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Analysis and investigation of seismic behavior for multistory-pavilion ancient pagodas in China

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Abstract

This paper introduces the architectural form, structural system, building materials, ground treatment methods, and seismic constructional measures of multistory-pavilion pagodas in seismic regions, analyzes the construction principle and seismic behavior of this kind of pagodas. It tries to give an objective reference to the similar ancient pagodas or buildings for seismic assessment, repair, and strengthening.

1. The architectural form and structural system of multistory pavilion pagodas

Multistory pavilion pagoda originated from the multistory and pavilion in China. Usually this kind of pagoda consists of four main parts, underground palace, pedestal, body, and laksata [1] (Fig.1). The underground palace and pedestal were built of stone or bricks. Most of the early time pagodas' bodies were wood structures, and the construction technology reached the zenith of ancient Chinese wooden structure technology. Since Tang dynasties, most of pagodas were built with the block of stone and brick in imitation of wooden structures.

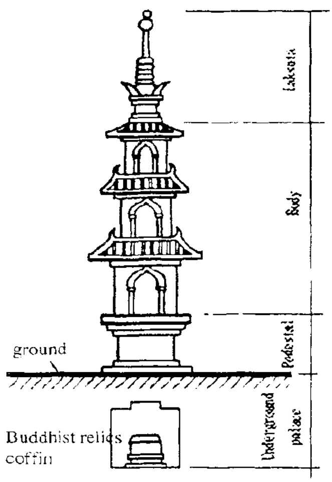

Fig.1 Structure of pagodas

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Because it's graceful shape and great bulk, multistory pavilion ancient pagoda become the building ascending to enjoy a distant view or the mark of navigation. The existent ancient pagodas have experienced the vicissitudes of history, and most of them have survived earthquake. These pagodas have become the symbol of ancient cities or scenic spots, and have important cultural values in Chinese history.

Multistory pavilion ancient pagodas were built with the symmetrical plan form in equilateral polygon (square, hexagon, octagon, etc), and the uniform contracting configurations from the first story to the top story. There are many a kinds of pagoda interior layouts (Fig. 2). Most of multistory pavilion pagodas used "turn-up along inside the wall" layout. Waist eaves and balustrades lay around pagoda body at every story. The height- width ratio of these pagodas is usually no more than three, so they have great structural stability. Because of these features of plans and structural shapes, the forms of vibration of pagodas are very simple and regular. It is of great advantage to seismic proof.

The body is the main part of a pagoda. According to the structural system of the body, multistory pavilion pagodas can be divided into three types: single tube, center column and tube-in-tube (Fig. 3).

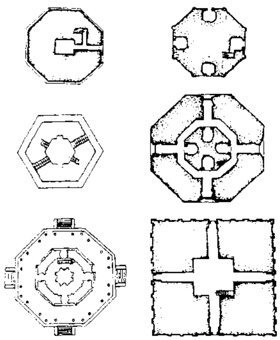

Fig.2 Pagoda's interior layouts

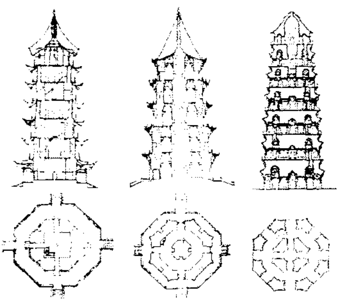

Fig. 3 Structural system of the body
(a) single tube, (b) center column, (c) tube-in- tube

2. The building material of multistory pavilion pagodas

Most of the early multistory pavilion pagodas were made up of wood. The ancient Chinese architects mastered a set of exquisite craftsmanship of manufacture wood structure, and built a number of elegant wooden structures. The most remarkable wooden pagoda is the Sakyamuni Pagoda (Fig.4) of Fogong Temple in Yingxian county Shanxi province, built in A.D. 1056. It is

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67.3 meters tall, the largest and highest wooden structure in the world. The tube-in-tube structural system consists of wooden columns and beams in all with very good seismic behavior. For nearly a thousand years, the pagoda has experienced many violent earthquakes.

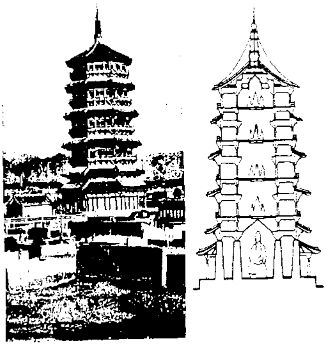

Fig.4 Sakyamuni Pagoda of Fogong Temple

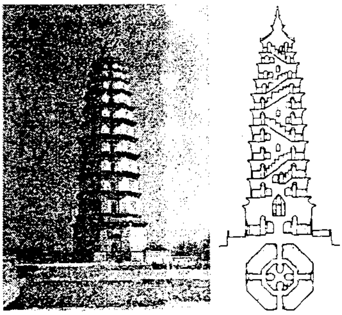

Fig.5 Hebai, Dingxian, Lookout Pagoda

With the development of construction technology, ancient Chinese workers built pagodas with brick and stone instead of wood gradually. Being excellent fire-resistance and durability of masonry structures, the ancient pagodas could remain longer time. Brick pagoda has very heavy weight and very big brittleness, so its earthquake response is very bigger than wooden pagoda's. The existent typical brick pagoda is the Lookout Pagoda (Fig.5) in Dingxian, Hebei province. It was built in A.D. 1005, octagonal, eleven-storied, 84 meters tall, tube-in-tube structural system. It's also the highest ancient pagoda in seismic regions. Except that the pagoda's roof had been damaged in earthquake at A.D. 1884, the pagoda's principal structure is very well up to now. The existent pagodas proved that brick structure had good seismic behavior as the brick materials were arranged reasonably.

3. Selection of site and ground treatment of multistory pavilion pagodas

Being big bulk and heavy weight, multistory-pavilion pagodas need firm foundation beds, especially for brick pagodas. Otherwise their seismic behavior and normal using would be influenced directly. Except that some ancient pagoda's bases were laid on rock beds or hardpans (Fig.6), many foundation beds of pagodas were soft-soil's. So these pagodas' grounds must be treated

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artificially. The ancient Chinese workers had explored effective treatment methods on pagodas' foundation bed as follow:

3.1 Lime and earth foundation

Replacing soft soil with lime earth in pagoda's foundation bed region, and rammed layer by layer. Wooden beams sometimes were laid in lime earth. The typification is the foundation bed of Xi'an Jianfu Temple Pagoda. Besides the soft-soil of the pagoda foundation soil were changed by lime earth, two-way wooden beams were laid into lime and earth foundation for reinforcement of foundation integrity.

3.2 Wooden piles' foundation

The typical example is the foundation bed of Guangxiaojiao Temple Pagoda in Taicang, Jiangsu province (Fig.7). This pagoda was built in A.D. 873. Its site is low-lying land near a pond, and ground water elevation is very high. There is a silt soil layer beneath the foundation base. So wooden piles were driven into soils, and nearly a meter lime soil was laid under the foundation base.

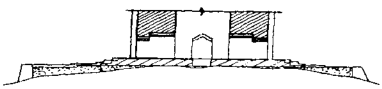

Fig.6 Foundation laid on rock beds or hardpans

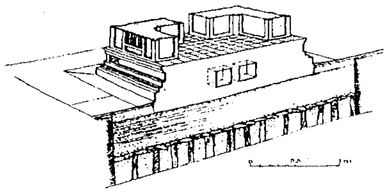

Fig.7 Foundation reinforced by wooden piles

3.3 Raft foundation

The typical example is the foundation bed of Shanghai Longhua Pagoda (Fig.8). This pagoda was built in A.D.977, brick bulk, octagonal, five storied, 40.4 meters tall. Its foundation bed soil was soft, and the raft foundation was used to reduce the settlement of ground. Under which there is thickness wooden plate and wooden pile with $140 \times 180 mm^2$ cross section in full base region.

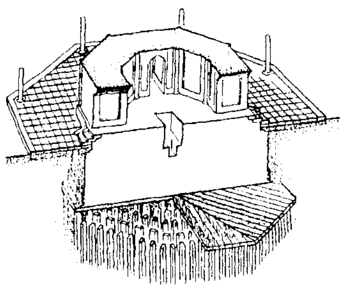

Fig.8 Raft foundation

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There occurred the collapse of pagodas, as foundation treatment unsuitably. For example, Famen Temple Pagoda in Shangxi, after its old wooden structure was damaged, the brick pagoda was rebuilt imitating the old wooden pagoda's shape, but the foundation bed was not been strengthened. The load of the brick pagoda exceeded the bearing capacity of the foundation bed. Soon after being built, this pagoda was cracking. The cracks widened by the earthquake of A.D. 1976, and the pagoda collapsed in a rainstorm of 1981.

4. The seismic constructional method of multistory pavilion pagodas

In practice the ancient Chinese architects had approached the follow constructional methods to improve the seismic behavior of multistory pavilion pagodas.

4.1 Dougong joints

Dougong (Fig. 9a) is a kind of creative structural member in ancient Chinese wooden structure. This wooden structural member is a flexible joint and an important energy dissipation element. It was used to connect of principal structure (in ancient wooden pagodas) and structural members in ancient pagodas. Under the earthquakes, the Dougongs will bear large deformations and dissipate earthquake energy, thus increase the structural ductile and improve the seismic behaviors of pagodas. For example, the Sakyamuni Wooden Pagoda of Fogong Temple in Yingxian, Shanxi province applied 54 kinds of dougong in its body (the Fig.9b is sketch of some kinds of Dougong in its part body).

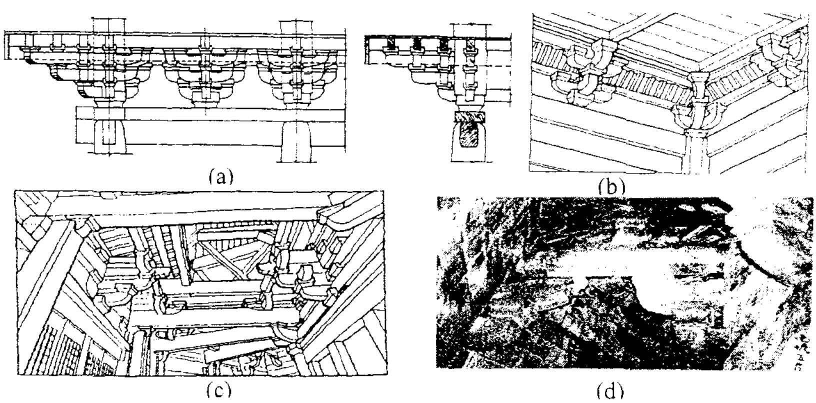

Fig. 9 Dougong joints and its application

Dougong also could be made of stone and brick, reinforced by flat steel bar to

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get the similar effect as wooden structure. The typical examples are double Pagodas in Kaiyuan Temple. Their main structural members are all made up of square granites. Stone dugongs were used at eaves and floors widely. Especially, stone Dougongs were symmetrically arranged at internal wall and center column. They support the stone beams at every floor, reduce the span of the stone beam, and make good use of the compression strength of stone material. Although these two pagodas experienced the earthquake of A.D.1604, they kept very well up to now. The Fig.9c is the sketch of stone dougongs in the room of the east Pagodas in Kaiyuan Temple, and the Fig.9d is the sketch of brick dougongs in the room of the double Pagodas in Luohan temple of Suzhou.

4.2 Radial bars and tie beams

The radial wooden tie bars were placed every story. For the convenience of access to pagodas, however, the wooden tie beams were parallel with the interior wall to form a complete girdle. They were applied in Song dynasty brick pagodas widely.

4.3 Reinforced system for the Laksata

As a structural part of a pagoda, the Laksata at the top center of the roof is used for fixing the rafters and the roof boarding. Aesthetically, it is the peak, the topmost symbol of a pagoda. Therefore, it is usually delicately exquisite, tall and slender like a mast, giving the impression of penetrating into the sky. Because the Laksata is very tall (about one fifth of a pagoda height), so earthquake could cause the "whip-ping effect" of a pagoda easily. The treatment method was that huge rod was deeply fixed in the pagoda's body by cross beams. The Laksata's wheels are strung together by the rod. On especially tall Laksatas, iron chains are attached to the huge rod of a Laksata for resisting earthquakes (Fig. 10). These methods reduced laksatas' "whip-ping effect", reinforced the connection of pagoda's roof and body.

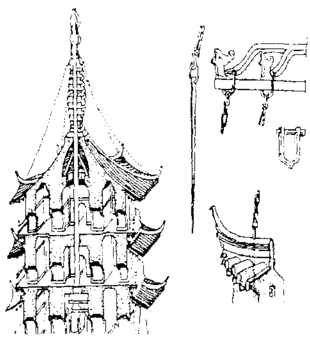

Fig. 10 Reinforced system for the Laksata

4.4 Wood bar or iron member put in brick pagoda's body

This method could reinforce brick wall's integrity. For example, nearly per one meter along the height, horizontal wooden beams were put in the walls of Dingxian county Lookout Pagoda.

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5. The analysis and test for dynamic behaviors of multistory pavilion pagodas

To understand the seismic behavior of the pagodas, Chinese scientists have researched and tested the dynamic behaviors on some multistory-pavilion pagodas in seismic regions, and have achieved the following results.

5.1 Calculating model

Most model of dynamic behavior about ancient pagodas based on cantilever beam with bottom end fixed, using continuous distributed parameter beam model or separated parameter beam model. Analysis methods of dynamic behavior have matrix iteration, energy method, Rayleigh-Ritz analysis, finite element method, etc. These methods could get the theoretical solution of structure dynamic behavior. Based on the comparison of theoretical value with experimental value, reference [2] provided a simplified formula for natural period of pagodas: $T = 0.0042 n_1 n_2 H^2 / D$. Where, n_1 is material elastic modulus factor, n_2 is hole size factor, H is the height of pagoda, and D is the diameter or side length of the pagoda's first floor. Obviously, this formula is not suitable any pagodas.

5.2 Test method

There are many testing methods for testing pagodas' dynamic behaviors. Pulsating testing method is the most suitable one that has no any damaged to ancient pagodas and has enough service ability. Using this method can obtain accurate parameter about natural vibration frequency, mode of vibration, damping ratio, etc. Jianli Yuan and Shengcai Li combined this method with computer-simulation technique in the project that seismic appraisal of Yangzhou Wenfeng Pagoda[3], and obtained the reliable result of dynamic behavior (Fig. 11). Some scholars used little rocket to make artificial impulse for testing, and obtained a certain result [4].

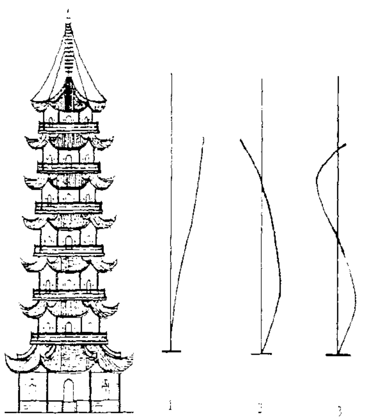

Fig. 11 Yangzhou Wenfeng Pagoda

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5.3 Dynamic behaviors

Based on the statistics and analysis of above references, that could find the following features of most multistory pavilion pagodas: 1) Ancient pagodas are little damping structure. The range is among 0.001 and 0.08. 2) First-mode of all vibration deformations is bending deformation. 3) Laksatas could make great influence to higher vibration modes of pagoda's structure. 4) The damaged states, constructional methods, and physical behaviors of material could also make great influence to dynamic behavior of structure. These influences should be introduced into the computer program as the model parameters, by computer simulate the actual test results to obtain the exact dynamic analysis model.

6. Conclusions

This study investigated and analyzed the structural features and dynamical behavior of multistory pavilion ancient pagodas in seismic regions. Some references can be given for seismic assessment, repair, and strengthening of the similar ancient pagodas or buildings.

6.1 A firm ground base has the advantage of seismic stability to any ancient buildings, especially for brick and stone pagodas. The foundation and base must be acted as the important checking objects to seismic assessment of an ancient building.

6.2 Let a reinforced ancient building keep regular plan form and uniform structural shape, which will provide a simple vibration response for the structure to undergo earthquakes.

6.3 The optimum repair material is wood to an ancient wooden building. The flexible wooden structure and joints will dissipate earthquake energy more efficiently.

6.4 Wooden tie beams and columns can be used to increase the seismic integrality of an ancient building. Similarly, steel or reinforced concrete tie beams and columns can be embedded in brick buildings for the same objective.

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