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Earthquake Response and Damage Analysis of Tianning Temple Pagoda

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Abstract: *The seismic dynamic response and damage distribution law of Tianning Temple Pagoda are investigated by establishing a finite element model of the ancient pagoda using ABAQUS analysis software. The dynamic characteristics are computed and compared with the numerical results obtained from empirical formula calculations. This comparison serves to validate the rationality of the model. According to the type of site and seismic design parameters, three seismic waves are selected as the ground motion, the acceleration and displacement response of ancient pagoda are calculated, and the vulnerable parts of Tianning Temple pagoda under earthquake are analyzed combined with the structural damage cloud map.The results indicate that the seventh level of Tianning Temple Tower has the most pronounced acceleration amplification effect, with the broadest range of horizontal interlayer displacement angles. The sixth layer exhibits the greatest horizontal displacement, distinguished by a rapid transition between the horizontal displacement and the displacement of the above layer. The oldest stratum of the Ancient pagoda exhibits the most extensive spectrum of tensile damage, the highest cumulative damage factor, and a somewhat severe level of damage. The findings can serve as a definitive guide for seismic protection of antique pagodas.*

Keywords: *Masonry pagoda*, *Seismic response*, *Damage factor*, *Dynamic characteristic*

1. Introduction

Tianning Temple Pagoda is located in Zhenzhou Town, Yizheng City, Yangzhou City, Jiangsu Province, China. It was constructed during the third year of the Tang Dynasty Jinglong period and subsequently demolished as a result of armed conflict. It was rebuilt in the Song Dynasty and was damaged again until it was rebuilt in the fourth year of the Hongwu Dynasty. Tianning Temple Pagoda has witnessed the rise and fall of the dynasties, prosperity and decline, and has become a symbol of the city's history, with high historical value, and was listed as a cultural relic protection unit in Jiangsu Province in 2002[1]. Yizheng City is affected by the Tanlu fault zone and the middle and lower reaches of Yangtze River - South Yellow Sea seismic zone, and many earthquakes have occurred in history, so there is a certain level of seismic activity in this area.Tianning Temple Pagoda is very easy to be damaged by earthquake because of its tall and slender characteristics, as well as a series of external factors such as long age, rain and snow erosion and man-made damage. To mitigate the impact of seismic events on the structural integrity of the tower, an analysis is conducted on the seismic performance of the ancient tower. This analysis aims to contribute to the existing body of knowledge in seismic research pertaining to the ancient tower.

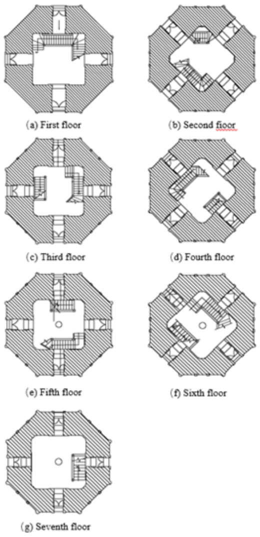
The examination of dynamic properties, seismic behavior, and structural deterioration of historical masonry towers constitutes a significant facet of seismic performance evaluation. Early research focused on theoretical analysis, such as Li Dehu[2] simplified the ancient tower into a cantilever bar model, Chen Ping[3] simplified the ancient tower into a discrete parameter bar system model with fixed bottom, etc., and calculated the natural vibration period and seismic capacity by different methods, but the simplification of the model led to the deviation of the dynamic characteristic value from the actual measurement. Subsequently, the utilization of computer technology has facilitated the application of finite element method and other numerical simulation techniques in the examination of dynamic properties, earthquake behavior, and structural deterioration of historical masonry towers. For example, Wei Junya[4] et al. simulated the dynamic characteristics of the Big Wild Goose Pagoda with ANSYS software, and Pasticier[5] et al. employed IDA incremental dynamic analysis using SAP2000 software to assess the seismic performance of historical structures. Furthermore, the researchers will employ a hybrid approach involving field measurement and numerical simulation techniques to investigate the dynamic properties. The acquisition of dynamic response data for the ancient pagoda is achieved through the utilization of pulsation tests and shaking table tests. These data are subsequently compared with the outcomes of numerical simulations in order to enhance the accuracy of evaluating the dynamic characteristics and damage conditions of the architectural structure. For example, Bijaya Jaishi[6] et al. employed the environmental ground pulse method to examine the dynamic properties of an ancient pagoda in Nepal. They validated the accuracy of the finite element model using the test data and conducted an analysis of the damage to the ancient pagoda using the vibration mode decomposition response spectrum method. As a result, they identified the most unfavorable configuration of the ancient pagoda. Saisi[7] et al. employed various methodologies, including geometric measurement, visual inspection, environmental vibration test, acoustic wave test, and jack loading test, to evaluate the structural state of Gabbia tower in Milan, Italy. Additionally, they conducted seismic vulnerability analysis, offering valuable insights for determining the capacity of ancient towers to withstand damage.

The aforementioned study presents a range of analytical techniques for assessing the dynamic properties and seismic behavior of historical masonry pagodas. It also serves as a valuable resource for evaluating the seismic performance of such structures. In conjunction with the findings of the aforementioned experts, this study used numerical simulation techniques to examine the seismic behavior of the tower of Tianning Temple. Through an examination of the acceleration and displacement characteristics of the ancient pagoda in response to various seismic waves, as well as an analysis of stress distribution, this study aims to investigate the damage mode of the ancient pagoda during earthquakes. Additionally, the study aims to identify the unfavorable positions of the pagoda, thereby establishing a foundation for the seismic protection objectives of Tianning Temple Pagoda.

2. Project Overview

Tianning Temple Pagoda (Figure.1) is a seven-storey eight-sided brick and wooden eaves pavilion tower. The outside of the tower is a normal eight-sided shape, imitating the shape of a pavilion, and the inside is a square shape, which is folded and staggered (Figure.2). The historic pagoda is equipped with four doors spread across each floor. The doorway positions are differentially altered by 45 degrees relative to the above and lower levels, resulting in staggered changes. The height of each layer gradually decreases from the bottom to the body, and the width is gradually narrowed, and the overall style is simple and elegant. The top of the tower is in the form of accumulating tips, beautiful in shape. The original Tianning Temple Pagoda was nearly 70m high, and the current tower is 42.78m high. The outer surface of the bottom of the ancient pagoda is 3.35m long, the wall is about 2.5m thick, the tower covers an area of 54m^2, and the building area is 383.08m^2.

Figure 1: Tianning Temple Pagoda.



(a) First floor (b) Second floor
(c) Third floor (d) Fourth floor
(e) Fifth floor (f) Sixth floor
(g) Seventh floor

Figure 2: Floor plan.

3. Finite Element Model Building

The tower bricks of Tianning Temple pagoda are mainly black bricks. The material density of ancient black bricks is about 2000kg/m^3, and the elastic modulus is generally within the range of

1000MPa~2000MPa[11]. In addition, according to the literature of many ancient pagodas with similar years and the same materials in China, the Poisson ratio of ancient pagodas is about 0.2. Based on the aforementioned information, in conjunction with the pertinent empirical data from brick samples[8] and the findings from field investigations, it has been determined that the masonry density of Tianning Temple Pagoda is 1800kg/m3, the elastic modulus is 1000MPa, and the Poisson ratio is 0.2. The finite element model was constructed with the ABAQUS analysis software, with the grid being partitioned by high-order tetrahedral geometric elements.

The masonry compression constitutive relation model in literature [9] has been widely used because of its good agreement with experimental results, strong applicability and easy parameter determination. Its expression is as follows:

$$\frac{\sigma}{f_m}=\frac{\eta}{1+(\eta-1)(\varepsilon/\varepsilon_m)^{\eta/(\eta-1)}}\frac{\varepsilon}{\varepsilon_m} \tag{1}$$

$$D_c=1-\frac{\eta}{1+(\eta-1)(\varepsilon/\varepsilon_m)^{\eta/(\eta-1)}} \tag{2}$$

σ is the external compressive stress; f_m represents the mean compressive strength of the masonry axis.; The ratio of the initial tangent modulus to the peak secant modulus, denoted as η , is determined to be 1.633; ε is the masonry pressure strain; ε_m represents the compressive strain value that corresponds to the average compressive strength of the masonry axis; D_c is the uniaxial compression damage parameter of masonry.

According to the literature [10], the tension constitutive connection of masonry and the tension damage variable can be expressed as follows:

$$\begin{cases}\dfrac{\sigma_t}{f_t}=\dfrac{\varepsilon}{\varepsilon_t},\dfrac{\varepsilon}{\varepsilon_t}\le 1\\[2ex] \dfrac{\sigma_t}{f_t}=\dfrac{\dfrac{\varepsilon}{\varepsilon_t}}{2\left(\dfrac{\varepsilon}{\varepsilon_t}-1\right)^{1.7}+\dfrac{\varepsilon}{\varepsilon_t}},\dfrac{\varepsilon}{\varepsilon_t}>1\end{cases} \tag{3}$$

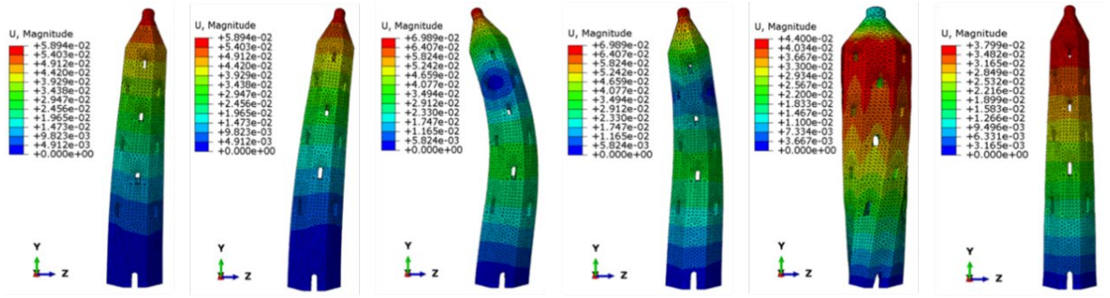
$$D_t=\begin{cases}1-\dfrac{f_t}{E_c\varepsilon_t},\dfrac{\varepsilon}{\varepsilon_t}\le 1\\[2ex] 1-\dfrac{\dfrac{f_t}{E_c\varepsilon_t}}{2\left(\dfrac{\varepsilon}{\varepsilon_t}-1\right)^{1.7}+\dfrac{\varepsilon}{\varepsilon_t}},\dfrac{\varepsilon}{\varepsilon_t}>1\end{cases} \tag{4}$$

σ_t is the external tensile stress; ε represents the measure of tensile strain in masonry; f_t represents the mean axial tensile strength of brickwork; ε_t represents the tensile strain value determined by the average axial tensile strength of masonry; D_t is the tensile damage parameter of masonry uniaxial; E_c is the elastic modulus of masonry.

Because Tianning Temple Pagoda is a key cultural relic protection unit, the masonry of the original ancient pagoda cannot be used as the test material. Considering that the black bricks on masonry houses in the 1980s have A good similarity with the materials of ancient pagodas, the test results obtained in reference [11] are 3.14Mpa for f_m ,0.04 for ε_m ,0.157Mpa for f_t ,and 0.00012 for ε_t .

4. Dynamic Characteristic Calculation

Through modal analysis, corresponding calculation results were extracted, and the first 6 vibration modes of Tianning Temple Pagoda were obtained, as shown in Figure 3. As depicted in the figure, the first four vibration modes of Tianning Temple Pagoda are mainly translational, the fifth vibration mode is mainly torsion, and the sixth vibration mode is vertical vibration.



(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4 (e) Mode 5 (f) Mode 6

Figure 3: The first 6 order mode diagram of Tianning pagoda.

In accordance with the technical law governing the prevention of industrial vibrations in historic buildings in China, the dynamic properties of ancient masonry pagodas can be determined using formula (5).

$$f_j = \frac{\alpha_j b_0}{2\pi H^2}\varphi \tag{5}$$

f_j represents the natural frequency of the structure at the J-order(Hz); α_j represents the comprehensive deformation coefficient associated with the J-order natural frequency of the structure; b_0 represents the lower width of the construction, which is the distance between two pairs of parallel sides (m); H is the aggregate height determined for the construction, encompassing the vertical distance from the uppermost point of the platform to the base of the tower brake(m); φ is the structural mass stiffness parameter (m/s).

This study compares the first three natural vibration frequencies of Tianning Temple pagoda, as determined by the aforementioned method, with the results obtained from finite element calculations. The findings are presented in Table1. The observation indicates that the disparity between the outcomes of the modal analysis and the empirical formula calculation is below 5%. Consequently, the magnitude of the mistake is minimal, so establishing the reasonableness of the established calculation model.

Table 1: Comparison of calculation results of natural vibration frequency.

Mode	Formula result [Hz]	Simulation result [Hz]	Error [%]
1	0.789	0.763	3.3
2	0.792	0.772	2.5
3	3.225	3.068	4.9

5. Seismic Response Analysis

In accordance with the stipulations outlined in China's building seismic design code, Yizheng City is classified as a 7 degree fortified area, falling under the Class II site category. The ground peak acceleration is measured at 0.15g, and the design earthquake group is classified as the first group. When using time history analysis method, at least two strong earthquake recorded waves and one synthetic wave should be selected. Therefore, in this paper, El-Centro wave, Taft wave and synthetic wave suitable for Class II sites are selected for dynamic analysis, and the duration of interception is 20s. Furthermore, the amplitude of seismic waves is specifically modified in response to frequent, fortification, and rare earthquakes, resulting in maximum acceleration peaks of 55cm/s^2, 150cm/s^2, and 310cm/s^2, respectively. Considering that the horizontal earthquake is more harmful, different seismic waves are applied along the X direction of the model to calculate the seismic response.

5.1. Acceleration response analysis

Figure 4 depicts the time history curve of acceleration for the uppermost level of Tianning Temple Pagoda, subjected to the influence of frequent, fortified, and rare El-Centro seismic waves. The image illustrates that the acceleration time history curves of the uppermost stratum of the ancient pagoda exhibit a high degree of similarity across various seismic waves. There exists a positive correlation between the peak value of seismic wave acceleration and the magnitude of acceleration shown by the uppermost layer. The observed phenomenon can be attributed to the heightened resonance effect exhibited by the uppermost stratum of the old pagoda when subjected to intense seismic activity, resulting in an increased acceleration.

The horizontal acceleration amplification coefficient curve of Tianning Temple Tower under various seismic waves, as a function of floor height, is depicted in Figure 5. The figure shows that the antique pagoda's top floor has a far higher acceleration amplification factor than the others. Due to its low cross-sectional stiffness, the highest level responds strongly to seismic stresses. A thorough investigation of Figure 5 shows that the acceleration amplification coefficient of each layer of the ancient pagoda is larger during frequent earthquakes than fortification and uncommon earthquakes. The ancient pagoda's reactivity to earthquake acceleration is reduced by its inelastic deformation during fortification and uncommon earthquakes, which absorbs seismic energy. The Taft wave accelerates the ancient pagoda more than the other two waves. This is because the Taft wave's characteristic period matches the ancient pagoda's natural vibration time. The ancient pagoda's dynamic reaction increases, resulting in a large acceleration amplification coefficient[12].

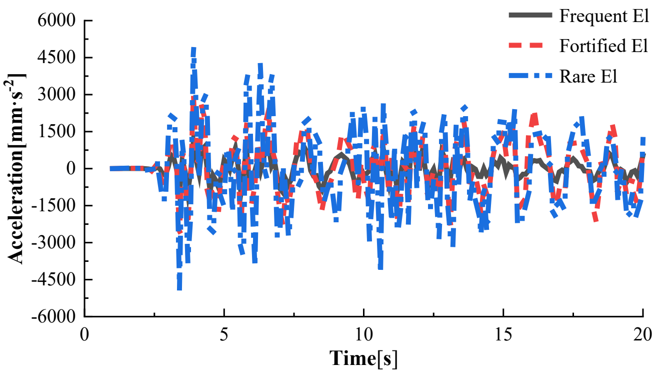


Figure 4: Acceleration time history of the top layer under El-Centro waves.

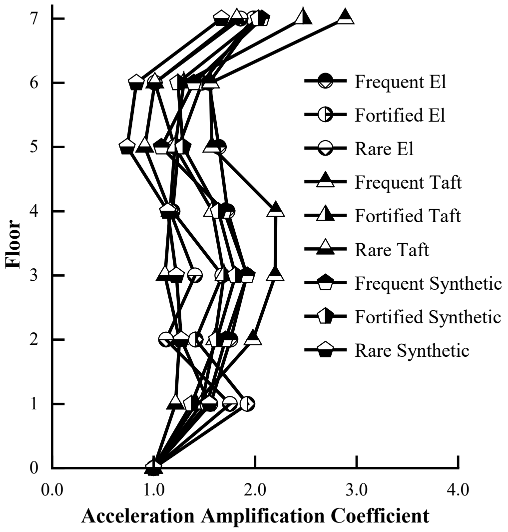
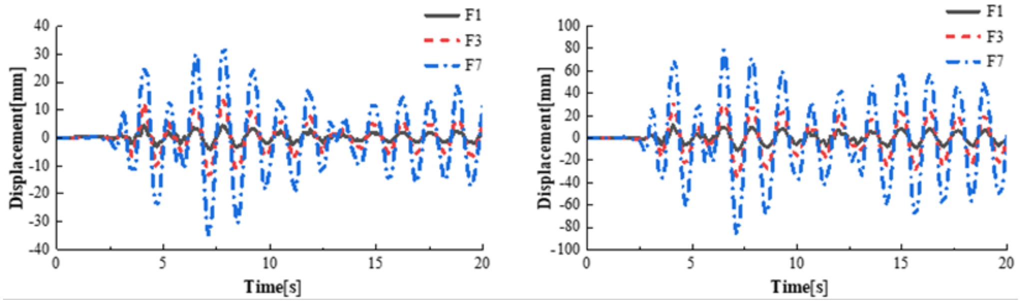


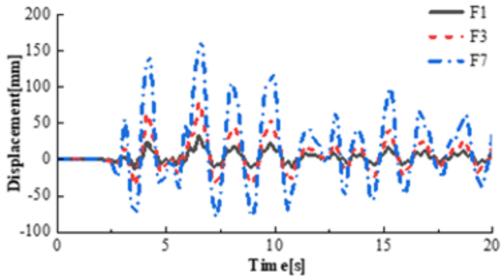
Figure 5: Horizontal acceleration amplification coefficient.

5.2. Displacement response analysis

Figure 6 depicts Tianning Temple Pagoda's 1st, 3rd, and 7th levels' horizontal displacements under frequent, fortified, and rare El-Centro seismic waves. It is evident that the horizontal displacements at the top of the ancient tower exhibit a clear time-history response as the height increases, and this response greatly intensifies with the increase in earthquake severity.



(a) Frequent earthquake (b) Fortified earthquake



(a) Rare earthquake

Figure 6: Horizontal displacements under the action of El-Centro seismic waves.

Table 2 presents the horizontal interstory displacements of Tianning Temple Pagoda in response to frequent, fortified, and rare Taft seismic waves. The data shown in the table demonstrates a positive correlation between earthquake intensity and both interstorey displacement and damage degree. In addition, the inter-story displacement of the first floor of the ancient tower is significantly larger than that of other positions, and there is a sudden change between the displacement of the second floor and the inter-story displacement of the third floor and above is relatively small, indicating that the first floor is the weak layer in the earthquake damage.

Table 2: Horizontal interstory displacements of ancient pagoda under Taft seismic waves.

Floor	Frequent earthquake displacement [mm]	Fortified earthquake displacement [mm]	Rare earthquake displacement [mm]
7	4.254	11.529	20.324
6	5.381	12.265	23.265
5	4.513	11.921	21.152
4	4.026	10.881	20.315
3	4.444	11.730	19.381
2	4.582	12.039	17.089
1	5.754	14.897	25.332

Table 3 shows that the displacement Angle between the layers of ancient pagodas grows from layer 1 to layer 7, peaks at layer 7, and increases with earthquake intensity. Inter-story displacement Angle can be used to assess tower elastic state, according to the Chinese seismic design Code. Limit of inter-story displacement Angle in elastic stage is 1/565, range in elastic-plastic limit stage is 1/100~1/200. The tower body is elastic under minor earthquakes. The tower's first floor is elastic and the second to seventh stories are elastic-plastic in a medium earthquake. At this time, the displacement Angle between layers of the upper tower body is larger. The first to fourth layers of the tower are in the elastoplastic stage, the fifth to seventh layers are in the limit stage, and the highest interlayer displacement Angle is 1/144.2 under big earthquakes. Thus, earthquakes beyond medium strength can cause the upper structure of the ancient pagoda to collapse.

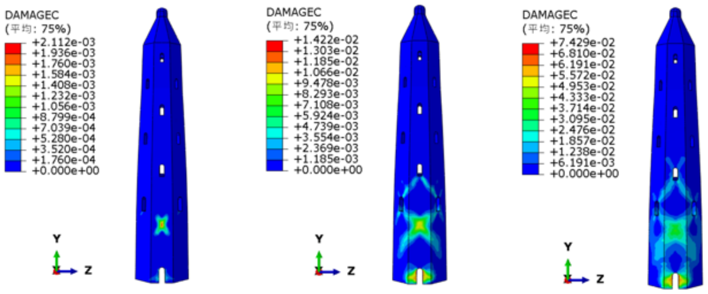
Table 3: Horizontal interlayer displacement Angle of ancient pagoda under Taft seismic waves.

Floor	Interlayer displacement Angle of Frequent earthquake	Interlayer displacement Angle of fortified earthquake	Interlayer displacement Angle of rare earthquake
7	1/688.8	1/254.1	1/144.2
6	1/724.8	1/317.9	1/167.6
5	1/908.5	1/343.9	1/193.8
4	1/1073.1	1/397.1	1/212.7
3	1/1086.9	1/411.8	1/249.2
2	1/1151.2	1/438.2	1/308.7
1	1/1824.8	1/704.8	1/414.5

6. Damage Analysis

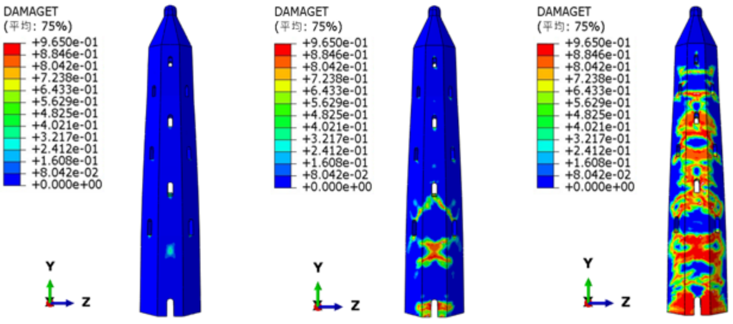
The amplitude-modulated El-Centro waves were input into the finite element model of Tianning Temple Pagoda, and the earthquake damage cloud image of the ancient tower structure was obtained, as shown in Figure.7-8. By comparing the damage cloud maps of Tianning Temple pagoda under three different conditions, it can be seen that compared with the compression damage, the damage area of the ancient pagoda under tension is wider and the damage degree is greater, which indicates that the damage of Tianning Temple pagoda under earthquake is mainly caused by tension damage.

Tianning Temple pagoda belongs to unreinforced masonry structure with low tensile strength, which is easy to be damaged under earthquake action. When subjected to a minor seismic event, the ancient pagoda experiences minimal tensile damage, primarily localized in the hole region and a limited area on the upper portion of the first layer. Under the action of middle earthquake, the tensile damage range of the hole area of the ancient pagoda is expanded and the damage degree is deepened. The tensile damage of the first floor is more serious, the cracks are formed between the third floor and the second floor, and the cross cracks appear in the upper part of the first floor. During large earthquakes, the entire structure of the ancient tower shows significant tensile damage, and various layers have different degrees of tensile damage, among which the cave entrance area of the 1st to 5th layers has the most serious damage, and a large number of cracks have appeared, and the damage has extended from the hole location to the surrounding wall area.



(a) Small earthquake (b) Medium earthquake (c) Large earthquake

Figure 7: Compression damage cloud image.

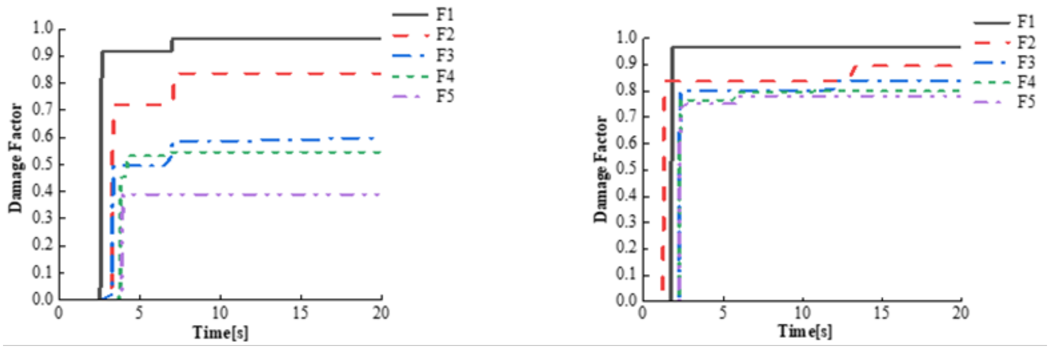


(a) Small earthquake (b) Medium earthquake (c) Large earthquake

Figure 8: Tensile damage cloud image.

Figure.9 show the change curve of tensile damage factor of Tianning Temple pagoda under the action of amplitude-modulated EI-Centro waves. Under the action of medium earthquake, the tensile damage of the first floor of the ancient pagoda occurred first when the seismic wave was loaded to 2.6s, and then the damage factor of each layer began to increase until it increased to the peak value, and then it was stable. It can be seen from the figure that the damage factor of the first layer is the largest, and finally reaches more than 0.9, which indicates that the first layer has the greatest damage degree under the action of moderate earthquake and is the weak layer of structure.

Under the action of the large earthquake, the tensile damage of the second floor of the ancient pagoda occurred first when the seismic wave was loaded to 1.3s, and then the damage factors of each floor increased rapidly. Compared with the change of damage factors under the action of medium earthquake, the damage factors of each layer of ancient pagoda increase faster and the peak value is higher under the action of large earthquake, and the damage factors of layers 1 to 5 of ancient pagoda finally reach above 0.7, indicating serious damage degree.



(a) Medium earthquake (b) Large earthquake

Figure 9: Damage time history under medium earthquake.

7. Conclusion

In this paper, with bricks and plastic damage constitutive model and introducing the damage factor, brick masonry materials based on the basic mechanical properties and seismic dynamic calculation of basic parameters, realized the Tianning Temple Pagoda seismic time history response numerical simulation.

Through the analysis of dynamic time history and stress response of the ancient pagoda, it can be seen that the acceleration amplification factor of the top layer of ancient pagoda is larger than that of other floors under earthquake action, and the acceleration amplification factor of ancient pagoda under small earthquake action is larger than that under medium and large earthquake action.

The horizontal interstory displacement and interstory displacement Angle of ancient Pagodas increase with seismic intensity, with the sixth layer having the largest displacement and the seventh layer having the largest angle.

The earthquake damage of the ancient pagoda is mainly tensile damage.In the medium earthquake, the damage factor of the bottom layer of the ancient pagoda is the largest and the damage is the most serious, and the damage of the other layers is mainly concentrated in the hole area. The damage factors of the first to the fifth floors of the ancient pagoda are substantial in response to the action of a significant earthquake. The damage of each floor has extended from the hole area to the surrounding wall area, resulting in a severe overall damage.

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