Evaluation of the Tensile Strength of Korean Yellow Poplar Lumber

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This study was conducted to confirm the feasibility of using yellow poplar, which is a fast-growing hardwood species in Korea, as a structural material. Lumber was produced, and the mechanical grading and the knot diameter ratio on the wide surface measurement were performed for each grade of lumber. It was confirmed that the majority mechanical grades of yellow poplar were E10, E11, and E12, and the size of knot in the surface increased as the mechanical grades decreased. A fitted distribution of tensile strength of the lumbers was the Weibull distribution. As a result of calculating the tensile allowable stress using the 5th percentile value calculated by the Weibull distribution and the non-parametric method according to the mechanical grade, all the experimental values were higher than the minimum allowable stresses presented in the Korean industrial standards. However, for the low grades, there was no significant difference from the standard values. This was thought to be due to the large size of knots in low-grade lumber. It was expected that the prospect of using yellow poplar structural member will be higher if additional research is conducted on the restriction of knot size according to the mechanical grade.

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INTRODUCTION

Globally, there is growing interest in the carbon neutrality concept. As a result, wood, which is a carbon sink and is a low greenhouse gas emissions material, is attracting attention as a major building material in many countries. However, because wood is a heterogeneous material, its mechanical properties vary depending on several factors, such as species and growth environment. Therefore, it is necessary to calculate the design value according to the grade to use it as a structural material. The design value should be calculated and regulated according to the grade of sawn timber. The grade of sawn timber is an important indicator of strength and quality and is the most important factor that determines the safety of wooden buildings. The strength performance of sawn timber can be predicted through grading, which makes it possible to design and analyze structures. Therefore, it is essential to calculate the design value according to the grade of sawn timber to use wood construction materials safely and efficiently.

Wood, unlike concrete or steel, cannot be artificially modified in terms of its physical properties. Therefore, it is necessary to study and experiment to identify the factors that affect its strength. In addition to the grade of sawn timber, several studies have reported the influence of factors on strength, such as drying temperature, density, knots, and slope of grain (Gerhards 1983; Nagai *et al*. 2011; Saad and Lengyel 2023). Typical types of defects in wood that cause failure of structural lumber mainly include ring failure, checks, wane, knots, and grain angle. In particular, failure occurs frequently in knots (the most common defect in wood caused by the growth of branches). Therefore, information of the size and location of knots is important because they have a significant effect on the mechanical performance of wood.

The development of engineered wood products, such as cross-laminated timber (CLT), has led to an increase in demand for timber construction and the possibility of high-rise timber buildings (Abdoli *et al.* 2023). At the same time, the importance of quality control of sawn timber for layers of engineering wood products, which is directly related to the safety and performance of engineered wood, and the design values based on the grading system, is emphasized.

In North America, NELMA (Northeastern Lumber Manufacturers Association) and NDS (National Design Specification for Wood Construction) provide design values for the grades of dimensional lumber for several species. In addition, for the efficient use of resources, studies have been conducted on the existing grading system of sawn timber, new grading systems, and MSR (Machine Stress Rating) for hardwood. Faust *et al*. (1990) reported that MSR could be applied to hardwood.

Research on the use of hardwood as structural materials has not been conducted much compared to that of softwood, but it is being done in a variety of ways. Yue *et al.* (2023) recommended heat treatment at 180 ℃ to improve the properties of structural Chinese poplar. Kim *et al.* (2010) investigated the physical and mechanical properties of heat-treated yellow poplar, and Lim *et al*. (2010) confirmed the possibility of use through the bending strength of structural yellow poplar lumber. Mohamadzadeh and Hindman (2015) conducted tests to compare the strength of CLT made by yellow poplar layers to general CLT. Okai *et al*. (2004) and Aicher *et al*. (2018) conducted strength experiments on hardwood lumber of several species. In addition, the feasibility of microwave scanning for grading of hardwood species was confirmed (Weidenhiller *et al*. 2019).

Yellow poplar has several advantages that make it a potential wood material. Yellow poplar has a straight and upright trunk and has a relatively low density compared to other hardwoods. Moreover, it is a relatively fast-growing species, which can help to reduce the environmental impact of forestry. Ryu *et al*. (2014) revealed that yellow poplar is an economic forestry species with a relatively short cutting age of 38 years. Kim (2013) reported that yellow poplar has carbon storage capacity and absorption rate that are more than 10 times higher than those of pine. However, research on the use of yellow poplar as a structural material is still insufficient. Therefore, further research is needed to determine whether yellow poplar can be graded according to the current lumber grading regulations and whether they meet the design values for each grade.

The purpose of this study was to confirm the feasibility of using yellow poplar lumber as a structural material. To this end, MSR was used to grade yellow poplar lumber according to the KS (Korean Industrial Standards), and the design values were reviewed for the graded lumber.

To calculate the design values through experiments, the 5th percentile value was calculated by parametric and non-parametric methods using the values obtained through tensile load testing of full-size specimens. The design values obtained through experiments were compared with the allowable stress values presented in the KS standards.

EXPERIMENTAL

Materials

Yellow poplar (*Liriodendron tulipifera*) used in this study was sourced from Gangjin, Jeollanam-do, South Korea. Thirty-seven logs were sawn and kiln-dried into lumber for tensile testing at the Jungbu Lumber Business Center of the Korea Forestry Association, located in Yeoju-si, Gyeonggi-do (Fig. 1). Table 1 shows the diameters of the logs and the quantity of lumber produced accordingly. The final dimensions of the yellow poplar lumber used in the tensile test were 89 (width) × 38 (thickness) × 3600 (length) mm^3, and the total number of specimens was 503. The specimens were stored in a constant temperature and humidity chamber with a temperature of 20 °C and a relative humidity of 65% for one week, and the moisture content and air-dry specific gravity were measured after the test by taking slices of 20 × 20 × 30 mm^3 near the fracture site in the specimen after tensile testing. The average dry density and moisture content of yellow poplar used in this study were 0.45 ± 0.04 g/cm^3 and 12.1 ± 1.9%, respectively.

Fig. 1. Yellow poplar lumber

Table 1. Number of Lumber Pieces and Logs According to Log Diameter Used for Testing

Diameter of Log (mm)	Number of Log (EA)	Number of Lumber (EA)
200 ≤ diameter < 300	16	152
300 ≤ diameter < 400	14	201
400 ≤ diameter < 500	3	86
diameter ≥ 500	8	64
Total	41	503

Experimental Method of Tensile Test

Machine grade classification

To evaluate the possibility of machine grading and the mechanical performance of yellow poplar lumber according to machine grade, MSR (Machine Stress Rated) was first performed. The equipment used for MSR was MGFE-251 (JMW, Japan). The machine grading system in Korea ranges from E6 to E14, with E6 meaning a modulus of elasticity of between 6 and 7 GPa. After grading, the knot diameter ratio of yellow poplar lumber was measured. Defects, such as elimination of surface, scratch, hole, and peeling bark, were evaluated as knot. The knot diameter ratio was measured on the wide side of the lumber and calculated as the percentage of the knot diameter to the width of the wide side. The knot diameter was measured as the distance between the tangential lines drawn at each end of the knot, parallel to the longitudinal direction of the face of the lumber with the knot. Detailed methods for determining the knot diameter ratio can be found in ASTM D3737 (2018) and KS F3020 (2023).

Tensile test

To evaluate the tensile strength of yellow poplar, the load was applied with the equipment (Kyoungsung, Korea) shown in Fig. 2. The maximum capacity of the equipment was 1000 kN. The tensile load was applied by 550 mm length grip at both ends of the specimen with hydraulic apparatus. In the tensile test, the spacing excluding the part for gripped specimen was 2500 mm. The width and thickness were 89 and 38 mm, as noted earlier. The test was performed at a speed of 8 mm/min to ensure that failure occurred within 5 min. The tensile strength was calculated from the maximum load obtained in the tensile test and the cross-sectional area of the specimen (Eq. 1).

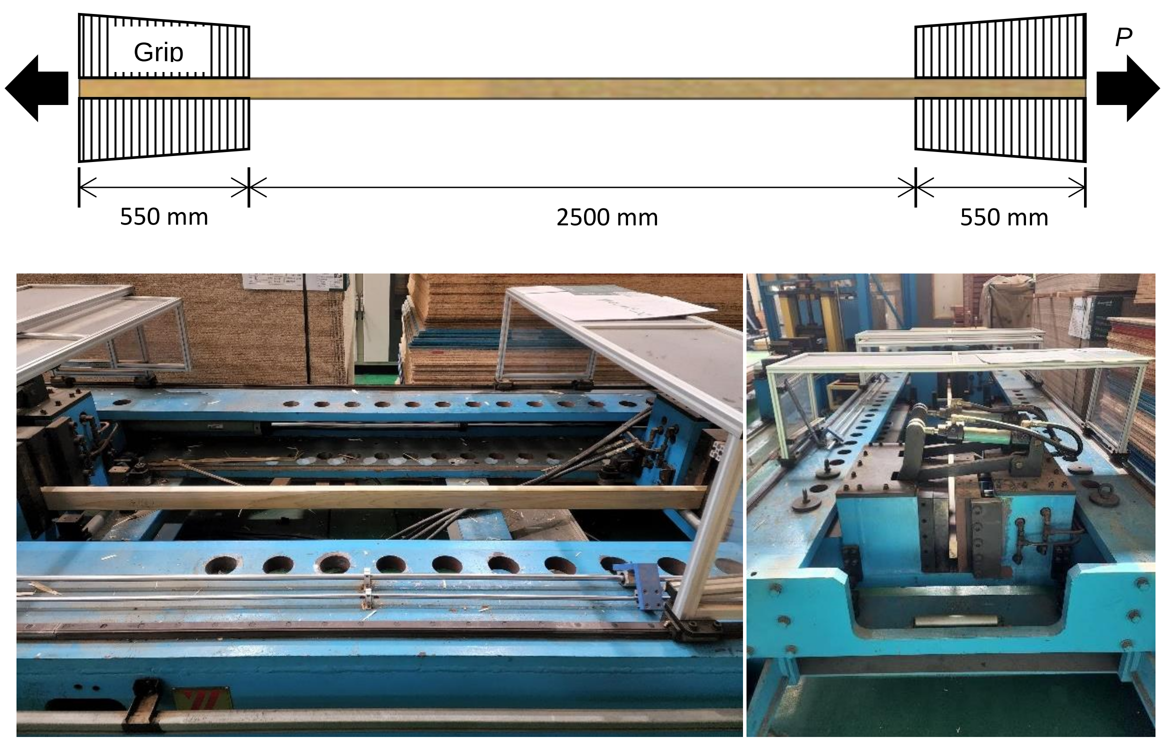


Fig. 2. Schematic diagram(upper) and photograph of tensile test

$$f_t = \frac{P_m}{b \times h} \tag{1}$$

where p_m is the maximum tensile load (N), b is thickness of lumber (mm), and h is depth of lumber (mm).

Calculation of 5th percentile value and allowable stress

Characteristic tensile strength was calculated according to the machine grading of yellow poplar. To calculate the characteristic values of the tensile strength, a 5th percentile value for the machine grading was first calculated. The 5th percentile value was calculated using parametric and non-parametric methods. For the parametric method, the normal, lognormal, and two-parameter Weibull distribution were used, as shown in Eqs. 2, 3, and 4. For the normal and lognormal distributions, a 5% lower bound was calculated by applying a *k*-factor based on the number of specimens, referring to ASTM D2915 (2010). For the non-parametric method, the order statistic based on the number of specimens was used to obtain a 5th percentile value at the 75% confidence level.

$$\text{Normal Distribution: } f\left(x \middle| m, v^2\right) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-(\ln x - m)^2 / 2v^2} \tag{2}$$

$$\text{Lognormal Distribution: } f\left(x \middle| m, v^2\right) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-(\ln x - m)^2 / 2v^2} \tag{3}$$

$$\text{Weibull Distribution: } f\left(x \middle| a, b\right) = \left(\frac{b}{a}\right)\left(\frac{x}{a}\right)^{b-1} e^{-(x/a)^b} \tag{4}$$

where e is Euler's constant, $\ln$ is natural log, μ is average of tensile strength (MPa), σ is standard deviation (MPa), $m = \ln\left(\mu^2 \big/ \sqrt{\sigma^2 + \mu^2}\right)$, $v = \sqrt{\ln\left(\sigma^2 / \mu^2 + 1\right)}$, a is scale parameter, and b is shape parameter. To evaluate the goodness of fit of each probability distribution, the Root Mean Squared Error (RMSE) was calculated as follows,

$$RMSE = \sqrt{\sum_{i=1}^{N} \left(n_{p,i} - n_{m,i}\right) / N} \tag{5}$$

where, N is classes number, $n_{p,i}$ is predicted frequency at the i^{th} class according to distribution, and $n_{m,i}$ is measured frequency at the i^{th} class by the tensile test. Tensile allowable stress was calculated by applying a reduction factor of 0.475, which considers the normal load duration and safety factor, to the 5th percentile value calculated by the optimal probability distribution. The tensile allowable stress was compared with the allowable properties calculated by the non-parametric method and the allowable properties according to the mechanical grades of softwood structural timbers in KS F3020 (2023).

RESULTS AND DISCUSSION

Grading and Knot Diameter Ratio Results

Figure 3 shows the machine grade classification results for yellow poplar lumber. The results of the machine grading showed that E10, E11, and E12 grades were the most common, and the number of specimens was the highest in the order of E11, E10, and E12. The proportion of E11, E10, and E12 grades in the total 503 specimens was 35.2%, 27.8%, and 17.7%, respectively. When compared with the results of the machine grading of lumber of Japanese larch, pine, and Korean red pine, which are mainly used species as structural members in Korea, the grade of yellow poplar lumber was similar to that of Japanese larch in this study. Kim *et al*. (2019) reported the results of machine grading of Japanese larch of 970 pieces and Korean red pine of 2050 pieces. For Japanese larch, the highest frequencies were found in the order of E10, E11, and E9 and for Korean red pine, it was reported that E8, E9, and E7 appeared in that order. Hong *et al*. (2015) reported that the machine grading results of pine of 418 pieces were E9, E10, and E8, with percentages of 22.7%, 18.1%, and 17.0%, respectively.

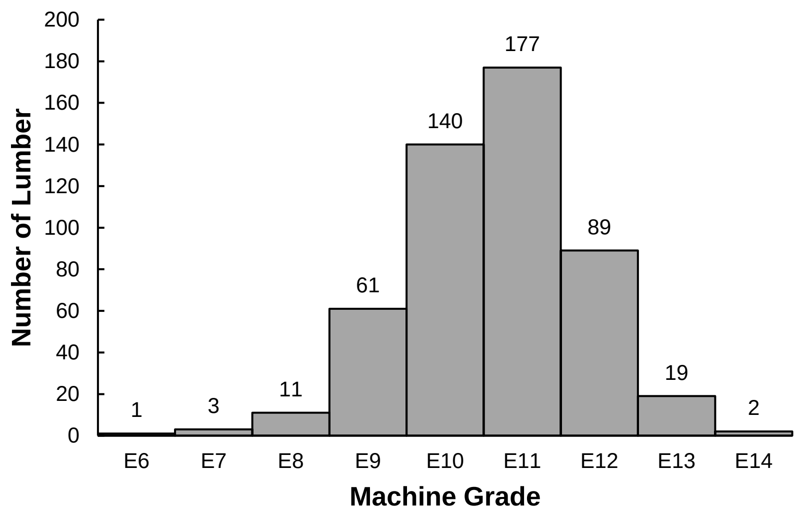


Fig. 3. Machine grade distribution of yellow poplar lumber for tensile test

After mechanical grading, the knot diameter ratio was measured and the results of the knot diameter ratio are shown in Table 2. In this study, the majority of the yellow poplar had a knot diameter ratio of 10 (8.9 mm) to 30 (26.7 mm). The percentage of lumber with that knot diameter ratio in the total number of lumbers was 38%. When comparing E10 and E11, which had similar numbers of logs per grade, higher machine grades tended to have a smaller knot. Gupta *et al.* (1996) reported a high correlation between knot class and the modulus of elasticity of the wide side of a narrow cross section.

Table 2. Number of Yellow Poplar Lumber by Knot Area Ratio

Grade	Knot Area Ratio (%)							
	< 10	10 to 20	20 to 30	30 to 40	40 to 50	50 to 60	60 over	Total
E6	-	-	-	-	-	-	1	1
E7	-	-	-	-	-	-	3	3
E8	-	2	-	1	1	-	7	11
E9	5	9	8	11	8	5	15	61
E10	15	23	20	18	23	10	31	140
E11	31	40	32	28	21	10	15	177
E12	7	26	21	15	9	5	6	89
E13	4	7	3	3	-	2	-	19
E14	-	2	-	-	-	-	-	2
Total	62	109	84	76	62	32	78	503

5th Percentile Value in Parametric Method

Figure 4 shows failure modes after tensile test. To obtain statistically significant results, only grades having a high number of repetitions were analyzed for yellow poplar tensile allowable properties. The grades used to analyze the results were E10, E11, and E12, and the number of specimens per grade was 140, 177, and 89, respectively (Table 2).

Fig. 4. Cause of tensile failure (left: knot, right: grain angle)

The 5th percentile value results of tensile strength for each distribution are presented in Table 3. Parameters to describe each distribution are also shown in Table 4. For grade E10, the 5th percentile value for the normal, lognormal, and Weibull distributions were 8.97, 13.95, and 12.70 MPa, respectively. For grade E11, the lower 5% limit of tensile strength for the same order of distribution were 17.38, 20.48, and 13.97 MPa, respectively, and for grade E12, the lower 5% limits of tensile strength were 24.98, 27.29, and 27.16 MPa, respectively. The 5th percentile value for yellow poplar lumber increased with increasing machine grade. The 5th percentile value calculated from the normal distribution was the lowest for all grades, while the 5th percentile value calculated from the lognormal distribution was the highest.

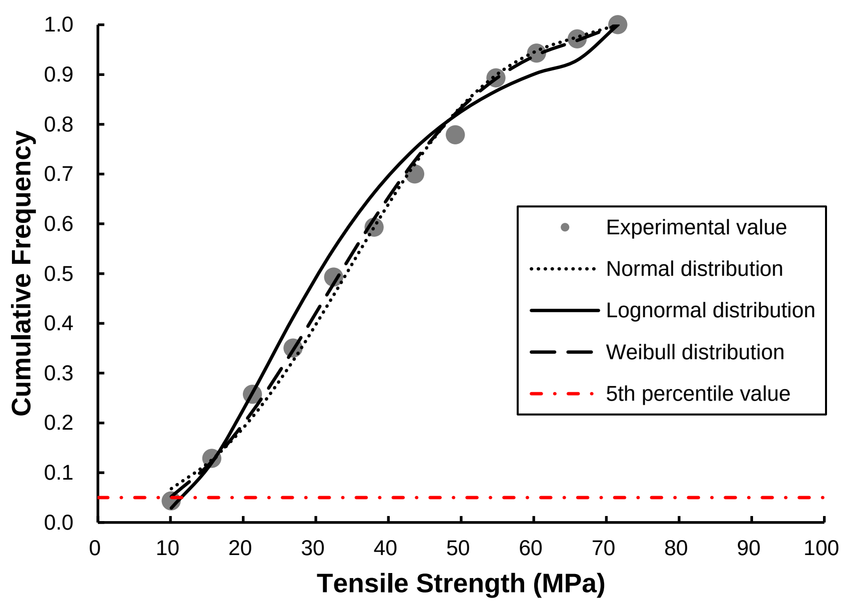
Table 3. 5th Percentile Value and RMSE for Tensile Strength in Various Distribution (Unit: MPa)

MSR Grade	5th Percentile Value			RMSE		
	Normal	Lognormal	Weibull	Normal	Lognormal	Weibull
E10	8.97	13.95	12.70	3.53	4.19	2.96
E11	17.38	20.48	19.61	4.70	6.55	4.45
E12	24.98	27.29	27.16	2.53	3.82	2.41

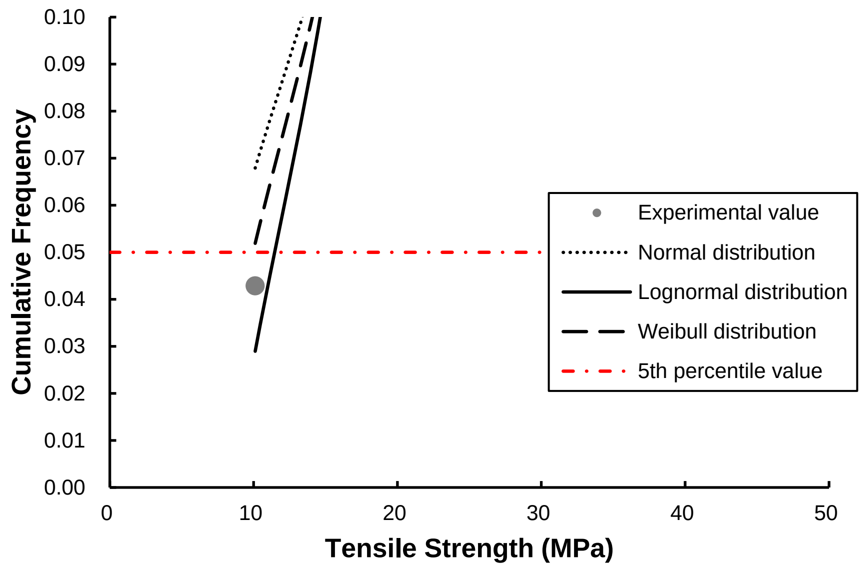
Table 4. Parameter for Each Distribution

MSR Grade	Normal Distribution		Lognormal Distribution		Weibull Distribution	
	Aver.	SD	Aver.	SD	Shape	Scale
E10	37.00	16.16	3.50	0.50	2.49	41.81
E11	45.01	15.99	3.73	0.41	3.15	50.37
E12	51.85	15.22	3.90	0.34	3.97	57.36

The RMSE for each distribution is shown in Table 3, and the results for cumulative relative frequencies of tensile strength, normal, lognormal, and Weibull distributions are shown in Figs. 5, 6, and 7. As shown in Figs. 5(b), 6(b), and 7(b), the 5th percentile value calculated by the probability distribution function was smaller for the normal, Weibull, and lognormal distributions, in that order. Comparing the RMSE between the actual strength and predicted strength by each distribution, the lowest RMSE was found in the Weibull distribution. Therefore, based on the RMSE results for tensile strength, the Weibull distribution was found suitable for calculating the 5th percentile value of tensile strength of yellow poplar lumber by the parametric method. Fok *et al*. (2001) reported that the Weibull theory is commonly used in fracture analysis of brittle materials, such as ceramics, and Moses and Prion (2004) stated that Weibull theory is now commonly used for wood predicted strength distributions.



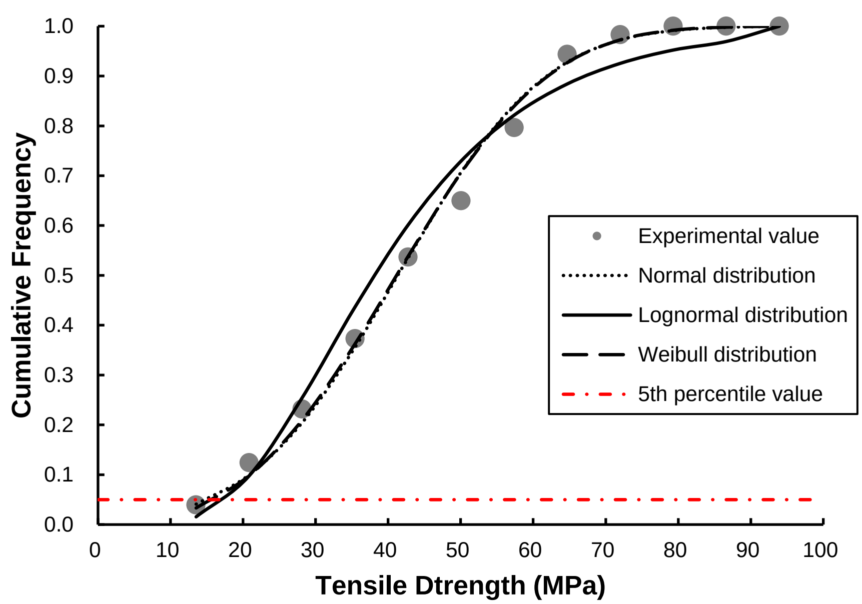
(a) Cumulative Distribution from 0 to 1



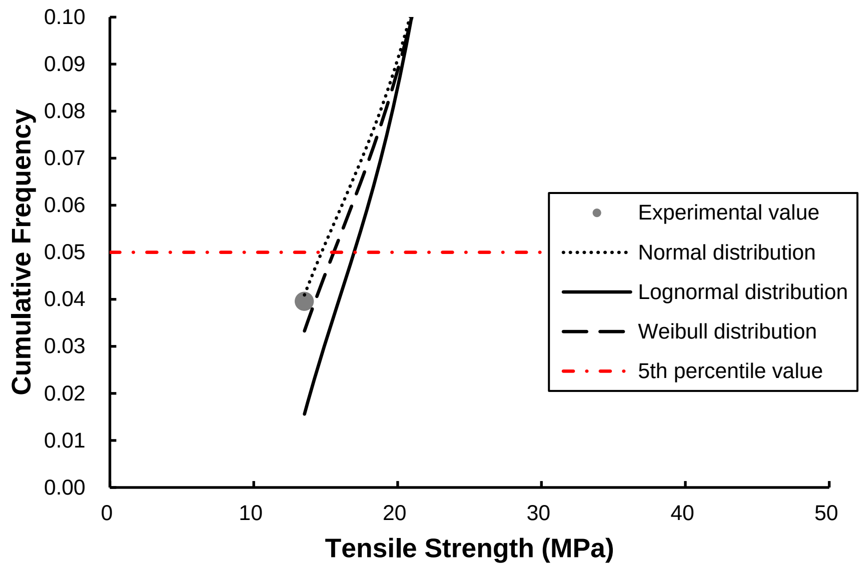
(b) Cumulative Distribution from 0 to 0.1

Fig. 5. Cumulative distribution of experimental value with three kinds of probability distributions in E10

Weibull's weakest link theory assumes that when brittle materials are used, the probability of a defect in a large specimen increases, making it more likely to fail at lower stresses. Vallée *et al*. (2017) also reported that the non-local implementation of Weibull's theory in capacity prediction is considered the most accurate from a mechanical point of view. In this study, the Weibull distribution was considered appropriate because brittle failure was confirmed in the tensile performance test.

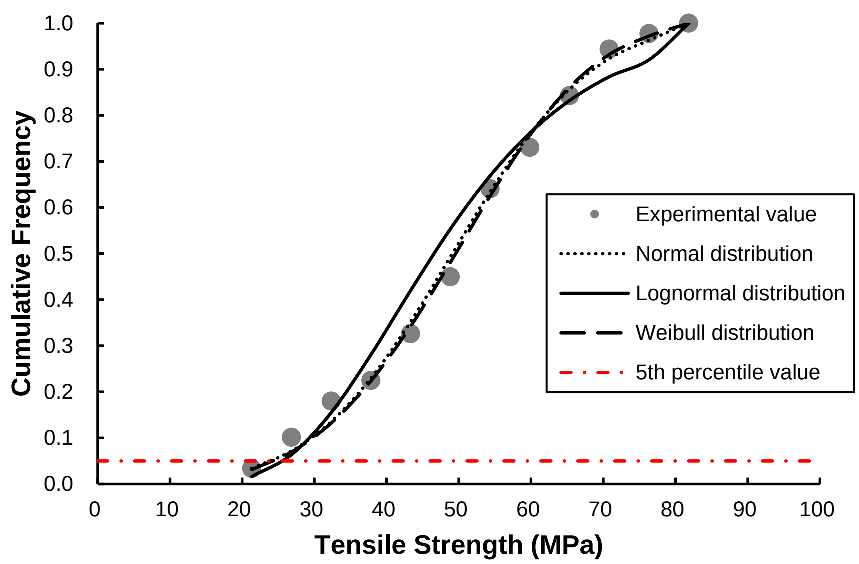


(a) Cumulative Distribution from 0 to 1

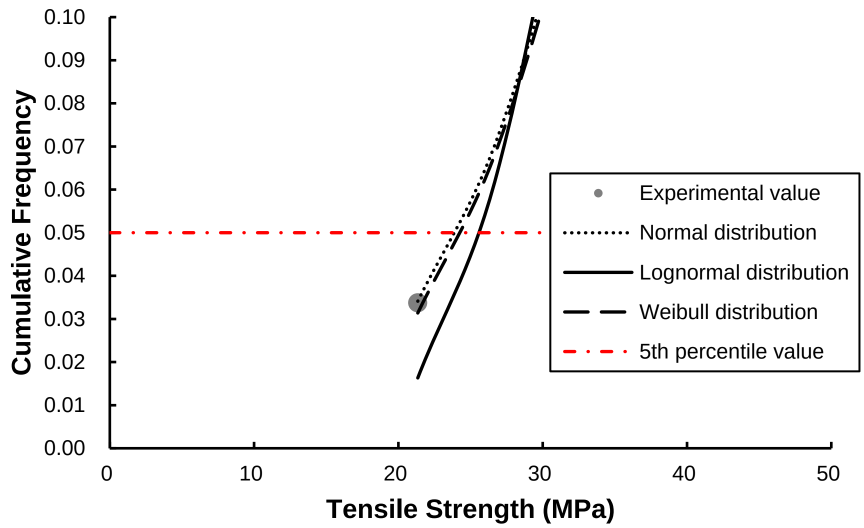


(b) Cumulative Distribution from 0 to 0.1

Fig. 6. Cumulative distributions of experimental values with three kinds of probability distributions in E11



(a) Cumulative Distribution from 0 to 1



(b) Cumulative Distribution from 0 to 0.1

Fig. 7. Cumulative distributions of experimental values with three kinds of probability distributions in E12

5th Percentile Value in Non-Parametric Method and Tensile Allowable Stress

For the non-parametric method, the tensile strengths were sorted in ascending order, and the 5th percentile value was chosen using an order statistic with 75% confidence based on the number of specimens in each class. The order statistics for the tensile strengths of machine classes E10, E11, and E12 were 3rd, 4th, and 1st, respectively. The results of calculating the allowable stresses for tensile strength of yellow poplar lumber are presented in Table 5. As mentioned in the method, the allowable stresses for tensile strengths were calculated by multiplying the 5th percentile value calculated using the Weibull distribution and the non-parametric method by 0.475. The respective allowable stresses calculated by the parametric and non-parametric methods were compared with the Korean Industrial Standard KS F 3020 (2023). As a result of the comparison, the tensile allowable stresses calculated by the non-parametric and parametric methods were higher than the literature values for all grades used to derive the results.

Table 5. Allowable Tensile Strengths of Yellow Poplar Lumber (Unit: MPa)

MSR Grade	5th Percentile Value		Allowable Strength		KS F 3020 (2023)
	Weibull	Non*	Weibull	Non	
E10	12.70	12.77	6.03	6.07	6.00
E11	19.61	17.12	9.31	8.13	7.40
E12	27.16	23.71	12.90	11.26	8.20

* Non-parametric method

When comparing the lower of the tensile allowable stresses calculated by the non-parametric and parametric methods with the literature values (KS F3020 (2023)), the errors observed with the literature values were 0.03, 0.73, and 3.06 MPa for classes E10, E11, and E12. It was confirmed that as the grade increases, the tensile allowable stress calculated by the experiment was larger than the literature value. It was presumed that this is related to the knot diameter ratio presented in Table 2. In this study, the higher grades of yellow poplar lumber had a smaller knot diameter ratio, and because of that, the difference between allowable tensile strength and the literature value in E10 was 0 MPa. There were some studies that the size of knot had a negative effect on the strength of lumber (Johnson and Kunesh 1975; Lam *et al*. 2005). In addition, Pang *et al.* (2021) reported that the size of knot is more important than the modulus of elasticity (MOE) as a strength attenuation factor when using lumber as a CLT layer. For this reason, the difference between the experimental and literature values increased as the grade increased.

In this study, the experimental tensile allowable stresses were higher than the literature values for all mechanical grades analyzed. This indicates that yellow poplar lumber can be classified by mechanical grade certified for softwood and that the design values presented in the standard can be used. However, the difference between the experimental and literature values was smaller as mechanical grades were lower. It was thought that this was because the knot area ratio is large in low grades. If additional research is conducted on limitation of the knot area ratio, it is considered that yellow poplar lumber for structural purpose can be used safely.

CONCLUSIONS

The tensile test was conducted using full-size lumber to assess the feasibility of using yellow poplar, which has a fast growth rate, as a structural material. Allowable tensile strengths were obtained according to mechanical grades of yellow poplar lumber.

1. The results of the mechanical grade classification of Korean yellow poplar showed that a large number of grades, such as E10, E11, and E12, were found, which are similar to those of Japanese larch.
2. The distribution characteristics of tensile strength of yellow poplar lumber were a two-parameter Weibull distribution.
3. The allowable tensile stress of yellow poplar sorted by mechanical grading was more than 20% higher than the literature value in the KS F standard in E12.
4. In lower grades, the allowable tensile stress was not significantly different from the literature value. It was considered to be because the size of knots in the surface of lower grade yellow poplar was large, resulting in a large decrease in strength.
5. It is expected that yellow poplar can be used as a structural material if further research is conducted on the limitation of knot area ratio in mechanical grade classification.

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