An Integrated NDT Approach for Determining Residual Strength of Ancient Wood Structural Members

Houjiang Zhang[1], Xiping Wang[2], Lei Zhu[3], Yanliang Sun[4], Robert J. Ross[5], and Brian K. Brashaw[6]

Abstract In structural inspection and evaluation of ancient wood structures, it is critical to determine the residual material properties of the key structural members so that the degraded or deficient members can be replaced or repaired to avoid structural failures. In this study, we evaluated stress wave and resistance micro-drilling techniques for their ability to predict material properties of ancient wood structure members. An integrated NDT approach was proposed to utilize both stress wave speed and relative resistance of micro-drilling as predictive parameters of the stiffness and residual strength of the wood members. The materials used in this study were Larch (*Larix principis-rupprechtii Mayr.*) timber obtained from Zhengjue Temple at Yuanmingyuan Imperial Garden in Beijing during a renovation project. Following stress wave measurements and micro-drilling tests, we conducted static bending and compression parallel-to-grain tests on the wood samples to determine the modulus of elasticity, bending strength, and compression strength. Our analysis indicated that combining stress wave speed and relative resistance in a linear regression model can provide better predictions of mechanical properties than using stress wave speed or relative resistance alone.

Keywords Ancient wood structure, mechanical properties, resistance micro-drilling, residual strength, stress wave speed

1. INTRODUCTION

China has thousands of years of history of using wood as a building material. The building system of China's historic wood structures was a perfect mixture of traditional Chinese arts and ancient building techniques. Many ancient wood structures built throughout the country have survived hundreds of years of aging and natural events and constitute unique national cultural heritages. It is imperative for the government to preserve these historic structures for future generations and ensure a safe tourism environment for many years to come.

[1] Houjiang Zhang, School of Technology, Beijing Forestry University, China, hjzhang6@bjfu.edu.cn
[2] Xiping Wang, USDA Forest Products Laboratory, USA, xwang@fs.fed.us .
[3] Lei Zhu, School of Technology, Beijing Forestry University, China, mogmogerly1985@163.COM
[4] Yanliang Sun, School of Technology, Beijing Forestry University, China, sunyanliang702@163.com
[5] Robert J. Ross, USDA Forest Products Laboratory, USA, rjross@fs.fed.us
[6] Brian K. Brashaw, Natural Resources Research Institute, University of Minnesota Duluth, USA, bbrashaw@nrri.umn.edu

Maintenance and repair has been an important task in structure preservation. In the past, engineers and wood workers in China accumulated a great amount of experiences in repairing damaged wood members. But timber inspection and evaluation techniques are lacking. Visual assessment and simple sounding are still the main methods being used in field.

There are two critical aspects in inspecting and evaluating ancient wood structural members: 1) detecting the internal defects that cannot be visually seen; and 2) determining the residual mechanical properties of the wood members. Many field and laboratory research have been focused on detecting internal wood defects, and achieved a great success in using a variety of NDT techniques, such as stress waves, sonic tomography, and resistance micro-drilling (Ross et al. 2004, 2006; Pellerin and Ross 2002; Duan et al. 2007a; Huang et al. 2007; Wang et al. 2008). However, research on determining the residual mechanical properties of the wood members is still lacking. Duan et al. (2007b) estimated the modulus of elasticity of ancient wooden structure members using stress wave method, and found a moderate relationship between stress wave speed and the modulus of elasticity. Ceraldi et al. (2001) reported that the strength of the ancient wooden materials was related to micro-drilling resistance. In this study, we evaluated an integrated NDT approach for predicting the stiffness and residual strength of the wood members. The approch included measuring both stress wave speed and relative resistance of micro-drilling in wood members and using a two-paramter model to derive modulus of elasticity as well as bending and compression strength of the materials.

2. MATERIALS AND METHOD

2.1 Materials

Four structural timbers used in this study were obtained from a historic wood structure in Beijing during a major renovation project. The structure, called Zhengjue Temple, is located in Yuanmingyuan Imperial Garden in Beijing. It was originally built in 1773, the 38th year during the reign of Emperor Qianlong of the Qing Dynasty. The Zhengjue Temple is the only surviving ancient architectural complex after four times of plunders of the Yuanmingyuan Imperial Garden. In year 2002, the recovery and reconstruction project of Zhengjue Temple was initiated and carried out by the Heritage Bureau of Haidian District. Figure 1 shows the Zhengjue Temple reopened after 9 years' renovation.

Figure 7 – Reopened Zhengjue Temple after 9 years' renovation.

The four wood members obtained from the Zhengjue Temple were identified as Larch (*Larix principis-rupprechtii Mayr.*). They were coded as Timber A, B, C, and D once transported to the laboratory at Beijing Forestry University. Member A was 24 cm in diameter and 1.8 m long, and member B was 24 cm in diameter and 3.2 m long. Members C and D had the same dimension,

12x20x45 cm. The average moisture content (MC) of the timbers was 9% based on moisture meter readings.

These four ancient structural timbers were cut into 20 x20 x300 mm of specimens based on Chinese standard (GB1929-91). Thirty specimens were obtained from each timber, resulting a total number of 120 samples for our laboratory experiments.

2.2. Experimental procedure

The experimental procedures include conducting stress wave measurements, micro-drilling test, static bending and compression tests on all selected specimens. The specimens were first measured for obtaining stress wave speed in longitudinal direction. Then the resistance micro-drilling tests were conducted near the ends of each specimen. Following the static bending tests, a 30-cm long section was cut from the undamaged portion of the specimen and used for compression test. The information of the specimens is shown in Table 1.

2.2.1. Stress wave test

Stress wave test of the specimens was conducted using a FAKOPP microsecond timer. During the test, two probes of the timer were inserted into two ends of the specimen, by a 45° angle with the longitudinal direction of the specimen. Measurement was repeated three time for each specimen. The average stress wave transmission times and the length of the specimen were used to calculate the stress wave speed for each specimen.

Table 6 — Size and number of wood specimens cut from the old timber.

Specimen No.	*Stress wave transmission Micro-drilling Static bending test*		*Compression test*	
	Size of specimen [mm]	*Number*	*Size of specimen* [mm]	*Number*
A	20 x 20 x 300	30	20 x 20 x 30	30
B		30		30
C		30		30
D		30		30
Total number		120		120

2.2.2. Micro-drilling test

The micro-drilling test was conducted using a resistance micro-drilling measurement instrument, Resistograph 4452-P, made in Germany. The unit of the micro-drilling resistance is Resi, defined by the instrument maker. Two ends of each specimen were drilled in the radial direction. The average resistance from these two drilling tests was used represent the resistance value of the specimen. Here, *F* is used to represent the value of micro-drilling resistance of the specimen.

2.2.3. Static bending test

Static bending test was conducted using a universal testing machine (model RGW-3010) to obtain modulus of elasticity (MOE) and modulus of rupture (MOR) of each specimen. Based on the Chinese standard GB1936.1-91, the specimen was loaded at the center point of the specimen and in the radial direction, with a supporting pan of 240 mm. Loading speed was kept constant as specified in the standard. During one bending test, modulus of rupture (MOR) and modulus of elasticity (MOE) are got at the same time.

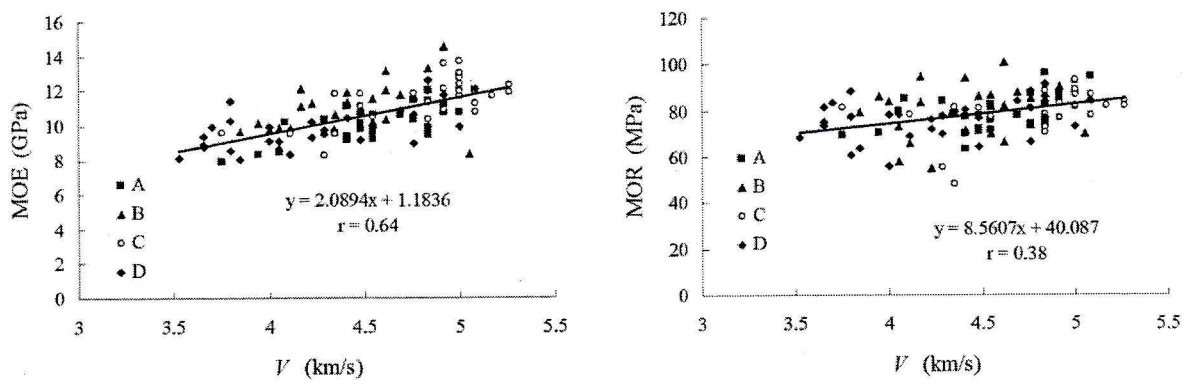
2.2.4. Compression test

Compression test was conducted on 20x20x30 mm specimens using a universal testing machine (model RGW-100). Test procedure outlined in the Chinese standard GB1935-91 was followed. Loading speed was 3 mm/min.

3. RESULTS AND ANALYSIS

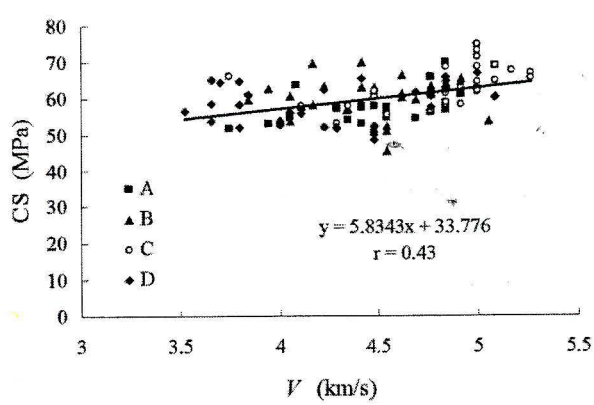
3.1. Relationships between stress wave speed and the mechanical properties

Figure 8 (a) shows the relationship between stress wave speed *(V)* and modulus of elasticity (MOE) of the specimens, with a correlation coefficient of r=0.64. Figure 8 (b) shows the relationship between stress wave speed *(V)* and modulus of rupture (MOR), with a correlation coefficient of r=0.38. Figure 8 (c) shows the relationship between stress wave speed *(V)* and compression strength (CS), with a correlation coefficient of r=0.43. It can be seen that there are linear correlations between the stress wave speed and three mechanical properties of wood, but the strength of the relationships are not strong.



(a) Modulus of elasticity (MOE)

(b) Modulus of rupture (MOR)



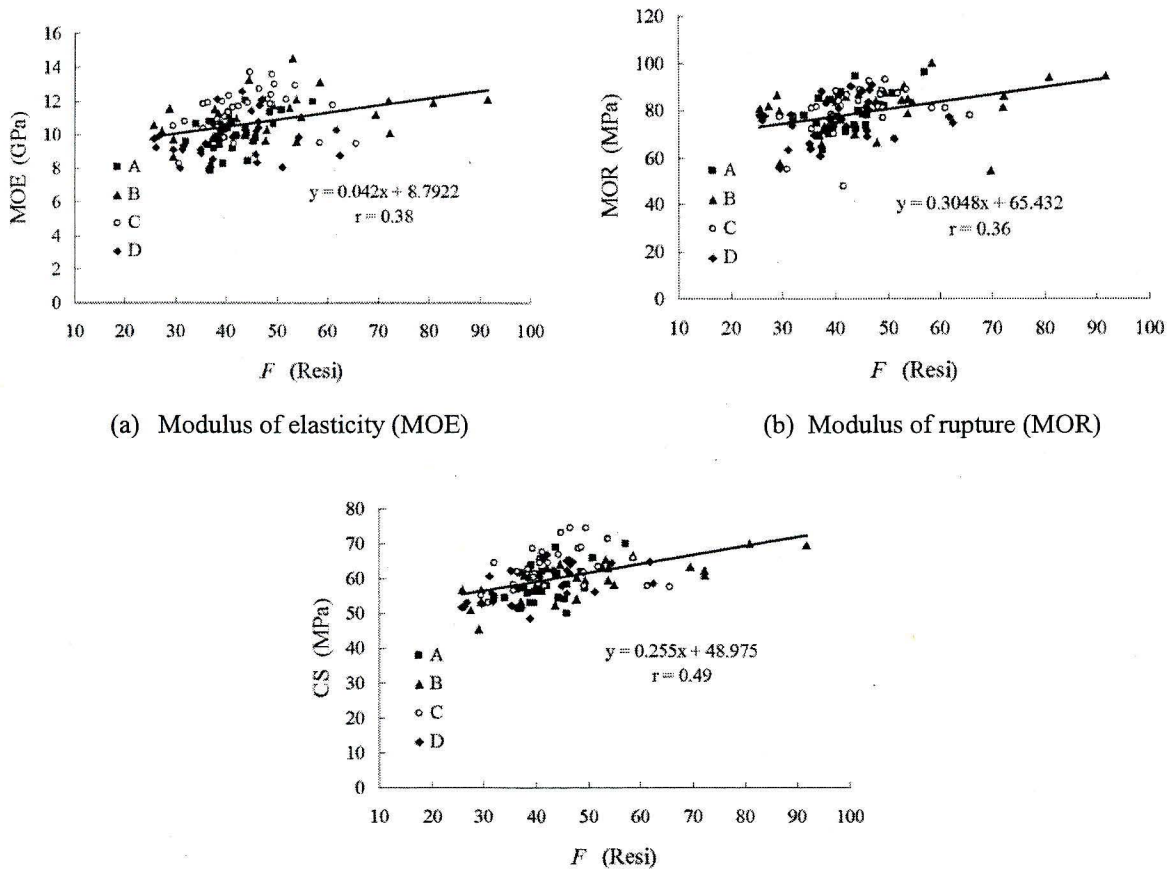
(c) Compression strength (CS)

Figure 8 — Relationship between stress wave speed and mechanical properties.

3.2. Relationships between micro-drilling resistance and the mechanical properties

Figure 9 (a) shows the relationship between micro-drilling resistance *(F)* and modulus of elasticity (MOE) of the specimens, with a correlation coefficient r=0.38. Figure 9 (b) shows the relationship between micro-drilling resistance *(F)* and modulus of rupture (MOR), with a correlation coefficient r=0.36. Figure 9 (c) shows the relationship between micro-drilling resistance *(F)* and compression

strength (CS), with a correlation coefficient r=0.49. The linear relationships between the micro-drilling resistance and three mechanical properties of wood are relatively weak.



(a) Modulus of elasticity (MOE)

(b) Modulus of rupture (MOR)

(c) Compression strength (CS)

Figure 9 – Relationship between micro-drilling resistance and mechanical properties.

3.3. Relationships between modulus of stress-resistance and the mechanical properties

Based on stress wave theory, the modulus of elasticity (MOE) of a material is directly related to the stress wave speed *(V)* and material density *(ɟ)* (Ross 2004):

$$\text{MOE} = ɟ V^2$$

In structure inspection, the density of the wood members is difficult to measure directly, but it can be predicted using the micro-drilling resistance *(F)*. Rinn et al. (1996) reported that the mean levels of the relative resistance from the Resisitograph profiles had a strong correlation with the gross density of the dry wood (R^2>0.8).

By substituting *p* with micro-drilling resistance force *F* in the stress wave equation, we proposed a new predicting parameter: FV^2. We defined this parameter as the *"modulus of stress-resistance"*, with a unit of ResiĀkm^2/s^2. The hypothesis is that the modulus of stress-resistance is a better predictor of the mechanical properties of dry wood, thus enables in-situ determination of the residual mechanical properties of structural members.

Figure 10 (a) shows the relationship between modulus of stress-resistance and modulus of elasticity (MOE) of the specimens, with a correlation coefficient r=0.71. Figure **10** (b) shows the relationship between modulus of stress-resistance and modulus of rupture (MOR), with correlation coefficient

r=0.55. Figure 10 (c) shows the relationship between modulus of stress-resistance and compression strength (CS), with correlation coefficient r=0.69. Comparing with the single parameter prediction, the two-parameter prediction that combines stress wave speed and micro-drilling resistance resulted in much better correlations to the MOE, MOR, and CS (Table 7).

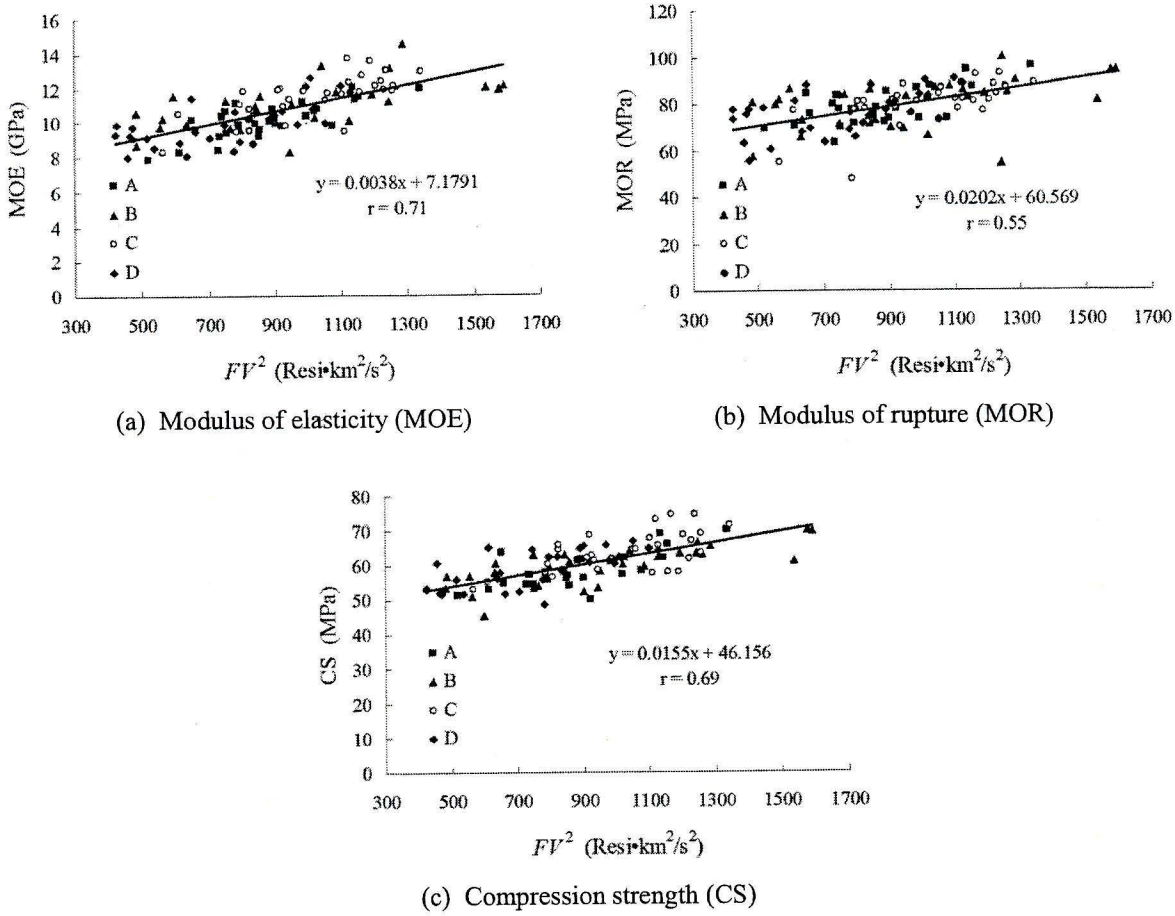


Figure **10** — Relationship between modulus of stress-resistance and comprkm/sn strength.

Table 7 —Summary of regression equations

	Regression equation y=ax+b				***Correlation coefficient***
	y	*x*	*a*	*b*	*r*
Modulus of elasticity (MOE)	MOE	*V*	2.0894	1.1836	0.64
	MOE	*F*	0.042	8.7922	0.38
	MOE	***FV²***	**0.0038**	**7.1791**	**0.71**
Modulus of rupture (MOR)	MOR	*V*	8.5607	40.087	0.38
	MOR	*F*	0.3048	65.432	0.36
	MOR	***FV²***	**0.0202**	**60.569**	**0.55**
Compression strength (CS)	CS	*V*	5.8343	33.776	0.43
	CS	*F*	0.255	48.975	0.49
	CS	***FV²***	**0.0155**	**46.156**	**0.69**

Note: *V*— Stress wave speed (lcm/s)

F— Micro-drilying resistance (Resi)

FV^2 — Modulus of stress-resistance (Resi•km²/s²)

MOE — Modulus of elasticity (GPa)

MOR— Modulus of rupture (MPa)

CS — Compression strength (MPa)

r — Correlation coefficient.

4. CONCLUSIONS

In this study, we evaluated stress wave and resistograph techniques for their ability to predict material properties of ancient wood structure members. An integrated NDT approach was proposed to utilize both stress wave speed and relative resistance of micro-drilling as predictive parameters of the stiffness and residual strength of the wood members. The results indicated that combining stress wave speed and relative resistance in a linear regression model provided better predictions of mechanical properties than using stress wave speed or relative resistance alone. This integrated NDT approach will be further evaluated in a field structure evaluation process.

ACKNOWLEDGMENTS

The project was supported by the Beijing Municipal Science & Technology Commission, China (Grant No. Z090506016609002).

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17th INTERNATIONAL NONDESTRUCTIVE TESTING AND EVALUATION OF WOOD SYMPOSIUM

SEPTEMBER 14-16, 2011

VOLUME 2

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