern softwoods, Northern species, Western wood, and Southern pine are the species that can be used in the production of CLT (ANSI/APA PRG 320, 2019). Each country tends to prefer wood procured from their own territory.

The minimum specific gravity of timber used as a building material allowed by the Canadian Lumber Standards Accreditation Board standard, CASO141 (Bejtka and Lam, 2008), and the National Design Specification for Wood Construction (Kramer *et al*., 2014) is 0.35. This is the lower limit value of CLT for connection systems and the minimum specific gravity of species commercially available in north America, western United States, and northern Canada.

Although only the use of species with a specific gravity of 0.35 or more is allowed, the use of species other than those specified in the CLT specification is not limited. Therefore, the layer composition of CLT is selected in the manufacturing process to meet the requirements of the physical and mechanical properties. In particular, there are increased attempts to utilize locally abundant and underutilized wood resources for CLT layers, although they might not have the specified strength properties (Espinoza and Buehlmann, 2018). Sitka spruce (Sikora *et al.*, 2016), Italian marine pine (Fragiacomo *et al*., 2015), European beech (Aicher *et al*., 2016 (a); Aicher *et al*., 2016 (b)), Southern pine (Hindman and Bouldin, 2015; Sharifnia and Hindman, 2017), hybrid poplar (Kramer *et al.*, 2014), Eucalyptus (Liao *et al.*, 2017), and Japanese cedar (Okabe *et al.*, 2014) have all been researched for their use for CLT layers.

In Republic of Korea, larch (*Larix leptolepis*) is the species most commonly used for CLT layers. The number of layer species is expanding through research on the yield and strength characteristics of cedar (*Cryptomeria japonica*) and pine (*Pinus densiflora*), considering the forest environment other than larch, and the evaluation of block shear strength of CLT specimens using Korean pine (*Pinus koraiensis*) and tulip tree (*Liriodendron tulipifera*) as a layer material.

Although species differ depending on the forest environment of each country, softwood is commonly used in CLT layers. In tropical zone such as Malaysia and Indonesia with different climates, however, there are ongoing base studies on strength and other relevant properties of hardwood so that they can be used as CLT layers instead of soft wood (Hamdan *et al*., 2016). Since hardwood has a similar or greater strength than softwood with equal density, they are believed to be good materials with good potential for use in CLT layers (Yusof *et al*., 2019).

As presented above, modern CLT was first developed in Europe, but it has spread around the world, and research is ongoing to establish standards and production processes through the optimization of species that reflect each country's forest environment and strength performance evaluations.

3. RESULTS and DISCUSSION

In the U.S. ANSI/APAPRA PRG 320 standard, which is the most commonly used of the many enacted standards, CLT is defined as a cross-laminated engineered wood with three or more layers of sawn lumber or structural composite lumber (SCL). SCL includes laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL), and oriented strand lumber (OSL) (Wood Handbook, 2021).

In general, CLT is used all over the world by manufacturing sawn lumber into glulam panels. CLT, which is arranged with alternate major and minor direction layers, has a out-of-plane shear strength and stiffness lower than those of in-plane flexural strength and stiffness. Therefore, when an out-of-plane load is applied, it causes excessive deflection followed by rolling shear failure due to the low out-of-plane shear strength, which is its principal drawback (Sylvian *et al*., 2011). The rolling shear phenomenon is shown in Fig. 3 and is closely related to the composition of wood cells. When shear force is applied to a bundle of longitudinally connected fiber in tangent and radial directions, the fibers do not break individually but roll

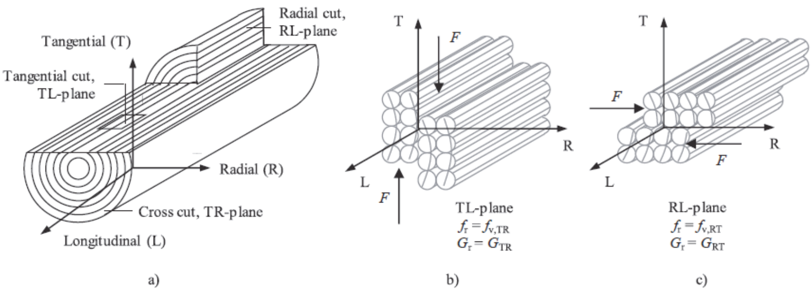


Fig. 3. Principal material axes in a long (a) and rolling shear planes TL (b) and RL (C) (Ehrhart and Brandner, 2018).

off, resulting in rolling failure at the weakest point (Enhart and Brandner, 2018). Rolling failure is mainly found in softwood, and it is generated and transmitted at the boundary when shear forces are applied due to the density difference between the earlywood (with density of approximately 300 kg/m^3) and latewood (with density of 900–1,000 kg/m^3). The shear properties are determined according to the earlywood ratio and earlywood density of the layers used (Enhart and Brandner, 2018).

The rolling shear phenomenon that occurs in the cross-laminated layer of CLT is shown in Fig. 4, and it is reported that shear deformation may occur due to low rolling shear stiffness (Fellmoser and Blaß, 2004).

It has been reported that the rolling shear strength and stiffness in the cross layer of CLT affect the bending-load behavior due to material anisotropy (Mestek *et al*., 2008). To control rolling shears, studies have been conducted on a number of factors, including the species used as layers and their density, thickness, moisture content, sawing method, and the size and shape of the cross-section of the sawn lumber. These studies have confirmed that rolling shear is controllable (Steiger *et al*., 2008).

Research has mainly focused on improving rolling shear strength in the cross layers of CLT, which have low stiffness and strength. Examples of typical research include the use of hardwood as cross-laminated layers, changes in the angle of the layers, and the use of SCL structural panels such as LVL, LSL, plywood, and oriented strand boards (OSB) for the layers. This is called "hybrid CLT" or "composite CLT" (Fig. 5).

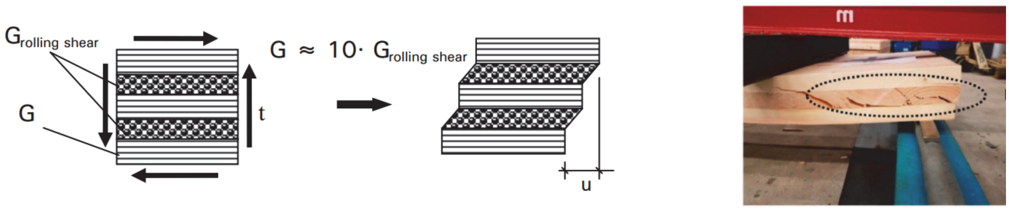
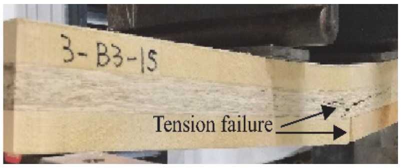


Fig. 4. Shear deformation of a CLT-element (Mestek *et al*., 2008) and the "rolling shear" effect in CLT panels subjected to out-of-plane flexure (Antonio *et al*., 2021).

Composite laminated panels (SPF & LSL)

Composite CLT (Bamboo PSL & Hemlock-fir)

Hybrid CLT (SPF & LVL)



Hybrid CLT (OSB & SPF)

Fig. 5. Composite CLT & Hybrid CLT (Davids *et al*., 2017; Wei *et al*., 2019; Wang *et al*., 2017; Li *et al*., 2020).

3.1. Cross–Laminated Timber using Hardwood and Softwood

Studies are being conducted on CLT strength characteristics to expand the species utilized, such as the mixed use of softwood and hardwood as well as using tropical hardwood, to improve the low rolling shear strength of CLT layers.

Ehrhart *et al*. (2015) evaluated the rolling shear modulus and shear strength of six European species, including Norway spruce (*Picea abies* (L.) H. Karst), pine (*Pinus sylvestris* L.), birch (*Betula pendula* Roth), beech (*Fagus sylvatica* L.), poplar (*Populus* spp.), and ash (*Fraxinus excelsior* L.), as shown in Table 1. Although the rolling shear strength and modulus is depend on the sawing direction and the ratio of the width and thickness of the layer, hardwood species showed values of rolling shear strength and modulus about 1.3–2.3 times higher than softwood species.

Aicher *et al*. (2016) assessed the rolling shear strength of European beech utilized as a layer material.

Table 1. Proposed rolling shear characteristics for $w_l/t_l \geq 4$ (Ehrhart *et al*., 2015)
(w_l: width, t_l: thickness, $f_{R,k}$: rolling shear strength, $G_{R,mean}$: shear modulus)

	$f_{R,k}$ (N/mm²)	$G_{R,mean}$ (N/mm²)
Spruce	1.4	100
Pine	1.7	150
Poplar	2.2	120
Birch	2.7	180
Ash, Beech	4.0	350

EOTA 2015 (European Organisation for Technical Assessment), specifies 50 N/mm² as the rolling shear modulus for spruce and fir used as layer materials for design purposes. The rolling shear modulus of the European beech is measured to be 370 N/mm², which is about 7 times the stiffness of softwood, and the rolling shear strength is 4.5 N/mm². Based on this, European beech has been proposed as an ideal material for CLT layer material under out-of-plane load conditions (Aicher *et al*., 2016 (a)). Furthermore, Aicher *et al.* (2016) evaluated the bending performance of CLT manufactured by using a combination of spruce (*Picea abies*) layers (major direction) and European beech layers (minor direction). The results showed a rolling shear modulus of 350 N/mm² and a rolling shear strength of 2.6 N/mm². It has been reported that the high rolling shear properties can neglect the decreased in shear strength of softwood CLT (Aicher *et al*., 2016 (b)).

Wang *et al*. (2014) produced 3-ply CLT to review the usability of poplar as the layer material and compared the bending and shear strength properties (Table 2). When poplar was used with Douglas fir as the layer material, the bending strength was improved, but the modulus of elasticity in bending and shear strength decreased. When using poplar as the cross-layer material with Douglas fir or Monterey pine as the layer material, the bending strength, modulus of elasticity in bending, and shear strength were all reduced by 10%, 7.5%, and 9.2%, respectively, compared with using a single species. When poplar was used as a cross

Table 2. CLT layups and test results (Wang *et al*., 2014)

Type	Out layers	Cross layers	$f_{b,0}$ (MPa)	E_0 (GPa)	$f_{v,0}$ (MPa)	$f_{v,90}$ (MPa)
1	Poplar	Poplar	41.66	5.97	2.00	1.21
2	Douglas fir	Poplar	31.56	8.07	1.97	1.09
3	Monterey Pine	Poplar	41.23	6.21	1.80	1.03
4	Monterey Pine	Monterey Pine	44.55	6.35	2.04	0.81
5	Douglas fir	Douglas fir	34.72	8.69	2.17	1.24

layer, it did not show a significant decrease in strength, so it was concluded that the mechanical properties of CLT using Douglas fir and Monterey pine layers and CLT including poplar were similar. Therefore, it is proposed that poplar can be used as cross-layer materials of CLT (Wang *et al*., 2014).

3.2. Changing the angle of mid-layer

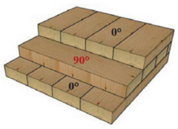
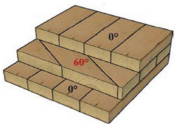
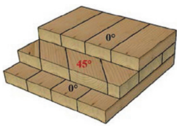
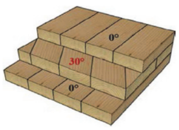
A number of studies have been conducted to improve rolling shear strength through evaluation of elastic coefficients in relation to layer angles and evaluation of the shear strength and stiffness of 3-ply CLT (Buck *et al*., 2016; Bahmanzad *et al*., 2020).

Bahmanzad *et al*. (2020) studied the shear strength properties of the Eastern hemlock species in relation to the angle of the cross-laminated layer arrangement in order to improve the planar shear of cross-laminated layers of CLT. The results of the elastic properties in relation to fiber direction and the short-span shear test on layer angle are set out in Tables 3 and 4. A cross-layer angle of 30° led to a shear failure strength 1.5 times greater than at 90° (Table 3), and 3-ply CLT arranged with a cross-layer angle of 30° demonstrated an effective shear stiffness 8.3 times greater than that of a cross-layer angle of 90° (Table 4). This confirmed that the failure mode caused by the cross-layer angle changes from rolling shear failure alone to tensile force

Table 3. Modulus of elasticity and shear modulus of eastern hemlock for different fiber orientations (Bahmanzad *et al*., 2020)

Species	Elastic properties (MPa)						
	E_L	E_T	$G_{0°}$	$G_{30°}$	$G_{45°}$	$G_{60°}$	$G_{90°}$
Eastern hemlock	8,300	276	520.56	191.68	104.11	83.43	61.36

Table 4. Summary mean results of the short-span shear test for fiber orientations of 30°, 45°, 60°, and 90° (Bahmanzad *et al*., 2020)

Mid-layer angle		Peak load (kN)	EI_{app} (10^9 N·mm²/m)	GA_{eff} (10^6 N/m)	$f_{v,max}$ (MPa)
	90°	88.3	117.3	9.5	2.03
	60°	95.9	286.3	19.9	2.2
	45°	102.7	375.9	34.9	2.4
	30°	129.1	486.3	78.7	3.0

and rolling shear failure. This supports the hypothesis that rolling shear and stiffness can be improved depending on the CLT cross-layer fiber orientation. Furthermore, the improvements shown in shear strength as a result of angle adjustments confirmed that it was possible to utilize low-quality wood for CLT through cross-layer angle adjustment for species that do not meet the required structural performance when the cross-layer angle is set at 90° during the CLT manufacturing process (Bahmanzad *et al*., 2020).

3.3. Cross-Laminated Timber Using Structural Composite Materials

In addition to research on the mixing of softwood and hardwood and cross-layer angle changes to improve shear strength, research on evaluating shear strength is also being actively conducted by applying existing engineered woods, such as OSB, LVL, LSL, PSL, and structural plywood as cross-layer materials.

Although the current specifications do not provide strength values, design values, or other values for the different structural composite lumber (SCL) types, they also place no restrictions on their use as a layer material. Therefore, data on strength performance for engineered wood have already been existed, and interest in SCL is increasing as it has the advantage of increasing wood yield. Hybrid CLT (Fig. 5), in which SCL is used as a layer material, is utilized primarily with the aim of calculating strength values to be included in the CLT specifications established in each country.

Wang *et al*. (2015), Davids *et al*. (2017), and

Table 5. Bending properties of CLT

CLT type	Panel type	Panel lay-up	Layer direction*	Specimen dimension (mm)	Span-depth ratio	Major direction	
						MOE (GPa)	MOR (MPa)
Hybrid CLT (Wang *et al*., 2015)	-	pine-pine-pine	//-⊥-//	114(T)×197(W)×2,438(L)	20	9.7	35.4
	LSL	pine-LSL[1]-pine	//-//-//			10.8	44.0
		LSL-pine-LSL	//-⊥-//			11.2	44.2
		LSL-LSL-LSL				11.6	48.2
Hybrid SPFs-LSL CLT (Davids *et al*., 2017)	-	SPFs-SPFs-SPFs	//-⊥-//	114(T)×406(W)×2,560(L)	20.4	7.3	40.7
	LSL	LSL[2]-LSL-LSL				5.3	33.4
		LSL-SPFs-LSL				5.5	33.6
		SPFs-LSL-SPFs				7.0	50.1
Composite laminated panels (Niederwestberg *et al*., 2018)	-	SPF-SPF-SPF-SPF-SPF	//-⊥-//-⊥-//	184(T)×195(W)×2,743(L)	13.6	8.0	110
	LSL	SPF-LSL-SPF-LSL-SPF[3]	//-//-//-//-//			9.5	164.5
		LSL-SPF-LSL-SPF-LSL	//-//-//-//-//			11.6	205.4
		LSL-SPF-LSL-SPF-LSL	//-⊥-//-⊥-//			8.9	106.3
Hybrid SPFs-LVL CLT (Wang *et al*., 2017)	-	SPF-SPF-SPF	//-⊥-//	114(T)×89(W)×2,000(L)	16.4	7.9	28.6
	LVL	SPF-LVL[4]-SPF				7.2	25.7
		LVL-SPF-LVL				9.3	30.1
Korean Larch CLT (Song and Hong, 2018)	Plywood	L-L-L[5]	//-⊥-//	81(T)×170(W)×1,700(L)	18.5	9.2-10.1	43.9-47.1
Korean Pine CLT (Pang *et al*., 2021)		PL-PL-PL[6]	//-⊥-//	90(T)×300(W)×2,900(L)	30	8.0-8.8	28.2-30.1

Table 5. Continue

CLT type	Panel type	Panel lay-up	Layer direction*	Specimen dimension (mm)	Span-depth ratio	Major direction	
						MOE (GPa)	MOR (MPa)
Ply-lam (Fujimoto *et al*., 2021)	Plywood	C-P-C-P-C[7)]	//-//-//-//-//	150(T)×300(W)×3,450(L)	21	12.3	49.0
CLT with plywood (Choi *et al*., 2018)	Plywood	D-P-D-P-D[8)]	//-//-//-//-//	40(T)×40(W)×600(L)	13	10.8	67.8
		D-P-D-P-D[9)]				8.6	43.9
Ply-lam CLT (Choi *et al*., 2021)	Plywood	L-P-L-P-L[10)]	//-//-//-//-//	75(T)×300(W)×2,400(L)	29	15.1	61.6
		D-P-D-P-D[11)]	//-//-//-//-//			13.0	65.5
Tropical Hybrid CLT (Nurdiansyah *et al*., 2020)	Bamboo laminated board	L-B.S-L[12)]	//-//-//	54(T)×305(W)×1,260(L)	19.6	21.83	39.41
Bamboo-wood composite cross laminated timber (Li *et al*., 2021)	Bamboo woven panel (BMCP)	L-L-L	//-⊥-//	51(T)×145(W)×1,630(L)	30	10.28	47.3
		L-BMCP-L[13)]	//-//-//			9.6	45.0
		BMCP-L-BMCP	//-⊥-//			6.27	31.3

* // and ⊥ represent the parallel and perpendicular to the majoir strength direction of CLT, Hybrid CLT, composite CLT
1) LSL was made from aspen poplar (*Populus tremuloides*) strand, 1.5E grade
2) LSL grade; 1.35E (MOE: 9.16 kN/mm^2, density: 0.71 g/cm^3)
3) LSL properties; 9.5 kN/mm^2, 41.7 N/mm^2, density: 0.64 g/cm^3
4) SPF; shear modulus 84.92 N/mm^2, shear strength 1.41 N/mm^2
LVL was made from douglas fir (*pseudotsuga menziesii*) veneer, 2.0E grade (shear modulus 47.88 N/mm^2, shear strength 1.07 N/mm^2)
5) L; korean larch (*Larix kaempferi* Carr.), outer tension laminae: 13 kN/mm^2, middle laminae: 7-9 kN/mm^2, outer compression laminae: 11kN/mm^2
6) PL; korean pine (*Pinus koraiensis*) (MOE: 8-9 kN/mm^2)
7) C; japanese cypress lamina, outer layer 11 kN/mm^2, inner layer 9 kN/mm^2,
P; korean larch (*larix kaempferi*) plywood (major direction–MOE 10.9 kN/mm^2, MOR 44.1 N/mm^2, minor direction–MOE 5.19 kN/mm^2, MOR 18.7 N/mm^2)
8) D; douglas fir lamina thickness: 9 mm, P; plywood: thickness 6 mm, korean larch veneer
9) D; douglas fir lamina thickness: 6 mm, P; plywood: thickness 9 mm, korean larch veneer
10) L; larch lamina (outer 11 kN/mm^2, inner 9 kN/mm^2), P; korean larch plywood. thickness 15 mm, density 0.5 g/cm^3, MOR 42.8 N/mm^2, MOE 7.1 kN/mm^2
11) D; douglas fir lamina (outer 12-13 kN/mm^2, inner 9-10 kN/mm^2), P; korean larch plywood. thickness 15 mm, density 0.5 g/cm^3, MOR 42.8 N/mm^2, MOE 7.1 kN/mm^2
12) L; Acacia mangium Willd, density 0.37 g/cm^3, MOR 15.3 N/mm^2, MOE 9.98 kN/mm^2,
B.S; Bamboo solid board, density 0.55 g/cm^3, MOR 22.5 N/mm^2, MOE 18.49 kN/mm^2
13) L; hem-fir (*Tsuga heterophylla* (*Raf.*) *Sarg×Abies amabilis* (*Dougl.) Forbes*) density 0.43 g/cm^3, MOE 11.8 kN/mm^2, MOR 69.5 N/mm^2
BMCP; Bamboo woven panel, density 0.79 g/cm^3, MOE 7.6 kN/mm^2, MOR 56.6 N/mm^2

Niederwestberg *et al*. (2018) conducted research using LSL as layers, and Wang *et al*. (2017) conducted a study on the bending and shear strength properties of LVL following changes to the cross-layer and layer composition. Fujimoto *et al*. (2021), Choi *et al*. (2018), Pang *et al*. (2019), Choi *et al*. (2021), and Choi *et al*. (2020) conducted research into bending properties and block shear strength when using structural plywood as a CLT cross-layer material, while Li *et al*. (2020 (b)), using OSB, and Li *et al*. (2020 (a)) and Nurdiansyah *et al*. (2020), using bamboo boards as a layer material, conducted research into shear

Table 6. Shear properties of CLT

CLT type	Panel lay-up	Layer direction*	Specimen dimension (mm)	Span-depth ratio	Shear strength (MPa)
Hybrid SPFs-LSL CLT (David *et al*., 2017)	SPFs-SPFs-SPFs	//-⊥-//	114(T)×406(W)×823(L)	5.4	2.03
	LSL-LSL-LSL				2.61
	LSL-SPFs-LSL				-
	SPFs-LSL-SPFs				2.96
Composite laminated panels (Niederwestberg *et al*., 2018)	SPF-SPF-SPF-SPF-SPF	//-⊥-//-⊥-//	184(T)×195(W)×1,200(L)	5.5	1.3
	SPF-LSL-SPF-LSL-SPF	//-//-//-//-//			2.9
	LSL-SPF-LSL-SPF-LSL	//-//-//-//-//			3.6
	LSL-SPF-LSL-SPF-LSL	//-⊥-//-⊥-//			1.4
Hybrid SPFs-LVL CLT (Wang *et al*., 2017)	SPF-SPF-SPF	//-⊥-//	114(T)×305(W)×610(L)	5	2.25
	SPF-LVL-SPF				2.11
	LVL-SPF-LVL				2.40
Ply-lam (Fujimoto *et al*., 2021)	C-P-C-P-C	//-//-//-//-//	150(T)×300(W)×1,050	5	3.87
Hybrid CLT with OSB[1)] (Li *et al*., 2020 (b))	SPF-SPF-SPF	//-⊥-//	72(T)×190(W)×720(L)	9	3.6
	SPF-OSB-SPF	//-//-//			7.0
	SPF-OSB-SPF	//-⊥-//			6.7
	OSB-SPF-OSB	//-⊥-//			5.4
	OSB-OSB-OSB	//-⊥-//			6.4
	SPF-SPF-SPF-SPF-SPF	//-⊥-//-⊥-//	120(T)190(W)×1,200(L)		3.7
	SPF-OSB-OSB-OSB-SPF	//-//-//-//-//			5.9
	SPF-OSB-OSB-OSB-SPF	//-⊥-//-⊥-//			5.7
	OSB-SPF-OSB-SPF-OSB	//-⊥-//-⊥-//			3.7
	OSB-OSB-OSB-OSB-OSB	//-⊥-//-⊥-//			5.9
Tropical Hybrid CLT (Nurdiansyah *et al*., 2020)	L-B.S-L	//-//-//	54(T)×305(W)×270(L)	4.6	6.93
Bamboo-wood composite cross laminated timber (Li *et al*., 2021)	L-L-L	//-⊥-//	51(T)×145(W)×406(L)	6	2.4
	L-BMCP-L	//-//-//			3.3
	BMCP-L-BMCP	//-⊥-//			2.5

* // and ⊥ represent the parallel and perpendicular to the major strength direction of CLT, Hybrid CLT, composite CLT
1) OSB: construction OSB (COSB) used as the core layer in container flooring. COSB has better mechanical properties than regular OSB.
COSB properties: density 0.72 g/cm^3, MOE 9.5 kN/mm², shear strength (f_v) 3.79 N/mm²

properties according to the changes in layer composition and number of laminated layers. The results of the research into the bending and shear strength properties of hybrid and composite CLT are shown in Table 5 and 6.

Wang *et al*. (2015) reported a 1.19 times increase in MOR and a 1.1 times increase in MOE when using LSL as a cross layer in existing CLT structures (species used for the layers was lodgepole pine [*Pinus contorta*]), and a 1.24 times increase in MOR and 1.15

times increase in MOE compared with existing CLT when utilizing LSL as the outermost layer and pine as the cross layer (Wang *et al*., 2015).

Furthermore, when Davids *et al*. (2017) and Wang *et al*. (2015) used LSL as the cross layer in SPF 3-ply CLT, MOR demonstrated a 1.23 times increase; however, MOE showed a similar average value and the rolling shear strength improved 1.45 times. When laminating the LSL in the same way as the general 3-layer CLT structure (arrangement //-⊥-//), rolling shear strength improved 1.28 times. This can improve the rolling shear strength when LSL is composed of CLT structure instead of sawn lumber (Davids *et al*., 2017; Wang *et al*., 2015).

Niederwestberg *et al*. (2018) researched bending and shear strength properties by preparing 5-ply CLT with SPF and LSL used as CLT layers. When using an LSL cross layer in SPF 5-layer CLT, MOR improved 1.49 times, MOE 1.18 times, and rolling shear strength 1.2 times. CLT (LSL-SPF-LSL-SPF-LSL-LSL with a parallel SPF layer) with LSL as the outermost layer demonstrated a 1.86 times improvement in MOR, a 1.13 times improvement in MOE, and a 1.77 times improvement in rolling shear strength. However, even with LSL used as the outermost layer, MOR, MOE, and rolling shear strength values were the same as those of CLT when the of 2 or 4-ply SPF was cross laminated (Niederwestberg *et al*., 2018; Davids *et al*., 2017).

Research by Wang *et al*. (2015), Davids *et al.* (2017), and Niederwestberg *et al*. (2018) confirmed that when using LSL as the cross layer, MOR improved 1.2 times and MOE 1.1 times. In particular, rolling shear strength improved 0.5−1.8 times. As the arrangement direction of LSL used as a cross-layer material is closely related to CLT bending properties, it was proposed that layers be placed in the same direction as the fibers to improve strength (Wang *et al*., 2015; Davids *et al*., 2017; Niederwestberg *et al*, 2018).

Wang *et al*. (2017) also researched bending and shear properties in relation to changes in the cross-layer and layer configuration while using SPF and LVL as CLT layers. Compared with SPF 3-layer CLT, CLT with LVL used as the cross-layer material showed a decrease in MOR by 10.1%, MOE by 8.9%, and rolling shear strength by 6.2%. This was determined to be due to the low planar shear properties of LVL when LVL was used in the orthogonoal direction for the cross layer (Fellmoser and Blaß, 2004). In addition, it was suggested that hybrid CLT can also improve bending strength performance due to the uniform mechanical properties of LVL as well as strength improvement when the outermost layer is used as LVL (Wang *et al*., 2017).

Fujimoto *et al*. (2021), Choi *et al*. (2018), Pang *et al*. (2019), Choi *et al*. (2020), and Choi *et al*. (2021) evaluated the strength characteristics of CLT with structural plywood laminated in a parallel direction to the CLT cross-layer material, known as ply-lam or ply-lam CLT (Fujimoto *et al*., 2021; Choi *et al*., 2018; Choi *et al*., 2021). Fujimoto *et al*. (2021) studied the manufacture and strength properties of ply-lam using Korean structural larch plywood (P) and a Japanese cypress layer (C) at the Miyazaki University and Wood Use Research Center in Japan. The composition of ply-lam consists of 5 layers (C-P-C-P-C) and the results of an MOR 49.0 MPa, an MOE 12.3 GPa, and a rolling shear strength 3.87 MPa showed results (Fujimoto *et al*., 2021). Choi *et al*. (2020) evaluated the block shear strength according to the lamination method of glulam, CLT, and ply-lam CLT. The block shear strength of ply-lam CLT was found to be over 7.1 N/mm², which is the glulam standard. Choi *et al*. (2021) manufactured ply-lam CLT using larch (machine grades E11, E9) and Douglas-fir layer material (machine grades E13−14, E9−10) and evaluated strength performance of ply-lam CLT. As there was no significant strength reduction according to the layer species and modulus of elasticity, they were able to confirm that the change in bending strength resulting from ply-lam CLT cross-layer plywood using different species was not significant (Choi *et al*., 2021). Song and Hong (2018) also conducted a study on the bending strength of larch (layer machine grades E13, E9, E11) in 3-ply CLT. Among the layers used for larch CLT and ply-lam CLT, the mechanical grades of the outermost layer subjected to compressive stress were different, but compared to CLT, the ply-lam CLT reported improved MOR 1.3 times and 1.5 times (Song and Hong, 2018).

Li *et al*. (2020 (b)) manufactured hybrid CLT using SPF and OSB and evaluated rolling shear strength according to the number of layers and direction of the arranged layers. In 3-layer CLT, it was reported that shear strength improved by 1.94 times when OSB was applied to the cross layer in the fiber direction, and 1.86 times when applied in the direction perpendicular to the fibers in the cross layer. In addition, when 2, 3, 4-ply were placed in the direction of the OSB fiber in a five-layer SPF CLT, the shear strength improved 1.59 times. It has been shown that the shear strength of the CLT cross-arranged with the OSB as in the general CLT structure is improved by 1.59 times than that of the general SPF CLT. Unlike previous studies on LVL and LSL, where single panels were placed in the same direction, OSB had a slight strength reduction of less than 5% depending on the direction of the cross-layer arrangement. LSL and OSB panels have the same arrangement of strands in the direction of the fiber, but as the adhesive area in the width direction is large due to the difference in width of strand between LSL and OSB (LSL strands are 12–16 mm and OSB strands are 30–80 mm), the shear strength was presumed to improve when at right angles to the fiber (Li *et al*., 2020 (b)). There was a difference between LSL and OSB not only in the size of the strand used but in the direction of the strands. Unlike LSL, in which the strands are arranged in a single direction, OSB has a multilayer structure, with the strands in each layer arranged differently, and it is manufactured by cross laminating in the same way as plywood. As the difference in strength as a result of fiber direction is not significant, it is presumed that there is no difference in strength as a result of fiber direction when used as a CLT layer material.

Nurdiansyah *et al*. (2020) studied the bending and shear properties of CLT by combining acacia laminate (*Acacia mangium* willd.) and bamboo solid boards. As a result, due to the high MOE of bamboo solid boards, CLT showed the highest MOE and shear strength values (Nurdiansyah *et al*., 2020). Li *et al*. (2021) used a hem-fir and bamboo woven panel (BMCP) as a layer material and evaluated the strength characteristics of three-ply CLT according to the layer composition. When using BMCP as the cross layer in conventional CLT, the bending characteristics showed similar values, but the shear strength increased 1.37 times from 2.4 MPa to 3.3 MPa (Li *et al*., 2021).

Research is continuously being conducted on the use of previously developed engineered wood and structural wood panels as cross-layer materials in order to improve the low rolling shear strength of CLT cross layers and the raw material yield. When structural composites such as LSL, LVL, OSB, plywood, and bamboo board are used as the cross-layer material, it can be seen that the strength is improved by up to 2 times for rolling shear, up to 1.5 times for MOE, and up to 1.35 times for MOR.

Therefore, it was decided that the selection of the structural wood material for manufacturing hybrid CLT suitable for the required strength characteristics is important because the bending characteristics of the structural wood material layer affect the shear and bending characteristics of the CLT (Davids *et al*., 2017; Wang *et al*., 2015).

When assessing prior research results indicating that the fiber orientation in materials used as cross-layer materials, such as LSL and LVL, may lead to a lower strength compared with conventional CLT, the direction of the CLT layers needs to be taken into account. However, for materials with the same bending properties both in terms of the fiber direction and direction orthogonal to the fiber, such as structural plywood and BMCP, strength in the minor direction can also be achieved when these panels are placed in the outermost layer.

4. CONCLUSION

In this study, basic data that can be used in the R&D for localization of CLT by analyzing the research and development trend of hybrid CLT to improve the low rolling shear strength of CLT, a large wooden panel used in high-rise wooden buildings in Europe and the United States, etc. was intended to provide. As a measure to improve shear strength, the strength characteristics of CLT were compared by using hardwood, changing angle of lamina, and using structural wood-based materials. The result is as follows.

1. When comparing the rolling shear strength and shear modulus of softwood and hardwood used to manufacture CLT, hardwood has both rolling shear strength and shear modulus values up to twice as high as those of softwood. The use of hardwoods a cross-layer material has advantages such as improvement of rolling shear properties and utilization of unused species, but it is judged that it is necessary to additionally evaluate the adhesion performance between softwoods and hardwoods.
2. CLT cross-layer materials are currently manufactured with a 90° arrangement, but we confirmed that adjusting the angle of the layers can lead to a 1.5 times improvement in rolling shear strength of CLT, an 8.3 times improvement in its shear modulus, and a 4.1 times improvement in its bending stiffness. Accordingly, it is judged that it is possible to improve the strength of CLT as well as expand the use of wood with low mechanical grade by adjusting the angle of layer arrangement.
3. By using structural wood-based materials with a proven strength performance, such as LVL, LSL, and plywood, for the CLT cross layer, MOR improved by up to 1.35 times, MOE by up to 1.5 times, and the rolling shear strength 1.59 times. Structural wood-based materials used in hybrid CLT with improved strength had bending property values of MOE 7.0 GPa or higher and MOR 40.0 MPa or higher. It can be confirmed that this is the standard of the bending characteristics of the structural wood-based material that can be used as a cross-layer material. In particular, materials manufactured by layering in the direction of the fiber and at right angles to the fiber, such as structural plywood and OSB, demonstrate a small difference in strength depending on the fiber direction of the test piece when an out-of-plane load is applied. When used as a layer material for CLT, it is judged that uniform strength values out-of-plan and in-plane strength can be obtained. However, for materials arranged in the same strand direction as LSL, as the bending properties are degraded to some extent when subjected to out-of-plane loads, materials with the same fiber orientation, such as LVL and LSL, require further study with a focus on the composition of their layers.

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APPENDIX

(Korean Version)

CLT의 rolling shear 향상을 위한 hybrid cross laminated timber 연구 동향

초록: 본 연구는 고층 목조건축에 사용되는 대형 목재 패널인 CLT의 낮은 rolling shear strength를 개선하기 위해 hybrid CLT의 연구 개발 동향을 분석하였다. 이를 통해 CLT의 국산화를 위한 연구개발 방향에 활용 가능한 기초자료를 마련하고자 하였고, 낮은 rolling shear strength를 향상시키기 위한 방안으로 활엽수 층재 사용, 층재 배열 각도 변화, 구조용 목질복합체의 사용이 주를 이루고 있다. 활엽수 층재는 침엽수 보다 rolling shear strength와 shear modulus 모두 2배 이상의 높은 값을 나타내므로 활엽수 층재 사용 및 미이용 수종의 활용이 가능함을 확인하였다. 층재 배열 각도 변화에 따라 rolling shear stength 1.5배, shear modulus 8.3배, bending stiffness 4.1배 향상되어 층재 배열 각도를 감소시킴으로써 CLT 강도 향상을 확인하였다. 구조용 목질재료는 기존에 강도성능이 확보된 재료로 층재로 사용하였을 때 최대 MOR 1.35배, MOE 1.5배, rolling shear strength 2배 향상되었고, 층재 간의 접착강도 또한 집성재 블록전단강도 기준인 7.0 N/mm²을 확보할 수 있었다. 선행연구 결과를 통해 MOE 7.0 GPa, MOR 40.0 MPa 이상의 휨 특성을 가진 구조용 목질재료를 사용하였을 때 강도성능이 향상됨을 확인하였다. 이를 통해 구조용 목질재료 층재 강도 기준으로 판단하였다. rolling shear strength 개선하기 위한 최적의 방법은 기존 규격에 의한 강도값을 가진 구조용 목질재료의 적용이 가장 유리할 것으로 판단하나, 구조용 목질재료의 섬유 배열에 따른 CLT 층재 배열 방향, 층재 간 접착 강도 등에 대한 추가적인 연구가 필요하다.

1. 서론

20세기 초 유럽에서 철근-콘크리트 구조 개발로 건축물 시공에 경제적인 재료로 주목받으며 전통목조건축에서 광물 기반의 콘크리트, 벽돌을 사용한 건축물로 대체되었다(Hong *et al*., 2015). 이때 건축 재료 중 목재의 시장점유율은 10% 이하이며 주로 경량목조건축으로 주거 및 비주거용 건물, 전시장 등에 사용되었다. 이후 주거용 건축물, 사무실, 학교 등의 시설 등 기타 건설 분야에 콘크리트 대신 목재를 사용하며 목조건축 시공사례 및 시장점유율이 증가하였다. 이뿐만 아니라 목재를 사용하지 않았던 국가에서도 목조건축물에 대한 관심도가 증가하게 되었다. 이는 집성재, LVL과 같은 공학목재에 대한 개발 및 도입뿐만 아니라 1990년대 초 오스트리아에서 Cross-lam 패널(Cross laminated timber; CLT)의 개발로 중저층 건축물에 목재 사용이 본격화되었다(Antonio *et al*., 2021).

CLT (Fig. 1)는 당시 제재산업에서 사이드보드 보다 더 높은 가치의 용도 개발 (Guttmann, 2008), scrap wood (Sander, 2011), 기계등급이 낮은 목재, 폐목재(Cameron, 2013) 등을 활용하기 위해 개발이 시작되었다. CLT는 3, 7, 9 홀수층으로 구성된 준강성복합체 및 판형 공학목재로 면내·외 하중을 견딜 수 있도록 교차층 층재를 90° 각도로 배치하여 만들어진 대형 목재 패널이다(Ehrhart and Brander, 2018; Karacabeylli *et al*., 2013).

CLT는 초기에 독일용어로 “Brettsperrholz (BSP)” 명하며 shells, grid-shells, spatial(3차원)과 관련된 “laminar laminated timber product”의 하위제품으로 분류되었고 이후 Cross laminated timber라는 이름을 얻게 되었다(Schickhofer and Hasewend, 2000). 이러한 CLT를 이용한 첫 번째 주거용 건물은 1995년 Moser에 의해 실현되었다. 1990년 오스트리아, 독일, 스위스 등 중부유럽과 Graz university of technology를 중심으로 연구가 수행되었고 이후 국제 연구 프로젝트로 이어졌다(Brandner *et al*., 2016). 그 결과에 의해 개발된 CLT는 유럽에서 2000년대 초 소규모 생산설비 구축 및 제품 생산을 시작하였다. 이후 유럽 외에 캐나다, 미국, 일본, 중국, 뉴질랜드와 같은 국가에서도 생산설비를 구축하며 생산과 연구개발, 표준화 활동이 활발하게 진행되고 있다.

CLT에 관한 활발한 연구는 고층목조건축물 증가로 이어졌다. 2009년 영국 런던 9층 목조 아파트 Stadthaus (Xiong *et al*., 2016), 2012년 호주 멜버른 10층 Forte 목조아파트(Li *et al*., 2019), 2014년 노르웨이 14층 아파트 “Treet” (Malo *et al*., 2016), 2017년 캐나다 벤쿠버 브리티쉬 콜롬비아대학 내 18층 목조건축물 기숙사(*Brock Commons*) 등의 목조건축물이 시공되었다(Fast *et al*., 2016) (Fig. 2).

고층목조건축물 시공 사례 증가는 CLT 시장의 성장으로 이어졌다. CLT 연간 생산량은 1996년 25,000 m³, 2010년 340,000 m³, 2015년 65만 m³이며 2020년 120만 m³ 까지 증가할 것으로 예측하며 급격히 성장하고 있다(Brandner *et al*., 2016). 유럽의 생산량 증가와 더불어 미국, 캐나다, 호주, 일본, 뉴질랜드 등 지역도 연간 CLT 생산량이 증가하고

있다(Ipbal, 2018; Pei *et al*., 2016; Goto *et al*., 2018).

급격히 증가하고 있는 CLT 시장과 더불어 대형 목재 패널인 CLT 관심도 및 고층 건축물의 시공사례 증가로 인하여 전 세계적으로 CLT에 관한 연구가 활발하게 진행되고 있다. CLT 재료 특성, 전단벽 구조성능, 열적 특성, 내화성능, 접합부 성능, 흡음성능 등 건축 재료로 적용하기 위한 다양한 연구가 진행되고 있다(Jang and Lee, 2019; Kang *et al*., 2019; Chio *et al*., 2018; Ahn *et al*., 2021; Park *et al*., 2020). 그 중 국가별 산림 환경에 맞는 수종별 CLT의 강도 특성 및 강도 성능을 보완한 CLT 개발 등에 대한 연구가 확대되고 있다. 여러 강도성능 중 CLT의 낮은 접착전단성능을 개선하기 위한 연구가 주로 진행되고 있다. 층재 배열에 따라 접착전단강도가 다르게 나타나며 red pine 수종을 층재로 사용하였을 때 집성재는 10 N/㎟, CLT는 3.5 N/㎟ 이상으로 집성재 접착전단강도의 35% 강도를 나타냈다(Kim, *et al*., 2013). 이를 향상시키기 위하여 잣나무 수종을 이용한 최적 접착제 도포량과 압력 조절하며 접착전단강도를 평가하였으며 도포량 250 g/㎡, 압력 0.8 MPa에서 최대 접착전단강도를 나타냈다. 최대 접착전단강도는 6.07 N/㎟로 집성재 규격에 명시된 접착전단강도 기준인 7.0 N/㎟에 도달하지 못하였다(Park *et al*., 2017). 교차층 연륜 각도가 증가함에 따라 접착전단강도가 증가하나, 접착전단강도 파괴유형은 집성재와 달리 CLT 층재에 가해진 전단력이 접착층 보다 교차 층재의 연륜에 먼저 도달하며 연륜에 따라 rolling shear 파괴 유형을 나타냈다(Kim *et al*., 2013; Song and Hong, 2016). rolling shear 파괴는 낮은 접착전단강도를 나타내며 이는 CLT의 낮은 rolling shear strength로 영향을 미친다고 보고된 바 있다.

이에 본 연구에서는 제정된 CLT 규격을 바탕으로 층재 수종에 따른 CLT 강도와 CLT의 rolling shear strength 향상을 위한 hybrid CLT에 관한 연구 현황을 파악하며 CLT의 국산화를 위한 연구개발 방향에 활용 가능한 기초자료를 마련하고자 한다.

2. 재료 및 방법

주로 건축 구조부재로 사용되는 CLT는 품질성능이 매우 중요하며 관련 규격 및 기준은 필수적이다. CLT 품질기준은 ISO 16696-1:2019를 비롯하여 유럽, 북미, 일본 등 각 나라마다 정의하고 있다. 2008년 유럽에서는 Timber Structure-Cross Laminated timber-Requirements (BS EN 16351:2015) 규격을 제정하였다(Brandiner *et al*., 2016). 이후 2012년 미국과 캐나다는 Standard for performance-Rated Cross Laminated timber (ANSI/APA PRG 320)를 제정하였고(Kaboli *et al*., 2020), 2013년 일본은 直交集成板の日本農林規 (JAS 3079, 2013)을 제정 및 공포하였다(Fujimoto *et al*., 2021). 국내 역시 CLT 제품 정의와 품질기준, 구조용 직교 집성판 성능 기준 및 검사 판정에 대한 KS 규격으로 “구조용 직교 집성판”을 2020년 제정하였으며 현재 심의 중에 있다.

각 국의 CLT 규격에는 층재 기계 등급별 섬유 방향에 따른 강도값을 제시하고 있으며 층재 수종은 각국의 산림환경에 따라 다르다. CLT를 최초로 개발한 오스트리아에서는 C24, C18, C16 강도 등급의 노르웨이 가문비나무(*Picea abise*)를 주로 사용하고 있다(Brandner *et al*., 2016). 이 외에 White fir (*abies alba*), Scots pine (*Pinus sylvestris*), European larch (*Laix decidua*), Douglas fir (*Pseudotsuga menziesii*)와 Swiss stone pine (*Pinus cembra*) 등의 수종을 사용하고 있다(Fink *et al*., 2018). 호주와 캐나다는 Spruce (*Picea spp.*), Lodgepole pine (*Pinus contorta*), Douglas-fir (*Pseudotsuga menziesii*) 등의 수종을 CLT 생산에 사용하고 있다(Zhou *et al*., 2014). 미국 CLT 규격에서는 Spruce-pine-fir, Douglas-fir, Larch, Eastern softwoods, Northern species, Western wood, Southern pine을 CLT grades 제작에 사용될 수 있는 수종으로 명시하였다(ANSI/APA PRG 320, 2019).

전 세계적으로 자국의 목재를 사용하고자하며 CAS O141 Canadian Lumber Standard Accreditation Board (CLSAB) (Bejtka and Lam, 2008)와 National Design Specification for Wood Construction (Kramer *et al*., 2014)에서 건축재료로 사용되는 목재의 최소 비중은 0.35로 허용하고 있다. 설정된 층재 비중 0.35는 CLT connection design의 하한 값이며 북미 지역, 미국 서부, 캐나다 북부의 상업적으로 이용 가능한 목재 수종별 최소 비중 값이다.

비중 0.35 이상 수종을 사용하도록 허용하고 있으나 CLT 규격에 제시된 수종 이외의 수종에 대한 사용을 제한하지는 않는다. 이에 요구하는 물리·기계적 특성을 충족하기 위하여 CLT 층재 구성을 고려하여 제조하고 있다. 특히 강도 특성이 확립되지 않으나 지역적으로 풍부하고 활용도가 낮은 목재 자원을 CLT 층재로 활용하기 위한 시도가 증가하고 있다 (Espinoza and Buehlmann, 2018).

Sitka spruce (Sikora *et al*., 2016), italian marine pine (Fragiacomo *et al*., 2015), european beech (Aicher *et al*., 2016 (a); Aicher *et al*., 2016 (b)), southern pine (Hindman and Bouldin, 2015; Sharifnia and Hindman, 2017), hybrid poplar (Kramer *et al*., 2014), eucalyptus (Liao *et al*., 2017), japanese cedar (Okabe *et al*., 2014) 등의 수종을 CLT 층재로 사용하기

위한 연구를 수행된 바 있다.

국내에서는 CLT 층재 수종으로 주로 낙엽송(*Larix leptolepis*)을 사용하고 있다. 낙엽송 이외에 산림환경을 고려하여 삼나무(*Cryptomeria japonica*), 소나무(*Pinus densiflora*)의 제재수율 및 강도특성 연구와 잣나무(*Pinus koraiensis*), 백합나무(*Liriodendron tulipifera*)를 층재로 이용한 시험편의 접착전단성능 평가 등 연구를 통하여 층재 수종을 확대하고자 한다(Jeong *et al*., 2013; Park *et al*., 2017; Kim and Jeon, 2019; Pang *et al*., 2021).

각 국의 산림환경에 따라 다르지만 CLT 층재 수종은 주로 침엽수를 사용하고 있다. 그러나 기후환경이 다른 말레이시아, 인도네시아와 같은 열대지방은 활엽수를 CLT 층재로 사용하기 위하여 강도 특성 등 기초 연구를 진행하고 있다(Hamdan *et al*., 2016). 활엽수는 동일 밀도 침엽수와 비슷하거나 더 큰 강도를 가지므로 좋은 재료로 판단하며 층재로 활용을 기대하고 있다(Yusof *et al*., 2019).

이처럼 현대의 CLT는 최초로 유럽에서 개발되었지만, 전 세계적으로 확산되어 각국의 산림환경에 맞는 수종 최적화 및 강도성능 평가를 통하여 규격, 생산 공정 확립 등의 연구가 진행되고 있다.

3. 결과 및 고찰

제정된 여러 규격 중 대표적으로 사용되고 있는 미국 ANSI/APA PRG 320 규격에서 CLT는 제재목 또는 Structural Composite Lumber(이하 SCL)이 3층 이상 교차 적층된 공학목재로 정의하고 있다. SCL 종류로 Laminated Veneer Lumber(이하 LVL), Parallel Strand Lumber(이하 PSL), Laminated Strand Lumber(이하 LSL), Oriented Strand Lumber(이하 OSL) 등이 있다(Wood handbook, 2021).

일반적으로 제재목을 집성판으로 제조하여 교차적층한 CLT가 전 세계적으로 사용되고 있다. CLT는 major direction layer와 minor direction layer로 배치하며 면내 휨강도와 강성보다 횡방향 전단강도와 강성이 낮아 면외하중이 작용하였을 때 과도한 처짐과 rolling shear 파괴가 발생하여 면외 전단강도가 낮다는 단점이 있다(Sylvian *et al*., 2011). rolling shear 현상은 Fig. 3과 같으며 목재의 세포 구성과 밀접한 관련이 있다. 길이방향으로 연결된 섬유다발에 접선 및 방사방향으로 전단력이 가해졌을 때 섬유 개별적으로 분쇄되지 않고, 섬유가 구르며(roll off) 가장 약한 부분에서 rolling 파괴가 나타난다(Enhart and Brandner, 2018). rolling 파괴는 주로 침엽수에서 많이 나타나며, 이는 조재(밀도 약 300 ㎏/㎥)와 만재(밀도 900-1,000 ㎏/㎥)의 밀도 차이에 의하여 전단력이 작용하였을 때 경계에서 발생 및 전달된다. 사용되는 층재의 조재 비율, 조재의 밀도에 따라 전단 특성을 결정하게 된다(Enhart and Brandner, 2018).

CLT의 교차 층재에서 발생되는 rolling shear 현상은 Fig. 4와 같으며 낮은 rolling shear stiffness로 인하여 전단변형을 일으킬 수 있다고 보고하였다(Fellmoser and Balβ , 2004).

CLT의 교차층에서 나타나는 rolling shear strength와 stiffness는 재료 이방성 때문에 휨 하중거동에 영향을 미친다고 보고된 바 있다(Mestek *et al*., 2008). rolling shear를 제어하기 위하여 층재 수종, 밀도, 두께, 함수율, 제재 방법, 제재목 횡단면 크기 및 형상 등 여러 가지 많은 요소에 대한 연구가 진행되었고 제어 가능함을 확인하였다(Steiger *et al*., 2008).

낮은 강성과 강도를 가지는 CLT 교차층의 rolling shear strength를 향상시키기 위한 연구가 주를 이루고 있다. 대표적으로 교차층 층재로 활엽수 사용, 층재 각도 변화, structural composite lumber 중 LVL, LSL과 합판, OSB와 같은 구조용 패널을 층재로 적용하는 등의 연구가 진행되고 있으며, 이를 “hybrid CLT” 또는 “Composite CLT”라고 한다(Fig. 5).

3.1. 활엽수와 침엽수를 층재로 사용한 CLT 연구

CLT 교차층 층재의 낮은 rolling shear strength 향상을 위해 침엽수와 활엽수 층재의 혼합사용, 열대 지방 활엽수 수종 활용 등 수종 확대를 위한 CLT 강도특성에 관한 연구가 진행되고 있다.

Ehrhart 등(2015)은 유럽 목재 수종 중 norway spruce (*Picea abies(L.) Karst.*), pine (*Pinus sylvestris L.*), birch (*Betula pendula* Roth), beech (*Fagus sylvatica L.*), poplar (*Populus spp.*), ash (*Fraxinus excelsior L.*) 6가지 수종을 이용하여 rolling shear modulus와 shear strength를 평가하였으며 그 결과 Table 1과 같다. 층재 제재 방향, 층재 너비와 두께의 비율에 따라 rolling shear strength와 modulus가 달라지지만 침엽수 수종보다는 활엽수 수종이 약 1.3-2.3배 높은 rolling shear strength와 modulus 값을 나타냈다.

Aicher 등(2016)은 european beech를 층재로 사용하기 위하여 rolling shear 강도를 평가하였다. EOTA 2015 (European Organisation for Technical Assessment)에서 설계 목적으로 spruce와 fir 층재 rolling shear modulus는 일반적으로 50 N/mm² 으로 제시하고 있다. 측정된 european beech의 rolling shear modulus는 370 N/mm²으로 침엽수 보다 약 7배 높은 강성을

가지며 rolling shear strength는 4.5 N/mm²의 값을 나타냈다. 이는 면외 하중 조건에서 CLT 교차층 층재로 적용하기 위한 이상적인 재료로 european beech 사용을 제안하였다(Aicher *et al*., 2016 (a)).

Aicher 등(2016)은 spruce (*Picea abies*) 층재(major direction layer)와 european beech (minor direction layer) 층재를 혼합 사용하여 CLT 제조 및 휨 성능을 평가하였다. 그 결과 rolling shear modulus 350 N/mm², rolling shear strength 2.6 N/mm²의 결과를 나타냈다. 높은 rolling shear 특성은 침엽수 CLT의 전단강도 저하를 무시할 수 있다고 보고하였다 (Aicher *et al*., 2016 (b)).

Wang 등(2014)은 CLT 층재로 poplar의 사용 가능성을 검토를 위해 3 ply CLT를 제작하여 휨 및 전단강도 특성을 비교하였다(Table 2). douglas fir 층재를 poplar로 사용하였을 때 휨강도는 향상되나, 휨탄성계수, 전단강도는 감소되는 결과를 나타냈다. douglas fir, monterey pine 층재에 교차층을 poplar로 사용하였을 때 단일 수종을 사용한 경우 보다 휨강도, 탄성계수, 전단강도 모두 10%, 7.5%, 9.2% 감소하였다. poplar를 교차층 층재로 사용했을 때 뚜렷한 강도 감소를 나타내지 않아 douglas fir와 monterey pine 층재를 사용한 CLT와 poplar를 포함한 CLT의 기계적 특성이 유사하다는 결론을 도출하였다. 이에 CLT 층재로 poplar를 교차층 층재로 사용 가능함을 제안하였다(Wang *et al*., 2014).

3.2. 교차층 층재의 배열 각도 변화

층재 각도에 따른 탄성계수 평가 및 3 ply CLT의 전단강도 및 강성 평가를 통해 rolling shear strength 개선을 위한 연구가 진행된 바 있다(Buck *et al*., 2016; Bahmanzad *et al*., 2020).

Bahmanzad 등(2020)은 CLT 교차층에 의한 planar shear 개선을 위하여 교차층 층재 배열 각도에 따른 eastern hemlock 수종을 이용하여 전단강도 특성을 연구하였다. 섬유방향에 따른 elastic properties와 층재 각도에 따른 short-span shear test 결과는 Table 3, Table 4와 같다. 교차층 각도 30°는 90°보다 1.5배 높은 전단파괴 강도를 가졌으며(Table 3), 교차층 각도를 30°로 배열한 3ply CLT는 교차층 각도 90° 보다 유효전단강성은 8.3배 더 큰 값을 나타냈다(Table 4). 이는 교차층 각도에 의한 파괴유형이 rolling shear에서 인장력과 rolling shear 파괴로 변화함을 확인하였다. CLT 교차층 섬유방향에 따라 rolling shear와 stiffness를 향상시킬 수 있다는 가설을 뒷받침하였다. 또한, 각도조절에 따른 전단강도 향상 결과를 통하여 CLT 제조과정에서 교차층 배열 각도를 90°로 배열하였을 때 구조성능을 충족하지 못하는 수종에 대해서는 교차층 각도 조절을 통하여 CLT에 저 품질 목재(lower-quality wood)의 활용가능성을 확인하였다(Bahmanzad *et al*., 2020).

3.3. 구조용 복합재료를 사용한 CLT에 관한 연구

교차층 전단강도 향상을 위하여 침엽수와 활엽수 수종 혼합, 교차층 각도 변화 등의 연구 외에 OSB, LVL, LSL, PSL, 구조용 합판 등 기존 공학목재를 교차층 층재로 적용함으로써 전단강도 특성 평가에 관한 연구도 활발히 진행되고 있다.

그러나 현재 규격에서는 SCL 종류에 따른 강도값, 설계값 등은 제시하고 있지 않으나 층재로 사용을 제한하고 있지도 않다. 이에 공학목재는 기존에 강도 특성에 관한 데이터가 이미 확보되어있고 목재 수율을 증가시킬 수 있는 장점으로 SCL에 대한 관심도가 높아지고 있다. SCL이 층재로 사용된 hybrid CLT (Fig. 5)는 주로 각 국가에 제정된 CLT 규격에 반영을 위한 강도 값 산출에 주로 목적을 두고 수행되고 있다.

Wang 등(2015), Davids 등(2017), Niederwestberg 등(2018)은 LSL을 층재로 이용한 연구를 진행하였으며, Wang 등(2017)은 LVL을 교차층 및 층재 구성 변화에 따른 휨 및 전단강도 특성에 관한 연구를 진행하였다. Fujimoto 등(2021), Choi 등(2018), Pang 등(2019), Choi 등(2021), Choi 등(2020)은 CLT 교차층 층재로 구조용 합판을 사용하였을 때 휨 특성과 블록전단강도에 관한 연구를 진행하였다. Li 등(2020 (b))은 OSB, Li 등(2020 (a))과 Nurdiansyah 등(2020)은 대나무 보드를 층재로 사용하며 층재 구성 변화, layer의 적층 수에 따른 전단특성에 관한 연구를 진행하였다. hybrid CLT와 composite CLT의 휨 및 전단 강도특성 결과는 Table 5, 6과 같다.

Wang 등(2015)은 기존 CLT 구조(층재수종: lodgepole pine, *pinus contorta*)에 LSL을 교차층으로 사용하였을 때 MOR은 1.19배, MOE는 1.1배 증가하였으며, LSL를 최외층, pine을 교차층으로 적용하였을 때 기존 CLT 보다 MOR는 1.24배, MOE는 1.15배 증가하였다고 보고하였다(Wang *et al*., 2015).

또한 Davids 등(2017)와 Wang 등(2015)은 SPFs 3ply CLT에 LSL을 교차층으로 사용하였을 때 MOR은 1.23배 증가하였으나 MOE는 유사한 평균값을 나타냈으며 rolling shear strength는 1.45배 향상되었다. LSL을 일반 3 layer CLT 구조(배열 //－⊥－//)와 동일하게 적층하였을 때 rolling shear strength는 1.28배 향상되었다. 이는 제재목 대신 LSL을 CLT 구조로 구성하였을 때 rolling shear strength를 향상시킬 수 있다(Davids *et al*., 2017; Wang *et al*., 2015).

Niederwestberg 등(2018)은 SPF와 LSL을 CLT 층재로 5 ply CLT를 제조하여 휨 및 전단 강도 특성을 연구하였다. SPF 5 layer CLT의 구성 중 교차층을 LSL로 사용하였을 때 MOR은 1.49배, MOE는 1.18배, rolling shear strength는 1.2배 향상된 강도를 나타냈다. LSL을 최외층재로 구성한 CLT (LSL-SPF-LSL-SPF-LSL, SPF 층재 배열은 평행으로 배치)는 MOR 1.86배, MOE 1.13배, rolling shear strength 1.77배 향상된 강도를 나타냈다. 그러나 최외층으로 LSL을 사용하더라도 2, 4 ply의 SPF를 교차로 적층하였을 때 CLT와 MOR, MOE, rolling shear strength 값이 동일하게 나타났다(Niederwestberg *et al*., 2018; Davids *et al*., 2017).

Wang 등(2015), Davids 등(2017), Niederwestberg 등(2018)의 연구를 통하여 교차층을 LSL로 사용하였을 때 MOR 1.2배, MOE 1.1배 이상 향상됨을 확인하였다. 특히 rolling shear strength는 0.5-1.8배 향상되었다. 교차층 층재로 사용되는 LSL의 배열 방향 또한 CLT 휨 특성과 밀접한 관련이 있으며 강도 향상을 위한 방안으로 층재와 섬유방향이 동일하게 배치하는 것을 제안하였다(Wang *et al*., 2015; Davids *et al*., 2017; Niederwestberg *et al*., 2018).

Wang 등(2017)은 또한 SPF와 LVL을 CLT 층재로 사용하며 교차층 및 층재 구성 변경에 따른 휨 및 전단특성을 연구하였다. SPF 3 layer CLT 보다 LVL을 교차층 층재로 사용한 CLT는 MOR 10.1%, MOE 8.9%, rolling shear strength 6.2% 감소하였다. 이는 교차층에 직교 방향으로 LVL을 사용하였을 때 LVL의 낮은 planar shear 특성으로 인한 것으로 판단하였다(Fellmoser and Blaß, 2004). 또한 최외층재를 LVL로 사용하였을 때 강도 향상은 물론 LVL의 균일한 기계적 특성으로 인하여 hybrid CLT 또한 휨 특성을 개선할 수 있음을 제안하였다(Wang *et al*., 2017).

Fujimoto 등(2021), Choi 등(2018), Pang 등(2019), Choi 등(2020), Choi 등(2021)은 구조용 합판을 CLT 교차층 층재로 평행방향으로 적층한 CLT에 대한 강도특성을 평가하였으며, 이를 Ply-lam 또는 Ply-lam CLT라고 한다(Fujimoto *et al*., 2021; Choi *et al*., 2018; Choi *et al*., 2021). Fujimoto 등(2021)은 일본 미야자키 대학 및 목재이용연구센터에서 한국 구조용 낙엽송 합판(P)과 일본 cypress 층재(C)를 이용하여 Ply-lam을 제조 및 강도 특성에 관한 연구를 하였다. Ply-lam의 구성은 5 layer로 C-P-C-P-C로 구성하며 MOR 49.0 MPa, MOE 12.3 GPa, rolling shear strength 3.87 MPa의 결과를 발표하였다(Fujimoto *et al*., 2021). Choi 등(2020)는 집성재, CLT, Ply-lam CLT의 층재 구성 방법에 따른 블록전단강도를 평가하였다. Ply-lam CLT의 블록전단강도는 집성재 기준인 7.1 N/mm² 이상으로 층간 접착력이 우수함을 확인하였다. Choi 등(2021)은 낙엽송(기계등급 E11, E9)과 douglas fir 층재(기계등급 E13-14, E9-10)를 사용하여 Ply-lam CLT 제조 및 강도성능을 평가하였다. 층재 수종 및 탄성계수에 따른 강도 감소가 크지 않아 Ply-lam CLT 교차층 합판으로 인하여 수종에 따른 휨 강도 변화는 크지 않음을 확인할 수 있었다(Choi *et al*., 2021). 또한, Song과 Hong (2018)은 낙엽송(층재 기계등급 E13, E9, E11) 3 ply CLT의 휨 강도에 관한 연구를 수행하였다(Song and Hong, 2018). 낙엽송 CLT와 Ply-lam CLT에 사용된 층재 기계등급 중 압축응력을 받는 최외층 층재 기계등급은 다르지만 CLT 보다 Ply-lam CLT는 MOR 1.3배, MOE 1.5배 향상되는 결과를 도출하였다.

Li 등(2020 (b))은 SPF와 OSB를 층재를 이용하며 층재 적층 수, 층재 배열 방향에 따른 hybrid CLT 제조 및 rolling shear strength를 평가하였다. 3 layer 기준 OSB를 교차층에 섬유방향으로 적용하였을 때 1.94배, 교차층에 섬유 직각방향으로 적용했을 때 1.86배 전단강도가 향상된다고 보고하였다. 또한, 5 layer SPF CLT에서 2, 3, 4 ply를 OSB 섬유방향으로 배치하였을 때 5 layer SPF CLT 보다 1.59배 전단강도가 향상되었다. 일반 CLT 구조와 동일하게 OSB를 교차 배열한 CLT도 일반 SPF CLT 보다 1.59배 전단강도가 향상됨을 밝힌 바 있다. 이는 앞선 단판이 동일 방향으로 구성된 LVL, LSL의 연구 결과와 달리 OSB는 교차층에 배열 방향에 따른 강도저하는 5% 이하로 미약하였다. LSL과 OSB 패널은 strand의 배열이 섬유방향으로 동일하나 LSL과 OSB에 사용되는 strand의 폭 길이(LSL strand 12-16 mm, OSB strand 30-80 mm) 차이로 strand의 폭 방향 접착 면적이 넓어 섬유 직각방향의 전단강도가 향상되었을 것으로 판단하였다(Li *et al*., 2020 (b)). 사용된 strand 크기뿐 아니라 LSL과 OSB는 strand 배열 방향에 차이가 있다. 단일 방향으로 strand 배열하는 LSL과 달리 OSB는 다층구조로 층별로 strand의 배열이 다르며 합판과 동일하게 교차로 적층하여 제조된다. 이에 섬유 배향에 따른 강도차이가 크지 않으므로 CLT 층재로 사용하였을 때 섬유 배향에 따른 강도차이를 나타내지 않는 것으로 판단된다.

Nurdiansyah 등(2020)은 acacia (*acacia mangium willd.*)와 대나무 solid board를 혼합 적층한 CLT 휨 및 전단특성을 연구하였다. 그 결과 대나무 solid board의 높은 MOE로 인하여 CLT 역시 가장 높은 MOE와 전단강도 값을 도출하였다(Nurdiansyah *et al*., 2020). Li 등(2021)은 hem-fir와 bamboo woven panel(이하 BMCP)을 층재로 이용하며 층재 구성에 따른 3 ply CLT의 강도 특성 평가를 하였다. 기존 CLT에서 교차층을 BMCP로 사용하였을 때 휨 특성은 유사한 값을 나타내나 전단강도는 2.4 MPa에서 1.37배 증가된 3.3 MPa을 나타냈다(Li *et al*., 2021).

CLT 교차층의 낮은 rolling shear strength를 개선과 원재료 수율 향상을 위하여 기존에 개발된 공학목재 및 구조용 목재 패널을 교차 층재로 사용하기 위한 연구가 지속적으로 수행되고 있다. 교차층 층재로 LSL, LVL, OSB, 합판, 대나무보드 등 구조용 복합체를 사용하였을 때 rolling shear는 최대 2배, MOE는 최대 1.5배, MOR은 최대 1.35배 이상 강도가 향상됨을 확인할 수 있다.

이에 구조용 목질재료 층재의 휨 특성은 CLT의 전단과 휨 특성에 영향을 미치므로 요구하는 강도특성에 맞는 hybrid CLT를 제조하기 위한 구조용 목질재료의 선정이 중요하다고 판단하였다(Davids *et al*., 2017; Wang *et al*., 2015).

반면 교차층 층재로 사용되는 재료의 섬유배향에 따라 기존의 CLT 보다 강도가 저하되는 선행연구 결과를 통하여 배향성을 가진 LSL, LVL 등의 재료는 CLT 층재 구성 방향에 대한 추가적인 고려가 필요하다. 반면 구조용 합판, 대나무보드(BMCP)와 같이 섬유방향과 섬유직각방향 휨 특성이 동일한 재료의 경우 최외층으로 배치하였을 때 minor 방향 강도 또한 확보할 수 있다.

4. 결론

본 연구에서는 유럽, 미국 등의 고층 목조건물에 사용되는 대형 목재 패널인 CLT의 낮은 rolling shear strength를 향상하기 위한 hybrid CLT의 연구 개발 동향 분석을 통하여 CLT의 국산화를 위한 연구개발 방향에 활용 가능한 기초자료를 마련하고자 하였다. rolling shear strength를 향상하기 위한 방안으로 활엽수 층재 사용, 층재 각도 변화, 구조용 목질재료 사용으로 CLT의 강도 특성을 비교하였으며 그 결과는 다음과 같다.

1. CLT 제조에 사용되는 침엽수와 활엽수의 rolling shear strength와 shear modulus 비교를 통하여 활엽수는 침엽수보다 rolling shear strength, shear modulus 모두 최대 2배 이상의 높은 값을 가진다. 교차층 층재로 활엽수를 사용함으로써 rolling shear 특성 향상 및 미이용 수종 활용 등 장점이 있지만 추가적으로 침엽수와 활엽수 층간 접착 성능 평가가 필요할 것으로 판단된다.
2. CLT 교차층 층재는 현재 90°로 배치하여 제조하고 있으나 층재 각도에 따른 CLT의 강도 결과 90°에서 30°로 변경하였을 때 rolling shear strength 1.5배 향상, shear modulus는 8.3배, bending stiffness 4.1배 향상되는 것을 확인하였다. 이에 층재 배열 각도 조절에 따라 CLT의 강도 향상은 물론 기계등급이 낮은 목재의 이용 확대가 가능할 것으로 판단된다.
3. CLT 교차층을 LVL, LSL, 합판 등과 같이 강도성능이 확보된 구조용 목질재료를 사용함으로써 MOR 최대 1.35배, MOE 최대 1.5배, rolling shear strength 2배 향상되었다. 강도가 향상된 hybrid CLT에 사용된 목질재료는 MOE 7.0 GPa 이상, MOR 40.0 MPa 이상의 휨 특성 값을 가졌다. 이는 교차층 층재로 사용가능한 구조용 목질재료의 휨 특성 기준임을 확인할 수 있었다. 특히 구조용 합판, OSB와 같이 섬유 방향 및 섬유 직각방향으로 교차되어 제조된 재료는 면외 하중이 가해졌을 때 시험편의 섬유 방향에 따른 강도차이가 작다. CLT의 층재로 사용하였을 때 면외·내의 균일한 강도 값을 확보할 수 있을 것으로 판단된다. 반면 LSL과 같이 strand 동일한 방향으로 배열된 재료의 경우 면외하중이 가해졌을 때 오히려 휨 특성을 감소시키므로 동일한 배향을 가진 LVL, LSL 등의 재료는 층재 구성에 대한 추가적인 연구가 필요하다.