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Simulation and Fast vulnerability analysis of a Chinese masonry pagoda

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Simulation and Fast vulnerability analysis of a Chinese masonry pagoda

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Abstract. As an important historical relic of human being, masonry pagoda is the great significance in the eastern and western architectural cultures. Most of the existing masonry pagodas in China which have been seriously damaged urgently need detailed structural safety assessment, repair and reinforcement. The paper choose a Chinese masonry pagoda as a case, conducted a series simulation analysis with Abauqs. Through numerical simulation, the seismic performance of the pagoda can be evaluated, which can not only predict the hidden danger and weak link in its structure, but also provide useful reference for the reinforcement and repair of the pagoda. It also adopts a very convenient 3D CAD method to quickly assess the seismic vulnerability of existing masonry pagoda according the reference.

1. Introduction

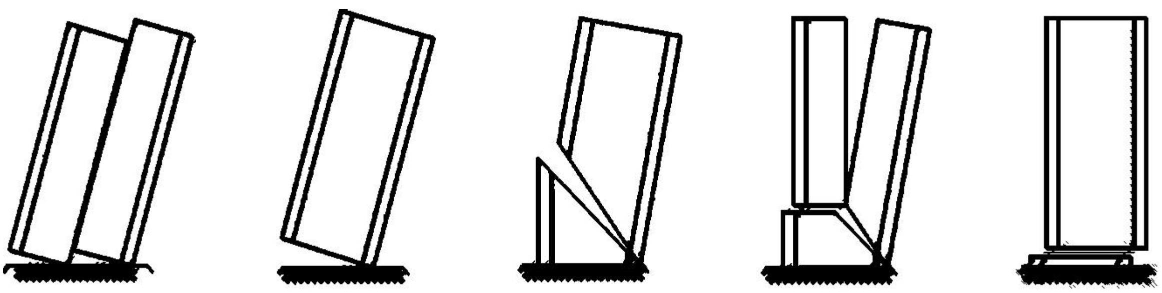
Chinese architecture has an established value worldwide. In particular, ancient masonry pagodas are an important symbol of the history and the culture of China, besides they have recognized importance in the international architectural stage. Ancient masonry pagodas have been extensively studied from both an architectural and structural point of view. Nowadays, many pagodas show signs of ageing. As every ancient structure, they have suffered natural and human-made actions. In particular, earthquakes had had an important role in pagodas' damage [1-4].

In the last years, a lot of research contributions on the seismic behavior of ancient masonry pagoda have been published by Chinese scholars about ancient masonry pagodas.

The current research work on the ancient pagoda is mainly carried out in the three aspects of classical theory, test data and numerical simulation [5]. 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. [6,7]. 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 [8]. 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 [9]. 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 [10].

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 [11-14]. 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 [15]. 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 [16]. 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 [17]. The dynamic characteristics are evaluated, and the influence of the parameters on the test results was discussed in detail.

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 [18, 19] (Figure 1).



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 1. Collapse mechanism for masonry towers selected in [18] (images adapted from [18]).

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2. Case study

The paper choose Longhu pagoda (Figure 2, Figure 3) as case study. Longhu pagoda 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. Because of its tall and straight appearance (around 12 m), it is the commanding point and visual center of Xiaoquan town. The early architectural features of Longhu pagoda are obvious, which is an significant evolution illustration of Chinese masonry pagoda. Meanwhile, it occupies an special position in the urban space with an important historical value. 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. The position of Longhu pagoda is not very far away from the epicenter (about 100 km). It was influenced by the east-west seismic wave, but did not collapse (Figure 4) [20,21].

Figure 2. Longhu Pagoda

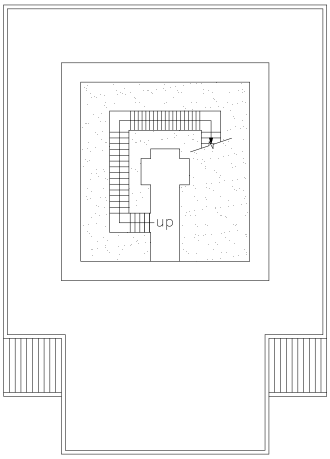


Figure 3. Ground floor of Longhu pagoda

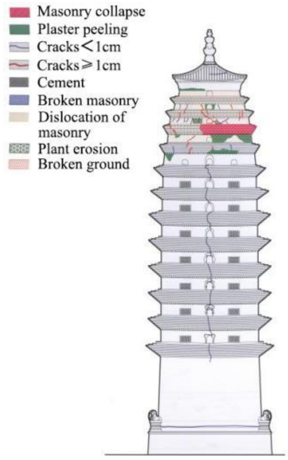
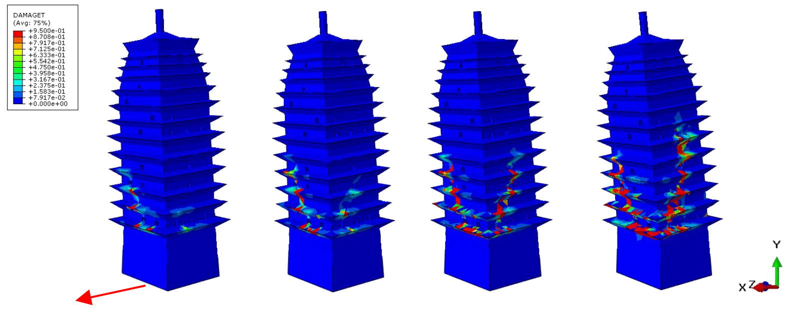


Figure 4. Cracks on the Longhu pagoda

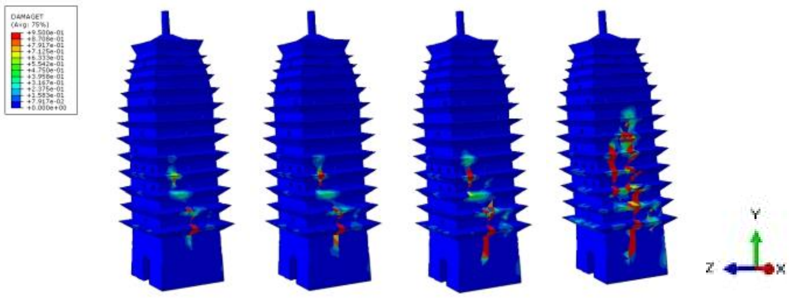
3. Simulation analysis

With the aim to analyze the seismic vulnerability of the pagoda and to study how the damage spread within the structure, several non-linear numerical simulations are performed by means of FE-based software Abaqus. A modal analysis is firstly performed in Abaqus. Frequency, period e participating mass are evaluated for each of the firsts 10 natural modes of the structure. Then the pushover analysis was conducted. It allows to exploit the ultimate plastic capacity of a structure under horizontal loads and to estimate the damage distribution at the ultimate state. Despite of the symmetry of the pagoda structure, some differences in the damage among the four directions (east, south, west, north) deserve to be deeply discussed (Figure 5 shows the results of the analysis along the X^+ and Z^+ direction). In this case some sensitivity analysis and four different pushover analyses are performed by applying a uniform distribution along the height. For each analysis it is provided the progressive crack configuration along with the capacity curve Load Factor-Displacement. At the same time, the paper performed some NLDAs as well (Figure 6). The scaling factors of the accelerograms have been set according to the modal and pushover analyses results through consideration made on the accelerograms' response spectra.

In the numerical simulation, the load factors and displacement were used as the analysis objects. The damage process of the pagoda was evolved, and its weak parts were found out. Pushover analyses have been performed under different load conditions and along the four principal bending directions to estimate the global capacities and collapse mechanisms. Moreover, pushover sensitivity analyses have been performed to understand the influence of the mechanical parameters needed to represent the non-linear material properties by the CDP model. The pushover results have been deeply commented.



a) pushover analysis in X^+ direction



b) pushover analysis in Z^+ direction

Figure 5. Results of pushover analysis in X^+ and Z^+ direction

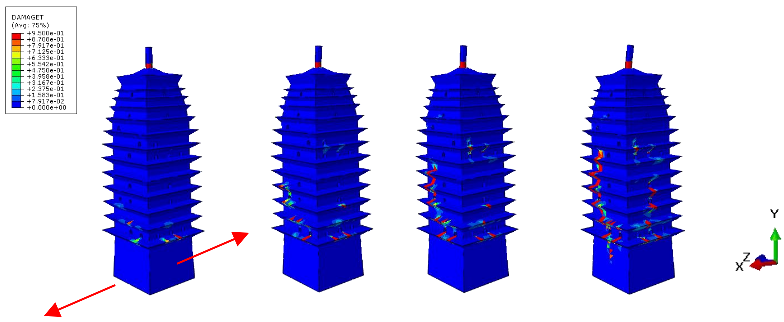


Figure 6. Results of non-liner dynamic analysis

4. 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 [18, 19].
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.
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 [8, 9] (Figure 1) 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 has been slightly modified by considering the negative work done by the block n.2 (Figure 7, Figure 8).

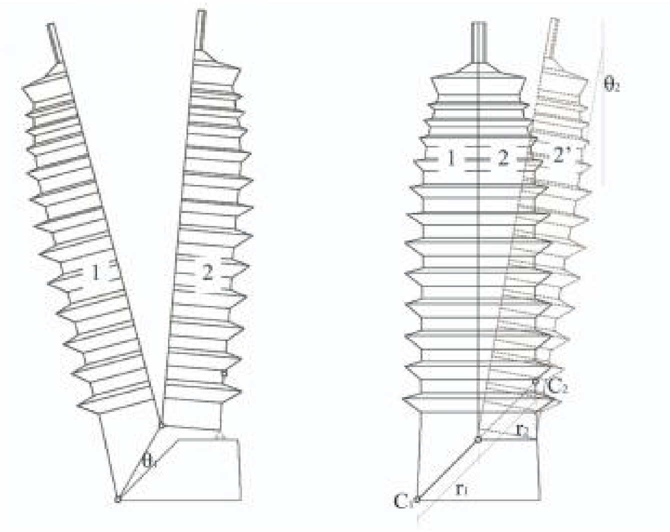
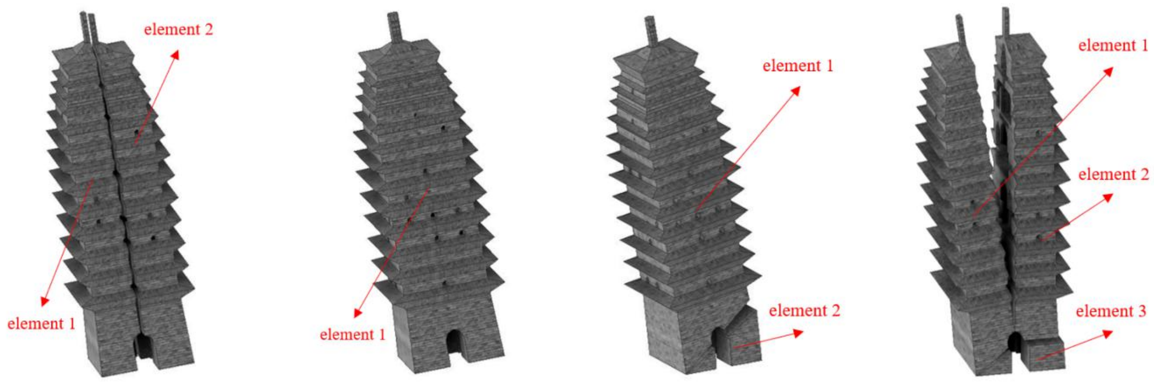


Figure 7. Collapse mechanism n.4 that considering the negative work done by the block n.2.



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 8. Some of the studied collapse mechanisms

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