ANALYSIS OF SEISMIC CHARACTERISTICS OF CHINESE ANCIENT TIMBER STRUCTURE

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ABSTRACT:
Timber structure is the main structural style of traditional ancient buildings in China, which is the valuable legacy of the ancient culture of China and plays an important role in the architecture history of the world. In this paper, the structural systems of Chinese historic timber structure are analyzed. On each system, the aseismic mechanism is given. According to the data of the earthquake damage and the structural characteristic of the Chinese ancient buildings, the method on the basis of the ultimate strength state of the structure is put forward to calculate the earthquake resistant capacity, which can be a reference for the appraisal and rehabilitation of the Chinese ancient timber structure.
KEYWORDS: ancient building, timber structure, aseismic mechanism analysis

1. INTRODUCTION

Chinese ancient architecture with centuries-old development has formed the special structural system after its five thousand years evolution. The timber structure with many virtues of simple technics, safty and good endurance is the most important structural system in the Chinese ancient architecture. So it is valuable to study the ancient timber structure, especially its skillful construction method and the prominent aseismatic capability, which has obtained the attention of the researchers all over the world. China is the country which the earthquakes happen frequently, the earthquake damage of many ancient timber structure buildings in the high intensity spaces appeared [1], so it is necessary to study the aseismatic capability and the earthquake resistant rules by knowing the earthquake damage characteristics of the Chinese ancient architecture. In this paper, the structural systems of Chinese ancient major carpentry architecture are analyzed. On each system, the aseismatic mechanism is introduced. The earthquake resistant characteristics of the ancient timber structure buildings are summed up. The method on the basis of the ultimate strength state of the structure is put forward to calculate the earthquake resistant capacity.

2. CONSTITUTION OF CHINESE ANCIENT TIMBER STRUCTURE

The monumental structure is the mature form in the ancient timber structures, it includes four layers: roof layer, bracket set and column-architrave layer [2-3].

2.1 roof layer

The roof layer is consist of beam frame and maintenance layers of the roof, it has good integrity property which can be seen as a rigid body. Because the profile of the roof is determined by means of a chu (rasing of the ridge purline) and a che(depression of the rafter line), the maintenance layers are curving and thick, the horizontal stiffness of the roof is big. So, the roof layer can be seen as rigid in the vertical direction. The axis-distortions of the beams of the beam frame system are neglected in the horizontal direction, so the horizontal stiffness of the roof layer is determined by the movement between the beams.

2.2 bracket sets (tou-kung) layer[4-7]

A set of tou-kung, or brackets, is an assemblage of a number of tou (blocks) and kung (arms), as is shown in figure 1. The function of the set is to transfer the load from the horizontal member above to the vertical member below. The horizontal stiffness bracket sets layer is weaker than the vertical stiffness, because the horizontal sets are connected only by the exposed beams (ming-fu) compared to the vertical sets, which shows the flexibility of the bracket sets in the horizontal direction. As the small beam frame is concerned, the upward earthquake actions can throw the beam frame up. When the frame falls, the instantaneous impact to the big beam is great, here, the bracket sets is acted as a good spring cushion to reduce the earthquake actions. Under the horizontal load, the joint distortions of the timber structure include turning and shear movement. The turning restriction is offered by mortise-tenon joint,

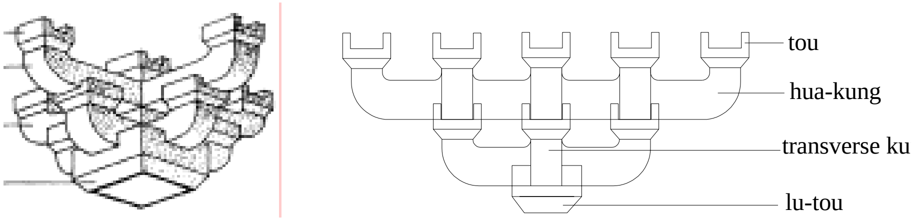


Figure 1 Component of the bracket sets (tou-kung)

and the shear restriction is offered by bracket sets. Different from the reinforced concrete column-beam joints, the bracket sets depend on the press and shear distortions between the tou and kung to resist the earthquake effect.

2.3 column-architrave layer

The column-architrave layer is made of column, architrave and sill. The function of the layer is to transfer the weight above to the top of column, the bottom of column lays on the stone base. In the horizontal direction, there are no support members between the columns. The horizontal earthquake actions are resisted only by the friction between the top of column and lu-tou, the foot of column and stone base, which leads to the coefficient of stiffness small.

3. EARTHQUAKE RESISTANT CHARACTERISTICS

According to the data of the earthquake, the grade of the earthquake damage of the Chinese ancient timber structure is given. The characteristics of the earthquake damage of every grade are described, as is shown in the table 1. From the analysis of the earthquake data we can see that the damage of the ancient timber structure buildings, such as the Imperial Palace, the Summer Palace and Kuan-yin Ke, Chi Hsien, Hepei province, appears frequently when the acceleration peak value of the earthquake reaches to 0.05g~0.2g, which shows that the ancient timber structure buildings are mangled easily by the low, medium intensity earthquake actions. The main damage styles are that the hip, main ridge in the room surface system are destroyed, and the Ch'ui-shou, Tsun-shou fall; the counterfort, fastigium are cracked, inclined and collapsed; some tenons of the timber frame are pulled out, the mortise-tenon joints are loose, and the obvious displacement of one or two feet of the columns appears. On the other hand, when the earthquake acceleration peak value is beyond 0.4g, many ancient timber buildings, such as the Wooden Pagoda of Fo-kung Ssu, Ying Hsien, Shansi province, are stand-up by the earthquake, which testifies the peculiarity of the good resistant collapse of them. The anti-collapse trait of the ancient timber buildings is connected with their structural types. One of the important characteristics is the technology of the combination of the tenon and mortise. The mature method of the tenon-mortise combination not only strengthens the intactness of the timber frame, but also the right tenon-mortise joint type can enhance the capability to resist the earthquake actions. In addition, the technology of the tou-kung is used in the timber structure, the function of the tou-kung is to disperse the energy of the earthquake.

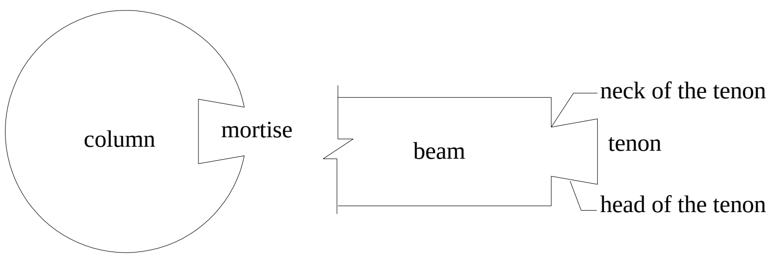
Table 1 Grade of the earthquake damage of the Chinese ancient timber structure

damage characteristics damage grade	Timber frame	Index of the earthquake damage of the wall(D)
Almost intactness	intactness	$D \le 0.1$
Slight damage	Timber frame is intact, cracks in the oil paint of the columns and beams appeared, some feet of the peristyle columns moved.	$0.1 < D \le 0.35$
Medium damage	Some tenons of the lintels between the peristyle columns and the hypostyle columns were pulled out, the feet of the columns moved, the cracks in the connection of the beam and columns appeared.	$0.35 < D \le 0.6$
Serious damage	Most tenons between the beams and columns were pulled out, the displacement of the column feet is large, the whole timber frame was inclined, many tou-kung were crushed to cracks.	$0.35 < D \le 0.9$
destruction	The timber frame was inclined seriously or collapsed, losing the supporting capability.	$D > 0.9$

4. ASEISMIC MECHANISM OF CHINESE ANCIENT TIMBER STRUCTURE [8]

4.1 tenon-mortise joint [9-10]

Because of the error in the make of the timber structure, the tenon can not combine the mortise completely. So the bending moment of the tenon-mortise joint is small under the horizontal load, which is similar to the hinge



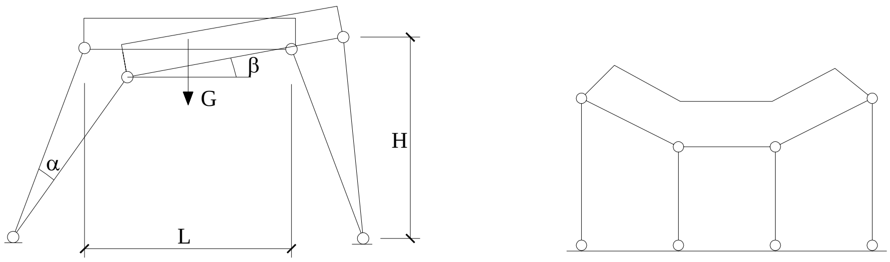
(a) swallow-tailed mortise (b) swallow-tailed tenon

Figure 2 Component of the tenon-mortise joint

joint. With the increase of the load gradually, the joint begins to be tightened, the restriction bending moment and the pulling out slippage become lager. Under the reverse loads, the tenon comes back to the primary place and repeats the process above. So, the destruction mechanism of the tenon-mortise joint is different from the reinforced concrete column-beam joint. The tenon-mortise joint whose area of the hysteresis loop is small depends on the friction between the tenon and mortise and not the destruction of the materials to disperse the energy of the earthquake. On the other hand, the reinforced concrete joint depends on the yielding of the materials and the creation of the plastic joint to reduce the earthquake actions.

4.2 ch'e-chiao and sheng-ch'i

The most important rules in columniation of the Chinese timber structure are ch'e-chiao (a slight inward incline of the columns, about 1:100)and sheng-ch'i(a gradual increase in the height of the columns from the central bay toward the corners of the buildings) which help give illusion of stability, as is shown in the figure 3. From



(a) ch'e-chiao (b) sheng-ch'i

Figure 3 Rules in columniation to resist the earthquake

figure (a) we can see that when the feet of the columns of the timber structure move, the columns create the rotary angles in the same direction. One side of the column angle is bigger and the other is smaller or zero, and the architrave becomes slantwise. From the geometry of the figure (a) we see that:

$$\alpha = \frac{x}{H}, \quad \beta = \frac{2x\sin\alpha}{L} \tag{3.1}$$

$$F = G\sin\beta \tag{3.2}$$

where α is the increasing rotary angle of the column; β is the angle of the horizontal architrave because of the lateral displacement of the particle; x is the lateral displacement of the column; H is the height of the column; L is the length of the architrave; G is the weight of the roof; F is the resuming force which is the part of the G .Some assumptions of the geometry are that:

$$L = H, \quad \sin\alpha = \alpha = \tan\alpha = x/H \tag{3.3}$$

So, Eq.(3.1), (3.2) can be written as:

$$\beta = \frac{2x\sin\alpha}{L} = \frac{2x^2}{H^2} \tag{3.4}$$

$$F = G\sin\beta = \frac{2Gx^2}{H^2} \tag{3.5}$$

It can be seen from the analysis of the formulas above, the resuming force F is bigger as soon as the lateral displacement of the column increases. The mechanism of the ch'e-chiao can still exert to its function unless the tenon-mortise joint is destroyed. Because the resuming force whose direction is contrary to the lateral displacement of the column frame always points to the balance position of the particle, the energy input the structure must resist the part of the weight of the roof along the axis of the architrave firstly, which can reduce the earthquake actions effectively. The meaning of sheng-ch'i is increasing the height of the columns toward the corners, the proof lays in the concave timber frame, and always on the decline plane whether the lateral displacement of the columns is right or left. So the sheng-ch'i can effectively restrict the horizontal displacement of the beam frame, and avoid the collapse of the timber structure.

5. ANALYSIS METHOD ON THE EARTHQUAKE RESISTANT CAPACITY

The structural types of the Chinese ancient buildings are special compared to the buildings nowadays. So far, there are no criterions, regulations about the analysis of the earthquake resistant capacity of the special structural types made. In this section, the method on the basis of the ultimate strength state of the structure is created to calculate the earthquake resistant capacity, According to the data of the earthquake damage and the structural characteristic of the Chinese ancient buildings. This method can be denoted by the equation as follows:

$$R - S_G - S_Q = 0 \qquad (5.1)$$

Where R is the required strength; S_G is the dead load; S_Q is the live load. R, S_G, S_Q are all variable which are confirmed by the probability model and the statistic characteristic. There is a great development of the structural calculating method on the basis of the invalid probability compared to the fixed value method, which leads the structural security analysis to a new stage from the experience analysis to the quantitative analysis on statistics.

6. CONCLUSIONS

This article has presented the constitution of Chinese ancient timber structure, and introduced the structural characteristic of every layer of the timber structure. According to the data of the earthquake, the grade of the earthquake damage of the Chinese ancient timber structure is given, the characteristics of the earthquake damage of every grade are described. The aseismic mechanism of Chinese ancient timber structure is analyzed. The mature method of the tenon-mortise combination not only strengthens the intactness of the timber frame, but also the right tenon-mortise joint type can enhance the capability to resist the earthquake actions. In addition, the technology of the tou-kung is used in the timber structure, the function of the tou-kung is to disperse the energy of the earthquake. The most important rules in columniation of the Chinese timber structure are ch'e-chiao and sheng-ch'i which effectively restrict the horizontal displacement of the beam frame. The method on the basis of the ultimate strength state of the structure has been created to calculate the earthquake resistant capacity, According to the data of the earthquake damage and the structural characteristic of the Chinese ancient buildings, which can be a reference for the appraisal and rehabilitation of the Chinese ancient timber structure.

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