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FULL 3D CAD PROCEDURE FOR THE LIMIT ANALYSIS OF LONGHU PAGODA IN CHINA

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Abstract

This paper adopts a very convenient 3D CAD method to quickly assess the seismic vulnerability of existing masonry towers. The study selected five typical collapse mechanisms, vertical splitting, base rocking, overturning with diagonal cracks (Heyman 1992), a combination of splitting and diagonal overturning and base sliding. The Longhu pagoda in China is selected as the research case. Based on the principle of virtual works, assuming that the masonry material is a no-tension material, and the collapse acceleration under loads G1 and G2 is calculated from the four main directions. The research results show that vertical splitting of collapse mechanism is the easiest to appear, which is in full compliance with the results of the on-site survey after the Longhu pagoda earthquake, further demonstrating the reliability of this method. This method does not require complex mathematical foundations, can be easily mastered by non-professionals, and at the same time greatly reduces the amount of simulation calculation, which is helpful for the promotion of seismic research of masonry structures.

Keywords: Masonry pagoda; limit analysis; Collapse mechanism, Collapse acceleration.

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1 INTRODUCTION

As one of the four ancient civilizations, Chinese ancient buildings are a precious heritage left over from history. The ancient masonry pagoda is a typical representative, which combines the crystallization of the world's wisdom and the essence of architectural art. With the development and changes of the times, most of the ancient pagodas left behind have become historical sites, which not only brighten the city's scenery, but also promote Chinese culture and enrich tourism resources. The ancient pagoda is mainly located in the north and south of China, with many styles and characteristics. After going through the changes of the times, the existing masonry pagodas have extremely high historical and cultural, aesthetic art and scientific research value. Therefore, trying to protect and repair the ancient masonry pagoda has become an important mission for contemporary people.

Masonry pagoda has the advantages of high compressive strength, low cost, convenient construction, fire resistance, and good heat and sound insulation performance. It is a brittle material with relatively high tensile and shear strength. These pagodas have undergone a century of historical vicissitudes and changes, and have withstood countless baptisms of nature, with more or less damage to a certain degree. However, according to investigations and studies, most of the damage or collapse of ancient masonry pagodas structures are mainly caused by earthquakes. Once an earthquake occurs, it will cause great harm to human society [1]. China is located in the middle of the Eurasian seismic belt and the Pacific Rim seismic belt. There are many and strong earthquakes. The area of seismic belts is also very wide and scattered. It is one of the countries that suffer the most from earthquake disasters in the world [2]. In view of this, it is of extraordinary significance to understand and master the structural form and construction technology of ancient masonry towers, study its dynamic characteristics under earthquake action, find out the weak links of the structure, and reduce the losses caused by earthquake disasters.

After subjected to earthquakes, the accumulation of damage will lead to collapse of pagoda that is major threat of structural safety. The main damage characteristics of pagodas which were made by earthquake are following (Figure 1): 1) the tilt and collapse of pagoda spire, 2) the tilt and bend of pagoda body, 3) the break in the middle part of the pagoda, 4) the split of pagoda body along the central axis, 5) overall collapse [3].



1) 2) 3) 4) 5)

Figure 1. Damage characteristics of pagodas [3].

Studying masonry towers seismic vulnerability is not a trivial task. The current research work of Chinese scholars on the ancient pagoda is mainly carried out in the three aspects of classical theory, test data and numerical simulation [4]. Among the others, a "cantilever rod model" has been proposed, combining different tools to simplify the structural analysis model,

and apply these theories to the study of real cases such as Quanzhou pagoda, Fawang pagoda, Wenfeng pagoda, etc. [5,6]. For example, Y. Shen et al. analyzed the dynamic characteristics and the seismic capacity of the ancient masonry Xiaoyan pagoda based on the historical survey and reinforcement data. They discussed its seismic performance [7]. F. Zhu et al. conducted a seismic simulation shaking table test of the China Dinosaur pagoda model structure to observe the weak links and failure mechanism of the model structure under the action of earthquakes. They conducted a comprehensive technical evaluation of the seismic capacity and the technical feasibility of the construction of the pagoda [8]. Seoul National University in Korea has cleverly built a five-story full-scale model to study the seismic performance of the masonry pagoda, conducted destructive tests on it. Through the actual test results, the earthquake effect of the prototype tower body was reversed [9].

Western scholars deeply studied the seismic vulnerability of ancient masonry towers in the past years applying even more sophisticated methods. Non-linear static and dynamic analyses have been widely used to apply the earthquake loads [10-13]. University of Minho, Portugal conducted material mechanical performance tests and ingenious static tests on 24 masonry walls, evaluated the earthquake resistance level of the masonry structure, and summarized the relevant non-destructive testing methods, which provided information for the improvement of its seismic resistance level [14]. A. Carpinteri, S. Invernizzi, G. Lacidogna et al. conducted non-disturbing non-destructive testing of two ancient masonry pagodas in Italy in the 13th century, and they also did preliminary linear analysis, which basically coincided with the measured stress level. Non-linear cracking and damage analysis was also carried out, the evolution of principal stress damage and damage distribution are predicted. It was found that the damage is mainly distributed in the local high strain area. The results of the numerical analysis provide meaningful guidance to the monitored parts and evaluate the seismic performance analysis [15]. S.T. Sperbeck et al. conducted on-site investigation and testing of ancient masonry pagodas, comprehensively analyzed the influencing factors, established an H-dimensional solid model, applied loads of different levels and directions, and changed boundary conditions [16]. The dynamic characteristics are evaluated, and the influence of the parameters on the test results was discussed in detail.

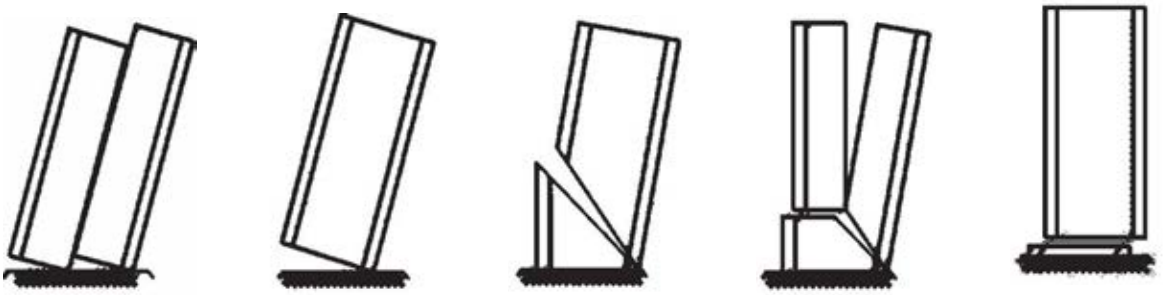
To sum up, based on meticulous field exploration and experimental research, it is possible to conduct dynamic characteristic testing and numerical calculation analysis on ancient masonry pagodas. In this way, the structural damage of the ancient masonry pagoda can be identified, and the seismic performance of the structure can be effectively evaluated, which provides a reference for the seismic resistance of the project.

However, all the above-mentioned researchers are based on strong mathematics, dynamics, and computer engineering. In the society where the seismic research of masonry buildings has become the common demand and desire of many people, such a professional research method is not conducive to the widespread dissemination of knowledge of ancient architectural heritage protection.

In order to overcome this drawback, Researchers have recently proposed a kinematic limit analysis where vulnerability can be estimated assuming that a tower fails for the formation of five possible different pre-assigned failure mechanisms, namely vertical splitting, base rocking, overturning with diagonal cracks (Heyman 1992), a combination of splitting and diagonal overturning and base sliding (Figure 2). G. Milani et al. has also used this method in the vulnerability assessment of a large number of Italian masonry buildings, which greatly proved the practical significance of this method [17,18].

This paper aims to apply a fast full 3D CAD limit analysis method to the seismic performance evaluation of Longhu pagoda. The research is based on the principle of virtual works, assuming that the masonry material is a no-tension material, and quickly assesses the

horizontal acceleration when the building collapses. The research only needs a detailed 3d model, basic mechanics knowledge and calculation ability, simple and easy to learn, can well adapt to the diversified requirements of research and protection of masonry structure buildings. At the same time, the amount of calculation for simulation research can be greatly reduced.



a) n.1: vertical splitting | b) n.2: base rocking | c) n.3: overturning with diagonal cracks (Heyman's diagonal rocking) | d) n.4: a combination of splitting and diagonal overturning | e) n.5: base sliding

Figure 2. Collapse mechanism for masonry towers selected in [17] (images adapted from [17]).

2 INFORMATION ABOUT LONGHU PAGODA

Longhu pagoda (Figure 3) which was built in 1342 A.D. is located in Xiaoquan, Deyang, Sichuan province (East longitude 104° 17′, North latitude 31° 15′) and is the only preserved masonry pagoda made in Yuan dynasty [19,20]. It has a square plan with 13 layers of eaves outside it, and it is roughly 33 meters tall which contains 2 meters of stylobate and 31 meters of body.



Figure 3. Longhu pagoda.



Figure 4. Damage of longhu pagoda

On May 12, 2008, a 8.0 magnitude Richter earthquake occurred in Wenchuan, Sichuan province, China, and the epicenter was in a small town whose name is Yingxiu. Wenchuan earthquake is destructive and has a strong impact, its maximum acceleration peak value which appeared after the start of the crustal movement (65 s - 82 s) is nearly 424 cm/s^2. According to incomplete statistics, the earthquake killed around 69227 people, injured 376443 people, and

17,923 people were missing. Large numbers of architectures were collapsed and cultural relics were severely damaged, which resulted immeasurable losses.

The position of Longhu pagoda is not very far away from the epicenter (about 100 km), and it was influenced by the east-west seismic wave. The post-earthquake disaster investigation showed that the Longhu pagoda had a north-south through crack from the bottom to the top of the body. The cracks developed along the height, and the higher the position, the larger its width. The pagoda body was shaken into two parts, east and west, and its integrity was severely damaged (Figure 4).

3 LIMIT ANALYSIS

In the previous literature, the kinematic theorem of limit analysis has been widely used to calculate the collapsed ground acceleration of a masonry structure, especially some masonry pagodas [21,22]. Compared with complex finite element simulation calculations, this method can predict the collapse mechanism and collapse acceleration of masonry pagodas more easily and conveniently. The calculation results are quite reliable and can be quickly grasped by non-professionals. At the same time, when conducting a more detailed and in-depth study of masonry structures, the results of limit analysis can be compared with pushover and nonlinear dynamic analysis to improve the accuracy of simulation calculations.

According to Figure 2, this paper applied the same research method in the limit analysis of Longhu pagoda. The collapse accelerations related to the five collapse mechanisms of Figure 1 have been computed on the real 3D geometric model, applying the kinematic theorem of limit analysis, and considering the masonry as a no-tension material with infinite compressive strength. It has been decided to do not optimize the position of the vertical cutting planes (as done in [22]) but to roughly position them as passing through the middle points of the base edges. The inclined planes of mechanisms n.3 and n.4 (Figure 2) have been posed with an inclination of 30 ° , 45 ° or 60 ° to the horizontal plane. Each collapse mechanism is simulated from four main directions (X^+, X^-, Z^+, Z^-). It is worth noting that a Mohr-Coulomb failure criterion has been used in mechanism n.5 calculation; and the friction angle has been taken equal to 30° following what stated in [23]. The analysis in load control, and the considered loading conditions are G1 and G2. G1: principal distribution of forces proportional to the mass and linearly proportional to the height of the structure (the so-called “inverted triangle”). G2: secondary distribution of forces proportional to the mass and constant along the height of the structure.

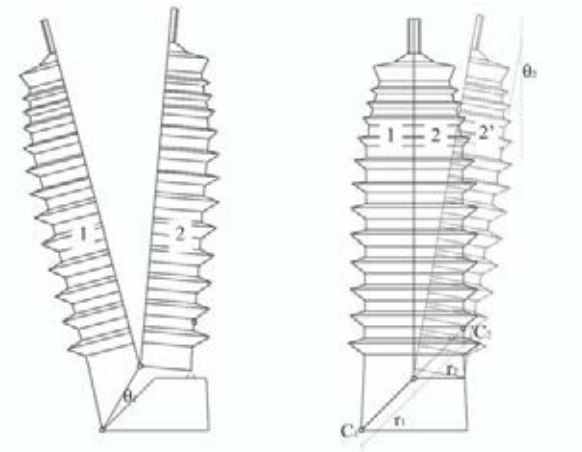
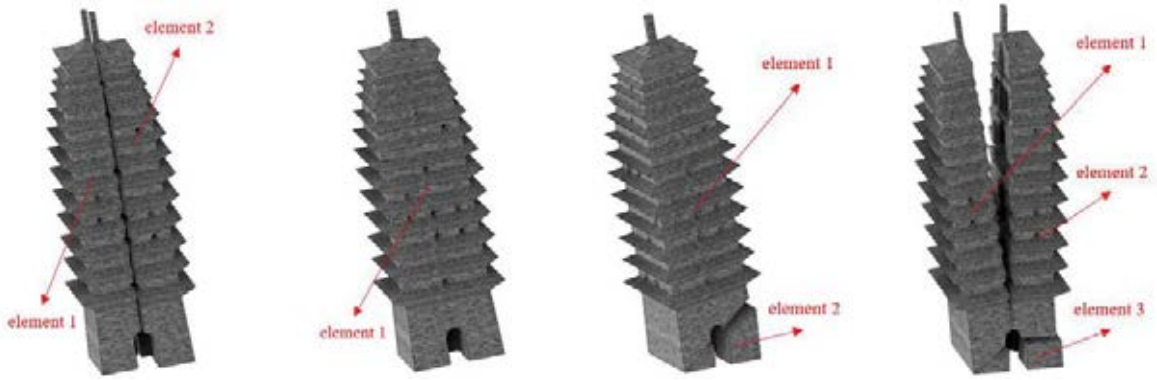


Figure 5. Collapse mechanism n.4 that considering the negative work done by the block n.2.



a) Mechanism n.1 along x+ b) Mechanism n.2 along x+ c) Mechanism n.3 along x+ d) Mechanism n.4 along x+

Figure 6. Some of the studied collapse mechanisms.

The mathematical basis of this method is very simple: only a first-order equation and basic geometry consideration are needed, and the collapse multiplier is easily computed for each mechanism. The kinematic theorem is applied through the equating of the work done by external forces (inertia forces) and internal forces (self-weight). However, some changes have been introduced in this paper with respect to reference [21,22] and they are here explained: the tensile strength has been considered as null (it was not in the reference research) and the mechanism n.4 (Figure 2) has been slightly modified by considering the negative work done by the block n.2 (Figure 5)

The collapse accelerations values for each mechanism are reported in Table 1, and Figure 6 represents some of the collapse mechanisms applied to the 3D model of the pagoda. The results have shown that the vertical splitting (mech. n.1) is always the most likely to occur.

Direction	Mechanism	Inclination Angle [°]	Collapse Acceleration G2 [g]	Collapse Acceleration G1 [g]
x	#1	/	**0.155**	**0.124**
x	#2	/	0.310	0.249
x-	#3	30	0.276	0.226
		45	0.252	0.215
		60	0.214	0.195
	#4	30	0.165	0.127
		45	0.180	0.138
		60	0.219	0.168
x+	#3	30	0.278	0.226
		45	0.255	0.216
		60	0.215	0.195
	#4	30	0.165	0.127
		45	0.181	0.138
		60	0.224	0.169
x	#5	/	0.577	0.577
z	#1	/	**0.155**	**0.125**
z	#2	/	0.310	0.249
z-	#3	30	0.280	0.228
		45	0.255	0.217
		60	0.215	0.196
	#4	30	0.167	0.128
		45	0.184	0.140
		60	0.225	0.171

z+	#3	30	0.274	0.226
		45	0.251	0.215
		60	0.216	0.195
	#4	30	0.166	0.128
		45	0.180	0.139
		60	0.222	0.169
z	#5	/	0.577	0.577

Table 1. Limit analysis results. The minimum of each direction is formatted in bold.

4 CONCLUSIONS

This paper uses a 3D CAD method to perform a quick limit analysis of the Longhu pagoda. It mainly calculated the collapse accelerations along the four main directions for four different collapse mechanisms under G1 and G2 loads. Under G1 load, a_g/g along the X direction is 0.155, and a_g/g along the Z direction is 0.124. Under G2 load, a_g/g along the X direction is 0.155, and a_g/g along the Z direction is 0.125. The research results show that collapse mechanism n.1 which is vertical splitting is the most likely occurrence. This is also consistent with the on-site survey of Longhu pagoda earthquake damage after the Wenchuan earthquake.

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