# Allowable Bending Properties of Machine-Graded Korean Yellow Poplar Lumber

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This study was conducted to investigate the feasibility of using yellow poplar as a structural member by determining allowable bending properties. Full-size lumber was classified by machine grading and the knot diameter ratio on the wide surface of lumber. The majority of machine grades of yellow poplar lumber with a cross-section of 38 × 89 mm$^2$ were E8, E9, and E10. It was confirmed that the size of the knot diameter ratio tended to be smaller for higher machine grades. In the lowest grade, E8, of most machine grades, the allowable bending strength was lower than the corresponding design value in Korean standards. Application of 0.5 knot diameter ratio to the E8 grade lumber increased the bending strength to 3 MPa of the allowable value to suit the design value. All the allowable modulus of elasticities values of the majority of machine grades were higher than the design values. From the results of this study, it was expected that Korean yellow poplar could be utilized for structural bending members.

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## INTRODUCTION

Global interest in wood, the only natural carbon storage and eco-friendly building material, is increasing with the 2050 carbon neutrality strategy. Wood, however, is a natural heterogeneous material, and its design values must be calculated and specified according to the quality or grade of wood to ensure reliability and safety for use as a building material. The grade of lumber is one of the basic and important indicators of the mechanical properties of wood (Nocetti *et al*. 2024). The lumber can be graded by visual or machine methods (Shim *et al*. 2006; Wang *et al*. 2008). The visual grading is performed by qualified individuals through measuring knots, splits, bow, and so on at all four sides of a piece of lumber. Machine grading uses an apparatus, such as machine stress rating (MSR), to evaluate one or more specific characteristics related to the strength and stiffness of lumber (Moltini *et al*. 2022). Visual grading is economical and easy to use but requires a large amount of numerical data to reflect the strength or stiffness of the material accurately. The modulus of elasticity (MOE), which is used for machine grading is one of the best indicators to predict the strength of timber, so it can be done safely and efficiently. Uzcategui *et al*. (2023) reported that the use of MSR in sawmills helps maintain or improve wood quality during utilization.

The physical and mechanical properties of timber vary due to numerous environmental factors, so it is necessary to investigate the results of these factors. Therefore, the performance of timber must be evaluated and supplemented through continuous research and experiment, and factors affecting characteristic values, such as density and defects, *etc*., have to be qualified. Density varies depending on the species of the tree and is directly proportional to the mechanical properties of timber (Sun *et al*. 2020). Defects in timber include knots, variations in grain angle, splitting, and cracking, and these defects can reduce the strength of timber. The knot is one of the most representative defects and has various effects on the mechanical properties of timber according to the sizes and locations. Therefore, it is necessary to investigate the relationship between mechanical properties and the information of knots at the sides of lumber through research (Koman *et al*. 2013; Uzcategui *et al*. 2023)

Research for using hardwood as structural materials is still insufficient. One of the first studies could be classifying lumber grades and calculating the design values according to the grading of lumber. Research on emerging grading methods has been investigated for improvement of the efficient use of lumber (Kline *et al*. 2003; Thomas 2017). Weidenhiller *et al*. (2019) confirmed the feasibility of using microwaves as a method to evaluate the strength and density of hardwood as well as softwood. Green (1997) applied MSR to grading hardwood, and Faust *et al*. (1990) reported that it is necessary to compare and investigate the relationship between strength and stiffness when applying MSR to hardwood.

In this study, yellow poplar was chosen to be used as a substitute for structural softwood. Yellow poplar is a broadleaved tree and a commercial species in Korea. Ryu *et al*. (2014) concluded that yellow poplar is an economic afforestation species because it has a relatively short forest harvesting time (approximately 38 years) compared to other commercial species with a final cutting age of more than 50 years. In addition, it was revealed that the yellow poplar has higher carbon storage and sequestration ability than major coniferous species in Korea such as Japanese larch and pine (Kim *et al*. 2010; Kim 2013). Meanwhile, research to use yellow poplar for structural purposes was also conducted. Mohamadzadeh and Hindman (2015) confirmed the mechanical performance of cross laminated timber (CLT) from yellow poplar and compared it with that of softwood CLT to determine whether the yellow poplar could be used as structural material. Hovanec (2015) conducted a study on the adhesion performance of yellow poplar to use as CLT layer material. Mettanurak *et al*. (2010) reported that it is possible to produce yellow poplar as structural materials if periods of extreme growth suppression are avoided. Kim *et al*. (2010) used heat treatment to overcome the disadvantage of wood color differences between heartwood and sapwood and found the optimal heat treatment condition for yellow poplar. Additionally, the physical and mechanical properties of heat-treated yellow poplar wood were evaluated. Lim *et al*. (2010) used softwood visual grading standards to classify yellow poplar lumber and confirmed the possibility of using yellow poplar lumber as a structural material. Kim *et al*. (2024) confirmed the feasibility of the application of MSR for yellow poplar lumber grading and calculated design value according to grading through full-size tensile tests.

In this study, a full-size bending test was conducted on machine grading yellow poplar using MSR. Bending characteristic values for machine graded yellow poplar lumber were calculated and compared with allowable values in the literature. A modulus of rupture (MOR) related to the characteristic value was determined using both parametric and non-parametric methods. In addition, the change in bending characteristic values was investigated according to the size of defects in the flatwise sides of yellow poplar lumber, and efficient and reliable calculation of design values for yellow poplar was attempted.

## EXPERIMENTAL

### Materials

The 42 logs of yellow poplar (*Liriodendron tulipifera*) used in this study were collected from Gangjin, Jeollanam-do, South Korea. Lumber was produced with kiln drying for bending tests (Fig. 1), and the manufactural location of lumber was the Jungbu Lumber Business Center of the Korea Forestry Association, located in Yeoju-si, Gyeonggi-do.

**Fig. 1.** Yellow poplar lumber

Table 1 shows information about the number of logs and lumbers according to a range of the log's diameter at breast height (DBH). The size of the yellow poplar lumber used in the full-size bending test was 89 (width) × 38 (thickness) × 2100 (length) $mm^3$. The total number of bending test specimens was 541. Before the bending test, the specimens were kept in a conditioned room at a temperature of 20 °C and a relative humidity of 65% for one week. Twenty-seven test specimens that had excessive cracks and warp were excluded after conditioning.

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

| Diameter of Log (mm) | Bending Test | | Tensile Test* | |
|---|---|---|---|---|
| | Number of Log (EA) | Number of Lumber (EA) | Number of Log (EA) | Number of Lumber (EA) |
| 200 ≤ Diameter < 300 | 1 | 4 | 16 | 152 |
| 300 ≤ Diameter < 400 | 21 | 176 | 14 | 201 |
| 400 ≤ Diameter < 500 | 11 | 163 | 3 | 86 |
| Diameter ≥ 500 | 9 | 198 | 8 | 64 |
| Total | 42 | 541 | 41 | 503 |

* Results in Kim *et al*. (2024)

The average air-dry density and moisture content of the lumber were 0.49 ± 0.05 g/cm$^3$ and 11.5 ± 2.3%, respectively. The values were obtained by measuring small specimens with a size of 20 × 20 × 30 mm$^3$, which were collected near the fracture location that occurred after the bending test, using the oven-dry method.

## Experimental Method of Bending Test

### *Machine grade classification*

To evaluate the bending characteristic values of yellow poplar lumber, machine grading was performed. The equipment used to classify the machine grading of lumber was MGFE-251 (JWM, Japan). The machine grading classification for lumber was done following KS F 3020 (2023). In the KS F 3020 (2023), the grading classifications are from E6 to E14, with E6 meaning an MOE of 6 GPa or more and less than 7 GPa. Defects such as knots, grain angle, and wane on the wide surface of lumber, were checked after conducting the machine grading. For the knot, the knot diameter ratio was measured according to ASTM D3737 (2018) and KS F 3020 (2023).

### *Bending test*

Figure 2 shows the third-point bending test, which was used in this study to evaluate the bending performance of yellow poplar lumber. The load was applied on an edge-wise lumber at a loading rate of 10 mm/min so that the maximum load was reached within 10 min using the Universal Testing Machine (MTS, USA) with a maximum capacity of 300 kN. The distance of the span of lumber was 1869 mm, which was 21 times the depth of 89 mm. The distance between the two load points was 623 mm, which was one-third of the span of lumber. During the bending test, the amount of deflection of the neutral axis of lumber was measured using a linear variable displacement transducer (LVDT) on a yoke. The MOR and MOE as bending properties were calculated, using Eqs. 1 and 2 as shown below.

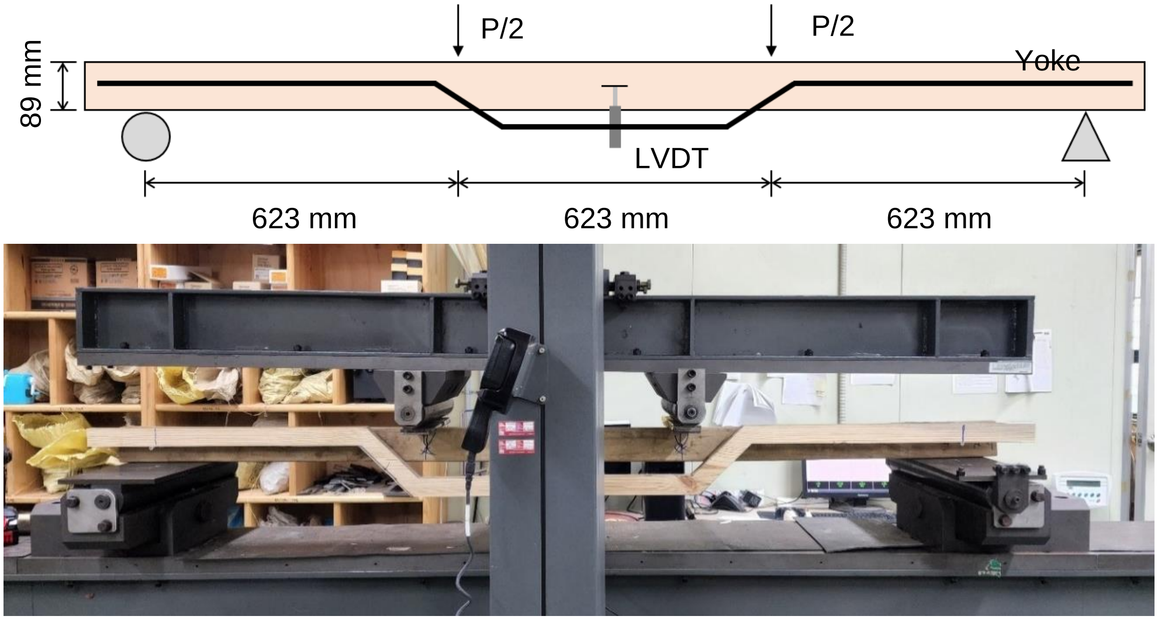


**Fig. 2.** Schematic diagram (upper) and photograph of bending test (bottom)

$$MOR = \frac{P_{\max} l}{bd^2} \tag{1}$$

$$MOE = \frac{23Pl^3}{108bd^3\Delta} \tag{2}$$

where $P_{\max}$ is the maximum load to failure (N), $l$ is span of lumber (mm), $b$ is width of lumber (mm), $d$ is depth of lumber (mm), $P$ is increment of load below proportional limit (N), and $\Delta$ is increment of deflection of lumber's neutral axis measured at midspan over distance $l$ and corresponding load $P$ (mm).

*Calculation of bending characteristic value*

The bending characteristic values of yellow poplar lumber were calculated according to the machine grades. The characteristic value for MOR was evaluated using a 5th percentile value and allowable stress, while that for MOE was assessed by average value. For the 5th percentile value, parametric and non-parametric methods were used. Kim *et al*. (2024) reported that the most suitable distribution for the parametric method was the 2-parameter Weibull distribution in tension test. Therefore, in this study, the Weibull distribution was also used as a parametric method as shown in Eq. 3,

$$f\left(x \middle| a,b\right) = \left(\frac{b}{a}\right)\left(\frac{x}{a}\right)^{b-1} e^{-\left(x/a\right)^b} \tag{3}$$

where $e$ is Euler's constant, $a$ is scale parameter, and $b$ is shape parameter. The Root Mean Squared Error (RMSE) was also calculated as follows,

$$RMSE = \sqrt{\sum_{i=1}^{N}\left(n_{p,i} - n_{m,i}\right)^2 / N} \tag{4}$$

where $N$ is classes number, $n_{p,i}$ is predicted frequency at the $i^{\text{th}}$ class according to distribution, and $n_{m,i}$ is measured frequency at the $i^{\text{th}}$ class by the bending test. In the case of the non-parametric method, the order statistic according to the number of test specimens was applied to obtain the 5th percentile value at the 75% confidence level. At last, a reduction factor of 0.475 regarding the normal load period and safety factor was applied to the calculated 5th percentile value for determining the allowable stress for MOR.

## RESULTS AND DISCUSSION

### Grading Results

Figure 3 shows the results of machine grading for yellow poplar lumber. The majority of the grades of yellow poplar lumber for bending tests were E8, E9, and E10. E9, E8, and E10 had the high proportions of yellow poplar in the order, with 30.2, 21.4, and 18.7%, respectively. It was confirmed that the yellow poplar lumber used in this study had a similar distribution of machine grades of pine in Korea when the other machine grading results of other species were compared. Hong *et al*. (2015) classified 365 pieces of pine lumber were into machine grades, and the highest percentages were found in the following order: E9 (22.7%), E10 (18.1%), and E8 (17.0%). Kim *et al*. (2019) also reported that as a result of categorizing Korean red pine into machine grades, E8, E9, and E7 accounted for the highest proportion in that order. Kim *et al*. (2007) reported that E7 (23.7%), E8 (18.9%), and E9 (17.5%) appeared in that order when studying pitch pine.

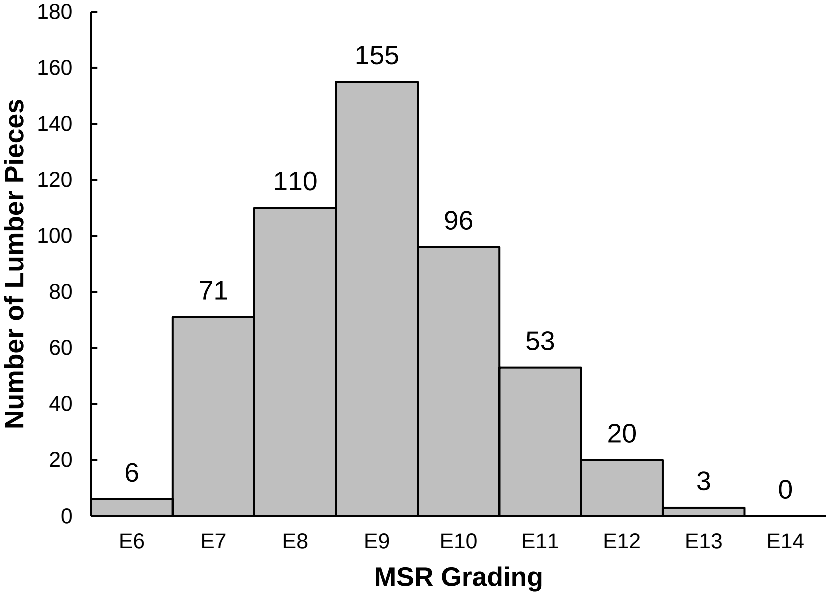


**Fig. 3.** MSR grade distribution of yellow poplar lumber for bending test

Kim *et al*. (2024) reported that the major proportion of machine grades for yellow poplar lumber were E10, E11, and E12. Compared with the result in this study, the proportion of machine grades was different even though the lumbers in both studies were collected from the same harvested area. It was considered that the difference between the two studies occurred due to the diameter of the logs used to produce lumber, as listed in Table 1. The largest number of lumber pieces in this study was produced from logs with a diameter of 500 mm or more, while the largest number of lumber pieces in Kim *et al*. (2024) was produced from logs with a diameter of more than 300 mm and less than 400 mm (Table 1). Øvrum *et al*. (2009) reported that the proportion of lumber with high machine grade increased as the diameter of logs decreased for Norway spruce. This was because the trees with small diameters tended to have high densities due to small knots and the narrow width of the annual ring. In contrast, Gronlund and Broman (1995) reported that the relationship between visual log classifying and machine grades of lumber produced from the Scots pine log was not sufficient. It was considered that additional research on the correlation between log classifying, such as diameter and lumber grading, is needed to conduct the establishment of production planning of yellow poplar lumber.

Table 2 contains the results of measuring the knot diameter ratio of flatwise after conducting the machine grading of yellow poplar. Yellow poplar with a knot diameter ratio of 10% to 30% accounted for the highest proportion. The total number of lumber pieces with the knot diameter ratio was 219 (42.8%). The corresponding knot diameter ranged from 8.9 mm to 26.7 mm. When comparing E8 and E10, the knot diameter ratio tended to be smaller for higher machine grades. There were the equivalent results that knot size and MOE of lumber have a negative correlation with a high coefficient of determination (Ethington *et al*. 1996; Hittawe *et al*. 2017)

**Table 2.** Knot Diameter Ratio of Yellow Poplar According to MSR (Unit: EA)

| Grade | Knot Diameter Ratio (%) | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|
| | < 10 | 10 to 20 | 20 to 30 | 30 to 40 | 40 to 50 | 50 to 60 | > 60 | |
| E6 | 1 | 0 | 0 | 1 | 1 | 1 | 2 | 6 |
| E7 | 9 | 10 | 14 | 6 | 12 | 5 | 15 | 71 |
| E8 | 3 | 8 | 26 | 17 | 21 | 11 | 24 | 110 |
| E9 | 13 | 26 | 36 | 29 | 15 | 13 | 23 | 155 |
| E10 | 11 | 28 | 21 | 13 | 11 | 8 | 4 | 96 |
| E11 | 4 | 13 | 21 | 9 | 4 | 2 | 0 | 53 |
| E12 | 3 | 10 | 5 | 0 | 1 | 0 | 1 | 20 |
| E13 | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 3 |

## Characteristic Value for Bending

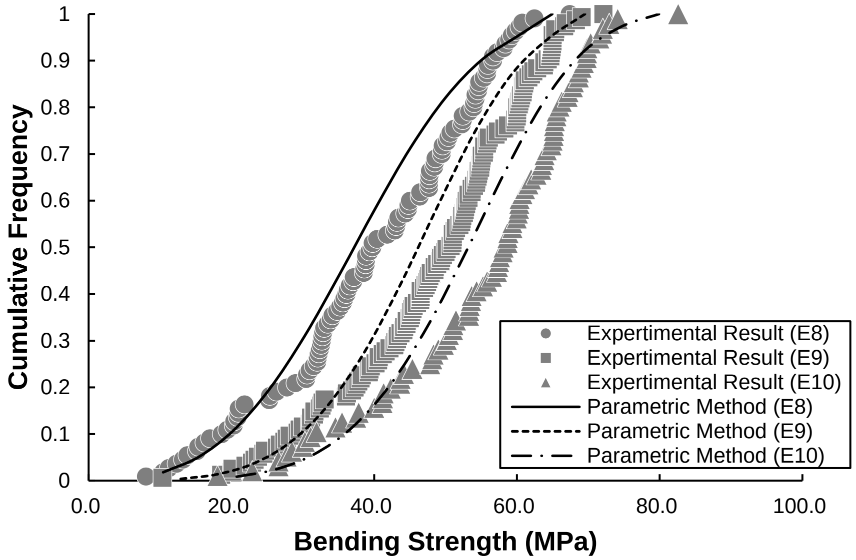
Figure 4 shows the failure modes after a bending test of yellow poplar lumber. The most frequent failure modes were observed as a round knot, grain angle, and tension in that order. Additionally, it was confirmed that failures occurred on the side in tension, which was the opposite of the loading point, rather than the side in compression. Brittle failure was mainly governed by bending tests of yellow poplar lumber. Therefore, it was considered that the allowable bending strength could be calculated by using the Weibull distribution for the parametric method, as in the previous study of the tensile properties of yellow poplar lumber Kim *et al*. (2024). This is because Weibull's weakest link theory assumes that the probability of defects in a larger body increases and the likelihood of brittle failure at low stress is higher (Moses and Prion 2004).

**Fig. 4.** Failure modes in bending test (from left: knot, grain angle, and tension)

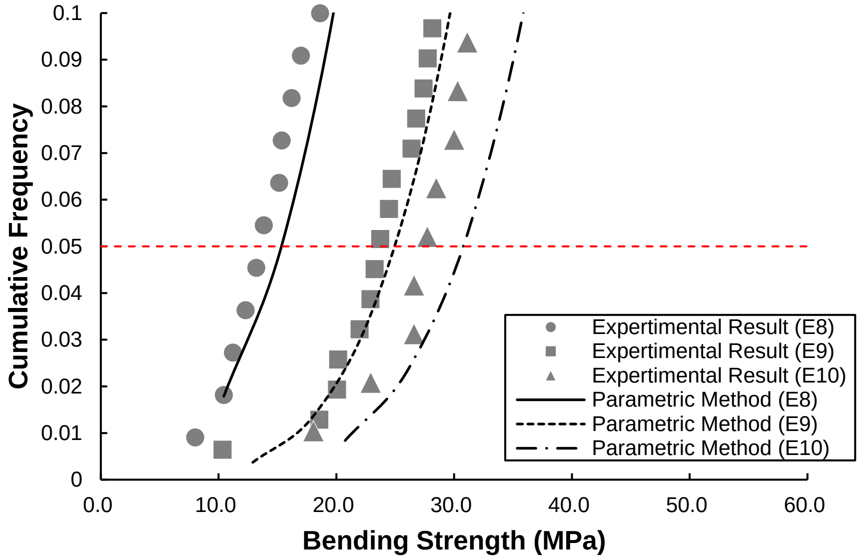
The bending characteristic values of yellow poplar lumber were analyzed for machine grades with test specimens of 95 and over to derive statistically significant results. In this study, E8, E9, and E10 were fitted with this condition. Table 3 presents the 5th percentile value of MOR derived by parametric and non-parametric methods. As mentioned before, Weibull distribution was applied for the parametric method. The 5th percentile value calculated using the non-parametric method was lower than that of the parametric method. The 5th percentile value obtained using the non-parametric method for E8, E9, and E10 were 12.3, 22.9, and 26.6 MPa, respectively. The ratio of the 5th percentile values of E8, E9, and E10 by non-parametric to parametric method were 0.61, 0.83, and 0.80. Ravenshorst (2015) also reported a consistent result in which the 5th percentile value calculated using the non-parametric method was lower than that calculated using the parametric method.

**Table 3.** 5th Percentile Value for MOR in Parametric and Non-Parametric Method

| Grade | Parametric Method (MPa) | | | | Non-Parametric Method (MPa) |
|---|---|---|---|---|---|
| | Parameter | | 5th Percentile Value (MPa) | RMSE (MPa) | |
| | Shape | Scale | | | |
| E8 | 3.25 | 44.42 | 17.8 | 8.88 | 12.3 |
| E9 | 4.56 | 52.85 | 27.5 | 14.89 | 22.9 |
| E10 | 5.08 | 60.05 | 33.4 | 9.19 | 26.6 |



**(a)** Cumulative distribution from 0 to 1



**(b)** Cumulative distribution from 0 to 0.1

**Fig. 5.** Cumulative distribution of experimental value and Weibull distributions according to E8, E9, and E10

Table 4 presents the results of the allowable properties for bending yellow poplar lumber. As shown in the Experimental section, the allowable bending strength was determined by multiplying the 5th percentile values, which were calculated using the parametric and non-parametric methods, by 0.475. For the non-parametric method, the order statistics for the 5th percentile values of MOR for machine grades of E8, E9, and E10 were 4th, 6th, and 3rd, respectively. The allowable MORs from the full-size bending test of yellow poplar in E8, E9, and E10 were 5.8, 10.9, and 12.6 MPa, respectively. The allowable MOR of E8 was lower than the value in the literature when the allowable MORs for each machine grade were compared with KS F 3020 (2023). This was because of the reduction of bending strength due to a knot being larger as the machine grade was lower. As shown in Table 2, it was confirmed that the knot diameter ratio, which significantly affects the reduction of mechanical properties of timber, increased as the machine grades decreased. The percentage of knot diameter ratios greater than 30% for all specimens was 66.4%, 51.6%, and 36.5% in E8, E9, and E10, respectively. There were reports that the knot size has a negative effect on the strength reduction of timber (Johnson and Kunesh 1975; Lam *et al*. 2005; Hittawe *et al*. 2015). Pang *et al*. (2021) also reported that the strength reduction ratio of CLT by the knot ratio of lumber was significant compared to that of the MOE of the lumber. The size of the knots was larger than the MOE as a reduction factor of CLT strength. The average MOE of yellow poplar lumber was 8.6, 9.4, and 10.1 GPa for E8, E9, and E10, respectively. It was confirmed that all machine grades showed higher values than the allowable properties of MOE when compared with the allowable properties in KS F3020 (2023).

**Table 4.** Allowable Properties of Yellow Poplar Lumber

| Grade | MOR (MPa) | | MOE (GPa) | KS F 3020 (2023) | |
|---|---|---|---|---|---|
| | Parametric | Non* | | MOR (MPa) | MOE (GPa) |
| E8 | 8.5 | 5.8 | 8.6<br>(0.12)** | 8.2 | 8.0 |
| E9 | 13.1 | 10.9 | 9.4<br>(0.09) | 9.0 | 9.0 |
| E10 | 15.9 | 12.6 | 10.1<br>(0.09) | 10.0 | 10.0 |

* Non-parametric method, ** Coefficient of variation

## Change of Properties According to Knot Diameter Ratio

It was confirmed that the allowable MOR of the lowest grade (E8) among the investigated grades was lower than the allowable properties in the KS F 3020 (2023). Based on the results, it was concluded that the machine grading was not enough to grade yellow poplar lumber for structural members. Hong *et al*. (2015) reported that reasonable grading might be possible if limiting criteria for major strength reduction defects, such as knots and grain angle, were considered additionally to the machine grading. Therefore, the knot diameter ratio in the wide surface of lumber was reflected.

Figure 6 shows the change in the number and the percentage of lumbers to the knot diameter ratio. The numbers of E8 grade lumber with knot diameter ratio less than 75%, 50%, and 25% were 99, 75, and 29, respectively. In the higher grade, the elimination percentage according to the knot diameter ratio criteria was lower. Percentages of E8 grade lumber were 90%, 68%, and 26% if the knot diameter ratio limitation was 75%, 50%, and 25 %, respectively. For E9 grade lumber, the percentages were 92%, 77%, and 42%, and for E10 grade, they were 100%, 90%, and 54%.

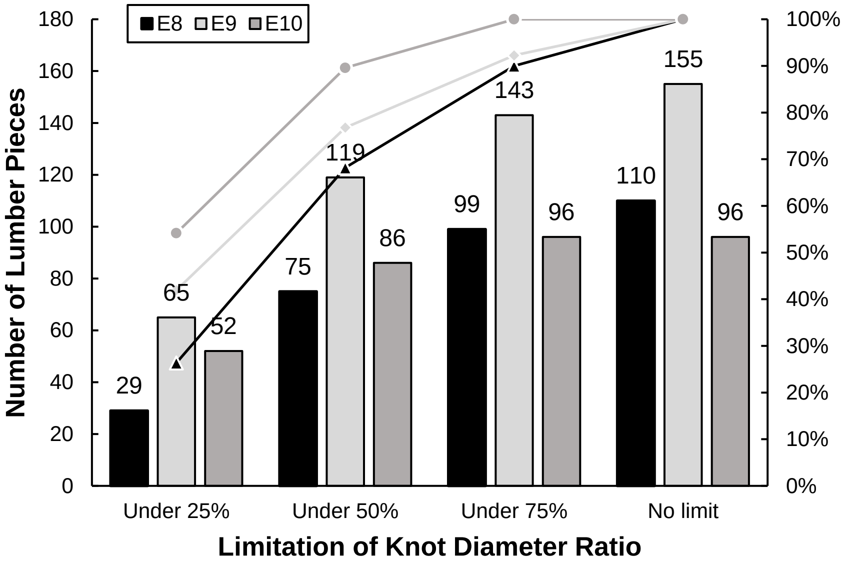


**Fig. 6.** Number of lumber and percentage according to limitation of knot diameter ratio and grades

Table 5 and Fig. 7 show the changes in allowable properties of E8, depending on the limit of the knot diameter ratio. The allowable MORs of yellow poplar lumber with knot diameter ratio limits of less than 75%, 50%, and 25% were 9.1, 11.7, and 16.7 MPa when derived using the parametric method with the Weibull distribution. In contrast, the allowable MORs corresponding to the knot diameter ratio limits were determined as 6.3, 8.8, and 14.5 MPa using the non-parametric method. However, there was no significant difference in the MOE of yellow poplar lumber depending on the limit of the knot diameter ratio (Table 5). It was confirmed that the knot diameter ratio limit of less than 75% was not appropriate because the allowable MOR derived by the non-parametric method and the full-size test were lower than the literature values.

**Table 5.** Allowable Properties in Various Limitations of Knot Diameter Ratio

| Type | | 5th Percentile Value | | | Allowable Property | | | KS F 3020 (2023) |
|---|---|---|---|---|---|---|---|---|
| | | < 25% | < 50% | < 75% | < 25% | < 50% | < 75% | |
| MOR (MPa) | Parametric | 35.2 | 24.5 | 19.1 | 16.7 | 11.7 | 9.1 | 8.2 |
| | Non* | 30.5 | 18.6 | 13.2 | 14.5 | 8.8 | 6.3 | |
| MOE (GPa) | | - | - | - | 8.7 (0.12)** | 8.6 (0.10) | 8.7 (0.12) | 8.0 |

* Non-parametric method, ** Coefficient of variation

It was concluded that yellow poplar lumber could be used safely using the 50% of knot diameter ratio limit. For the limit of 50%, the allowable properties were higher than the literature values in KS F 3020 (2023). When the knot diameter ratio limit was less than 50%, the allowable MOR of yellow poplar lumber derived using a non-parametric method increased 3 MPa compared with the case having no limit of the knot diameter ratio. It was judged that the knot diameter ratio limit of 50% might be reasonable considering the comprehensive comparison of the acceptable number of lumbers and the tolerance of bending properties. The knot diameter ratio limit of less than 50% was similar to the visual classification of layer quality for glued laminated timber (GLT) in the North American national lumber grading authority (NLGA). The NLGA stipulated that the knot area ratio in lamination should not exceed 0.5 of a cross-section of lumber.

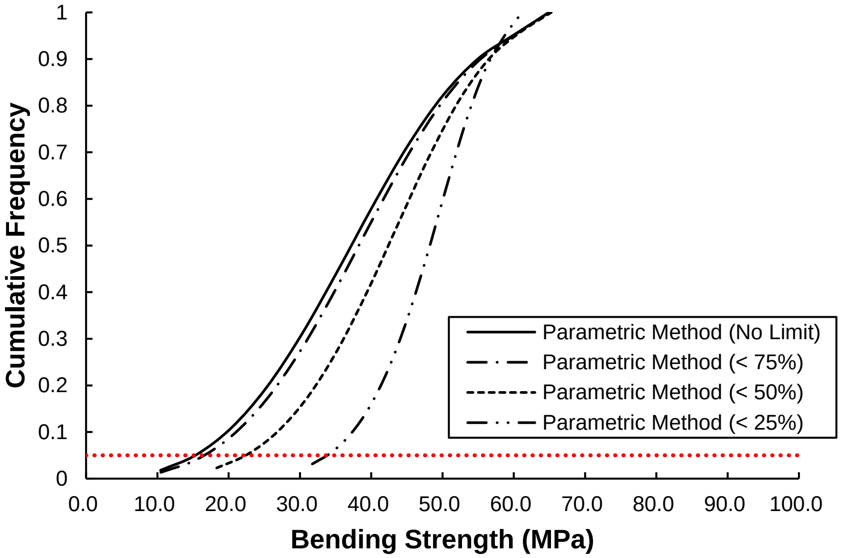


**Fig. 7.** Change of 5th percentile value according to range of knot diameter ratio in E8

## CONCLUSIONS

The allowable properties in bending (MOR, MOE) were evaluated according to the machine grading of the full-size lumber to utilize yellow poplar as a structural member, which is a kind of fast-growth broadleaved tree.

1. As a result of the machine grading of Korean yellow poplar, the major proportion of machine grades were E8, E9, and E10, and the grade proportion was similar to pine.
2. It was confirmed that knot, grain angle, and tension failure occurred frequently after conducting the bending test. The 5th percentile value of MOR was lower in the non-parametric method than in the parametric method using the Weibull distribution.
3. An additional visual grading, which was limited to knot diameter ratio, needed to be combined with machine grading to classify yellow poplar appropriately to structural bending member. The allowable MOR using machine grading without a knot diameter ratio limitation was lower than the literature value in E8.
4. The knot diameter ratio of 0.5 was reasonable, considering structural safety and economic feasibility. It was expected that yellow poplar could be utilized for structural purposes by using machine grading and the knot diameter ratio limitation of 0.5

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