Research on Wind Vibration Performance of Chinese Early Traditional Timber Structure – A case study of the Main hall of Tianning Temple

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Abstract. In order to study the wind vibration performance of Chinese early traditional timber structure, the main hall of Tianning Temple in Jinhua of Zhejiang province was taken as an example. Firstly, based on the precise geometric information acquired by 3D laser scanning, the calculation model of the main hall was built by the finite element software of SAP2000, and its dynamic characteristics were analyzed. Then, the time history curves of fluctuating wind speed and fluctuating wind pressure based on AR model was generated by the software of MATLAB. The generated wind pressure was applied to the FEM model and analyzed. The results show that the top ten natural frequencies of this structure are among 3.617 Hz~18.672 Hz. The wind vibration response of this structure is mainly influenced by the top four natural modes. The wind vibration coefficients obtained by the time history analysis of wind pressure are 1.1~1.5 times of the wind vibration coefficients calculated according to the Chinese current load code. These results can provide a reference for analysis of wind vibration performance of Chinese early traditional timber structure.

1 Introduction

Chinese traditional timber buildings, developing from origin to mature, experienced thousands of years and vicissitudes of this oriental civilized country. These ancient buildings need to be preserved well by us, but it is common to find some damages in the Chinese traditional timber buildings under strong wind action. Therefore, in order to scientifically conserve these excellent historical buildings, it is urgent to study the wind vibration performance of Chinese traditional timber buildings.

At present, domestic and international researches on structural wind engineering are concentrated in the high-rise structure, large-span structure and bridge structure, there is very few research on the traditional timber buildings under wind action. D.L. Wu[1] studied the reasonable wind direction of ancient pagoda through the wind tunnel test of architectural model, the structural shape coefficients of wind load were obtained. T.Y.Li[2] studied the structural shape coefficients of wind load of Yingxian timber tower, and the bottom moment and the bottom pressure under wind action were also analyzed through the experiment. S.H.Yang[3], H.R.Liu[4] studied the structural shape coefficients of wind load of the Hall of Supreme Harmony based on CFD numerical

simulation software of FLUENT. L.Luo[5] studied the wind pressure distribution of a traditional high-rise wooden pagoda in four representative wind directions with the RNG k- ϵ turbulence model based on the software of FLUENT. D. J. Henderson, et al[6] studied the structural performance of the wooden roof under wind action.

In summary, the current research on wind vibration characteristic of Chinese ancient timber buildings is still infant. In this paper, the main hall of Tianning Temple in Jinhua of Zhejiang Province was taken as an example to study the wind vibration performance of Chinese early traditional timber structure, this building was rebuilt in 1318 AD in Yuan Dynasty of ancient China, **the architectural form, the building structure, and the architectural configurations of this building all conform to the characteristics of Chinese traditional timber buildings in the Song dynasty and the Yuan dynasty**, so it is a very typical Chinese early traditional timber structure.

2 Finite element model

The main hall of Tianning Temple is a Chinese traditional timber building with Xieshan roof style, the building plane is square, the length and the width are all 12.72 m, **the height of this building is 12.13m, the**

diameter of the columns is 450mm. The building appearance is as shown in Fig.1. In order to obtain the accurate geometrical dimension, the precise scanning was carried out by 3D laser scanner. The partial 3D scanning diagrams of the main hall of Tianning Temple are as shown in Fig.2.

(a)Outside appearance

(b)Inside appearance

Fig.1 Main Hall of Tianning Temple

(a)cross profile

(b)longitudinal profile

Fig.2 3D scanning diagrams of the main hall of Tianning Temple

The main hall of Tianning Temple is mainly composed of columns, beams, purlins, bucket arches and wood rafters. The beams and the columns are connected by the mortise-tenon joints. The finite element software of SAP2000 was used to establish the calculation model of the main hall, as shown in Fig.3. The software of SAP2000 is very powerful and convenient to analyze the structural performance of spatial truss structures, and the main hall of Tianning Temple is just a spatial truss structure. In the model, the semi-rigidity of the mortise-and-tenon joints is considered, the collection of the columns and the ground is hinged, the bucket arches are simulated by the diagonal members, the structural damping ratio is 0.05, the calculation model contains 1190 nodes and 1286 members. According to relevant reference [7], the main material of the load-bearing members of this hall is Chinese fir. This type of wood material was first used in Chinese timber buildings in

about 200 BC, now it is still widely used to built Chinese timber buildings. The strength of Chinese fir is obtained according to the *Chinese Code for design of timber structures*, considering that the main hall was built about seven hundred years ago and referring to the reduction factors suggested by the *Chinese technical code for maintenance and strengthening of ancient timber buildings*, the reduction factor of compression design strength parallel to grain of wood is 0.75, and the corresponding strength is 7.5N/mm^2 . The reduction factor of bending strength is 0.7, and the corresponding strength is 7.7N/mm^2 . The reduction factor of shear design strength parallel to grain of wood is 0.7, and the corresponding strength is 0.98. The reduction factor of elastic modulus is 0.75, and the corresponding elastic modulus is 6750N/mm^2 . The reduction factor of compression design strength perpendicular to grain of wood is 0.75, and the corresponding strength is 1.35N/mm^2 . According to the on-site investigation, there are 16 pieces of top tiles, and 32 pieces of bottom tiles per square meter on the roof of the main hall. The thickness of roof lime cover is 12cm, so the standard value of dead load of the roof is 3.5 kN/mm^2 .

Fig.3 Finite element model of the main hall of Tianning Temple

3 Modal analysis

According to the dynamic analysis, the top ten modes of this main hall are obtained, as shown in Table.1. Its natural frequencies are among 3.617 Hz to 18.672 Hz. The top three mode shapes of this hall are as shown in Fig.4. The results show that the most possible deformation under strong wind is the depth-direction vibration, the width-direction vibration, and the torsional vibration. The natural frequency of the depth-direction vibration is a little smaller than that of the width-direction vibration.

Table 1. Top ten modes of the main hall of Tianning Temple

Mode	Natural vibration period (s)	Natural vibration frequency (Hz)
1	0.276	3.617
2	0.275	3.642
3	0.199	5.037
4	0.132	7.577
5	0.080	12.512

6	0.071	14.126
7	0.069	14.420
8	0.058	17.155
9	0.056	17.858
10	0.054	18.672

4 Generation of the wind pressure

According to relevant references [8-9], in engineering practice, the wind speed is regarded as the superposition of the average wind speed and the fluctuating wind speed, as shown in Equation 1:

$$V(t) = \bar{v} + v(t)$$
 (1)

The relationship between the wind pressure history and the wind speed history is shown in Equation 2. (Zhang X T 1985)

$$W(t)=V^2(t)/1600$$
 (2)

Here W(t) is wind pressure history, V(t) is wind speed history, $\bar{v}$ is average wind speed, considering the recurrence interval is 100 years, and according to the Chinese load code for the design of building structures GB50009-2012 E.2, the converted average wind speed is $\bar{v}=25.3$ m/s, v(t) is the fluctuating wind speed history.

The characteristic of fluctuating wind speed can be described by power spectrum and correlation function [10-11]. The power spectrum and the correlation function can be transformed through Winner-Khintchine formula. In this paper, the Auto-Re-pressive (AR) method is used to simulate the fluctuating wind speed.

The AR model of the fluctuating wind speed with M dimensions can be described as Equation 3.

$$u(t) = -\sum_{k=1}^p \Phi_k [u(t - k\Delta t)] + N(t)$$
 (3)

Here Φ_k is the auto regressive coefficient matrix of AR model, which is $M \times M$ orders; p is the order of AR model; N(t) is a random process which has been given the variance; Δt is the time step. The 18 related points in acting surface of the wind pressure are chosen to analyze, as shown in Table.2. The MATLAB is used to generate the wind speed, then the wind pressure can be obtained by Equation 1 and Equation 2, as shown in Fig.5.

Table 2. Coordinate of the related points (unit: mm)

Coordinate				Coordinate			
	X	Y	Z		X	Y	Z
1	320	456	936	10	626	125	263
	2	9	4		4	31	5
2	932	456	936	11	160	625	927
	5	9	4		1	8	0
3	320	154	743	12	432	786	743
	2	5	9		1	9	
4	932	154	743	13	432	470	743
	5	5	9		3	9	
5	626	0	263	14	0	626	263
	4		5		6	5	
6	932	780	936	15	109	725	927
	5	9	4		26	8	0
7	320	780	936	16	120	470	743
	2	9	4		96	3	9
8	932	110	743	17	120	786	743
	5	19	9		96	1	9
9	320	110	743	18	125	626	263
	2	19	9		27	6	5

(a) Time history curve of wind speed of Point 3

(b) Time history curve of wind speed of Point 7
Fig.5 Time history curves of wind speed

5 Wind vibration analysis

5.1 Analysis of the displacement response

The observation points of the displacement response are shown in Fig.6. According to the analysis of the displacement response, under the wind load with the recurrence interval of 100 years, the lateral deformations of this building are all meet the requirements of the code of GB50009-2012. The acceleration response spectrum curves of the two observation points are shown in Fig.7 and Fig.8. The results show that the frequencies are among 3.6 Hz to 7.6 Hz in the peak area of the typical two observation points. According to the former dynamic analysis, the top four natural frequencies are 3.62 Hz, 3.64 Hz, 5.04 Hz and 7.58 Hz respectively, and they are very close to the frequencies in the peak area. The results show that the wind vibration response of this building is mainly influenced by the top four natural modes.

(a) observation points at the columns and the walls

(b) observation points at the roof

Fig.6 Observation points of the displacement response

(a) the depth-direction

(b) the width-direction

Fig.7 Acceleration response spectrum curve of N1

(a) the depth-direction

(b) the width-direction

Fig.8 Acceleration response spectrum curve of N28

5.2 Comparison between the wind vibration coefficients obtained by time history analysis and the wind vibration coefficients calculated according to the code

The wind vibration coefficient is obtained by time history analysis under wind pressure, as shown in Equation 4.

$$\beta_d = 1 + U_d / U_s \quad (4)$$

Here U_d is the maximum dynamic displacement of node. U_s is the static displacement under the average wind pressure. The average wind load $F_i = A_i w_i$, A_i is the area of wind pressure, w_i is the standard value of average wind pressure.

The wind vibration coefficient is calculated according to the code of GB50009-2012, as shown in Equation 5.

$$\beta_z = 1 + \frac{\xi v \varphi_z}{\mu_z} \quad (5)$$

Here ξ is fluctuating amplifying coefficient, while $w_0 T_1^2 = 0.50 \times 0.4958^2 = 0.1229$, $\xi = 1.51$, the result is obtained from Table 7.4.3 of the Code. v is fluctuating influence coefficient, while $H/B = 0.67$ and $H \leq 30m$, $v = 0.46$, this result is

obtained from Table 7.4.3-3 of the Code. φ_z is mode factor obtained from Table F.0.4 of the Code. μ_z is height variation coefficient of wind pressure obtained from Table 8.2 of the Code, and it is 1.0.

The comparative analysis of the two wind vibration coefficients was shown in Table.3.

Table 3. Comparison on the two wind vibration coefficients

z/H	Po-int	U_d+U_s (mm)	U_s (mm)	β_d	φ_z	β_z	β_d/β_z
0.5	N1	3.9	2.11	1.85	0.38	1.26	1.5
0.5	N2	6.5	3.4	1.91	0.38	1.26	1.5
0.5	N3	3.88	2.11	1.84	0.38	1.26	1.5
0.5	N4	3.88	2.09	1.85	0.38	1.26	1.5
0.5	N5	3.88	2.09	1.86	0.38	1.26	1.5
0.5	N6	6.03	3.21	1.88	0.38	1.26	1.5
0.5	N7	3.89	2.09	1.86	0.38	1.26	1.5
0.5	N8	3.89	2.09	1.86	0.38	1.26	1.5
0.7	N9	4.9	2.66	1.84	0.67	1.46	1.2
0.7	N10	6.05	3.39	1.78	0.67	1.46	1.2
0.7	N11	4.92	2.67	1.84	0.67	1.46	1.2
0.7	N12	4.93	2.67	1.84	0.67	1.46	1.2
0.7	N13	4.93	2.67	1.84	0.67	1.46	1.2
0.7	N14	5.83	3.49	1.67	0.67	1.46	1.2
0.7	N15	4.9	2.66	1.84	0.67	1.46	1.2
0.7	N16	4.9	2.66	1.85	0.67	1.46	1.2
0.8	N17	5.28	2.77	1.91	0.74	1.51	1.2
0.8	N18	6.43	3.56	1.81	0.74	1.51	1.2
0.8	N19	5.08	2.78	1.83	0.74	1.51	1.2
0.8	N20	5.05	2.76	1.83	0.74	1.51	1.2
0.8	N21	5.09	2.79	1.82	0.74	1.51	1.2
0.8	N22	5.84	3.35	1.74	0.74	1.51	1.2
0.8	N23	5.05	2.77	1.82	0.74	1.51	1.2
0.8	N24	5.03	2.75	1.83	0.74	1.51	1.2
0.9	N25	6.02	3.39	1.77	0.86	1.59	1.1
0.9	N26	6.53	3.69	1.77	0.86	1.59	1.1
1	N27	5.26	2.91	1.81	1	1.69	1.1
1	N28	5.54	3.21	1.73	1	1.69	1.1
1	N29	5.28	2.92	1.81	1	1.69	1.1

The results in Tab.3 show that the wind vibration coefficients calculated according to the code decrease with the decrease of the building height. But the wind vibration coefficients obtained by time history analysis fluctuate with the building height, because the building width is nearly the same as the building height, and the transverse rigidity of the structure isn't distributed uniformly. So the method of wind vibration coefficients

obtained according to the code is suitable for high-rise structure which weight varies uniformly with height, but is not suitable for Chinese traditional ancient timber structure like the main hall of Tianning Temple. The results also show that the wind vibration coefficients obtained by time history analysis is 1.1~1.5 times larger than the wind vibration coefficients calculated according to the code. So, if the wind vibration coefficients of this type of timber structure are calculated according to the Chinese load code, the wind-induced response is not accurate and the structure leads to be unsafe.

6 Conclusions

- 1) In this paper, the software of SAP2000 was used to establish the calculation model of the main hall of Tianning Temple with consideration of the semi-rigidity characteristics of the mortise-tenon joints. According to the dynamic analysis, its natural frequencies are among 3.617 Hz~18.672 Hz. The most possible deformation under strong wind is the depth-direction vibration, the width-direction vibration, and the torsional vibration. The natural frequency of the depth-direction vibration is a little smaller than that of the width-direction vibration.
- 2) Through the analysis of the wind vibration response, the wind vibration response of this structure is mainly influenced by the top four natural modes.
- 3) Through the comparative analysis of the wind vibration coefficients obtained by time history analysis and the wind vibration coefficients calculated according to the Chinese load code, the wind vibration coefficients calculated according to the code decrease with the decrease of the building height, but the wind vibration coefficients obtained by time history analysis fluctuate with the building height. The wind vibration coefficients obtained by time history analysis is 1.1~1.5 times larger than the wind vibration coefficients calculated according to the code. So, if the wind vibration coefficients of this type of timber structure are calculated according to the code, the wind-induced response is not accurate and the structure leads to be unsafe.

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