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EFFECT OF THICKNESS OF ADHESIVE ON SHEAR PROPERTIES OF WOOD-STEEL JOINT

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ABSTRACT: To contribute to achieving carbon neutrality 2050 by increasing the use of harvested wood products, the Korean Forest Service is trying to expand public wood buildings. Since public wood buildings often require large spans, it is important to ensure the rigidity of the structural materials, and various studies are being conducted in Korea. One of them is considering wood-steel joints using adhesives, and this paper contains the results of a study to establish the basic shear properties of wood-steel joints composed of epoxy. To investigate the influence of the thickness of the adhesive layer on the shear property of wood-steel joints, pull-out tests were performed on joints made with four different adhesive layer thicknesses. The results showed that the highest shear performance was achieved when the adhesive layer thickness was 1.5 mm, with shear strength and shear stiffness of 23.0 kN and 248.2 kN/mm, respectively. When the shear modulus of wood-steel joints was measured using digital image correlation, it was confirmed that it decreased with the thickness of the adhesive. When the adhesive thickness was 1.5 mm, the shear modulus of the joint was 81.1 MPa.

KEYWORDS: adhesive layer, larch, pull-out, shear property, wood-steel joint

1–INTRODUCTION

In November 2011, the 17th Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) in Durban recognized carbon credits for nationally harvested wood products (HWP) [1]. Meanwhile, the wooden construction market in Korea is growing at a rate of about 10,000 buildings per year [2]. It is centered on small-scale light-frame houses, and most of the materials used are imported. Currently, the Korean wood construction market is unfavorable for achieving carbon neutrality in 2050 using HWP. Therefore, efforts are underway to revitalize heavy wood construction, which is economically and industrially advantageous, centered on the Korea Forest Service [3]. To this end, the Korea Forest Service has a policy to increase the proportion of domestic wood used in new public buildings.

Public buildings are larger and higher than small houses. Therefore, structural members or joint with high rigidity are required to build public wooden buildings. The main method for increasing the rigidity of structural wood based materials is to composite with other materials. Fiorelli and Dias (2011) [4] conducted a study on increasing the stiffness of glulam using Fiber-reinforced polymer (FRP). Plevris and Triantafillou (1992) [5] reported that adding FRP to the outermost layer of structural glulam can increase the design value of the elastic modulus. For the beams reinforced at 1.1% of their height, it was observed a 25% increase in their load capacity, whereas for those reinforced at 3.3%, a 60% increase was observed. Yang *et al.* (2016) [6] conducted a study on increasing the structural performance of glulam using structural glulam and steel. In this study, the structural performance of glulam was derived according to the location of the steel plate in the glulam. Recently, as mid-rise wooden structures utilizing CLT are expanding, research on members composited with concrete is also actively being conducted. Sikora and Liu (2018) [7] evaluated the shear performance according to the type of joint for composing concrete and CLT. Lukaszewska *et al.* (2010) [8] evaluated the flexural performance of CLT floors composited with concrete and reported the performance thereof.

Research on joints for connecting materials and materials has been conducted steadily. Types of fasteners used in joints for wood structures include bolts, drift pins, and nails. Research on joints for wood structures has been mainly conducted on shear performance. Research to predict shear performance has been conducted mainly on the European Yield Model (EYM). Accordingly, research on the shear

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strength and stiffness of joints utilizing inserted steel plates has been conducted. Research on the change in joint performance according to the type of load has also been conducted recently for joints (hold-downs, brackets) used in CLT. Asgari (2020) [9] reported that there is a significant difference in joint performance under static and quasi-static loads. Research has also been conducted to improve joint pull-out performance and moment resistance performance [10-12]. In particular, research results on joints with high pull-out performance and moment resistance performance by adding adhesive to fastener joints were reported [13]. There are various types of adhesives used in wood structure joints, but Tlustochowicz *et al.* (2010) [14] reported that high joint performance can be expected when using epoxy-based adhesives.

Meanwhile, with the development of measuring technology, it is possible to measure the strain or stress distribution of materials in a non-contact manner. Among them, digital image correlation (DIC) is one of the most widely used methods, and it is a method of measuring the strain on the surface of a material using optics. Li *et al.* (2013) [15] measured the Poisson's ratio of wood using DIC. It reported that the Poisson's ratios for the balsam fir (*Abies balsamea* (L.) Mill.) were 0.104, and 0.331 for μ_{RT} and μ_{TR}, respectively. Melinda *et al.* (2025) [16] used DIC in the bending performance test of timber beams strengthened with near-surface mounted (NSM) and cabon FRP plate to analyze the fracture mode and investigate the stress distribution within the member. In general, DIC has been reported to be an effective method for measuring the strain of inhomogeneous materials such as wood or materials with complex compositions.

This study was conducted to establish basic data required for composing wood and steel with adhesive. The thickness of adhesive required in the manufacturing process of composing wood and steel and the difference in performance according to it were confirmed.

2 – MATERIALS AND METHODS

2.1 MATERIALS

The wood used to compose wood and steel with adhesive was larch (*Larix kaempferi*) glulam. The larch glulam was a symmetrical different-grade composition glulam specified in KS F 3021 (Structural glued lminated timber) [17], and its grade was 10S-30B. The larch glulam layer thickness was 30 mm and it consisted of four layers. Among the four layers of larch glulam, the machine graded of the two outermost layers was E12, and the machine graded of the remaining two inner layers was E11. Here, E12 grade means a grade that appeared between 12 and 13 GPa when the elastic modulus of the layer was measured with MSR. When the air-dry specific gravity and moisture content of the larch were measured by collecting small specimens after the experiment, they were 0.52 and 12.3%, respectively.

The steel plate having a yield strength of 205 MPa was used. The thickness of the steel was 10 mm, and the width and length of the plate were 60 and 120 mm, respectively. The surface of the steel was sandblasted with 16 mesh silica sand. Compared to before the sandblasting, the surface roughness increased somewhat.

The adhesive used in this study was a two-component epoxy adhesive from Company R for structural use that can be applied by injection into holes or grooves. The viscosity of the epoxy was 140 poise. The thickness of the adhesive between the wood and steel suggested by the manufacturer was to be at least 2 mm.

2.2 METHODS

2.2.1 Manufacture of Wood-steel Joint

In order to establish a method for synthesizing wood and steel with an adhesive, test specimens were produced according to the thickness of the adhesive as shown in Fig. 1.

Figure 1. Manufacture procedure of wood-steel joint.

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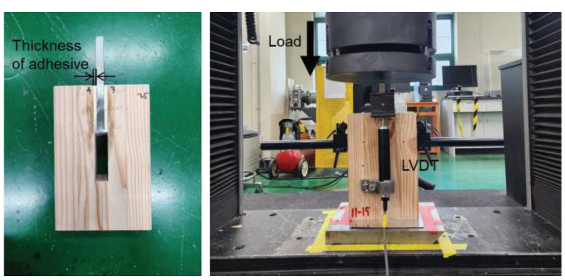
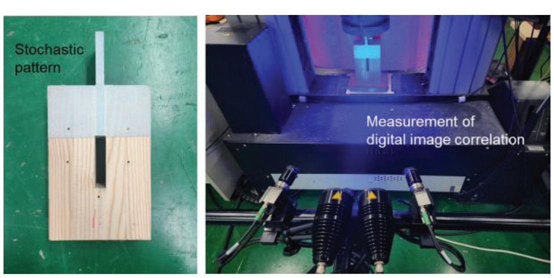
The 10S-30B glulam measuring 120 (width) × 60 (depth) × 180 (length) mm was prepared, and slots of 11, 13, 15, and 17 mm were made in the glulam. The length of the slot was 120 mm. It was fixed so that the center of the slot and the center of the steel plate with a thickness of 10 mm were aligned. The adhesive mentioned above was injected through an 8 mm diameter hole on the side of the laminated lumber. After 24 hours of curing, it was used in the test. The final target gaps between the glulam and the steel plate were 0.5, 1.5, 2.5, and 3.5 mm, respectively. The area where the wood and the steel plate were bonded by the adhesive was 65 × 60 mm, forming a two-sided shear section. The reason for leaving the part of the gluam without the slot was to prevent the specimen from spreading during the experiment.

2.2.2 Pull-out Test

A pull-out test was performed on the wood-steel joints. A compressive load was applied to the steel plate using a Universal Testing Machine (UTM) (Instron, USA). Pins were installed on the load-applying plate to evenly apply the load to the steel. The loading speed was 0.2 mm/min. As shown in Figure 2, an LVDT (Linear Variable Displacement Transducer) (CDP-25, TML, Japan) was placed on the front side of the specimen, and a DIC (Digital Image Correlation) (Aramis, GOM, Germany) was used on the back side to measure the displacement and shear strain during the pull-out test.



(a) Front view (LVDT).



(b) Back view (DIC).

Figure 2.Displacement measurement during pull-out test.

The experiment was conducted until the specimen failed, and 10 repeated experiments were performed for each adhesive layer thickness of 0.5, 1.5, 2.5, and 3.5 mm. The maximum shear stress and shear modulus were calculated as (1) and (2), respectively.

$$\tau_{max} = P_{max}/A \qquad (1)$$

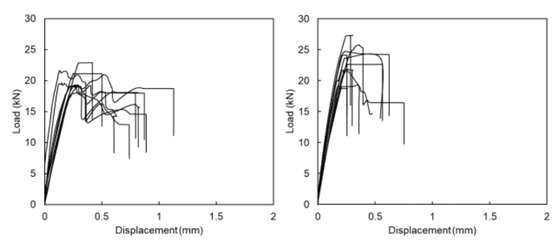
where, τ_{max} is shear stress (MPa), P_{max} is maximum load (N), A is area over shear force (mm^2).

$$G = Fl/A\Delta \qquad (2)$$

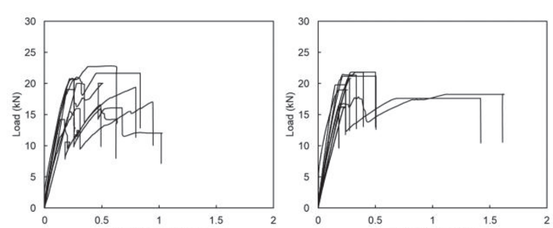
where, G is shear modulus (MPa), l is initial length (mm), F is shear force applied to the material (N), Δ is the amount by which the material is displaced (mm).

3 – RESULTS AND DISCUSSIONS

Fig. 3 presents the load-displacement curves of the pull-out tests, and Table 1 presents the shear load capacity, shear stress, and shear stiffness results of the wood-to-steel joints in various adhesive layer thickness. The shear stiffness was calculated as the slope between 0.1 and 0.4 of the maximum load in the load-displacement curve of each pull-out experiment. The shear load capacity, shear stress, and shear stiffness tended to increase and then decrease with increasing adhesive layer thickness. The shear stresses were 5.71, 6.39, 5.55, and 5.62 MPa when the adhesive layer thicknesses were 0.5, 1.5, 2.5, and 3.5 mm, respectively. The shear stiffnesses were 229.40, 249.15, 177.10, and 208.61 kN/mm, respectively, in the same order. An analysis of variance (ANOVA) results (significance level 95%) confirmed that the shear performance of the joint with a 1.5 mm adhesive layer thickness was significantly different from those of the joints with other adhesive layer thicknesses.



(a) 0.5 (left) and 1.5 mm (right) thickness.



(b) 2.5 (left) and 3.5 mm (right) thickness.

Figure 3. Load-displacement curve in various thicknesses of adhesive.

Table 1: Load resistance and stress according to thickness of adhesive

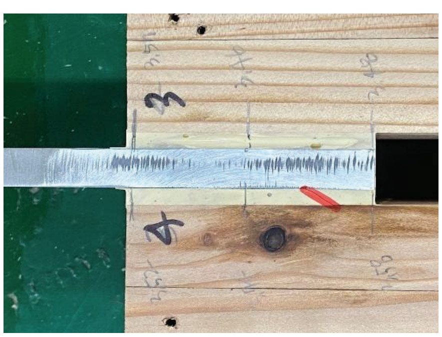
Thickness (mm)	Maximum Value		T_{max}[a] (MPa)	Shear Stiffness (kN/mm)
	Dis.[b] (mm)	*Load* (kN)		
0.5	0.29 (0.41)[c]	20.57 (0.09)	5.71 (0.09)	229.40 (0.31)
1.5	0.33 (0.39)	23.02 (0.12)	6.39 (0.12)	249.15 (0.15)
2.5	0.50 (0.53)	19.98 (0.14)	5.55 (0.14)	177.10 (0.16)
3.5	0.37 (0.76)	20.22 (0.09)	5.62 (0.09)	208.61 (0.21)

[a] Tmax: Shear Stress, [b] Dis.: Displacement measured from LVDT, [c] Coefficeint of variable (CoV) = average / standard deviation

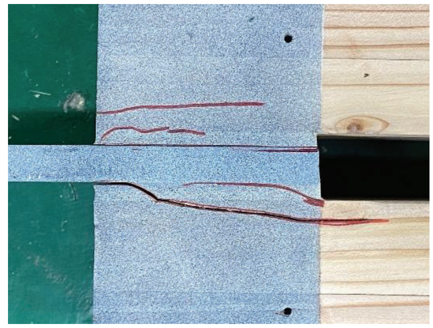
Shear load capacity and stress showed lower coefficients of variation than shear stiffness. KS F 2201 (General requirements for testing of wood) [17] presents coefficients of variation according to the physical properties of wood. The range of coefficients of variation for strength of wood was 0.15 to 0.2, whereas the coefficient of variation for modulus of elasticity related to stiffness was 0.20. Compared with the experimental values, shear load capacity and stress were lower than those in the literature, whereas shear stiffness showed higher coefficients of variation than those in the literature. This is thought to be because the variation of displacement measured in the pull-out experiment was large.

After the pull-out experiment, the failure modes of the wood-steel joint were observed as interface failure, cohesive failure, and adherend failure, as shown in Fig. 4.

(a) Interface failure.



(b) Cohesive failure.



(c) Adherend failure.

Figure 4. Failure mode (red line in picture) near adhesive in wood-steel joint after pull-out test.

Failure modes were recorded on the front and back surfaces of the wood-steel joints, and when multiple failures occurred on the same surface, they were measured and recorded independently. Table 2 shows the probability of failure occurrence for the total number of measurements. As a result, it was confirmed that interface failure occurred most frequently regardless of the adhesive layer thickness. Cohesive failure occurred most frequently when the adhesive layer thickness was 2.5 mm, whereas adgerend failure occurred most frequently when the adhesive layer thickness was 0.5 mm. However, it seemed that there was no correlation between failure modes and shear properties.

Table 2: Failure occasion probability according to modes

Thickness (mm)	Probability of Failure Mode (%)		
	Interface	*Cohesive*	*Adherend*
0.5	75	10	40
1.5	75	25	15
2.5	90	60	25
3.5	60	35	25

Fig. 5 shows the displacement distribution that occurred in the direction parallel to the compressive load on the back surface of the wood-steel joint. This distribution was measured when the maximum load occurred during the pull-out experiment. When examining the displacement distribution, it was confirmed that the displacement of the steel plate where the load was applied was commonly the largest. In addition, displacement also occurred at the part furthest from the steel plate. It was confirmed that the displacement that occurred at the farthest part, the corner of the glulam, was approximately 0.23 mm. It was considered that the load transmitted to the adhesive surface and wood through the steel plate contributed to not only shear deformation but also compressive deformation. Therefore, the shear modulus derived from this experiment might be not the shear modulus measured by pure shear.

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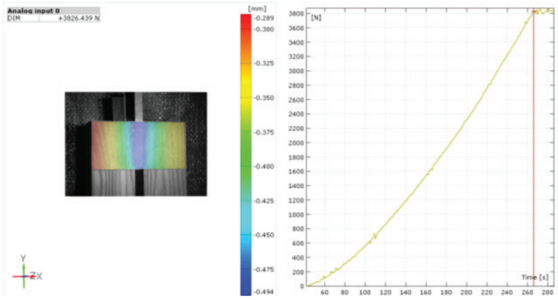
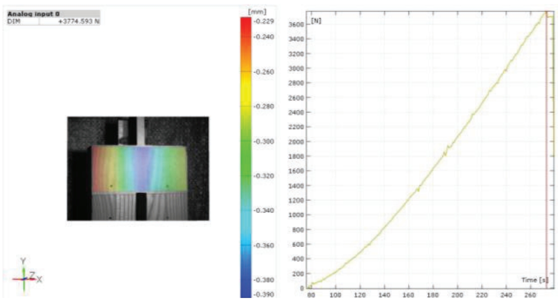
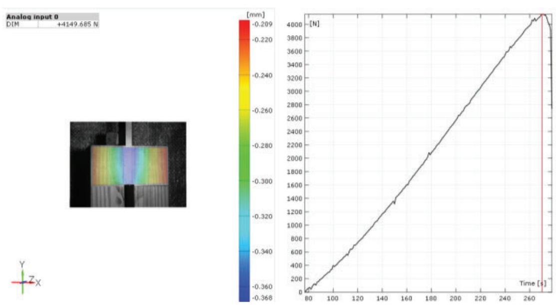


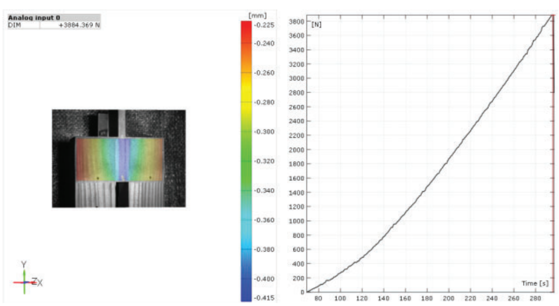
(a) 0.5 mm thickness.



(b) 1.5 mm thickness.

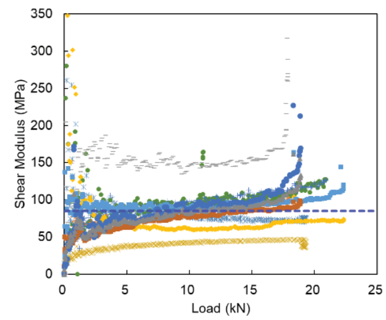


(c) 2.5 mm thickness.

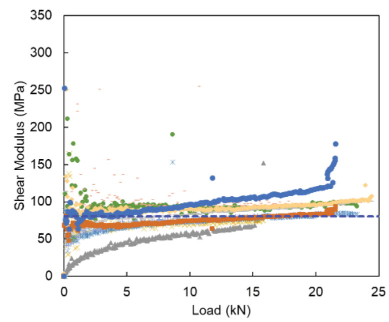


(d) 3.5 mm thickness.
Figure 5. Distribution of displacement at maximum load.

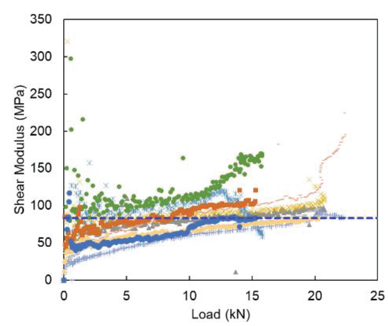
Fig. 6 shows a graph of shear modulus measured according to load. The load was limited to the maximum load, and ratio of the initial length and material displacement required to calculate the shear modulus were measured using DIC. The shear modulus was not constant for shear loads of 0.5 kN or less and 15 kN or more, so it was excluded from the calculation. It is thought that this is because the shear strain was small for 0.5 kN or less, and the shear strain was not properly measured for 15 kN or more due to failure, and so on.



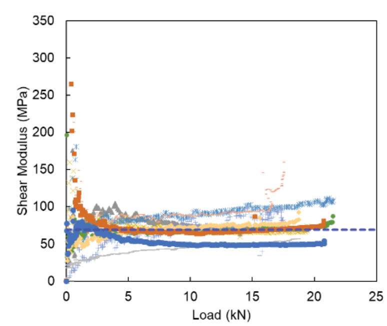
(a) 0.5 mm thickness



(b) 1.5 mm thickness



(c) 2.5 mm thickness



(d) 3.5 mm thickness
Figure 6. Shear modulus according to thickness of adhesive.

The average shear moduli of wood-steel joints with adhesive layer thicknesses of 0.5, 1.5, 2.5, and 3.5 mm were calculated to be 85.0, 80.6, 81.7, and 69.2 MPa, respectively. The ANOVA showed that there was no significant difference in the average shear moduli of wood-steel joints with adhesive layer thicknesses of 1.5 and 2.5 mm. It was confirmed that there was a significant difference in the shear moduli of wood-steel joints with adhesive layer thicknesses of 0.5 and 1.5 mm and those with adhesive layer thicknesses of 0.5 and 3.5 mm. Therefore, it was confirmed that the average shear modulus decreased as the adhesive layer thickness increased. This is thought to be because the shear strain increased as the adhesive layer thickness increased. In the CLT handbook [18], the shear modulus of wood is stated to be 1/16 of the modulus of elasticity along the longitudinal direction. In this study, the lamination of glulam to which the steel was bonded was confirmed to be E11 grade, and the modulus of elasticity of E11 grade was 11 GPa; the shear modulus and rolling shear modulus were calculated to be 687.5 and 68.8 MPa, respectively. Therefore, the average shear modulus of the wood-steel joint was confirmed to be higher than the rolling shear modulus.

4 – CONCLUSION

It was confirmed that the shear performance of the wood-steel joint was the best when the adhesive layer thickness was 1.5 mm. This is because the shear load capacity and shear stiffness were the highest at 6.39 MPa and 249.15 kN/mm, respectively, in the wood-steel joint with a 1.5 mm thickness of adhesive layer, and the shear modulus was the second highest at 81.1 MPa. However, since the displacement was 0.33 mm when the maximum shear load occurred and brittle failure mainly occurred, it was judged that it would be difficult to secure structural stability if the wood-steel joint was constructed using only the adhesive. Therefore, it was concluded that the adhesive could be used as an additional means to improve the stiffness of the joint.

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