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The Inspection and Appraisal of the Yonghemen Structure of the Qing Dynasty in Beijing

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Abstracts: Beijing has concentrated many of the excellent wooden structures of ancient architecture, but some of the ancient buildings are inevitably damaged by natural and human factors because of the time passed by. Therefore, the regular inspection of the wood condition and the analysis of the safety performance of the wooden structure have become an indispensable work for the protection of ancient architecture. The Lama Temple is an outstanding example of the wooden structure of ancient architecture in Beijing. This research introduces the inspection and appraisal of the Yonghemen, which is one of the buildings in the Lama Temple, representing this kind of structures. First, surveying and mapping of the structure were completed, and detailed investigation and measurement of the stress and deformation states of the bearing member and the primary node were carried out to check structural safety. Meanwhile, several nondestructive inspection technologies were adopted during testing. For instance, radar was used to detect the foundation, Impulse tomography and resistograph were used to detect the wood quality, and also a pulsating method for identifying dynamic parameters of structure was adopted. Finally, the safety of building was appraised and rated in the end of the research based on the above detection results. Moreover, some suggestions for future monitor and protection were put forward.

Keywords: Yonghemen, Ancient Architecture, Wooden Structure, Nondestructive, Inspection, Appraisal

1. Introduction

As we all know, there are a variety of ancient buildings in Beijing. According to the building material, they can be divided into wooden structure, brick structure, stone structure, clay structure and mixed structure, among which wooden structure is widely distributed in China. But wooden structure is susceptible to biological deterioration and fires, resulting in very few ancient buildings remained. At present, most of the existing wooden architectures were built during the Ming and Qing Dynasties. As the capital of the Ming and Qing Dynasties, Beijing has concentrated a lot of excellent wooden architectures, which have precious historical value and are regarded as valuable architectural culture heritage of China. However, as time goes by, some of the structures have been damaged and some are in danger of collapse due to various natural disasters and human activities [1-2]. Therefore, it is essential to inspect and appraise the wooden structures of ancient buildings systematically so as to learn their current situation and find out the potential risks [3-4]. This research aims to provide the inspection and appraisal of similar buildings with some references through inspecting and appraising the Yonghemen's wooden structure in Beijing[5-7].

2. Project Overview

The Lama Temple is located in the east of Yonghegong Street, Dongcheng District, Beijing. It is the largest Tibetan Buddhist temple in Beijing, which was built in the Qing Emperor Kangxi 33 years (1694). The temple was announced as the first batch of important national-level preservation units of cultural relics in 1961 and was confirmed as a national key Buddhist temple in Han area by the state council in 1983. It is mainly composed of three archway, six halls named Yonghemen, the Lama Temple Hall (Main Hall), Yong-woo Hall, Falun Hall, Wanfu Club and Suicheng Temple, and seven courtyards. The general layout plan of the Lama Temple is shown in Figure 1. This research mainly introduces the inspection and appraisal of the Yonghemen (Figure 2).

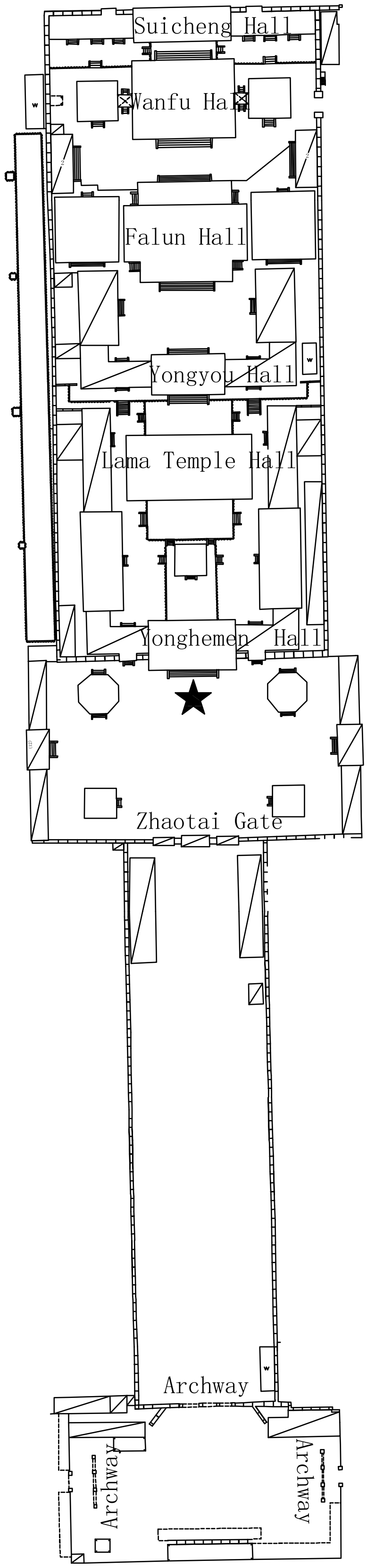

Figure 1. *General layout plan of The Lama Temple.*

Figure 2. *Building photo of south facades.*

3. On-site Detection

3.1. Surveying and Mapping

Based on the previous mapping data, detailed surveying and mapping of the structure's facades and the size of its main components were carried out. (some of the mapping are shown in Figure 3-5)

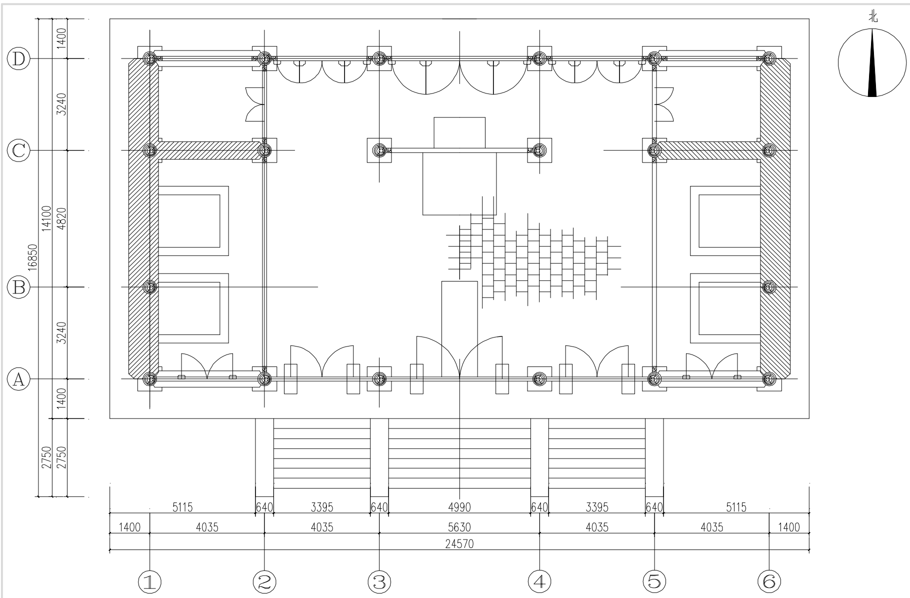

Figure 3. *Mapping plan of building.*

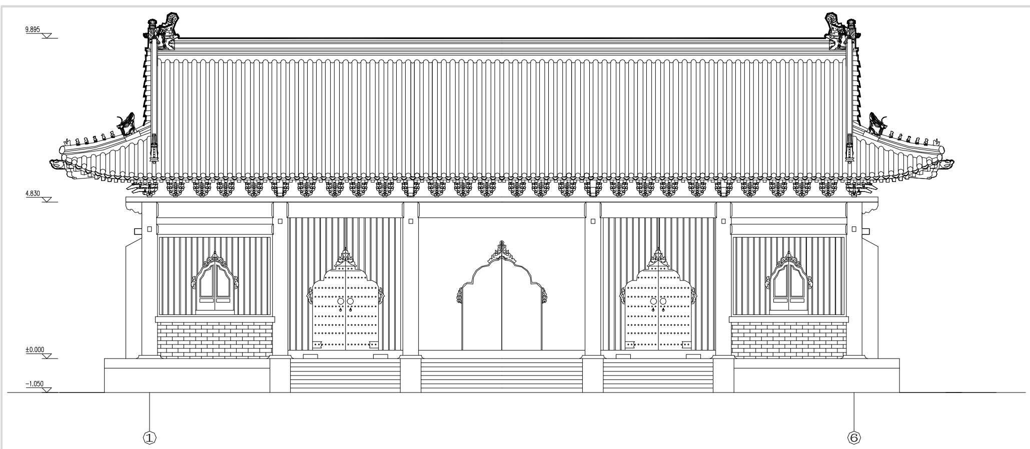

Figure 4. *Southern facade of building.*

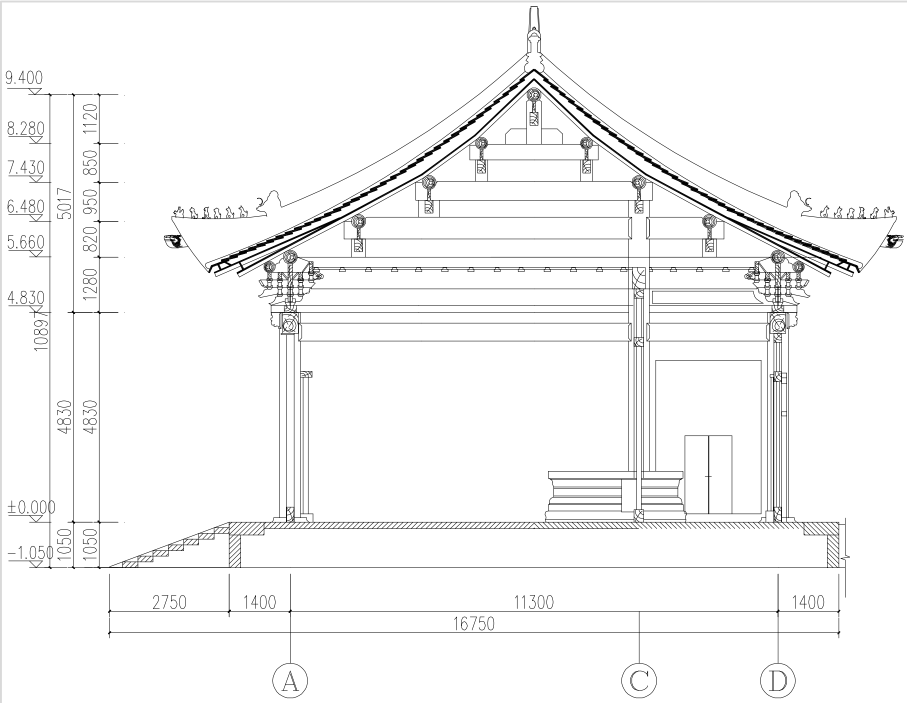

__Figure 5.__ Profile of the middle room.

3.2. Detection of the Foundation

1) Shape

The foundation of the building is rectangular, and its top and four sides are made of stones. The height of foundation is 1.05m.

2) Building material

According to the on-site detection, the stones of foundation are basically intact, and only a small part of the stones desquamate and fracture due to weathering. The photo of foundation is shown in Figure 6.

__Figure 6.__ Photo of the foundation.

3) Non-destructive testing of the foundation

In order to verify whether the foundation has cavities or cracks inside without damaging the building, ground-penetrating radar was used to detect the interior of foundation.

Ground-penetrating radar technique is a kind of geophysical exploration method based on the electric property difference existing between different media. And it determines the distribution of substance inside the object by analyzing the reflection and refraction of high-frequency impulse electromagnetic waves in the discontinuity of electromagnetic properties. Since this technology is featured by the advantages of being non-destructive, fast, precise, high-resolution and easy-to-operate, it is suitable for the detection of ancient cultural relics.

In this research, Zond-12 geological radar with an antenna frequency of 300MHz was used to scan and detect the ground outside the apron and inside the building. (The photo of radar test is shown in Figure 7, and the plots of test results are shown in Figure 8-9). Through the detection, it was found that there was no cavity in the ground outside the apron but the water remained inside some parts made the reflected wave decline quickly. Meanwhile, no obvious defect was found inside the indoor ground. The detection results of radar could provide references for future inspection.

__Figure 7.__ Photo of radar test.

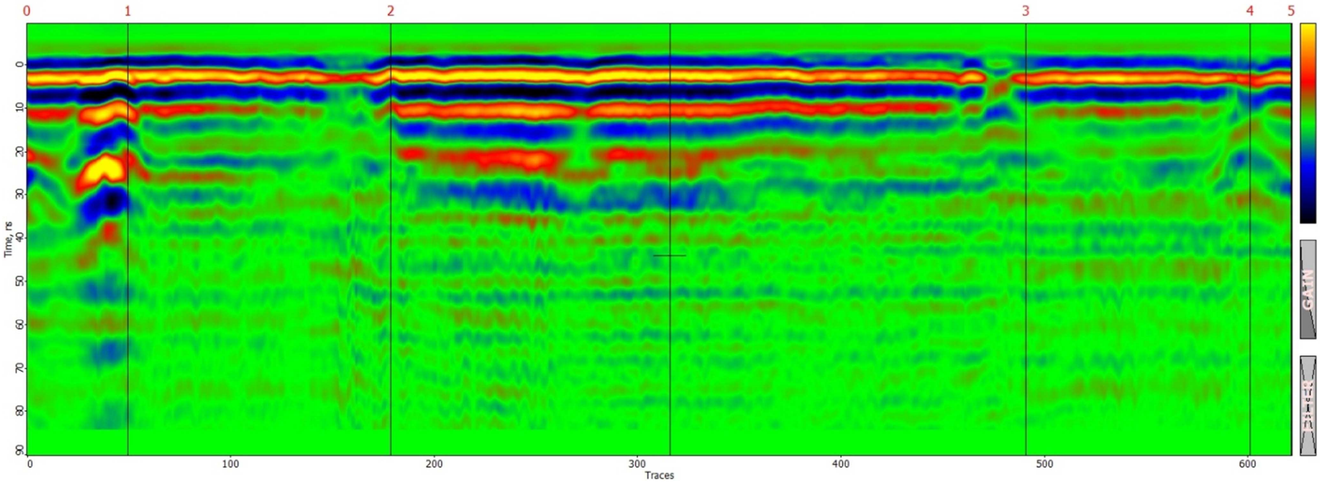

Figure 8. *Part of the images of the outdoor ground radar scan.*

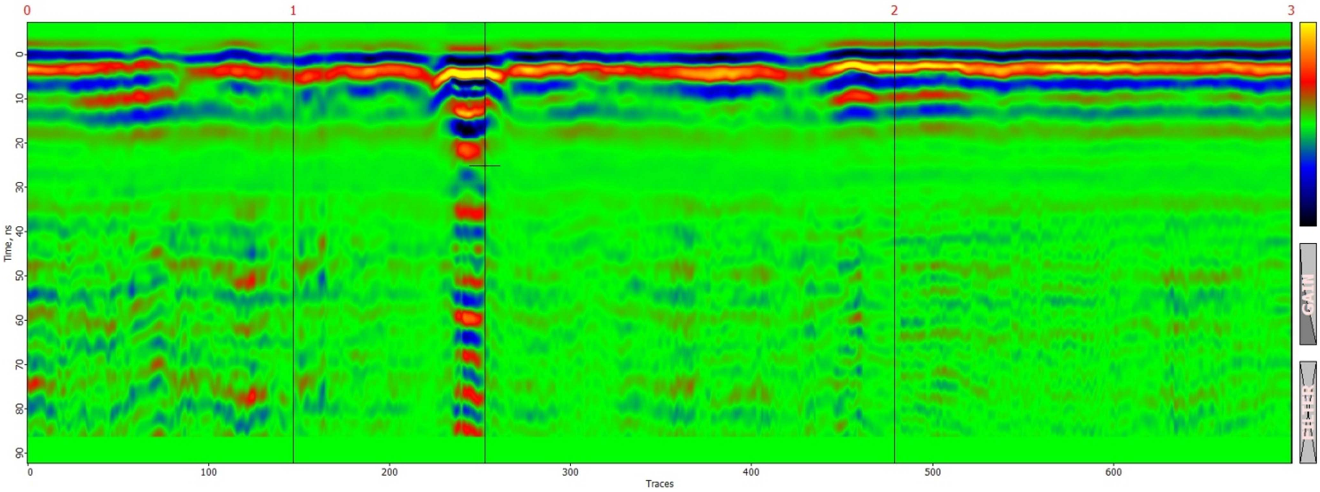

Figure 9. *Part of the images of the indoor ground radar scan.*

4) The deformation and bearing capacity of the foundation

No obvious crack or deformation caused by the uneven settlement of the foundation was found in the pedestal and superstructure. In order to learn the deformation of the pedestal precisely, the relative height differences between the upper surfaces of the building's base stones were measured. The result showed that there were height differences between the base stones, and the height difference between the base stones in the C-5 axis and A-1 axis in the southwest was bigger than any other place, reaching 23mm. Since there might be some deviations in early construction, the height differences can not be just regarded as the settlement difference of the foundation. In addition, taking into consideration the fact that no structure was found deformed because of the uneven settlement of the foundation, the bearing condition of the building can be considered as good. It is suggested that continuous observation and measurement of the relative height differences between base stones should be carried out later, and corresponding measures might be taken when any obvious abnormalities happened.

3.3. Inspection of Load-bearing Wooden Structures

3.3.1. Inspection of the Wood Quality

1) Inspection method

In this work, all the parts of the building within reach were checked by observation, hammering and other methods, and the material status of the wooden components like moisture content, cracking and decay was recorded. At the same time, non-destructive testing instruments like resistograph and three-dimensional stress wave scanner were used to further analyze the problematic wooden components.

Resistograph is a kind of wood small-destructive testing equipment which drives a micro-probe (with diameter about 1.5mm) into the wood at a constant speed with the help of a motor so as to measure the relative resistance of the wood. The resistograph will transmit the resistance parameters to the internal data acquisition card and then displays the resistance curve image after conversion. Since there is a positive relationship between the test values and wood density, namely, the wood density will change along with the resistance, it is possible to work out the relationship between the test values of the resistograph and the physical and mechanical properties (density, elastic modulus, etc.) of wooden components. Besides, the plan and stereograms of defects can be obtained by driving the micro-probe into different part of the wooden components [8]. The photo of resistograph test is shown in Figure 10.

Figure 10. *Photo of resistograph test.*

Figure 11. *Photo of stress wave test.*

Stress wave scanner is mainly composed of sensors and a computing system. The scanner works like this: strike the sensors installed on the wooden components to be tested to produce stress wave, and the propagation speed of the stress wave will then be processed by a computer, and reflected on an image showing the defects of the wooden components so as to determine the wood quality[9]. The photo of stress wave test is shown in Figure 11.

2) Inspection Results

(1) Moisture content: According to the measurement data, the moisture content of Yonghemen's wooden structure was mostly between 12% to 18%.

(2) Appearance inspection: Many shrinkage cracks existed in the wooden components like beams and purlins, but no obvious defect was found in other wooden components.

(3) Deep inspection of wooden columns: According to the inspection, the quality of the column is good, and there is no sign of decay. In order to further check the material of the wooden columns, resistograph and three-dimensional stress wave scanner were used to inspect the columns include A-2, A-6, B-3, B-4, C-3, and C-4 axes which had higher moisture and produced abnormal noise after knocking. The results showed that no serious defect was found in the wooden columns.

a) Resistograph test results

The test results of some wooden columns are shown in Figure 12-13. The orange region indicates that the wood may be moderately decay while the red region means the wood may exist severely decay and cracks.

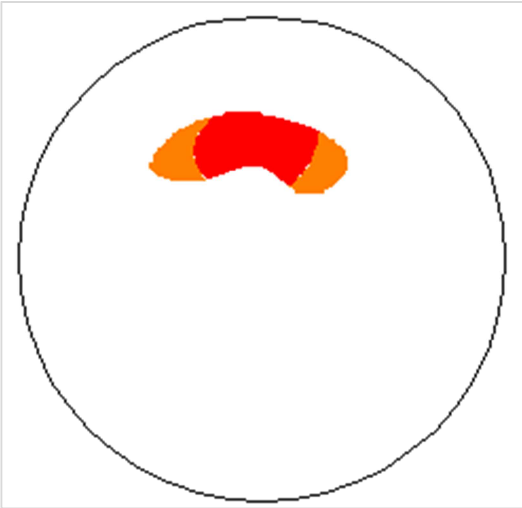

Figure 12. *Resistograph test results of the A-6 axis column.*

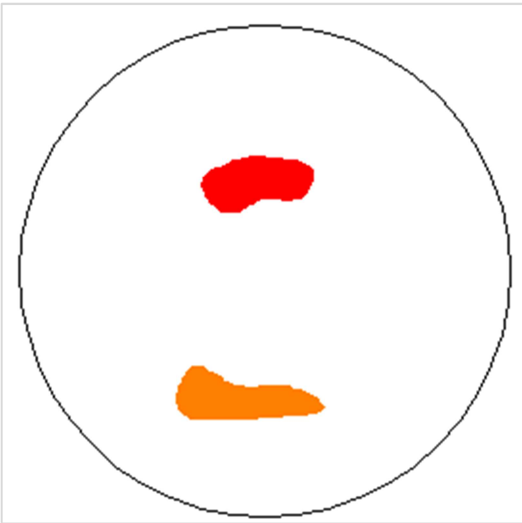

Figure 13. *Resistograph test results of the C-4 axis column.*

b) Three-dimensional stress wave test results

The test results of some wooden columns by three-dimensional stress wave canner are show in Figure 14 -15, and Figure 16 is the color bar used to judge the defects inside the wood. (It changes from healthy wood to decayed wood from left to right).

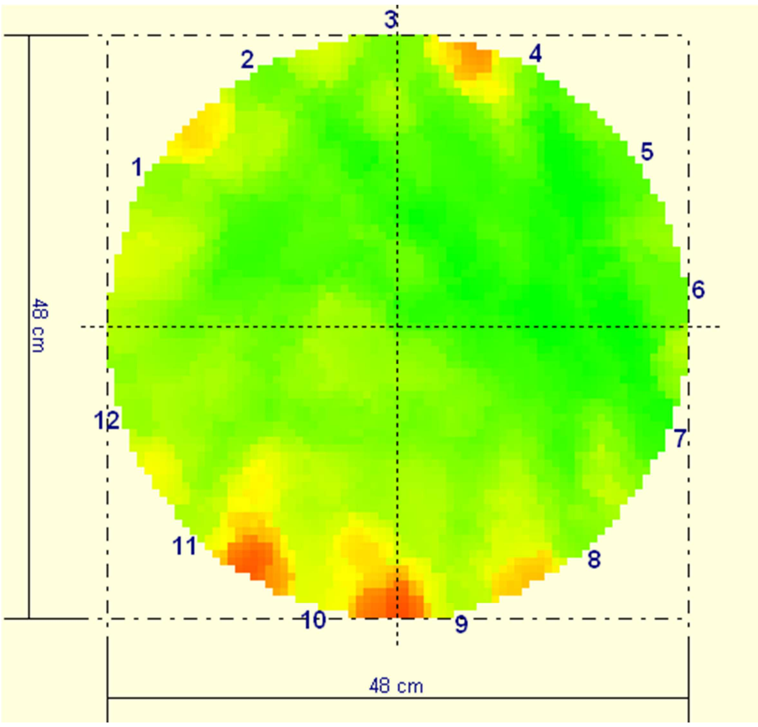

Figure 14. *Stress wave test results of the B-3 axis column.*

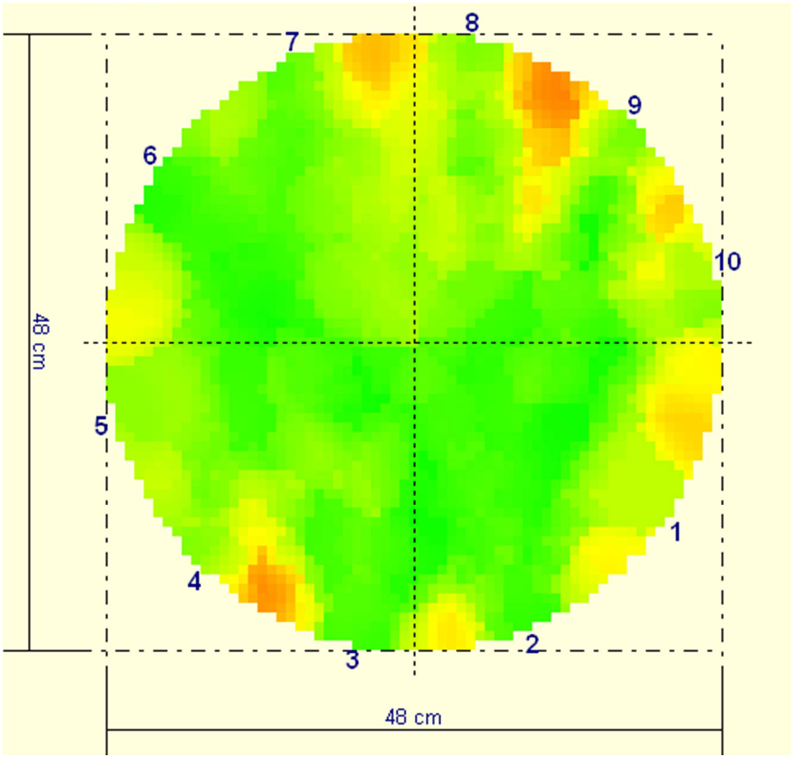

Figure 15. *Stress wave test results of the C-4 axis column.*

Figure 16. *Color bar of tress wave to judge defects.*

3.3.2. Identification of Tree Species

Through the identification of tree species, the physical and mechanical properties of the wood used in the building can be obtained, thus providing clues to the structural calculation and analysis of the wooden structure as well as the later replacement of wooden structures. Under the condition that the appearance, structure and functions of the building would not be affected by the test, some wooden components were sampled, sliced and processed by professionals. Then specialists obtained the identification results after observing the slices under optical microscope and referring to related literatures. The identification results of some wood species are shown in Table 1.

Table 1. *Identification results of some wood species.*

NO.	Name of wooden components	Position	Chinese name of tree species	Latin name of tree species
1	short column	upper principal purlin A-C-4	Mongolia scotch pine	Pinus sp.
2	3-purlin beam	A-C-2	Mongolia scotch pine	Pinus sp.
3	5-purlin beam	A-C-2	Mongolia scotch pine	Pinus sp.
4	7-purlin beam	A-C-2	Mongolia scotch pine	Pinus sp.
5	ceiling beam	A-C-2	Mongolia scotch pine	Pinus sp.
6	one-step cross beam	B-C-3	Mongolia scotch pine	Pinus sp.

3.3.3. Force Status of Main Wooden Components and Joints

1) The wooden columns remained the original state and no obvious bending deformation was found. The column footing and the base stones were in good condition, and no slip was found.
2) The ends of some beams fractured due to the action of forces.
3) The joints between beams and columns became loose, and some tenons were pulled out from mortises, which was commonly seen in the both sides of the C-axis hypostyle column on the north side, and the joints among hypostyle columns, 6-purlin beams and one-step cross beams. In addition, there were splits on the mortises of many king posts and short columns, and the length of some tenons pulled out of the mortises was more than 2/5 of its total length. And all of these are the defects mentioned in the *Technical Code for Maintenance and Strengthening of Ancient Timber Buildings* (GB 50165-92).

   Base on the above analysis, the reasons are as follows: There are 9 purlins in the beam frame, namely, a 6-purlin beam, a one-step cross beam and a two-step cross beam. The hypostyle column divides the beam frame into two parts, which are connected by mortise-tenon joints between the one-step cross beam and two-step cross beam, Baotou beam and central column. Due to the poor connection effect of the mortise-and-tenon joint, the tenons are likely to be pulled out from the mortises under external force, thus making the structure appear loose.
4) No obvious damage to the bucket arch was found.
5) The one-step cross beam and 6-purlin beam have already been strengthened by flat steel while other defects remain to be dealt with.

A typical timber beam is shown in Figure 17, while some defects are shown in Figures 18-19.

Figure 17. *Photo of timber beam.*

Figure 18. *Photo of mortise extraction.*

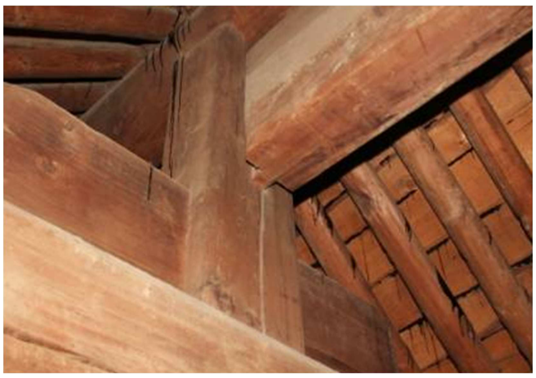

Figure 19. *Photo of splitting mortise.*

3.3.4. The Integrity of the Wooden Structure

The tilt of timber columns was measured at the scene, and the results are as shown in Figure 20 [10]. The data below the columns are the relative vertical deviation of the upper end and the lower end within the height of 3m at the bottom of the columns, and the numbers indicate the deviation of the upper part of the columns. It can be seen from the figures that the upper ends of the hypostyle columns and eave columns in the north are leaning to the south side, 2-A axis and 3-A axis hypostyle columns in the south are leaning to the south side, 2-A axis and 3-A axis columns are leaning to the north side.

In the conventional practices of ancient buildings, tilt angle would be set for hypostyle columns and eave columns, thus making them lean to the middle. The current shift extent of 2-A and 3-A axis columns is different from that during the construction, and there is a tendency to tilt outward while it is still within the limitation.

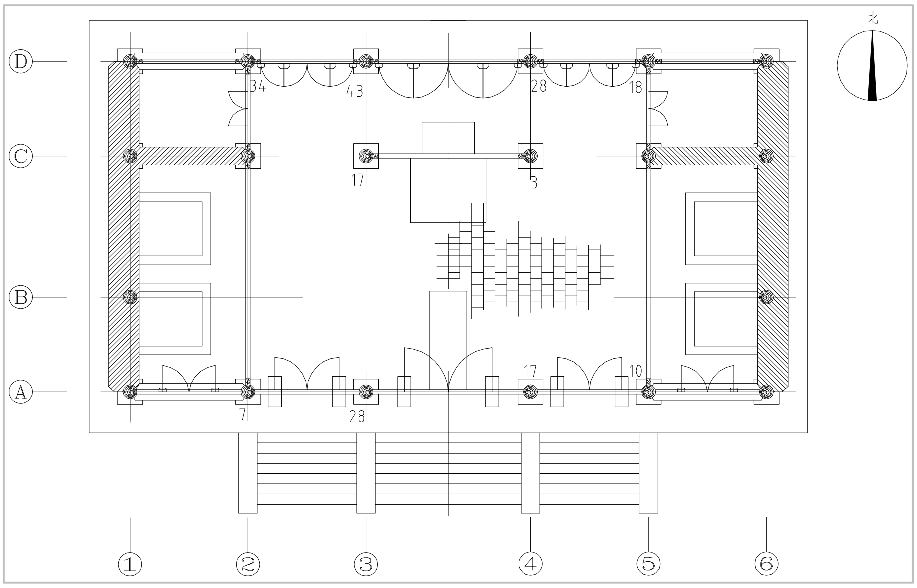

Figure 20. *Tilt measurement results of column(mm).*

Table 2. *Statistic table of tilt measurement results.*

NO	Column axis	Column top tilt mm (gauge length: 3m)	Tilt direction	Tilt value
1	2-A	7	South	0.23%
2	3-A	28	South	0.93%
3	4-A	17	North	0.57%
4	5-A	10	North	0.33%
5	3-C	17	South	0.57%
6	4-C	3	South	0.10%
7	2-D	34	South	1.13%
8	3-D	43	South	1.43%
9	4-D	28	South	0.93%
10	5-D	18	South	0.60%

3.3.5. Structural Vibration Test

Pulsating method was adopted to measure the natural frequency of Yonghemen structure. Micro-tremor is a kind of weak vibration signal caused by the vibration inside the crust, ground vibration induced by vehicles and wind. The response of the structure to the ground micro-tremor signals can be measured by high-precision sensors and data acquisition systems. In essence, the pulsation method means to use a broadband vibration exciter to excite the structure. And when its frequency is close to the natural frequency of the structure, it will cause resonance of the structure, that is, to obtain the natural frequency of the structure by amplifying the exciter's frequency which is close to the structure's.

In this research, ultra-low frequency vibrometer and data acquisition and analysis software were used to carry out the vibration measurement of the structure. The vibrometer was placed on the ceiling beam of the 6-axis beam frame. The test results are shown in Figure 21. After testing, the fundamental frequency of the structure was 3.00HZ. According to GB/T 50452-2008, the natural frequency is: $f_1 = \lambda_1 \varphi / 2\pi H = 1.571 \times 52 / (2 \times 3.14 \times 4.830) = 2.69$HZ, which is close to the test result of 3.00HZ[11-12].

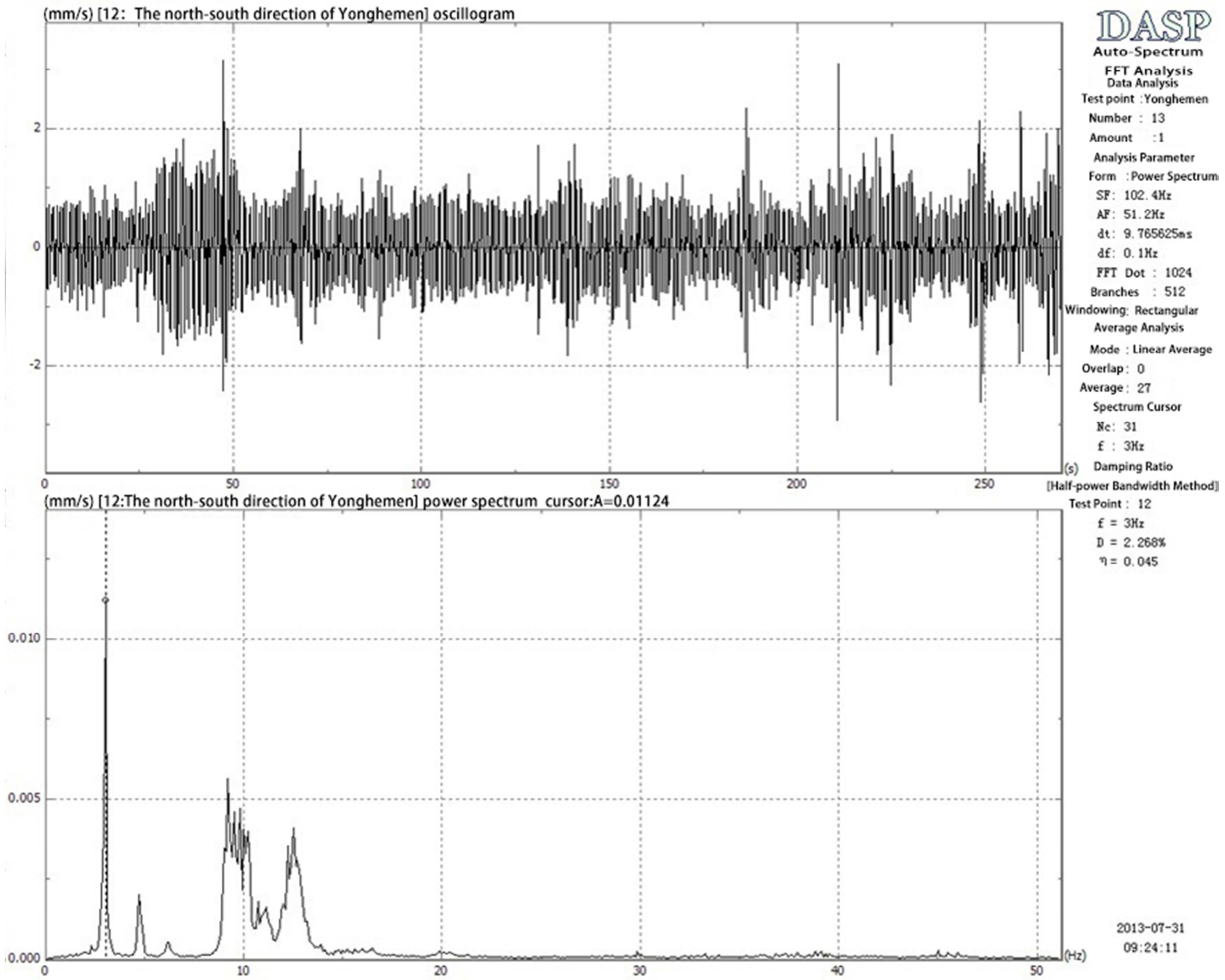

Figure 21. *Results of vibration measurement.*

4. Conclusions of the Detection and Appraisal

Based on the previous detection and test results, the overall performance of the structure is basically good. Despite some defects are exist in the joints, it won't have significant influence on the load bearing of the structure. According to the *Technical Code for Maintenance and Strengthening of Ancient Timber Buildings* (GB 50165 -92), Yonghemen can be rated as type 2 buildings, and the defects remain to be observed and dealt with.

5. Conclusions

This study introduces the inspection and appraisal of Yonghemen's wooden structure. Except for normal inspections, various kinds of non-destructive testing techniques and devices like radar, micro-drilling resistograph, stress wave scanner, pulsating method and tree species identification were used to inspect the ancient building comprehensively. These not only improved the accuracy of the inspection but also verified the results repeatedly, thus ensuring the accuracy of the inspection results. All in all, this research is of great significance to the inspection, evaluation, protection and maintenance of ancient buildings' wooden structures. Each technology has some limitations, it is necessary to use a variety of methods to improve the accuracy of the test results in the future, and continue to develop new technologies, so that non-destructive testing technology of defect detection in the ancient building can be better applied.

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