Evaluation of the Bending Performance of Glued CLT-Concrete Composite Floors Based on the CFRP Reinforcement Ratio

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A study was conducted on the reinforcement of cross-laminated timber (CLT) concrete composite floors with carbon fiber reinforced plastic (CFRP) to improve its mechanical performance and reliability in wood composite structures. A four-point bending test evaluation was completed on three types of cross-laminated timber concrete composite floors produced with different carbon fiber reinforced plastic reinforcement ratios (33%, 66%, and 100%) on the entire surface of the tensile portion. An increase in the carbon fiber reinforced plastic reinforcement ratio of the composite floors led to an increased bending capacity and a slightly improved yield performance. In the case of a composite floor with a reinforcement ratio of 33%, premature failure occurred in the elastic region due to defects of the CLT such as knots and slopes of the grain. Failure mode analysis revealed that tensile and shear failure coexist when the composite floor has a CFRP reinforcement ratio of 33%. In contrast, reinforcement ratios of 66% and 100% prevented premature failures in the elastic region caused by defects and induced a consistent failure mode. These reinforcement effects reduced the variability in the increased bending capacity of the composite floors and improved the accuracy of the theoretical prediction design *via* the γ-method. Meanwhile, the shear connections between the cross-laminated timber and concrete *via* epoxy adhesive exhibited full-composite behavior without being affected by the reinforcement ratio.

DOI: 10.15376/biores.17.2.2243-2258

Keywords: Cross-laminated timber (CLT); CLT-concrete composite; Gamma method; Carbon fiber reinforced plastic (CFRP); Bending test

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INTRODUCTION

The cross-laminated timber (CLT) construction method, which can reduce the weight of a building by approximately one-fifth compared to its weight when the same surface area is built using the concrete construction method, has the advantages of short construction duration and low cost. In addition, this method is increasingly used because it not only reduces carbon emissions, which are inevitable in modern urban development and growth, but also effectively stores carbon (Lehman 2012; Guo *et al*. 2017). Due to the advantages of the CLT method, the construction of high-rise timer buildings has become possible, which naturally has led to strict requirements for fire resistance and vibration performance (Barber 2015; Jiang and Crocetti 2019; Shephard *et al*. 2021). In the CLT construction method, fire resistance and vibration performance requirements can be satisfied through design that allows for sufficient material thickness; however, this method incurs high construction costs and results in inefficiencies, *e.g.*, reduced facility space or low floor height. A CLT-concrete composite floor is a system reinforced by combining concrete and CLT, which alone cannot satisfy fire resistance and vibration performance requirements, such that the upper concrete layer resists compressive stress and the lower CLT layer resists tensile stress under a bending moment. This floor system is currently applied in the construction of high-rise buildings *via* the CLT method and has been extensively studied (Loebus *et al*. 2017; Mai *et al*. 2018; Lamothe *et al*. 2020; Thai *et al*. 2020; Hadigheh *et al*. 2021). The ratio of the combination of the materials is considered to be extremely important for the performance evaluation of this floor system, for which heterogeneous materials are combined into a single construction material through shear connections. Methods for combining CLT and concrete primarily include mechanical shear connections and adhesive connections. In general, a mechanical shear connection combines two main materials by inserting fasteners such as structural self-tapping screws (STS) or lag bolts screws to a certain depth into the surface of the CLT and subsequently pouring wet concrete onto it. A typical chemical shear connection method is to apply adhesive to the surface of CLT and then pour concrete thereon for curing. The mechanical shear connection method uses self-tapping screws (STS), lag bolts, *etc*., which have been verified through ongoing studies, providing design guidance, unlike the shear connection method using adhesives (Fu *et al*. 2020b). Nonetheless, studies in this field have reported that the shear connection method using adhesives achieves a strong bending performance similar to the mechanical method and provides outstanding composite effects between the CLT and concrete (Kanócz and Bajzecerová 2015; Tannert *et al*. 2017; Fu *et al*. 2020a,b). Furthermore, the adhesion layer created by adhesives inhibits the penetration of moisture from the concrete into the CLT during the curing period, decreasing the influence of moisture on both components. Prior studies have demonstrated that this effect of adhesion layers induces homogeneous compressive strength in concrete after curing and minimizes the degradation of the floor quality by preventing the loss of delamination performance in the CLT (Song *et al*. 2021).

When a CLT-concrete composite floor is placed under a bending load with no rebar inserted into the concrete, the CLT located in the tensile portion has a considerable effect on the load-deflection behavior of the entire floor (Kanócz and Bajzecerová 2015; Barbosa and Blank 2017; Thilén 2017; Jiang and Crocetti 2019; Fu *et al.* 2020b). In the inherent failure mode of CLT, it is typical for a fracture to begin at the outermost tensile layer (longitudinal layer) and progress to a rolling shear failure in the transverse layer (Liao *et al*. 2017; He *et al*. 2018; Pang and Jeong 2019; Li *et al*. 2020; Choi *et al*. 2021; Pang *et al*. 2021). The laminae that comprise CLT are likely to have natural defects, *e.g.*, knots and slopes in the grain, and even the finger joint process used to eliminate these defects can be an additional shortcoming. The manufacturing standards, including APA PRG 320 (2012) and EN16351 (2015), recommend that defects should not be located near the tensile portion or the load points, but it is difficult to fully control defects due to the nature of wood. Therefore, defects often result in failures in the low load-deflection region, contributing to a loss of confidence in the strength of the floor. As a solution, carbon fiber reinforced plastic (CFRP), with a resin and carbon filaments oriented in the fiber direction or fabric shape, is used to reinforce the tensile portion of the floor. Carbon fiber reinforced plastic reinforcement is a lightweight method using a material with a specific strength and a specific modulus that are 12 times and 3 times greater than those of low-carbon steel, respectively, although they vary slightly depending on the type of resin used as the matrix (Lester and Nutt 2018). Therefore, as the CFRP reinforcement of materials has to withstand bending stresses to improve performance and reduce weight, it has long been applied to solid wood or glulam to strengthen timber structures (Tingley *et al*. 1996; Ogawa 2000; Gentry 2011; Raftery and Harte 2011). Research on composite CLT reinforced with CFRP is currently insufficient, and there is no construction market for it. However, as part of a demonstration project to replace a part of a 15-story or higher high-rise modular building with a concrete slab structure with a lightweight CLT composite flooring, a study on the bending performance of reinforced CLT according to the shape of CFRP was conducted prior to this study. Therefore, there is a possibility of utilizing CLT-concrete composite flooring reinforced with FRP (Song *et al*. 2019).

The study's aim was to improve the bending performance and reliability of glued CLT-concrete composite floors through CFRP reinforcement, as well as to concurrently examine the appropriate reinforcement ratio of CFRP. The bending behavior of the composite floors fabricated with various CFRP reinforcement ratios was evaluated *via* four-point static bending tests. The test results provided the load-deflection relationship, load capacity, and failure mode. The bending performance indicators of the test were also evaluated against a theoretical bending performance prediction model, *i.e.*, the γ-method.

EXPERIMENTAL

Material Properties

Cross-laminated timber (CLT)

Larix kaempferi Carr. laminae were used in the production of the CLT. The dimensions of the laminae were 30 mm (T) × 89 mm (W), and the average air-dry moisture content and average air-dry specific gravity were 12% ± 1% and 0.54 ± 0.04, respectively. The longitudinal layer (the outermost layer) and the transverse layer (the core layer) of the CLT consisted of laminae with a modulus of elasticity of 15 and 11 GPa, respectively. The modulus of elasticity of the laminae was measured using the natural frequency of the longitudinal vibration; visual classification procedures were not taken into account. The study by Song and Hong (2016) was referred to for the adhesion process during CLT production. Phenol-resorcinol formaldehyde (PRF) was used as the adhesive, and the adhesive was spread only onto the flat surface of the laminae, with a spread amount of 400 g/m^2 (single spread). The CLT spread with the adhesive was pressed at a pressure of 0.98 MPa for 24 h at a temperature of 25 °C and cured for more than a week after removing the pressure. The properties of the CLT used in the CLT-concrete composite floors are listed in Table 1.

Table 1. Properties of the Cross-laminated Timber (CLT)

Species	*Larix kaempferi* Carr.
Depth	90 mm
Layout	3 layers (30 mm + 30 mm + 30 mm)
Density	591 kg/m^3
Modulus of elasticity of longitudinal layers (E_0)	15 GPa
Modulus of elasticity of transverse layer (E_{90})	11 GPa
Adhesive	Phenol-resorcinol formaldehyde (PRF)
Target application rate	400 g/m^2 (Single spread)
Applied pressure	0.98 MPa

Concrete

The specific strength of the concrete was 24 MPa. The ratio of water to cement was 0.43, and the coarse aggregate size was less than 25 mm. The compressive strength test for concrete was conducted with cylindrical specimens in accordance with ASTM standard C39 (2012). The compressive strength of the concrete was found to be 34.9 MPa ± 2 MPa after 7 d of curing and 40.7 MPa ± 1 MPa after 28 d of curing.

Table 2. Mechanical Properties of the Concrete

	Specified Strength (MPa)	Water to Cement Ratio	Coarse Aggregate (mm)	Density (g/cm^3)	Compressive Strength (MPa)	
					After 7 d	After 28 d
WCC	24	0.43	25	2.4	34.9 ± 2	40.7 ± 1

Bending Test for the Reinforced Cross-laminated Timber (CLT)-concrete Composite Floors

Reinforced cross-laminated timber (CLT)-concrete composite floors

The CLT-concrete composite floors were produced in three types depending on the CFRP reinforcement ratio in the tensile portion of the CLT (as shown in Fig. 1). The reinforcement ratio of the Type-R33 sample was 33% (a volumetric ratio of 0.003), and the center of the tensile portion of CLT was reinforced. The reinforcement ratio of the Type-R66 sample was 66% (a volumetric ratio of 0.005), and both edges of the tensile portion of CLT were reinforced. The Type-R100 sample was reinforced across the entire surface of the tensile portion of the CLT with a volumetric ratio of 0.008.

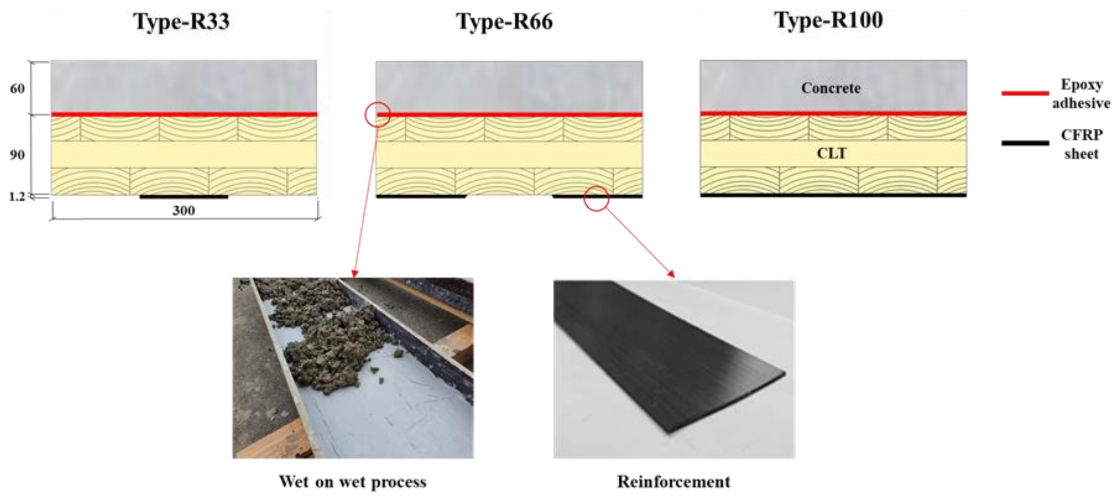


Fig. 1. Schematic diagram (cross-section) of the reinforced CLT-concrete composite floors according to their reinforcement ratio

Wet concrete was placed at a thickness of 60 mm on the three-layered CLT (a thickness of 90 mm), and an epoxy adhesive (Sikadur-31, Sika AG, Baar, Switzerland) was used for the shear connections between the two primary components to minimize the effects of the concrete moisture on the CLT (Song *et al*. 2021). For the same reason, a sealant treatment was applied to the contact surface between the formwork and the floor. A sheet-type CFRP product was used for reinforcement, which was molded by combining carbon filaments oriented in the fiber direction with an unsaturated polyester resin. The product was 1.2 mm in thickness, had a tensile strength of 2557 MPa, and a modulus of elasticity of 470000 MPa (Park *et al*. 2009). A polyurethane adhesive (P84, Otto-Chemie, Bavaria, Germany) was used to attach the CFRP sheet to the CLT (Song *et al*. 2019). Three composite floors were produced for each type and were evaluated after the concrete had been cured for more than 20 d.

Table 3. Summary of the Reinforced Cross-laminated Timber (CLT)-concrete Composite Floor Specimens

Specimen	Concrete	Timber	Reinforcement	Volumetric Ratio	Shear Connection Between the Concrete and CLT	Adhesion Between the Concrete and CLT
Type-R33	wet construction method	CLT	CFRP sheet	0.003	Epoxy	Polyurethane
Type-R66				0.005		
Type-R100				0.008		

Bending test

As shown in Fig. 2, the bending test was performed under a 4-point load with a span to depth ratio of 21 to 1 and a load distance to depth ratio of 6 to 1.

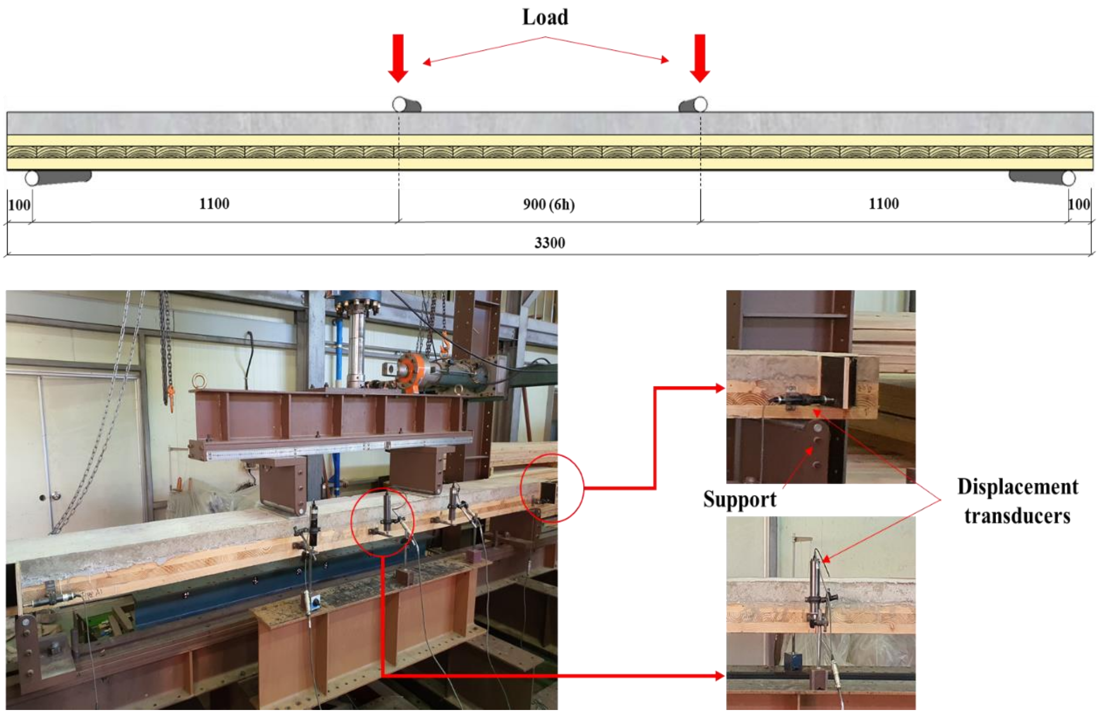


Fig. 2. Test set-up for the reinforced CLT-concrete composite floors

The global deflection and local deflection of the floors under changing loads were measured using displacement transducers with a maximum capacity of 50 mm (Tokyo Sokki Kenkyujo Co., Ltd., Tokyo, Japan) installed perpendicularly at the center of the slab and at each load point. Additionally, the slip between the CLT and concrete was measured with displacement transducers with a maximum capacity of 25 mm (Tokyo Sokki Kenkyujo Co. Ltd.) installed horizontally on both sides of the CLT. The loading speed was 5 mm/min.

RESULTS AND DISCUSSION

Laboratory Bending Test

Load-deflection curve

The behavior of the load-deflection curve of the Type-R33 samples with the smallest GFRP reinforcement ratio (as shown in Fig. 3) was as follows: the Type-R33-1 sample moved in almost a straight line to the maximum load and failed at approximately 96 kN after exhibiting slight yielding behavior. However, the two other specimens (R33-2 and R33-3) showed local failures in the outermost tensile layer of the CLT in the elastic region.

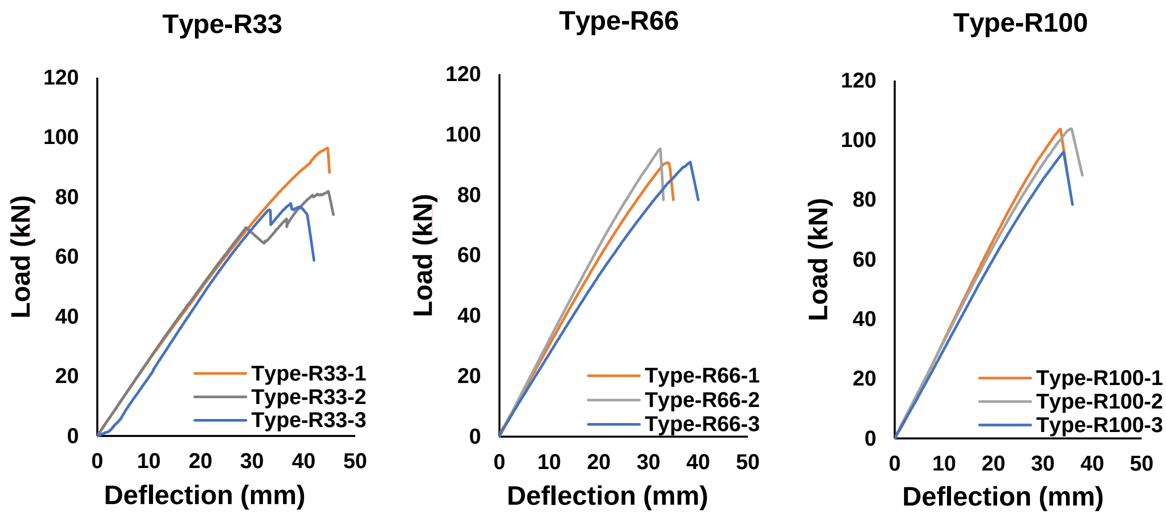


Fig. 3. Load-deflection curves of the reinforced CLT-concrete composite floors

Table 4. Results of the Bending Test for the Reinforced Cross-laminated Timber (CLT)-concrete Composite Floors

Specimen	Type-R33			Type-R66			Type-R100		
	1	2	3	1	2	3	1	2	3
CLT moisture content (%)	11.7	11.4	11.7	11.7	11.9	12.1	11.3	13.9	12.3
Max load (kN)	96.4	81.8	77.9	90.3	95.2	90.8	103.7	103.7	96.0
Average (kN)	85.4 (9.3)*			92.1 (2.4)*			101.1 (3.6)*		
Global deflection (mm)	44.7	44.8	42.4	34.1	32.4	38.4	33.5	35.8	34.2
Average (mm)	44.0			35.0			34.5		
Local deflection (mm)	40.0	37.2	36.9	32.2	29.1	35.2	31.0	31.8	30.1
Average (mm)	38.0			33.2			31.0		
Global/local	1.16			1.05			1.11		
Slip (mm)	0.09			0.16			0.09		
Note: * Coefficient of variation									

The maximum load of these specimens were 81.8 and 77.9 kN, respectively (Table 4), and the aforementioned local failures in the elastic region were the direct cause of the relatively lower maximum load measurements compared with those of the R33-1 sample. Upon examining local deflection in the Type-R33 samples, Type-R33-2 and Type-R33-3 appeared to have been more considerably affected by shear deformation than the Type-R33-1 sample; however, in fact, the two specimens had already failed in the outermost tensile layer.

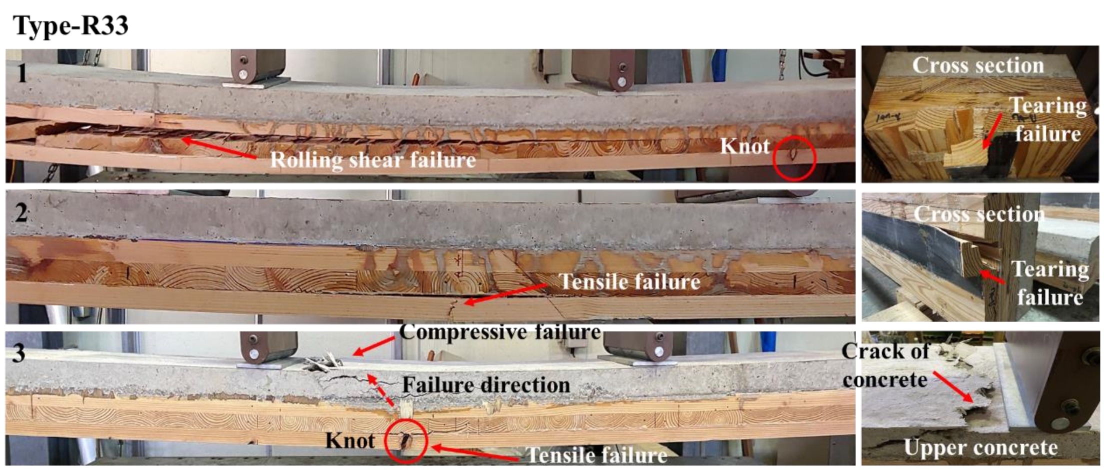
In the case of the Type-R66 samples, all specimens showed load-deflection curve behavior induced by the reinforcement effect. While the slope of the load-deflection curve varied slightly between the specimens, no specimens showed local failure in the elastic region, unlike the Type-R33 samples. Their load-deflection curves indicated a small yield region after exhibiting elastic behavior. The specimens eventually failed at approximately 92 kN. The global deflection and local deflection of the Type-R66-3 sample were found to be slightly high; however, the deflections of the specimens, excluding the Type-R66-3 sample, were similar to those of the Type-R100 samples. The 66% reinforcement of the tensile portion of the CLT-concrete composite floor using CFRP resulted in a decrease in global deflection of 21% and an increase in the maximum load of 8% when compared to the 33% reinforcement examples.

The Type-R100 samples showed a slightly greater slope in the load-deflection curves but similar behavior overall compared with the Type-R66 samples. No local failure was observed in the elastic region because of the complete reinforcement effect of the tensile portion of the composite floors. In addition, the deviation in deflection with respect to the maximum load and position was found to be minimal. The three specimens failed at approximately 101 kN after exhibiting yielding behavior past the elastic region with an increase in the maximum load of 18% and 10% compared to the Type-R33 and Type-R66 samples, respectively.

Failure modes

Different failure modes were observed in the three Type-R33 specimens (as shown in Fig. 4). In the Type-R33-1 sample, the reinforcement *via* CFRP prevented tensile failures in the outermost tensile layer of the CLT in the elastic region, even when the outermost tensile layer had a knot. Subsequently, rolling shear failures occurred instantly along the growth ring in the transverse layer with a relatively low shear force, while no visible signs of cracks were seen in the yield region. It was thought that the knot in this specimen was located a long distance away from the load point and did not directly affect the tensile failure of the CLT.

In the case of the Type-R33-2 sample, rolling shear failures were observed in the transverse layer along with a failure in the unblemished outermost tensile layer. No plastic compression was observed in the concrete part of these two specimens. In contrast, a fracture started from the knot in the Type-R33-3 sample in the tensile portion, which did not cause rolling shear failures but rather local plasticity in the compressive region by progressing vertically within a short time. The composite floors reinforced with 33% CFRP did not exhibit any reinforcement effect, as the inconsistent failure times and failure modes directly led to relatively higher coefficients of variation than those of the Type-R100 and Type-R66 samples.



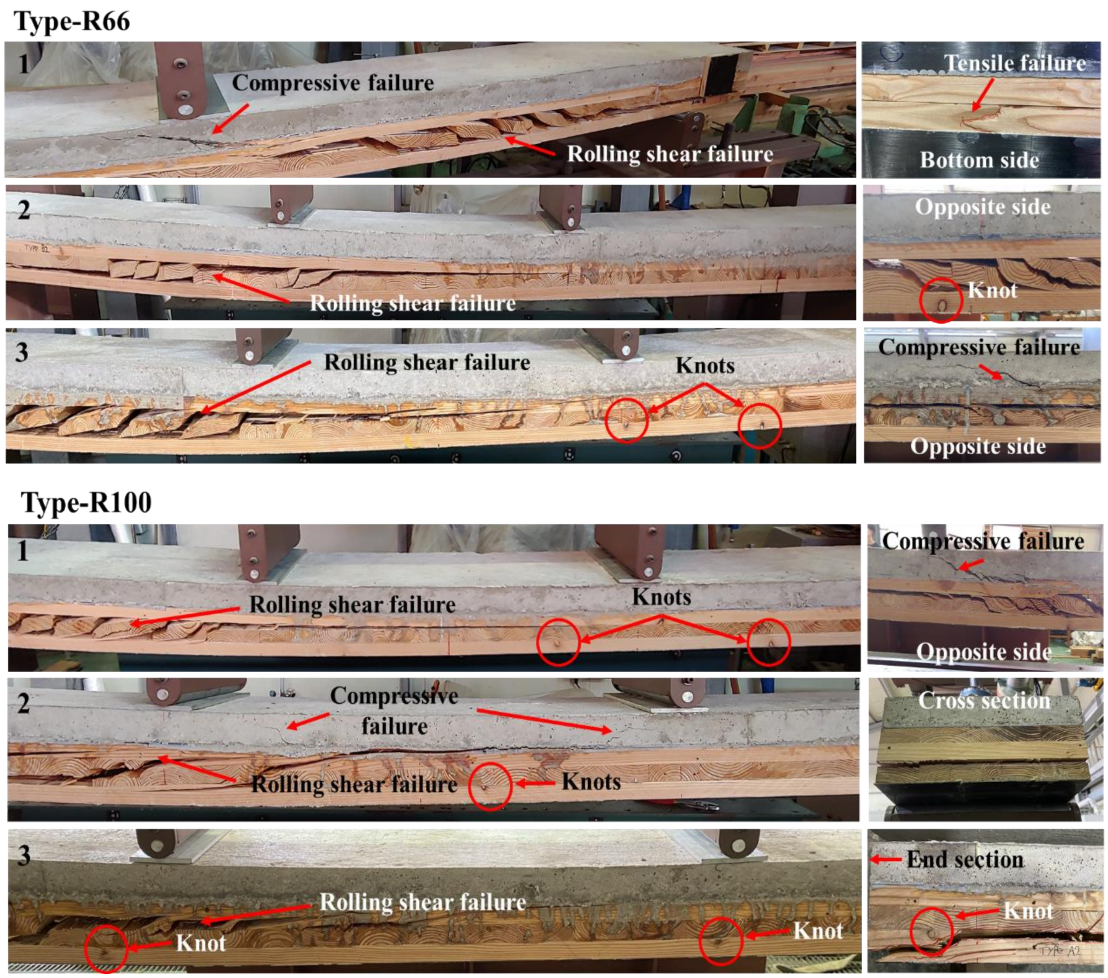


Fig. 4. Failure modes of the reinforced CLT-concrete composite floors

In contrast, the results may raise additional questions regarding the differences in the strength and failure modes depending on the reinforcement location of the CFRP under the same reinforcement ratio. Given the same reinforcement ratio, it is difficult to assert that the reinforcement location has no effect on the strength or failure mode. However, the tearing of the CFRP near a load point in the fiber direction along with the attached outermost tensile layer in the Type-R33-1 and Type-R33-2 samples suggests that the reinforcement ratio likely affected the failure mode more meaningfully than the reinforcement location.

Unlike the Type-R33 samples, all the Type-R66 specimens demonstrated a reinforcement effect *via* CFRP. These specimens did not have any premature tensile failures in the elastic region due to defects in the tensile portion, and the reinforcement effect led to a similar failure mode among the three specimens; this resulted in an increase in the confidence in the bending performance (CV of 2.4%). The Type-R66-1 sample showed yielding behavior without tensile failure in the outermost tensile layer, which was instantly followed by a large rolling shear failure in the transverse layer. Along with the rolling shear failure, plastic compression occurred at the compression area of the floor, causing the compression laminae and concrete to fail together. Nevertheless, adhesion between the two materials *via* the epoxy adhesive was maintained perfectly. Local tensile failure was observed in the outermost tensile layer without the reinforcement attachment after the load on the specimen was removed. It is believed that this local tensile failure happened together with the rolling shear failure, as no reduction in load occurred because of the failures in the elastic region or the plastic region until the final failure on the load-deformation curve of the Type-R66-1 sample. Despite the presence of defects in the outermost tensile layer near the load points in the Type-R66-2 and Type-R66-3 samples, rolling shear failures occurred without tensile failures. However, plastic compression was observed in the Type-R66-3 sample but not in the Type-R66-2 sample. It was confirmed that plastic compression did not drastically affect the confidence in the bending performance for the Type-R66 samples.

In the Type-R100 samples, failures resulting from defects, *e.g.*, knots and slopes in the grain, or premature failures in the low deformation region did not occur in the outermost tensile layer of the CLT when the entire surface of the tensile portion was reinforced *via* CFRP. Similar to the Type-R66 samples, the failure mode of the Type-R100 samples switched to shear failure after being suppressed in the outermost tensile layer, which caused rolling shear failures in the transverse layers. However, unlike the Type-R66 samples, plastic compression was observed in the compression region of all specimens, which indicated improved shear capacity. In the Type-R100-3 sample, a rolling shear failure propagated until it was diverted by the knot near the end section of the floor, after which the failure continued along the slope of the grain in the outermost tensile layer. However, it was considered unreasonable to classify this as tensile failure.

Slip between the cross-laminated timber (CLT) and concrete

The three types of reinforced composite floors shear-connected with an epoxy adhesive had a small amount of slip between the CLT and concrete, regardless of the GFRP reinforcement ratio (Table 4). The slip of the CLT-concrete composite floor reinforced with CFRP by mechanical shear connections measured by Baek *et al*. (2021) was 13 times larger on average than the results obtained in this study. Slip between CLT and concrete was visually observed after failure in composite floorings with mechanical shear connections in other previous studies (Higgins *et al*. 2017; Jiang and Crocetti 2019; Thilén 2017). However, the performance degradation of the composite floor is not necessarily caused by these factors. It is thought that it is more affected by the properties and shape of the fasteners and the spacing between them. The test results demonstrated that the measured slip was small when the effect of the shear force within the global deflection was strong, *i.e.*, in the Type-R100 and Type-R33 samples, while the slip was found to be relatively large when the effect of the shear force within the global deflection was weak, *i.e.*, in the Type-R66 samples. However, this small slip between the CLT and concrete was not caused by shear deformation but by bending deformation of the composite floors. In fact, the adhesion layer was still intact even after the specimens completely failed, and no slip from the shear could be visually seen at the shear connections between the two primary components. Therefore, it was concluded in this study that all composite floors that were shear-connected with the epoxy adhesive behaved as full composites.

Summary of laboratory bending test

The load-deflection curve of the reinforced composite floors showed linear behavior until either a local failure in the elastic region, *i.e.*, in the Type-R33 samples, or a complete failure in the yield region, *i.e.*, in the Type-R100 and Type-R66 samples, occurred along with a brittle failure. The linear behavior and brittle failures were also observed in non-composite CLT, which implies that CLT designed to withstand tensile stress has a major effect on the behavior of the load-deflection curve (Kanócz and Bajzecerová 2015; Song and Hong 2018; Song *et al*. 2019 Fu *et al*. 2020b). In contrast, the plain concrete located in the compression section did not have any particular effect on the behavior of the load-deflection curve, but it did have an effect on the bending capacity of the floor. It has been reported that the level of ductile behavior of reinforced, laminated timbers primarily depends on the quality of the tensile laminae (Raftery and Harte 2011). However, when the ratio of reinforcement with CFRP sheets in the tensile portion of a composite floor is 66% or greater, a more dominant ductile behavior was observed compared to that of a floor with a reinforcement ratio of 33%, which indicated that the reinforcement ratio also affected the ductile behavior.

It was confirmed that a GFRP reinforcement ratio of 66% or higher in the tensile portion of the composite floor was sufficient to prevent failures caused by defects present in the outermost tensile layer of the CLT as well as prevent premature failures in the elastic region. An increase in the GFRP reinforcement ratio prevented normal bending failures in the outermost tensile layer, while the switch in the failure mode to shear failures abruptly manifested in the transverse layer after a brief yielding behavior. Rolling shear failure in the transverse layer is a typical failure mode of CLT under a bending load along with tensile failures occurring in the outermost tensile layer. Previous studies have demonstrated that there is no difference in strength between the two failure modes, except for premature failures occurring in the low deformation region caused by defects in the outermost tensile layer (Song and Hong 2018). Wood is organic and contains numerous defects, resulting in a large variability in material strength properties. An increase in the reinforcement ratio in the tensile portion of the composite floor can not only improve the bending strength but also prevent premature failures due to natural defects found in CLT. In addition, this increase results in a consistent failure mode of the composite floor, which reduces the variability in the improved bending strength.

Theoretical Study

γ-method

The composition theory of mechanically jointed beams, also known as the 'γ-method', was used for the theoretical analysis of the bending performance of the glued CLT-concrete composite floors. This method is used when there are at least two components that are individually joined *via* mechanical fasteners or layers of material with relatively low shear stiffness. For CLT with layers glued together, the slip module is replaced by the rolling shear module (G_r). Thus, if only the laminae of the longitudinal layers in the floor are assumed to be able to withstand the load, the rolling shear stiffness of the transverse layer of the CLT may be considered as the stiffness (or deformation) caused by the “imaginary fasteners” connecting these laminae. In other words, the laminae of the transverse layer serve as connectors, and the connection efficiency factor (γ) is calculated based on the rolling shear module, as shown in Eq. 1,

$$\gamma_i = \frac{1}{1+\pi^2 \frac{E_i A_i}{l^2} \frac{h_1'}{G_r b}} \tag{1}$$

where E_i is Young’s modulus of the i^{th} layer, A_i is the cross-section area of the i^{th} layer, h_i is the thickness of the i^{th} layer, l is the span length, G_r is the rolling shear module, and b is the width of the composite floor, which substitutes the components related to the slip of the connectors. This factor, considered as being the degree of composition, ranges between 0 and 1, and the magnitude of the value and the effective flexural rigidity of the composite cross-section are proportional. The factor is 0 when there is no connection between the composite materials, or "no-composite", and 1 when there is a complete, rigid connection between the composite materials, or "full-composite".

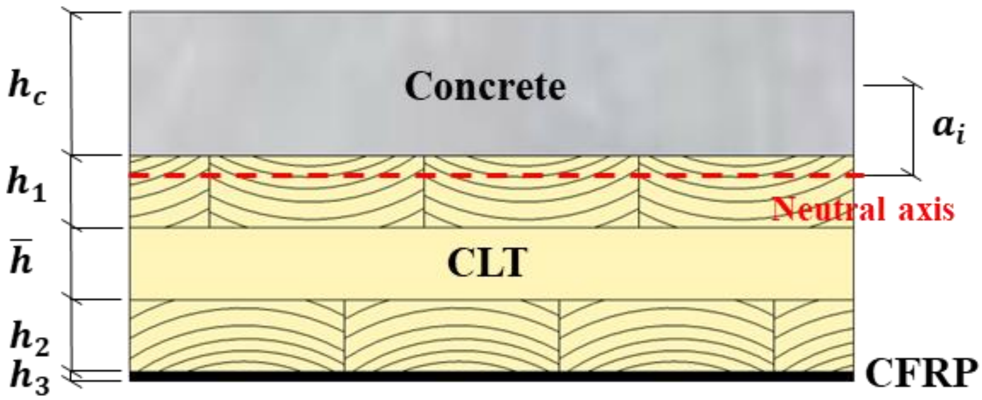


Fig. 5. Composite section of the reinforced CLT-concrete composite floor

Based on the γ-method, the flexural rigidity and the bending moment were calculated using Eqs. 2 and 3, respectively,

$$EI_{eff} = \sum(E_i I_i + \gamma_i E_i A_i a_i^2) \quad (2)$$

$$M = \emptyset \cdot F_b \cdot \frac{(EI)_{eff}}{E_i(\gamma_i a_i + 0.5h_i)} \quad (3)$$

where EI_{eff} is the effective bending stiffness of the composite section, I_i is the moment of inertia of the i^{th} layer, a_i is the distance between the center of the i^{th} layer and the neutral axis of the composite section, M is the bending moment, $Ø$ is the resistance factor (0.9), and F_b is the referenced strength bending strength of *Larix kaempferi* Carr.

The G_r required for the composition process of CLT, as calculated by Eq. 4,

$$G = E/16,\ G_r = G/10 \quad (4)$$

was estimated to be 1/10 of the shear modulus in the fiber direction, according to BS EN standard 16351 (2015), and a modulus of elasticity of 70 MPa was calculated and applied based on 320 *Larix kaempferi* Carr. laminae (Song and Hong 2018). The range of the connection efficiency factor (γ), calculated based on G_r, was 0.81 to 0.82. As such, 50 MPa were applied as the F_b, which was the approximate bending strength value of *Larix kaempferi* Carr. (Pang *et al*. 2011). Next, the γ value for the concrete and CLT combined with the epoxy adhesive was considered to behave as a full composite, so it was set to 1. The γ for the samples combined with a polyurethane adhesive was also set to 1 for the same reason. The distance from the center axis of the composite cross-section to the center of concrete was defined as a_c, as calculated by Eq. 5,

$$a_c = \frac{h_c + h_1}{2} - a_1 \quad (5)$$

where a_1 is the distance from the center axis of the composite cross-section to the center of compression layer of the CLT, as calculated by Eq. 6,

$$a_1 = \frac{r_c E_c A_c\left(\frac{h_c}{2} + \frac{h_1}{2}\right) - r_2 E_2 A_2\left(\frac{h_2}{2} + \frac{h_1}{2} + \bar{h}\right)}{\sum_c^3 r_i E_i A_i} \quad (6)$$

where a_2 is the distance from the center axis of the composite cross-section to the center of tensile layer of the CLT, as calculated by Eq. 7,

$$a_2 = a_1 + \frac{h_1}{2} + \frac{h_2}{2} + \bar{h} \tag{7}$$

where a_3 is the distance from the center axis of the composite cross-section to the center of the CFRP, as calculated by Eq. 8,

$$a_3 = a_2 + 0.6 + \frac{h_2}{2} \tag{8}$$

The epoxy adhesion layer between the concrete and CLT and the polyurethane adhesion layer between the CLT and CFRP were too thin and were ignored in the theoretical analysis of the bending performance. The theoretical flexural rigidity (EI_{Gamma}) and bending moment ($M_{b,Gamma}$) of the reinforced composite floors were predicted to be higher by 5.1% and 4.4% on average, respectively, compared with the experimental bending performance. The theoretical value for EI was predicted to be lower than the experimental value; however, there were no considerable differences between the different reinforcement ratios. The measured value for M_b tended to be underestimated as the reinforcement ratio increased. This is believed to be the result of excessive reinforcement of the tensile portion of the composite floor. As observed in the "Laboratory Test" section, the GFRP reinforcement of the tensile portion above a certain ratio prevented failures in the outermost tensile layer, causing shear failures to become the dominant failure, which occurred in the middle layer of the CLT with a low shear force. Therefore, despite the reinforcement of the entire surface of the tensile portion, failures inevitably occurred in the middle layer; therefore, the $M_{b,Test}$ was not proportional to the reinforcement ratio.

Table 5. Comparison of the Experimental Value and the Theoretical Value for the Bending Properties of Reinforced Composite Flooring

Specimen	EI_{Test} (k·Nm^2)	EI_{Gamma} (k·Nm^2)	EI_{Gamma}/EI_{Test} (%)	$M_{b,Test}$ (k·Nm^2)	$M_{b,Gamma}$ (k·Nm^2)	$M_{b,Gamma}/M_{b,Test}$ (%)
Type-R33	1210	1158	-4.3	44.8	42.0	-6.2
Type-R66	1471	1352	-8.1	48.4	49.0	1.2
Type-R100	1600	1555	-2.8	53.1	56.2	5.8

CONCLUSIONS

1. The shear connection process of cross-laminated timber (CLT) and wet concrete using epoxy adhesive showed full composite behavior between CLT and concrete, regardless of the ratio of carbon fiber reinforced plastic (CFRP) reinforcement added to the tensile portion of composite floors. Therefore, the strength reliability of the wet-on-wet process for CLT-concrete composite floors using epoxy adhesive was confirmed.
2. As the CFRP reinforcement ratio for the tensile portion of the composite floors was increased, the bending capacity increased, and the yield performance was slightly improved. However, due to the low shear strength of the CLT transverse layer, the

reinforcement efficiency decreased as the reinforcement ratio increased. This result is supported by an underestimation of the actual bending moment compared to the theoretical bending moment of the composite floors with a reinforcement ratio of 100%.

3. For the entire surface of the tensile portion of the composite floors, even when only 2/3 of the entire surface was reinforced with CFRP, the premature fracture resulting from the natural defects of CLT in the elastic region was completely suppressed. In addition, the effect of inducing a constant failure mode lowered the variability in the bending performance of composite floors composed of heterogeneous materials, suggesting the possibility that CLT-concrete composite floors could be designed less conservatively.

ACKNOWLEDGEMENTS

This study has been worked with the support of a research grant of Kangwon National University in 2019.

REFERENCES CITED

ANSI/APA PRG 320 (2012). “Standards for performance-rated cross-laminated timber,” American National Standards Institute, Washington, D.C.

ASTM C39 (2012). “Standard test method for compressive strength of cylindrical concrete specimens,” ASTM International, West Conshohocken, PA.

Baek, S. Y., Song, Y. J., Yu, S. H., Kim, D. H., and Hong, S. I. (2021). “Bending performance of cross-laminated timber-concrete composite slabs according to the composite method,” *BioResources* 16(4), 8227-8238. DOI: 10.15376/biores.16.4.8227-8238

Barber, D. (2015). “Tall timber buildings: What’s next in fire safety?” *Fire Technology* 51(6), 1279-1284. DOI: 10.1007/s10694-015-0497-7

BS EN 16351 (2015). “Timber structures - Cross laminated timber – Requirements,” British Standards Institution, London, United Kingdom.

Choi, G. W., Yang, S. M., Lee, H. J., Kim, J. H., Choi, K. H., and Kang, S. G. (2021). “Evaluation of flexural performance according to the plywood bonding method of ply-lam CLT,” *Journal of the Korean Wood Science and Technology* 49(2), 107-121. DOI: 10.5658/WOOD.2021.49.2.107

Fu, Q., Yan, L., and Kasal, B. (2020a). “Testing methods for shear strength of bond line between concrete and different types of engineered wood,” *International Journal of Adhesion and Adhesives* 102, 1-12. DOI: 10.1016/j.ijadhadh.2020.102671

Fu, Q., Yan, L., Ning, T., Wang, B., and Kasal, B. (2020b). "Behavior of adhesively bonded engineered wood - Wood chip concrete composite decks: Experimental and analytical studies,” *Construction and Building Materials* 247, 1-10. DOI: 10.1016/j.conbuildmat.2020.118578

Gentry, T. R. (2011). “Performance of glued-laminated timbers with FRP shear and flexural reinforcement,” *Journal of Composites for Construction* 15(5), 861-870. DOI: 10.1061/(asce)cc.1943-5614.0000206

Guo, H., Liu, Y., Meng, Y., Huang, H., Sun, C., and Shao, Y. (2017). "A comparison of the energy saving and carbon reduction performance between reinforced concrete and cross-laminated timber structures in residential buildings in the severe cold region of China," *Sustainability* 9(8), 1-15. DOI: 10.3390/su9081426

Hadigheh, S. A., McDougall, R., Wiseman, C., and Reid, L. (2021). "Evaluation of composite action in cross laminated timber-concrete composite beams with CFRP reinforcing bar and plate connectors using Digital Image Correlation (DIC)," *Engineering Structures* 232, 1-17. DOI: 10.1016/j.engstruct.2020.111791

He, M., Sun, X., and Li, Z. (2018). "Bending and compressive properties of cross-laminated timber (CLT) panels made from Canadian hemlock," *Construction and Building Materials* 185, 175-183. DOI: 10.1016/j.conbuildmat.2018.07.072

Higgins, C. H., Barbosa, A. R., and Blank, C. (2017). *Structural Tests of Concrete Composite-Cross-Laminated Timber Floors Final Report* (Report No. 17-01), School of Civil and Construction Engineering, Oregon State University, Corvallis, OR.

Jiang, Y., and Crocetti, R. (2019). "CLT-concrete composite floors with notched shear connectors," *Construction and Building Materials* 195, 127-139. DOI: 10.1016/j.conbuildmat.2018.11.066

Kanócz, J., and Bajzecerová, V. (2015). "Timber-concrete composite elements with various composite connections. Part 3: Adhesive connection," *Wood Research* 60(6), 939-952.

Lamothe, S., Sorelli, L., Blanchet, P., and Galimard, P. (2020). "Engineering ductile notch connections for composite floors made of laminated timber and high or ultra-high performance fiber reinforced concrete," *Engineering Structures* 211, 1-12. DOI: 10.1016/j.engstruct.2020.110415

Lehmann, S. (2012). "Developing a prefabricated low-carbon construction system using cross-laminated timber (CLT) panels for multistorey inner-city infill housing in Australia," *Journal of Green Building* 7(3) 131-150. DOI: 10.3992/jgb.7.3.131

Lester, C., and Nutt, S. (2018). *Composite materials: Advantages and Cost Factors*, Elevated Materials, Los Angeles, CA.

Li, X., Ashraf, M., Subhani, M., Kremer, P., Kafle, B., and Ghabraie, K. (2020). "Experimental and numerical study on bending properties of heterogeneous lamella layups in cross laminated timber using Australian *Radiata* Pine," *Construction and Building Materials* 247, 1-14. DOI: 10.1016/j.conbuildmat.2020.118525

Liao, Y., Tu, D., Zhou, J., Zhou, H, Yun, H., Gu, J., and Hu, C. (2017). "Feasibility of manufacturing cross-laminated timber using fast-grown small diameter eucalyptus lumbers," *Construction and Building Materials* 132, 508-515. DOI: 10.1016/j.conbuildmat.2016.12.027

Loebus, S., Dietsch, P., and Winter, S. (2017). "Two-way spanning CLT-concrete-composite-slabs," in: *Proceedings of the INTER International Network on Timber Engineering Research*, 28-31 August, Kyoto, Japan, pp. 263-279.

Mai, K. Q., Park, A., Nguyen, K. T., and Lee, K. (2018). "Full-scale static and dynamic experiments of hybrid CLT-concrete composite floor," *Construction and Building Materials* 170, 55-65. DOI: 10.1016/j.conbuildmat.2018.03.042

Ogawa, H. (2000). "Architectural application of carbon fibers: Development of new carbon fiber reinforced glulam," *Carbon* 38(2), 211-226. DOI: 10.1016/s0008-6223(99)00146-3

Pang, S.-J., and Jeong, G. Y. (2019). "Effects of combinations of lamina grade and thickness, and span-to-depth ratios on bending properties of cross-laminated timber

(CLT) floor," *Construction and Building Materials* 222, 142-151. DOI: 10.1016/j.conbuildmat.2019.06.012

Pang, S-J., Oh, J.-K., Park, C.-Y., Park, J.-S., Park, M.-J., and Lee, J.-J. (2011). "Characteristic evaluation of bending strength distributions on revised Korean visual grading rule," *Journal of the Korean Wood Science and Technology* 39(1), 1-7. DOI: 10.5658/wood.2011.39.1.1

Pang, S.-J., Shim, K.-B., and Kim, K-H. (2021). "Effects of knot area ratio on the bending properties of cross-laminated timber made from Korean pine," *Wood Science and Technology* 55(2), 489-503. DOI: 10.1007/s00226-020-01255-5

Park, J.-C., Shin, Y.-J., and Hong., S.-I. (2009). "Bending performance of glulam beams reinforced with carbon fiber-reinforced plastics bonded with polyvinyl acetate-based adhesive," *Journal of the Korean Wood Science and Technology* 37(4), 364-371.

Raftery, G. M., and Harte, A. M. (2011). "Low-grade glued laminated timber reinforced with FRP plate," *Composites*: *Part B Engineering* 42(4), 724-735. DOI: 10.1016/j.compositesb.2011.01.029

Shephard, A. B., Fischer, E. C., Barbosa, A. R., and Sinha, A. (2021). "Fundamental behavior of timber concrete-composite floors in fire," *Journal of Structural Engineering* 147(2), 1-15. DOI: 10.1061/(asce)st.1943-541x.0002890

Song, Y.-J., and Hong, S.-I. (2016). "Evaluation of bonding strength of larch cross-laminated timber," *Journal of the Korean Wood Science and Technology* 44(4), 607-615. DOI: 10.5658/wood.2016.44.4.607

Song, Y.-J., and Hong, S.-I. (2018). "Performance evaluation of the bending strength of larch cross-laminated timber," *Wood Research* 63(1), 105-115.

Song, Y.-J., Baek, S.-Y., Lee, I.-H., and Hong, S.-I. (2021). "Variations of moisture content in manufacturing CLT-concrete composite slab using wet construction method," *BioResources* 16(1), 372-386. DOI: 10.15376/biores.16.1.372-386

Song, Y.-J., Lee, I.-H., Song, D.-B., and Hong, S.-I. (2019). "Evaluation of delamination and bending performance of composite CLT reinforced with CFRP," *Wood and Fiber Science* 51(4), 1-10. DOI: 10.22382/wfs-2019-034

Tannert, T., Endacott, B., Brunner, M., and Vallée, T. (2017). "Long-term performance of adhesively bonded timber-concrete composites," *International Journal of Adhesion and Adhesives* 72, 51-61. DOI: 10.1016/j.ijadhadh.2016.10.005

Thai, M. V., Ménard, S., Elachachi, S. M., and Galimard, P. (2020). "Performance of notched connectors for CLT-concrete composite floors," *Buildings* 10(7), 1-21. DOI: 10.3390/buildings10070122

Thilén, J. (2017). *Testing of CLT-Concrete Composite Decks*, Master's Thesis, Lund University, Lund, Sweden.

Tingley, D. A., Gilham, P. C., and Kent, S. M. (1996). "Long term load performance of FRP reinforced glulam bridge girders," in: *National Conference on Wood Transportation Structures* (FPL-GTR-94), U. S. Department of Agriculture, Forest Products Laboratory, Madison, WI.

Article submitted: June 18, 2021; Peer review completed: September 11, 2021; Revised version received and accepted: February 21, 2022; Published: February 24, 2022.
DOI: 10.15376/biores.17.2.2243-2258