Study on Vibration Character and Dynamical Response of Shen-Wu Gate in the Forbidden City in China

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ABSTRACT :

Ancient buildings in China are mainly made of wood which have the character of earthquake resistance.The Shen-Wu Gate in the Forbidden City is an good example.Considering constitutions such as Tenon-Mortise joints,Tou-Kung ,Cejiao and so on ,its finite element model is built.Modal as well as dynamical analysis are carried out to study vibration characters and dynamical responses of the structure.Results show that the base frequency of Shen-Wu Gate is 1.07Hz,its main vibration modes focus on 1^{st} ,2^{nd} and 9^{th} in x,z and y directions;Under three-direction seismic forces (peak acceleration value reaches 400g) the structure responses with large deformation and acceleration values but remains stable.

KEYWORDS: Wooden structure,vibration character,seismic response,ancient building in China,Shen-Wu Gate in the Forbidden City

1.INTRODUCTION

Chinese ancient buildings are worth protecting for their historical,artistic and scientific values.For thousands of years they have experienced sorts of earthquakes but remain intact,a good example is the Shen-Wu Gate in the Forbidden City(Fig.1).The building was built in 1420 A.D,For about 600 years it has experienced over 200 times earthquakes (include 4 times of 8-degree intensity) but remains in good condition.The character of earthquake resistance of the Shen-Wu Gate is related closely to its constitution.

Figure 1 Shen-Wu Gate in the Forbidden City

Many scholars have studied about the aseismic characters of Chinese ancient buildings:Wang.T studied the mechanical characters of Ying-Xian wooden pagoda under seismic forces,based on the assumption that the tenon-mortise joints were of swivel joints(Wang,1992); Yu M.H,Zhao J.H (Zhao et al.1998)and Fang D.P(Fang et al.2001) introduced semi-rigid elements to simulate Tenon-Mortise joints to study vibration characters of Chinese ancient buildings;Zhao H.T and Xue J.Y studied aseismic characters of Tenon-Mortise joints and Tou-Kung of Chinese ancient buildings mainly by experiments(Yao et al.2006;Zhang,2003).

On the basement of achievements above, vibration characters as well as dynamical responses of Shen-Wu Gate under seismic forces will be studied in the following by introducing 2 nodes semi-rigid elements to simulate Tenon-Mortise joints and Tou-Kung ,constitution of Cejiao will also be considered.Results will be helpful for ancient building protection and remedy.

2.MECHANICAL MODEL

The Shen-Wu Gate belongs to *Wudian*-a type of Chinese ancient building which has five fastigiums. 32 columns are used to support the structure.The main section sizes of beams and columns are shown in Table 1.

Table 1 Section size (mm)

Name	Front column	Inner column	Tie beam	Top beam	Middle beam	Bottom beam
Size	D=750	D=750	470x900	540x630	600x720	870x920

The Shen-Wu Gate composes Tenon-Moritse joints and Tou-Kungs ,both can be simulated as 2-node spring elements which has 6 freedoms.When simulated as Tenon-Mortise joints, stiffness values of the spring element are $K_x = K_z$ =1.69x10^{6}N/m, K_y =0, $K_{\theta x} = K_{\theta y} = K_{\theta z}$ =1.5x10^{5}N·m(Yao et al.2006;Zhang,2003);When simulated as Tou-Kung stiffness values are $K_x = K_z$ =0.3x10^{6}N/m, K_y =5.5x10^{6}N/m, $K_{\theta x} = K_{\theta y} = K_{\theta z}$ =0(Sui,2006).Where,x and z represent horizontal directions while y represents vertical direction.Considering the constitution of Cejiao whose size is 0.043 m(Ma,1992), Finite element model of Shen-Wu Gate is built which is shown in Figure 2.

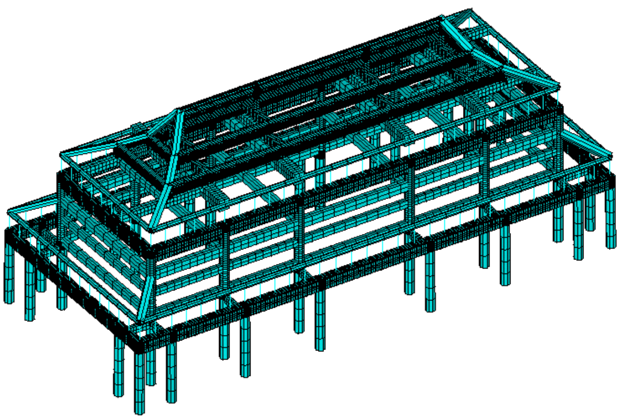


Figure 2 Finte element model of Shen-Wu Gate

Under seismic forces motion equation of the model is:

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=-[M]\{I\}\ddot{x}_g(t) \quad (2.1)$$

Where
$[M]$:Mass matrix of the model;
$[K]$:Stiffness matrix of the model, $[K]=[K_1]+[K_2]+[K_3]$;
$[K_1]$:Stiffness matrix without considering Tou-Kung or Tenon-Mortise joints;
$[K_2]$:Stiffness matrix of Tenon-Mortise joints;
$[K_3]$:Stiffness matrix of Tou-Kungs;
$[C]$:Damping matrix, $[C]=[C_1]+[C_2]+[C_3]$;
$[C_1]$:Damping matrix without considering Tou-Kung or Tenon-Mortise joints;
$[C_2]$:Damping matrix of Tenon-Mortise joints;
$[C_3]$:Damping matrix of Tou-Kungs;
$\{x(t)\}$, $\{\dot{x}(t)\}$, $\{\ddot{x}(t)\}$:Relative vectors of displacement,velocity and acceleration of the model against the ground.
$\{I\}$:Unit column vector;
As under seismic forces the structure will be in elasto-plastic status,whose maximum response is related to the loading process,thus time-history method is used for analysis.

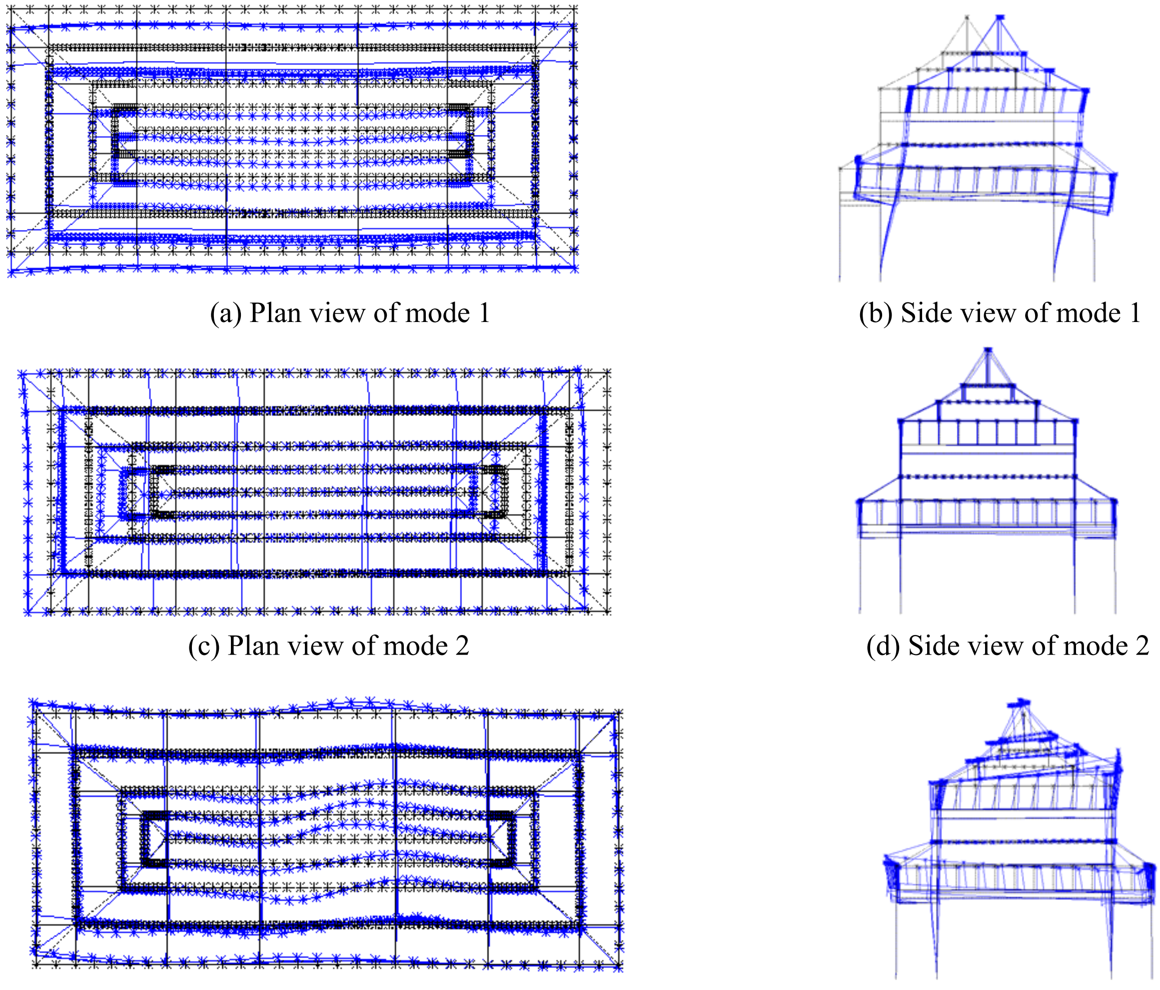
3.MODAL ANALYSIS

In order to study vibration characters of Shen-Wu Gate,modal analysis is carried out and results of the first 10 modes are obtained which are shown in Table 2:

Table 2 Results of vibration analysis

Number	Fre (Hz)	Modal ratio			Number	Fre (Hz)	Modal ratio		
		X	Y	Z			X	Y	Z
1	1.07	1.00	0.01	0	6	3.87	0.02	0.69	0.01
2	1.20	0.02	0.05	1.00	7	4.42	0.12	0.01	0
3	1.33	0.02	0.01	0.01	8	5.09	0.05	0.40	0.01
4	2.40	0.02	0.01	0.04	9	5.29	0.03	1.00	0.01
5	3.36	0.05	0.24	0.01	10	5.43	0.04	0.41	0

From table 2 it is clear that the base frequency of Shen-Wu Gate is 1.07Hz,which is just the same as the value provided by Chinese Ancient Building Remedy Code(GB50165-92).Besides, vibrations focuses on 1st mode in x direction,9th mode in y direction and 2nd mode in z direction.None of the main modes have any relation in x,y or z directions.Figure 3 shows the 1st,2nd and 9th modes which indicates the mode 1 and 2 are of horizontal translation while mode 9 are of local vertical vibration.



(a) Plan view of mode 1 (b) Side view of mode 1

(c) Plan view of mode 2 (d) Side view of mode 2

(e)Plan view of 9th mode (f)Side view of 9th mode

Figure 3 Main modes

4.SEISMIC RESPONSE

Elcentro waves in 3 directions are imposed on the structure.For each direction the peak acceleration value is 400g, time duration is 0.02 second and the total loading time is 20 seconds.The damping ratio of the structure is 0.05(Zhao et al.1999).In order to study the responses of displacement and inner forces of the structure under seismic forces,typical nodes and elements of the middle span is selected:Element at the bottom of the left column(numbering 7889) and element at the bottom of left inner column(numbering 7057) whose axial forces will be studied;Node on the roof(numbering 18245) and node on the top of right column(numbering 3601) whose responses of displacement and acceleration will be studied;Node in the middle of bottom beam(numbering 4155) whose response of moment will be studied.all the selected nodes and elements are shown in Figure 4.Correlative material parameters are(Jiang,2005):Bending elastic ratio E=9GPa, Trimming elastic ratio G=0.28GPa,material dense ρ=450kg/m^3,acceptable value of bend strength is 29.6MPa and acceptable value of compression strength is 19.8MPa.

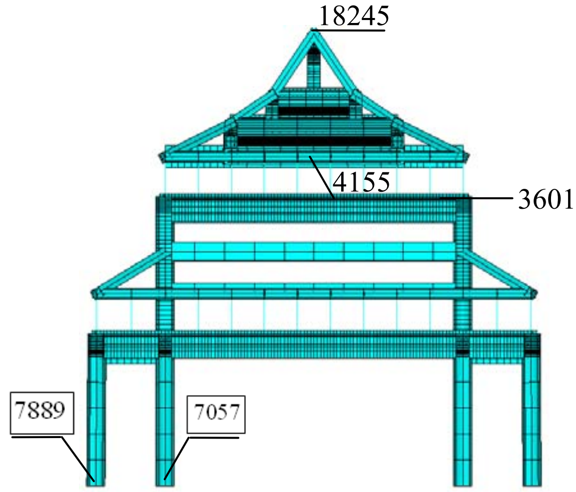
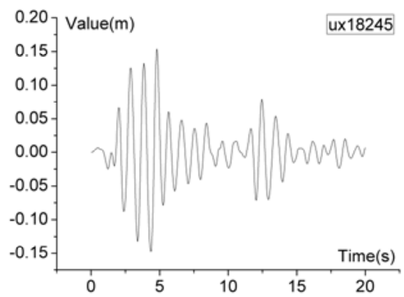
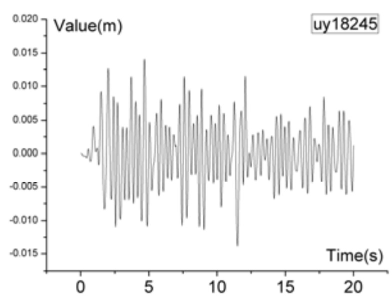


Figure 4 Positions for the selected nodes and elements

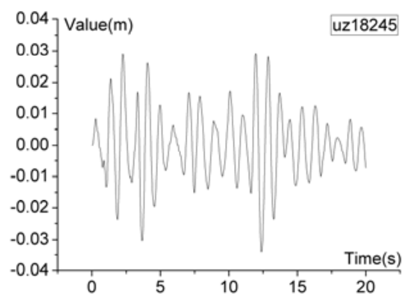
Figure 5 shows the responses of displacement and acceleration of node 18245.The maximum displacement of the node in x direction reaches 0.153m ,while its maximum value of acceleration in x direction reaches 8.5m/s^2,both far exceed the values in other two directions.Besides, the displacement curves indicate that the node vibrates based on the balance location and maintains stable vibrating status.



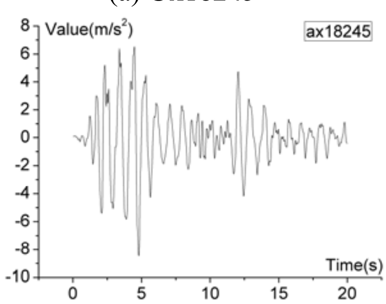
(a) Ux18245



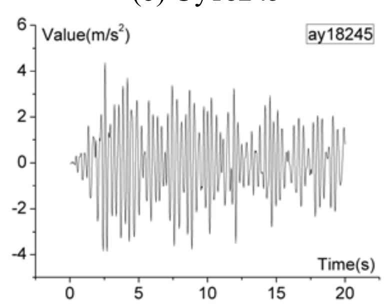
(b) Uy18245



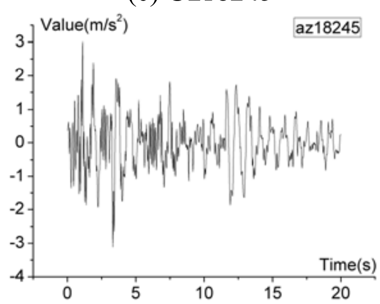
(c) Uz18245



(d) Ax18245



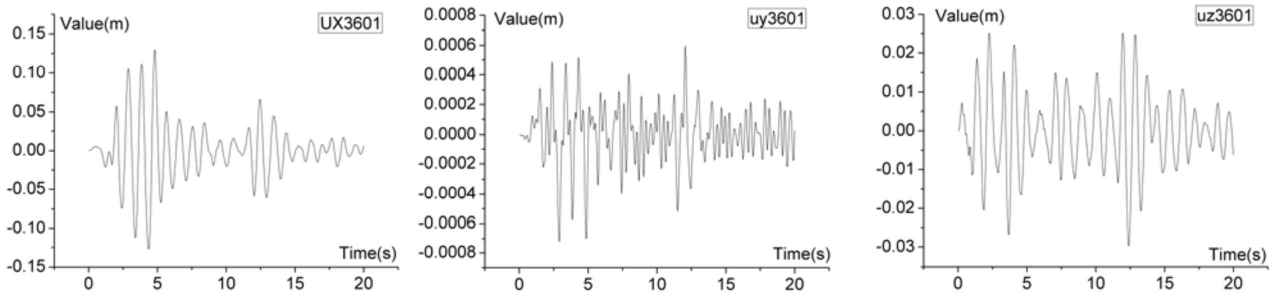
(e) Ay18245



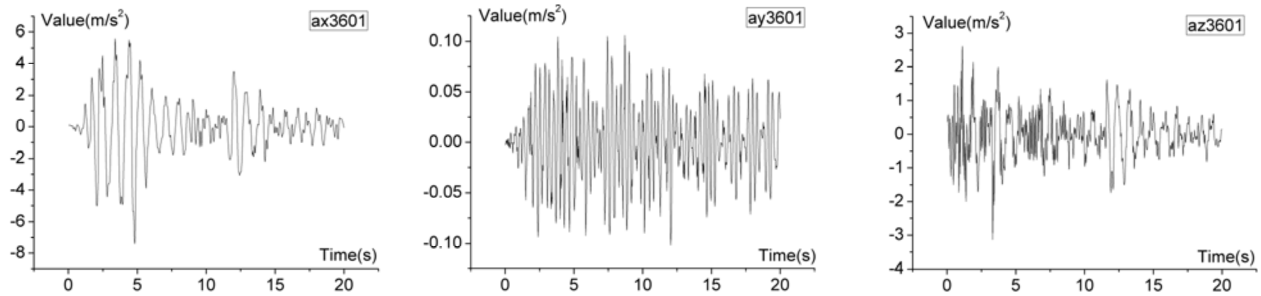
(f) Az18245

Figure 5 Seismic response of node 18245

Figure 6 shows the response curves of displacement and acceleration of node 3601.The peak value in x direction of displacement is 0.138m, of acceleration is 7.1m/s^2,which exceed those of the other two directions,but are lower than those of node 18245 on the roof.Thus the roof position is most easily to be destroyed under seismic forces.



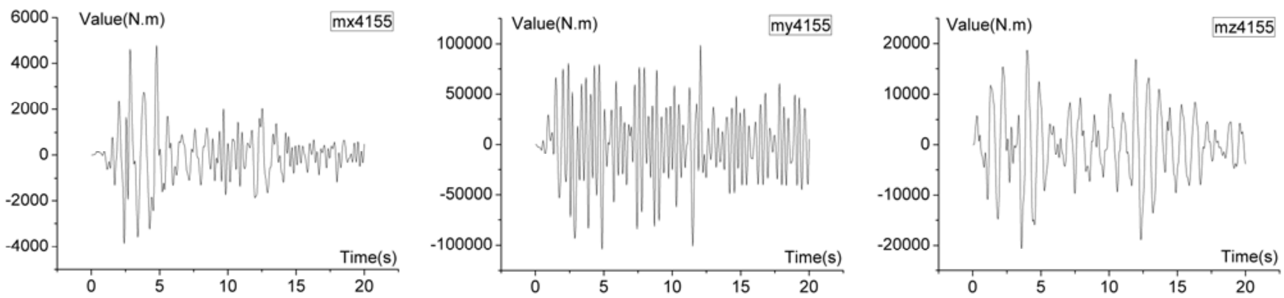
(a) Ux3601 (b) Uy3601 (c) Uz3601



(d) Ax3601 (e) Ay3601 (f) Az3601

Figure 6 Response curves of node 3601

Figure 7 shows moment responses of node 4155.After combination the maximum moment value is obtained as 1.1×10^5 N·m,and the bend stress of bottom beam (Size:870x920mm):0.89MPa< 29.6MPa.



(A) Mx (B) My (C) Mz

Figure 7 Moment response of node 4155

Figure 8 shows the response curves of axial forces of element 7889 and 7057.It is clear that the response of element 7057 far exceeds that of element 7889,whose peak value reaches 286061N,the axial stress (D=750mm)is 0.65MPa<19.8MPa.

(a)F7889 (b)F7057

Figure 8 Response of axial forces

5.CONCLUSION

(1) The base frequency of Shen-Wu Gate is 1.07Hz,its main modes are 1st,2nd and 9th ,none of the main modes has correlation in 3 directions.

(2) Under seismic forces the structure responses with large displacement and acceleration value,but it remains stable vibrating status.Besides,peak value of inner forces of the selected nodes and elements are below the acceptable value.

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