Post-Earthquake Analyses of Damaged Heritage Structures in Sichuan

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Abstract

As one of the four great ancient civilizations in the world, there are many cultural heritage buildings in China. Usually, these buildings are located in mountainous areas, where near the earthquake faults. In-depth understanding of the seismic performance of cultural heritage buildings is necessary for us to protect them from the destruction of earthquakes, as well as protecting our civilization. In this paper, firstly, typical failure modes of the cultural heritage buildings in the Wenchuan earthquake were revealed. And then, the key factors influencing the seismic performance of traditional wood structures were analysed and the concept of strong component-weak connection joint was highlighted. Besides, a numerical simulation of the earthquake damage analysis of a typical traditional wood-stone-brick composite structure was carried out. The influence of the connection stiffness between column and foundation on the structural response was detailed, as well as the influence of the stone wall. Lastly, some suggestions for new construction of archaized wood structures and the repair of heritage buildings were summarised.

Keywords

Cultural heritage building; Tenon-mortise connection; Strong component-weak connection joint; Seismic damage

1 Introduction

As the only uninterruptedly ancient civilization, China has many cultural heritage buildings. As the ancient poetry says, ‘A mountain needn't be high, it is famous so long as there is a deity on it’. So, these cultural heritage buildings are usually located in mountainous areas. At the same time, China is also a country with frequent earthquakes and natural disasters. In recent years, the cultural heritage buildings suffered damage and threat in all kinds of disasters. Wenchuan earthquake in Sichuan in 2008, the destruction of many cultural heritage buildings is a very painful story (Fig.1). Different from general buildings, the existence of the cultural heritage building is not only the value of the building itself, more important is the historical value, cultural value and humanistic value. Once the cultural heritage buildings are destroyed, they are non-renewable and irreparable. Therefore, to protect cultural heritage buildings from the destruction of all kinds of disasters is to protect the crystallization of the development of human civilization. Therefore, the exploration of cultural heritage building protection strategy is very important.

Fig.1 Destroyed cultural heritage buildings in the Wenchuan earthquake

In this paper, typical failure modes of the cultural heritage buildings in the Wenchuan earthquake were summarised and the key factors influencing the seismic performance of traditional wood structures were analysed. Besides, the earthquake damage analysis of a typical traditional wood-stone-brick composite structure was carried out. The influence of the connection stiffness between column and foundation on the structural response was detailed, as well as the influence of the stone wall. Lastly, some suggestions for new construction of archaized wood structures and the repair of heritage buildings were proposed.

2. Typical damage of cultural heritage buildings in the Wenchuan Earthquake

In China, cultural heritage buildings are usually wood or brick or masonry structures. In the Wenchuan earthquake, brick and stone masonry structures suffered serious damage. Although many masonry structures collapsed irreparably, most of the wood structures suffered less earthquake damage. The main damage forms (Fig.2) are column foot movement, tenon pull-out, maintenance walls damages, etc. Fortunately, these damaged wood structures can be easily repaired.

(a) column foot movement (b) tenon pull-out (c) maintenance walls damage

Fig.2 Typical damage modes of cultural heritage buildings in the Wenchuan earthquake

3. Key Factors Influencing Seismic Performance of Traditional Wood Structures

In the connection method between components, Chinese traditional wood structure (Fig.3) is different from the modern wood structure (Fig.4). When encountering earthquake, Chinese traditional building shows good seismic performance. The main differences are detailed below.

Fig.3 Chinese traditional wooden structure

Fig.4 Modern wooden structure

3.1 Connection method between column foot and foundation

One of the key factors influencing the seismic performance of the traditional wood structure is the connection method between column foot and foundation. In traditional wood structure, the column foot directly put on a stone foundation without other connections (Fig.5). When the horizontal seismic action is small, the friction force between the column foot and the stone foundation can effectively prevent slipping of the column foot. But, when the horizontal seismic action is large enough, the relative slip may occur between the column foot and foundation. During the slipping, the earthquake energy is dissipated.

(a) Type 1(before slipping) (b) Type 2(before slipping) (c) Type 3 (After slipping)

Fig.5 Typical Connection method between column foot and foundation

Usually, the mechanical model of the column foot is simplified as sliding support connected with a hook element and a constant force spring element, and the hinge support at the column foot can only be compressed, as shown in Fig.6.

Assuming the disengagement force of the hook element is as Eq. (1):

$$N_t = \mu_j N \tag{1}$$

Assuming the elastic restoring force of the constant force spring is as Eq. (2):

$$N_{\mathrm{D}} = \mu_k N \tag{2}$$

In which, N is the vertical reaction at the column bottom, μ_{j} is the static friction coefficient and μ_{k} is the dynamic friction coefficient.

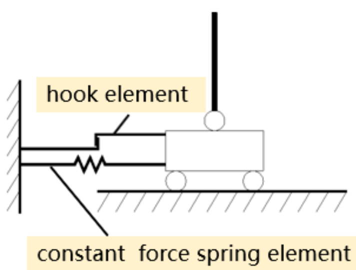


Fig.6 Simplified mechanical model of the column foot

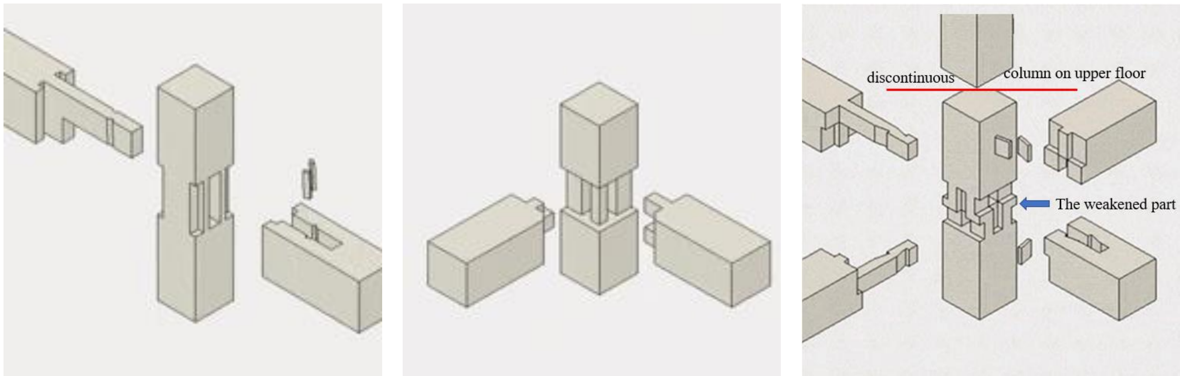
3.2 Connection method between beams and columns

Tenon-mortise joint (Fig.7) is a special connection method between beams and columns for traditional buildings in China. It is made up of tenons and frame holes. It is the wisdom crystallization of Chinese ancients, which is widely used in architectures and furniture. At the tenon-mortise joint, the section of the column is weakened greatly, and the end of the column cannot bear large bending moment, so the columns on the upper and lower floors are discontinuous. The structural characteristics of tenon-mortise connections are as follows: When the earthquake is moderate, the wood beams connected to the joint will rotate in joint; but when the earthquake is strong, the tenon will be pulled out from the joint.

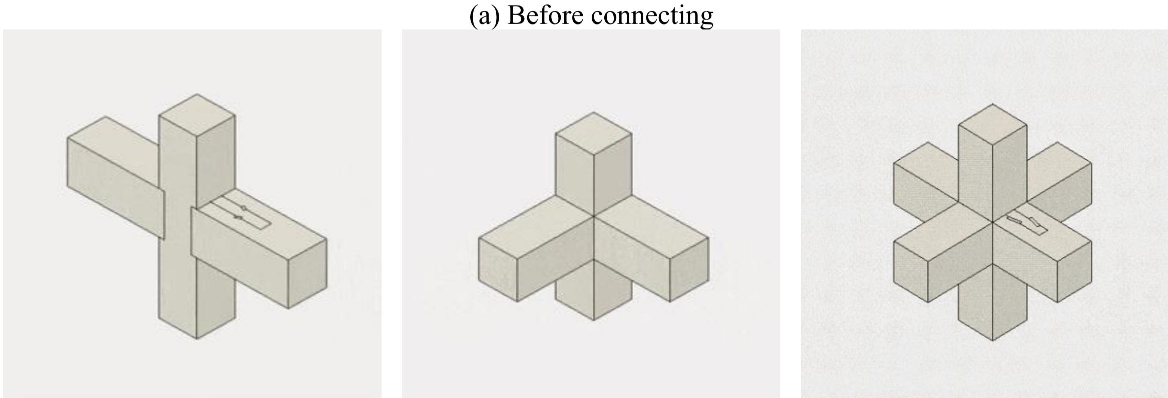
The seismic characteristic of traditional wood structures is strong component - weak connection joint, which is opposite to our basic design concept of frame structures. The capacity of beam end rotation and pull-out resistance are the key factors of seismic capacity for traditional wood structures. If the rotation deformation is hindered, the end of the beams or columns will be damaged. The mechanical model of the tenon-mortise joint can be simplified as a combination of a rotational spring and a damper, as shown in Fig.8, and can be expressed in Eq. (3):

$$M=K\varphi \tag{3}$$

in which, M is the bending moment, K is the rotational stiffness and φ is the Angular displacement.



(a) Before connecting



(b) After connecting

Fig.7 Typical tenon-mortise joints

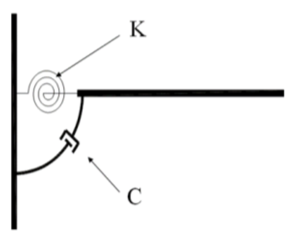


Fig. 8 Simplified mechanical model of tenon-mortise joint

Assuming the relative rotational stiffness coefficient of tenon-mortise joint denoted as μ, where $\mu \in [0,1]$. When μ=0, means the joint is hinge; when μ=1, means the joint is rigid. According to the test results (Fig.9), the relative rotational stiffness coefficient is probably only 0.0018, and the ratio of the transmitted moment to the fixed moment is probably only 0.18. It can be seen that the use of tenon-mortise joint leads to a significant reduction of the bending moment of beam end. The subsequent calculation results (Fig.10) show that when the relative rotational stiffness coefficient μ tends to zero, the structure tends to be hinge connection state and the axial forces of the components increase. In addition, tenon pullout may occur in the components with large axial tension force. When μ is about 0.1, the axial force curve shapes change sharply.

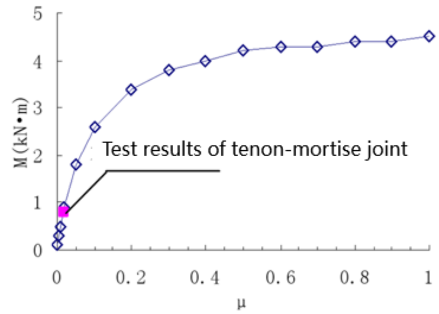


Fig. 9 Test results of the relative rotational stiffness coefficient of tenon-mortise joint

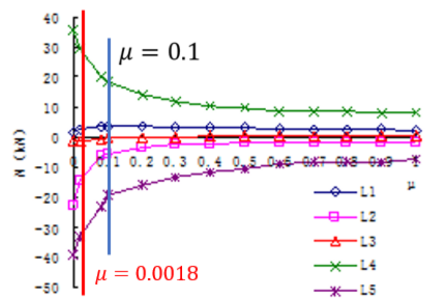


Fig. 10 Simulation results of the relation between μ and the axial force

4 Earthquake Damage Analysis of The Typical Traditional Wood-Stone-Brick Composite Structure

The excellent seismic performance of traditional completely wooden structures under moderate and low-intensity earthquake has been confirmed by many researchers. However, in practice, many columns are often stone or brick, and some walls are slabstone, etc. Especially on the ground floor, stone columns or brick columns have advantages in moisture-proof. Therefore, more attention should be paid to the seismic performance of these wood structures mixed with stone and brick.

Here is an example, as shown in Fig. 11. The building was built in the early last century, with two floors. The ground columns are brick and stone, and the second-floor columns are all round wooden. The stone column feet of the building are connected with the foundations in the same way as the wood column, but the brick column feet are fixed on the foundation. The joints between wood beams and columns are tenon-mortise connections. The maintenance walls are made of wood plate, but the bottom of the left wall is made of stone plate.

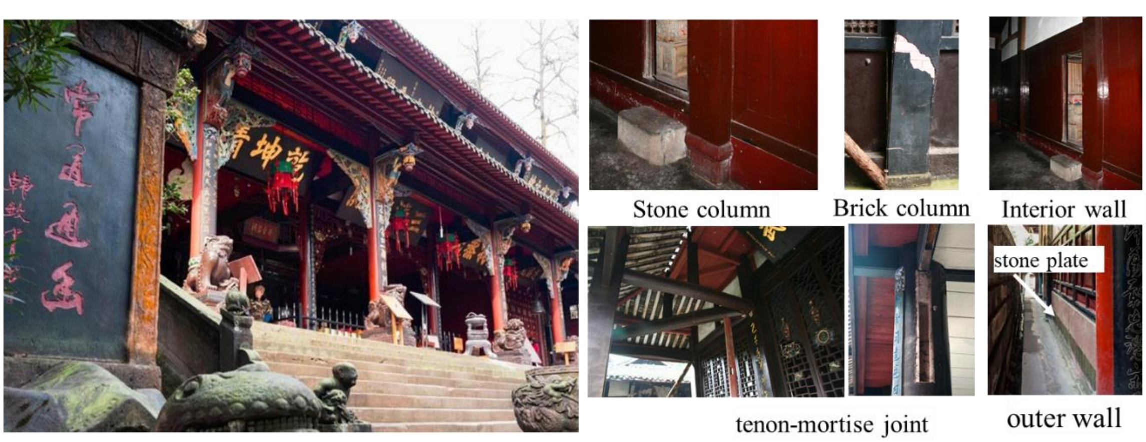


Fig. 11 A typical traditional wood-stone-brick composite structure

A numerical simulation analysis was carried out to back-analysis the seismic damage. In the model (Fig.12), building data, materials and component dimensions are in accordance with the measured records and the reference data of relevant codes. The numerical model is as close as possible to the actual structure. Virtual slabs are used to transfer load on the roof, and shell elements are used to simulate stone walls and wood walls. Whether beam elements or shell elements, finite stiffness is used for joints. According to the similarity of site type, the simulated ground motion is input.

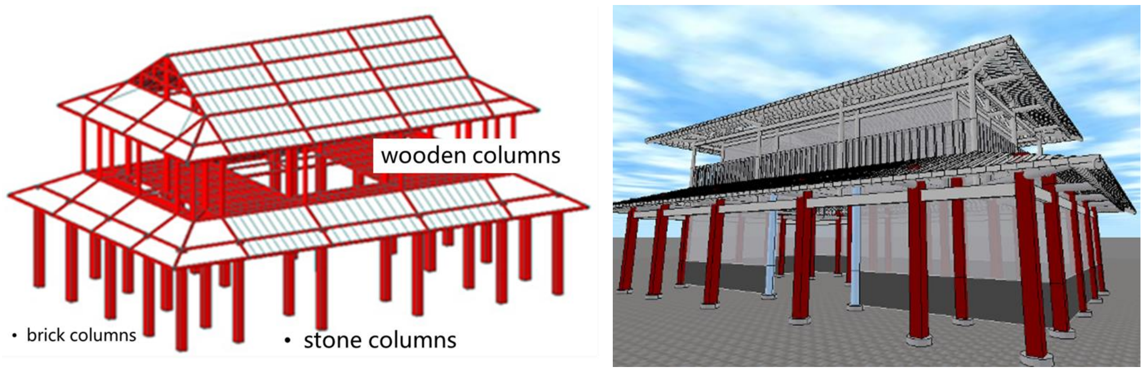
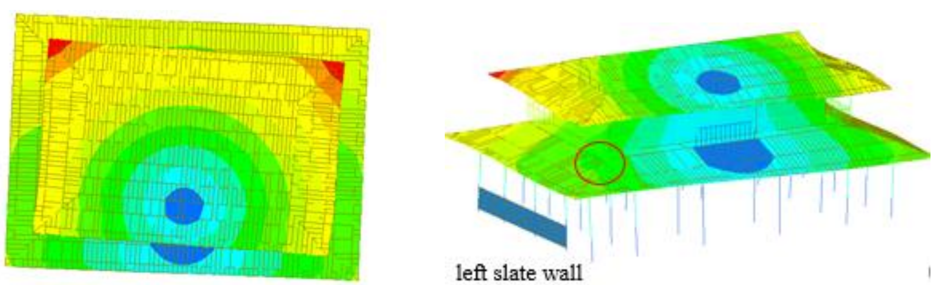


Fig.12 The simulation model of the typical traditional wood-stone-brick composite structure

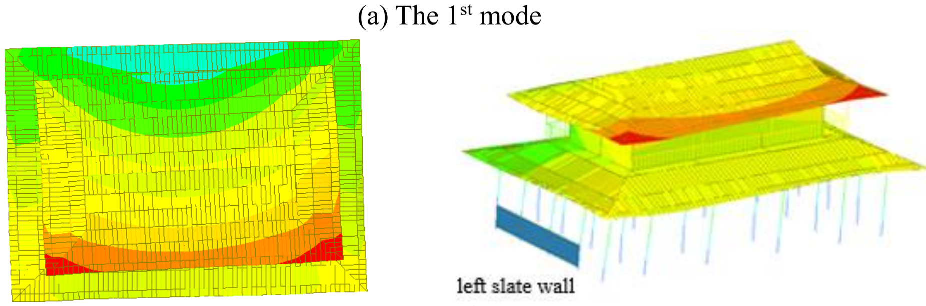
The purposes of the analysis are as follows:1) The characteristics of modes; 2) The influence of the connection stiffness between column and foundation on the structural response; 3) The influence of the left stone wall on the structural response.

4.1 Characteristics of modes

It can be seen from the mode diagrams (Fig.13) that the former two main modes of the structure show the characteristic of torsional vibration because of the left slate wall, which causes the inclined beams at the left corner to be in a tension state, thus causing the joint damage, which is consistent with the actual earthquake damage (Fig.2b).



(a) The 1^{st} mode

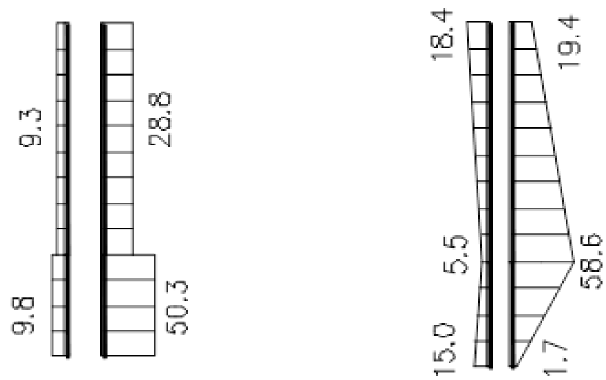


(b) The 2^{nd} mode

Fig. 13 Former two modes of the structure

4.2 Influence of the slate wall on the brick column

The calculation results (Fig.14) show that the larger bending moment and shear force of the left brick column are caused by the slate wall at the junction of the slate wall and wood wall. This is completely consistent with the actual earthquake damage (Fig.11).

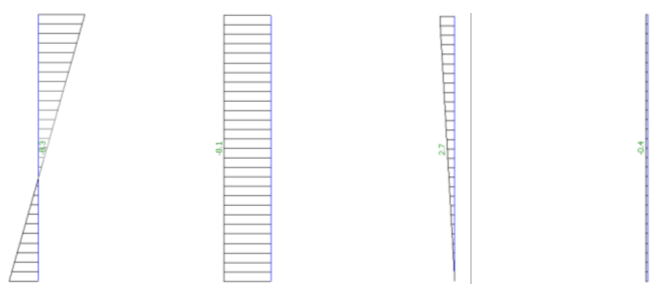


(a) Without slate wall (b) With slate wall

Fig.14 Simulated internal moment and shear force with/without slate wall

4.3 Column Foot and Foundation

According to the numerical analysis (Fig.15), it can be concluded that the moment and shear force of the stone column are smaller when the stone column foot is connected with the foundation stone in the traditional way, while the rigid connection between the brick column foot and the foundation leads to a larger fixed end moment and shear force on the brick column bottom. The simulated results are in accordance with the actual earthquake damages of the columns (Fig.16).



(a) Brick column (b) Stone column

Fig.15 Simulated internal moment and shear force of brick/stone columns

(a) Brick column (b) Stone column

Fig.16 Actual earthquake damages of brick/stone columns

5 Summary

- At present, in some tourist areas of China, buildings with traditional wood structures are being built. Based on the earthquake damage characteristics of traditional wood structures in the Wenchuan earthquake, the newly built traditional wood buildings are easily repaired when they are subjected to moderate and low-intensity earthquakes.
- The design philosophy of traditional wood structures is to realize weak joints with certain deformation ability through tenon-mortise connection. The columns on the upper and lower floors are discontinuous, and the column foot floats on the stone foundation.
- For the restoration of ancient buildings, it is necessary to avoid restricting the deformation of joints.
- The restoration method by steel plates is not advisable, because the strengthening measure at the joint has changed the original force transmission. The bending moment at the beam end is greatly increased, which leads to an increase of the bending moment at the column end. The ideal strengthening method is to restrict the pull-out of the beam tenon but not the rotation of the beam tenon.

All along, we only pay attention to the external cultural elements of ancient buildings. But the attention to the inheritance and protection of the structure characteristics is insufficient. We must realize that the unique structural characteristics are also the cultural elements that need to be protected in the restoration of ancient buildings.