Prediction of Withdrawal Resistance of Self-Tapping Screws in Softwood Structural Lumber

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The withdrawal resistance of self-tapping screws (STS) in Korean structural softwood in the vertical fiber direction was examined. Four representative softwood species were selected based on their specific gravity. Three STS fastener diameters were used for an STS penetration depth of 50 mm. The withdrawal capacity tended to increase with the specific gravity of the specimens and as the diameter of the STS increased. Primarily, the difference in strength was maximized as the STS diameter increased from 8 to 10 mm. Predictive experimental equations were proposed based on the experimental values of the relationship between the specific gravity of the structural material and the withdrawal resistance according to the diameter of the STS. The values were compared with the predicted values calculated using fastener and screw prediction equations proposed by the National Design Specification for Wood Construction (NDS) and European Standards (EN). The results calculated using the NDS prediction equations yielded a peak difference of 43% compared with the experimental withdrawal capacity, whereas the EN prediction equations yielded a difference of 0.7 to 1.14 times the experimental values. The ratios between the withdrawal capacity predicted by the proposed prediction equations and the experimental withdrawal capacity were the most similar, ranging from 0.80 to 1.15.

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Keywords: Japanese larch; Korean red pine; Korean pine; Japanese cedar; Softwood; Self-tapping screw; Withdrawal capacity; Withdrawal resistance

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INTRODUCTION

Engineered wood has garnered global recognition due to its carbon storage capacity and is emerging as an alternative to achieve carbon-neutral policies in the construction industry. Moreover, the utilization of engineered wood in architectural designs has accelerated the construction of multistory buildings, driven by advancements in joining technologies. Typically, various types of fasteners, including nails, drift pins, and bolts, are employed in wooden structures to address the contrasting mechanical properties of wood (brittle) and steel (ductile) and effectively distribute external loads (Gavric *et al*. 2015; Hassanieh *et al.* 2016).

Recently, structural laminated lumber (glulam) and cross-laminated timber (CLT) have gained traction as building materials, leading to a surge in the use of self-tapping screws (STS). The STS are widely used as fasteners in softwood CLT joints because of their strong bonding properties and advantageous workability (Uibel and Blaß 2007; Frese *et al.* 2010; Ringhofer *et al*. 2015; Ayoubi 2016). Unlike traditional fasteners, the wood is crushed and cut during STS insertion. Thus, STS can be inserted without the need for pre-drilling and can be joined without precise prework, which makes it particularly advantageous in construction projects where time efficiency is crucial. In Europe, standardized design strengths for various STS types (classified according to diameter and length), including methods for joining wood, wood-to-steel plate connections, and insertion into glulam and CLT, have been established. However, determining suitable strength values for domestic wood species remains a topic of ongoing research (Lee *et al*. 2022).

In the design of STS joints, the performance of fastener bending, wood embedment, and withdrawal capacity plays a pivotal role (Stamatopoulos and Malo 2015; Hoelz *et al*. 2021). The design of timber structures by EN 1995-1-1 (2004) recognizes that not only the embedment strength but also the withdrawal capacity affects the shear strength of timber structure joints. Therefore, the withdrawal capacity is incorporated in the joint prediction equations, where the specific withdrawal capacity applied depends on the fastener type. For nails, 15% to 50% of the maximum withdrawal capacity is applied to the joint prediction equations. This value is 25% for bolts and 0% for dowels; however, the maximum withdrawal capacity applied for screws is 100%. This underscores the importance of deriving an accurate prediction of the withdrawal capacity of screws, as it contributes to deriving precise joint design values. Screw prediction equations have been reported for the design values of EN and prediction equations for nails, lag screws, and wood screws for the National Design Specification for Wood Construction (NDS, 2018); however, no prediction equations have been reported for STS. Considering this gap in the literature, it is imperative to assess the suitability of withdrawal capacity prediction equations for existing screws for the experimental withdrawal capacity of STS.

The variation in withdrawal capacity of fasteners depends more on specific gravity than on wood species. In countries outside of Korea, the embedment and withdrawal capacity performance based on specific gravity of native species are standardized; however, there are no prediction equations for the withdrawal capacity of STS according to domestic species and specific gravity. The structural softwood species in South Korea include Japanese larch, Korean red pine, Korean pine, and Japanese cedar (KS F 3020 2018). These species are grouped together based on their similar strength properties, with separate allowable stress values designated for each species.

In this study, the withdrawal resistance performance of STS fasteners was evaluated in Japanese larch, Korean red pine, Korean pine, and Japanese cedar, which are representative structural materials of Korean softwood. Moreover, the authors derived and solved prediction equations based on key factors contributing to resistance performance.

EXPERIMENTAL

Materials

The Korean softwoods used as test materials in this study were Japanese larch (*Larix kaempferi* (Lamb.) Carriere), Korean red pine (*Pinus densiflora*), Korean pine (*Pinus koraiensis*), and Japanese cedar (*Cryptomeria japonica*) (Fig. 1). The average specific gravity for each species was calculated as follows: 0.5 for Japanese larch, 0.44 for Korean red pine, 0.49 for Korean pine, and 0.32 for Japanese cedar. All timbers were purchased from sawmills, and all wood was kiln dried. The withdrawal strength of the radial or tangential sections was measured. The experiment was conducted by randomly extracting sapwood and mature wood. The specimens were constructed of timber with a cross-section measuring 50 mm × 50 mm. The fastener used in the withdrawal capacity test was HSB, self-tapping screws (hereinafter referred to as STS), which were obtained from Rothoblaas (Italia) (Fig. 2). The 120 mm long STSs were classified into three groups based on their diameters: 8, 10, and 12 mm. The shank diameters (ds) were 5.8, 7, and 8 mm, and the shank cutter diameters (dc) were 6.8, 8.4, and 9 mm. The inner diameter (d2) and outer diameter (d1) of the threads are reported in Table 1.

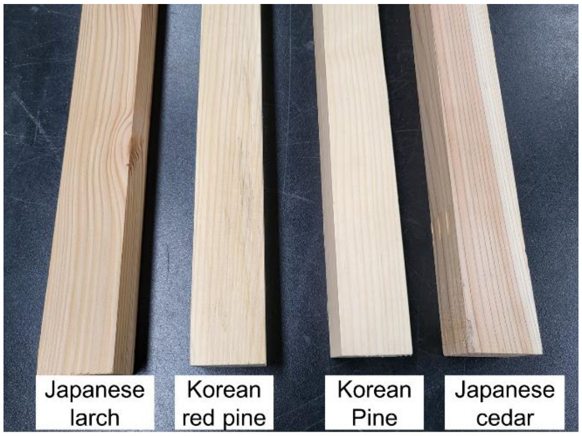

Fig. 1. Photograph of Korean structural softwood timbers

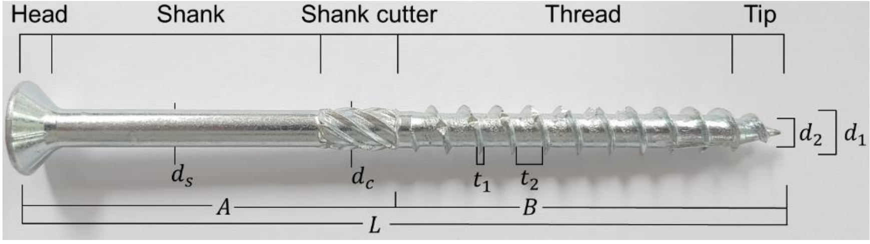

Fig. 2. Photograph of STS

Table 1. STS Codes and Dimensions (mm)

CODE	d_1	d_2	L	A	B	d_s	d_c	t_1	t_2
HBS8120	8	5.4	120	60	60	5.8	6.8	1.25	4
HBS10120	10	6.4	120	60	60	7	8.4	1.4	4.1
HBS12120	12	6.8	120	40	80	8	9	2.2	3.8

Specimen Production for Withdrawal Capacity and Testing Methods

For the withdrawal capacity testing, 30 specimens were produced for each species, with 10 specimens per STS diameter, totaling 120 specimens tested for all 4 species. All specimens were stored in a chamber under constant temperature and humidity for over a week, resulting in an equilibrium moisture content of 12 ± 2%. The STS produced specimens using a drill without drilling in the direction perpendicular to the fiber to include the thread length, excluding the tip portion. The withdrawal capacity tests were conducted by securing the lower part of the wood with the lower jig of the Instron machine and anchoring the STS head with the upper jig (Fig. 3). Withdrawal speeds were determined based on preliminary experiments, ensuring failure occurred within 1.0 to 3 min. The STS with diameters of 8, 10, and 12 mm were tested at rates of 3, 4, and 5 mm/min, respectively.

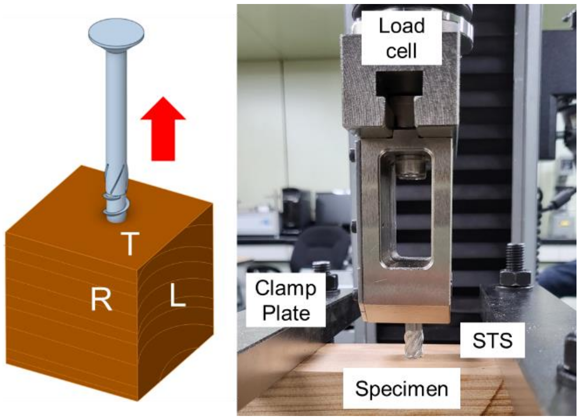

Fig. 3. Withdrawal capacity specimens and test methods of Korean softwood with STS (L: longitudinal section, R: radial section, T: tangential section)

RESULTS AND DISCUSSION

STS Withdrawal Capacity of Domestic Softwood Structural Materials

The withdrawal capacity tests on domestic softwood species indicated that the average maximum load generally increased as the STS diameter increased across all species. This trend can be attributed to the enhanced contact area between the timber and STS resulting from the larger thread diameter of the STS (Table 2).

Table 2. Comparison of Withdrawal Capacity According to Species and STS Diameter

Species		STS Diameter (kN)		
		8 mm	10 mm	12 mm
Larch	mean	6.06	7.28	8.37
	S.D.	0.26	0.62	0.52
	CV (%)	4.3	8.52	6.19
Red pine	mean	5.73	7.83	8.52
	S.D.	0.31	0.32	0.53
	CV (%)	5.46	4.07	6.65
Korean pine	mean	7.04	10.12	11.59
	S.D.	0.29	0.74	0.24
	CV (%)	4.06	7.31	2.18
Cedar	mean	4.36	5.81	6.60
	S.D.	0.3	0.33	0.48
	CV (%)	7.63	5.64	7.24

For Japanese larch, compared to the 8 mm specimens, the average maximum load increased 20% for the 10 mm specimens and 15% for the 10 and 12 mm specimens.

Similarly, Korean red pine, Korean pine, and Japanese cedar exhibited an increase of 9%, 15%, and 14%, respectively, in the average maximum load when comparing 10-mm and 12-mm specimens, mirroring the pattern observed in Japanese larch. However, there was a notable 37% increase when comparing 8-mm specimens and 10-mm and increments of 44% and 33% for Korean pine and Japanese cedar, respectively. This aligns with the findings of Khai and Young (2022), who reported that withdrawal capacity increases with both STS diameter and penetration depth. Notably, the coefficient of variation of all specimens was relatively low, ranging from 2.18% to 8.52%, indicating high reliability of the obtained values. These trends conclusively demonstrate that the withdrawal capacity is primarily influenced by the diameter and specific gravity of the STS.

Relationship between Withdrawal Resistance and Specific Gravity of STS

All specimens were subjected to withdrawal resistance testing, and a portion of the timber was cut to measure the moisture content and specific gravity. Prior to testing, the specimens were placed in a constant temperature and humidity chamber, and the moisture content was maintained in the range of 12 ± 2%. The average specific gravity values were measured as follows: 0.5 for Japanese larch, 0.44 for Korean red pine, 0.49 for Korean pine, and 0.32 for Japanese cedar. These values are consistent with those reported by Yang *et al*. (2017) as follows: 0.52 for Japanese larch, 0.45 for Korean red pine, 0.44 for Korean pine, and 0.35 for Japanese cedar. Jang and Kang (2023) reported the specific gravity of Japanese larch and Korean pine as 0.52 and 0.5, respectively. Although the average specific gravity of larch in this study was relatively low, Korean pine, chosen as a publicly available material with a relatively high specific gravity, presented challenges in making species-based comparisons. Therefore, the specific gravity and withdrawal resistance were compared and reviewed. In general, the physical properties of wood tend to improve as the specific gravity increases (Zhang 1995; Bouafif *et al*. 2009; Ogunsanwo 2011). Regression analysis of withdrawal resistance according to specific gravity and diameter showed that withdrawal resistance tended to increase as specific gravity improved for all STS diameters (Fig. 4).

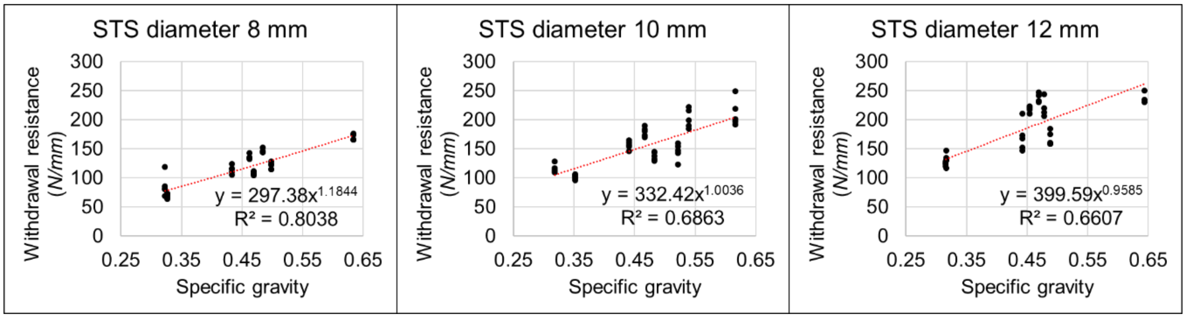

Fig. 4. Regression analysis graph according to STS withdrawal resistance and softwood specific gravity

STS Withdrawal Capacity Prediction of Domestic Softwood Structural Materials

The withdrawal capacity prediction using STS of structural materials was predicted using the EN's screw withdrawal capacity prediction equations and NDS wood screws and lag screws prediction equations, and the results were compared with experimental values. Additionally, new prediction equations for STS were proposed based on experimental data.

The NDS offers three types of prediction equations: nails, wood screws, and lag screws; however, in this study, predictions were performed using wood screw and lag screw equations. The wood screw formula was established as $F_W = 98.1dG^2l$, and the lag screw formula was $F_L = 116d^{0.75}G^{1.5}l$, where F_W and F_L are the withdrawal capacities (N), G is the specific gravity, d is the fastener diameter (mm), and l is the STS length (mm). When the fastener is inserted in the fiber direction of the timber, an end grain factor of $C_{eg} = 0.75$ is applied. However, there were substantial discrepancies observed compared to experimental withdrawal capacities.

The EN prediction equations propose STS withdrawal capacities that are tailored to domestic species. $F_{EN} = \frac{nF_{ax}dlk}{1.2cos^2\alpha + sin^2\alpha}$, where F_{EN} is the withdrawal capacity (N), n is the number of screws, and F_{ax} is the withdrawal resistance of the wood fiber in the vertical direction. $F_{ax} = 0.52d^{-0.5}l^{-0.1}\rho^{0.8}$ (N/mm^2), where d is the diameter of the screw, l is the length of the thread (mm), ρ is the density of wood (kg/m^3), k is the fastener diameter coefficient, and α is the angle between the longitudinal direction of the screw and the wood fiber direction. Comparing experimental values to EN's prediction values, Japanese cedar exhibited the closest match, with discrepancies ranging from 6% to 11%. Conversely, Korean pine, which had a higher specific gravity, showed larger deviations, varying from 4% to 25%.

To address this, experimental equations for withdrawal resistance were used to calculate corresponding constants using MATLAB software (Mathworks, R2021b, Natick, MA, USA) based on the following basic equation: $F_{STS} = aG^bd^c$, where F_{STS} is the withdrawal resistance (N/mm), G is the specific gravity, d is the diameter of the STS (mm), and a, b, and c are constants. The constants a, b, and c were calculated as 24.14, 0.936, and 1.126, respectively. Consequently, the authors' experimental equation, $W_{STS} = 24.14G^{0.936}d^{1.126}$, calculated through multiple regression analysis based on experimental values, can predict the withdrawal capacity according to the specific gravity of domestic softwood species and the diameter of STS. The strength difference between the experimental value and the value predicted using the prediction cushion equation was similar at 0.8 to 1.15 times. This outcome, with a coefficient of determination (R^2) of 0.82, and a significantly smaller P-value compared to the significance level alpha value of 0.05, underscores the viability and accuracy of the authors' proposed withdrawal capacity prediction equations.

Table 3 lists the predicted withdrawal capacity calculated using the withdrawal capacity prediction equations of EN and NDS and the experimental equations calculated through multiple regression analysis.

The NDS-predicted withdrawal capacity differed from the experimental value up to 43%. This depends on discrepancy that can be attributed to variations in the resistance and shape of the thread. For lag screws and wood screws, the thread height is low, and the spacing is narrow; therefore, a small area is embedded in the wood. However, STS has a high thread height and wider spacing; therefore, the withdrawal resistance and shear strength of wood are applied to larger areas (Tepfers 1973; Hoelz *et al*. 2021). Compared to lag screws or wood screws, the STS screws possess a larger withdrawal capacity because the stress and shear strength are distributed over a larger area of wood. The experimental equations in this study uncovered results similar to the experimental withdrawal capacity of STS compared to the screw prediction equations of EN, which yielded differences ranging from 0.7 to 1.14 times the experimental value, but the experimental equations exhibited differences ranging from 0.8 to 1.15 times the experimental values. Therefore, it is imperative to develop withdrawal capacity predictive equations that account for the type, shape, and connecting mechanisms of the fastener. Based on the single timber withdrawal resistance prediction equations proposed in this study, it is possible to envision the formulating of CLT withdrawal capacity prediction equations in the future, thereby further enriching our understanding and practical applications in this domain.

Table 3. Withdrawal Capacity Prediction Value of Korean Softwood Using STS

Species	STS Diameter	Measured Withdrawal Capacity (kN)	NDS Prediction Equations (kN)		EN Prediction Equations (kN)	Experimental Equations of STS (kN)
		F	F_W (wood screws)	F_L (lag screws)	F_{EN}	F_{STS}
Japanese larch	8	6.06	9.81	9.75	6.90	6.78
	10	7.28	12.26	11.53	7.71	8.22
	12	8.37	14.72	13.22	8.45	9.65
Korean red pine	8	5.73	7.60	8.05	6.23	5.93
	10	7.83	9.50	9.52	6.96	7.37
	12	8.52	11.40	10.91	7.63	8.80
Korean pine	8	7.04	9.42	9.46	6.79	6.64
	10	10.12	11.78	11.19	7.59	8.07
	12	11.59	14.13	12.83	8.31	9.51
Japanese cedar	8	4.36	4.02	4.99	4.83	4.24
	10	5.81	5.02	5.90	5.40	5.68
	12	6.60	6.03	6.77	5.91	7.11

CONCLUSIONS

This study focused on four softwood species used as structural materials in South Korea, evaluated their withdrawal resistance performance for the STS joint design, and calculated withdrawal resistance prediction equations. The key findings were as follows:

1. Within the same species, the STS withdrawal resistance performance test demonstrated that for all species, the average maximum load tended to improve as the STS diameter increased. The coefficient of variation was calculated to be relatively low, at 2.18% to 8.52%, signifying a high degree of reliability in the obtained values.
2. The specific gravity exhibited a higher correlation with withdrawal resistance than the softwood species. Consequently, the authors established withdrawal resistance prediction equations that incorporated the specific gravity and fastener diameter.
3. A significant discrepancy was observed between the NDS lag screw and wood screw prediction equations and the actual STS withdrawal capacity. The EN screw prediction equations were relatively similar to the STS withdrawal capacity but exhibited a difference of up to 30%.

4. Based on these results, prediction equations were calculated by performing multiple regression analyses of the diameter and withdrawal capacity of the STS. Among all prediction equations, the experimental equations displayed the closest resemblance to the experimental values. The experimental equations exhibited a low alpha value and a coefficient of determination of 0.82, indicating their suitability for predicting withdrawal capacity.

In the future, it is expected that a clearer prediction equation will be produced if the results for juvenile wood and mature wood, sapwood, and heartwood are measured in detail. The results of this study lay the foundation for a fundamental database pertaining to domestic softwood species. This database is anticipated to play a pivotal role in the field, offering valuable insights for future research and practical applications.

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