Improved Design of Self-tapping Screw (STS) for Korean Larch and Red Pine Cross Laminated Timber (CLT)

In-Hwan Lee,[a] Sang-min Lee,[a] and Keon-Ho Kim [b,*]

In this study, the finite element method (FEM) was used to determine the effect of the optimal angle of the thread and double thread application among self-tapping screw (STS) design information on the improvement of the withdrawal capacity of the connection. It was modeled by reflecting the design information of an Italian STS distributed in the domestic wooden building market, and the stress distribution of the connections was compared according to the change in the thread angle. A cross laminated timber (CLT) composed of five layers was modeled as a member. The STS modeling was centered on the threaded area, and two threaded angles were applied: 90° and 95°. Additionally, the stress changes were compared when double threads located in the middle of the thread pitch in the screw pitch were applied to improve the withdrawal capacity of the connection. The domestic STSs were manufactured using four materials and two shapes. The finite element analysis and strength performance tests of the STS types indicated that the material properties, angle of the screw thread, and shape of the screw thread affect the Korean CLT withdrawal capacity.

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Contact information: a: Wood Engineering Division, Forest Products and Industry Department, National Institute of Forest Science, 57 Hoegi-ro, Dongdaemun-gu, Seoul 02455, Republic of Korea; b: Wood Industry Division, Forest Products and Industry Department, National Institute of Forest Science
**Corresponding author: keon@korea.kr*

INTRODUCTION

In order to respond to the climate change crisis, many countries have been establishing a carbon-neutral plan. IPCC (2018) reported that greenhouse gas emissions in the construction sector account for a significant proportion. Limiting global warming to 2° requires achieving global carbon neutrality by 2070, and reaching the 1.5° target requires achieving global carbon neutrality by 2050. Wooden construction using timber, a carbon storage material used as an eco-friendly building material, has been recognized as an important part of realizing carbon neutrality. With the recent development of high-rise wooden construction technology, construction projects using cross-laminated timber (CLTs) have increased (Lee *et al.* 2022; Muñoz *et al.* 2022). In the CLT structure, the performances of the CLT and CLT fasteners have been found to be the most crucial factors. Self-tapping screws (STS) are attracting increasing attention as CLT fasteners owing to their excellent performance and high fastening force (Ringhofer *et al.* 2015; Sullivan *et al.* 2018; Srivaro *et al.* 2021). In Korea, STS research is ongoing (Lee and Kim 2023; Lee and Kim 2024).

The specific gravity of the species mainly used in Europe, North America, or Japan is approximately 0.35 to 0.45 (Unterwieser and Schickhofer 2013; Yusoh *et al.* 2021). However, larch (356,208 m^3, 64.3 %) and red pine (131,873 m^3, 23.8 %), with an average weight of 0.52 and 0.45, comprise the majority of softwood lumber producers in Korea (Wood Utilization Survey 2021). Therefore, various studies on larch and red pine CLT have been conducted in Korea (Song and Hong 2016; Choi *et al.* 2018; Pang and Jeong 2019; Song *et al.* 2019; Lee and Kim 2021). Larch CLT requires higher performance for fasteners owing to their superior physical properties and relatively high specific gravity. Therefore, high-performance STS must be developed.

To improve the performance of a self-tapping screw used as a fastener for CLT, the design conditions must be determined. The strength performance according to the type of fastener and the mechanical performance of the member are crucial factors for predicting the shear performance of a CLT connection.

The variables in the withdrawal capacity performance of STS suitable for larch and red pine were angle, material, and shape. The design information of the Italian STS for its angle was analyzed using FEM (Finite element analysis) to compare the stress distribution according to the angle change. The STS material was reviewed in terms of bending strength performance by varying the type of material and heat treatment conditions. The withdrawal resistance strength performance of the STS shape was compared by applying double-screw threads. However, the new STS must be reviewed for availability as a fastener through a joint shear test if it shows good withdrawal capacity performance on the arch.

EXPERIMENTAL

Material and Methods

FEM by angle of thread

FEM was performed on the withdrawal resistance capability according to the thread angle of the STS fastener and the CLT fiber direction. The FEM model implemented the cross-section of the STS and that of the larch, as shown in Fig. 1. The withdrawal resistance strength performance of both types were evaluated with different thread angles. The FEM model was analyzed using the static structure of the ANSYS 2023 R2 program. The physical properties of the wood were set as listed in Table 1, and those of the STS were set as basic structural steel. The contact condition between the STS and Lac was set as no separator. The larch timber part without contact surface with the STS was fixed. To measure the detailed behavior, the mesh was set to 0.5 mm. Certain information was applied upward to the STS to observe similar behavior as that in the withdrawal strength test. The data used in the analytical model were obtained from the literature and are listed in Table 1.

Table 1. Orthotropic Material Properties Used in FE Simulations taken from Wood-Handbook (2010) and Warguła (2020) (at approximately 12% moisture content)

Mechanical Parameters	Moduli of Elasticity (GPa)			Shear Moduli (GPa)			Poisson's Ratios		
Species	E_L	E_R	E_T	G_{LR}	G_{LT}	G_{RT}	ν_{LR}	ν_{LT}	ν_{RT}
Larix kaempferi	10.25	0.41	0.42	1.94	2.68	2.68	0.66	0.64	0.89
Pinus densiflora	10.50	0.44	0.36	0.84	2.18	2.18	0.44	0.45	0.94

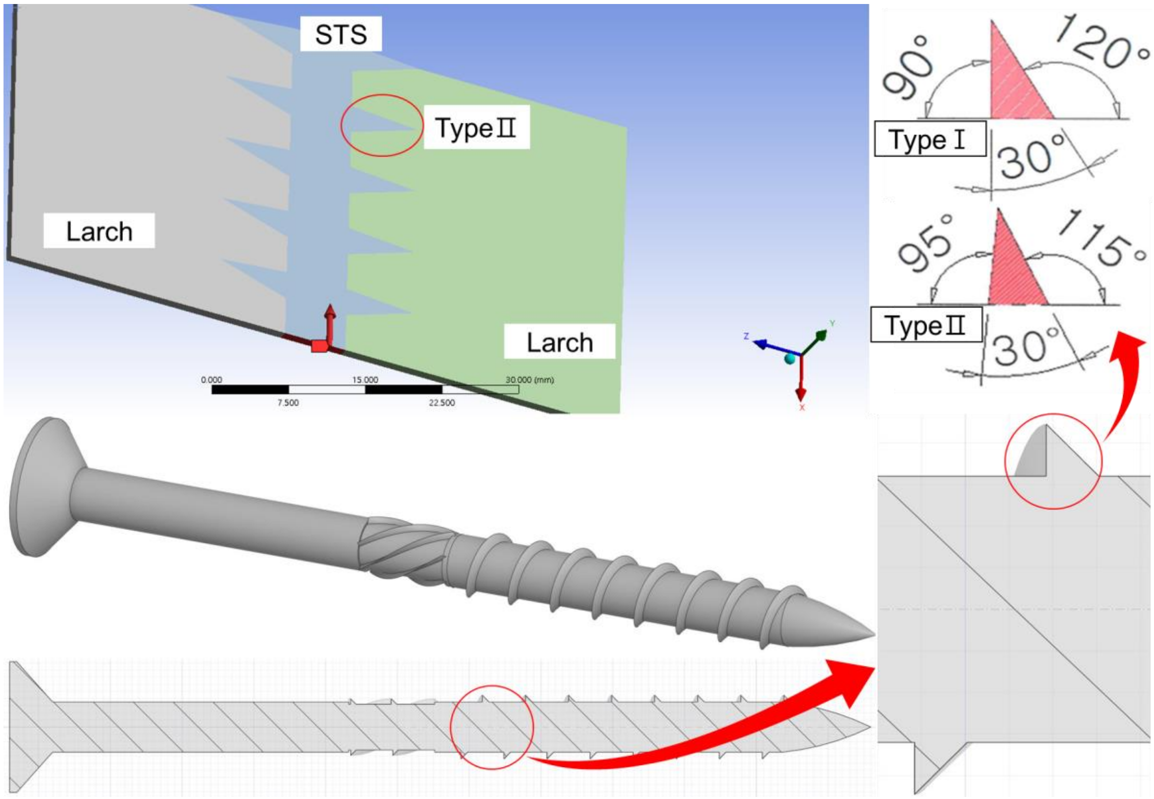

Fig. 1. Schematic diagram of FEM cross section model and thread angle using STS

Material Properties of STS

Because the strength of the screw thread is related to the strength characteristics of the material, the STS material was changed to reinforce the stress-intensive screw thread, and an STS bending strength test was conducted. Four types of Korean STS are produced depending on the material, and the number of heat treatments, methods, and materials differs for each type. HBS 10 (Rothoblaas, Italy) was produced in Europe.

Table 2. Material Properties of STS

Type	Model	Tensile Strength Kgf/mm^2	Heat Treatments
A	S18A	50 Minimum	2
B	S45C	78 Minimum	-
C	51B20	94 Minimum	1
D	SCM435	94 Minimum	1

A bending performance test based on the STS material was performed under a concentrated load with a span of 80 mm.

Shape of Screw Threads

The thread interval of the STS was wider than that of the normal thread, increasing the volume of timber because that of the thread interval supports the thread when the thread is drawn. Despite the additional thread being processed, the timing would not be crushed and supported owing to the higher specific gravity of the Larch CLT and red pine CLT than the species commonly used in Europe or the United States. In addition, the resistance will increase when STS is inserted into the timber if the thread size remains the same. Therefore, additional processing of small threads between those of the existing STS improves the withdrawal capacity. The shape of the thread was divided into the basic shapes of the European STS and double thread. A new thread was machined in the space between the existing thread and the thread (Fig. 2). A withdrawal resistance strength test according to the shape of the screw thread was performed according to KS F ISO9087.

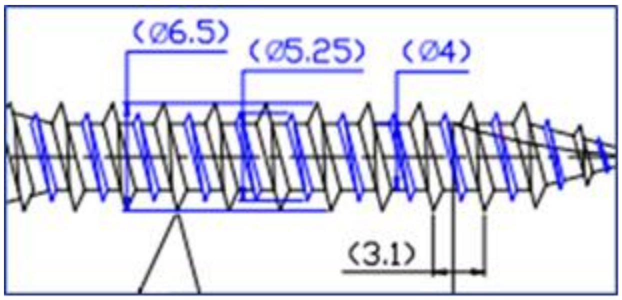

Fig. 2. Korea STS design for double threaded applications

Performance Evaluation of Larch CLT and Pine CLT Withdrawal Capacity

The Japanese larch (*Larix kaempferi* (Lamb.) Carriere) and Korean red pine (*Pinus densiflora*) were used for the withdrawal capacity test drawn after STS was inserted into the CLT 3ply. The average specific gravities of Japanese larch are 0.5, and Korean red pine are 0.44. Two types of STS, HBS 10 (Rothoblaas, Italy) and an STS developed based on the experiments in this study were used. The withdrawal capability test was performed by fixing the lower part of the CLT to the lower jig of the instrument and the STS head to the upper jig (Fig. 3). The withdrawal speed was set to fail within 1.0 to 3 min. The speed was 4 mm/min.

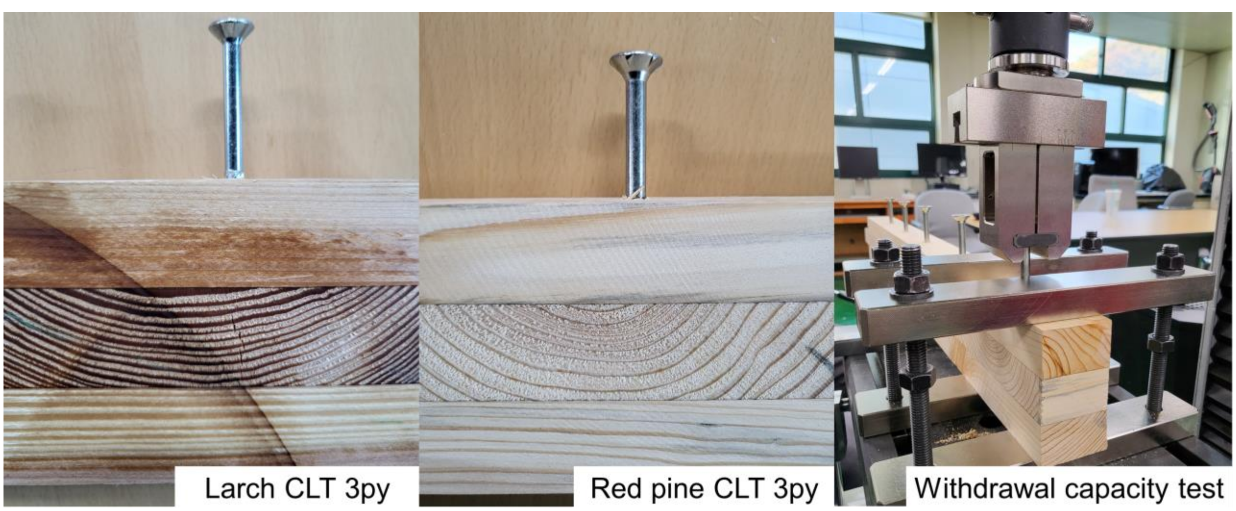

Fig. 3. Images of withdrawal specimens and strength test method

RESULTS AND DISCUSSION

Effect of Angle of Thread on Withdrawal properties of STS

The strength applied to the FEM model was 7226 N, calculated based on the maximum withdrawal resistance of the STS inserted into the larch CLT.

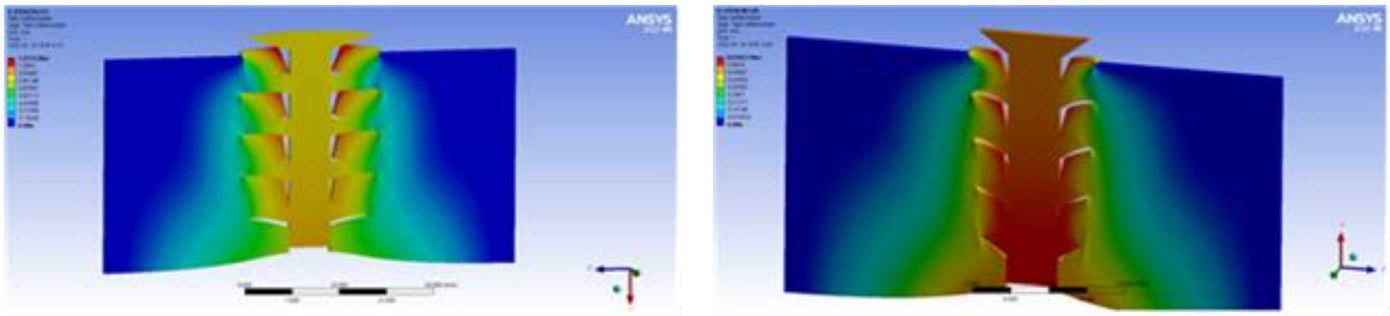

Fig. 4. FEM deformation distribution for each angle of screw thread (left: A type – Max. deformation 1.2175 mm, right: B type – Max. deformation 0.638 mm)

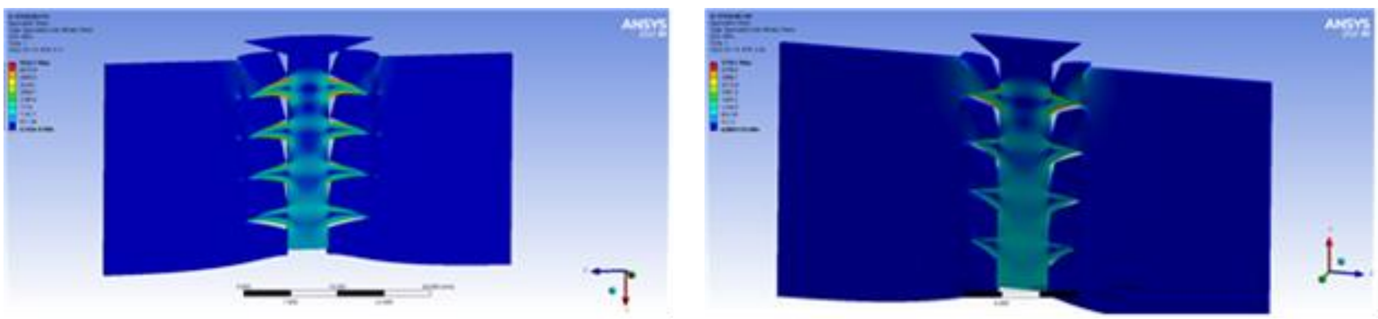

Fig. 5. FEM stress distribution of STS (top: A type - Max stress 5140 MPa, bottom: B type – Max. stress 3710 MPa)

From the FEM analysis, the STS with a thread angle of 90° was deformed by 0.638 mm at the same withdrawal load, but the STS with a thread angle of 95° was deformed by 1.218 mm (Fig. 4). In addition, the maximum stress that the STS receives was 38.6 % higher at 95° than at a thread angle of 90° (Fig. 5).

Maximum stress and deformation were observed under the thread. Therefore, the angle of the STS screw thread and verification experiments must be optimized and conducted in the future.

Improvement Effects of Material Properties of the Threads of STS

When a withdrawal load is applied, the resistance stress is concentrated on the screw thread; therefore, the strength characteristics of the STS material are crucial.

As shown in Table 2, the bending strength of the Type C steel was excellent. However, Type D has better ductility than Type C (Fig. 6). When STSs are used as CLT fasteners, the ductility of the connection is a crucial factor in securing structural stability.

Table 3. Bending Strength Performance According to STS Fabrication Method

Producer	Italy STS	Korea STS (Diameter 10 mm)			
STS type	HBS10	Type A	Type B	Type C	Type D
Ave. MOR (MPa)	2858	1250	2000	3510	3269
CV	0.91	3.13	6.70	1.71	3.62

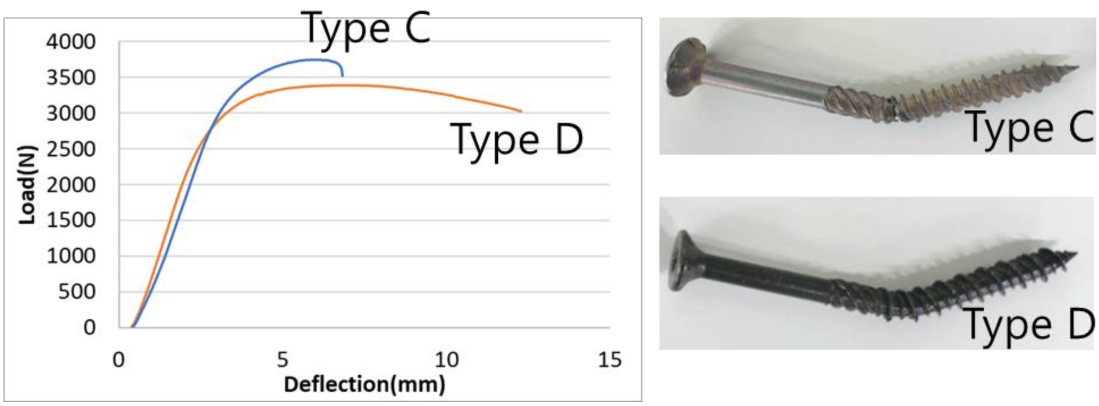

Fig. 6. Load-deformation curves and failure modes of the STS bending strength specimen.

Comparison of Withdrawal Resistance by the Tip and Double Thread

The withdrawal resistance strength according to the groove of the tip for penetrating the STS, was compared. The groove of the STS had little effect on the STS withdrawal resistance of the CLT. However, many grooves were required to facilitate fastener insertion (Fig. 7).

Fig. 7. Processing tip of Korea STS fastener (Type D)

Table 4. Comparison of 3 CLT Withdrawal Resistance Loads of STS According to Tip Type

	Korea STS			Italy STS
	Groove x	Groove 1	Groove 2	
	Withdrawal Resistance (kN)			
1	10.00	8.69	10.22	
2	10.65	12.99	11.28	
3	10.74	12.51	10.26	
4	9.95	9.89	11.67	
mean (kN)	10.34	11.02	10.86	12.44
CV	0.04	0.16	0.06	0.02

Withdrawal Capacity Performance of Korean CLT Using New STS

Figure 8 compares the STS of the final production and the existing HBS 10. Table 5 presents the dimensions of the two STS. In the figure, d_s is the shank diameter, d_c is the shank cutter diameter; d_1 is the outer thread; d_2 is the inner thread; d_3 is the middle thread; and t_2 is the pitch between threads. As shown in Table 6, the withdrawal resistance performance of the STS with double screws was 1.05 times greater for deciduous pine CLT and 1.06 times greater for pine CLT than for single screws. Because the shape of the screw affects the withdrawal performance, various FEM analyses are needed to optimize the STS shape, such as the internal diameter, external diameter, pitch, and double screw, in the future.

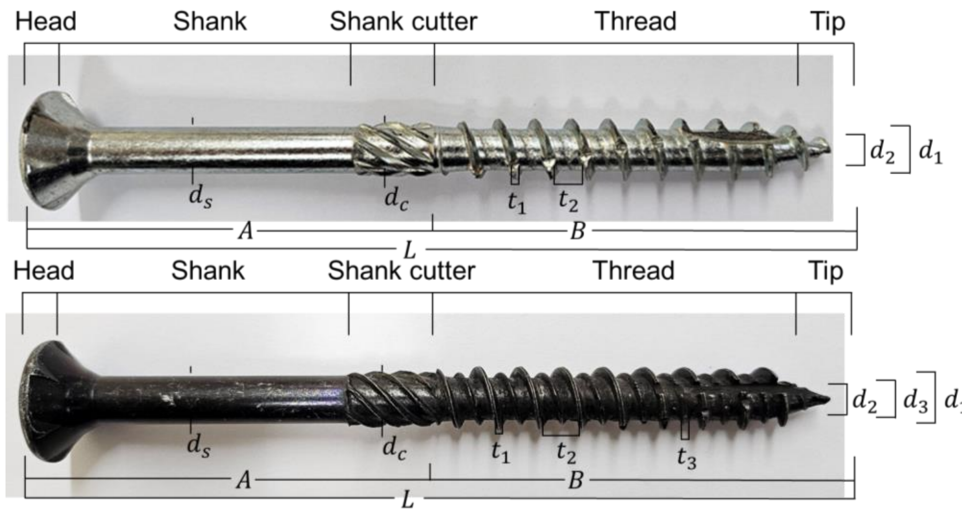

Fig. 8. Images of STS samples (top and bottom: HBS10, new STS)

Table 5. STS Dimensions (mm)

	L	*A*	*B*	d_s	d_c	d_1	d_2	d_3	t_2
HBS10	120	60	60	7	7.5	10	6.4	-	5.6
New STS	120	60	60	7	7.5	9.7	4.2	8.3	5.7

Table 6. Comparison of Withdrawal Resistance of 3ply CLT using Korea STS

Manufacturer	Imported STS		Domestic STS			
CLT species	Larch	Red Pine	Larch		Red Pine	
Thread types	Single		Single	Double	Single	Double
Withdrawal resistance mean (MPa)	158.4	121.6	151.9	159.6	144.2	152.5
CV	0.14	0.05	0.14	0.17	0.08	0.08

Type A: single thread, Type B: double thread

CONCLUSIONS

In this study, various variables were applied to self-tapping screws (STS), and their performances were verified to develop a new type of STS, a connecting fastener suitable for Korean larch and red pine cross-laminated timber (CLT). The results are as follows:

1. The additional machining of small threads between the threads of the STS improves the withdrawal capacity.
2. The thread angle of the Italian STS, widely used as a CLT fastener, exhibits good withdrawal resistance strength when adjusted from 95 ° to 90 °.
3. The STS with the best material was the STS that treated the SCM435 model once with heat treatment.
4. The tip of the STS did not affect the withdrawal performance.

A new STS was produced under these conditions. The new STS was inserted into the larch CLT and red pine CLT to verify the withdrawal capacity. The larch CLT was improved by 0.8 %, and the red pine CLT was improved by 25.4 %.

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