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Numerical Simulation Analysis of Chinese Timber Frame Ancient Buildings - An Example of the Hall of Supreme Harmony in the Forbidden City

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Abstract: Chinese ancient architecture is renowned for its unique large wooden structures and standards. However, the safety of the wooden structures in the Forbidden City has gradually deteriorated over long-term use. At present, most building safety evaluation methods rely on qualitative assessments rather than quantitative identifications. In the process of conducting safety evaluations, it is necessary to conduct sufficient analysis and judgment of building damage to determine the safety status of ancient buildings. To ensure the safety of the buildings, this study takes the Hall of Supreme Harmony in the Forbidden City as an example, using numerical simulation methods to analyze the components of Chinese wooden ancient architecture through finite element analysis, with the aim of quantitatively protecting China's traditional architectural cultural heritage. This study provides a scientific basis for the protection of China's traditional architectural cultural heritage and has high practical significance. The results showed that the deformation peak and internal force were within the allowable range according to relevant specifications.

Keywords: Wooden Ancient Structures, Safety assessment, Numerical simulation analysis, Finite element analysis, The Hall of Supreme Harmony.

1. Introduction

Chinese ancient architecture often used large timber frame technology, which has a complex structure and unique cultural value. It is crucial to detect structural damage and assess the safety of large buildings such as the Hall of Supreme Harmony and make timely decisions to ensure their health and ultimately improve public safety [1]. In addition, in the context of the country's high attention to the safety of existing buildings, how to conduct accurate and reliable evaluation work has become an important topic. In "Reflections on Establishing a Research-oriented Protection Mechanism for Ancient Buildings in the Forbidden City", Shan Jixiang pointed out that the evaluation work is disconnected from practical work, and there is generally a lack of special evaluation.

This article focuses on the research of safety evaluation methods for ancient buildings. In addition to the numerical simulation method used in this article, the main methods for safety evaluation of ancient buildings include expert evaluation, monitoring and analysis, and comprehensive evaluation. Currently, most adopt statistical analysis methods based on regular monitoring, such as the Analytic Hierarchy Process[2], Grey System Theory[3], fuzzy mathematics[4], and there are also static load experimental assessment methods, residual damage condition index methods, etc. However, these methods have problems such as subjectivity, instability, and low accuracy, because these methods mainly rely on qualitative identification in evaluation, with quantitative identification as a supplement. For quantitative identification methods, the existing health monitoring systems are not suitable for detecting wooden structure buildings and are biased towards reinforced concrete structure buildings.

Firstly, this paper takes the Hall of Supreme Harmony in the Forbidden City in Beijing as an example to investigate the wooden structural components, including their construction period, materials, and other relevant information, and conducts an inspection of their current state. Secondly, the necessary wooden components are analyzed and simplified in the stress model, and the finite element model of the Hall of Supreme Harmony is established using Abaqus software. Finally, based on the finite element analysis method, this paper conducts a simulation study on the wooden components of the Hall of Supreme Harmony, and analyzes and compares the results generated by the simulation. In the analysis process, this paper uses Abaqus software to perform static analysis on the current state solid model of the components, analyzes the internal forces and displacements of the structure under self-weight load, and obtains the stress-strain distribution and maximum value results of the wooden components of the Hall of Supreme Harmony.

In the safety evaluation of ancient buildings, this paper applies the numerical simulation method to study the positioning and quantitative evaluation methods for the deformation and stress of ancient buildings themselves based on deformation anomalies and stress anomalies. This method effectively separates the qualitative identification affected by human factors from the stress-strain analysis of building structures, achieving more accurate and digital health status recognition. This paper obtains a large amount of information about the structural health status for repair personnel through numerical simulation analysis results. Taking the Hall of Supreme Harmony as an example, although there are related literature[5] that conduct static load analysis by reconstructing standard models, due to maintenance and other reasons, there are significant differences between its current state and the standard model, so it is necessary to reconstruct the current state model for damage condition judgment. This method conducts analysis without damaging the ancient building, protecting the integrity and originality of the ancient building, bringing new ideas to the numerical simulation method of ancient wooden structure buildings, and providing reference for the protection and maintenance of ancient buildings.

2. Numerical Simulation Model for Timber Frame Ancient Buildings

In this paper, a simplified standard model of the Taihe Hall was established using the static mechanics theory and referring to data from ancient texts [7]. Using 3D laser scanning and 3D point cloud segmentation techniques, the 3D point cloud model of the Taihe Hall was obtained by applying the 2005 scanned point cloud data of the Hall to obtain the 3D point cloud models of the timber column, girder, epipelagic spar frame and short column, and applying deformation algorithms to obtain the The present-day model of the Hall of Harmony was obtained by applying deformation algorithms. Using the Abaqus finite element programme as a tool, the finite element model of the Hall was reconstructed and the wood components were calculated to find the components with large deformations and to calculate their Mises (tensile, shear and bending) stress maxima. Finally, these maximum values were compared with the strength tolerance values to determine if they were within the normal serviceability limit states.

The Hall of Supreme Harmony, located in the Forbidden City of Beijing, China, is a traditional Chinese wooden structure with a total area of 2381m^2. Its dimensions are 64m in the east-west direction, 37.21m in the north-south direction, and 26.92m in height. The roof is a roundridgeroof gablehiproof style supported by 32 Eaves columns and 40 Hypostyle columns[5]. The columns are connected by picket beams below the upper picket, architraves on the lower eaves, main aisle exposed tiebeams, huatai tiebeams, binding tiebeams, upper eaves architraves, kuakong beams and a large number of cushion board members, making the timber frame have a high degree of integrity and stability. and stability. The epipelagic spar frame is mainly made up of longitudinal beams, spar frames and vertical short columns. On top of the roof truss, the purlins and cantilevered corner beams are erected, followed by the rafters, the looking sheathing, the tarpaulin back and other components. The load-bearing elements of the epipelagic spar frame can be simplified to a structural system consisting of short column, main aisle exposed tiebeams and basepin beam. The mechanical model of the Hall of Peace can be reduced to a structural system consisting of a bucket arch, an epipelagic spar frame, a spar frame and a column grid.

3. Finite Element Model Reconstruction of the Hall of Supreme Harmony

(1) The bucket arch

The structural design of the bucket arch of the Hall of Supreme Harmony is different from that of other load-bearing structures such as beams and columns in that its main role is not to bear weight, but to distribute the weight of the spar frames and floor slabs evenly to the walls and The main function is not to carry the load, but to distribute the weight of the spar frames and floor slabs evenly over the walls and columns. The beams and the tiebeam and the column grid are connected by bucket arches, which can increase the number of elastic bearings and improve the bearing state of the beams and tiebeam, reducing the bending moments and deformation peaks of the beams and tiebeam [6].

In the reconstruction of the bucket arch in the finite element model, a three-dimensional semi-rigid nodal cell is used to describe the stiffness of the nodes of the bucket arch in different directions. $K\theta x$, $K\theta y$ and $K\theta z$ represent the rotational stiffness of the nodes in the x, y and z directions respectively. The stiffness of the bucket arch node can be $Kx=Ky=Kz=1550$ KN/m and $K\theta x=K\theta y=K\theta z=3.1\times10^5$ KN-m.

(2) The epipelagic spar frame

A structure consisting of a combination of load transfer from purlins of different heights is known as a 'spar frame'. In The Hall of Supreme Harmony, the weight of the roof is transferred by spreading the weight evenly from the rafters to the purlins, from the purlins to the beams and tiebeam, and finally from the beams and tiebeam to the columns. The bucket arch acts as a transitional structure, allowing the weight of the roof to be transferred evenly to the columns and beams. To simplify the calculations in the finite element model, the mass of the roof is reduced to a uniformly distributed mass based on the size of the roof mass shared by each member, and the load is applied to the upper surface of the short column and the ends of the main aisle exposed tiebeam at the top and bottom.

(3) The spar frame and column grid

The spar frame and column grid of the finite element model of the Hall of Supreme Harmony are composed of Hypostyle column, Eaves column, Picket beams below the upper picket, Large frontal square, main aisle exposed tiebeam, Huatai tiebeam, and Huatai square. The columns are composed of Hypostyle column, Eaves column, Picket beams below the upper picket, large frontal square, main aisle exposed tiebeam, Huatai tiebeams, Binding tiebeams, Upper eaves frontal square and spanning architraves. architraves and kuakong beams. As the wooden columns of the Hall of Supreme Harmony have been reinforced by modern techniques [7], rigid connections are used in the finite element model between the spar frame and the column grid, except for the bucket arch connection.

(4) Other wooden components

The wood column and the column base form a sliding system, but because the friction between them is usually high, they can be set up as an articulated structure[8]. In this case, the degrees of freedom retained by the nodes at the base of the column in the finite element model are ROTX, ROTY and ROTZ, which is in accordance with the results of the mechanical analysis.

Walls in ancient Chinese buildings were mainly used for enclosure purposes and often did not have load-bearing roles, interior spaces were separated flexibly and the separating elements were not necessarily walls, but various elements. Therefore, the force analysis model used in this paper does not include walls.

The finite element mesh model of the supreme harmony is shown in Figure 1. For the parameters of the supreme harmony components, refer to the book Three Centuries of the supreme harmony[7], as shown in Table 1:

Table 1. Data on some of the components of the hall of supreme harmony

Wooden component name		Number	Measured scale (mm)
Column	Eaves column	32	height7390
			diameter780
	Hypostyle column	28	height12730
			diameter1060
	Short column	16	height3445
			diameter680
Beam	Main aisle exposed tiebeam	28	length5390
			height900
			width700
	Picket beams below the upper picket	28	length4170
			height550
	Kuakong beams	24	length11180 (for eight)
			length7465 (for sixteen)
			height960
			width670
	Basepin beam	8	length11180
			height630
			thickness430
Tiebeam	Large architraves on the lower eaves	32	length11180 (for two)
			length8460 (for two)
			length7465 (for two)
			length4260 (for eight)
			length5550 (for sixteen)
			height805
			width510
	Upper eaves architraves	24	length11180 (for two)
			length8460 (for two)
			length8370 (for two)
			length6465 (for four)
			length5560 (for twelve)
			height1050
			thickness600
	Huatai tiebeams	24	length11180 (for two)
			length7465 (for four)
			length5550 (for sixteen)
			length8465 (for two)
			height720
			thickness520
	Binding tiebeams	24	length11180 (for two)
			length7465 (for four)
			length5550 (for sixteen)
			length8465 (for two)
			height800
			width520

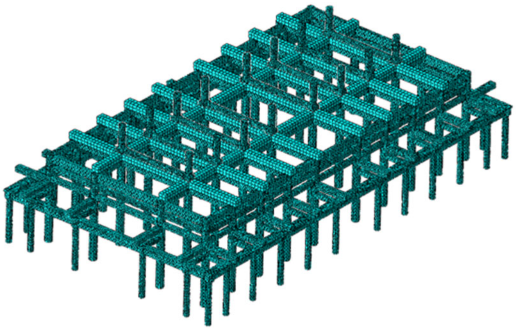

Figure 1. Finite element mesh model of the hall of supreme harmony

For the relevant parameters of the finite element model ,the roof mass of the Hall of Supreme Harmony is considered to be uniformly loaded, including the self-weight of the beam frame on the main body of the Shun beam, the self-weight of the beam frame on the mountain side of the Totem and the roof load transmitted down to the short column,. The loads involved are: 440 kN on the short beam[9], 1851.2[10] kN on the hill, 148.1 kN on the main aisle exposed tiebeam of the Hypostyle column, and 210.4 kN[11] on the ground floor of the main aisle exposed tiebeam.

Timber parameters: material density ρ = 610 kg/m^3, overall gravitational acceleration of the model g = 9.8 m/s^2. The roof loads are applied at the short column and at the two upper and lower floors of the main aisle exposed tiebeam. The timber elasticity parameters are detailed in Table 2:

Table 2. Parameters of the finite element model

Wood elasticity parameters	Parameter values
Modulus of elasticity of wood in the smooth grain (MPa)	EL=7000
Tangential modulus of elasticity of wood (MPa)	ET≈350
Radial modulus of elasticity of wood (MPa)	ER≈700
Z Poisson's ratio	0.3
X Poisson's ratio	0.3
Y Poisson's ratio	0.3
XY -plane shear modulus	GLT≈420
YZ -plane shear modulus	GRT≈126
XZ -plane shear modulus	GLR≈525

4. Results and Analysis

(1) Stress analysis

The results of the static analysis show that the maximum Mises stress on the structure under roof and self-weight loads is 0.526 MPa, which is less than the allowable value of 8.5 MPa for the tensile strength of timber, and that the maximum Mises stress on the structure is 0.526 MPa at the bottom of the short column and near the junction with the Hypostyle column. This is shown in Figure 2.

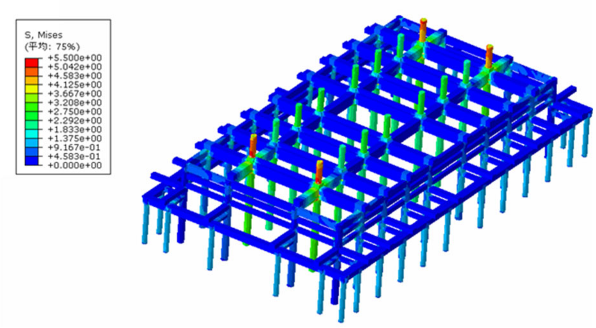

Figure 2. Model force clouds

(2)Strain analysis

After static analysis, as the direction of action of the self-weight load is perpendicular to the horizontal direction, the displacement of the structure in the horizontal direction is small. The deformation distribution of The Hall of Supreme Harmony under the self-weight load showed the following characteristics: the deformation of the upper frame was significantly larger than that of the lower frame; the deformation of the axially stressed members was mainly distributed in the vicinity of the short column and the adjacent Hypostyle column on the two mountain faces, of which The maximum value is 17.81 mm, which occurs near the two mountain faces of the short column, the direction downwards; the largest deformation of the bending members occurs in the mountain faces of the child column below the inner hypostyle column, the maximum bending vector height in the structure is 2.06 mm, in the range of the code tolerance [12] (the column bending vector height tolerance value l/250, where l is the non-bending vector height of the column. Here l is the unsupported length of the column, l = 12,730 mm, and the permissible value is 50.92 mm). The areas with large deformation of the bending members are mainly located near the Kuakong beams on the lower side of the hill, where the maximum vertical displacement is 15.23 mm, which is within the tolerance range of the code (vertical bending tolerance value $l^2/2100h+h/15$, where l is the length of the member, l=11180 mm, and h is the thickness of the member, h=960 mm; the tolerance value is 126.00 mm;the value is 126.00 mm). This is shown in Figure 3.

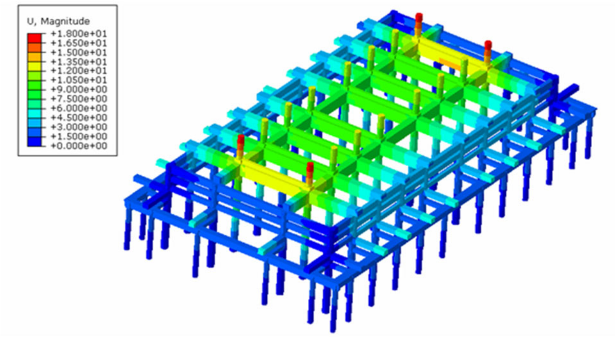

Figure 3. Model deformation clouds

5. Conclusion

In this paper, based on the static analysis of the wooden structure of ancient buildings, a finite element model of The Hall of Supreme Harmony was reconstructed using Abaqus software, with solid units selected according to its structural characteristics, and parameters and their value ranges determined. Static calculations were carried out under roof and self-weight loads to obtain the damage results of the model in its current state, and stress and strain clouds were obtained. The results show that the maximum values of stress and strain in the members are far less than the code allowable values, with the maximum stress reaching 0.526 MPa, which is less than the allowable value of 8.5 MPa for the tensile strength of timber; the maximum value of deformation in the axially stressed members reaches 17.81 mm, and the maximum bending vector height of deformation in the bending members is 2.06 mm, which are within the corresponding allowable values. This indicates that the building is currently very healthy. The Hall of Supreme Harmony is structurally stable and will remain in good condition for a long time.

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