IMPROVEMENT OF PREDICTION ACCURACY OF GLULAM MODULUS OF ELASTICITY BY CONSIDERING NEUTRAL AXIS SHIFT IN BENDING

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Abstract. There is a discrepancy between the estimated modulus of elasticity (MOE) of glulam based on the dynamic MOE of laminates and measured MOE. The discrepancy is greater for glulam manufactured with mixed species. This study was undertaken to reduce the discrepancy between those MOE values. The error rate of predicting MOE of glulam by the transformed section method, without considering tension and compression modulus differences, was about 30%. To estimate the MOE of glulam more accurately, the differences between compression and tension modulus should be taken into account in the transformed section method. The measured tensile and compressive strain at the center of glulam under a bending load showed the movement of neutral axis toward the tension side of glulam. Therefore, the compression and tension modulus differences for each species should be identified before estimating the MOE of glulam. The prediction of glulam MOE was improved significantly by reflecting the ratio of compression and tension modulus vs dynamic MOE of laminates. The outermost of laminates in the compression side under bending load experienced plastic behavior and failure. This caused the neutral axis to move to the tension side and increased tension stress to cause the glulam to fail abruptly in tension. To improve the bending performance of glulam, reinforcing compression laminates need to be considered.

Keywords: Glulam, MOE, transformed section method, neutral axis, reinforcement.

INTRODUCTION

The use of structural glued laminated timber (glulam), the first generation of engineered wood, is increasing in the Korean timber construction area. The broadening use of glulam in Korea is mainly because of a deficit of high-quality and large dimension timber resources, expanding scales and design complexities in timber constructions, and increasing environmental concerns. Two of the advantages of using structural glulam are the easy-to-predict performances and quality control.

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In general, the modulus of elasticity (MOE) of glulam is predicted by the transformed section method based on the MOE of laminates. In ASTM D 3737 (ASTM 2005), the allowable bending MOE of glulam is defined by 95% of the predicted MOE values by the transformed section method (Lee and Kim 2000; Lee et al 2005).

To use pitch pine lumber as laminates for glulam in Korea, the Korea Forest Research Institute has studied the quality and performance of pitch pine laminates. Pitch pine was treated as a low value-added species in Korea as a result of reasons such as difficulties in resin control and drying and relatively low strength properties. To use low-quality pitch pine lumber as laminae for structural glulam, Kim et al (2007) reported that pitch pine is suitable for mixed-species glulam with larch in terms of adhesion. However, the predicted MOE of mixed-species glulam by the transformed section method was greater than the measured MOE. The error rate of predicted MOE ranged from 10 – 30% (Kim et al 2007). MOE overestimation may cause difficulties in design and use of mixed-species glulam.

Therefore, this study investigated how to improve the accuracy of MOE prediction for mixed-species glulam with pitch pine and larch. The parameters for predicting MOE of glulam were dynamic MOE of laminates and modified MOE in the tension and compression direction from the dynamic MOE.

MATERIALS AND METHODS

Materials

Pitch pine (*Pinus rigida*) and larch (*Larix kaempferi Carr.*), which are both planted in Korea, were used for laminates of glulam. Pitch pine laminates ($38 \times 140 \times 3600$ mm) were cut from 89 logs. The minimum diameter of breast height logs was 25 cm, and the length was 3.6 m. The pitch pine laminates were kiln-dried to a target MC of 10%. Two hundred larch laminates were bought from the National Forestry Cooperative Federation's sawmill. The average MC and air-dry density were 9.9% and 510 kg/m^3 for pitch pine and 12% and 520 kg/m^3 for larch.

The dynamic MOE (MOE_D) of laminates was measured by PUNDIT (CNS Farnell), which measures ultrasonic transmission velocity. The MOE_D was calculated using Eq 1 using the ultrasonic velocity (V) between 3.4 m points, and the air-dry density (ρ).

$$MOE_D = V^2 \times \rho \qquad (1)$$

Manufacturing Glulam

Eight laminates were symmetrically arrayed based on the MOE_D to produce glulam specimens with a target MOE of 11.00 – 13.00 GPa. Two different types of glulam were manufactured and these were single species (pitch pine, P-type) and mixed-species glulam (pitch pine and larch). The mixed-species glulams were classified into two groups, LP- and RA. LP-type glulam consisted of four outside laminates of larch and four inside laminates of pitch pine. The laminates of RA-type glulam (random type) were combined not by species, but by MOE_D. Three specimens for P-type and five specimens for LP- and RA-type glulam were manufactured for testing and evaluation.

Resorcinol resin (room-temperature curable, Deernol No. 40; Oshika Shinko Co, Ltd, Tokyo) was used. The adhesives were mixed with 100 parts resin and 15 parts hardener. The spread of adhesives was 250 g/m^2, and the pressing time was 24 h under 1176 kPa pressure. After being planed, the dimension of glulam specimen was 272 mm thick, 135 mm wide, and 3.6 m long.

Bending Tests of Glulam

To evaluate the bending properties of glulam, all specimens were loaded by a universal testing machine (Instron 5585, 200 kN capacity) until failure. The specimens were simply supported and loaded by a concentrated load at the third point of the beam. The span length was 3.3 m and loading rate was 5 mm/min. To measure the strain distribution and neutral axis shift through the beam depth, five 67 mm long strain gauges (KC-70-120-A1-11L1M2R type; Kyowa Electronic Instruments Co, Ltd, Tokyo) were attached at the center of the beam. The locations of the strain gauges are shown in Fig 1.

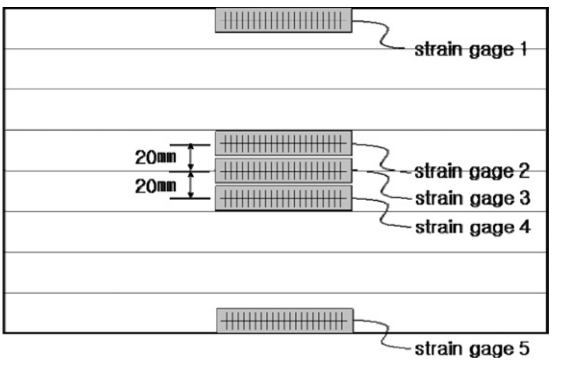


Figure 1. The location of strain gauges.

The deflection of the glulam beam was measured by an LVDT (B-Series 50.0; Solartron Metrology, West Sussex, UK) that was installed at the center of the beam. MOE of the glulam was calculated from the load-deflection relation based on elementary beam theory.

Tension and Compression Tests of Laminates

To compare dynamic MOE and tension and compression modulus of laminates, tension and compression tests were conducted on the universal testing machine. The width and thickness of the specimens were the same as the glulam laminates. The gauge length of the both tests was 500 mm and the displacement was measured by two LVDTs and the average displacement calculated (Fig 2). The tension and compression modulus of laminates was calculated from the stress–strain relation.

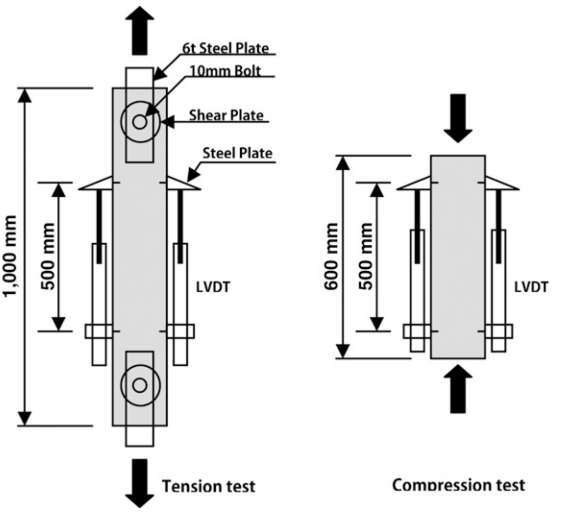


Figure 2. Configuration for tension and compression tests of actual size laminates.

RESULTS AND DISCUSSION

Prediction of Modulus of Elasticity by Transformed Section Method with Dynamic Modulus of Elasticity of Laminates

The MOE of the glulam was predicted by the transformed section method (Eq 2) and the test results are shown in Table 1 (Bodig and Jayne 1981). The MOE of laminates to predict MOE of glulam in Table 1 was assumed that the tension and compression modulus were the same as the dynamic MOE.

$$E_G = \frac{2}{I}\sum_{i=1}^{n} E^i \left[I_L + A\left(d^i\right)^2\right] \tag{2}$$

where E_G = predicted MOE of beam

E^i = dynamic MOE of ith laminate

I = moment of inertia of beam

n = number of laminates

I_L = moment of inertia of the laminate

A = cross-sectional area of the laminate

d^i = distance between the neutral axis of the beam and ith laminate

To predict the MOE by the transformed section method, the neutral axis, $\bar{x}$, of the tested glulam was calculated by Eq 3 (Bodig and Jayne 1981).

$$\bar{x} = \frac{\sum_{i=1}^{n} E^i t^i \sum_{1}^{i-1} t^{i-1} + (t^i/2)}{\sum_{i=1}^{n} E^i t^i} \tag{3}$$

where E^i = dynamic MOE of ith laminate

t^i = thickness of ith laminate

n = number of laminates

To remove the effects of shear, the span-to-depth ratio in the bending test should be at least 18 (KS 2005). In this study, however, the ratio was about 12 because of the limitation of laminate length and test equipment. It is probably one of the reasons for underestimating the MOE of the glulam. To adjust measured E_1 to standardized conditions, it is necessary to account for the effect of shear deflection on beam deflection. Equation 4 was suggested to determine the apparent MOE, E_2, based on any set of conditions of span-depth ratio and load configuration. The equations were derived using simple beam theory for a simply supported beam composed of isotropic, homogeneous material. Experimental evidence suggested that these

Table 1. *Predicted and measured modulus of elasticity (MOE; GPa) of glulam.*

	P type			LR type			RA type		
	Predicted[a]	Measured	Ratio	Predicted[a]	Measured	Ratio	Predicted[a]	Measured	Ratio
1	11.43	9.237	1.24	11.63	9.505	1.22	12.61	11.31	1.11
2	11.49	7.672	1.50	11.65	10.59	1.10	12.58	9.524	1.32
3	11.38	8.788	1.29	11.73	10.74	1.09	12.70	10.59	1.20
4	—	—	—	11.65	9.507	1.23	12.73	10.51	1.21
5	—	—	—	11.64	9.743	1.19	12.84	11.14	1.15
Average	11.43	8.566	1.33	11.66	10.02	1.16	12.69	10.61	1.20

[a] The MOE was predicted by the dynamic MOE of laminates in tension and compression laminates.

equations produce reasonable results with solid wood when converting between load conditions at a fixed span-depth ratio (ASTM 2003).

$$E_2 = \frac{1 + K_1\left(\frac{h_1}{L_1}\right)^2\left(\frac{E}{G}\right)}{1 + K_2\left(\frac{h_2}{L_2}\right)^2\left(\frac{E}{G}\right)}E_1 \qquad (4)$$

where h = thickness of the beam

L = span length of the beam

E = MOE without shear effects

G = shear modulus

K = 0.939 (concentrated loading at the third span, deflection measured at the midspan)

An average MOE (E_1) was obtained from the test of a simply supported beam loaded at the third point. The deflection was measured at the center of span, and span-depth ratio was about 12 (h_1/L_1 = 0.0824). The E/G ratio was assumed as 16. The correction constant for this test condition for a standardized test condition with span-depth ratio 18 (h_2/L_2 = 0.0556) was 1.053.

Therefore, 1.053 should be multiplied by the measured MOE (E_1) for this test condition to calculate the corrected MOE (E_2) of glulam. The corrected MOE of the glulam, however, showed about 10% difference from the predicted MOE.

In general, the predicted MOE was greater than the measured value. The MOE of P type was predicted about 30% greater than the measured MOE, the greatest discrepancy among the groups. LR- and RA-type glulam showed about 20% differences between the predicted and measured values.

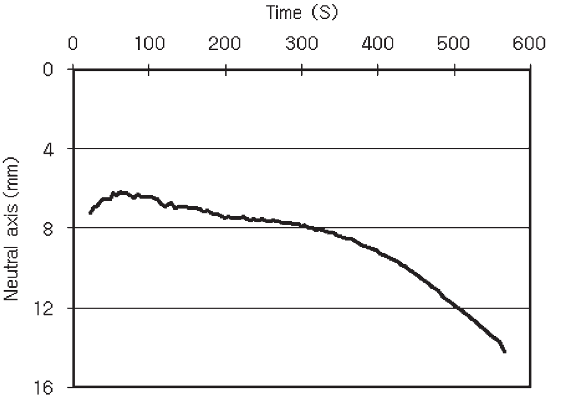


Figure 3. Neutral axis shift by time (LR-2).

Neutral Axis Location Under Bending Stress

The strain measured by five strain gauges showed a linear relationship with distance from the center of the beam. As the load reached a maximum, Gauges 1 and 5 could not measure the strain correctly because of the local failure of the beam and limitation of measurement of the strain gauges. Therefore, the neutral axis shift of glulam (N) was calculated using a linear relation between strain gauges 2 (S_2) and 4 (S_4) (Eq 5). An example of neutral axis shift is shown in Fig 3. Because of the instability of the data in the initial stage of the test, the first 20 s of recordings were neglected.

$$N(mm) = 20 - \frac{40}{S_2 - S_4}S_4 \qquad (5)$$

where S_2 = strain at Gauge 2

S_4 = strain at Gauge 4

20 = distance from the center of beam to strain Gauges 2 and 4 (mm)

40 = distance between the two strain gauges (S_2 and S_4) (mm)

The (+) direction of the neutral axis shift meant that it moved to the tension side of the beam, from the center to the bottom part of beam. In the initial stage of the test, the neutral axis was located 6 – 7 mm from the center. As the load increased, the neutral axis moved up to 15 mm at the point of failure. The exact locations of the neutral axis were different between specimens, but it showed the same tendency for each.

The location of the neutral axis is shown in Table 2 with the measured neutral axis at the initial and final stages of the tests. Five tests, P-2, P-3, LR-1, RA-1, and RA-3, did not follow the trends of the others. Observation after testing revealed that those beams failed through the glue line because of manufacturing defects (Fig 4); therefore, they were excluded from the analysis.

The predicted neutral axis shift of glulam based on the MOE_D of laminates by the transformed section method (Eq 2) was located 1 mm from the center line of the beam. However, the neutral axis that was measured by the strain gauge during testing moved to the tension side about 10 – 20 mm from the center line. The differences between calculated and measured neutral axis movement implied that the differences between the compressive and tensile MOE of laminates were not taken into account.

To estimate the differences of tension and compression modulus of laminates, actual size laminates were tested in tension and compression.

Predicted Modulus of Elasticity of Glulam

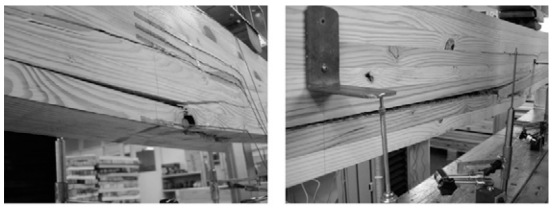
The tension and compression modulus of actual size laminates were calculated and compared with dynamic MOE of laminates (Table 3). The dynamic MOE and the tension modulus of laminates were close, but the differences between the dynamic MOE and the compression modulus were great. The tension and compression modulus for solid wood has been shown to differ with compression modulus being generally lower than tension modulus (Janowiak et al 2001; Yadama et al 2006). Schneider and Philips (1991) also reported that the modular ratio between tension and compression for sugar maple and basswood ranged from 1.24 – 1.88. However, the tested laminates in this study were actual size laminates with defects to induce grain angle deviation. The grain angle deviation might cause low modulus under compression.

Therefore, the MOE of laminates in tension and compression was modified by the ratio of dynamic MOE vs tension and compression modulus. The ratios, 0.45 and 0.48, were multiplied by the dynamic MOE for modifying

Table 2. *Calculated and measured location of the neutral axis.*

				Measured (mm)		
			Calculated[a] (mm)	Initial	Failure	Increase
P	type	1	1.08	13.26	19.39	6.13
		2	1.14	0.23	2.86	2.63
		3	2.15	3.01	3.88	0.87
LR	type	1	0.24	0.85	3.28	2.43
		2	0.38	6.87	14.22	7.35
		3	0.91	11.51	17.5	5.99
		4	1.48	11.49	14.28	2.79
		5	1.55	18.22	24.62	6.40
RA	type	1	0.62	–1.41	–5.18	–3.77
		2	0.65	17.66	21.81	4.15
		3	1.52	15.61	15.84	0.23
		4	2.23	23.71	33.46	9.75
		5	6.15	19.47	24.82	5.35

[a] The location of the neutral axis is calculated by the dynamic modulus of elasticity of laminates in tension and compression laminates.



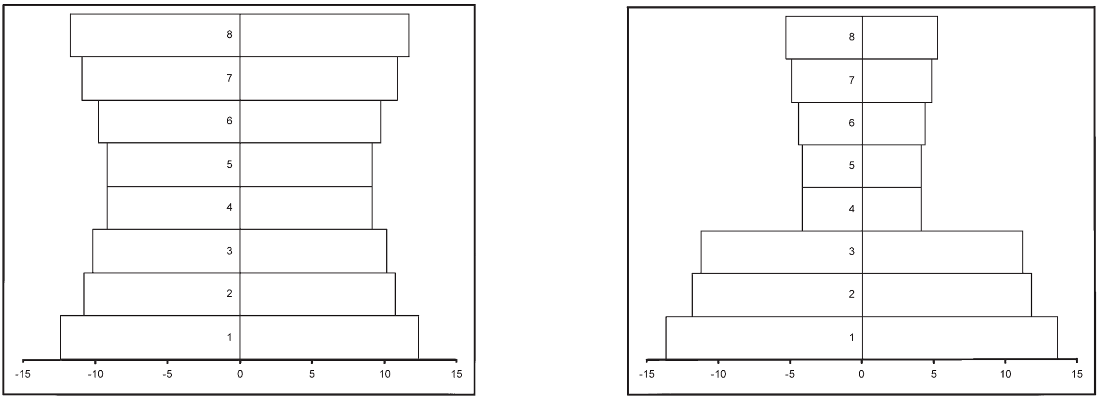
P-2 RA-3

Figure 4. Failure of glue line for rejected specimens.

Table 3. *Comparison of Young's modulus between tensile and compressive loading.*

	Modulus of elasticity (GPa)			
Species	Dynamic	Tensile	Compressive	Ratio (%) (C/T)
Pitch pine	8.310	9.129 (1.392)	3.701 (0.470)	46.4
Larch	9.600	9.917 (2.170)	4.599 (0.437)	45.5

SD shown in parentheses.



Dynamic MOE of laminates *Modified by the rate of compression and tension*

Figure 5. Modified modulus of elasticity of glulam laminates (Type P-1).

compression modulus of pitch pine and larch laminates and ratios of 1.1 and 1.03 for modifying tension modulus of pitch pine and larch laminates. Figure 5 shows the changes of MOE in the glulam.

Based on the modified MOE of laminates, the shift in the neutral axis for each glulam was calculated by the transformed section modulus method. The shift of the neutral axis and comparison between predicted and measured MOE are shown in Table 4.

Table 4. *The location of neutral axis and predicted modulus of elasticity (MOE) of glulam.*

		Location of neutral axis[a] (mm)	MOE (GPa)		
			Predicted	Measured	Ratio
P type	1	30.5	9.205	9.237	1.00
LR type	2	27.8	10.03	10.59	0.95
	3	27.3	9.978	10.74	0.93
	4	26.7	9.921	9.507	1.04
	5	26.6	9.911	9.743	1.02
RA type	2	28.8	10.34	9.524	1.09
	4	26.5	10.72	10.51	1.02
	5	22.8	10.93	11.14	0.98
Average		27.1	10.13	10.12	0.96

[a] The location of neutral axis was calculated by the modified MOE of laminates from dynamic MOE.

Recommendation for Improvement of Bending Performance of Glulam

In general, the failure of glulam under a bending load could be observed visually at the outmost tension laminate. Therefore, the research to improve bending properties of glulam focused on reinforcing the outermost tension-side laminate. Also, there are numerous quality limitations for choosing outmost laminates in related standards such as ASTM D 3737-05 and KS F3021 to assure the quality of glulam.

The measured neutral axis during testing revealed that it moved to the tension side of the beam as the bending load increased (Fig 3; Table 2). One of the main reasons for the neutral axis movement is the different modulus between the compression and tension directions. As a result of the shift of the neutral axis, the tensile stress of the glulam increased dramatically and the glulam failed abruptly. Among test specimens, some specimens showed compression failure on the compression side before catastrophic tension failure.

To delay the shift of the neutral axis to the tension side of the glulam under a bending load, reinforcing the compression laminate should be considered to increase the bending performance of glulam. In that way, the bending stress could be evenly spread throughout the beam and result in greater bending strength and less deflection under the bending load.

CONCLUSIONS

In this study, to improve the accuracy of the MOE prediction of glulam, the neutral axis shift under bending stress was measured and estimated. Information obtained about the neutral axis shift could improve the accuracy of the prediction of MOE of glulam by using the transformed section method. The conclusions of the research are as follows.

The error rate of prediction MOE of mixed-species glulam by the transformed section method without considering tension and compression modulus differences was about 30%.

To estimate the MOE of glulam more accurately, the difference of compression and tension modulus should be taken into account in the transformed section method. Therefore, the compression and tension modulus differences of each species should be identified before estimating MOE.

The accuracy of prediction of glulam MOE was improved significantly by reflecting the ratio of compression and tension modulus vs dynamic MOE of laminates.

The mechanism of the bending load bearing and failure indicated that the compressive side of glulam laminates experienced plastic behavior and failure. This caused the neutral axis to move to the tension side and increased tension stress caused the glulam to fail abruptly in tension. To improve the bending performance of glulam, the compressive yield stress of laminates needs to be considered.

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