Dimensional Changes of Cross-Laminated Specimens Produced under Different Conditions due to Humidity Variation

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Cross-laminated timber (CLT) is becoming increasingly adopted into wooden construction of South Korea. Due to the lack of standards and protocol for CLT, there are many problems in the production and utilization phases. This study focused on the deformation and defects of CLT due to humidity variations. In this study, small, cross-laminated specimens were manufactured using three layers of laminated larch planks that had various moisture contents. The dimensional changes of these specimens were measured in response to changing internal conditions including side adhesion or moisture content variation and external conditions such as humidity. Shrinkage in width and thickness was less than 1.0% when using dry planks as the cross-laminated specimen. However, high-moisture content (MC) planks were not suitable when used as the surface layer of the CLT, as the shrinkage in width and thickness were greater than 2.0%. When high-MC planks are used in the inner layer, their shrinkage must be less than 2% to prevent splitting caused by a MC difference between the surface and inner planks. For this purpose, laminates with a MC less than 15% should be used for CLT.

Keywords: Cross-laminated timber; Dimensional change; Larch; Shrinkage; Ultimate deformation

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INTRODUCTION

Wood, as a hygroscopic material, exchanges moisture with surrounding air. Moisture changes in wood are accompanied by deformation such as shrinkage and swelling. In particular, the prolonged exposure of a wooden building to moisture affects the durability and safety of building (Glass and Zelinka 2010). Cross-laminated timber (CLT) is an engineered wood that was developed in Austria (Schickhofer and Brandner 2013). To make CLT panels, several layers of lumber boards are stacked cross-wise and glued together on their wide faces (Gagnon *et al.* 2013). The dimensional changes of CLT panels are smaller than those of dried lumber because CLT is alternately laminated in the longitudinal and transverse directions (Gagnon and Popovski 2011). Because CLT panels can be utilized in many ways, including as floors and walls of buildings, many studies have examined their mechanical properties. The properties of bending strength, shear strength (Okabe *et al.* 2014; Fredriksson *et al.* 2015; Espinoza *et al.* 2016; Lu *et al.* 2018), and elastic limit (Gsell *et al.* 2007; Gülzow *et al.* 2011) have been of particular interest. On the other hand, there are few studies on hygrothermal behavior of CLT.

If a CLT panel is exposed to a change in the external conditions, such as temperature and relative humidity (RH), different degrees of shrinkage in various layers of the CLT can cause several problems. The twisting of CLT laminas caused by differences in shrinkage and swelling can result in their separation from the adhesive layer of the CLT, and the stress between the surface and internal layer of the lamina can cause end checking. Studies concerned with the moisture transfer and moisture content (MC) of CLT have measured thermal conductivity and the equilibrium MC (Popper *et al.* 2004a; 2004b; Bader *et al.* 2007). A theoretical approach has been shown regarding warping (Xu and Suchsland 1996). The stresses and strains were evaluated as a function of moisture changes (Gereke *et al.* 2009). The monitoring (Wang 2016; Schmidt *et al.* 2019) and simulation (McClung *et al.* 2014) of hygrothermal behavior of CLT according to the surrounding environment were performed at a laboratory scale.

The usage of CLT has gradually increased since it was introduced in South Korea for the construction of high-rise wooden buildings. Because there are no standards and protocols for CLT in South Korea, many problems arise in the construction and utilization of CLT manufactured using domestic species. In South Korea, the surface of CLT panels is often exposed to indoor conditions, which may result in gaps between laminas and lead to defects such as cracks. This study evaluated the stress and strain of CLT by MC changes to solve the problems of end checking and the separation of the laminas from the adhesive. The shrinkage and swelling in the width and thickness of cross-laminated specimens that were made under different production conditions and exposed to changes in the external conditions were measured. The MCs of cross-laminated planks due to humidity were predicted using a finite difference method that incorporated the diffusion coefficient (Yeo *et al.* 2008) and the surface emission coefficient (Yeo and Smith 2005). The stress of cross-laminated specimens that were exposed to changes in the external conditions was determined and compared with the tensile strength of larch wood with different MCs. The occurrence of end checking was analyzed and predicted by comparing the stress and tensile strength. Additionally, limits of the MC and the elastic strain of the laminas are proposed.

EXPERIMENTAL

Materials

Domestic larch (*Larix kaempferi*) trees were felled in the area of Yeongdong-gun, Chungcheongbuk-do, Republic of Korea. The larch logs were cut into 150 mm wide × 50 mm thick × 1,200 mm long boards using a band saw sawmill. The boards were dried in a laboratory-scale kiln according to the FPL T10-C4 Kiln Drying Schedule standard (Boone *et al.* 1988). The initial MC of the boards ranged from 55 to 110%, and the oven-dry specific gravity of the larch wood averaged 0.473 (0.021 SD). Forty-five larch planks (90 mm wide × 30 mm thick × 270 mm long) for cross-laminated specimen manufacturing were obtained from the larch board during drying. The MCs of planks were determined as the average of MC specimens taken from each of the four sides of plank. The moisture variations of the four MC specimens were up to 1.6% in each plank. The average MC of the planks ranged from 3.6 to 25.1%.

In this experiment, the commercial product P84 (Otto-Chemie, Fridolfing, Germany) was used as the one-component polyurethane resin for the manufacturing the cross-laminated specimens. Commercial products generally come with a technical datasheet that describes detailed gluing conditions. The optimum gluing conditions of 45-

min pressing time, 1.0 MPa pressure, and 175 g/m^2 of adhesive of P84 for larch wood (Kim *et al.* 2013; Han *et al.* 2017) were used to manufacture the cross-laminated specimens. Seven cross-laminated specimens were manufactured, and they varied in terms of their MC, laminating position, and edge gluing (Table 1).

Table 1. Manufacturing Conditions of the Cross-laminated Specimens

Specimen	Pressing Time (min)	Pressure (MPa)	Amount of Adhesive (g/m^2)	Moisture Content (%)		Edge Gluing
				Surface Layer	Internal Layer	
No. 1	45	1.0	175	11.7 – 12.9	11.3	No
No. 2				10.0 – 11.9	11.6	Yes
No. 3				9.8 – 11.1	25.1	No
No. 4				10.0 – 10.7	25.1	Yes
No. 5				24.8	9.8	No
No. 6				6.1 – 9.1	12.0 – 12.8	No
No. 7				3.6 – 5.4	13.2 – 16.8	No

Dimensional Changes of the Cross-laminated Specimens due to Humidity Conditions

The seven cross-laminated specimens were humidified using a thermo-hygrostat (Hanbaek Scientific Technology Co., Bucheon, Republic of Korea) at 25 °C and 60% RH (10.8% equilibrium MC) for three weeks. After humidifying, changes in the width and thickness of the specimens in accordance with the equilibrium MC were measured during drying under two conditions (80% and 40% RH). Each condition was performed for three weeks and repeated twice. The sides of the three layers of the cross-laminated specimens were classified into two types. The type A side was composed of a longitudinal plank in the surface layer and three transverse planks in the internal layer (Fig. 1a). In contrast, the type B side was composed of three transverse planks in the surface layer and a longitudinal plank in the internal layer (Fig. 1b). For the type A side, WA1, WA2, WA3, and TA were defined as the width change of the internal layer, the width change of the surface layer, the width change of the internal plank, and the thickness change of the specimen, respectively. For the type B side, WB1, WB2, WB3, and TB were defined as the width change of the internal layer, the width change of the surface layer, the width change of the surface plank, and the thickness change of the specimen, respectively. Image files of the two types of sides were obtained using a scanner (Perfection V200 Photo; Epson, Suwa, Japan). Shrinkage and swelling of the width and thickness of the specimens were measured relative to a scale bar using an image analysis program (ProgRes Capture Pro 2.7; Bimeince, Suwon, Republic of Korea).

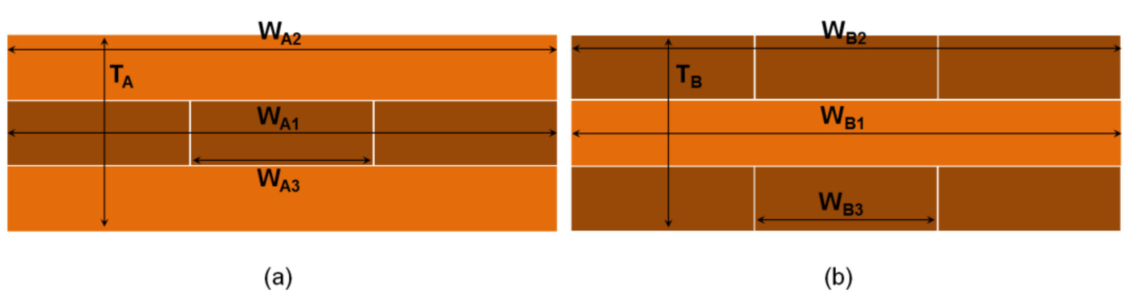

Fig. 1. Two sides of the cross-laminated specimens, (a) type A and (b) type B

Finite Difference Method for Prediction of the Moisture Content Distribution in the Cross-laminated Specimens

Moisture profiles of the cross-laminated specimens were predicted using the two-dimensional finite difference method. The difference between the experimental value and the predicted value of the model was 6.30% in a previous study (Han 2014). The diffusion coefficients and surface emission coefficients of domestic larch wood, which were measured at various temperatures and RH conditions in a previous study (Han *et al.* 2007), were used to predict the moisture profiles of the cross-laminated specimens. The nodes in the finite difference method were classified into three types: the interior node, the convective boundary node, and the exterior corner node with a convective boundary (Fig. 2). The rate of change of the moisture concentration in the three nodes can be expressed using the finite difference method as follows. Equations 1, 2, and 3 present the rate of change of the moisture concentration in the interior node, the convective boundary node, and the exterior corner node with a convective boundary, respectively,

$$D_x \cdot \frac{C_{m+1,n}^{p+1}+C_{m-1,n}^{p+1}-2C_{m,n}^{p+1}}{(\Delta x)^2} + D_y \cdot \frac{C_{m,n+1}^{p+1}+C_{m,n-1}^{p+1}-2C_{m,n}^{p+1}}{(\Delta y)^2} = \frac{C_{m,n}^{p+1}-C_{m,n}^{p}}{\Delta t} \quad (1)$$

$$D_x \cdot \Delta y \cdot \frac{C_{m-1,n}^{p+1}-C_{m,n}^{p+1}}{\Delta x} + D_y \cdot \left(\frac{\Delta x}{2}\right) \cdot \frac{C_{m,n-1}^{p+1}+C_{m,n+1}^{p+1}-2C_{m,n}^{p+1}}{\Delta y} + S \cdot \Delta y \cdot \left(C_e - C_{m,n}^{p+1}\right) = \left(\frac{\Delta x \cdot \Delta y}{2}\right) \cdot \frac{C_{m,n}^{p+1}-C_{m,n}^{p}}{\Delta t} \quad (2)$$

$$D_x \cdot \left(\frac{\Delta y}{2}\right) \cdot \frac{C_{m-1,n}^{p+1}-C_{m,n}^{p+1}}{\Delta x} + D_y \cdot \left(\frac{\Delta x}{2}\right) \cdot \frac{C_{m,n-1}^{p+1}-C_{m,n}^{p+1}}{\Delta y} + S \cdot \left(\frac{\Delta x+\Delta y}{2}\right) \cdot \left(C_e - C_{m,n}^{p+1}\right) = \left(\frac{\Delta x \cdot \Delta y}{4}\right) \cdot \frac{C_{m,n}^{p+1}-C_{m,n}^{p}}{\Delta t} \quad (3)$$

where D_x is the diffusion coefficient in the x-direction (m^2/s), D_y is the diffusion coefficient in the y-direction, C is the moisture concentration (kg/m^3), x and y are distances in the direction of the flow (m), t is time (s), S is the surface emission coefficient (m/s), m and n are increments in the x- and y-direction, respectively, p is the time increment, and e is the equilibrium state.

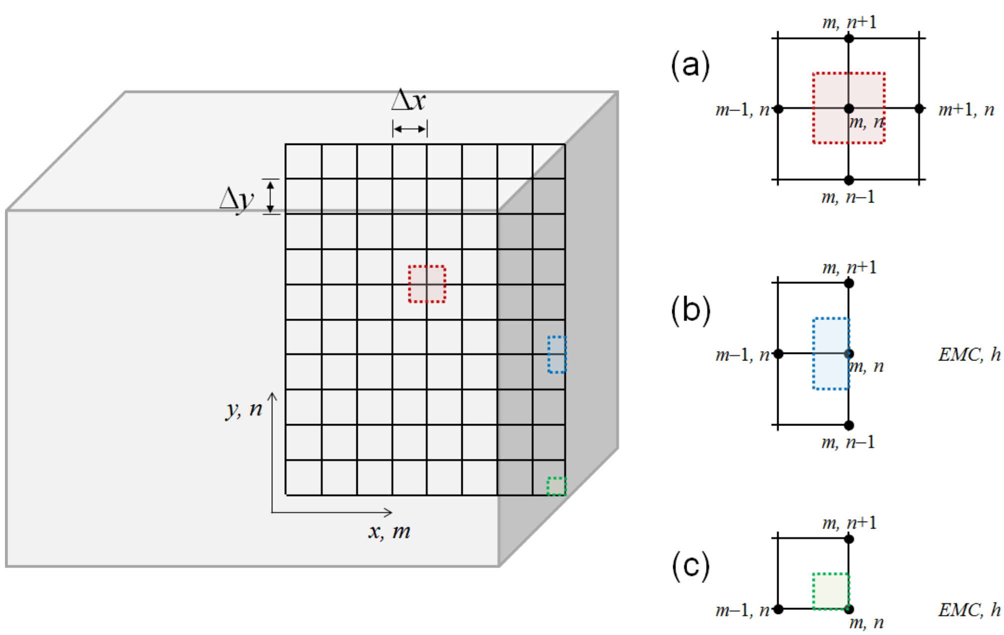

Fig. 2. Three nodes in the finite difference method, (a) interior node, (b) convective boundary node, and (c) exterior corner node with a convective boundary

Hygrothermal Properties for Larch Wood Measurement of Shrinkage, the Modulus of Elasticity, and Tensile Strength in the Transverse Direction for Larch Wood in Accordance with the Moisture Content

Theoretically, shrinkage in a stress-free process (free shrinkage) can be measured using very thin specimens if the moisture gradient between the surface and internal layer is small (Stamm 1964). The transverse shrinkage of the domestic larch trees was measured, and knot-free, straight-grained specimens with 50 mm (tangential) × 50 mm (radial) × 2 mm (longitudinal) dimensions were prepared. Drying was performed at 25 °C by varying the RH (99, 90, 60, and 30%) using a thermos-hygrostat to minimize the drying stress. After drying, the specimens were oven-dried at 105 °C, and their weights and dimensions were measured. The MCs of the specimens were calculated based on their oven-dry weights.

Digital image correlation (DIC) for shrinkage analysis was performed using MATLAB (MathWorks, Natick, MA, USA) based on code developed at the Johns Hopkins University and the Karlsruhe Institute of Technology (Eberl *et al.* 2011). The DIC process for the shrinkage analysis was described in a previous study (Han *et al.* 2016).

The domestic larch wood was used to measure the modulus of elasticity (MOE) and tensile strength in the transverse direction according to the KS F 2207 standard (2004). The larch wood was dried to analyze the moisture dependence of the dynamic mechanical properties at 25 °C by varying the RH (99, 90, 60, and 30%) using a thermos-hygrostat. After drying, specimens with 20 mm (radial) × 20 mm (longitudinal) × 60 mm (tangential) dimensions were prepared. A universal testing machine with a 980 N maximum load (Zwick, Ulm, Germany) was used to apply the load at a loading rate of 2 mm/min to the specimens, and the maximum load was determined when the specimens broke. The transverse MOE (E_e) was calculated from the relationship between the load and deformation,

$$E_e = \frac{P_l \cdot l}{\Delta_l \cdot A} \tag{4}$$

where, E_e is the MOE (N/mm^2), P_l is the difference between the upper and lower loads in the proportional limit (N), l is the gauge length (mm), Δ_l is the tensile deformation caused by P_l (mm), and A is the area of the cross-section (mm^2). The transverse tensile strength (σ_t) was calculated from the maximum load,

$$\sigma_t = \frac{P_{max}}{A} \tag{5}$$

where, σ_t is the tensile strength (N/mm^2) and P_{max} is the maximum load (N).

RESULTS AND DISCUSSION

Changes in the Width and Thickness of the Cross-laminated Specimens

The dimensional changes in shrinkage or swelling of the cross-laminated specimens based on the dimensions after humidifying are shown in Fig. 3. The dimensional changes of cross-laminated specimens tended to repeat shrinkage and swelling depended on the humidity variation. The shrinkages and swellings in the width of each specimen ranged from 0.492 to 2.145% and from 0.459 to 2.542%, respectively, while the shrinkages and swellings in thickness ranged from 0 to 1.653% and from 1.513 to 2.435%, respectively.

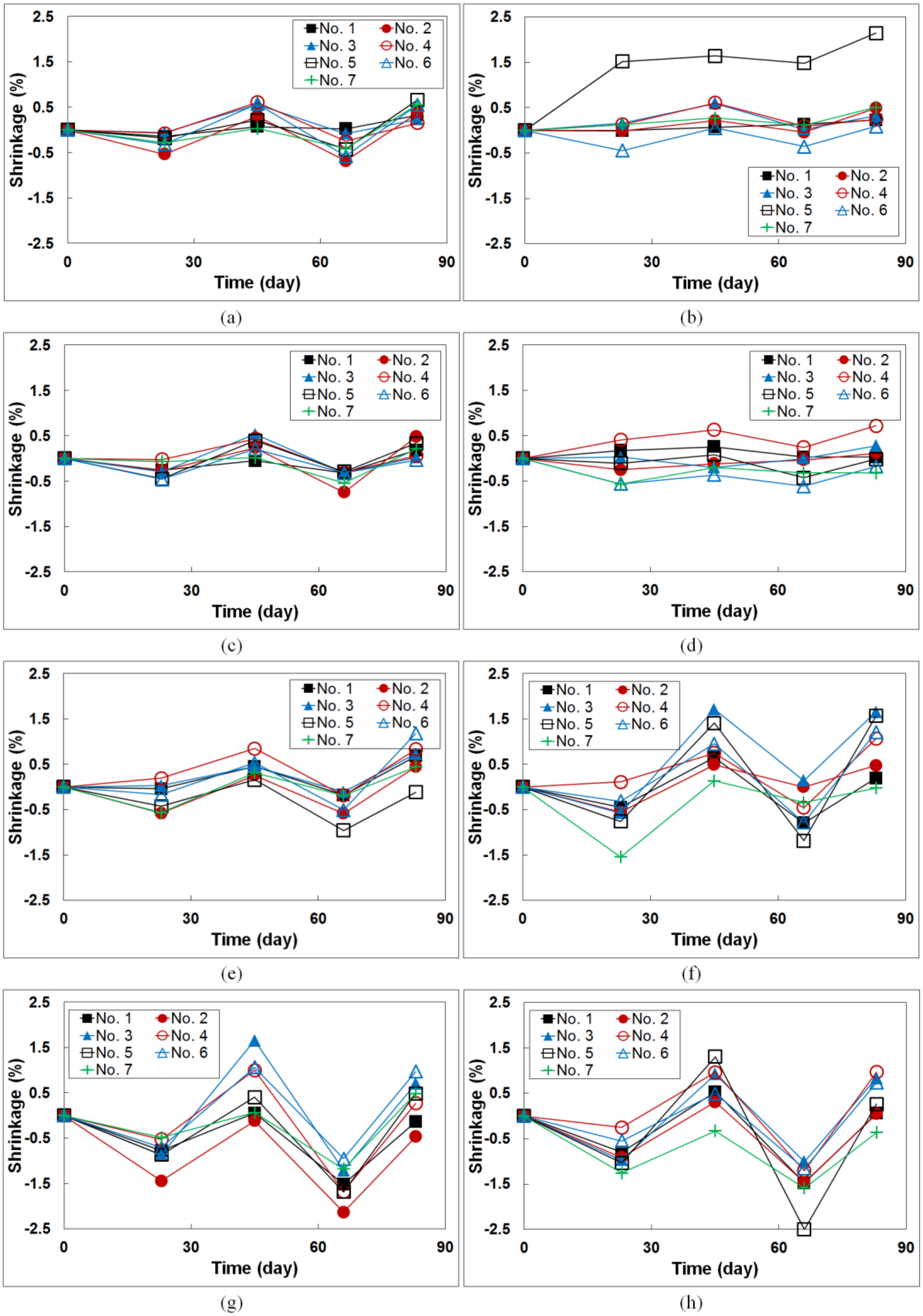

Fig. 3. Changes in the width and thickness of the specimens, (a) WA1, (b) WA2, (c) WA3, (d) WB1, (e) WB2, (f) WB3, (g) TA, and (h) TB

Because width change was restrained by a plank glued in longitudinal direction, the thickness change, which is relatively freely deformed, was larger. The maximum shrinkage and swelling in the width were generally measured for WB3, which is the width of the plank in the surface layer of the cross-laminated specimens. Because this plank was exposed to changes in humidity, it experienced larger changes in shrinkage and swelling. The initial large shrinkage of No. 5 specimen in Fig. 2(b) was considered as a failure of the surface layer to equilibrium state during 25 °C and 60% RH humidifying. Edge gluing reduced the shrinkage and swelling of the surface layer of the cross-laminated specimens. If high-MC planks were used to manufacture the cross-laminated specimens, shrinkage increased. In contrast, swelling increased when low-MC planks were used.

When a cross-laminated specimen is exposed to wet or dry ambient air, the deformation of the inner surface of the surface planks is restrained by the internal planks. This may cause the defects on the inner and surface of specimens. A space between the plank on the surface layer and an adjacent plank on the surface layer occurs because the outer surface of the surface plank, which is exposed to the air, deforms freely. When using high-MC planks as surface layers, substantial warping and delamination of the cross-laminated specimens were observed (Fig. 4a; specimen No. 5). Spaces between the planks in the surface layer occurred in the cross-laminated specimens that were manufactured with kiln-dried larch wood (Fig. 4b; specimen No. 1). The spaces were reduced using planks with a relatively low MC because the shrinkage of these planks was low (specimens No. 6 and No. 7), whereas end checking occurred occasionally in the cross-sections of the planks when high-MC planks were used as the internal layer (Fig. 4c; specimen No. 3). These problems adversely affect the appearance and usefulness of CLT that is exposed to air.

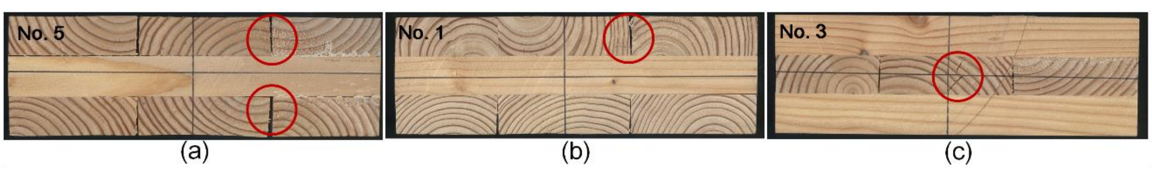

Fig. 4. (a) Warping and delamination of planks, (b) spaces between the plank and an adjacent plank in the surface layer, and (c) and end checking of the cross-sections of the planks

Shrinkage Below the Fiber Saturation Point, the Modulus of Elasticity, and Tensile Strength in the Transverse Direction for Larch Wood

The specimens with a 52.4% (12.7 SD) initial MC were humidified to different MCs below the fiber saturation point (FSP) by decreasing the RH from 99 to 30% at a constant temperature of 25 °C. Additionally, the specimens humidified at 30% RH were oven-dried at 105 °C. The transverse shrinkage of the larch wood specimen below the FSP is shown in Fig. 5. The shrinkage was 5.29% in the transverse direction when the MC decreased from 28.5 to 5.9%. The regression equation used to predict the transverse shrinkage below the FSP is presented in the form of a linear function in Eq. 6,

$$\varepsilon_T = -0.218 \cdot x + 6.148 \tag{6}$$

where, ε_T is the shrinkage in the transverse direction (%) and x is the moisture content (%).

The temperature and MC of a specimen affects its MOE and tensile strength (Sandoz 1993; Zhan *et al.* 2009; Chan *et al.* 2011). In this study, the MOE and tensile strength in the transverse direction were measured at 25 °C. The MOE and tensile strength, which were measured at equilibrium MC conditions ranging from 28.5 to 5.9%, ranged from 124 to 225 MPa and from 2.2 to 5.3 MPa, respectively (Fig. 6). The MOE and tensile strength gradually increased when the MC decreased from 28.5 to 5.9%. The linear relationship between the MOE and the MC was determined using Eq. 7,

$$E_e(x) = -5.33x + 254.79 \quad (7)$$

where, E_e is the MOE (N/mm^2). The linear relationship between the tensile strength and the MC was determined using Eq. 8,

$$\sigma_{t,x} = -0.17x + 6.15 \quad (8)$$

where, σ_t is the tensile strength (N/mm^2). The R^2 values of the linear models of MOE and tensile strength were 0.960 and 0.969, respectively.

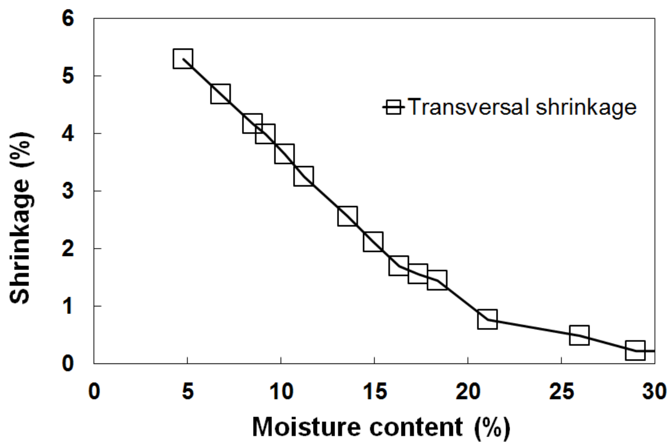

Fig. 5. Transverse shrinkage for larch wood below the fiber saturation point

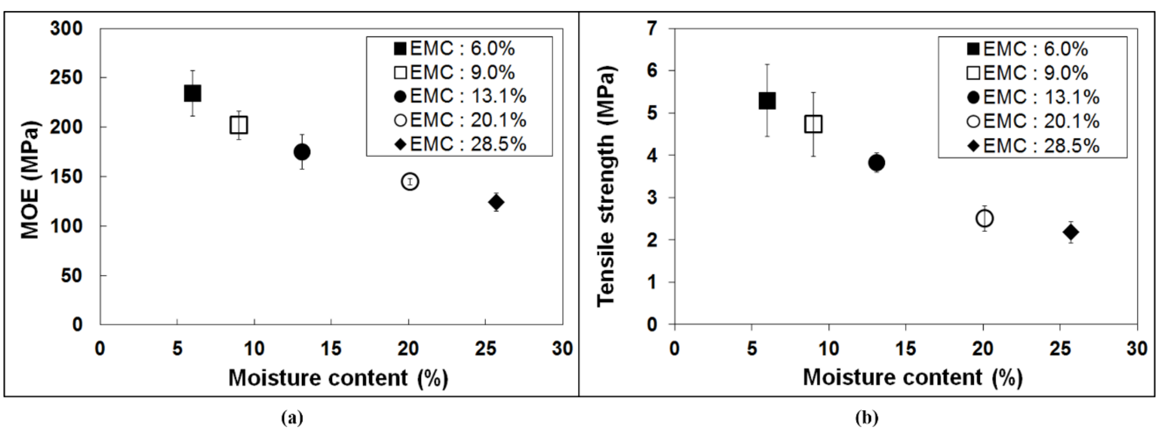

Fig. 6. (a) MOE and (b) tensile strength in the transverse direction for larch wood

Prediction of Moisture Distribution and End Checking Occurrence

Drying stress of a cross-laminated specimen is the result of restrained shrinkage caused by an uneven moisture distribution between the end and center parts of an internal layer plank. End checking in response to changes in the ambient RH occurs in the cross-section of an internal layer plank when the stress exceeds the tensile strength in the transverse direction. End checking occurred in specimen No. 3 after 60 h of humidifying at 25 °C and 60% RH (Fig. 4c). In this study, the two-dimensional (radial × longitudinal)

MC distribution was predicted using the two-dimensional finite difference method to apply the diffusion coefficient and surface emission coefficient of domestic larch wood. The applied diffusion coefficients in the radial and longitudinal directions and the surface emission coefficient at 25 °C and 60% RH were 3.5×10^{-10} m^2/s, 1.5×10^{-9} m^2/s, and 1.1×10^{-7} m^2/s, respectively (Han *et al.* 2007). The MC distribution in the internal layer plank after 60 h of humidifying is shown in Fig. 7. The red, blue, and green nodes are interior nodes, convective boundary nodes, and exterior corner nodes with convective boundaries, respectively.

The average MC of the boundary layer, including the boundary node and exterior node, was 15.4%. The shrinkage, MOE, and tensile strength in the transverse direction at a MC of 15.4% were 2.12%, 172.7 MPa, and 3.61 MPa, as calculated using Eq. 6 , 7, and 8, respectively. Because the MC of the cross-section of a plank rapidly equilibrates to the MC of the ambient air, it can be assumed that the stress due to the elastic strain, excluding visco-elastic strain, acts on the cross-section. Therefore, the stress on the cross-section is the product of the elastic strain and the MOE at a given MC. Because the tensile stress at a 15.4% MC was greater than the 3.61 MPa tensile strength, end checking can occur in the cross-section of an internal layer plank. End checking did not occur by the shrinkage of the plank in the proportional limit. The tensile strength, the MOE in the transverse direction, and elastic strain in the proportional limit in accordance with the MC are shown in Table 2. It is assumed that the indoor conditions during heating in winter were 25 °C and 20% RH. If CLT is exposed to indoor air, the MC of the cross-section of the lamina can rapidly reach the 4.5% equilibrium MC of the indoor air. To prevent end checking, the transverse shrinkage of lamina in accordance with the MC must be smaller than the elastic strain of 0.023 in the proportional limit, as shown in Table 2. The domestic larch boards that are available for CLT must be dried below a MC of 15.1%, as determined by Eq. 6: $6.148 - 0.218 \times MC < 2.30$.

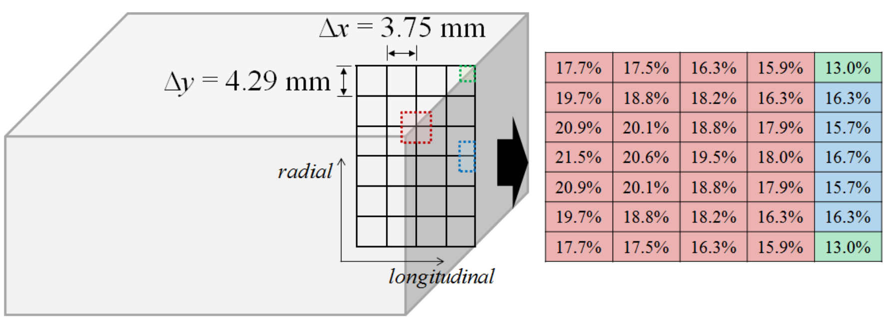

Fig. 7. Prediction of the moisture content distribution of the internal layer plank in cross-laminated specimens after 60 h of humidifying

Table 2. Tensile Strength, the MOE in the Transverse Direction, and the Elastic Strain in the Proportional Limit in Accordance with the MC

MC of the Lamina (%)	Tensile Strength In the Transversal Direction (MPa)	MOE in the Transversal Direction (MPa)	Elastic Strain in the Proportional Limit
4.5	5.41	231	0.023
10	4.50	201	0.022
15	3.67	175	0.021
20	2.84	148	0.019

CONCLUSIONS

1. The shrinkages and swellings in the width of each specimen ranged from 0.492 to 2.145% and from 0.459 to 2.542%, respectively, while the shrinkages and swellings in thickness ranged from 0 to 1.653% and from 1.513 to 2.435%, respectively. The dimensional changes varied according to the initial MCs of the planks in the cross-laminated specimens. Edge gluing reduced the shrinkage and swelling of the surface layer of the cross-laminated specimens.
2. Substantial warping and delamination of the cross-laminated specimens occurred when high-MC planks were used as the surface layers. End checking occurred occasionally in the cross-sections of planks when high-MC planks were used as the internal layer. To prevent end checking in response to changes in humidity, the shrinkage of laminas in indoor conditions during heating in winter should be less than the elastic strain of 2.3% in the proportional limit. For this reason, CLTs should be manufactured using laminas with MCs less than 15.1%.

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