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# Study on the estimation of the strength properties of structural glued laminated timber I: determination of optimum MOE as input variable

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**Abstract** There have been many attempts to predict the performance of glulam beams. Several approaches have been taken, from early empirical techniques to more sophisticated stochastic methods. In recent years, more emphasis has been placed on the modeling of material properties. Generally, the modulus of elasticity (MOE) has been used as a criterion of laminar strength for the prediction of glulam performance in the traditional models. Most of the current models are based on MOE that was measured using the long span test; that is, they account only for variability between pieces of lumber. Therefore, these models do not account for the variation of material properties within a given piece of lumber. Five methods were considered to choose the appropriate one that could effectively predict the performance of glulam in this study. Prediction of glulam performance was done by the transformed section method. MOEs measured with the five methods were applied to a strength prediction program to compare the actual test results and the predicted results. MOEs used as input variables are as follows: long span MOE of the static bending test, localized MOE of the static bending test, long span MOE of the stress wave test, localized MOE of the stress wave test, and MOE of the machine stress rating (MSR) test. Results of the localized test showed excellent signification compared to those of the long span test. The MSR method, when used as input variable, obtained the most approximate result, so it is considered adequate for predicting the strength of glulam.

**Key words** Long span MOE · Localized MOE · Machine stress rating test · Stress wave test · Glulam

## Introduction

There have been many attempts to predict the performance of glulam beams. Several approaches have been taken, from early empirical techniques to more sophisticated stochastic methods. In recent years, more emphasis has been placed on the prediction of material properties. At first, glulam performance was predicted with a regression approach that has been proven by the test results for laminar strength and glulam strength.[1–6] Efforts to predict glulam beam performance were also done by empirical methods, referred to as the $I_K/I_G$ method. This method accounts for the strength-reducing influence of knots as a function of the moment of inertia and is the basis for the current industry standard. However, statistical distributions of glulam beam strength are not predicted with this method, and the influence of end joints cannot be studied. Another approach taken to analyze glulam beams was the transformed section method.[7–9] The input value for this method consisted of beam geometry and configuration as well as allowable fiber stresses for each lamination. A model developed by Bender and Taylor was widely used to predict glulam performance, but this method has a weak point in that only long span MOE was used as an input value.[10]

Because of the recent shift to reliability-based design, the major focus of glulam research has been to model statistical distributions of beam strength accurately. To meet this objective, numerical methods have been widely used to develop more accurate criteria of strength prediction.[11–13]

All these traditional methods have been used lamina strength as an input value to predict glulam performance. Specifically, for material reuse and economic reasons the modulus of elasticity (MOE) has generally been used instead of the modulus of resistance (MOR) as a criterion of lamina strength for the prediction of glulam performance.

It is well known that the MOE of timber is positively correlated with bending strength. This correlation is applied to nondestructive testing and grading of lumber by machines, but the correlation is somewhat poor and depends

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on the way in which the MOE is measured. Correlation coefficients of 0.65–0.70 are typical when the MOE is determined as an apparent modulus during a bending test of the lumber piece over its entire length. It is also known that if the approximate variation of MOE is measured along the span the correlation improves when strengths are compared with the lowest, most localized MOE values. It can then be assumed that the efficiency of MOE as a predictor of strength could be improved if MOE were truly a localized measure, reflecting the point-to-point variation along the piece of lumber. However, most current models are based on MOEs measured in long span tests; that is they account only for the variability among different pieces of lumber. Therefore, these models could not account for the variation of material properties within a given piece of lumber. This information for within-piece variability is critical for the structural analysis techniques that require localized properties of individual elements, such as the finite element method.

The MOE of lumber shows a significant variation from the evaluating methods. Hence, the accuracy of prediction for glulam performance depends on the evaluation methods of MOE of lamina. Therefore, five test methods were considered before choosing the appropriate one that could effectively predict the performance of glulam. MOEs that were used as input variables are as follows: localized MOE for the stress wave method; long span MOE for the stress wave method; localized MOE for the static bending method; long span MOE for the static bending method; and mean MOE for the bending test by machinery (MSR, machine stress rating) method. Thus, five evaluation methods were used to choose the appropriate method for input variables. Glulam performance was predicted using these five results as input variables. It is desirable to obtain MOR by measuring each lamina to predict glulam MOR; however, if the MOR of the lamina were used as an input variable, accurate correlation between laminar strength and glulam strength could not be used to determine the loss of lamina during the test. So, the MOR of glulam was also predicted with the MOE of lamina. In other words, the MOR of lamina was converted by the MOE of lamina, and then the MOR of glulam was predicted with these converted MORs of lamina. The objective of this study was to determine the most effective method for selecting the appropriate input variable for predicting glulam performance.

## Materials and methods

### Lamina

Specimen for lamina of structural glulam was Japanese larch (*Larix leptolepis*). The representative sample consisted of a total of 200 pieces of 48 × 148 × 3600 mm lumber. The lumber was seasoned to a moisture content of 12% (dry basis) in a kiln. The final lumber after planing (35 × 145 × 3600 mm) was used as each lamina. The location and size of knots were recorded for each lamina.

To manufacture glulam with maximum combination of lamina, the laminae were divided into three groups (60 pieces of lumber per group) according to the MOE determined by the machine stress rating (MSR) test as follows:

| Group no. | MOE ($10^3$ kg/cm$^2$) |
|---|---|
| I | >118 |
| II | 100–118 |
| III | <100 |

### Glulam

A combination of laminae were used, as classified as Fig. 1, because of the limitation of the number of laminae. The glulam were assembled with six laminations. The depth of the glulam was 210 mm, the final width 130 mm, and the length 3000 mm. Resorcinol resin was used to manufacture the glulam. The mixing ratio of the resin and hardner was 100:15 g. The mixing condition was 30 °C and 65% relative humidity (RH). Three glulams per each combination of lamina, for a total of 30 glulams, were manufactured.

### Span for localized MOE

Traditional long span MOE and localized MOE that exhibit significant within-piece variability have both been used to evaluate the MOE of laminae. The main issue of a localized MOE evaluation method is always the length of the localized span. Based on much research, the need to consider local properties of lumber is stressed, with a variety of criteria suggested for the local span.[1,2,5,11,13] A widely used criterion is 60 cm element length, so 60 cm was chosen as the local span in this study.

### Measurement of MOE for lamina

The MOE for each lamina was measured by static bending test, stress wave test, and machinery bending test. The static bending test and the stress wave test were each conducted by two methods: the long span method and the localized method. A total of five evaluating methods were used to measure the MOE of lamina.

### Stress wave test

The long span MOE and the localized MOE of lamina were measured by stress wave timer (Metriguard 239A stress wave timer), as shown in Fig. 2. To measure the localized MOE, stress wave times were obtained at 60-cm intervals along the length of the lamina. To measure the long span MOE, stress wave times was obtained for the entire length of the lamina. The measurement technique involves introducing the stress wave to the lamina by mechanical impact. From the stress wave time measurement, the times taken to travel the 60-cm intervals and the entire length were mea-

**Fig. 1.** Combination of lamina to manufacture structural glued laminated timber. *Group number classified by MSR

| No.1 | No.2 | No.3 | No.4 | No.5 | No.6 | No.7 | No.8 | No.9 | No.10 |
|---|---|---|---|---|---|---|---|---|---|
| III* | II | II | II | I | I | I | I | I | I |
| III | III | II | II | III | II | II | I | I | I |
| III | III | III | II | III | III | II | III | II | I |
| III | III | III | II | III | III | II | III | II | I |
| III | III | II | II | III | II | II | I | I | I |
| III | II | II | II | I | I | I | I | I | I |

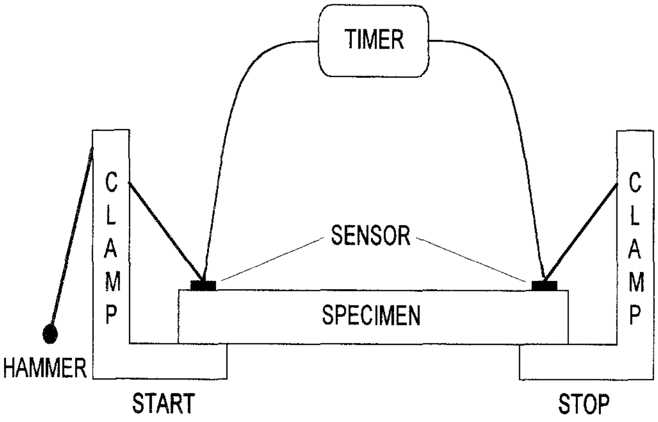

**Fig. 2.** Configuration for the measurement of stress wave time of lamina

sured. Based on the actual distance of this interval, the propagation velocity of the stress wave was calculated. MOEs of the 60-cm segment and the entire length were then calculated by Eq (1):

$$\mathrm{MOE}_{\mathrm{SW}} = \frac{D \times C^2}{g} \qquad (1)$$

where $\mathrm{MOE}_{\mathrm{SW}}$ is the stress wave modulus of elasticity by stress wave time (kg/cm$^2$), $C$ is the stress wave propagation velocity (cm/s), $D$ is the density of the lamina (kg/cm$^3$), and $g$ is the acceleration of gravity (980 cm/s$^2$).

### Static bending test

The long span MOE was measured using flatwise bending over a 3-m span with three-point loading. Localized MOE was measured on four contiguous 60-cm segments within each lamina using flatwise bending over a span of 1.8 m with four-point loading (Fig. 3).

### Bending test by machinery

The MOE was also measured by a grading machine. Sampling was carried with 15 specimens in advance, and 194 specimens were tested to measure the MOE. The MSR machine is shown in Fig. 4.

### Measurement of MOE and MOR of glulam

The MOE and MOR of glulam were measured over a 3-m span with five-point loading. The ultimate load, proportional limit load, and deflection were recorded for calculation of MOE and MOR of glulam.

### Modification of measured MOE

The MOE values of primary concern are apparent values $E_{\mathrm{ai}}$, used in deflection equations that attribute all deflection to moment. These apparent moduli may be standardized for a specific span/depth ratio and load configuration. Standardization should reflect, as far as possible, conditions of anticipated end use. When tests at standardized conditions of load and span are not possible, to adjust the $E_{\mathrm{ai}}$ to standardized conditions it is necessary to account for the effect of shear deflection on beam deflection. Factors to adjust $E_{\mathrm{ai}}$ for the span/depth ratio and load configuration may be derived from Eq. 2.[15]

$$E_{ai2} = \frac{1 + \mathrm{k}_1\left(\frac{h_1}{L_1}\right)^2 \cdot \left(\frac{E}{G}\right)}{1 + \mathrm{k}_2\left(\frac{h_2}{L_2}\right)^2 \cdot \left(\frac{E}{G}\right)} E_{\mathrm{ai}} \qquad (2)$$

where $h$ is the depth of the beam; $L$ is the total beam span between supports; $E_{\mathrm{ai2}}$ is the apparent modulus of elasticity based on any set of conditions of the span/depth ratio and load configuration; $E_{\mathrm{ai}}$ is the modulus of elasticity based on another set of conditions; $G$ is the modulus of rigidity; $k_1$ is 1.25 in this study; and $k_2$ is 0.91 in this study.

## Results and discussion

### MOE of lamina

The measured MOEs for each method were used to predict the performance of glulam. The cumulative probability function is shown in Fig. 5, and the correlation indices among methods are indicated in Table 1. According to the results of MOE of lamina, there was more difference be-

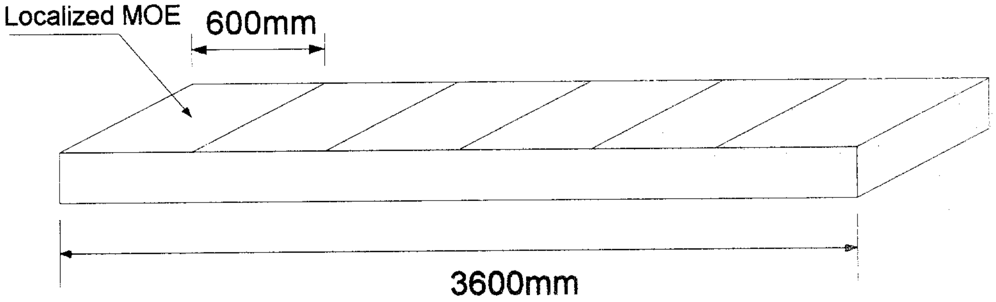

**Fig. 3.** Unit of localized modulus of elasticity (MOE) for each method

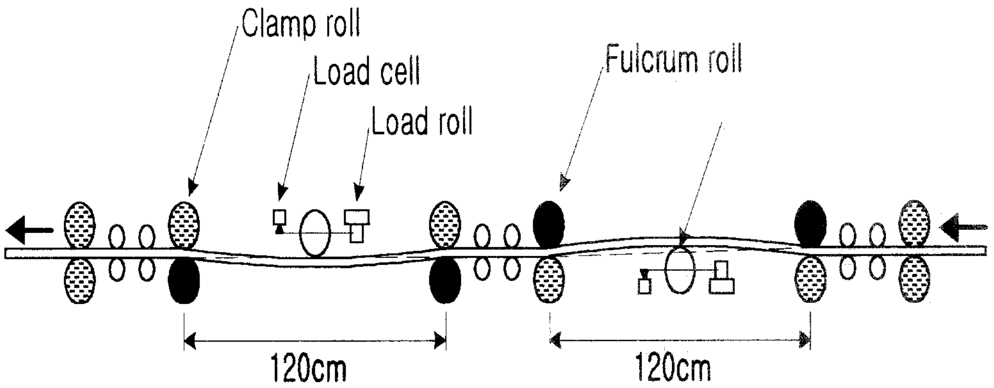

**Fig. 4.** Simplified configuration of machine stress rating (MSR) machine

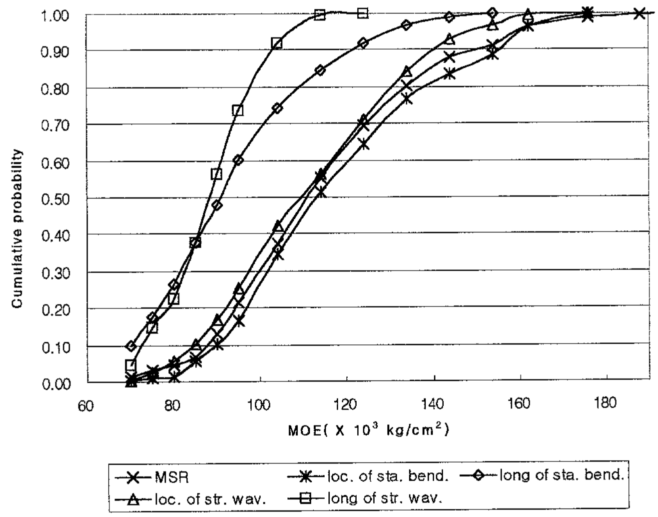

**Fig. 5.** Cumulative probability distributions of MOE for each method

**Table 1.** Correlation indices of each method

| Method | A | B | C | D | E |
|---|---|---|---|---|---|
| MSR (A) | 1 | 0.94 | 0.80 | 0.91 | 0.76 |
| Static bending | | | | | |
| Localized MOE (B) | – | 1 | 0.72 | 0.89 | 0.75 |
| Long span MOE (C) | – | – | 1 | 0.81 | 0.84 |
| Stress wave | | | | | |
| Localized MOE (D) | – | – | – | 1 | 0.76 |
| Long span MOE (E) | – | – | – | – | 1 |

MSR, machine stress rating; MOE, modulus of elasticity

tween the long span MOE and the localized MOE than the difference among the other methods. It is interesting that the result of MSR method is similar to the localized results of each method. All five results were applied to the prediction program of glulam performance.

## MOR of lamina

There were many regression equations between MOR and MOE.[1,2,13,16] Most equations were based on the long span test. Although there were problems with the long span test, the MORs of lamina were calculated using Eq. 3 without measurement, because lamina must been used when manufacturing glulam.

$$\mathrm{MOR} = 4.78 \times 10^{-3} \times \mathrm{MOE} + 0.2 \qquad (3)$$

Equation 3 is the regression equation reported by Hashizume et al.[16] These predicted MORs of lamina were used as input variables to predict glulam MOR.

## MOE and MOR of glulam

According to the results in Table 2, only one piece of glulam (8C) did not fail under 10 tons, and most pieces were destroyed in the area adjacent to the knot. Only two pieces of glulam (4B, 10B) failed outside the loaded area. Failure

**Table 2.** Bending test results for MOE and MOR of glulam

| | MOE ($\times 10^3$ kg/cm$^2$) | Average | MOR (kg/cm$^2$) | Average | Failure mode |
|---|---|---|---|---|---|
| Sample 1 | | | | | |
| A | 73.1 | 75.1 | 313.60 | 276.0 | Simple tension |
| B | 71.9 | | 246.05 | | Simple tension |
| C | 80.2 | | 268.24 | | Cross grain tension |
| Sample 2 | | | | | |
| A | 83.5 | 79.3 | 300.63 | 316.0 | Simple tension |
| B | 82.5 | | 326.84 | | Simple tension |
| C | 71.9 | | 320.52 | | Simple tension |
| Sample 3 | | | | | |
| A | 88.4 | 83.3 | 362.76 | 365.8 | Cross grain tension |
| B | 76.3 | | 290.98 | | Simple tension |
| C | 85.3 | | 443.55 | | Cross grain tension |
| Sample 4 | | | | | |
| A | 86.2 | 86.8 | 441.45 | 454.8 | Simple tension |
| B | 88.3 | | 401.47 | | Simple tension |
| C | 85.9 | | 521.41 | | Cross grain tension |
| Sample 5 | | | | | |
| A | 83.8 | 85.8 | 339.84 | 421.2 | Cross grain tension |
| B | 85.8 | | 445.96 | | Splintering tension |
| C | 87.9 | | 477.72 | | Simple tension |
| Sample 6 | | | | | |
| A | 91.8 | 93.7 | 565.40 | 481.5 | Splintering tension |
| B | 98.3 | | 525.92 | | Cross grain tension |
| C | 91.1 | | 353.13 | | Simple tension |
| Sample 7 | | | | | |
| A | 95.9 | 96.8 | 406.45 | 454.0 | Simple tension |
| B | 97.3 | | 520.99 | | Cross grain tension |
| C | 97.2 | | 434.56 | | Horizontal shear |
| Sample 8 | | | | | |
| A | 88.4 | 92.8 | 315.89 | 375.0 | Cross grain tension |
| B | 86.9 | | 434.14 | | Simple tension |
| C | 103.0 | | – | | Not failed |
| Sample 9 | | | | | |
| A | 93.7 | 93.7 | 422.55 | 419.6 | Cross grain tension |
| B | 89.7 | | 376.70 | | Cross grain tension |
| C | 97.8 | | 459.65 | | Simple tension |
| Sample 10 | | | | | |
| A | 107.7 | 98.6 | 587.34 | 530.3 | Cross grain tension |
| B | 93.5 | | 583.99 | | Simple tension |
| C | 94.5 | | 419.65 | | Cross grain tension |

MOR, modulus of resistance

mostly developed in the vicinity of the knot area, and principal failure modes were simple tension mode and cross-grain tension mode. Growth defect factors, such as knot and grain deviation, had more effect on failure development than the strength factors, such as MOR and MOE. Therefore, although the MSR result is economical and less time-consuming for glulam manufacturing of main structural members that require special attention, caution must also be considered for visual grading results, which could reflect detailed growth defects of members. Even if similar grade laminas are used for manufacturing glulam, growth defects must be avoided next to the loaded area.

Figure 6 shows the predicted MORs and measured MORs of glulam. The results in Fig. 6 show that the predicted MOR of glulam was highly sensitive to the MOE of lamina. Therefore, the MOE of lamina can be used as an input variable to predict the MOR of glulam.

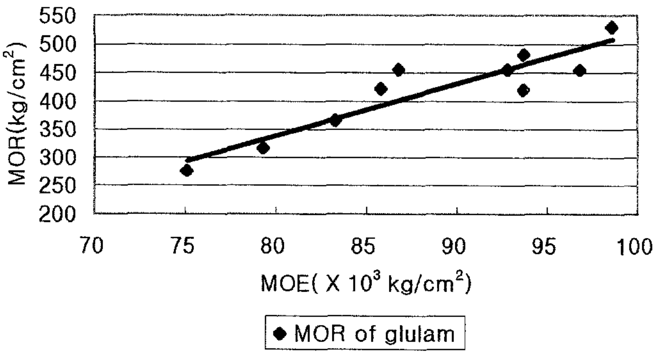

**Fig. 6.** Relation between predicted modulus of rupture (MOR) of glulam and measured MOR of lamina (results of stress wave test)

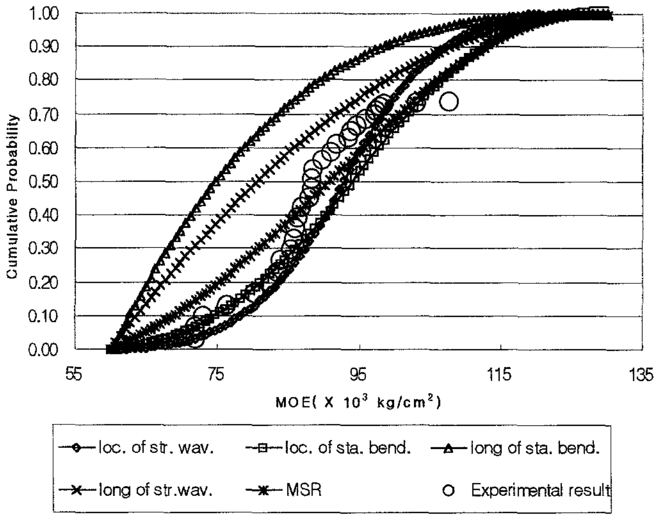

**Fig. 7.** Comparison of simulated results and actual test results for MOE of glulam (input variable is the MOE of lamina for stress wave test)

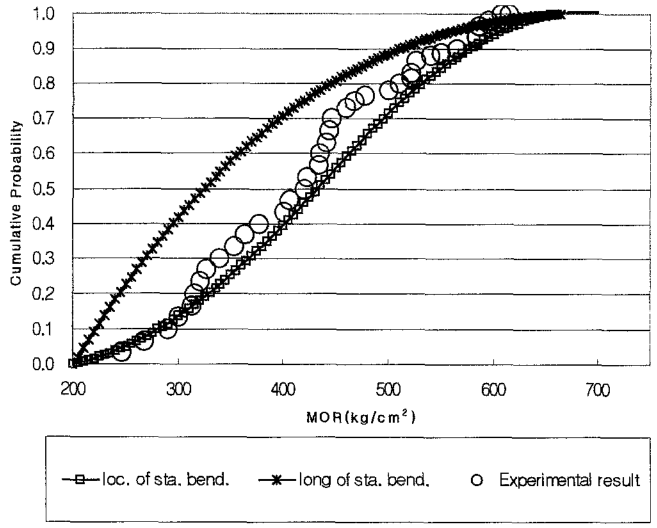

**Fig. 8.** Comparison of simulated results and actual test results for MOR of glulam (input variable is the MOE of lamina for stress wave test)

### Comparison of simulated and actual test results

Figures 7 and 8 show the cumulative probability distribution between simulated results and actual test results of the 6-Lam Japanese larch glulam beam. For all five input variables the simulated MOE and MOR of glulam were in close agreement with the actual test results, but there was a small difference between the predicted values depending on the results of the long span tests and the localized tests. This difference may be based on the hypothesis that localized properties more often reflect the detailed local strength-reducing factor of a member than long span properties, but more research is needed to make it clear. Also, according to previous research results, the mechanical properties of the lumber exhibit significant variability within individual pieces as well as between pieces.

**Table 3.** Correlation matrix of MOE for each method

| Test | MSR test | Static bending test | Stress wave test | Actual test |
|---|---|---|---|---|
| MSR | 1 | 0.85 | 0.87 | 0.95 |
| Static bending | – | 1 | 0.90 | 0.91 |
| Stress wave | – | – | 1 | 0.92 |
| Actual | – | – | – | 1 |

**Table 4.** Correlation matrix of MOR for each method

| Test | MSR test | Static bending test | Stress wave test | Actual test |
|---|---|---|---|---|
| MSR | 1 | 0.81 | 0.82 | 0.87 |
| Static bending | – | 1 | 0.79 | 0.85 |
| Stress wave | – | – | 1 | 0.90 |
| Actual | – | – | – | 1 |

Using the results of localized tests shows excellent correlation, rather than using those derived by the long span test. When the MSR result was used as an input variable, the most approximate result was obtained. Therefore, it is believed that the MSR test results as input data are adequate to predict the strength of glulam. MSR is the most economical and involves little loss of measurement time; it is also appropriate to process automation among each evaluation method to determine the strength of lamina.

Tables 3 and 4 show the correlation indices among actual test results and MSR results, localized static bending results, and localized stress wave results.

## Conclusions

Based on the results of the strength test of lamina, there was a more segnificant difference between the long span MOE and the localized MOE than among the other testing methods. All five input variables were applied in the strength prediction study to compare the actual results and the predicted results. There was a little difference between the predicted values depending on the results of the long span tests and the localized tests. When predicting the MOE and MOR of glulam, the results using the localized MOE of lamina showed better correlation rather than those using the long span MOE of lamina.

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