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Nondestructive Bending Strength Evaluation of Woodceramics Using Resonance Frequency Mode (I)[*1]

– Carbonizing Temperature –

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ABSTRACT

Nondestructive evaluation (NDE) technique method using a resonance frequency mode was carried out for woodceramics produced at different carbonizing temperatures (600°C, 800°C, 1000°C, 1200°C, 1500°C) at the phenol resin impregnation rate of 70%, for three kinds of species (*Pinus densifora, Pinus koraiensis, Larix leptolepis*), respectively.

There was a poor relationship between density and static bending MOR. However, close correlations were found between dynamic MOE_d and static bending MOR, and between static MOEs and MOR. Especially, the correlation coefficient was highest between MOE_d and static bending MOR. Therefore, the MOE_d using the resonance frequency mode is useful as a NDE method for predicting the MOR of woodceramics produced at different carbonizing temperatures.

Keywords : nondestructive evaluation (NDE), carbonizing temperature, woodceramics, resonance frequency, MOE, MOR

1. INTRODUCTION

Nondestructive evaluation (NDE) techniques have been extensively used for sorting or grading of wood products. Examples include visual grading and machine stress rating (MSR) of lumber. Dynamic modulus of elasticity (MOE_d) and ultrasonic techniques also have been used for the same purpose. There are two methods to measure dynamic MOE_d using a resonance frequency and the velocity of acoustic propagation. The resonance frequency can be achieved by a free vibration and/or the fast Fourier transform (FFT) analyzer of impact hammer signals. The dynamic MOE_d method using the resonance frequency has been extensively used for the characterization of wood for musical instruments (Sobue *et al.*, 1984; Hong, 1985, 1990; Byeon & Hong, 1997). The MOE_d method by an impact hammer has been developed as a simple and efficient method. Gehards (1974) showed that the stress wave speed are affected

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by such as moisture and temperature, grain angle, knot. In North America, the lumber grade was established by the MSR method (Galligan *et al.*, 1977) and computer simulation system to improve grade was also established (Biernacki *et al.*, 1997). A longitudinal stress wave and transverse vibration methods were developed for the estimation of modulus of the elasticity for lumber (Ross & Pellerin, 1991; Ross *et al.*, 1991, 1994).

The applications of stress wave signals by impact for log have been reported by several researchers (Aratake *et al.*, 1992; Ross *et al.*, 1997; Jang, 2000). Aratake *et al.* (1992) found that Sugi scaffolding boards can be graded with considering large spike knots. Ross *et al.* (1997) and Jang (2000) found that relationship between the MOE of the logs and the lumber obtained from the logs is high.

Another stress wave application approaches have been accomplished in degraded wood (Ross *et al.*, 1994, 1997). Ross *et al.* (1994) found that the stress wave evaluation technique is effective to detect the presence of wet wood in red oak lumber. Ross *et al.* (1997) also found that the stress wave characteristics have a good coincidence with compressive strength values of biologically degraded wood. The stress wave was also used by Cha (1996) for the development of glulam from Korean small diameter log.

Basic relationship between ultrasonic transmission and wood property was studied (Jang, 2000; Kang & Lee, 2000; Lee *et al.*, 2003). The ultrasonic was also used to evaluate the property of laminated wood (Hong *et al.*, 2001) and to assess wooden ancient buildings (Lee *et al.*, 2001).

The NDE of wood using the ultrasonic has been used to detect non-visible defects such as honeycomb or closed surface checks (Anderson *et al.*, 1997; Fuller, 1995). Lemaster & Dornfeld (1987) also showed that the ultrasonic is sensitive to the type of defects such as decay, knots, voids and cross grain. Most NDE technique applications focus on sorting and/or grading the lumber and/or log.

However, there was few researches in the application of stress wave for NDE of a woodceramics material. It is not suitable method to use impact hammer to evaluate the strength property because of its brittle property.

Therefore, NDE technique using the resonance frequency by free vibration mode was applied to woodceramics produced at different carbonizing temperatures, and the relationship between the resonance frequency parameter and static bending strength properties has been analysed.

2. MATERIALS & METHODS

2.1. Woodceramics specimen

Woodceramics produced at different carbonizing temperatures were used in order to estimate bending strength and resonance frequency. Woodceramics were made of sawdust board (density: 0.6 g/cm^3, moisture content: 8.5%, impregnation resin content: 70% of PF) impregnated with phenol resin from three kinds of species, *Pinus densifora, Pinus koraiensis,* and *Larix leptolepis* and carbonized in vacuum atmosphere at 600, 800, 1000, 1200 and 1500°C. The size of specimen was $10\times10\times90$ mm for the resonance frequency measurement and bending test.

2.2. Resonance mode and bending test

The resonance frequency was first measured by a free transverse vibration at both ends system apparatus which was composed of sine generator (B&K, 1023), universal counter timer (GSP, 5001), and oscilloscope (HP, 1740A). The value at frequency counter timer was measured

Table 1. Summary of regression parameters for relationships between density, MOR, MOE_{dT}, MOE_{dS} and MOEs for woodceramics produced at different carbonizing temperatures

Parameter	Regression model	Coefficient of determination R^2	Correlation coefficient r
Density vs. MOEs	y=19131x+1399	0.059	0.242
Density vs. MOR	y=91x+3.85	0.079	0.281
Density vs. MOE_{dT}	y=78232x-29766	0.417	0.646
Density vs. MOE_{dS}	y=90042x-31456	0.312	0.559
MOE_{dT} vs. MOE_{dS}	y=1.12x+3730	0.664	0.815
MOEs vs. MOR	y=0.0017x+46	0.181	0.425
MOEs vs. MOE_{dT}	y=0.647x+20610	0.178	0.422
MOEs vs. MOE_{dS}	y=0.2751x+33975	0.017	0.131
MOE_{dT} vs. MOR	y=0.0018x+17.9	0.465	0.682
MOE_{dS} vs. MOR	y=0.0012x+29.8	0.357	0.597

MOEs: static modulus of elasticity; MOE_{dT}: dynamic MOE of tension plane on the basis of bending test; MOE_{dS}: dynamic MOE of side plane on the basis of bending test; MOR: modulus of rupture.

when the relative amplitude value was highest in oscilloscope. Two frequency values of specimen at tension(T) and side(S) planes were measured on the basis of bending test for MOE_d. Resonance frequency(f) and dynamic modulus of elasticity (MOE_{dT}-tension plane, MOE_{dS}-side plane) were calculated by the following equations:

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

where, f_0: value at frequency counter timer, α: value according to vibration type-8.2, h: thickness of specimen (cm), l: length of specimen (cm).

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

where, ρ: density (g/cm^3), m: value according to basic vibration-4.73, h: thickness of specimen (cm), l: length of specimen (cm).

After resonance frequency measurement, bending strength property test for the same specimen was performed by three point loading method (concentrated load at midspan and supported at its ends) in a universal testing machine (UTM, Taeshin accuracy machine, TSU-2). The span was 70 mm, and the cross-head speed was set at 0.6 mm/min. The static modulus of elasticity (MOEs) and modulus of rupture (MOR) were calculated from the test result.

3. RESULTS & DISCUSSION

3.1. Relationship between density and MOE_d

Least squares regression analysis method has been used in the field of wood properties, because mechanical properties of wood are linearly related (Bodig & Jayne, 1982; Bucur, 1995). Regression parameters are presented in Table 1. Fig. 1 and 2 show relationship between density and two MOE_d of tension (MOE_{dT}) and side (MOE_{dS}) planes on the basis of bending test.

The correlation coefficients for woodceramics produced at carbonizing temperatures were 0.646

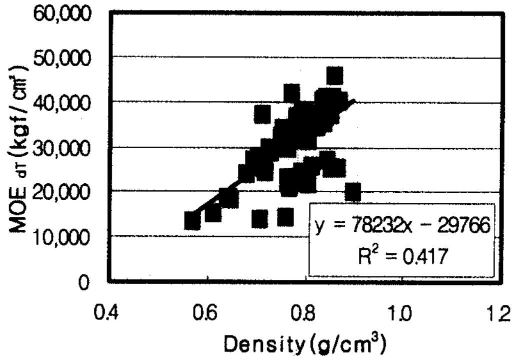

Fig. 1. Relationship between density and MOE$_{dT}$. (MOE$_{dT}$: dynamic MOE of tension plane on the basis of bending test)

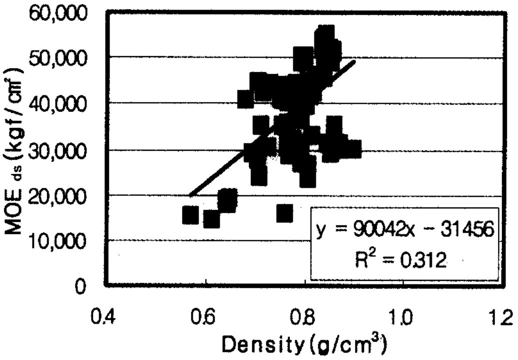

Fig. 2. Relationship between density and MOE$_{dS}$. (MOE$_{dS}$: dynamic MOE of side plane on the basis of bending test)

and 0.559, respectively. The correlation coefficient of density versus MOE$_{dT}$ was higher than that of density versus MOE$_{dS}$. It is considered to be caused by the vibration propagation affected by some coarse tissues including a dent at a side plane.

3.2. Relationship between density and mechanical properties

Relationships between density and MOEs, and MOR for woodceramics were analyzed. The regression coefficients showed that correlations between density and bending MOEs and MOR for woodceramics produced at different carbonizing temperatures were weak. This fact seems that the quality effect of material on MOEs and MOR is different from location, that is, the effect of outer is much higher than that of inner, however, density is just an average value of the material. In the end, outer density and mechanical properties of woodceramics were higher than those of inner.

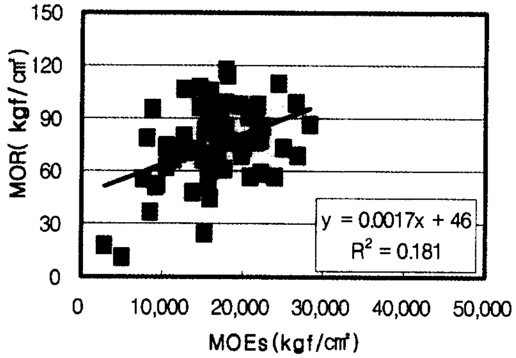

Fig. 3. Relationship between MOEs and MOR for woodceramics. (MOEs: static modulus of elasticity; MOR=modulus of rupture)

These results were different from normal solid wood and finger-jointed wood (Arakawa *et al.*, 2000).

3.3. Relationship between MOE$_d$ and mechanical properties

Relationships between MOE$_d$ and MOEs, MOR for woodceramics were analyzed (Fig. 3, 4 and 5). Generally, close correlation of MOE$_d$ and MOEs for clear solid wood was reported by stress wave mode (Ross & Pellerin, 1991). But, poor correlations were found in MOE$_d$ and MOEs for woodceramics produced by different carbonizing temperatures.

However, higher correlation coefficients of 0.682 and 0.597 were obtained for the regressions of MOE$_{dT}$ on MOR and MOE$_{dS}$ on MOR of which woodceramics produced by carbonizing temperatures. The correlation coefficient of MOEs and MOR for the woodceramics pro-

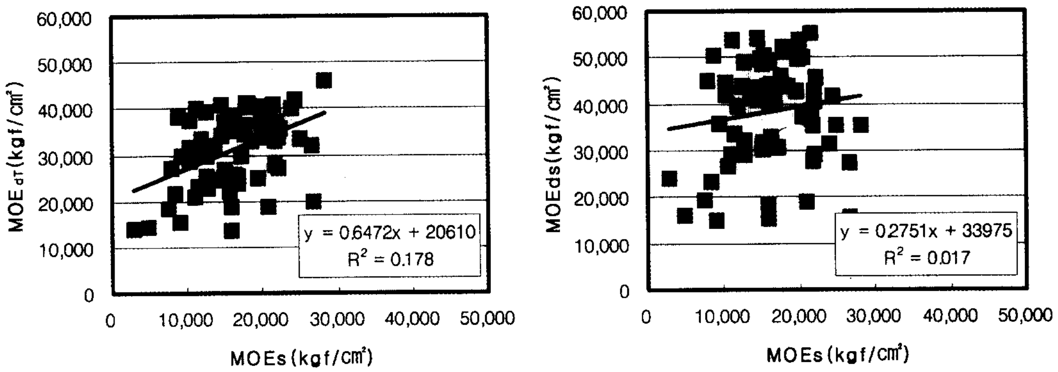

Fig. 4. Relationship betwee MOEs and MOE$_{dT}$, MOEs and MOE$_{dS}$ for woodceramics. (MOEs: static modulus of elasticity; MOE$_{dT}$: dynamic MOE of tension plane on the basis of bending test; MOE$_{dS}$: dynamic MOE of side plane on the basis of bending test)

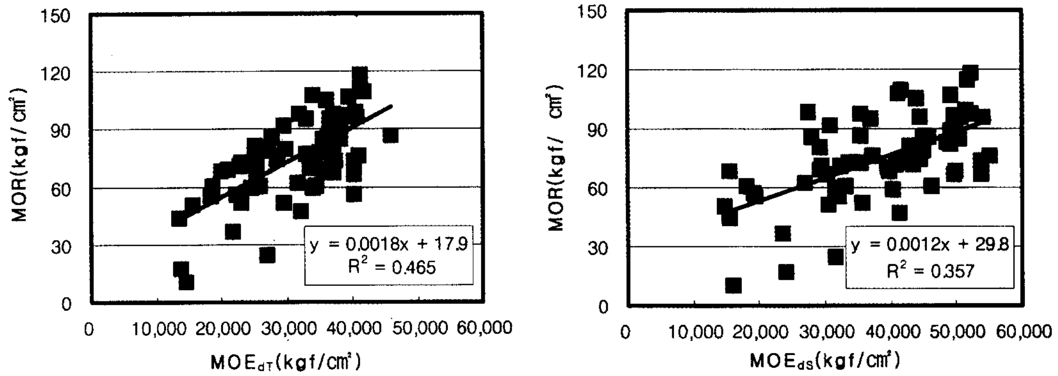

Fig. 5. Relationship between MOE$_{dT}$ and MOR, MOE$_{dS}$ and MOR for woodceramics. (MOE$_{dT}$: dynamic MOE of tension plane on the basis of bending test; MOE$_{dS}$: dynamic MOE of side plane on the basis of bending test; MOR: modulus of rupture)

duced at different carbonizing temperatures was 0.425 and the value of correlation coefficient is lower than those of MOE$_{dT}$ and MOR, MOE$_{dS}$ and MOR. And the value is lower than that of normal solid wood (Arakawa *et al.*, 1992; Jang, 2000). The result may be different from the typical load-deflection diagram for woodceramics comparing with solid wood (Fig. 6).

No curve was found even until maximum load for woodceramics, but almost linear straight line was observed in Fig. 6. It might be considered that the low slope of variation in lower load-deflection diagram for woodceramics causes low correlation coefficient in MOEs and MOR.

3.4. Predicting MOR of woodceramics

MOE$_d$ (T and S planes) and MOEs were separately correlated to MOR for woodceramics, and the results were written in Table 1.

The results showed that the correlations existed in MOE$_d$ and MOR, MOEs and MOR, and the correlation between MOE$_{dT}$ and MOR was much higher than that between MOEs and MOR. Therefore, MOE$_d$ is probably a good

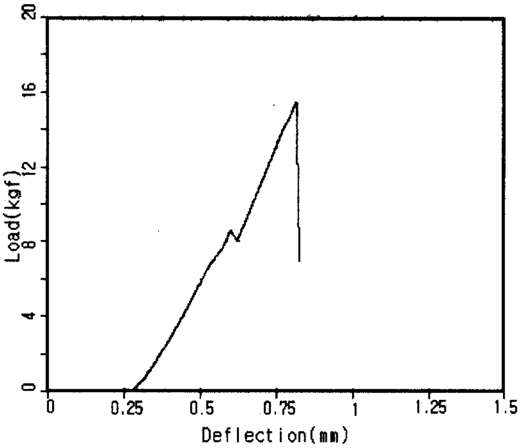

Fig. 6. Typical load-deflection diagram for woodceramics.

strength predictor for woodceramics produced at different carbonizing temperatures.

4. CONCLUSIONS

Nondestructive testing method using resonance frequency mode was carried out for woodceramics produced at different carbonizing temperatures.

There was a poor relationship between density and bending MOR. However, close correlations were found between MOE_d and static bending MOR, and between MOEs and MOR. Especially, the correlation coefficient was highest between MOE_d and static bending MOR. Therefore, the MOE_d using resonance frequency mode is useful as a NDE method for predicting the MOR of woodceramics produced at different carbonizing temperatures.

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