J. Korean Wood Sci. Technol. 2016, 44(4): 607~615 pISSN: 1017-0715 eISSN: 2233-7180
http://dx.doi.org/DOI:10.5658/WOOD.2016.44.4.607

Original Article

Evaluation of Bonding Strength of Larch Cross-Laminated Timber[1]

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ABSTRACT

The delamination along the annual ring on the cross-section of laminae and the bonding strength according to the tangential angle between laminae were evaluated for the production of 3-ply cross-laminated timber (CLT) using domestic larch. Since there is no standard for CLT in Korea, the production and test of specimens for bonding strength followed the standard procedure of "Structural glued laminated timber" (KS F 3021). The standard specifies to exclude any measurement from the cracks of timbers resulted from drying or knots during delamination test of the glued laminated timbers. However, the failure of cross-sectional tissues along the annual rings was observed near the glue-line of all specimens during the delamination test. Because this phenomenon can generate defects in the CLT that may be exposed to various temperatures and relative humidities after the actual construction, the delamination percentage was measured by including this wood failure. As a result, the delamination percentage of the CLT which had been combined in such a way that the annual rings of outer lamina were directed inward was the lowest, which was around 13%, regardless of the annual ring direction of the middle lamina. On the other hand, the delamination percentage of the CLT which had been combined in such a way that the annual rings of outer lamina were directed outward was the highest, which was around 26%. Furthermore, end-split occurred in the outer lamina during the drying process of the boiling delamination test, which affected the delamination percentage. Therefore, the soaking delamination test was found to be more appropriate for evaluating the delamination strength of CLT. The block shear strength of larch CLT was 3.9 ± 0.9 MPa on average, which was 46% lower than the block shear strength requirement (7.1 MPa) of the standard, but satisfied the criteria of the block shear strength (3.5 MPa) of the European Standard (prEN 16351:2013).

Keywords: cross-laminated timber, *Larix kaempferi*, delamination, block shear, rolling shear, wood failure

1. INTRODUCTION

Cross-laminated timber (CLT) which was first developed in Europe in the 1990s is a new type of wood-based panel that is being manufactured by crossly laminating the laminae at right angle of fiber direction unlike glued laminated timbers whose fiber direction is in parallel. CLTs can be used for walls, flooring, and roofs with large sections, and are being highlighted for

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their replaceability with concrete, brick and metal structures (Mohammad *et al*., 2012). Compared to existing construction materials, the CLT has higher specific strength and better dimensional stability and carbon storage effect due to its cross lamination (Darby *et al*., 2013). Furthermore, it shortens construction time because horizontal and vertical members are prefabricated in factories and assembled on site through mechanical jointing or adhesive bonding. Above all, buildings constructed with CLTs have strong rigidity, good toughness and energy dispersion performance (van de Kuilen *et al*., 2010; Ceccotti, 2008; Ceccotti *et al*., 2006). Therefore, CLTs can be used for middle and high story buildings as well as low story buildings, which is the greatest advantage (Popovski and Karacabeyli, 2012). For this reason, the Waugh Thistleton architecture firm, together with KLH from Austria, completed the construction of Stadhaus in London, U.K., which is a residential apartment, in just 49 weeks, for which they used concrete for the first floor and CLTs for the rest eight floors. The Lend Lease Australia architecture firm constructed the ten-story wooden building Forte, which is the highest wooden building in existence, in Melbourne, Australia (Robertson *et al*., 2012; Pei *et al*., 2014). Furthermore, in Japan, they constructed a dormitory building as a pure CLT structure with no columns and beams for the first time in 2014. CLTs have been used not only in high-story houses, but also in schools in Frankfurt and Dusseldorf. The Richmond Olympic ice rink in Vancouver, Canada started remodeling in 2006 and replaced the entire roof with glued laminated timbers and CLTs. Thus, the uses of CLTs are spreading from Europe to North America and from North America to Oceania and Asia while professional research on them is being actively conducted. Now they can build 30-story or higher wooden buildings using CLTs in other countries, but in Korea, no one can produce proper CLTs and there are no established quality standards for CLT products. Therefore, more diverse, systematic research of CLTs is required, starting from the manufacturing process. In particular, the bonding strength between laminae is a critical factor due to the manufacturing characteristics of CLTs which are cross-laminated. Recently, Kim *et al*. (2013) performed block shear strength test, which is one of the bonding strength evaluation tests, for CLTs and found similar tendencies to the results of overseas studies even though the species of trees were different. On the other hand, there are no domestic studies about the delamination of CLTs between laminae. Furthermore, no delamination tests of CLTs combined along the annual rings of laminae have been conducted in Korea yet. The delamination phenomenon is likely to stand out in Korea due to large variations of temperature and humidity. Moreover, the delamination of multi-layered timbers during a fire has been found to accelerate carbonization (Per Wilinder, 2010). Therefore, efforts must be made to reduce delamination which can generate defects after construction.

Meanwhile, according to the statistics of Korea Forest Service, the timber self- sufficiency rate has been rising every year from 13.5% in 2010 to 16.7% in 2014, but our dependence on imported timbers is still high. Among them, larch is acting as a substitute for imported woods together with pine trees (Statistical Yearbook of Forestry, 2014). Therefore, in order to stimulate domestic timber use and find a possible commercialization of larch CLTs, this study evaluated the delamination percentage and block shear strength of CLTs that have been combined in various ways along the annual rings of the cross section of larch laminae.

2. MATERIALS and METHODS

2.1. Production of larch CLTs for the evaluation of bonding strength

Larch (*Larix kaemfrei* carr.) laminae with an average air-dry moisture content of 14%, an average air-dry specific gravity of 0.52, and a size of 27 mm (T) × 89 mm (W) were used. The laminae were combined by crossing at the right angle to the fiber direction with no class divisions and laminated with resorcinol resin. The lamination was performed in a total of three layers, with a glue spread of 300 g/m^2 and a pressure of 0.9 N/mm^2.

2.2. Soaking and boiling delamination tests

The soaking and boiling delamination specimens were collected at 100 mm inward from the end of larch CLTs with a width, length, and height of 80 mm, 75 mm, and 81 mm according to the standard procedure (KS F 3021, 2013).

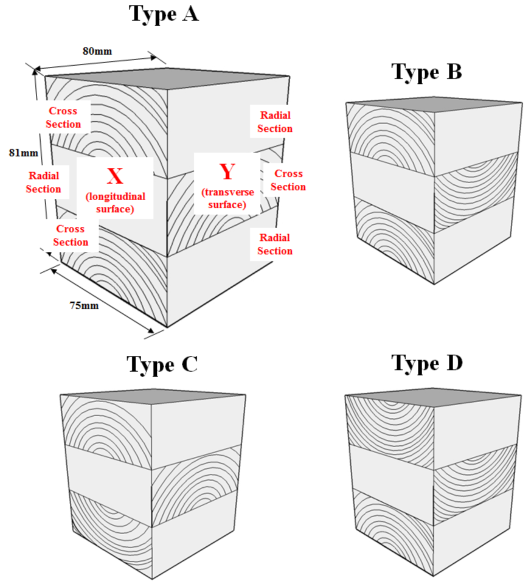

Fig. 1. Delamination specimens combined along the annual ring of cross section.

The specimens were classified into four types according to the up and down directions of the annual rings on the cross section as shown in Fig. 1. Type A was combined in such a way that the annual rings of the cross sections of all layers were arranged in the same direction. Type B was combined in such a way that the directions of the annual rings of the outer lamina would be identical, but opposite to those of the middle lamina. Type C was combined in such a way that the directions of annual rings of the outer lamina would be outward regardless of those of the middle lamina. Type D was combined in such a way that the directions of annual rings of the outer lamina would be inward regardless of those of the middle lamina. For the number of specimens, a total of 80 specimens were produced with 10 soaking and boiling delamination specimens for each type. These specimens were tested according to the standard procedure (KS F 3021, 2013). After testing, the delamination length of the glue-line was measured for every glue-line of the specimens. Furthermore, the surface where the first and third layers are cross sections and the second layer is a radial section was referred to as X (longitudinal surface), and the surface where the first and third layers are radial sections and the second layer is a cross section was referred to as Y (transverse surface).

2.3. Block shear test

As with the delamination specimens, the block shear test specimens were collected at 100 mm inward from the end of the larch CLT according to the standard procedure (KS F 3021, 2013). As shown on the left in Fig. 2, the annual ring contact angles from the reference line of the bonding surface were divided into 0∼9°, 10∼19°, and 20∼29°, and the specimens were collected randomly regardless of the direction of annual rings of the cross section. A total of 30 specimens were collected with 10 specimens of each angle.

The block shear test was conducted by applying loads until failure of the specimen at the loading rate of 9800 N/min with a universal test machine (Instron 4482) that can apply loads

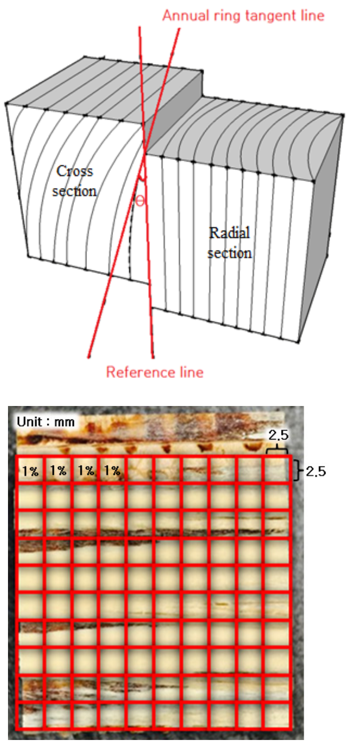

Fig. 2. Shape of block shear test specimen and wood failure percentage measurement method.

in parallel to the glue-line. To determine the wood failure percentage, the wood failure area was measured by dividing the bonding surface of the block shear specimen into 100 units as shown on the right of Fig. 2.

3. RESULTS and DISCUSSION

3.1. Soaking and boiling delamination tests of larch CLT

The soaking and boiling delamination percentage according to the direction of annual rings of the laminae are shown in Table 1. The average soaking delamination percentage and

Table 1. Delamination test results for CLTs according to the combination of laminae

	Specimens	Soaking delamination (%)			Boiling delamination (%)			Ave. delamination (%)	Korea standard requirement	Pass or Fail
		X section	Y section	Ave. soaking delamination	X section	Y section	Ave. boiling delamination			
1st measure*	Type A	1.2	1.1	1.1	1.9	0.4	1.1	1.1	Under 5%	Pass
	Type B	0.4	0.6	0.5	0.7	0.3	0.5	0.5		Pass
	Type C	0.6	1.1	0.9	1.0	1.4	1.2	1.1		Pass
	Type D	1.6	2.3	1.9	1.5	0.7	1.1	1.5		Pass
2nd measured**	Type A	21.9	29.2	25.6	11.1	9.5	10.3	18.0		Fail
	Type B	20.5	49.4	35.0	23.5	8.0	15.7	25.4		Fail
	Type C	16.5	68.4	42.5	6.9	14.4	10.6	26.6		Fail
	Type D	19.4	11.6	15.5	18.2	5.6	11.9	13.7		Fail

* Measurement method according to KS F 3021
** Measurement method according to KS F 3021, including wood failures along the annual rings on the cross sections near the glue-line.

the average boiling delamination percentage of Type A were both 1.1%, those of Type B were both 0.5%, those of Type C were 0.9% and 1.2%, respectively, and those of Type D were 1.9% and 1.1%. The test results indicated that all the four combinations satisfied the standard requirement (KS F 3021, 2013), which is the domestic standard for glued laminated timbers.

The standard procedure (KS F 3021, 2013) advises to exclude from measurement the crack of timbers resulting from drying or knots during delamination tests of laminated timbers. However, the cross sections of all surfaces are exposed in CLT because laminae are cross-laminated unlike glued laminated timbers. For this reason, in this study, the tissues of cross-sections that are relatively weaker than tissues of radial-sections failed along the annual rings near the glue-line of all specimens during delamination test as shown in Fig. 3. This phenomenon can be a defect of CLTs that can appear according to the variations of temperature and humidity after actual construction. In this study, therefore, the wood failures along the annual rings on the cross section near the glue-line were also included in the delamination length and measured again. As a result, as shown in Table 1 the average soaking delamination percentage and the average boiling delamination percentage of Type A were measured at 25.6% and 10.3%, respectively. Those of Type B were measured at 1.36 times and

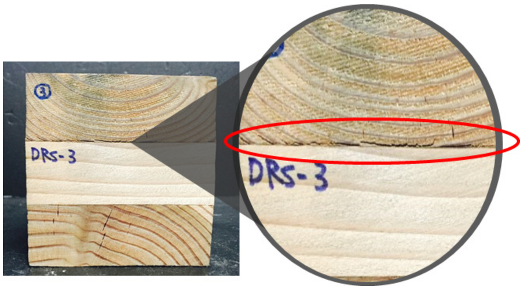

Fig. 3. Wood failures along the annual rings on the cross sections near the glue-line.

1.52 times of those of Type A, respectively, and those of Type C at 1.66 times and 1.03 times. The average soaking delamination percentage and the average boiling delamination percentage of Type D were 0.61 times and 1.16 times, which were the lowest delamination percentages among the four types. All the specimens of four types passed KS when the delamination by wood failure was not included, but the specimens failed to satisfy the standard when they were remeasured with the delamination by wood failure included. Among them, type C showed the greatest delamination percentage. Therefore, this combination should be avoided when producing CLTs. For timbers that are drying, the late wood has a greater density than the early wood. As a result, the late wood is shrunken more and the 'cup' phenomenon occurs where the timber is bent in the opposite direction of the annual rings on the cross section. The cup phenomena according to the combination of annual rings are shown in Fig. 4. For types A, B, and C, the cup shape is bent in opposite direction to the middle layer, and this shape causes a stress on the cross section to be delaminated from the middle layer while the bonded CLT is being dried. For type D, however, cross sections on both sides converge toward the middle layer and a low stress is generated in the glue-line unlike other combinations, resulting in a low delamination percentage (Wood Handbook, 2010).

The delamination percentages according to the section are as follows. The average soaking delamination percentage and the boiling delamination percentage of the X section of type A were 22.0% and 11.1%, respectively and those of the Y section were 29.3% and 9.5%, respectively. Those of the X section of type B were 20.5% and 23.5%, respectively and those of Y the section were 49.5% and 8.0%, respectively. Those of the X section of type C were 16.5% and 6.9%, respectively and those of Y the section were 68.4% and 14.4%, respectively. Those of the X section of type D were 19.5% and 18.2%, respectively and those of Y the section were 11.7% and 5.6%, respectively. In all combinations except type D, the average delamination percentage of the Y section was higher than that of the X section.

Fig. 4. End-split occurred in the outer lamina during the drying process of the boiling delamination test.

Contrary to expectations, the delamination percentage in soaking test was higher than that in boiling test which is a harsher test condition in all four combinations. The reason for this is that cross-sectional end-split occurred on the laminae in the surface layer before delamination

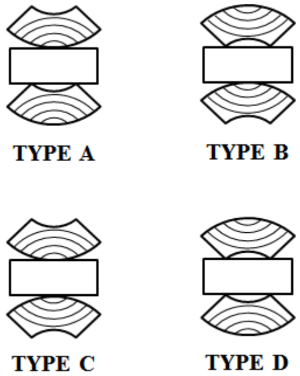

Fig. 5. Schematic diagram of cup phenomenon according to the combination of laminae.

or wood failure happened in the glue-line during the test process of the boiling delamination specimens as shown in Fig. 5. Constant-rate drying occurs in the surface layer of timber during the early stage of drying, and water moves from the inner layer to the surface layer and evaporates. The water movement speed from the inside to the surface layer of timber is slower than the constant-rate drying speed of the surface layer, and the moisture content of the surface layer decreases rapidly. As the drying time progresses, due to the differences in the water movement speed and evaporation speed between the inner and surface layers of timber, the surface layer shrinks, but the inner layer maintains swelling or equilibrium state depending on the position of fiber saturation point. As a result, the shrinking and swelling differences between the surface layer and the inner layer causes tensile stress in the surface layer and compressive stress in the inner layer, leading to deformations in the laminae (Bergman, 2010). In other words, end-splits were caused because the timber could not endure deformations in the process of boiling and during timbers, and the low delamination percentage in the glue-line was measured because the stress that must occur in the glue-line was diffused through the end-splits. Therefore, using the soaking test for evaluating the delamination strength of CLT will be more accurate than using the boiling test.

3.2. Block shear test of larch CLT

The block shear strength of larch CLT was 3.9 ± 0.9 MPa on average, which was lower by about 46% than the block shear strength standard 7.1 MPa for glued laminated timbers specified in KS F 3021, but passed the criterion for block shear strength (3.5 MPa) of the prEN 16351 standard. Furthermore, this was lower by about 63% than the result (10.3 MPa) of the block shear strength test of glued laminated timber by Park *et al*. (2009) who used the same resorcinol resin and larch laminae as those in this study. A similar tendency was also found in the result of Kim *et al*. (2013) who conducted the block shear strength test of CLTs that they had produced with Japanese red pine and PUR adhesive. The reason that CLT has a lower block shear strength than glued laminated timber is ‘rolling shear’. Rolling shear refers to the shear stress that causes shear deformation on the surface that is orthogonal from the direction of fibers when a shear force is applied to the glue-line of the timbers that are laminated at right angles of the fiber direction such as plywood or CLT (P. Fellmoser *et al*., 2004). That is, the main direction of the resistance to CLT typically coincides with the direction of the outer lamina. Therefore, when load is applied to CLT, deformations in the vertical laminae increase due to the load (mandegarian, etc.). The block shear test in this study generated rolling shear failures in 57% of the specimens, and fractures in the glue-line in 37%, and general shear fracture in 6%.

The average block shear strengths according to the annual ring contact angle are as follows: 3.2 ± 0.8 MPa at 0∼9°, 3.4 ± 0.6 MPa at 10°∼19°, and 4.8 ± 1.3 MPa at 20°∼29°. The shear strength tended to increase together with the annual ring contact angle, but the deviation also increased. The wood failure percentage according to the annual ring contact angle was 62.8% at 0∼9°, 62.2% at 10°∼19°, and 72.2% at 20∼29%. The average wood failure percentage was 65.7%, which satisfied the passing criterion of 65% of KS F 3201.

4. CONCLUSION

The delamination along the annual ring on the cross-section of laminae and the bonding strength according to the tangential angle between laminae were evaluated for the production of 3-ply cross-laminated timber (CLT) using domestic larch. As a result of the delamination tests for CLT combinations according to the annual ring direction of larch laminae, end-split developed in the outer lamina of specimens during the drying process of the boiling delamination test, which affected the delamination percentage of the glue-line. Therefore, soaking delamination test was found to be more accurate than the boiling delamination test in the evaluation of CLT's delamination strength. The standard (KS F 3021) advised to exclude from measurement the cracks of timbers resulting from drying or knot during delamination test, but the tissues on the cross-section failed along the annual rings near the glue-line of all specimens during the delamination test for CLTs. This phenomenon can be a defect of CLT that can appear depending on the variations of temperature and humidity after actual construction. Therefore, to measure the delamination percentage by including this wood failure in the delamination length is believed to be a more accurate test method. The highest soaking delamination percentage was measured when the directions of all the annual rings of the outer laminae were outward regardless of the annual ring direction of the lamina adjacent to the outer lamina. Therefore, this combination must be avoided when producing CLTs. On the other hand, the soaking delamination rate of the combination where the directions of annual rings of the outer laminae were inward regardless of the direction of the annual rings of the lamina adjacent to the outer lamina was the lowest at 15.5%. This combination is expected to minimize the delamination and wood failure that develop in the glue-line resulting from variations of temperature and humidity after construction.

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