The Screening Method of the Internal Defects in Wood Members of the Ancient Architectures by Hammering Sound

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Defects have a serious impact on the load carrying capacity and the safety of ancient architectural wood members. Common screening methods to identify defects cause damage to this wood. To protect ancient architecture, it is necessary to develop a method that can screen for internal defects and estimate their size quickly and efficiently without destruction. This paper studied the detection mechanism of the sound hammering method for screening internal defects in wood. Wood members generated different kinds of vibration through hammering experiments, and the vibration produced by hammering wood with internal-hole defects was divided into three kinds: local surface vibration, the whole structure vibration, and defective-part vibration. The parameters and their variation of these three kinds of vibration were investigated by a mechanical vibration simplified model, and the method for screening the internal defects based on sound hammering was proposed. The feasibility of the method was verified by experiments.

Keywords: Historic wood structural members; Internal defect; Screening; Hammering sound

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INTRODUCTION

China, one of the world's four major ancient civilizations, has an abundance of ancient timber buildings that are partially or wholly built out of wood (Chen 2005). These ancient buildings are the historical and cultural inheritance of the Chinese heritage; they are also important cultural and historical relics for the entire world. Recently, stress wave and micro drilling resistance have been used in nondestructive testing of internal defects in the wood (Anthony and Bodig 1989; Cawley 1990; Bodig 2001; Fikret and Bailian 2003; Liao *et al.* 2014). The wooden structures of stadiums, bridges, and ships have been evaluated using stress wave analysis (Ross 1982; Ross *et al.* 1996). The ancient buildings of Tibet, Beijing, and other cities have also been examined *via* the stress wave method (Duan *et al.* 2007; Chen *et al.* 2012). Micro-drilling resistance has been used to detect defects and mechanical characteristics of ancient buildings (Frank 1994a,b; Huang *et al.* 2008; Liao *et al.* 2013a). A percussion method is being used increasingly as a preliminary screening for these methods. However, the new methods are not perfect; some issues remain, such as poor maneuverability and damage to the ancient buildings being tested (Liao *et al.* 2013b; Chul and Jung 2015). Differences in the sound quality of wooden pieces tapped by a small hammer have been used to detect the existence of internal holes, decay and other defects. This method is perhaps the most simple and primitive, relying to a large extent on the experience of the testing personnel. This detection method does not cause damage to the wood, but it is too subjective and lacks a scientific basis for detection. Moreover, the test results are often incomplete, biased, or ambiguous. Currently, the percussion sound detection method is used for objects with relative size, such as eggs, apples, rotors, wood-based panels, and wood pieces (Goodrum and Elster 1992; Zhang and Ma 2001; Wang *et al.* 2004). The research and application of this method on large wood structures are limited.

Wood contains internal defects such as porosity and decay. When decay is developed to a certain degree, its knock sound effect is potentially similar to the porosity sound effect. The detection of internal defects *via* wooden percussion screening has lacked a systematic and scientific basis. In this study, the wooden parts of load-bearing components in ancient Chinese buildings were selected as research objects. Detection mechanisms for porosity and severe decay defects in these ancient wooden structures were examined. The wooden building components made by larch (*Larix gmelinii*) were verified experimentally. To a certain extent, these findings confirmed the theoretical study of percussion detection.

EXPERIMENTAL

Theoretical Basis

According to differences of each object's factors and surrounding conditions, the knocked objects produce different vibrational modes, which fall into the categories of the whole structure vibration and local vibrations. These two kinds of vibrations are suitable for defect detection in a vibrating body. The whole structure vibration method is mainly used to detect flaws in rigid material, whereas the local vibration method is mainly used to detect flaws in non-rigid material. Using a small hammer to knock or tap on wooden structures, the percussion position will produce a local vibration due to the rigid nature of non-timber wood. When the knocking conditions meet a particular requirement, a small hammer may arouse the overall vibration of the wood sections which can be called the whole structure vibration. Whether it arouses the whole structure vibration or not, percussion action causes local vibration of the wood surface.

(1) Surface local vibration. When the small hammer taps the ancient wood structure, it can result in the deformation of surface parts (Fig. 1); this deformation process can produce certain vibrations. Assuming that wood can be modeled as a kind of isotropic material, a preliminary analysis can be undertaken. The wood surface is simplified into a preliminary, local, vibration-free vibration spring.

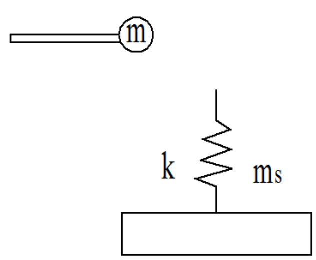

Fig. 1. The simplified diagram of local vibration

The elastic coefficient related to the simplified elastic model should be also related to local mechanical impedance and elastic coefficient. If the quality of the small hammer is m, the frequency formula of the simplified model is as follows:

$$\omega_1 = \sqrt{\frac{k}{m}} \tag{1}$$

where ω_1 is the natural angular frequency of free vibration (rad/s) and k is spring the spring constant.

In addition to the contact area between the small hammer and wood surface, the elastic coefficient k of the equivalent spring is related to the thickness of the wood parallel to the knocked-direction. The vibration frequency formula of the simplified model for wood surface is shown in Eq. 2,

$$\omega' = \sqrt{\frac{E_1 A}{hm}} = 2\pi f' \tag{2}$$

where ω' is the natural angular frequency of free vibration (rad/s), h is the thickness of the wood members (m), E_1 is the compressive MOE (Pa), m is the quality of hammer (kg), f' is the natural frequency of free vibration, and A is the effective area (m^2).

(2) The whole structure vibration. In the structural design of and detection methods for ancient buildings (according to the force and structure characteristics), the support conditions of load-bearing wood structures such as beams, architraves, and purlins are simplified double-ended supports. In the process of bending vibrations, and according to the characteristics of free vibration, the energy of first order natural frequency is significantly greater than the energy of other order natural frequency. The order 1 frequency formula, for two ends of supporting beam vibration, and for the simplified model of overall vibration of wood components is shown in Eq. 3,

$$\omega_1 = \left(\frac{\pi}{l}\right)^2 \sqrt{\frac{EI}{\rho A}} = 2\pi f \tag{3}$$

where ω_1 is the first natural angular frequency of free vibration (rad/s), l is the length of the beam (m), E is the MOE (Pa), I is area moments of inertia, ρ is the density (kg/m^3), f is the natural frequency of free vibration, and A is the effective area (m^2).

(3) Defect site vibration. When the small hammer is positioned in relation to the wood's internal defect, as shown in Fig. 2 (defect site), the dotted line part of the structure may also be knocked to produce a single vibration. In this study, the lower part of the dotted line structure was considered to be an approximately straight line to study the vibration caused by defects. When the small hammer taps the defective sections of ancient wood structures, the vibration caused by the defects is preliminarily simplified as the vibration of rectangular plates of four branches.

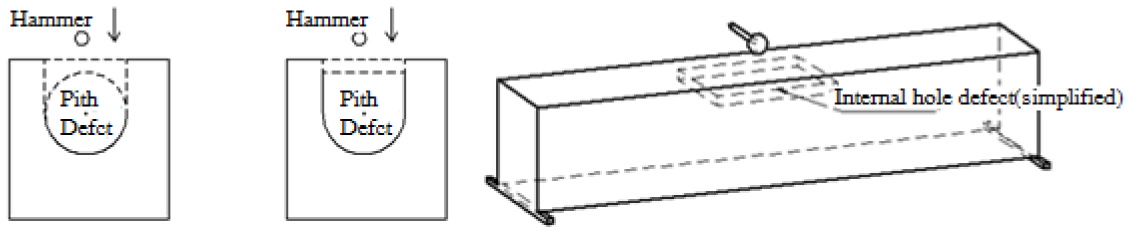

Fig. 2. The simplified model of hole defects

According to the characteristics of free vibration (which is similar to the whole structure vibration), the order-1 frequency formula of defect sites' vibration in a simplified model is described as follows,

$$\omega_{11} = k\pi^2 \sqrt{\frac{D}{\rho h}} \left[\left(\frac{1}{a}\right)^2 + \left(\frac{1}{b}\right)^2 \right] \tag{4}$$

$$D = \frac{Eh^3}{12(1-\mu^2)} \tag{5}$$

where ω_{11} is the first natural angular frequency of free vibration (rad/s), h is the thickness of the plate (m), D is the bending rigidity of the plate (Pa), ρ is the density(kg/m^3), μ is the Poisson ratio, a, b is the length of the side (m), k is the correction coefficient, and E is the MOE (Pa).

After simplifying and analysing the three types of vibration presented above, it can be concluded that the wooden structures can produce the whole structure and surface local vibrations when the wood is defect-free (internally and externally). Under certain conditions, the surface local vibration may be dominant. When the defect sites of wooden structures with internal defects are knocked, the result is frequently the whole structure, surface local, and defect-site vibrations. In this study, three kinds of vibration frequencies were analysed to detect internal defects in the wood structures. The vibration frequency was related to the size of the internal defects and to their distance from the surface. Sound signals of defective sections are not covered up by sound signals of the other two types of vibration, so when defect sites are knocked, a new frequency of defect-free wood structure is created. In this way, internal defects are detected.

Materials

Larch wood was selected as the ancient wooden structure building material, and it had a moisture content of 10.9%. In the allowable range of the tested sites and conditions, logs were machined into four rectangular wood components with dimensions of 1200 mm × 200 mm × 200 mm. The surface of these samples was processed to simulate the actual conditions of a planned ancient architecture (Fig. 3).

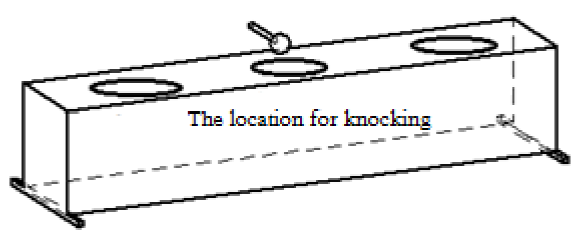

Fig. 3. The experimental specimens of larch and the area of test

Vibration Detection Test

(1) Four rectangular wood components were first numbered sequentially and then placed in manner of both ends of the supporting (Fig. 3). The center zone of the striking

surface and the different sections near the supporting points were knocked multiple times for each wood structure.

(2) Defect processing of rectangular wood components. Defects with dimensions of 250 mm × 40 mm × 100 mm, 225 mm × 40 mm × 100 mm, and 200 mm × 40 mm × 100 mm were machined in wood structures number 1 and number 3. Defects with dimensions of 175 mm × 40 mm × 100 mm, 150 mm × 40 mm × 100 mm, 125 mm × 40 mm × 100 mm, and 100 mm × 40 mm × 100 mm were present in number 2 and number 4. The thickness (*h*) of the defective part (the part between the defect and surface) was 20 mm, as shown in Fig. 4. Wood structures number 1 and number 2 comprised group 1, whereas number 3 and number 4 were group 2. After the defects were machined, artificial void defects were used to simulate the defects of ancient buildings.

(3) After the knocking experiments were completed in step two above, the rectangular wood structure was successively machined. The defective part thickness was 15 mm, 10 mm, and 5 mm. Wood structures with three different types of defects (with distinct defective part thickness) were knocked for three tapping tests.

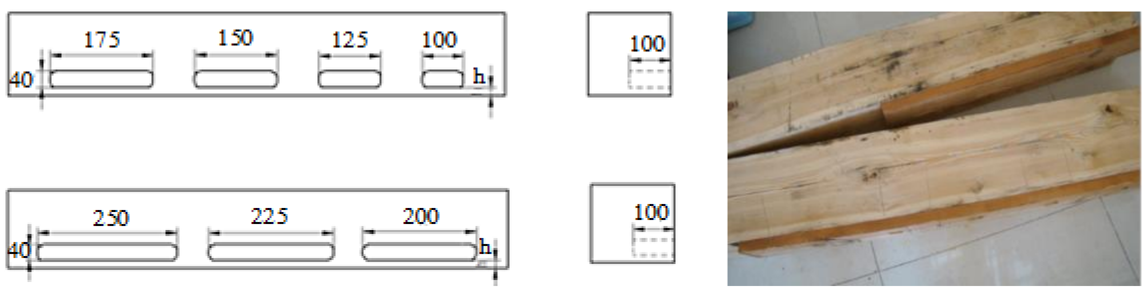

Fig. 4. Schematic diagram of hole defects

RESULTS AND DISCUSSION

Sound signals were collected *via* a sound acquisition system and analyzed with LabVIEW software (Fig. 5). The vibration frequency of wood structures without defects corresponded to the whole structure vibration frequency, and the surface local vibration was covered up by the whole structure vibration. When the defects are detected, the frequency-domain plot will appear new frequency or some other difference. Table 1 shows frequency parameters for different defect sites of wood structures. Through analysis of sound signal for each group of wood structure, the following conclusions were drawn. (1) The frequency of the whole structure vibration of wood structures was slightly changed by processing defects. As more wood is removed, the whole structure vibration frequency became smaller. For on-site detection of internal defects for ancient buildings, the situation of the wood structure is constant; therefore, the sound signals of the whole structure vibration frequency would not change. (2) When the depth of the defect edge and its corresponding edge were constant (and they increased simultaneously), the frequency of sound signals initially corresponded only to the natural frequency of the whole structure vibration. Gradually, it then contained the frequency of the defective sections. Eventually, it only corresponded to the vibration frequency of defect sites (here, the whole structure vibration frequency of the wooden structure was covered up).

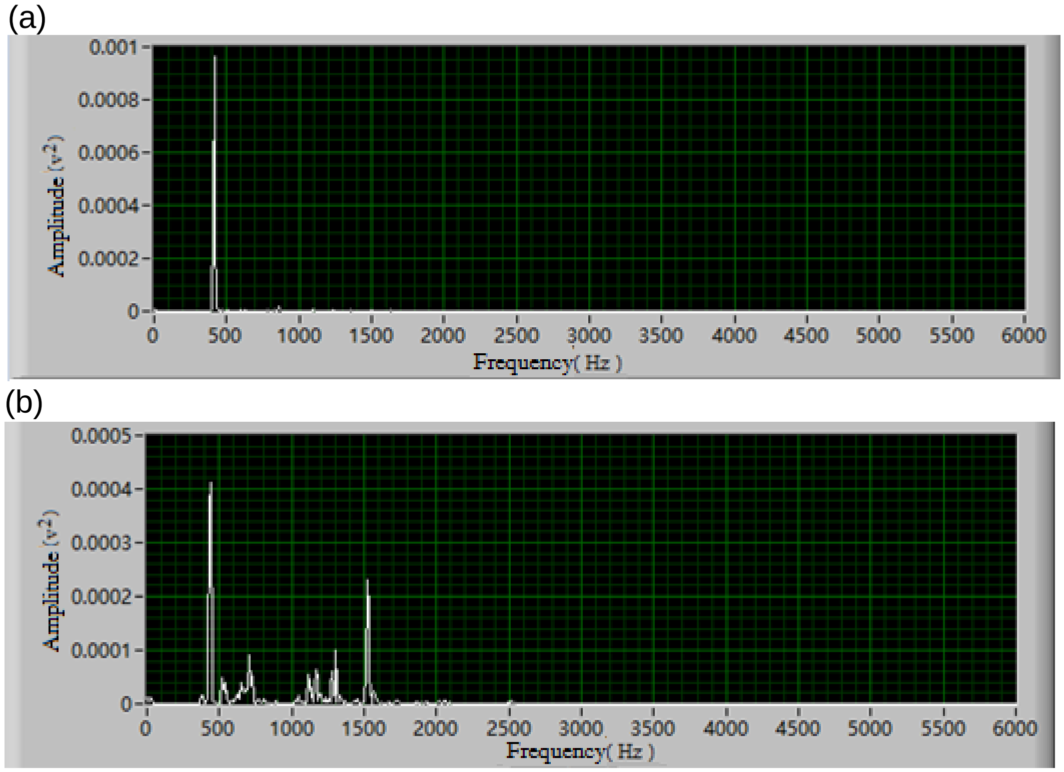

Fig. 5. The frequency-domain plot of hammering wood members for (a) the wood member of NO.1 without defect,(b) the wood member of NO.1 with defect of length 200mm,Thickness 10 mm

Table 1. The Characteristics of the Frequency-Domain Plot

Parameters	Number	Thickness of Defect *h* (mm)	Length of Defect (mm)						
			250	225	200	175	150	125	100
Frequency of defective parts (Hz)	1	20	1656	1736	1886	0	0	0	0
	2		1671	1852	1902	0	0	0	0
	1	15	1308	1750	1550	1801	0	0	0
	2		1280	1405	1540	1824	0	0	0
	1	10	1028	1140	1303	1502	1697	0	0
	2		986	1098	1252	1432	1653	0	0
	1	5	624	698	791	900	1052	1201	1782
	2		619	687	746	946	1120	1252	1746
Frequency of the whole structure vibration （Hz）	1	20	0	405	405	405	405	405	405
	2		0	401	401	401	401	401	401
	1	15	0	402	402	402	402	402	402
	2		0	398	398	398	398	398	398
	1	10	0	0	399	399	399	399	399
	2		0	0	394	394	394	394	394
	1	5	0	0	0	379	379	379	379
	2		0	0	0	381	381	381	381

Note: 0 means no the vibration frequency in frequency domain graph.

(3) The depth of the defect edge and its corresponding edge were constant. The vibration frequencies of defect sites were obtained through a frequency domain diagram of the sound signal. This frequency decreased when its corresponding edge increased. (4) When the length of defect sites was constant and the thickness decreased, in the frequency domain

diagram of sound signal the vibration frequency of the defective parts appeared to be non-existent. When the vibration frequency of the defective sites occurred, this frequency decreased when the depth of the defect edge also decreased.

According to theoretical research, the compressive elastic modulus of larch wood is 1.2×10^9 Pa. The blend elastic modulus is 1.25×10^{10} Pa, and its density is 610 kg/m^3. Thus, the estimated the whole structure vibration frequency of the simplified model of the rectangular wood structure is 285 Hz. The correction coefficient (k) of the vibration frequency of defect sites is 0.6. Figure 6 shows a comparison diagram between the experimental data of the first group of wooden structures, as well as the obtained data of the simplified model.

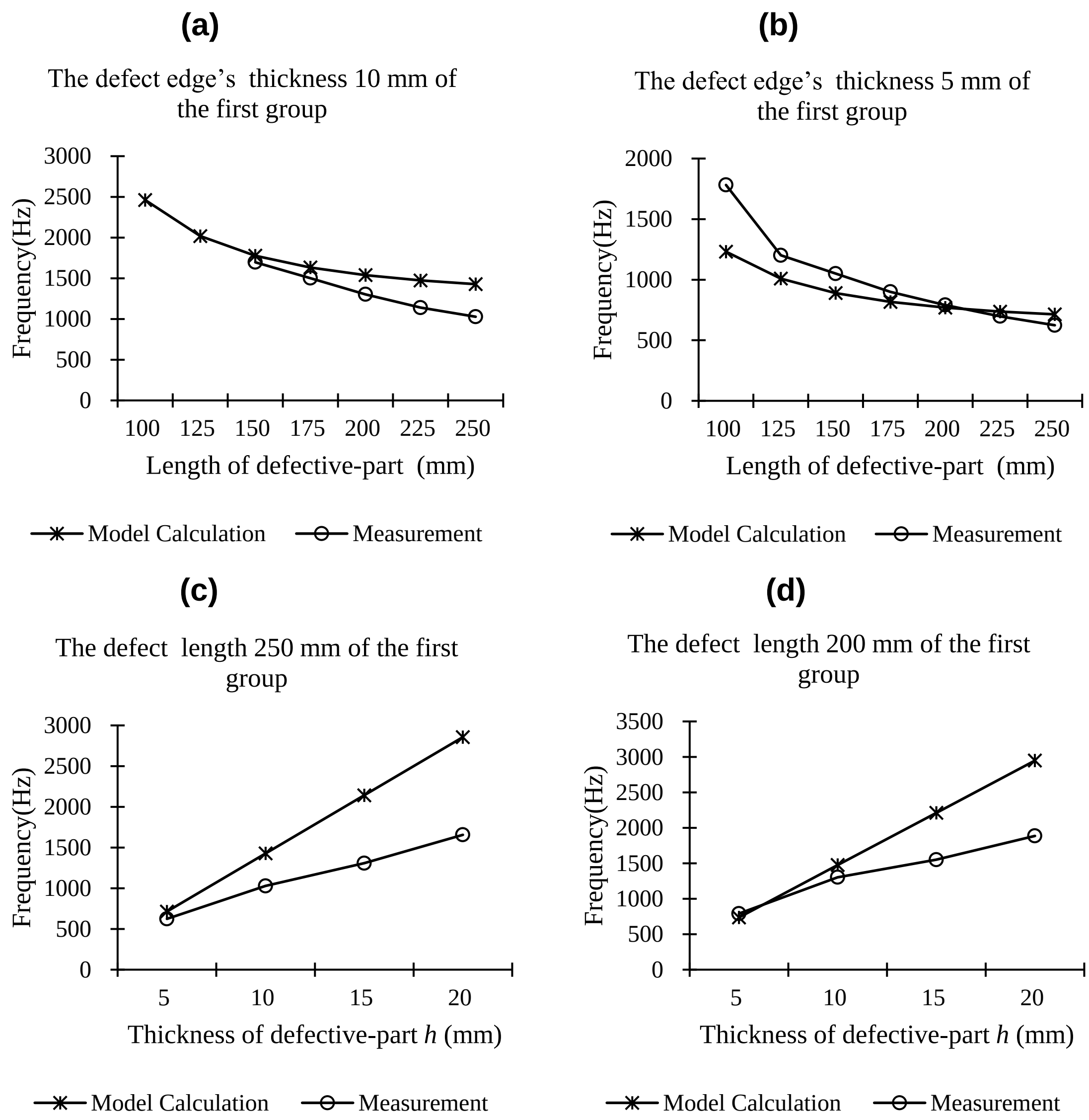

Fig. 6. The relationship between the frequency and defect size by the first group for (a) varying length with thickness 10 mm,(b) varying length with thickness 5 mm, (c) varying thickness with length 250 mm, and (d) varying thickness with length 200 mm

Analysis of the vibration frequency of defective sections (in the frequency domain diagram of the rectangular wood components' sound signal) showed that its changes were consistent with the order-1 natural frequency of the free vibration of the rectangular thin plate with simple supported edges. When the defective edge had a constant depth, the vibration frequency of the defective sites decreased when defect length increased (Fig. 6(a), (b)). When the length of defective sites was constant, the vibration frequency of defective sites also increased as defect depth increased (Fig. 6(c), (d)). No sound signals at number 4 of 125 mm and 100 mm were detected, indicating that the vibration frequency of defective sites was covered up by the wooden structure's whole structure vibration frequency. The vibration energy of defective sites increased when (1) the contact area of knocking direction increased and (2) when the distance from the surface decreased. In the frequency domain diagram, the vibration frequency of defective sites appeared non-existent when the area perpendicular to the knocking direction increased or when the distance from the surface decreased. Finally, the vibration was covered up by the natural frequency of the wooden structure's whole vibration. Additionally, the vibration frequency of defective sites decreased when the area perpendicular to knocking direction increased, and it decreased when the distance from the knocked surface decreased.

It is understood that the defects for testing are artificial, and a real defect (such as decay or hole) may be different from the artificial defect. The model and theoretical basis were researched using some special samples. More samples with different defects will be tested in the further research.

CONCLUSIONS

1. When a wooden structure with and without internal defects is knocked, it can produce whole structure vibrations and surface local vibrations. When a wooden structure with internal defects is knocked, a third kind of defect-related vibration appears.
2. By analyzing three types of vibration, it was found that each vibration frequency can be used to screen the featured parameters of wooden structure with internal defects. Changes in defective vibration frequency can be used to preliminarily assess the size of any present defects and their distance from the surface.
3. In factual testing, several of the vibrations did not appear or were covered up by each other. When only the defects are knocked, the sound signals of defective vibrations are not covered by sound signals of the other two types of vibrations.
4. The findings allow us to conclude that a totally non-destructive method of testing provides a scientific basis for detecting internal defects in the wood used to build ancient buildings.

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