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

Seung Min YANG² · Hwa Hyung LEE³ · Seog Goo KANG²,†

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 lamina. Block shear strength between the layer materials was also secured by 7.0 N/mm², 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; Karacabeyli 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,
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/m² 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 a 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 abies) 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 ma-
rine 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 an 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).](image-url)
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...of 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).

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. 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 1. Proposed rolling shear characteristics for \( \frac{w_l}{t_l} \geq 4 \) (Ehrhart et al., 2015)

<table>
<thead>
<tr>
<th>Type</th>
<th>( f_{R,k} ) (N/mm²)</th>
<th>( G_{R,mean} ) (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce</td>
<td>1.4</td>
<td>100</td>
</tr>
<tr>
<td>Pine</td>
<td>1.7</td>
<td>150</td>
</tr>
<tr>
<td>Poplar</td>
<td>2.2</td>
<td>120</td>
</tr>
<tr>
<td>Birch</td>
<td>2.7</td>
<td>180</td>
</tr>
<tr>
<td>Ash, Beech</td>
<td>4.0</td>
<td>350</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Type</th>
<th>Out layers</th>
<th>Cross layers</th>
<th>( f_{b,0} ) (MPa)</th>
<th>( E_0 ) (GPa)</th>
<th>( f_{\theta,0} ) (MPa)</th>
<th>( f_{\theta,90} ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Poplar</td>
<td>Poplar</td>
<td>41.66</td>
<td>5.97</td>
<td>2.00</td>
<td>1.21</td>
</tr>
<tr>
<td>2</td>
<td>Douglas fir</td>
<td>Poplar</td>
<td>31.56</td>
<td>8.07</td>
<td>1.97</td>
<td>1.09</td>
</tr>
<tr>
<td>3</td>
<td>Monterey Pine</td>
<td>Poplar</td>
<td>41.23</td>
<td>6.21</td>
<td>1.80</td>
<td>1.03</td>
</tr>
<tr>
<td>4</td>
<td>Monterey Pine</td>
<td>Monterey Pine</td>
<td>44.55</td>
<td>6.35</td>
<td>2.04</td>
<td>0.81</td>
</tr>
<tr>
<td>5</td>
<td>Douglas fir</td>
<td>Douglas fir</td>
<td>34.72</td>
<td>8.69</td>
<td>2.17</td>
<td>1.24</td>
</tr>
</tbody>
</table>
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)

<table>
<thead>
<tr>
<th>Species</th>
<th>$E_L$</th>
<th>$E_T$</th>
<th>$G_W$</th>
<th>$G_{30}^\circ$</th>
<th>$G_{45}^\circ$</th>
<th>$G_{60}^\circ$</th>
<th>$G_{90}^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern hemlock</td>
<td>8,300</td>
<td>276</td>
<td>520.56</td>
<td>191.68</td>
<td>104.11</td>
<td>83.43</td>
<td>61.36</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Mid-layer angle</th>
<th>Peak load (kN)</th>
<th>$E_{L,app}$ ($10^9$ N·mm²/m)</th>
<th>$G_{A,eff}$ ($10^6$ N/m)</th>
<th>$f_{v,max}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90°</td>
<td>88.3</td>
<td>117.3</td>
<td>9.5</td>
<td>2.03</td>
</tr>
<tr>
<td>60°</td>
<td>95.9</td>
<td>286.3</td>
<td>19.9</td>
<td>2.2</td>
</tr>
<tr>
<td>45°</td>
<td>102.7</td>
<td>375.9</td>
<td>34.9</td>
<td>2.4</td>
</tr>
<tr>
<td>30°</td>
<td>129.1</td>
<td>486.3</td>
<td>78.7</td>
<td>3.0</td>
</tr>
</tbody>
</table>
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

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

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 5. Continue

<table>
<thead>
<tr>
<th>CLT type</th>
<th>Panel type</th>
<th>Panel lay-up</th>
<th>Layer direction*</th>
<th>Specimen dimension (mm)</th>
<th>Span-depth ratio</th>
<th>Major direction MOE (GPa)</th>
<th>MOR (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ply-lam (Fujimoto et al., 2021)</td>
<td>Plywood</td>
<td>C-P-C-P-C</td>
<td>/-/-/-/-/-/-/-/-/-/</td>
<td>150(T)×300(W)×3,450(L)</td>
<td>21</td>
<td>12.3</td>
<td>49.0</td>
</tr>
<tr>
<td>CLT with plywood (Choi et al., 2018)</td>
<td>Plywood</td>
<td>D-P-D-P-D</td>
<td>/-/-/-/-/-/-/-/-/-/</td>
<td>40(T)×40(W)×600(L)</td>
<td>13</td>
<td>10.8</td>
<td>67.8</td>
</tr>
<tr>
<td>Ply-lam CLT (Choi et al., 2021)</td>
<td>Plywood</td>
<td>L-P-L-P-L</td>
<td>/-/-/-/-/-/-/-/-/-/</td>
<td>75(T)×300(W)×2,400(L)</td>
<td>29</td>
<td>15.1</td>
<td>61.6</td>
</tr>
<tr>
<td>Tropical Hybrid CLT (Nurdiansyah et al., 2020)</td>
<td>Bamboo laminated board</td>
<td>L-B.S-L</td>
<td>/-/-/-/-/-/-/-/-/-/</td>
<td>54(T)×305(W)×1,260(L)</td>
<td>19.6</td>
<td>21.8</td>
<td>39.41</td>
</tr>
<tr>
<td>Bamboo-wood composite cross laminated timber (Li et al., 2021)</td>
<td>Bamboo woven panel (BMCP)</td>
<td>L-L-L</td>
<td>/-/-/-/-/-/-/-/-/-/</td>
<td>51(T)×145(W)×1,630(L)</td>
<td>30</td>
<td>9.6</td>
<td>45.0</td>
</tr>
</tbody>
</table>
<pre><code>                                                             | BMCP-L-BMCP                     | /-/-/-/-/-/-/-/-/-/ | 6.27               | 31.3        |
</code></pre>

* // and ⊥ represent the parallel and perpendicular to the major 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/mm², density: 0.71 g/cm³)
3) LSL properties; 9.5 kN/mm², 41.7 N/mm², density: 0.64 g/cm³
4) SPF; shear modulus 84.92 N/mm², shear strength 1.41 N/mm²
   LVL was made from douglas fir (*Pseudotsuga menziesii*) veneer, 2.0E grade (shear modulus 47.88 N/mm², shear strength 1.07 N/mm²)
5) L; korean larch (*Larix kaempferi* Carr.), outer tension laminae: 13 kN/mm², middle laminae: 7-9 kN/mm², outer compression laminae: 11kN/mm²
6) PL; korean pine (*Pinus koraiensis*) (MOE: 8-9 kN/mm²)
7) C; japanese Cypress lamina, outer layer 11 kN/mm², inner layer 9 kN/mm²,
   P; korean larch (*Larix kaempferi*) plywood (major direction–MOE 10.9 kN/mm², MOR 44.1 N/mm², minor direction–MOE 5.19 kN/mm², MOR 18.7 N/mm²)
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/mm², inner 9 kN/mm²), P; korean larch plywood. thickness 15 mm, density 0.5 g/cm³, MOR 42.8 N/mm², MOE 7.1 kN/mm²
11) D; douglas fir lamina (outer 12-13 kN/mm², inner 9-10 kN/mm²), P; korean larch plywood. thickness 15 mm, density 0.5 g/cm³, MOR 42.8 N/mm², MOE 7.1 kN/mm²
12) L; Acacia mangium Willd, density 0.37 g/cm³, MOR 15.3 N/mm², MOE 9.98 kN/mm², B.S; Bamboo solid board, density 0.55 g/cm³, MOR 22.5 N/mm², MOE 18.49 kN/mm²
13) L; hem-fir (*Tsuga heterophylla* (Raf.) Sarg×*Abies amabilis* (Dougl.) Forbes) density 0.43 g/cm³, MOE 11.8 kN/mm², MOR 69.5 N/mm²
   BMCP; Bamboo woven panel, density 0.79 g/cm³, MOE 7.6 kN/mm², MOR 56.6 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).

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 orthogonal 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.

ACKNOWLEDGMENT

This study was carried out with the support of R&D Program for Forest Science Technology (Project
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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 마련하였으며, 낮은 rolling shear strength를 향상시키기 위한 방안으로 활엽수 층재 사용, 층재 배열 각도 변화, 구조용 목질복합재의 사용이 주를 이루고 있다. 활엽수 층재는 절두수 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 strength 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 간 합착강도 또한 집성재 블록전단기준 기준이 7.0 N/mm²를 초과할 수 있었다. 선행연구 결과를 통해 MOE 7.0 GPa, MOR 40.0 MPa 이상의 횡 특성을 가진 구조용 목질재료를 사용하였을 때 강도성을 향상할 수 있음을 확인하였다. 이를 통해 구조용 목질재료 층재 강도 기준을 충족할 수 있었다. rolling shear strength 개선하기 위한 최적의 방법은 기존 규칙에 의한 강도값을 가진 구조용 목질재료의 적용이 가장 유리한 것으로 판단하여, 구조용 목질재료의 설치 범위에 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 기계적인 재료로 주목받으며 전통목조건축에서 강물 기반의 콘크리트, 벽돌을 사용한 건축물로 대체되었다(Hong et al., 2015). 이때 건축 재료 중 목재의 시장점유율은 10% 이하였으며 주로 경량목조건축으로 주거 및 비주거용 건물, 전시장 등에 사용되었다. 이후 주거용 건축물, 사무실, 학교 등의 시설 등 기타 건설 분야에 콘크리트 대신 목재를 사용하여 목조건축 시공사례 및 시장점유율이 증가하였다. 이 뿐만 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 주거용 건축물에 목재 사용이 본격화되었다(Antonio et al., 2021).

CLT (Fig. 1)는 당시 재계산업에서 사이드보드 보다 더 높은 가치의 용도 개발(Guttmann, 2008), scrap wood (Sander, 2011), 기계등급이 낮은 목재, 재목재(Cameron, 2013) 등을 활용하기 위해 개발이 시작되었다. CLT는 3, 7, 9 호수층으로 구성된 조립성목재이며 단면의 하중을 견딜 수 있도록 교차층 층재를 90° 각도로 배치하여 만들어진 대형 목재 패널이다(Ehrhart and Brander, 2018; Karacabeyli et al., 2013). CLT는 초기에 독일어로 “Breitsterrholz (BSP)” 명하여 shells, grid-shells, spatial(3차원)과 관련된 “laminar laminated timber product”의 하위재료로 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 구축하여 생산과 연구개발을 확대한 환경이 발전해져가고 있다.

CLT에 관한 활발한 연구는 고층목조건축물 증가로 이어졌다. 2009년 영국 런던 9층 목조 아파트 Stadthaus (Xiong et al., 2016), 2012년 호주 멜버른 10층 Forte 목조건축물(Li et al., 2019), 2014년 노르웨이 14층 아파트 “Treet” (Malo et al., 2016), 2017년 캐나다 벤쿠버 브리티쉬 콘비아대학 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 m³까지 증가할 것으로 예측하며 급격히 상장하고 있다(Brandner et al., 2016). 유럽의 생산량 증가와 더불어 미국, 캐나다, 호주, 일본, 뉴질랜드 등 지역도 연간 CLT 생산양이 증가하고.
Research Trends in Hybrid Cross-Laminated Timber (CLT) to Enhance the Rolling Shear Strength of CLT

발표된 CLT는 패널을 통해 여러 목재를 섬유성으로 가공하고 있는 CLT를 포함한다. 제조회사는 CLT의 재료 특성 및 기계적 특성을 가질 수 있음을 고려하여 제조하고 있다. CLT 재료는 사목성, 전단력, 견고성, 내화성, 접합부 성능, 환경성을 갖춘 재료로 사용하기 위해 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 접착전단강도를 개선하기 위한 연구가 주로 진행되고 있다. 총레배열에 따라 접착전단강도가 다르게 나타나며 red pine 수종을 층재로 사용하였을 때 접착성은 10 N/mm², CLT는 3.5 N/mm² 이상으로 접착력가 접착전단강도의 35% 단위를 나타내었다(Kim et al., 2013). 이를 향상시키기 위하여 점착성 수종을 이용한 최적 접착제 도포량과 압력 조절하여 접착전단강도를 평가하였으며 도포량 2019년 Chio 도달하며 잣나무 수종을 이용한 최적 접착제 도포량과 압력 조절하여 접착전단강도를 평가하였다.

2. 재료 및 방법


각국의 CLT 규격에는 층재 기재 장밀별 섬유 방향에 따른 강도값을 제시하고 있으며 층재 수종은 각국의 산림환경에 따라 다룬다. CLT를 최초로 개발한 오스트리아에서는 C24, C18, C16 강도 등급의 노르웨이 가문비나무(Picea abies)를 주로 사용하고 있다(Brandner et al., 2016). 이 외에 White fir (abies alba), Scots pine (Pinus sylvestris), European larch (Larix 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 명시하였 다(ANSI/APA PRG 320, 2019).

전 세계적으로 각국의 목재를 사용하여 CAS O141 Canadian Lumber Standard Accreditation Board (CLSAB) (Bejtká and Lam, 2008)와 National Design Specification for Wood Construction (Kramer et al., 2014)에서 제조업체로 사용되는 목재의 최소 비중은 0.35로 허용하고 있다. 설정된 층재 비중 0.35는 CLT connection design의 하한 값이며 북미 지역, 미국 서부, 캐나다 북부의 산림적으로 이용 가능한 목재 수용 법 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 구성원을 고려하여 제조하고 있다. 특히 강도 특성이 확립되지 않으나 지역적으로 공용하고 활용도를 낮은 목재 자원을 CLT 층재로 활용하기 위한 시도가 증가하고 있다(Espinoza and Buehmlan, 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; Sharifinia 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 수중으로 주로 낙엽송(Larix leptolepis)을 사용하고 있다. 낙엽송 이외에 산림환경을 고려하여 삼나무(Cryptomeria japonica), 소나무(Pinus densiflora)의 제재수용 및 강도특성 연구와 갖나무(Pinus koraiensis), 백합나무(Liriodendron tulipifera)를 층재로 이용한 시험판의 접착전단성능 평가 등의 연구를 통하여 층재 수중을 확대로하고자 한다(Jeong et al., 2013; Park et al., 2017; Kim and Jeon, 2019; Pang et al., 2021).

각 국의 산림환경에 따라 다르지만 CLT 층재 수중은 주로 층재수용 및 강도수용 연구를 수행하고 있다. 그러나 기후환경이 다른 말레이시아, 인도네시아와 같은 열대지역은 활엽수를 CLT 층재로 사용하기 위하여 강도 특성 등 기초 연구를 진행하고 있다(Hamdan et al., 2016). 활엽수는 동일 밀도 접착수용과 비교하거나 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 수중 최적화 및 강도특성 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 제재 가득한 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 접착판으로 제조하여 교차작용한 CLT가 전 세계적으로 사용되고 있다. CLT는 major direction layer와 minor direction layer으로 구성하며 면밀한 층재와 강성으로 사용할 수 있고, 면밀한 층재와 강성이 낮아 면밀화작용이 없는 경우 교차작용의 층재와 강성은 낮다는 단점이 있다(Sylvian et al., 2011). rolling shear 현상은 Fig. 3과 같이 몇가지 세로 구성과 밀집도가 미여한 관련이 있다. 강행방향으로 연결된 섬유단면에 접선 및 방사형으로 전단력이 가해졌을 때 폐쇄로 개발적으로 분쇄되지 않고, 섬유가 구르며(roll off) 가장 약한 부분에서 rolling 파괴가 나타난다(Enhart and Brandner, 2018). rolling 파괴는 주로 접착수용에서 많이 나타나며, 이는 조재(밀도 약 300 kg/m³와 밀도(밀도 900-1,000 kg/m³)의 밀도 차이에 의하여 전단력이 작용하였을 때에 생기는 역량 및 전단력은 사용되는 조재의 조재, 조재의 밀도에 따라 전단 특성을 결정하게 된다(Enhart and Brandner, 2018).

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

CLT의 교차층에서 나타나는 rolling shear strength의 stiffness는 재료 이방성 때문에 휘 하중등의 영향을 미친다고 보고된 바 있다(Mestek et al., 2008). rolling shear을 이용하기 위하여 층재 수중, 밀도, 두께, 함수수, 재료, 방식, 전단특 성도, 접선 및 접함, 크기 및 형상 등 여러 가지 많은 요소에 대한 연구가 진행되었고, 제어 가능성을 확인하였다(Steiger et al., 2008).

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

3.1. 활엽수와 층재를 층재로 사용한 CLT 연구

CLT 교차 층재의 낮은 rolling shear 상황을 위해 층재수용과 활엽수 층재의 혼합사용, 열대 지방 활엽수 수중 활엽수 층재 수중 활용 등 수중 확대를 위한 CLT 강도특성에 관한 연구가 진행되고 있다.

Elhrart 등(2015)은 유럽 목재 수중 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 층재 방향, 층재 너비과 두께의 비율에 따라 rolling shear strength와 modulus가 달라지만 층재수용보다는 활엽수 수중의 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/mm²으로 제시하고 있다. 층재된 european beech의 rolling shear modulus는 370 N/mm²으로 층재수용보다 약 7배 높은 강성을
가지며 rolling shear strength는 4.5 N/mm²의 값을 나타냈다. 이는 면의 하중 조건에서 CLT 교차층 층재로 적용하기 위한 이상적인 재료로 european beech을 사용한 연구가 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 중단 성능을 평가하였다. 그 결과 rolling shear modulus 350 N/mm², rolling shear strength 2.6 N/mm²의 결과를 나타냈다. 높은 rolling shear 특성을 보이는 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 횡 및 전단강도 특성을 비교하였다(Table 2). douglas fir 층재를 poplar로 사용하였을 때 횡강도는 향상되나, 횡단성수와 전단강도는 감소되는 결과를 나타냈다. douglas fir, monterey pine 층재에 교차층을 poplar로 사용하였을 때 단일 수용을 사용한 경우보다 횡강도, 전단성수와 전단강도 모두 10%, 7.5%, 9.2% 감소하였다. poplar로 교차층 층재를 사용했을 때 두ittest 강도 감소를 나타내지 않아 douglas fir과 monterey pine 층재를 사용한 CLT와 poplar를 포함한 CLT의 기계적 특성이 유사하다는 결론을 도출하였다. 이에 CLT 층재로 poplar로 교차층 층재로 사용가능성을 제안하였다(Wang et al., 2014).

3.2. 교차층 층재의 배열 각도 변화

층재 각도에 따른 성능의 평가를 위해서 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 수종의 성능을 이용하여 전단강도 특성을 연구하였다. 심유방향에 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°에 배향한 3ply CLT는 교차층 각도 90°보다 유효전단강성은 8.3배 더 큰 값을 나타냈다(Table 4). 이는 교차층 각도에 의한 교차층 배열의 성능에 대한 관심도가 높아지고 있다. CLT 교차층 성유방향에 따라 rolling shear의 stiffness를 향상시킬 수 있다는 가설을 탐방치하였다. 또한, 각도조절에 따른 전단강도 향상 결과를 통하여 CLT 제조과정에서 교차층 배열 각도를 90°로 배향하였다. 이는 교차층 강도의 증가로 층재의 전단파괴 강도는 증가한다. 이에 층재에 대한 연구를 진행하였다. 교차층 각도 조절을 통하여 CLT의 전단파괴 강도를 향상시킬 수 있다(Bahmanzad et al., 2020).

3.3. 구조용 복합재료로 사용한 CLT에 관한 연구

가지와 전단강도 향상을 위하여 교차층 수용구조를 구성하였으며, 교차층 각도 변화 등의 구조에 따라 OSB, LVL, LSL, PSL, 구조용 합판 등 기존의 구조재 구조의 층재 층재로 적용함으로써 전단강도 특성 평가를 위한 연구도 활발히 진행되고 있다. 그러나 현재의 구조재에서는 SCL 종류의 따른 강도차, 설계값 등은 제시하지 않고 있으나 축조를 사용할 필요도 없어 구조물의 성능에 대한 기술적 적용이 필요하다. 복합재로 사용된 hybrid CLT (Fig. 5)는 주로 각 국가에 제정된 CLT 규격에 반영한 강도가 산출에 주로 목표를 두고 수행하고 있다.


Niederwestberg 등(2018)은 SPF와 LSL을 CLT 층계로 5 ply CLT를 제조하여 휘 및 전단 강도 특성을 연구하였다. SPF 5 layer CLT의 구성 중 교차층을 LSL로 사용하였을 때 MOR는 1.49배, MOE는 1.18배, rolling shear strength는 1.2배 향상된 강도를 나타냈다. LSL을 최외층계로 구성한 CLT (LSL-SPF-LSL-SPF-LSL, SPF 전단 배열은 평행형으로 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 적용하였을 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 향상함을 확인하였다. 특히 rolling shear strength는 0.5-1.8배 향상되었다. 교차층의 배열에 따라 LSL의 배열 생성을 구성하는 CLT의 특성을 확인할 수 있었으며, 전단성능과의 관계가 있으며 강도 향상을 위한 방안으로 층계와 섬유방향의 동일하게 배치하는 것을 제안하였다(Wang et al., 2015; Davids et al., 2017; Niederwestberg et al., 2018).

Wang 등(2017)은 또한 SPF와 LSL을 CLT 층계로 사용하여 교차층 및 층계 구성 변경에 따른 휘 및 전단특성을 연구하였던 SPF 3 layer CLT 보다 LVL을 교차층으로 사용한 CLT는 MOR 10.1%, MOE 8.9%, rolling shear strength 6.2% 감소하였다. 이를 교차층에 직교 방향으로 LVL을 배치하였을 때 LVL의 낮은 planar shear 특성을 인한 것으로 판단하였다(Fellmoser and Blaß, 2004). 또한 최외층계는 LVL로 사용하였을 때 강도 향상은 물론 LVL의 길임한 기계적 특성으로 인하여 hybrid CLT 또한 휘 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 합판(V-LCL) CLT 교차층 층계로 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 미야기 지역을 머리에 이용하여 CLT층계의 기계등급을 연구하였다. 한국 구조용 나무합성합판(P)과 일본 cypress재 등재를 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)은 접선체, CLT, Ply-lam CLT의 층계 구성 방향에 따른 롤링전단강도를 평가하였다. Ply-lam CLT의 롤링전단강도는 접선체 기준인 7.1 N/mm² 이상으로 점차 점차적으로 우수함을 확인하였다. Choi 등(2021)은 나무재(기계등급 E11, E9)과 douglas fir를 이용하여 Ply-lam CLT 제조에 관한 연구를 수행하였다(Song and Hong, 2018). 나무재의 roiling 성능에 따른 강도차이가 모두 Ply-lam CLT를 적용한 경우 향상된 결과를 도출하였다. Li 등(2020b)은 SPF와 OSB를 층계로 응용하여 층계 적용 수, 층계 배열 방향에 따른 CLT 제조 및 롤링 sheart strength를 평가하였다. 3 layer 기준 OSB를 교차층에 섬유방향으로 적용하였을 때 1.94배, 교차층에 섬유 직교방향으로 적용하였을 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 구조의 동일하게 OSB를 교차 배열한 CLT의 롤링 전단강도는 일반 SPF CLT 보다 1.59배 전단강도가 향상된 것으로 나타났다. 이는 앞선 단판이 동일 방향으로 구성된 LVL, LSL의 연구 결과와 달리 OSB는 교차층에 배열 방향에 따른 강도변화는 5% 이하로 미약하였다. LSL과 OSB 패널은手臂 배열의 섬유방향으로 동일하거나 LSL과 OSB에서 사용하는 순서의 롤링값(LSL strand 12-16 mm, OSB strand 30-80 mm)이 다르며 기본 방향을 달리 섬유 직교방향의 전단강도가 향상되었음을 것으로 판단하였다(Li et al., 2020b). 사용된 순서의 롤링값의 차이로 LSL과 OSB는 롤링 방향에 따라 다르며 합판 동일하게 교차로 적용하여 제조된다. 이에 섬유 방향에 따른 강도차이가 크게 없으므로 CLT 층계로 사용하였을 때 섬유 방향에 따른 강도차이를 나타내지 않는 것으로 판단된다.

Nurdiansyah 등(2020)은 acacia (acacia mangium willd.)의 데나무 solid board를 혼합적층한 CLT 휘 및 전단특성을 연구하였다. 그 결과 데나무 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 층계로 응용하여 층계 구조에 따른 3 ply CLT의 강도 특성을 평가하였다. 기존 CLT에서 교차층을 BMCP로 사용하였을 때 휘 특성은 유사한 값을 나타내며 전단강도는 2.4 MPa에서 1.37배 증가한 3.3 MPa를 나타냈다(Li et al., 2021).
CLT 교차층의 낮은 rolling shear strength를 개선과 원재료 수용 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 복합재를 사용하였을 때 rolling shear는 최대 2배, MOE는 최대 1.5배, MOR은 최대 1.35배 이상 강도가 향상된 것을 확인할 수 있다.

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

반면 교차층 층재로 사용되는 재료의 섬유배향에 따라 기존의 CLT보다 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 섬유방향 및 섬유직각방향 휨 특성이 동일한 재료의 경우 최외층으로 배치하였을 때 minor 방향 강도 또한 향상될 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 목재재료 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 중간 집착 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 목재재료를 사용함으로써 MOR 최대 1.35배, MOE 최대 1.5배, rolling shear strength 2배 향상되었다. 강도가 향상된 hybrid CLT에 사용된 목재재료는 MOR 7.0 GPa 이상, 40.0 MPa 이상의 휨 특성 값을 가졌다. 이는 교차층 층재로 사용가능한 구조용 목재재료의 휨 특성 기준을 충족할 수 있었다. 특히 구조용 합판, OSB와 같이 섬유 방향 및 섬유직각방향으로 교차되어 제조된 재료는 면의 하중이 가해졌을 때 시험편의 섬유 방향에 따른 강도차이가 작다. CLT의 층재로 사용하였을 때 면의나의 급한 강도 값을 확보할 수 있도록 사용한다. 반면 LVL과 같이 strand 동일한 방향으로 배열된 재료의 경우 면의하중이 가해졌을 때 오히려 휨 특성을 감소시키므로 동일한 배향을 가진 LVL, LSL 등의 재료는 층재 구성에 대한 추가적인 연구가 필요하다.