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RESEARCH ARTICLE

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Measurement of the dynamic modulus of elasticity of wood panels

Abstract This study investigated the dynamic modulus of elasticity (DMOE) of wood panels of *Fraxinus mandshurica*, *Pinus koraiensis*, and *Juglans mandshurica* using the natural frequency measurement system of fast Fourier transform (FFT). The results were compared with the static modulus of elasticity (E_S) tested by a mechanical test machine. The results show a significant correlation between E_S, transverse vibration DMOE (E_F), and longitudinal vibration DMOE (E_L). For all of these species, the correlation between E_S, E_F and E_L is more significant than the individual species, which indicated that the FFT method is universal. The correlations between E_S and sample's density (ρ) are significant, but the correlation coefficient of E_S and ρ is lower than those between E_F, E_L and E_S. The E_S of wood is more accurately tested by the analysis based on FFT measurement than by the estimation based on density.

Keywords lumber, non-destructive test, dynamic modulus of elasticity

1 Introduction

Non-destructive test (NDT) on wood is a technique that is applied to evaluate a material's defect and physical mechanical properties without any destructive effect on the wood (Li, 1991). Therefore, this technique has been widely used to determine the properties of wood-based materials in the last decades.

A typical NDT using sound transmits sound waves through wood and the resonant characteristics of wood are correlated with its physical and mechanical properties. Thus, it is possible to determine the mechanical strength using NDT technique by measuring the resonant frequencies and the transmit velocity of mechanical wave in wood. The modulus of elasticity (MOE) of wood is one of the most important parameters in reflecting the mechanical strength of wood. Thus, fast and accurate measurement of MOE of wood is considerably important for the NDT technique (Liu et al., 2004). So far, the most accurate method in measuring wood MOE is static bending test. However, this method is time-consuming, and impractical. There are many studies to evaluate wood properties by determining its dynamic MOE (Nobuo et al., 1991; Haines et al., 1996; Ilic, 2001) and some techniques have already been applied in industrial production settings.

In China, such researches have been done since the 1980s by ultrasonic impulse and FFT analysis techniques (Dai et al., 1987; Zhao et al., 1988; Wang et al., 1995; Hu, 1997; Li et al., 2003). Nevertheless, these studies were only laboratory work using small size samples (generally 300 mm×20 mm×20 mm) as described in the national standard (please refer which standard). In the industrial production setting, however, the wood panels are much larger in size (generally, up to 4 m×300 mm×60 mm or even more). Studies of NDT on large panels are few and further work needs to be carried out.

This paper studied the measurement of dynamic MOE of solid wood panels by vibration method based on the Fast Fourier Transform (FFT) analysis of hammered sound. The correlation between dynamic MOE and static MOE, and the feasibility of static MOE estimation by dynamic MOE were analyzed.

2 Materials and methods

2.1 Materials

The species of wood used in this study are *Juglans mandshurica*, *Fraxinus mandshurica*, and *Pinus koraiensis*. The wood are

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kiln-dry products obtained from the market. Before processing, the wood were conditioned at 20°C and 65% relative humidity for 3 months. Table 1 shows the dimensions and densities of samples.

Table 1 Dimension and density of samples

No.	Species	Number of sample/n	Length/mm	Width/mm	Thickness/mm	Density /(g·cm^{-3})
1	*J. mandshurica*	14	1000–2100	131.8–230.0	23.1–31.3	0.436–0.531
2	*F. mandshurica*	14	1500–2100	161.1–225.2	27.3–30.6	0.572–0.754
3	*P. koraiensis*	6	2000	139.0–206.2	20.1–26.2	0.401–0.481

2.2 Determination of dynamic MOE

This study used two modes to measure the dynamic MOE of wood: longitudinal vibration (Fig. 1) and flexural vibration (Fig. 2). For the longitudinal vibration mode, wood sample was supported at the 1st node by the cardboard. A sensitive microphone was placed on the end of the sample, and a hammer stroked on the other end. The vibration signals were analyzed by FFT. The longitudinal dynamic MOE (E_L) was calculated by Eq. (1) (Li, 2002).

$$E_L=4L^2f_m^{\ 2}\rho/m^2 \quad (1)$$

where E_L is the longitudinal dynamic MOE (GPa), L is the length of sample (m), f_m is the longitudinal resonant frequency (Hz), ρ is the density of sample (kg·m^{-3}), and m is the the times of the harmonic frequency.

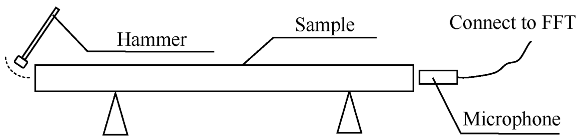

Fig. 1 Test principle chart of longitudinal resonance

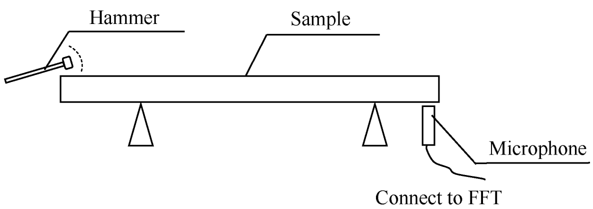

Fig. 2 Test principle chart of transverse resonance

Similar to the test of longitudinal vibration, the sample was supported at the 1st node (0.224L) by the cardboard in the flexural vibration mode (Fig. 2). However, the microphone was placed under the sample end and the hammer stroked upon the other end. The vibration signals were analyzed by FFT. The flexural dynamic MOE (E_S) was calculated by Eq. (2) (Li, 2002).

$$E_S=48\pi^2\rho L^4 f_m^{\ 2}/(m^4T^2) \quad (2)$$

where E_S is the flexural dynamic MOE (GPa), L is the length of sample (m), T is the thickness of sample (m), f_m is the flexural resonant frequency (Hz), ρ is the density of sample (kg·m^{-3}), and m is the coefficient of vibration.

2.3 Determination of static MOE

The static MOE (E_S) of wood sample was measured using a mechanical test machine (AG–10TA, Japan) referring to Chinese standard GB 1936.2–91. Some adjustments were done to correspond with the size of wood samples, for instance, changing the presser head dimension, increasing the load from 10–20 kN to 20–40 kN and changing the flexural value.

3 Results and discussion

The dynamic and static moduli of elasticity of tested samples are shown in Table 2.

Table 2 Dynamic and static modulus of elasticity of samples

No.	Species	E_L/Gpa	E_F/Gpa	E_S/Gpa
1	*J. mandshurica*	11.433–15.267	11.239–14.727	7.440–12.717
2	*F. mandshurica*	13.183–20.439	12.716–20.064	7.251–14.365
3	*P. koraiensis*	9.007–12.079	8.526–12.927	6.889–8.735

E_L is the MOE of longitudinal vibration, E_F is the MOE of transverse vibration, E_S is the static MOE.

3.1 Correlation analysis of flexural dynamic MOE and static MOE

Figures 3–5 show the relationship between flexural vibration dynamic MOE (E_F) and static MOE (E_S) of individual species samples. Figure 6 shows the relationship between flexural vibration dynamic MOE (E_F) and static MOE (E_S) in the collectivity group including all samples. The correlation between E_F and E_S of individual species sample group and collectivity sample group was analyzed by unitary linearity regression (Table 3). The results show that the correlation coefficients between E_F and E_S of individual species sample group and collectivity sample group were above 0.8. A significantly linear correlation between E_F and E_S of *J. mandshurica* group and *F. mandshurica* group was found, and *P. koraiensis* group had a linear correlation. In the three

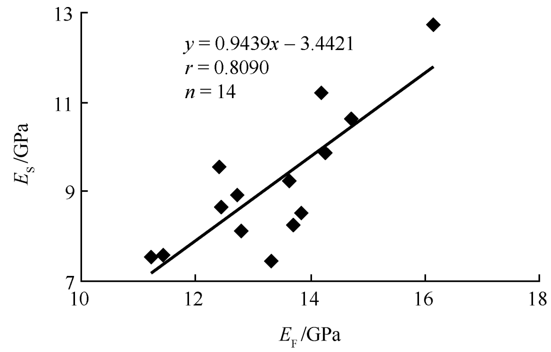

Fig. 3 The correlation of E_S and E_F of *J. mandshurica*

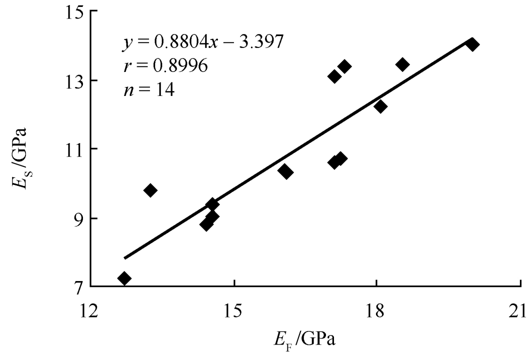

Fig. 4 The correlation of E_S and E_F of *F. mandshurica*

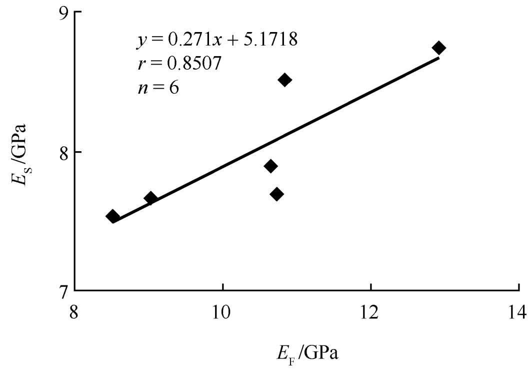

Fig. 5 The correlation of E_S and E_F of *P. koraiensis*

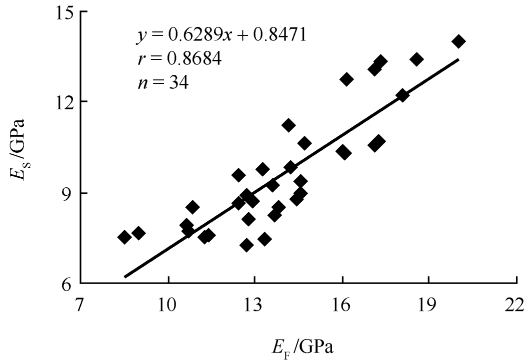

Fig. 6 The correlation of E_S and E_F of whole samples

Table 3 The correlation equation between E_S and E_F

Species	Number of sample	Linear regression: *y=ax+b*				*r*	Significance
		y	*x*	*a*	*b*		
J. mandshurica	14	E_S	E_F	0.943,9	–3.442,1	0.809,0	**
F. mandshurica	14	E_S	E_F	0.880,4	–3.397,0	0.899,6	**
P. koraiensis	6	E_S	E_F	0.271,0	5.171,8	0.850,7	*
Collectivity sample	34	E_S	E_F	0.628,9	0.847,1	0.868,4	**

* is marker relation, ** is the most marked relation.

species groups, the correlation coefficient of *F. mandshurica* was highest. When all samples composed a collectivity group, it showed a significantly linear correlation between E_F and E_S.

3.2 Correlation analysis of longitudinal dynamic MOE and static MOE

Figures 7–9 display the relationship between longitudinal vibration dynamic MOE (E_L) and static MOE (E_S) of individual sample group. The relationship between longitudinal vibration dynamic MOE (E_L) and static MOE (E_S) in the collectivity group is plotted in Fig. 10. The correlation between E_L and E_S of individual species sample group and collectivity sample group were analyzed using unitary linearity regression and the results showed the significantly linear correlations (Table 4). The coefficients were above 0.79 except for the *P. koraiensis* group. Among the three species groups, *F. mandshurica* had the highest correlation coefficient, and lowest for *P. koraiensis*. In the collectivity group, it showed a significantly linear correlation between E_L and E_S.

For the *P. koraiensis* group, the correlation between E_S and E_L was not significant. This may be explained by the variation of its wood quality because the wood of *P. koraiensis* has many knots and is slightly decayed. It was found that the resonant frequency was difficult to measure in the experiment and the formant of frequency spectrum was confused to some degree. Thus, the regression formula must be corrected to increase the correlation between dynamic and static MOE of wood with defects. More work needs to be carried out to get accurate test results on the mechanical strength of decayed wood by vibration.

From the above analysis, the correlation coefficients between E_L and E_S were less than those between E_F and E_S as expected because the test mode of E_S was flexural distortion, while flexural vibration was used for the test mode of E_F; both are based on the flexural theory. The test mode of E_L is longitudinal vibration, which is different from E_S and E_F. Therefore, it showed more significance in the correlation between E_F and E_S than between E_L and E_S. This is consistent with the testing results using small size samples (Ilic, 2001).

Tables 3 and 4 show that the slope (*a*) and vertical intercept (*b*) of the regression formulas of E_F-E_S, E_L-E_S are quite close in all sample groups. That is to say the regression lines are parallel and the distance between lines is short, suggesting that it is feasible to evaluate the static MOE by testing dynamic MOE by vibration method. The slope (*a*) of the regression lines of *J. mandshurica* and *F. mandshurica* groups are close to 1, but that of *P. koraiensis* is less than 0.3. The regression formula vertical intercept (*b*) of *J. mandshurica* and *F. mandshurica* are below 0 and that of *P. koraiensis* is above 0. These results indicate that the mechanic strength of *P. koraiensis* was low, and the evaluation precision for static MOE was lower than both species of *J. mandshurica* and *F. mandshurica*.

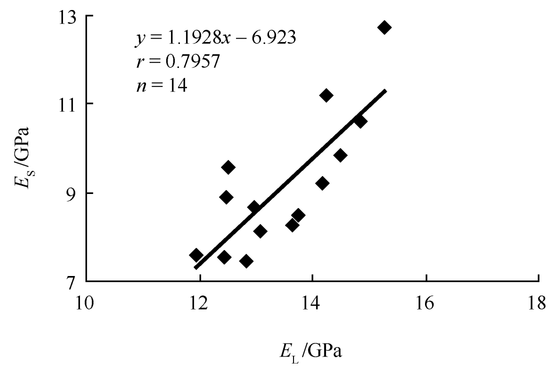

Fig. 7 The correlation of E_S and E_L of *J. mandshurica*

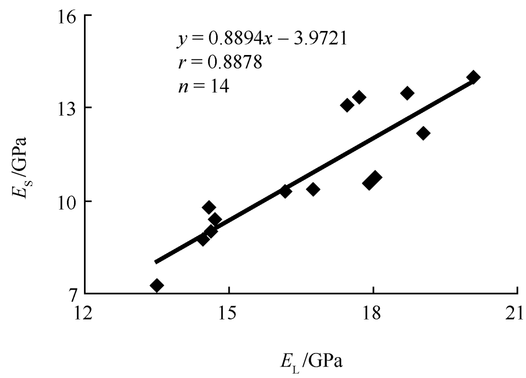

Fig. 8 The correlation of E_S and E_L of *F. mandshurica*

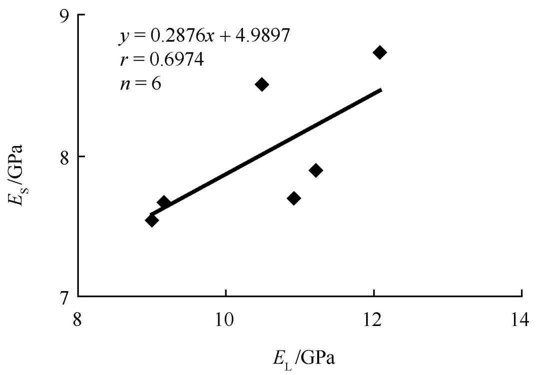

Fig. 9 The correlation of E_S and E_L of *P. koraiensis*

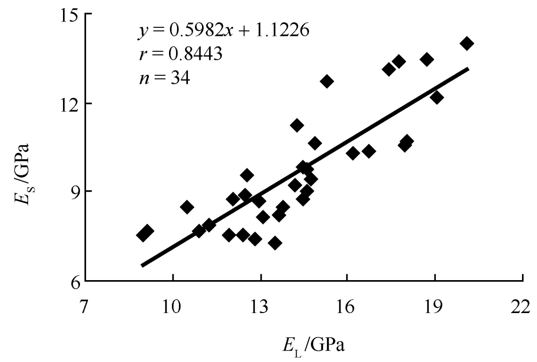

Fig. 10 The correlation of E_S and E_L of whole samples

Table 4 The correlation equation between E_S and E_L

Species	Number of sample	Linear regression：*y=ax+b*				*r*	Significance
		y	*x*	*a*	*b*		
J. mandshurica	14	E_S	E_L	1.192,8	–6.923,0	0.795,7	**
F. mandshurica	14	E_S	E_L	0.889,4	–3.972,1	0.887,8	**
P. koraiensis	6	E_S	E_L	0.287,6	4.989,7	0.697,4	
Collectivity sample	34	E_S	E_L	0.598,2	1.122,6	0.844,3	**

** is the most marked relation.

3.3 Correlation analysis among E_S, E_F, E_L

The correlation coefficients between E_S and E_F, E_S and E_L, E_F and E_L of individual species sample group and collectivity group are shown in Fig. 11.

In all sample groups, it followed the relationship: $r_{E_F-E_L} > r_{E_S-E_F} > r_{E_S-E_L}$, showing that the correlation between static and dynamic MOE is very significant and the correlation between E_S and E_L is not significant.

Based on the analysis and Fig. 11, the correlations between static and dynamic MOE are more significant ($r_{E_S-E_F}$ =0.868,4, $r_{E_S-E_L}$ =0.844,3, $r_{E_F-E_L}$ =0.983,4) in the collectivity group than in the individual group. Thus, it is possible to automatically measure the MOE of wood by the vibration method.

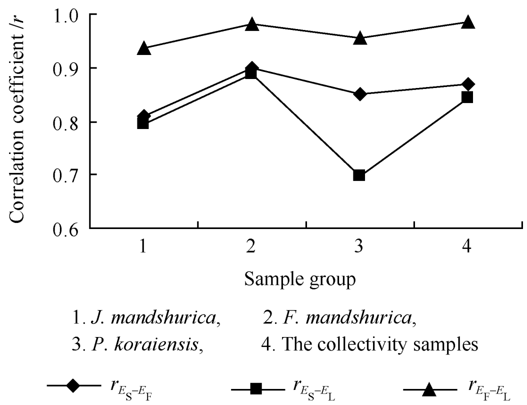

Fig. 11 The relationship of different correlation coefficient

3.4 Correlation of MOE and density

As it is known, wood strength is affected by its density. The previous research has indicated that the correlation between wood density and MOE is significant to some extent (Zhao, 1988). In this study, the correlation between wood density and static MOE is significant ($r_{E_S-\rho}$=0.722,0). The correlation between dynamic MOE (E_F, E_L) and static MOE (E_S) is more significant (the correlation coefficient is 0.8–0.9, except the *P. koraiensis*) than that between E_S and density, which suggests that E_S of wood estimated by FFT is more exact than by density.

Furthermore, all wood samples were divided into 3 groups without considering species to investigate the effect of wood density on the correlation between dynamic and static MOE. The correlations between E_S and E_F, E_S and E_L were analyzed at the different density levels (Table 5). The results showed that the correlations between E_S and E_F, E_S and E_L were significant and $r_{E_S-E_F}$ was larger than $r_{E_S-E_L}$. Moreover, the correlation coefficients ($r_{E_S-E_F}$, $r_{E_S-E_L}$) increased with the density; however, the effect of increasing wood density on the correlation between static and dynamic MOE is not clear.

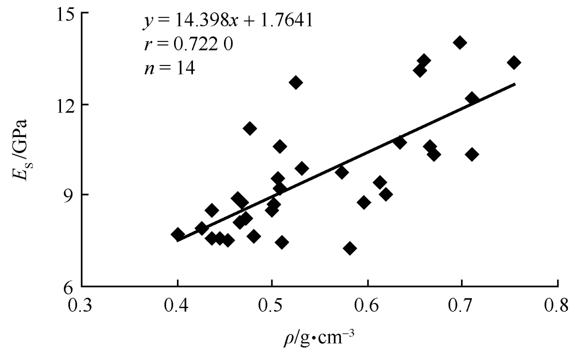

Fig. 12 The correlation of ρ and E_S

4 Conclusions

The study showed a significantly linear correlation between static MOE (E_S) and dynamic MOE (E_L and E_F) in the individual species samples group and collectivity sample group. The correlation coefficient between E_S and E_L (r=0.844,3) is smaller than that between E_S and E_F (r=0.868,4).

The correlation between E_S and E_L, E_F of collectivity sample group is more significant than the individual species samples group, suggesting that the FFT method in evaluating the wood MOE is practical in the real-time strength- inspecting machine.

The correlation between E_S and density was significant, but lower than that between E_F, E_L and static E_S. It indicated that the E_S of wood estimated by FFT method is more exact than by density.

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