PREDICTING TENSILE AND COMPRESSIVE MODULI OF STRUCTURAL LUMBER

*Kwang-Mo Kim**
Research Scientist

Kug-Bo Shim
Research Scientist
Department of Forest Products
Korea Forest Research Institute
Seoul, 130-712, Korea

Conroy Lum
Group Leader, Wood Engineering
Building Systems Department
FPInnovations–Wood Products
Vancouver, BC, Canada

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Abstract. Nondestructive bending modulus of elasticity (MOE) of lumber is commonly used as input data to estimate mechanical properties of glued lumber or laminated timber components. Many standard and nonstandard test methods exist to determine MOE. However, when glued components are loaded, the stresses imposed on the lumber subcomponents are quite different from stresses used in determining MOE of the lumber. It is well known that the bending MOE of lumber is somewhat different from its tensile and compressive moduli. Therefore, defining the differences and relationships between bending MOE and tensile and compressive moduli is important. This study predicted the tensile and compressive modulus from dynamic and static bending MOE of major softwood structural lumber in Korea. The measured MOE and tensile and compressive moduli from the same specimens by various test methods were found to differ. In particular, the tensile modulus was twice the compressive modulus for the same specimen. Edgewise bending MOE, which showed the highest correlation with tensile and compressive moduli, was suggested as a suitable input parameter for predicting tensile and compressive moduli. Predicting tensile and compressive moduli from dynamic or flatwise bending MOE of structural lumber is also possible, although with a different relationship. With better prediction of tensile and compression moduli, it is expected that the properties of engineered wood or timber structures can be more accurately estimated.

Keywords: Structural lumber, glulam, tensile modulus, compressive modulus, flatwise bending MOE, edgewise bending MOE, dynamic MOE.

INTRODUCTION

The Korea Forest Research Institute has undertaken studies to improve the properties of glued laminated timber (glulam) with the goal of achieving higher value from the forest resource (Shim and Yeo 2004; Shim et al 2005; Kim et al 2007, 2009c). Kim et al (2007, 2009c) examined how the static bending modulus of elasticity (MOE) of glulam could be predicted by the transformed section method and noted that the predicted bending MOE of glulam was overestimated by about 10-30% when the dynamic MOE of lumber was chosen as input data.

Shim et al (2009) proposed an improved method of predicting the bending MOE of glulam based on neutral axis movement under bending stress. This approach is based on the observation that the measured tensile and compressive modulus from actual-size structural lumber is different from the dynamic or static bending MOE of lumber, which are typically used as input data

* Corresponding author: lovewood@forest.go.kr

of lumber to predict the bending MOE of glulam members. In particular, the neutral axis under a bending load will be positioned closer to the tension side than if results were based on the dynamic MOE of the lumber. This difference appears to be caused by the tensile modulus of structural lumber being about two times greater than the compressive modulus, as opposed to being equal, the assumption when dynamic or static bending MOE of lumber is used. Shim et al (2009) reported that the differences between tensile and compressive modulus were caused by growth characteristics in the lumber, such as grain deviation near knots or the existence of immature wood. Although tensile and compressive modulus of lumber are more suitable for predicting glulam performance, ongoing measurements of the tensile and compressive modulus in a manufacturing plant environment are labor-intensive and require expensive test equipment. Consequently, this study was carried out to establish methods for predicting the tensile and compressive modulus based on the dynamic or static bending MOE of major softwood lumber in Korea.

MATERIALS AND METHODS

Materials

Six major domestic softwood species were selected for testing. Ten pieces of lumber for each species from various sources were prepared and kiln-dried. The sample selection was not intended to be representative of a particular grade or species but to cover a range of wood density and was judged to be adequate for an exploratory assessment of possible species effects. Species, sizes, moisture contents, and oven-dry densities of specimens are shown in Table 1.

Measurements

The test procedures used are summarized in Table 2 and Fig 1.

Surface images. Digital images of the four sides of each piece of lumber were taken before measuring MOE. A lumber scanning system and image merging algorithm were used to obtain digital images of the central 3 m of each piece of lumber so that the growth characteristics could be further evaluated (Kim et al 2009a, 2009b).

Dynamic modulus of elasticity. A PUNDIT (CNS Farnell Ltd, Borehamwood, Hertfordshire, UK) ultrasonic tester was used to measure the ultrasonic transmission time through the central 1 and 3 m of each piece of lumber at three different transducer locations at the end of the lumber. The dynamic MOE (MOE_D) was calculated with Eq 1 (Shim et al 2009). Ultrasonic transmission velocity (V) was calculated by the average transmission time divided by the specimen length. Mass density (ρ) was determined by the weight and dimensions.

$$MOE_D = V^2 \times \rho \tag{1}$$

Edgewise bending modulus of elasticity. The edgewise bending MOE was measured by continuous MOE measuring equipment (5 kN; Dryingeng Co Ltd, Gwangju, Korea). The equipment was designed to meet the requirements of Korean standard KS F 3021-2005, B type bending test (KSA 2005) for measuring the MOE of

Table 1. Species, sizes, moisture contents, and oven-dry densities of specimens.

Species		Size (mm) Depth	Width	Length	Moisture content (%)	Oven-dry density (kg/m^3)
Korean red pine	*Pinus densiflora* Siebold & Zucc.	38	140	3600	8.7	440
Korean larch	*Larix kaempferi* (Lamb.) Carriere	33	152	3600	10.5	510
Pitch pine	*Pinus rigida* Mill.	34	148	3600	9.5	500
Korean pine	*Pinus koraiensis* Siebold & Zucc.	39	150	3600	10.6	420
Japanese cedar	*Cryptomeria japonica* (L.f.) D.Don	30	120	3600	11.0	320
Japanese cypress	Chamaecyparis obtuse (Siebold & Zucc.) Endl.	30	149	3600	11.8	460

Table 2. Modulus of elasticity measuring procedure and corresponding length of measurement.

Procedure	Measurements	Gauge length[a] (m)
1	Edgewise bending MOE	3.0 (3.6)
2	Surface image	3.0
3	Dynamic MOE	
4	Tensile modulus	1.0 (3.0)
5	Flatwise bending MOE	1.0 (1.4)
6	Dynamic MOE	1.0
7	Compressive modulus	

[a] Gauge length means overall test span for bending tests. The actual specimen lengths, if different from the gauge length, are presented in parentheses.
MOE, modulus of elasticity.

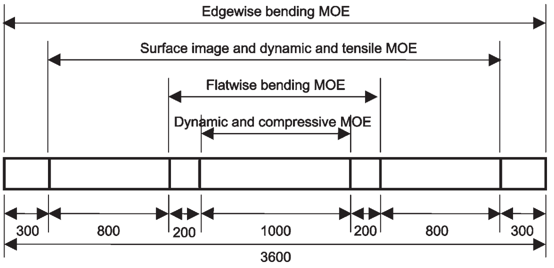

Figure 1. Length of specimens for each measurement procedure (all dimensions in millimeters).

laminations for glulam. A center-point bending load was applied to a simple span of 3 m with 10 mm/min cross-head speed. Change of load was measured by imposing a midspan deflection of 5 mm. Because this arrangement is sensitive to crook in the lumber at the time of testing, the pieces were measured twice, once with each edge in tension. The MOE results from the two tests were then averaged to cancel out the effect of crook.

Flatwise bending modulus of elasticity. Flatwise bending MOE was measured in a universal testing machine (200 kN; Instron 5585, Norwood, MA). The tests were performed in accordance with KSA (2005). A center-point bending load was applied with 5 mm/min cross-head speed. The load limitation to measure flatwise deflection of lumber was 500 N for five of the six species tested. For the weakest species, Japanese cedar, the load limitation was reduced to 200 N. As with the edgewise MOE measurement, the average deflection value of two flatwise measurements taken in opposite directions was used to calculate flatwise MOE of lumber. Specimen length for flatwise MOE measurement was 1.4 m, and span length was 1 m.

Tensile modulus. Tensile modulus of the full cross-section specimens was measured in a tension testing machine (1 MN; Kyoung Sung Testing Machine Co, Ltd, Ansan, Gyeonggi, Korea) with 600-mm-long grips and 2 mm/min cross-head speed. The 3-m-long specimens were centered in the testing machine so that the middle 1 m could be subjected to uniform tensile stress. Specimen displacement was measured by two LVDT at 40-kN tensile load for five of the six species. The LVDT were centered on the opposite wide faces at midspan. For the Japanese cedar samples, the tensile load was limited to 25 kN. The MOE for all samples was calculated from the average displacements measured by the two LVDTs at a target load level.

Compressive modulus. A universal testing machine (Instron 5585) was used for testing the compressive modulus. Wood plates were installed around the specimens to prevent buckling under compressive loading but at a sufficient distance from the specimen surface to minimize friction. The specimen length was 1 m, and the cross-head speed was 2 mm/min. Compressive displacement was measured across the yield point of the specimen because it was the last step of the test procedures. The maximum slope was selected from the load-displacement curve to remove the effect of initial surface crushing or adjustment of test equipment.

RESULTS AND DISCUSSION

Modulus of Elasticity Differences by Various Test Methods

Average values of MOE for different test methods are shown in Table 3. Every load-displacement curve was observed during the loading test. If the load was beyond the proportional limit, the specimen was considered to have failed and was excluded from the remaining tests. Three specimens of Korean

Table 3. Average modulus of elasticity values of each species by loading methods (GPa).[a]

Species	Dynamic		Bending		Tensile modulus	Compressive modulus
	3 m	1 m	Edgewise	Flatwise		
Korean red pine	12.16 (10)	12.42 (8)	8.16 (10)	8.66 (8)	11.23 (10)	6.13 (8)
Korean larch	13.42 (10)	14.00 (10)	9.70 (10)	9.92 (10)	13.01 (10)	6.90 (10)
Pitch pine	8.89 (10)	9.97 (10)	6.59 (10)	6.82 (10)	8.32 (10)	4.62 (10)
Korean pine	10.63 (7)	10.89 (6)	6.26 (7)	8.04 (6)	9.27 (7)	4.81 (6)
Japanese cedar	8.50 (10)	8.81 (10)	6.49 (10)	7.05 (10)	8.80 (10)	4.61 (10)
Japanese cypress	13.17 (10)	13.79 (10)	9.66 (10)	10.71 (10)	13.28 (10)	7.05 (10)
Average	11.15 (57)	11.68 (54)	7.89 (57)	8.56 (54)	10.81 (57)	5.73 (54)

[a] Number of specimens appears in parentheses.

pine were considered to be failed during the edgewise bending test, whereas two specimens of Korean red pine and one of Korean pine failed under tensile loading. The low failure loads were attributed to either a large knot or knot clusters (Fig 2).

Of the six species tested, Korean larch and Japanese cypress had the highest MOE values and pitch pine and Japanese cedar had the lowest. Because of the limited sample sizes, the MOE values in Table 3 may not be representative of those species.

The dynamic MOE test yielded on average the greatest values, and tensile modulus, flatwise bending MOE, edgewise bending MOE, and compressive modulus followed in that order. Although the value of tensile and compressive modulus of Korean larch and pitch pine was greater than the results in Shim et al (2009), the observation that the tensile modulus was about two times greater than compressive modulus was similar to that observed in Shim et al (2009). The differences between the tensile and compressive modulus of structural lumber are caused by how the zones of low localized modulus impact the overall or "apparent" modulus of the piece. Grain deviation near defects, such as knots and immature wood, will probably show lower localized modulus in compression than in tension (Shim et al 2009).

The bending MOE was approximately equal to the average of the tensile and compressive modulus. Edgewise bending MOE was computed by the transformed section method using tensile and compressive modulus from the same specimen. Figure 3 shows a very close relationship (R^2 = 0.927) between the measured and estimated MOE. Given this result, the testing methods for measuring tensile and compressive modulus appear to be reasonable.

The ratio of compressive and tensile modulus for each species is shown in Fig 4. The ratio

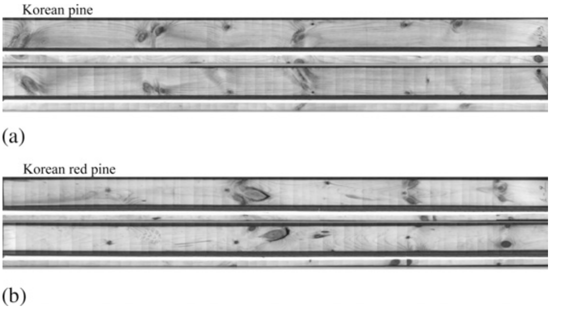

Figure 2. Surface images of damaged specimens during a tensile test.

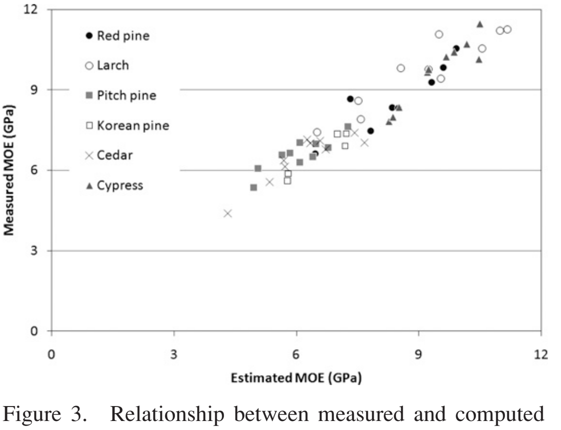

Figure 3. Relationship between measured and computed edgewise bending modulus of elasticity.

ranged between 0.52 and 0.56 and was found to be consistent between species. Shim et al (2009) reported the ratio of compressive and tensile modulus as 0.464 for pitch pine, 0.455 for Korean larch, and 0.528 for Japanese cedar. The ratios in this study were slightly greater than previously reported except for Japanese cedar. However, the ratios of compressive and tensile modulus measured from small clear specimens (Schneider and Philips 1991; Janowiak et al 2001; Yadama et al 2006) were smaller than the ratios measured from the structural lumber.

Prediction of Tensile and Compressive Modulus

The correlation coefficients between any two of the four MOE measuring methods are shown in Table 4. All coefficients were higher than 0.8, suggesting good correlations. Because the dynamic and static bending MOE are easy to measure, these methods are generally used for developing MOE input data for predicting the mechanical properties of lumber or glulam. Equipment to measure dynamic and static bending MOE is commercially available. Measuring the tensile and compressive modulus, however, is not as easy, and the equipment needed is not yet available except for laboratory use. For these reasons, bending MOE of lumber is normally cited in the literature for determining the MOE of lumber.

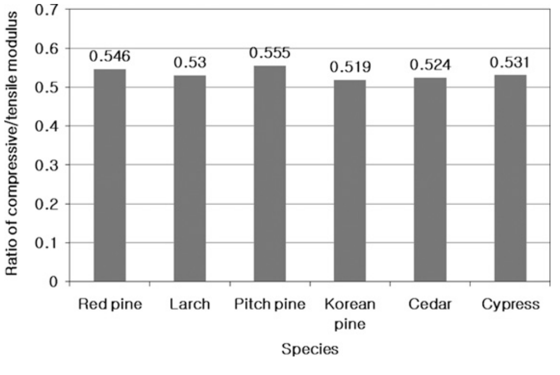

Figure 4. Ratios of compressive and tensile modulus by species.

Based on the results of this study, the edgewise bending MOE, which had the highest correlation with tensile and compressive modulus, is suggested as the preferred input parameter for predicting tensile and compressive modulus. The linear regression coefficients for predicting tensile and compressive modulus for each species from edgewise MOE of lumber were obtained using the regression function of Microsoft Office Excel software (version 2007; Microsoft Inc, Redmond, WA) and are shown in Table 5. The relationships between the predicted and measured modulus are shown in Fig 5. It is also possible to derive parameters for predicting tensile and compressive modulus from flatwise MOE or dynamic MOE. The root mean square error (RMSE) of predicted and measured MOE was calculated with Eq 2 and shown in Fig 6. The predicting equations were constructed from the coefficients of each species and total species values.

$$\mathrm{RMSE} = \sqrt{\frac{\sum(\text{Predicted MOE} - \text{Measured MOE})^2}{\text{Number of specimen}}} \qquad (2)$$

Table 4. Correlation coefficients among different modulus of elasticity measuring methods.

Species		Dynamic 3 m	Dynamic 1 m	Bending Edgewise	Bending Flatwise	Tensile modulus	Compressive modulus
Dynamic	3 m	1	0.921	0.827	0.834	0.805	0.876
	1 m	0.921	1	0.865	0.824	0.806	0.893
Bending	Edgewise	0.827	0.865	1	0.833	0.841	0.949
	Flatwise	0.834	0.824	0.833	1	0.812	0.878
Tensile		0.805	0.806	0.841	0.812	1	0.879
Compressive		0.876	0.893	0.949	0.878	0.879	1

Table 5. Regression coefficients to predict tensile and compressive modulus based on edgewise bending modulus of elasticity.

	Tensile modulus			Compressive modulus		
	Gradient	y-axis intercept	Coefficient of determination	Gradient	y-axis intercept	Coefficient of determination
Korean red pine	1.674	−2431	0.711	0.571	1206	0.961
Korean larch	1.698	−3465	0.833	0.716	−54	0.782
Pitch pine	1.399	−903	0.642	0.780	−527	0.678
Korean pine	1.307	1071	0.926	0.521	1392	0.749
Japanese cedar	1.343	85	0.706	0.729	−117	0.838
Japanese cypress	0.674	6771	0.610	0.589	1360	0.934
All species	1.383	−208	0.841	0.712	17	0.949

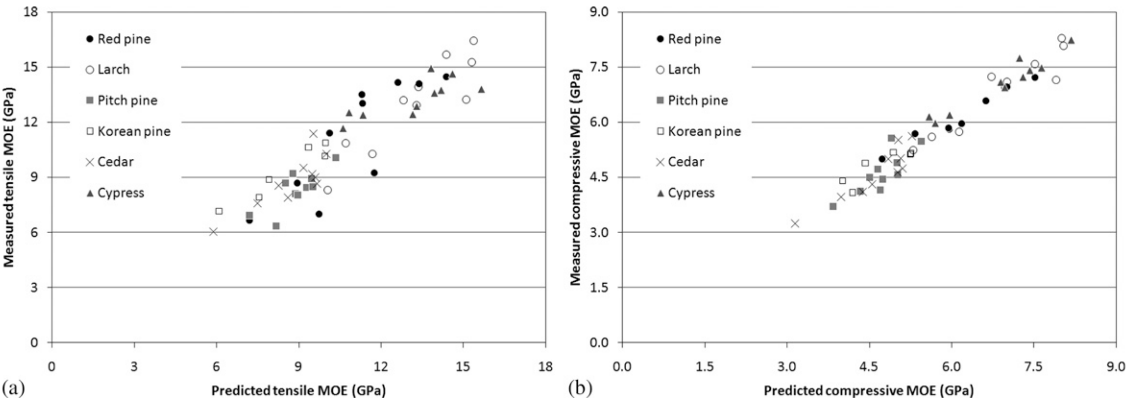

Figure 5. Prediction accuracy of tensile and compressive modulus based on the edgewise bending modulus of elasticity. *Same here with units. (a) Tensile modulus. (b) Compressive modulus.

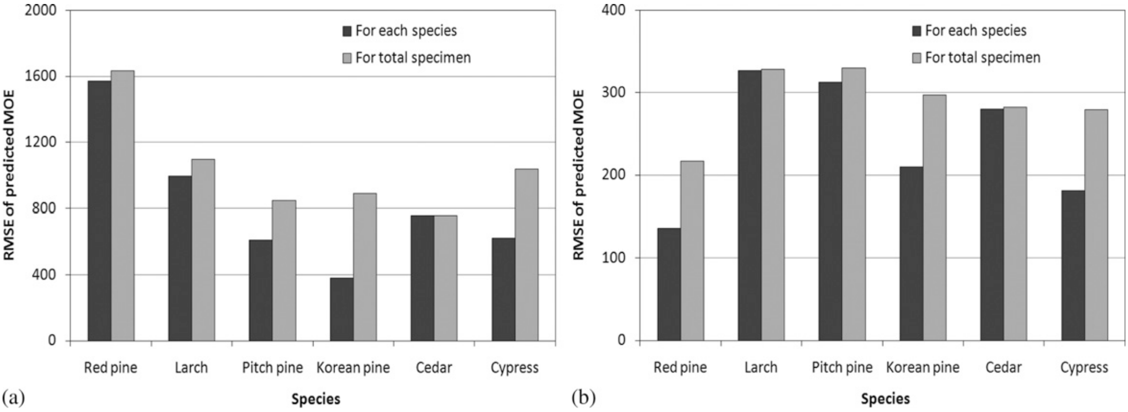

Figure 6. Root mean square errors of predicted modulus of elasticity for each species (MPA). *Same here with units. (a) Tensile modulus. (b) Compressive modulus.

The RMSE of tensile modulus was typically about 800 MPa, while the RMSE of compressive modulus was generally lower than 400 MPa. Although the RMSE calculated from all the species data was greater than that calculated for individual species, the differences were judged to not be significant. The difference would probably be smaller if the species data were more representative of a larger geographical area. For convenience, it is therefore reasonable to use a single equation based on all species for predicting the tensile and compressive modulus of lumber (Eqs 3 and 4).

$$\text{Tensile modulus} = 1.383 \times \text{edgewise bending MOE} - 208 \quad (3)$$

$$\text{Compressive modulus} = 0.712 \times \text{edgewise bending MOE} + 17 \quad (4)$$

CONCLUSIONS

This study predicted the tensile and compressive modulus from dynamic or static MOE of major softwood lumber in Korea. The conclusions are:

1. The measured MOEs of the same specimen by various test methods are different. In particular, the tensile modulus was about twice the compressive modulus for the same specimen.
2. The edgewise bending MOE, which showed the highest correlation with tensile and compressive modulus, is suggested as the input parameter for predicting tensile and compressive modulus. Predicting tensile and compressive modulus from flatwise or dynamic MOE is also possible.
3. Given the differences in the modulus depending on the test mode, the accuracy in estimating the properties of engineered wood or timber structures can be improved by using the tensile and compressive modulus derived from various MOEs as opposed to simply using the edgewise bending MOE.

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