Incremental Dynamic Analysis of Guangyue Tower Timber Structure

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Abstract. This paper takes the wooden structure of Guangyue Tower as an example, selects ANSYS finite element software, establishes the upper wooden structure and the finite element model considering the whole structure of the high platform respectively, uses the incremental dynamic analysis method, and uses different ground motion intensity parameters to carry on the dynamic time history analysis to it. The results show that the existence of the high platform magnifies the displacement response of the wooden structure, which is not conducive to the seismic resistance of the wooden structure; IDA curve expressed by ground motion intensity parameter PGA can better reflect the overall change of the structure, which is helpful to improve the effectiveness of seismic performance evaluation of Guangyue Tower.

Keywords. Timber structure, numerical simulation, incremental dynamic analysis.

1. Introduction
In order to protect the timber structure of ancient buildings, experts and scholars launched a series of studies. Qian Zhou [1] conducted a shaking table test study on an ancient building model of the Palace Museum, and pointed out that the roof has a certain amplification effect on the seismic force, and the collapse of the wall does not affect the overall stability of the structure. Dafeng Gao [2] made the timber structure model of the Arrow building in Yongning Gate, Xi'an, and carried out the shaking table test and research, and summarized a set of earthquake damage assessment system. Qifang Xie [3] studied the scale model of Xi'an Zhonglou 1:6 through the shaking table test, and concluded that the model structure had good deformation capacity. Jianyang Xue [4] obtained the change rule of dynamic characteristics of the structure under the action of earthquake through the shaking table test. At present, the seismic performance of ancient timber structures is mostly studied quantitatively by means of experiments, but there are few analyses on the damage probability and the post-earthquake loss of historic buildings, and the earthquake risk assessment system of ancient timber structures is not perfect.

This paper takes Guangyue Tower as the research object, establishes the timber structure of Guangyue Tower and the finite element model considering the whole structure of high platform, and conducts incremental dynamic analysis on them, discusses the effectiveness of seismic assessment with different ground vibration intensity parameters, in order to lay a foundation for the establishment of the earthquake risk assessment system of Guangyue Tower.

2. Establishment of the Finite Element Model of Guangyue Tower
In this paper, BEAM188 unit is used to simulate columns, beams and other components. The timber
material parameters are shown in table 1. SHELL181 unit is used to simulate the floor slab. MASS21 unit is used to apply the roof load equivalent to the concentrated mass to the top of each gold column [5].

| Material | The density of (kg/ m$^3$) | Modulus of elasticity (Pa) | Poisson’s ratio |
|----------|-----------------------------|-----------------------------|----------------|
| Wood     | 410                         | 6.23×10$^9$                 | 0.25           |

COMBIN14 simulation was used for the connection between the mortise and tenon joints and the foot of the column, in which the connection stiffness value of mortise and tenon joints was selected from the inversion result of the mortise and tenon joint stiffness of Guangyue Tower [5]. At the same time, considering that the axial and tangential directions of the two principal axes in the horizontal plane ($x$-$z$ plane) were opposite, the connection stiffness values of the two groups were set as shown in table 2.

| Name | $K_x$ (N/m) | $K_y$ (N/m) | $K_z$ (N/m) | $K_{dx}$ (N/m) | $K_{dy}$ (N/m) | $K_{dz}$ (N/m) |
|------|-------------|-------------|-------------|----------------|----------------|----------------|
| X-direction stiffness (N/m) | 2.0×10$^8$   | 2.5×10$^9$  | 9×10$^7$    | 7×10$^{10}$    | 7×10$^{10}$    | 7×10$^{10}$    |
| Z-direction stiffness(N/m)  | 9×10$^7$     | 2.5×10$^9$  | 2.0×10$^8$  | 7×10$^{10}$    | 7×10$^{10}$    | 7×10$^{10}$    |

SOLID45 unit was used to simulate the high platform, and the interior of it was mainly artificially layered and uniformly tamped plain fill [7]. The physical and mechanical performance parameters are shown in table 3. The finite element model is shown in figures 1 and 2.

**Table 3.** Parameters of rammed earth materials for high base.

| Material   | Density (kg/ m$^3$) | Modulus of elasticity (Pa) | Thickness (m) | Poisson’s ratio |
|------------|---------------------|-----------------------------|---------------|----------------|
| Rammed earth | 1870               | 2.09×10$^7$                | 9.38          | 0.347          |
3. Modal Analysis
The Block Lanczos method was used to conduct modal analysis on the finite element model of Guangyue Tower, and the natural frequency of the model structure was calculated. The first 6 natural frequencies and periods of vibration were shown in the table 4 below:

| Vibration mode | 1    | 2    | 3    | 4    | 5    | 6    |
|----------------|------|------|------|------|------|------|
| Timber structure | Natural frequency of vibration /Hz | 1.6106 | 1.6364 | 2.3451 | 5.7310 | 6.1314 | 7.0953 |
|                 | Natural vibration period T/s | 0.6209 | 0.6111 | 0.4264 | 0.1745 | 0.1631 | 0.1409 |
| Overall structure | Natural frequency of vibration /Hz | 1.6053 | 1.6309 | 2.3410 | 3.5412 | 3.5416 | 4.0342 |
|                 | Natural vibration period T/s | 0.6230 | 0.6132 | 0.4272 | 0.2824 | 0.2824 | 0.2479 |

Referring to the results of modal analysis after field measurement in Guangyue Tower [6], the measured measurement of the timber structure of Guangyue Tower is very close to the fundamental frequency of the calculation model, indicating that the dynamic characteristics of the established finite element model are close to the dynamic characteristics of the original structure. Therefore, the finite element model of Guangyue Tower can be used to analyze the dynamic response of the structure under the action of earthquake.

4. Incremental Dynamic Analysis
Guangyue Tower where seismic fortification intensity of 7 degrees (0.15 g), earthquakes are grouped into the second group, site category for III class. In this paper, 9 seismic waves and 1 artificial wave were selected from PEER seismic wave database for incremental dynamic analysis and calculation considering the calculation accuracy and cost. As shown in figure 3, the average seismic influence coefficient curve of the selected seismic wave satisfying multiple time-history curves should be no more than 20% different from that of the seismic influence coefficient curve adopted by mode decomposition response spectrum method at the period of the main mode.

![Figure 3. Comparison of seismic wave response spectrum curves.](image)
4.1. Incremental Dynamic Analysis under Different Intensity Indicators

In this paper, the maximum inter-storey displacement Angle Max is selected as the earthquake response parameter of Guangyue Tower, and the value of each limit state is shown in table 5 [8]. The ground motion intensity parameters of $S_a$, $PGA$ and $PGV$ are analyzed respectively, so as to obtain the intensity parameters suitable for evaluating the seismic performance of Guangyue Tower.

Table 5. The maximum interlayer displacement Angle Max corresponding to each stage.

| The performance level | Basic intact OP | Slightly damaged IO | Life safety LS | To prevent the collapse CP |
|-----------------------|-----------------|---------------------|----------------|---------------------------|
| Extreme value point   | $1/442$         | $1/148$             | $1/48$         | $1/16$                    |

Based on Hunt&Fill method [9], $S_a$ was used as the ground motion intensity parameter for amplitude modulation calculation, and IDA curve clusters on $S_a$-$\theta_{max}$ were drawn, as shown in figures 4 and 5:

Figure 4. Timber structure IDA curve cluster.
Figure 5. Overall structure of IDA curve cluster.

$S_a$ is converted into the corresponding ground motion intensity parameters $PGA$ and $PGV$, so as to obtain the IDA curve of the Guangyue Tower timber structure and the overall structure with high platform consideration about $PGA$-$\theta_{max}$ and $PGV$-$\theta_{max}$, as shown in figures 6 and 7:

Figure 6. IDA curve of timber structure.
It can be seen from figures 4 and 5 that in the initial stage of the IDA curve cluster, the curves are relatively concentrated and the inter-layer displacement Angle of the structure is small. As the inter-layer displacement Angle of the structure increases, the IDA curve cluster gradually becomes discrete and the degree of dispersion becomes more and more obvious.

It can be seen from figures 4-7 that the dispersion degree of IDA curve of Guangyue Tower timber structure and the overall structure considering the high platform foundation is not significantly different. The response value of the overall structure is larger than that of the timber structure, indicating that the presence of high platform will amplify the displacement response of the wooden structure, which proves that the presence of high platform is not conducive to the seismic resistance of the wooden structure.

By comprehensively comparing IDA curve clusters with different ground motion intensity indicators ($S_a$, $PGA$, $PGV$), it can be found that under the action of different ground motion intensity parameters, the shape of IDA curve clusters of the same structure is different, and the curve discreteness is also different. By comparing and observing IDA curve clusters with different ground motion intensity parameters, it can be intuitively found that the shape of IDA curve clusters represented by $PGA$ as the intensity parameter is more concentrated, and its discreteness is less than that of IDA curve clusters represented by $S_a$ and $PGV$ as the intensity parameters.

4.2. Analysis of Ground Motion Intensity Parameters

The above IDA analysis results were calculated by using the quantile statistical method, and three quantile curves of IDA curve cluster of 16%, 50% and 84% under different strength parameters were obtained, as shown in figures 8 and 9, so as to quantify the dispersion degree of IDA curve cluster, and the performance evaluation of Guangyue Tower based on statistical probability was carried out by using the quantile curve.

Figure 8. Sectional curves of timber structure under different strength parameters.
Compared to the same structure under the effect of different intensity of ground motion parameters of quantile curve, can be found in the initial stages of curve, three kinds of strength parameters under IDA curve discrete are small, anywhere the vibration structure of IDA curve discrete began to increase, with $PGA$ as the strength parameters of IDA curve relative to the rest of the two kinds of strength parameters is concentrated. Therefore, IDA curve expressed by ground motion intensity parameter $PGA$ can better reflect the overall change of the structure during the whole reaction process of Guanyue Tower, which is helpful to improve the effectiveness of seismic performance evaluation of Guanyue Tower.

According to the definition of failure state and performance level division of Guanyue Tower timber structure, combined with the quantile curve in figure 8 and 9, the corresponding ground motion intensity of the structure under each limit state is determined. The statistical results are shown in table 6.

| Percentile curve | Timber structure | The overall structure |
|------------------|------------------|----------------------|
|                  | 16%   | 50%   | 84%   | 16%   | 50%   | 84%   |
| Basic intact ($\theta_{max}=1/442$) | $S_a$(g) | 0.149 | 0.227 | 0.649 | 0.015 | 0.019 | 0.028 |
|                  | $PGA$(g) | 0.044 | 0.081 | 0.153 | 0.010 | 0.015 | 0.037 |
|                  | $PGV$(cm/s) | 0.031 | 0.044 | 0.079 | 0.003 | 0.006 | 0.009 |
| Slightly damaged ($\theta_{max}=1/148$) | $S_a$(g) | 0.350 | 0.525 | 1.040 | 0.284 | 0.403 | 0.863 |
|                  | $PGA$(g) | 0.170 | 0.280 | 0.466 | 0.139 | 0.245 | 0.413 |
|                  | $PGV$(cm/s) | 0.083 | 0.130 | 0.233 | 0.071 | 0.112 | 0.205 |
| Life safety ($\theta_{max}=1/48$) | $S_a$(g) | 0.776 | 1.218 | 1.677 | 0.722 | 1.163 | 1.623 |
|                  | $PGA$(g) | 0.453 | 0.595 | 0.784 | 0.432 | 0.630 | 0.780 |
|                  | $PGV$(cm/s) | 0.226 | 0.309 | 0.417 | 0.210 | 0.297 | 0.415 |
| To prevent the collapse ($\theta_{max}=1/16$) | $S_a$(g) | 1.423 | 1.864 | 2.248 | 1.407 | 1.839 | 2.235 |
|                  | $PGA$(g) | 0.855 | 0.934 | 1.032 | 0.840 | 0.927 | 1.023 |
|                  | $PGV$(cm/s) | 0.460 | 0.567 | 0.637 | 0.446 | 0.549 | 0.624 |

According to the relationship between quantile and exceedance probability, when $S_a=0.776g$ ($PGA=0.453g$, $PGV=0.226m/s$) without considering the high base, 16% of the ground motion records made the timber structure exceed the life safety limit. In the case that the ground motion records corresponding to the same limit state exceed probability, the ground motion intensity value of the whole structure considering the high platform is $S_a=0.722g$ ($PGA=0.432g$, $PGV=0.210m/s$), that is, the existence of the high platform will make the corresponding ground motion intensity decrease when the structure reaches the life limit safety state. By comparing the corresponding result values under different limit states in the two tables, it is further proved that the existence of high base is unfavorable
to the seismic resistance of the timber structure.

5. Conclusion
Based on ANSYS finite element analysis software, this paper carries out incremental dynamic analysis of Guangyue Tower, and the main conclusions are as follows:

(1) The dispersion of different ground motion intensity parameters was compared and analyzed, and the results showed that the whole reaction process in Guangyue Tower IDA curve expressed by ground motion intensity parameter PGA can better reflect the overall change of the structure, which is helpful to improve the effectiveness of seismic performance evaluation of Guangyue Tower.

(2) According to the relationship between quantile and exceedance probability, the existence of high platform will reduce the ground vibration intensity when the structure reaches the life limit safety state, which indicates that the existence of high platform is unfavorable to the seismic resistance of timber structure.

Acknowledgments
The writers appreciate the financial support provided by National Natural Science Foundation of China (No.51378245), Graduate Education Quality Improvement Plan Project of Shandong Province (SDYJG19062, SDYY16102) and Scientific Research Fund Project Liaocheng University (318011901).

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