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Feasibility of Non-Korean Standard Glulam Using a Lower Grade Lamina of Japanese cedar for Structural Use*1

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ABSTRACT

Japanese cedar has low density and poor mechanical performance. Manufacturing glue-laminated timber (glulam) is the best way to compensate for its poor mechanical performance. The Korean Standard (KS) confines outermost lamina of glulam to higher grade than E8, but the yield of higher than grade E8 from logs is only 6.5%. Therefore, the aim of this study is to investigate the possibility of non-Korean-Standard glulam in structural applications. Allowable stresses determined by both hand-calculation and Monte-Carlo simulation show a higher allowable stress than that of the KS-standard glulam of 6S-22B. In the Korean Standard (KS), knot characteristics are not taken into account. Japanese cedar has relatively small knots. We believe that the small knots in Japanese cedar contribute to a higher allowable stress than the KS-standard glulam would predict. The species classification of KS is required to be further subdivided into sub-species groups based on knot characteristics.

Keywords : glued laminated timber, Japanese cedar, low density species, machine grade, lamina, Monte-Carlo simulation

1. INTRODUCTION

Recently, a shortage of lumber, coupled with the demand to enhance the utilization of wood, has led to an interest in fast growing species such as Japanese cedar. Japanese cedar has frequently been used for structural purposes in other country, particularly in Japan. In Korea, the harvested quantity of Japanese cedar has increased, but it has not been used for structural purposes because of its low density and relatively low mechanical performance.

Glulam was developed for structural applications of large-scale buildings and domes. Compared to sawn timber, as well as to other structural materials, glulam has several distinct advantages: size capability, architectural effects, seasoning, variation of cross sections, grades, and its environmental footprint (Breyer, 1993). Especially in countries, such as Korea, that have difficulty cultivating larger-diameter trees, glulam has been thought to be the best alternative

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material for large cross-sectional applications. The large cross sectional pieces can be made by laminating small cross sectional pieces of lumber; hence the manufacture of glulam is one possibility for utilizing Japanese cedar for structural purposes.

For most materials, allowable properties can be determined via numerous full-scale tests. In the case of glulam, however, it is nearly impossible to conduct a large number of full-scale tests to give the statistical values for any specific combination. There have been many attempts to predict the mechanical performance of glulam. Freas (1954) proposed an empirical method, referred to as the I_k/I_g method. This method accounts for the strength reducing influence of knots as a function of their moments of inertia. This method was adapted to the current American standard, ASTM D 3737.

However, statistical distributions of glulam strength are not predicted with the I_k/I_g method (Lee *et al.*, 2000). Therefore, the major focus of research on glulam has been to model statistical distributions accurately. Foschi and Barrett (1980), Brown and Suddarth (1977), Foschi *et al.* (1989) and Lee *et al.* (2005) have provided methods for predicting the statistical distribution of glulam strength using a finite element model and a Monte-Carlo simulation.

The Korean Standard for structural glued laminated timber (Korean Standard Association, 2005) does not specify a method for predicting the mechanical performance of glulam, nor for determining allowable stress, but the standard does provide a method for manufacturing the glulam and limitations to guarantee its mechanical performance. The Korean Standard (KS) prohibits the outermost lamina of KS-glulam from being lower than E7. Because Japanese cedar has a relatively low modulus of elasticity (MOE), reducing the costs of production is difficult when the structural glulam is going to be manufactured with Japanese cedar.

Because enlarging the cross section can increase the resistance of glulam, non-KS-standard glulam was manufactured in this study. This study aims to investigate the feasibility of non-standard glulam for structural applications and to determine the allowable stress.

2. MATERIALS and METHODS

2.1. Yield of Outermost Lamina Allowed by Korean Standard from Log

This study used Japanese cedar (*Cryptomeria japonica*) grown in Seogwipo-si, Jeju, Korea. Each cross section measured 38 mm by 140 mm by 3600 mm. To investigate the frequency of lumber to be allowed as the outermost laminar by Korean Standard (KS), five hundred seventy three pieces of lumber were prepared and moisture content was approximately 15%. The conventional grading machine (MGFE-251, IIDA KOGYO co. ltd.) graded the specimens by the stiffness. The outermost lamina of KS-glulam must have higher stiffness than 8 kN/mm^2. The rate of outermost lamina allowed by KS was investigated.

2.2. Measurement of Input Variables for Prediction of Allowable Stress

2.2.1. Materials

In this study, another set of specimens was prepared from commercial mill in Seogwipo-si, Jeju, Korea, to investigate the knot and bending properties. Each cross section measured 38 mm by 140 mm by 3,600 mm. Three hundred eighty five pieces of machine-graded Japanese cedar lumber were prepared (Table 1) and dried to a moisture content of approximately 15%. The average oven-dry density was 410 kg/cm^3.

Table 1. Number of specimens of each mechanical grade

Lamina grade[1]	Number of specimens
E7	15
E6	43
E5	86
E4[2]	139
E3[2]	102

[1] This grade was provided by Korean Standard F3021. For example, an MOE of E7lamina should be in the range of 7,000 N/mm^2 to 7,999 N/mm^2

[2] These grades are not compliant with KS F3021. To increase the utilization of Japanese cedar, the rejected laminas were sorted into these two grades.

2.2.2. Investigation of Knot Data

The locations and sizes of knots were measured following ASTM 3737, and the knot area ratio (KAR) was evaluated with a database program.

2.2.3. Bending Test for Small Clear Specimens

From the graded specimens, three small clear specimens were cut from each piece of lumber. They were tested using the ASTM D 2555 standard.

2.3. Investigation of the Bending Strength of Non-standard Glulam

2.3.1. Glulam Manufacture

In this study we used 38 mm by 140 mm by 3600 mm Japanese cedar grown in Seogwipo-si, Jeju, Korea. One hundred two pieces of lumber were prepared and dried to a moisture content of approximately 15%.

The lumbers were graded by grading machine (MGFE-251). No lumber contained end-joint and edge-joint. Resorcinol adhesive was used for lamination.

Table 2. Combinations of non-standard glulamusing lower grade laminas

Combination	Lamina grade[1]	Number of pieces of glulam
C7	753357	5
C6	654456	6
C5	544445	6

[1] KS F 3021. The lamina grades were written without the letter "E."

To facilitate the spreading of adhesive, each lumber was planed to a thickness of 35 mm. Six-ply horizontally laminated glulam was manufactured via lamination. The final cross section measured approximately 210 by 140 mm. According to the Korean Standard (KS F 3021), the outermost lamina must be higher than grade E8, and the MOE should be higher than 8,000 N/mm^2. Non-standard glulam was manufactured according to the non-standard combination shown in Table 2.

2.3.2. Full-scale Bending Tests and Verification of a Strength Prediction Model

The I_k/I_g method provided by ASTM D3737-08 is widely used to determine allowable stress of glulam. This method calculates I_k/I_g value using knot statistics evaluated for each lamina grade and determines allowable stress of glulam by empirical regression curve between I_k/I_g value and glulam strength.

To investigate the influence of knots on glulam strength, full-scale three-point bending tests were carried out for the manufactured glulam in accordance with ASTM D 198. The span was 3.0 m and the loading speed was 10 mm/min. The knot-containing cross section of interest was placed on the loading point. The knot area ratio was measured and the sum of KAR within 300 mm length along the piece of lumber was calculated. The I_k/I_g was calculated by dividing the moment of inertia for knot by that for the gross cross section. The relationship between the I_k/I_g value and the bending strength was investigated.

2.4. Prediction of Allowable Stress of Glulam

It is very difficult and expensive to experimentally determine the allowable stress of glulam, because glulam has a large cross section, and various combinations are available. There are two methods for determining the allowable stress of glulam: a hand-calculation model based on the I_k/I_g method and the Monte-Carlo simulation.

2.4.1. Hand-calculation with the I_k/I_g Method

The allowable stress of glulam was calculated in accordance with ASTM D3737-08, which is widely called the I_k/I_g method. The values determined in 2.2 were used as input variable.

2.4.2. Monte-Carlo Simulation for Glulam Strength

Monte-Carlo simulations are frequently used to evaluate the strength of glulam because glulam's large size makes experimental investigation difficult and expensive.

The Monte-Carlo simulation in this study was fundamentally based on the I_k/I_g method, which was first proposed by Freas (1954) and modified by ASTM International. Basically, the method for predicting the bending strength of glulam was the same as that of ASTM D3737.

However, several modifications to the model were required for our Monte-Carlo simulation. ASTM D3737 was intended to determine allowable stress. To guarantee bending strength over the range of expected strengths, the depression curve below the average relation curve between the I_k/I_g value and bending strength is used to predict the bending strength of glulam (Freas, 1954). This study was intended to predict the bending strength of virtual glulams and to determine allowable stress using a statistical method. Therefore, Freas (1954)'s average relation curve (Eq. 1) was used for strength prediction, instead of the depression curve of ASTM D3737.

$$SMF_{knot,i} = \left(1 + 3\frac{I_k}{I_g}\right)\left(1 - \frac{I_k}{I_g}\right)^3 \qquad (1)$$

where I_k is the moment of inertia for knot and I_g is the moment of inertia for the gross cross section. When I_k was calculated, the knot area ratio for each lamina was generated by the best-fit distribution for KAR of the lamina grade, and the I_k value was calculated based on the generated KAR of each lamination. The $SMF_{knot,i}$ is the bending strength ratio of *i*th zone.

$$F = \min\left\{K(BSI_i)(SMF_{knot,i})\left(\frac{\frac{D}{z}}{d_i}\right)\left(\frac{E_T}{E_i}\right)\left(\frac{I_T}{I_g}\right)\right\} \qquad (2)$$

The bending strength of virtual glulam can be predicted using Eq. (2). This equation was adopted by ASTM D3737-08. In ASTM D 3737-08, F is the allowable bending stress. However, when carrying out the Monte-Carlo simulation, F was defined as the predicted bending strength for a virtual glulam. BSI_i is the strength index for bending. Originally, in the calculation of ASTM D 3737, this value should be determined by bending test of small clear specimen in accordance with Test Methods D 2555 and it should be determined by calculating the fifth percentile of MOR, dividing by the adjustment factor of 2.1, and multiplying by 0.743 to adjust to a 0.3 m depth. In the Monte-Carlo simulation, however, BSI_i was determined by generatingby the best-fit distribution determined by the bending test using small clear specimens

Table 3. Yield rates from logs of Japanese cedar grown in Jeju, Korea

Lamina grade[1]	Percentage	Cumulative ratio
E11[2]	0.0	0.0
E10[2]	0.5	0.5
E9[2]	2.0	2.5
E8[2]	4.0	6.5
E7	11.8	18.3
E6	19.8	38.1
E5	27.2	65.3
Others	34.7	100.0

[1] This grade was provided by Korean Standard F3021. For example, an MOE of E10for lamina should be in the range of 10,000 N/mm^2 to 10,999 N/mm^2

[2] This grade can be used for the outermost lamina of Korean-Standard glulam.

(ASTM D 2555), and multiplying by 0.745. Other notations of Eq. (2) not explained in this paragraph were the same as ASTM D 3737-08.

Finally, one thousand simulations and strength predictions of glulam were carried out for each combination via the repetitive generation of input variables for lamina. The fifth percentile value of the predicted bending strength of virtual glulam was determined, and the allowable stress was calculated by dividing the fifth percentile value by an adjustment factor of 2.1.

3. RESULTS and DISCUSSION

3.1. Yield of Outermost Lamina Allowed by Korean Standard

Table 3 shows the yield rate from logs of Japanese cedar grown in Jeju, Korea. The Korean Standard (KS) prohibits the outermost lamina of KS-glulam from being lower than E7. Only 6.5% of Japanese cedar can be used as the outermost lamina of glulam. Because the lumbers to be able to be the outermost lamina are not sufficient, reducing the costs of production is difficult when the structural glulam is going to be manufactured with Japanese cedar.

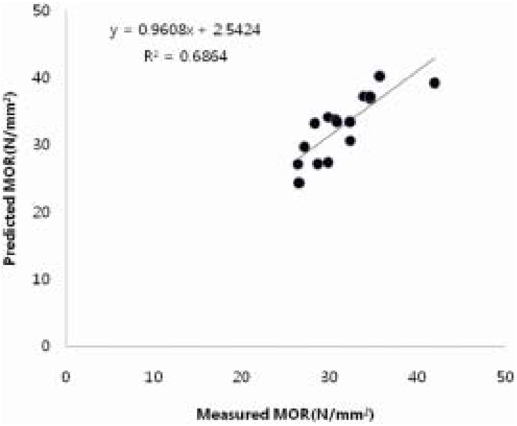

Fig. 1. Model verification for non-Korean-Standard glulam.

3.2. Verification of the I_k/I_g Method for the Strength Prediction of Glulam

To verify Freas (1954)'s model for predicting the bending strength of glulam, a full-scale bending test was conducted. The knot area ratio (KAR) was investigated, and I_k/I_g was calculated based on the KAR. Small clear specimens were cut from each lamina of the glulam, and their bending strengths were used as the basis strength variable. Fig. 1 shows the relationship between the predicted MOR and the actual MOR of non-standard glulam.

In both the hand-calculation and the Monte-Carlo simulation, the accuracy of determining the allowable stress depends on this correlation. Certainly, there is a need to improve the prediction of glulam strength, but this method, the I_k/I_g method, has been verified by numerous researchers since 1954. When compared to other species, Japanese cedar does not show a lower

Table 4. Bending strengths of small clear specimens for each machine grade

Grade	Stress index	Average	St. dev.	Distribution fitting	
				Distribution	$KS_{0.01}$ test[1]
E3	2.23	20.5	8.6	Normal	Accept
E4	2.91	32.1	14.5	Normal	Accept
E5	3.55	32.5	13.7	Normal	Accept
E6	3.04	32.5	14.5	Normal	Accept
E7	3.89	35.7	15.1	Normal	Accept

[1] Results of the Kolmogorov-Smirnov test. The hypothesis is "Bending strength follows a normal distribution." The significance level is 0.01.

Table 5. Knot characteristics for each machine grade

Grade	Average	99.5 percentile	St. dev.	Distribution fitting	
				Distribution	$KS_{0.01}$ test[1]
E3	0.177	0.725	0.160	Exponential	Accept
E4	0.158	0.661	0.152	Exponential	Accept
E5	0.118	0.596	0.126	Exponential	Accept
E6	0.111	0.536	0.121	Exponential	Accept
E7	0.092	0.433	0.129	Exponential	Accept

[1] Result of the Kolmogorov-Smirnov test. The hypothesis is "Knot area ratio follows exponential distribution." The significance level is 0.01.

correlation than Japanese larch (R^2 = 0.63, Lee *et al.*, 2005). From this result, we concluded that the I_k/I_g method can be reasonably applied to Japanese cedar glulam, even though improvements are required.

3.3. Determination of Input Variables

To determine the allowable stress of glulam, two characteristic are required: stress index and knot information. Tables 4 and 5 show the input variables for the hand-calculation: the stress index, average, and 99.5th percentile value of the knot area ratio.

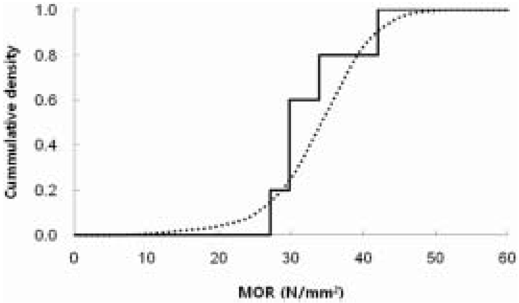

Fig. 2. Comparison of the cumulative densities in the simulation and the actual test of C7 glulam (Solid line: actual test, dashed line: simulation).

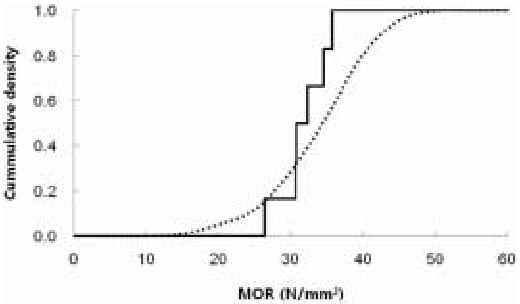

Fig. 3. Comparison of the cumulative densities in the simulation and the actual test of C6 glulam (Solid line: actual test, dashed line: simulation).

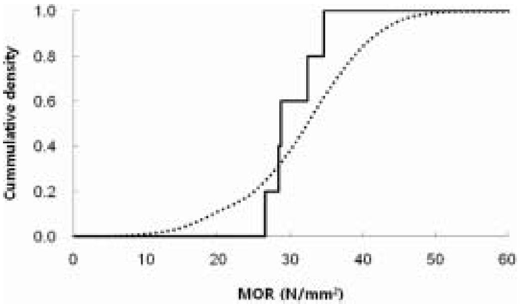

Fig. 4. Comparison of the cumulative densities of the simulation and the actual test of C5 glulam (Solid line: actual test, dashed line: simulation).

Table 6. Comparison of allowable stress between hand-calculation, monte-carlo simulation and the Korean standard glulam (unit: N/mm^2)

Combination		Experiment			Allowable stress		
Name	Lamina grade	Min.	Avg.	Allowance of 6S-22B[1]	Hand-calculation (ASTM)	Monte-Carlo Simulation	KS[2]
C7	753357	27.17	32.56	22	11.85	10.64	6
C6	654456	26.41	31.78	22	11.36	9.83	6
C5	544445	26.53	30.11	22	10.32	7.79	6

[1] Minimum bending strength, which the 6S-22B KS-standard glulam must satisfy in experiment.

[2] Allowable stress of 6S-22B KS-standard glulam, which is the lowest grade glulamallowed under the Korean Standard.

Tables 4 and 5 also show the distribution characteristics of bending strength and knots for the Monte-Carlo simulation. When bending strength was predicted by the Monte-Carlo simulation, the basic strengths of clear specimens and the knot area ratio were randomly generated via the normal distribution and exponential distribution of Tables 4 and 5.

The accuracy of the Monte-Carlo simulation depends on the goodness-of-fit of the input variables. Therefore, the Kolmogorov-Smirnov (KS) test was carried out to determine the goodnesses-of-fit for probability distributions for both input variables. Tables 4 and 5 show the results of the KS test for goodness-of-fit. It was found that bending strength follows a normal distribution at a significance level of 0.01, and that the exponential distribution is suitable for knot area ratio at a significance level of 0.01.

3.4. Allowable Stress of Non-standard Glulam

Allowable stress of all tested non-standard glulam showed bending strengths higher than that of 6S-22B KS-standard glulam, even though the glulam was laminated in a combination that does not satisfy the limitation of Korean Standard.

Table 6 shows the comparison of allowable stresses between the 6S-22B Korean Standard glulam and the hand-calculation and Monte Carlo simulation for non-Standard glulam. Hand-calculation using the I_k/I_g method results in a higher allowable stress value than the 6S-22B Korean Standard glulam, even though the tested glulam combination was manufactured with a lamina of a lower grade than that allowed by the Korean Standard. Figs. 2, 3 and 4 show the results of the Monte-Carlo simulation. The results of actual tests were within the range of the simulation and the allowable stress by the Monte-Carlo simulation was also a higher value than that of the 6S-22B standard glulam. Because the tested glulam had a higher allowable stress than does the 6S-22B KS-standard glulam, we considered the possibility that it can be safely used for structural applications even though it does not satisfy the limitations of the Korean Standard.

Table 7. Knot Sizes Measured on the Wide Faces of Three Species

	KS species group	Knot size (mm)	
		Average	St. dev.
Japanese larch	A	32.3	16.6
Red pine	B	70.5	36.2
Japanese cedar	D	27.8	13.4

Table 7 shows that the comparison of knot sizes between Japanese cedar and other species.

We found that Japanese cedar has relatively smaller knots. The Korean Standard provides the allowable stresses for four species groups, which are classified by density, rather than by knot characteristics. We considered that the relatively-small knot area ratio of Japanese cedar leads to a higher allowable stress than that expected by the Korean Standard.

It is well-known that two factors affecting the bending strength of glulam are the presence and size of knots and the MOE. MOE can be considered by machine grading, but knot characteristics are not taken into account in the Korean Standard. Certainly, species-classification by density can provide adequate agreement for the determination of allowable stress, but we propose that the species groups be divided into sub-species groups by knot characteristics.

4. CONCLUSION

The aim of this study was to investigate the feasibility of non-KS-standard glulam for structural applications.

Even though non-KS-standard glulam is manufactured by laminating lower grade lamina that do not satisfy the limitations of the Korean Standard, the possibility remains that they could be used safely for structural purposes. Allowable stresses determined both by hand-calculation and Monte-Carlo simulation showed higher values than that of the KS-standard glulam of 6S-22B. Even though the tested combinations were not manufacturedin accordance with the KS standard, they appear to qualify for structural use.

Japanese cedar has relatively small-sized knots, and the KS standard does not consider knot characteristics in species classification. We posit that these factors lead to a higher allowable stress than that predicted by the Korean Standard.

We found that the allowable stress provided by the KS standard was much lower than those of the actual test and simulation results. The Korean Standard does not take knot characteristics into account. In the case of species containing small knots, such as Japanese cedar, the underestimation of allowable stress may be sufficiently significant that it should not be disregarded. We propose that species groups be divided into sub-species groups based on knot characteristics.

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