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Nondestructive Evaluation of Bending Strength Performances for Red Pine Containing Knots Using Flexural Vibration Techniques[*1]

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ABSTRACT

This paper deals with flexural vibration techniques as a means of predicting bending strength properties for quarter-sawn and flat-sawn planes of red pine containing knots. Dynamic modulus of elasticity (MOE_d) was calculated from resonance frequency obtained from the flexural vibration induced by a magnetic driver in quarter-sawn and flat-sawn planes of red pine containing knots. The dynamic MOE were well correlated to bending strength properties. Their correlation coefficients ranged from 0.866 to 0.800 for the regression between dynamic MOE and static bending MOE or MOR. The difference of the values between quarter-sawn and flat-sawn was very small. These values were higher than correlation between percentage of total knot diameter to total width of red pine specimen (K_T(%)) as well as K_O(%) base upon ASTM D 3737 and static bending strength properties (correlation coefficient r = 0.448~0.704), and were similar to those between static bending MOE and bending MOR (r = 0.850). These results indicate that dynamic MOE obtained from resonance frequency induced by flexural vibration of magnetic driver is able to effectively use for predicting of static bending strength of red pine containing knots as well as static MOE.

Keywords : flexural vibration, resonance frequency, dynamic MOE, knot, strength

1. INTRODUCTION

Nondestructive evaluation (NDE) techniques, such as machine stress rating (MSR), longitudinal and flexural vibrations, acoustic emission, acoustic ultrasonic, and x-ray have been used in past studies to predict the structural performance of timber (Beall and wilcox, 1987; Wilcox, 1988). The application of NDE techniques to improve the quality of dimension lumber is of particular importance because of the commercial interest in producing structural wood products with reliable performance. Interest in using methods that measure dynamic MOE from resonance frequency and the velocity of acoustic propagation has been growing for the last sev-

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eral years. Basic relations between ultrasonic propagation and wood properties (Park *et al.*, 2003; Jang, 2000; Kang & Lee, 2000; Lee *et al.*, 2003) and researches on NDE of woods containing knots using acoustic ultrasonic (Lemaster & Dornfeld, 1987) and longitudinal vibration (Cha, 1996) have been reported. Moreover, there are a few studies looking at dynamic MOE measured by using the resonance frequency induced by a magnetic driver under a both ends free condition, whereas this technique has been extensively used for detecting the characterization of solid wood and chemically modified wood for musical instruments (Kataoka and Ono, 1976; Norimoto, 1982; Tonosaki *et al.*, 1983; Sobue *et al.*, 1984; Hong, 1985, 1990; Yano *et al.*, 1986a, b; Akitsu *et al.*, 1991). However, NDE technique using resonance frequency induced by magnetic driver is expected to be used as an effective and simple NDE method for woods containing knots, whereas there are little researches applying the resonance frequency induced by a magnetic driver for woods containing knots.

Therefore, following previous reports on NDE of finger-jointed woods using the resonance frequency induced by a magnetic driver (Byeon *et al.*, 2005) and woods containing knots using resonance frequency induced by a mini shaker (Ahn *et al.*, 2005), the NDE for woods containing knots using resonance frequency induced by a magnetic driver was conducted, and static strength properties of red pine containing knots were estimated by dynamic MOE.

2. MATERIALS and METHODS

2.1. Specimen Preparation

Domestic red pine (*Pinus densiflora* Sieb. et Zucc.) containing different sizes of knots were prepared for this study. The knots were classified with the ratio of total knot diameter versus total width of red pine specimen for four planes (K_T(%)), and the K_T(%) was calculated by following equation (1) and the number of specimen based upon K_T(%) is shown in Table 1, and compared with K_o(%) calculated by equation (2) based upon ASTM D 3737.

$$K_T = (D_1+D_2+D_3+D_4)/(W_1+W_2+W_3+W_4) \times 100\ (\%) \tag{1}$$

where D_1, D_2, D_3 and D_4 are the diameters of each knot distributed in four planes of specimen, W_1, W_2, W_3 and W_4 are each width for four planes of specimen.

$$K_O = D/W \times 100\ (\%) \tag{2}$$

where D is a knot diameter in tension plane of bending test, W is width of specimen in tension plane of bending test.

The dimension of the specimens was 20 mm (T)×20 mm (R)×320 mm (L), and the knots were located at the center of the specimen. 100 specimens were prepared, and the measurements were made for quarter-sawn and flat-sawn planes, respectively. The specimens were maintained in a room temperature of 20°C, 65% RH for 3 weeks. Density and static bending MOE were measured, and the densities ranged from 0.44 g/cm^3 to 0.73 g/cm^3 (average value: 0.57, standard deviation: 0.05) at air-dried condition, and the static bending MOE ranged from 18,000 kgf/cm^2 to 114,000 kgf/cm^2.

2.2. Dynamic MOE Measurement by a Magnetic Driver (both ends free condition)

Vibration was induced via a small steel plate (Φ=5 mm) attached to the bottom end of the specimens and suspended by two threads at the

Table 1. Distribution of specimen based upon percentage of knot diameter to width of red pine specimen containing knots

Percentage of knots	Number of specimen for K_O (%)	Number of specimen for K_T (%)
0~9	0	1
10~19	0	10
20~29	0	16
30~39	0	15
40~49	4	25
50~59	10	18
60~69	5	10
70~79	6	1
80~89	10	4
90~100	65	0

Notes; K_O: Percentage of knot diameter to width of specimen in tension plane of bending test (ASTM D 3737), K_T: Percentage of total knot diameter to total width of specimen.

magnetic driver as shown in Fig. 1. The vibration was received at a small steel plate (Φ=5 mm) attached to the other end. The test was made for quarter-sawn and flat-sawn planes of red pine specimens containing knots under both ends free condition. The test apparatus consisted of a sine wave generator (Type 1023, B&K), a universal counter timer (Type 5001, GSP) and an oscilloscope (Type 1740A, HP). The value of the frequency counter timer was recorded when the relative amplitude indicated the highest value on the oscilloscope. Resonance frequency (f) and dynamic MOE (MOE$_d$) were calculated by the following equations (3) and (4) (Kataoka and Ono, 1975):

$$f = f_0(1+\alpha h^2/l^2) \tag{3}$$

where f_0 is the value obtained from frequency counter timer, α is the value according to vibration type-8.2, h is the thickness of specimen (mm), l is the length of specimen (mm).

$$\mathrm{MOE_d} = 48\pi^2 \rho l^4 f^2 / m^4 h^2 \tag{4}$$

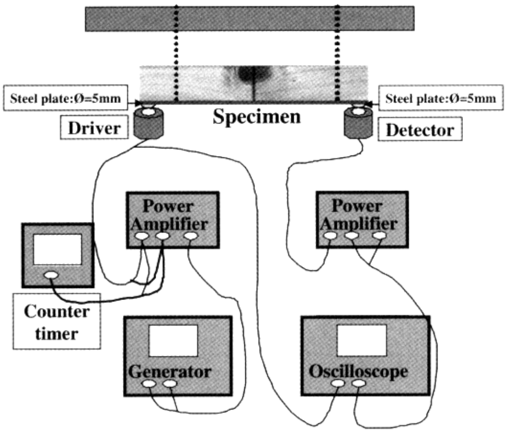

Fig. 1. Schematic diagram of flexural vibration techniques by a magnetic driver.

where ρ is the density (g/cm^3), m is the value according to basic vibration-4.73.

2.3. Static Bending Test

After the measurement of resonance frequency, static bending test was performed on the same specimens using a hydraulic testing machine (EHF-ED10-20L, Shimadzu) with center point

Table 2. Summary of regression parameters for regression analyses of percentage of knot diameter to width of red pine specimen containing knots and static bending strength properties

Test method	Regression Model	*r*
Bending	$\text{MOE}_B = -708K_T + 80710$	-0.704**
	$\text{MOE}_B = -482K_O + 87476$	-0.448**
	$\text{MOR}_B = -6.45K_T + 711$	-0.693**
	$\text{MOR}_B = -708K_O + 805$	-0.477**

Notes; MOE_B: Bending modulus of elasticity (kgf/cm^2), MOR_B: Bending modulus of rupture (kgf/cm^2), K_T: Percentage of total knot diameter to total width of specimen, K_O: Percentage of knot diameter to width of specimen in tension plane of bending test (ASTM D 3737). *r*: Correlation coefficient, **: Significant at 1% level.

loading method. The test span was 250 mm and the cross-head speed was set at 1mm/min. Static bending modulus of elasticity (MOE_B) and modulus of rupture (MOR_B) were calculated from the load and deflection within proportional limit and at maximum load. In all cases, the failure occurred at the part of knot in the red pine specimens.

3. RESULTS and DISCUSSION

3.1. Relation between Dynamic MOE (MOE_d) and Density

The density of red pine containing knots ranged from 0.44 to 0.73 g/cm^3 at air-dried conditions. Generally, close correlations between density and static strength performances for clear solid wood were reported (Ilic, 2001; Ross and Pelletin, 1991). Ayarkwa *et al.* (2001) clarified that correlations between density and MOE_d obtained from longitudinal vibration were generally strong like correlations between density and bending strength performances for both solid and finger-jointed specimens for each of the Obeche (*Triplochiton scletoxylon*), Makore (*Tieghemella heckelii*) and Moabi (*Baillonella toxisperma*). However, in this study, no correlations were found not only between density and MOE_d (correlation coefficient $r = 0.125$) but also between density and static bending strength performances for red pine containing knots ($r = 0.020$). This is considered because the regression analysis was performed without classifying tight knots and loose knots.

3.2. Relation between the Percentage of Knots and Static Bending Strength Properties

Regression parameters for regression analyses of knot percentage and static bending strength properties are shown in Table 2. In general, static bending strength properties markedly decreased with increasing the percentage of knot diameter to width of specimen. This is considered because the slope in elastic region was decreased by increase of the deviation of the grain and the rupture of wood fibers by knots with increasing knot percent to width of specimen, and strain beyond proportional limit was decreased by stress concentration around knots and decay and cracks of the knots. The extent of decrease was greater in the percentage of total knot diameter to total width of specimen (K_T(%)) than in the percentage of a knot diameter in tension plane of bending test to a width of specimen in tension plane of bending test (K_O(%)). And the correlation coefficients between static bending strength

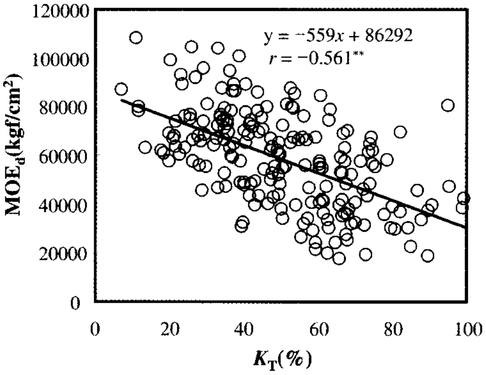

Fig. 2. Relation between percentage of knot to width of specimen (K_T(%)) and dynamic MOE (MOE_d) for red pine containing knots.

Notes; r: Correlation coefficient, ** : Significant at 1% level.

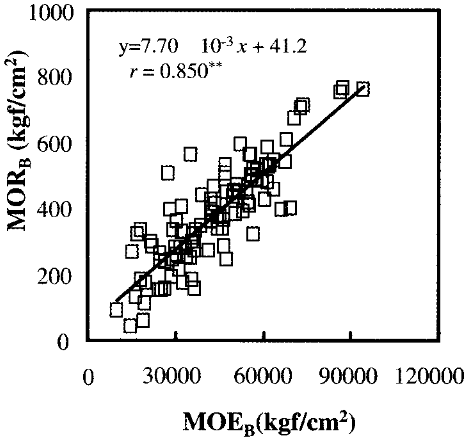

Fig. 3. Relations between static bending MOE (MOE_B) and MOR (MOR_B) for red pine containing knots.

properties were considerably greater in K_T(%) than in K_O(%). This is considered because the ASTM D 3737 method is considered only for width of knot regardless of depth of knot.

3.3. Relation between the Percentage of Knots and Dynamic MOE (MOE_d)

Fig. 2 shows the relation between the percentage of knot diameter versus the width of red pine specimen (K_T(%)) and dynamic MOE (MOE_d). The MOE_d decreased with increasing K_T(%) like the relation of static strength properties and knot percentage. The correlation coefficient for regression between K_T(%) and MOE_d showed 0.561, and it was smaller than in the relation of static bending MOE and the knot percentages. This is considered that MOE_d was decreased by decrease of density or cracks in the knots with increasing K_T(%), whereas the extent of the decrease was smaller than static bending MOE influenced directly by the deviation and rupture of the grain added with the facts mentioned above. This correlation coefficient also had the higher value than that (r = 0.313) for regression between MOE_d and the K_O(%) based upon ASTM D 3737.

Table 3. Summary of regression parameters for regression analyses of dynamic MOE and static bending strength properties for red pine containing knots

Test method	Regression model	r
Bending	$MOR_B = 7.70\times10^{-3}MOE_B + 41.2$	0.850**
	$MOE_{dQ} = 9.60\times10^{-1}MOE_B + 13780$	0.866**
	$MOE_{dF} = 1.01MOE_B + 14154$	0.868**
	$MOR_B = 6.50\times10^{-3}MOE_{dQ} + 14.0$	0.800**
	$MOR_B = 6.40\times10^{-3}MOE_{dF} + 5.76$	0.820**

Notes; MOE_B: Bending modulus of elasticity (kgf/cm^2), MOR_B: Bending modulus of rupture (kgf/cm^2), MOE_{dQ}: Dynamic MOE (kgf/cm^2) obtained from resonance frequency by flexural vibration of a magnetic driver in quarter-sawn plane, MOE_{dF}: Dynamic MOE (kgf/cm^2) obtained from resonance frequency by flexural vibration of a magnetic driver in flat-sawn plane, r: Correlation coefficient, **: Significant at 1% level.

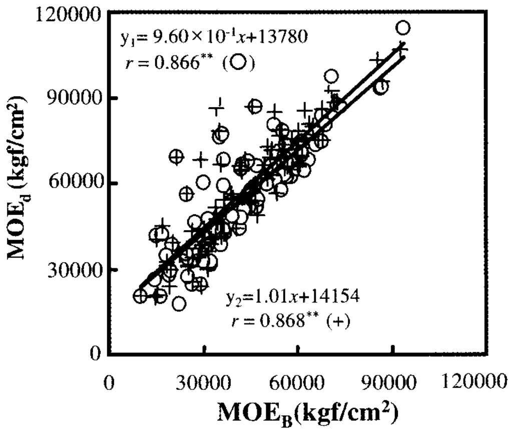

Fig. 4. Relations between MOE$_d$ and MOE$_B$ for red pine containing knots.

Notes; y_1: Quarter sawn plane (MOE$_{dQ}$), y_2: Flat sawn plane (MOE$_{dF}$), MOE$_{dQ}$ and MOE$_{dF}$: See notes in Table 3.

3.4. Relations between Static Bending MOE (MOE$_B$) and MOR$_B$

Fig. 3 and Table 3 show the correlations between static bending MOE (MOE$_B$) and MOR$_B$ for red pine containing knots. Generally, it was a strong correlation between static MOE$_B$ and MOR$_B$ as reported in several studies for solid woods and finger-jointed woods (Ayarkwa *et al.*, 2001; Byeon *et al.*, 2001, Park *et al.*, 2004). In this study, the correlation coefficient for the regression between static MOE$_B$ and MOR$_B$ for red pine containing knots was 0.850 (significant at 1% level). This result indicated that there was a general linear relationship between static MOE$_B$ and MOR$_B$ like several studies mentioned above. These correlation coefficients were markedly higher than that of the K_T(%) and MOR$_B$. Therefore, it can be said that static bending MOE is a good predictor of bending strength of red pine containing knots when the percentage of knots diameter to the width of red pine beam is relatively large, like several reports mentioned above for solid woods and finger-jointed woods.

3.5. Relations between Dynamic MOE (MOE$_d$) and Static Bending MOE (MOE$_B$)

Least squares regression analyses were performed to examine the correlation between MOE$_d$ calculated from resonance frequency induced by a magnetic driver and MOE$_B$. The derived regression parameters are summarized in Table 3, and the relation between the MOE$_d$ and MOE$_B$ for red pine containing knots is shown in Fig. 4. The correlation coefficients for the regression between the MOE$_d$ and MOE$_B$ were 0.866 and 0.868 in quarter-sawn and flat-sawn planes, respectively. A strong correlation significant at 1% level was found between both MOEs. These values were slightly lower than those between both MOEs of red pine finger-jointed woods by resonance frequency of a magnetic driver of previous report (Byeon *et al.*, 2005), whereas were higher than those of another previous report (Ahn *et al.*, 2005) which reported for regressions between MOE$_d$ as calculated from resonance frequencies by a mini shaker and MOE$_B$ for both planes (r = 0.819, 0.803). These results also agreed with the results of solid wood reported by Matsumoto and Tsutsumi (1968) and Norimoto (1982) and with the results by Bender *et al.* (1990) and Ayarkwa *et al.* (2001) for longitudinal vibration of finger-jointed wood. Therefore, it is concluded that dynamic MOE$_d$ obtained from resonance frequency of magnetic driver can be used to reasonably predict static MOE$_B$ in red pine containing knots.

3.6. Relations between Dynamic MOE (MOE$_d$) and Static Bending Strength (MOR$_B$)

The relations between MOE$_d$ as calculated from their resonance frequency and MOR$_B$ are shown in Fig. 5. The correlation coefficients between MOE$_d$ and MOR$_B$ were 0.800 and

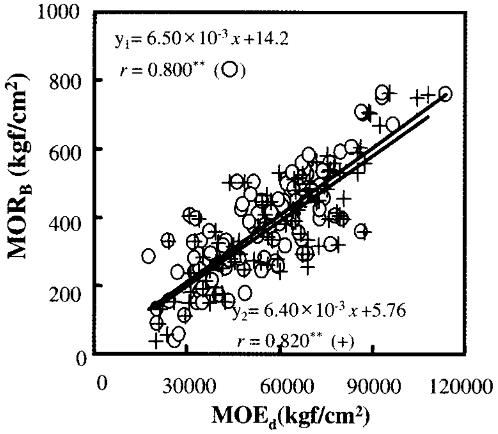

Fig. 5. Relations between MOE_d and MOR_B for red pine containing knots.

Notes; y_1: Ouarter sawn plane (MOE_{dQ}), y_2: Flat sawn plane (MOE_{dF}), MOE_{dQ} and MOE_{dF}: See notes in Table 3.

0.820 for quarter-sawn and flat-sawn planes, respectively. It was found that there was a strong correlation whose correlation coefficients were higher than those between K_T(%) and MOR_B, and especially, were considerably higher than those between K_O(%) based upon ASTM D 3737 and MOR_B. These results corresponded to the result of several researches which showed strong correlations between MOE_d and MOR_B for red pine containing knots (Ahn *et al.*, 2005) and red pine finger-jointed woods (Byeon *et al.*, 2005; Bender *et al.*, 1990; Ayarkwa *et al.*, 2001). Also, it agreed with the result for effect of knots to strength properties of knotty woods using longitudinal vibration reported by Cha (1996). These results showed that dynamic MOE calculated from resonance frequency induced by a magnetic driver had more close correlation with static strength properties than the percentage of knots in red pine, thus static bending strength properties were able to be estimated from the dynamic MOE (MOE_d). Therefore, the MOE_d obtained from resonance frequency by flexural vibration of a magnetic driver like the MOE_B is useful as a NDE method to predict the static bending strength of red pine containing knots.

4. CONCLUSIONS

Nondestructive evaluation using resonance frequency by flexural vibration of magnetic driver was carried out to predict bending strength performances for red pine containing knots.

There were no correlation between density and dynamic MOE for red pine containing knots owing to influence of knots. Static bending strength properties decreased with increasing percentage of knot diameter to width of specimen (K_T(%)), the extent of decrease was greater in K_T(%) than K_O(%) based upon ASTM D 3737. It was found that there were very close correlations between dynamic MOE and static bending strength properties. Their correlation coefficients were higher than those between K_T(%) as well as K_O(%) base upon ASTM D 3737 and static bending strength properties, and were similar to those for the static MOE and MOR. This result indicates that dynamic MOE has more close relation with static bending strength properties than K_T(%) or K_O(%), and dynamic MOE obtained from resonance frequency induced by flexural vibration of magnetic driver is able to effectively use for predicting of static bending strength of red pine containing knots with static MOE.

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