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Determining Modulus of Elasticity of Ancient Structural Timber

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Abstract: During maintenance of ancient timber architectures, it is important to determine mechanical properties of the wood component materials non-destructively and effectively, so that degraded members may be replaced or repaired to avoid structural failure. Experimental materials are four larch (*Larix principis-rupprechtii Mayr.*) components, which were taken down from the drum-tower of Zhengjue Temple of Yuanmingyuan (Old Summer Palace), Beijing, China. The larch components were cut into standard specimens first, and then stress wave transmission times, resistograph and densities were tested. Product of resitograph and stress wave speed squared is defined as modulus of stress-resistograph. Comparing with the modulus of elasticity (MOE) of the specimens tested by the traditional bending test method, it is found that there is a linear relationships between the modulus of stress-resistograph and modulus of elasticity (MOE), and the correlation coefficients are 0.7111. In order to better evaluate the modulus of elasticity (MOE) with the modulus of stress-resistograph, 95% confidence regression lines are suggested to be used for the future calculation.

1 Introduction

China is a rich cultural country with a long history of 5000 years, has a huge number of ancient timber architectures which are Chinese important cultural heritage. During maintenance of the ancient timber architectures, it is important to non-destructively and effectively determine wood used and structural safety, so that degraded members may be replaced or repaired to avoid structural failure (Shang 2008). So far, visual inspection and simple strike are mostly used to the examining job. Those two examining methods are very simple, but inspection results are not very accurate, lack of quantitative data.

There are two important aspects in the inspection of an ancient timber architecture component: examining inner defects and determining mechanical properties of the materials. Many researchers did a lot of work on the examining inner defects (Ross 2004, Pellerin 2002, Duan 2007, Huang 2007), and they found several successful methods, such as stress wave method, sonic tomograph method, micro-drilling method (Resistograph). Study on determining mechanical properties of the materials is less. Duan et al. (2007) investigated modulus of elasticity of ancient wooden structure members by stress wave method, and found there is a relationship between stress wave speed and the modulus of elasticity. Ceraldi et al. (2001) found the strength of the ancient wooden materials is related with resistograph. However, so far, there is no research about determining modulus of elasticity (MOE) of the materials with both stress wave and resistograph integrated.

Experimental materials of this study are four larch (*Larix principis-rupprechtii Mayr.*) components, which were taken down from the drum-tower of Zhengjue Temple of Yuanmingyuan (Old Summer Palace), Beijing, China. The stress wave transmission times, resistograph and densities were tested for quantitatively evaluating the modulus of elasticity of the wood. The final goal of this study is to do some basic work on in-situ nondestructive test and evaluation of mechanical properties of ancient timber component materials.

2 Research idea

Modulus of elasticity (MOE) of wood has a good relationship with stress wave speed and density (Ross 2004): MOE=ρv^2. Where ρ is the density of wood, and v is stress wave speed in the wood. The stress wave speed is easy to be measured with a stress wave timer. For the density of wood, traditional weighting method is not suitable for in-situ test, since it will cause damage on the wood components. Isik et al. (2003) found that wood density of standing trees has a good relationship with resistograph. So it can be supposed that wood density of ancient timber architecture components should has a relationship with resistograph too. One of work of this paper is to investigate this relationship.

We defined Product of resitograph and stress wave speed squared (Fv^2) as modulus of stress-resistograph. Its unit is Resi·km^2/s^2. Where, F is resistograph (unit: Resi), and v is stress wave speed (unit: km/s). It is hoped that through the modulus of stress-resistograph, the modulus of elasticity of the wood can be predicted. As a result, one specimen will be taken of several tests, including stress wave transmission test, resistograph test, density test and traditional bending test. Based on these tests, quantitative relationships between the modulus of stress-resistograph and modulus of elasticity of the wood would be built up.

3 Experimental method

3.1 Experimental materials

Experimental materials are old wood which were taken down from the drum-tower of Zhengjue Temple of Yuanmingyuan (Old Summer Palace), Beijing, China. The temple was built up in 1773 in Qing dynasty, and it has 237 years of history. Four wood components were moved back into our laboratory. The four wood components were numbered A, B, C, D. In which, A and B are two bars and C and D are two cuboid components. Sizes of A and B are Φ240×1800 mm and Φ240×3200 mm respectively. Sizes of C and D are all 120×200×450 mm. The four wood components are all larch (*Larix principis-rupprechtii Mayr.*) by the species identification result. Moisture content of the components is 9%.

3.2 Specimens and experimental methods

The experiments include stress wave transmission test, resistograph test, density test and traditional bending test. To get several experimental parameters from one specimen simple, the size of the specimen of every test will be changed according to the test standards.

First, cutting the four wood components into 20×20×300 mm of specimens. The length direction of the specimen is same as wood grain direction and the cutting was based on Chinese standard (GB1929-91). The specimens should not have visible defects, such as decay, crack and holes. These specimens were used to do the stress wave transmission test and traditional bending test. Then two 20 mm length specimens were cut from undamaged parts of every previous specimen, which were used to do the resistograph test and density test. Size and number of the specimens are listed in Table 1.

Table 1 Size and number of specimens

Specimen No.	Stress wave transmission test and traditional bending test		Resistograph test and density test	
	Size of specimen (mm)	Number	Size of specimen (mm)	Number
A	20×20×300	30	20×20×20	60
B		30		60
C		30		60
D		30		60
Total number		120		240

(1) Stress wave transmission test

FAKOPP microsecond timer was used to the stress wave transmission test. During the test, two probes of the timer were inserted into two ends of the specimen, by 45° angle with longitudinal direction of the specimen. Average value of three times of impacting was as the stress wave transmission time of the specimen. Then calculated stress wave speed from the length of the specimen and the stress wave transmission time.

(2) Traditional bending test

Purpose of this test is to test modulus of elasticity (MOE). Mid-point bending test is used according to Chinese standard GB1936.1-91. Size of specimen is 20×20×300 mm. Test apparatus is universal mechanical testing machine, model RGW-3010, made by Shenzhen Reger Instrument Company, China. Span of two supports is 240 mm. Loading speed is constant, and making specimen break down within 2~3 minutes. The loading direction is along the radial direction of the wood.

(3) Density test and resistograph test

Density test is based on Chinese standard GB1933-91. The specimen used is 20×20×20 mm in size. Two specimens are cut off from the previous 300 mm length specimen, and average of densities of these two specimen will be as density of the 300 mm length specimen.

The resistograph test uses micro-drill resistance measurement instrument, Resistograph 4452-P, made in Germany. Unit of the resistograph is Resi, defined by the instrument maker. Every specimen will be drilled. Drilling direction is along the radial direction of the wood from the outside to the inside. Average of resistograph of these two 20 mm specimens will be as resistograph value of the 300 mm length specimen

4 Experimental results and analysis

4.1 Relationship between wood density and resistograph

By the influence of annual rings, the resistograph appears a fluctuant curve through 20 mm thickness of the specimen. Average value of the fluctuant curve is as resistograph of the specimen. Fig.1 is Relationship between wood density of the four larch and resistograph. It can be seen there is a linear relationship between wood density and resistograph, and bigger density, larger resistograph. Linear regression equation is y=2.9275x+491.39, and coefficient of determination is 0.4367, correlation coefficient is 0.6608. So, it can be concluded that from resistograph, wood density can be computed for the old larch wood.

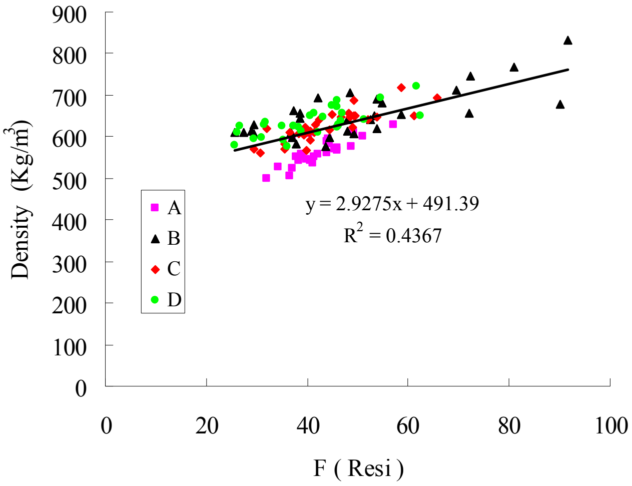

Fig.1 Relationship between wood density and resistograph

4.2 MOE test by stress wave speed and resostograph

Fig.2 is experimental result of relationship between MOE and stress wave speed and resistograph. The horizontal axis is modulus of stress-resistograph, and vertical axis is modulus of elasticity (MOE). Broken line on the figure is regression line of modulus of stress-resistograph and MOE. It can be seen that for the four larch, there is a linear regression relationship between modulus of stress-resistograph and MOE. The coefficient of determination is 0.5056, and the correlation coefficient is 0.7111. So, it can be concluded that from modulus of stress-resistograph, MOE of the larch can be computed.

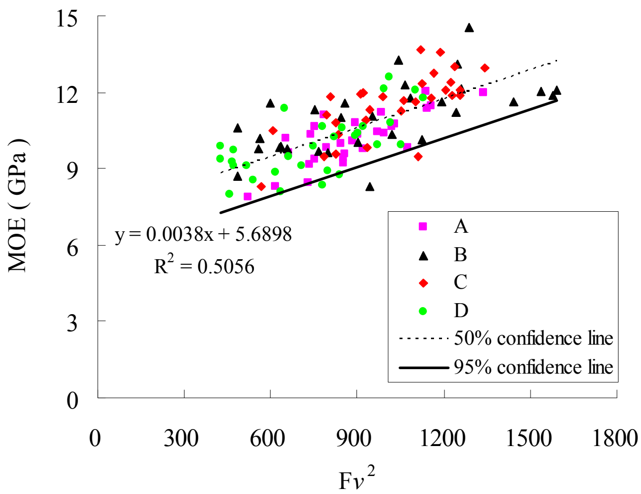

Fig.2 Relationship between MOE and modulus of stress-resistograph

When the broken regression line is used to calculate MOE from Fv^2, confidence is 50%. i.e., based on the broken regression line, from Fv^2 to calculate MOE, there is 50% possibility bigger than real MOE, and has 50% possibility less than real MOE. Since MOE calculated will be used to evaluate carrying capacity and safety in the future, the case of 50% possibility bigger than real MOE will make low reliability. To solve this problem, we processed the data, and get 95%

confidence regression line, the real line on the figure. Regression equation of the real line is y=3.77x+5.6898. i.e., based on the real regression line, from Fv^2 to calculate MOE, there is only 5% possibility bigger than the real MOE. In this way, practicability of the test data is greatly improved.

Table 2 is a summary of the four regression equations, which are relationship between density and resistograph, relationship between MOE and modulus of stress-resistograph. For larch served in ancient timber architecture, from Fv^2, MOE should be calculated effectively.

Table 2 Summary of regression equations

y	x	Regression equation	R^2	*r*	Confidence
ρ	F	y=2.9275x+491.39	0.4367	0.6608	50%
MOE	Fv^2	y=0.0038x+5.6898	0.5056	0.7111	95%

Note：ρ -- density (kg/m^3), F -- resistograph (Resi), Fv^2 -- modulus of stress-resistograph (Resi·km^2/s^2), MOE -- modulus of elasticity (GPa), R^2-- coefficient of determination, *r*-- correlation coefficient

5 Conclusion

Experimental materials are larch (*Larix principis-rupprechtii Mayr.*) which were taken down from the drum-tower of Zhengjue Temple of Yuanmingyuan (Old Summer Palace), Beijing, China. The materials were cut into standard specimens first, and then stress wave transmission times, resistograph and densities were tested. The final goal is to do some basic work on in-situ nondestructive test and evaluation of mechanical properties of ancient timber component materials. Conclusions we got are below.

1) There is a linear relationship between wood density and resistograph, and bigger density, larger resistograph. Linear regression equation is y=2.9275x+491.39, and coefficient of determination is 0.4367, correlation coefficient is 0.6608.
2) Product of resitograph and stress wave speed squared is defined as modulus of stress-resistograph. Comparing with the modulus of elasticity (MOE) of the specimens taken by the traditional test methods, it is found that there are linear relationships between the modulus of stress-resistograph and modulus of elasticity (MOE), and the correlation coefficients reaches to 0.7111. In order to better evaluate the mechanical properties with parameter the modulus of stress-resistograph, 95% confidence regression lines are suggested to be used for the future calculation.

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