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Bending Strength of Korean Softwood Species for 120 × 180 mm Structural Members[*1]

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ABSTRACT

The goal of this study is to investigate bending properties of domestic timber. Three representative structural timber from *Larix kaempferi*, *Pinus koraiensis*, and *Pinus densiflora*, in the northeastern South Korea were selected. Visual grading for the timber was conducted based on KFRI notification 2009-01 and the bending strength for the timber was evaluated based on ASTM D 198 bending. The high percentage of grade 1 and 2 for *Larix kaempferi* shows that the KFRI notification was optimized for this species. The bending strength distributions from *Pinus koraiensis* and *Pinus densiflora* were very similar. It could be possible to specify the allowable bending properties of these two Specification using a united species group similar to spruce-pine-fir. Lastly, the bending strength of 120 × 180 mm structural members was higher than both existing values in KBC 2009 and design values for timber of imported species described in the NDS. Thus, 120 mm thick domestic softwoods could replace the commercial imported species and the KBC should be modified to provide design values for both timber and dimensional lumber, respectively, like NDS.

Keywords : bending strength, softwood, timber, visual grading, allowable stress

1. INTRODUCTION

Over the last few decades, South Korea has successfully greened the land devastated during World War II. The extensively reforested land produces many trees, which provide wood products, wood composites, and sawn wood. Sawn wood is one of the most effective ways of using wood with less processing. The grading methods used to ensure the safety of structures constructed from various species of Korean sawn wood have been investigated by many researchers (Jang, 1989; Oh, 1996; Park *et al.*, 2004; Lee *et al.*, 2003; Lim *et al.*, 2010; Pang *et al.*, 2011).

Historically, the most common method of grading wood has been through visual observation. The National Design Specification (NDS) provides the design values to be used for vari-

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Table 1. Sample arrangement of bending test for three different grade timber from Korean species

Grade	Number of specimens		
	Larix kaempferi	*Pinus koraiensis*	*Pinus densiflora*
1	268 (66%)	9 (5%)	33 (13%)
2	121 (30%)	96 (51%)	147 (58%)
3	20 (5%)	82 (44%)	73 (29%)
Total	409 (100%)	187 (100%)	253 (100%)

ous species of wood in accordance with various visual-grading rules. Sawn timber is an inhomogeneous material; thus, the mechanical behavior of timber cannot be derived with any reliability from the properties of clear wood. Therefore, it is necessary to determine the strength properties of structural timber by direct testing of timber elements according to a standardized methodology (Foley, 2001).

Traditional Korean wooden buildings have been built with large-dimensional structural timber. The NDS provides design values for timber that is more than 114 mm (5 inches) thick, as well as for lumber between 38 mm (2 inches) and 89 mm (4 inches) thick; however, the Korean Building Code (KBC 2009) provides just one design value for structural members. Although several researchers (Oh *et al.*, 1993; Lee *et al.*, 2003; Park *et al.*, 2010) have tried to investigate the bending strength of Korean softwood species to determine their strength properties, allowable stress, and distribution types to evaluate the usefulness of Korean visual-grading rules, the specimens considered have been dimensional lumber with a nominal thickness of 38 mm. The properties of timber with a nominal thickness of more than 114 mm have never been evaluated in Korea, and existing KBC 2009 does not provide appropriate design values for Korean softwood timber.

The aim of this study was to evaluate the bending strength of 120 × 180 mm structural members made from Korean softwood species and to compare the allowable bending stresses with both the existing values of KBC and imported species described in the NDS.

2. MATERIALS and METHODS

2.1. Materials

The three most reforested and commercially important softwood species, *Larix kaempferi* (oven-dry density: 540 kg/m^3), *Pinus koraiensis* (oven-dry density: 450 kg/m^3), and *Pinus densiflora* (oven-dry density: 440 kg/m^3), in northeastern South Korea were prepared to evaluate their bending strength. After kiln drying, the surfaces were planed so that the final cross-sections were 120 × 180 mm, and the lengths were 3,600 mm. The moisture content of the specimens was 12% (± 2). The number of specimens and the visual-grading results are listed in Table 1.

2.2. Methods

2.2.1. Visual Grading and Measurement of MOR

Each specimen was visually graded according to the KFRI Notification 2009-01. The location and size of each knot, curve, and crack were investigated. A third-point bending test was carried out for the bending-strength measurements with a universal testing machine (Instron, Ltd.) following ASTM D-198 (Fig. 1). The loading span was 3 m, and the loading speed was 10 mm/min.

Fig. 1. Test set-up for evaluating the bending strengths of specimens (third-point loading).

2.2.2. Distributions of MOR from the Three Species

To find the goodness-of-fit distribution, the parameters for the normal, lognormal, and Weibull distributions were determined, and the root mean square error (RMSE) of the distribution types was compared. The distribution type with the lowest RMSE was identified as the goodness-of-fit distribution. The probability density functions of each distribution and RMSE formula were as follows.

*Weibull distribution :

$$f_T(t) = -\overline{F_T}(t) = \lambda(t)\exp\left[-\int_t^0 \lambda(s)ds\right] \quad (1)$$

$$= (\frac{\alpha}{\beta})t^{\alpha-1}\exp(\frac{-t^{\alpha}}{\beta})I_{(0,\infty)}(t)$$

The 5% exclusion limit: $5\% = \beta(-\ln 0.95)^{\frac{1}{\alpha}}$

*Normal distribution :

$$f_x(x) = f_x(x,\mu,\sigma^2) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \quad (2)$$

$-\infty < x < \infty,\ -\infty < \mu < \infty,\ 0 < \sigma$

The 5% exclusion limit: $5\% = \mu - (\sigma \times 1.645)$

*Lognormal distribution :

$$f_x(x) = f_x(x,\mu,\sigma^2) = \frac{1}{x\sqrt{2\pi}\sigma}\exp\left[-\frac{1}{2\sigma^2}(\ln x-\mu)^2\right] \quad (3)$$

$0 < x < \infty,\ -\infty < \mu < \infty,\ 0 < \sigma$

$E(X) = e^{(\mu+\frac{\sigma^2}{2})}$

$Var(X) = e^{2\mu+2\sigma^2} - e^{2\mu+\sigma^2}$

The 5% exclusion limit: $5\% = \exp(\mu - (\sigma \times 1.645))$

*The RMSE formula :

$$A = \begin{bmatrix} x_{1,1} \\ x_{1,2} \\ \vdots \\ x_{1,n} \end{bmatrix} \quad and \quad B = \begin{bmatrix} x_{2,1} \\ x_{2,2} \\ \vdots \\ x_{2,n} \end{bmatrix}$$

A: actual MOR values in ascending order

B: MOR values in Normal, lognormal, or Weibull cumulative distribution function

$$RMSE(A,B) = \sqrt{\frac{\sum_{i=1}^{n}(x_{1,i} - x_{2,i})^2}{n}} \quad (4)$$

2.2.3. Allowable Properties for Timber design

Most allowable properties were based on the concept of a 5% exclusion limit. In this study, the 5% exclusion limit for bending strength was obtained in goodness-of-fit distribution. This property when divided by adjustment factor gives the respective allowable design property. The factor includes an adjustment for normal duration of load and a factor of safety.

$$\sigma_{allow} = \frac{MOR_{0.05}}{Adjustment\ factor} \quad (5)$$

Where, $MOR_{0.05}$: the 5% exclusion limit
Adjustment factor: 2.1 (Modulus of Rupture)

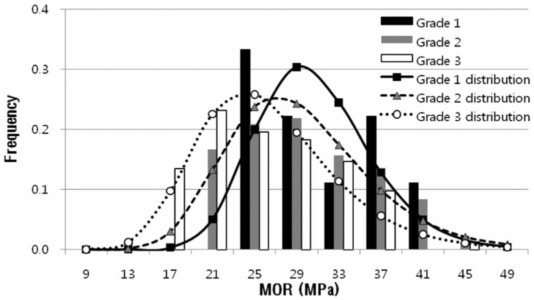

Fig. 2. MOR histograms for *Pinus koraiensis.*

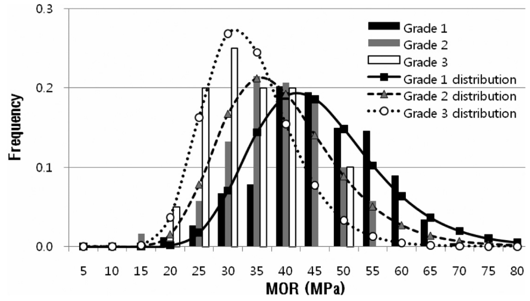

Fig. 4. MOR histograms for *Larix kaempferi.*

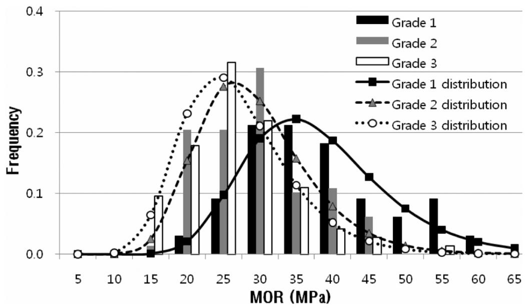

Fig. 3. MOR histograms for *Pinus densiflora.*

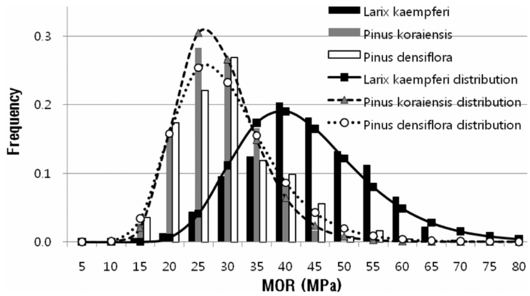

Fig. 5. MOR histograms for 120 × 180 mm domestic softwoods.

3. RESULTS and DISCUSSION

In the visual-grading results based on the KFRI notification 2009-1, the percent of the specimens that were grade 1 or 2 for structural purposes was 96% for *Larix kaempferi*, 61% for *Pinus koraiensis*, and 71% for *Pinus densiflora* (see Table 1). The high percentage for *Larix kaempferi* shows that the KFRI notification was optimized for this species. Most previous research (Oh *et al.*, 1993; Lee *et al.*, 2003; Park *et al.*, 2010) has focused on *Larix kaempferi*, and the results have influenced the KFRI notification.

For *Pinus koraiensis* and *Pinus densiflora*, the percentage of specimens that were grade 2 was high, although the percentage that were grade 1 was low. This was caused by the existence of large gathered knots in the species. Therefore, to increase the percentage of specimens that are grade 1 for *Pinus koraiensis* and *Pinus densiflora*, we need other grading rules that include an optimized knot ratio for a particular species. Also, we could prune away the ragged edges of the wood to reduce the ratio of knots in the timber.

A probability density function (PDF) was used to analyze the distribution of the modulus of rupture (MOR) within each species. The distribution curves for grades 1 and 2 of *Pinus koraiensis* (see Fig. 2) and grades 2 and 3 of *Pinus densiflora* (see Fig. 3) overlapped much more than did the distribution curves for *Larix kaempferi* (see Fig. 4). This indicates that the grades of the first two species were not clearly defined. To analyze the distribution character-

Table 2. Average MOR values of three different grade timbers from Korean species

Grade	MOR (MPa)		
	Larix kaempferi	*Pinus koraiensis*	*Pinus densiflora*
1	43.2 (0.23)[a)]	28.7 (0.18)	32.1 (0.25)
2	36.8 (0.25)	27.3 (0.23)	24.1 (0.28)
3	31.4 (0.25)	24.3 (0.26)	22.0 (0.31)
Total	40.8 (0.25)	26.0 (0.25)	24.6 (0.31)

a) Coefficient of variation.

Table 3. Comparison of allowable bending stress between Korean softwoods (120 × 180 mm) and imported species described in the NDS (timber; 114 × 114 mm and larger)

Grade	Allowable bending stress (MPa)							
	Domestic species						Imported species (NDS)	
	Larix kaempferi		*Pinus koraiensis*		*Pinus densiflora*		D-Larch	S-P-F
	120 × 180	KBC[a)]	120 × 180	KBC	120 × 180	KBC		
1	13.2	8.0	9.4	6.0	10.5	7.5	11.0[b)] 9.0[c)]	7.6[b)] 6.2[c)]
2	10.9	6.0	7.9	5.0	7.8	6.0	6.0[d)]	4.1[d)]
3	9.8	3.5	6.7	3.0	6.8	3.5	-	-
All	12.0		7.9		7.5		-	-

a) Allowable bending stresses in Korean Building Code 2009.
b) Select Structural grade in the NDS.
c) No.1 grade in the NDS.
d) No.2 grade in the NDS.

istics of the three species, all of the bending strength was compared without classifying the specimens by the grading rules (see Fig. 5). The PDF in Fig. 5 shows *Pinus koraiensis* and *Pinus densiflora* positioned on the left side, with significant overlapping of the curves, unlike *Larix kaempferi*. As the shapes of the PDFs for *Pinus koraiensis* and *Pinus densiflora* were very similar, it was thought possible to represent their strength properties using a united species group similar to spruce-pine-fir.

The average MOR was higher for *Larix kaempferi* than for *Pinus densiflora* (see Table 2). The values for *Pinus koraiensis* and *Pinus densiflora* were similar. Therefore, *Larix kaempferi* and *Pinus koraiensis* could replace *Pinus densiflora*, which has been used traditionally in Korean wooden buildings, provided problems are not encountered with drying, manufacturing, or economic efficiency.

To compare the bending strength of the three species with both existing values in KBC 2009 and design values of species imported from aboard, the allowable stresses (see Table 3) were calculated with 5% exclusion limit of the goodness-of-fit distribution, which was determined from the lowest RMSE, as shown in Table 4. For *Larix kaempferi*, the normal distribution was closest to the actual data distribution; however, for both *Pinus densiflora* and *Pinus koraiensis*, the lognormal distribution was closest to the experimental data.

Table 4. Root mean square error of MOR distributions from Korean softwoods

Distribution	*Larix kaempferi*				*Pinus koraiensis*				*Pinus densiflora*			
	No.1	No.2	No.3	All	No.1	No.2	No.3	All	No.1	No.2	No.3	All
Normal ($\times 10^{-2}$)	**1.7**	**1.4**	6.4	**1.4**	6.8	3.2	2.9	2.5	5.0	4.2	4.6	4.0
Weibull ($\times 10^{-2}$)	2.0	2.3	6.1	2.0	**5.6**	4.2	3.5	3.5	5.4	8.7	7.2	4.6
Lognormal ($\times 10^{-2}$)	3.3	2.7	**5.4**	3.0	6.2	**1.9**	**2.6**	**1.8**	**2.4**	**2.1**	**2.0**	**1.2**

Generally, 120 × 180 mm specimens had higher allowable bending stresses than existing those in KBC (see Table 3). The similar tendency was confirmed in NDS where most allowable properties of timber were higher than those of dimensional lumber. It means that the mechanical properties of timber were different with dimensional lumber, and thus, the design values of timber should be provided separately with dimensional lumber.

The NDS distinguishes between the design values for timber over 114 mm (5 inches) thick and those for dimensional lumber 38 mm (2 inches) to 89 mm (4 inches) thick, although the KBC does not distinguish the allowable stress values and provides just one design value for structural members. To compare with imported species, the design values for timber also described in Table 3. Typically, the allowable bending stresses for *Larix kaempferi* were greater than those for Douglas-fir-Larch (D-Larch), whereas *Pinus koraiensis* and *Pinus densiflora* had higher strength than did spruce-pine-fir (S-P-F). Therefore, in this simple comparison, the Korean softwood species investigated in this study performed better than commercially imported species. However, when timber is used in applications where the moisture content exceeds 19% for an extended time period, wet-service factors should be included, as suggested in the NDS. Because the design values of timber in the NDS were tested in green specimens, most of the wet-service factors are high, and the factor for bending strength is 1.0. Given that the three species considered in this study were dried before testing, it is possible that they could have a lower performance than imported species under wet conditions.

4. CONCLUSIONS

Structural timber from three Korean softwood species were visually graded and tested for bending properties. The allowable stresses were compared with both the existing values in KBC 2009 and commercially imported species (D-Larch and S-P-F) described in the NDS. The following conclusions were drawn.

1) The visual-grading results and PDF histograms showed that the KFRI notification has been optimized for *Larix kaempferi*. For both *Pinus koraiensis* and *Pinus densiflora*, the percentage of specimens that were grade 2 was high, but the percentage that were grade 1 was low.

2) The shapes of the PDFs were very similar for *Pinus koraiensis* and *Pinus densiflora*. Therefore, it could be possible to describe their strength properties using a single united species group such as Spruce-Pine-Fir.

3) In a simple comparison, the allowable bending stresses for 120 × 180 mm structural members were higher than both existing values in KBC 2009 and design values for timber of imported species described in the NDS. Thus, 120 mm thick domestic softwoods could replace the commercially imported species. And the KBC should be modified to provide design val-

ues for both timber and dimensional lumber, respectively, like NDS, since the mechanical properties of timber were different from those of dimensional lumber.

This study was just focused on evaluating bending strength of 120 mm thick domestic softwoods. And thus, in the future, it will be necessary to study for modifying grading rules, solving the problems related to uniting species, and distinguishing the other properties of domestic softwoods between dimensional lumber and timber.

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