Study on Constitution and Aseismic Character of Shen-Wu Gate in the Forbidden City in China

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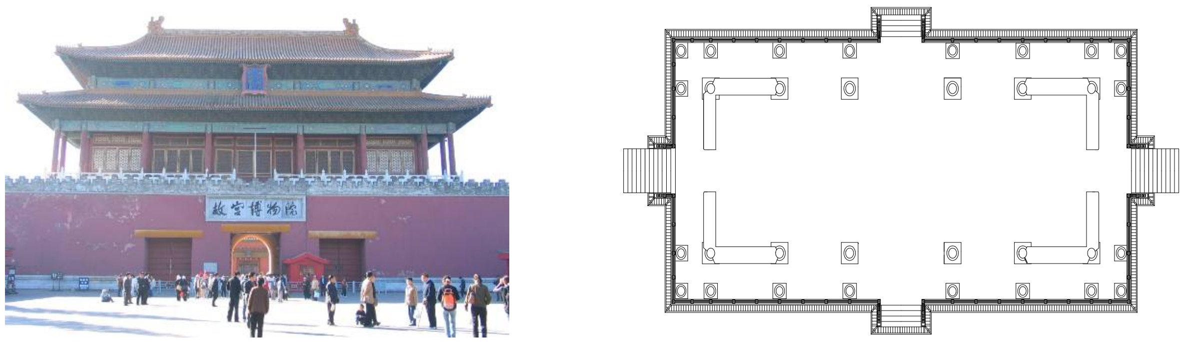
ABSTRACT :
The Shen-Wu Gate in the Forbidden City in China is an ancient wooden building which is composed of base,column,Tou-Kung,Beam Frame and Roof.According to the constitution characters of Shen-Wu Gate,its finite element model is built.According to Chinese Seismic Design Code, response spectrum analysis is applied to appraise its aseismic capacity.Results of displacement and inner forces show that the Shen-Wu Gate can resist 8-degree intensity of seldomly occurred earthquake.

KEYWORDS: Wooden construction,aseismic character,response spectrum analysis,Chinese ancient buildings, Shen-Wu Gate in the Forbidden City

The Shen-Wu Gate in the Forbidden City in China is a 2-storey wooden building which was built in Ming Dynasty(1420 A.D).Its length is 41.74 m,width 12.28 m and height 21.9 m.From plan view it is composed of 4 rows and 8 lines of columns.Its area of structure is 2381m^2.In ancient time there was a big bell in the building for giving the correct time. Elevation photo and plan layout of the building are shown in Figure 1.



(a)Photo (b)Plan view

Figure 1 Shen-Wu Gate in the Forbidden City

Research data shows that for almost 600 years after it was built,the building has experienced earthquakes for 222 times,including 4 times of 8-degree intensity.However,except for some tiles falling down and part filler walls leaning,the main structure remains intact(Jiang,1983). The building is composed of members as following:Base,Beams And Columns,Tou-Kung,Beam Frames and Roof.The aseismic characters of the members will be studied in the following and aseismic capability of the building will be appraised.Results will be helpful for ancient building remedy and protection.

1.ASEISMIC CONSTITUTION

1.1. BASE

There is no survey data about the base of Shen-Wu Gate,but deduced by another building which is similar to it,the base constitution can be obtained as shown in Figure 2(a).Under the layer of clay soil there are round woods,which indicates that the base of Shen-Wu Gate is composed of wood pile and platform.The length of each wood pile is about 2.1m ,each diameter is 0.2m.Pile foundation of Shen-Wu Gate strengthens the soft layer to prevent the building from uneven deposition.Above the wood piles are round wood layer,clay soil layer,lime soil layer and brick layer.It has to be mentioned that the round wood layer provides a sliding face which can absorb vibration.

(a)Base (b)Column (c) Tou-kung (d)Beam Frame (e)Roof

Figure 2 Constitution of Shen-Wu Gate

1.2.Column

The assemblage of the column has to meet the demands of Cejiao and Shengqi ,which is shown in Figure 2(b). Cejiao means a slightly inward incline of the column.Cejiao not only enhance the stability of the structure but also makes the columns bear some horizontal forces. Shengqi means a gradual increase in the height of the columns from the central bay toward the corners of building.Shengqi makes the structure in a suck face which is helpful for the stability and aseismic capability of the structure.

1.3. Tenon-Mortise joints

Beams and columns of the Shen-Wu Gate are connected by Tenon-Mortise joints,which is shown in Figure 2(c).Although Tenon-Mortise connection mode reduces the bearing area of beam and column,their sections are big enough to bear large loads.On the other hand,Tenon-Mortise joints are of semi-rigid joints.During the process that tenon pulled from mortise,the structure produces large displacement,which not only changes the its globality ,but also deallocates the inner forces of the structure itself.Energy dissipation occurs by friction and compression between tenon and mortise,which is just like assembling a damper on the beam and column connection joint to reduce response of earthquake.

1.4. Tou-Kung(Bracket sets)

On top of both outer columns and inner columns there are loops of Tou-Kungs(bracket sets) ,one of which is shown in Figure2(c).A set of Tou-Kung is made up of layers of wood components in both longitudinal and cross directions.Under horizontal seismic forces Tou-Kung absorbs vibration by shearing and sliding among components;While under vertical seismic forces the Tou-Kung oscillates up and down just like a ball and isolates vibrations.

1.5.Beam Frame

Beam Frame of Shen-Wu Gate lies on the top of Tou-Kung.In vertical direction it is composed by different length of beams,as shown in Figure 2(d).In lengthwise direction it is tied by purlins.The height of Beam Frame is low - just 1/4 size of the span,which guarantees the stability of the building under seismic forces(Xue et at.2000).

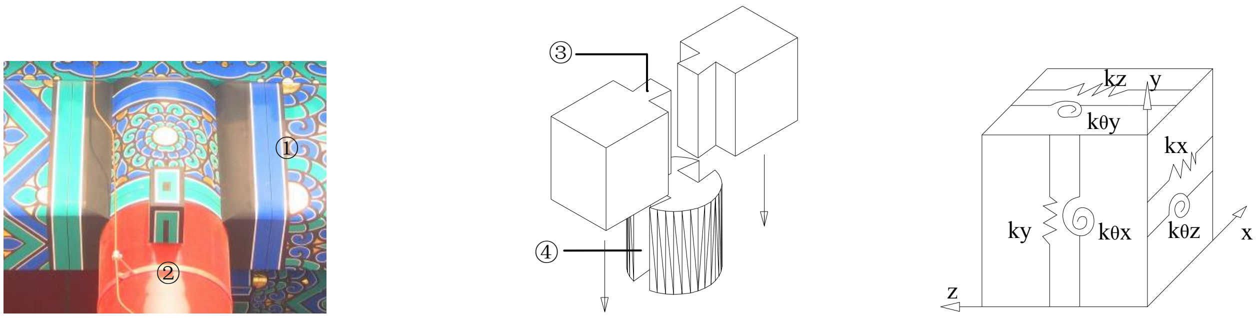
1.6. Roof

The roof of Shen-Wu Gate is heavy,which strengthens the stability as well as entirety of the structure.Besides,the heavy roof is a necessary condition for the shear intensity of column roots.According to its constitution,the roof is made up of roof boarding and rafters,which make the roof a “curve board” with very large stiffness.The photo of roof is shown in Figure 2(e).

2.MECHANICAL MODEL

2.1.Tenon-Mortise Joints

Beams and columns of Shen-Wu Gate are connected by Tenon-Mortise joints(figure 3).Under seismic forces there is energy dissipation of the structure by friction and extrusion between tenon and mortise.The technique of tenon-mortise connection mode is a typical character of Chinese ancient buildings.



(a)Photo (b)Assembling Method (c)Simulating Method

①Beam②Column③Tenon④Mortise

Figure 3 Tenon-Mortise joints

Considering the Tenon-Mortise joint is semi-rigid joint,it can be simulated by a 2-node spring element.The spring element is composed of 6 separate springs which are shown in figure 3(c).The stiffness matrix for the element is shown in equation (1)(Fang et al.2001).where, k_x , k_y and k_z represent stiffness in x,y and z directions,while $k_{\theta x}$, $k_{\theta y}$ and $k_{\theta z}$ represent torsional stiffness round z,x and y axis. The introduction of spring element is just like adding 6 springs on the joint of beam and column.

$$[K]=\begin{bmatrix} K_x & 0 & 0 & 0 & 0 & 0 & -K_x & 0 & 0 & 0 & 0 & 0 \\ 0 & K_{\theta x} & 0 & 0 & 0 & 0 & 0 & -K_{\theta x} & 0 & 0 & 0 & 0 \\ 0 & 0 & K_y & 0 & 0 & 0 & 0 & 0 & -K_y & 0 & 0 & 0 \\ 0 & 0 & 0 & K_{\theta y} & 0 & 0 & 0 & 0 & 0 & -K_{\theta y} & 0 & 0 \\ 0 & 0 & 0 & 0 & K_z & 0 & 0 & 0 & 0 & 0 & -K_z & 0 \\ 0 & 0 & 0 & 0 & 0 & K_{\theta z} & 0 & 0 & 0 & 0 & 0 & -K_{\theta z} \\ -K_x & 0 & 0 & 0 & 0 & 0 & K_x & 0 & 0 & 0 & 0 & 0 \\ 0 & -K_{\theta x} & 0 & 0 & 0 & 0 & 0 & K_{\theta x} & 0 & 0 & 0 & 0 \\ 0 & 0 & -K_y & 0 & 0 & 0 & 0 & 0 & K_y & 0 & 0 & 0 \\ 0 & 0 & 0 & -K_{\theta y} & 0 & 0 & 0 & 0 & 0 & K_{\theta y} & 0 & 0 \\ 0 & 0 & 0 & 0 & -K_z & 0 & 0 & 0 & 0 & 0 & K_z & 0 \\ 0 & 0 & 0 & 0 & 0 & -K_{\theta z} & 0 & 0 & 0 & 0 & 0 & K_{\theta z} \end{bmatrix} \qquad (2.1)$$

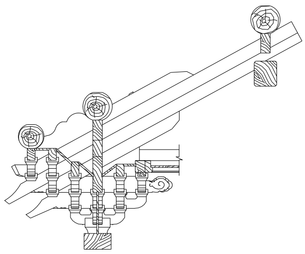
By experimental achievements of Xi’An University of Architechture and Technology(Yao et al.2006;Zhang,2003),stiffness values of the spring element can be obtained as following:

$$K_x = K_z = 1.69\times10^6 N/m\,,\quad K_y = 0\,, K_{\theta x} = K_{\theta y} = K_{\theta z} = 1.5\times10^5 N/m^2 \qquad (2.2)$$

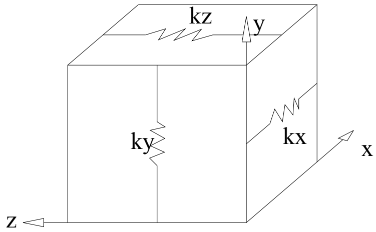
2.2.Tou-Kung

The Tou-Kungs of Shen-Wu Gate lie On the roof ledge position, each is composed of layers of wood components in both longitudinal and cross directions,as shown in Figure(4).Under seismic forces the Tou-Kungs vibrate like springs which produce isolation.

(a)photo



(b)layers of constitution



(c)simulating methods

Figure 4 Tou-Kung

As the Tou-Kung can isolate vibration in x,y and z directions,it can also be simulated by a 2-node spring element,but not like Tenon-Mortise joints,the spring element here does not produce torsion.According to obtained experimental achievements,the stiffness of Tou-Kung can be valued as following(Sui,2006):

$$K_x = K_z = 0.3\times 10^6\, N/m\,, K_y = 5.5\times 10^6\, N/m\,,\quad K_{\theta x} = K_{\theta y} = K_{\theta z} = 0 \tag{2.3}$$

2.4.Finite Element Model

The height of outer column of Shen-Wu Gate is 6.18m,considering the constitution of Cejiao,the column root is moved outside by the size of 0.043m during assemblage.Considering restriction condition of the column roots as ream,finite element model of Shen-Wu Gate is built,as shown in Figure 5,which includes 5091 beam and column elements,671 roof mass elements,160 Tou-Kung elements and 48 Tenon-Mortise joint elements.

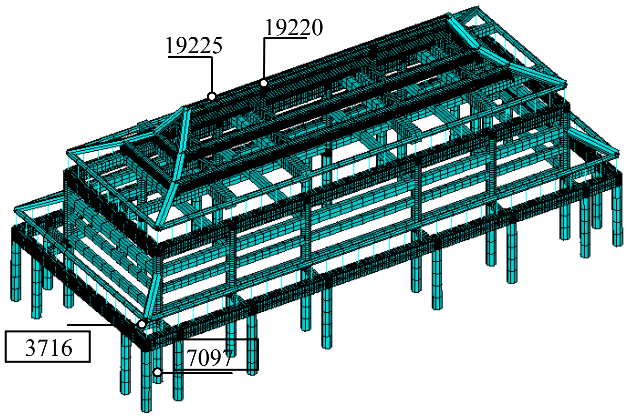


Figure 5 Finite element model of shen-wu gate

3.ASEISMIC ANALYSIS

3.1.Intensity Parameters

An obvious fault of wood material is that its intensity decreases under long-time loading.According to data from Chinese Wood Structure Design Manual,after 10000 days of loading ,the intensity of wood decreases as following:Compression strength parallel to grain:0.5-0.59;Tensile strength parallel to grain:0.5;Bending strength:0.5,Shearing-strength along the grain:0.5-0.55(Jiang,2005).According to survey results,the wood species of Shen-Wu Gate is of phoebe Nanmu,whose normal intensity values have been provided by Chinese Forestry Academy.Their reduced values are listed in Table 1 which will be reference for aseismic capability appraisement in the following.

Table 1 Intensity value of wood(MPa)

	Tensile	compression	shearing	bending
Normal value	74	39.6	7.7	82.3
Reduced value	37	19.8	3.85	29.6

3.2.Spectrum Curve

Spectrum analysis is a substitute method for time-history analysis,which is used for determining displacement and inner forces of the structure under random loads.In engineering curve of seismic influence coefficient α which is corresponding to average response spectrum is often used to calculate seismic forces.The relationship between α and ground absolute acceleration response spectrum is(Shen et at.2000):

$$\alpha(\omega,\xi) = S_a(\omega,\xi)/g \tag{3.1}$$

As the equation for seismic forces is:

$$\{f(t)\} = -[M][\ddot{u}(t) + \{I\}\ddot{u}_g(t)] \tag{3.2}$$

And

$$\sum_{j=1}^{N} \gamma_j \{\phi\}_j = \{I\} \tag{3.3}$$

By equation (3.1)-(3.3),it is obtained that for j mode,the maximum value of seismic force $\{f(t)\}_j$ is:

$$\{F\}_j = [M]\{\phi\}_j \gamma_j \left|\ddot{\delta}_j(t) + \ddot{u}_g(t)\right|_{\max} = [M]\{\phi\}_j \gamma_j S_a(\omega_j,\xi_j) = [M]g\{\phi\}_j \gamma_j \alpha(\omega,\xi) \tag{3.4}$$

In equation (3.4), $[M]$ represents mass matrix of the structure, $\{\phi\}_j$ represents j mode, $\ddot{u}(t)$ represents acceleration of the structure, $\ddot{u}_g(t)$ represents ground acceleration, $\{I\}$ represents unit vector, γ_j represents participation coefficient for j mode, $\ddot{\delta}_j(t)$ reprensent generalized coordinate, ω represents angular frequency, ξ represents damping ratio.

By equation (3.4) the maximum seismic force of each mode can be obtained.Then by static combination the maximum response of the structure will be obtained.

Considering the damping ratio of the structure is $\xi = 0.05$,according to Chinese Seismic Design Code, $\alpha(\omega,\xi)$ can be expressed by the following curve(Xue et at.2007):

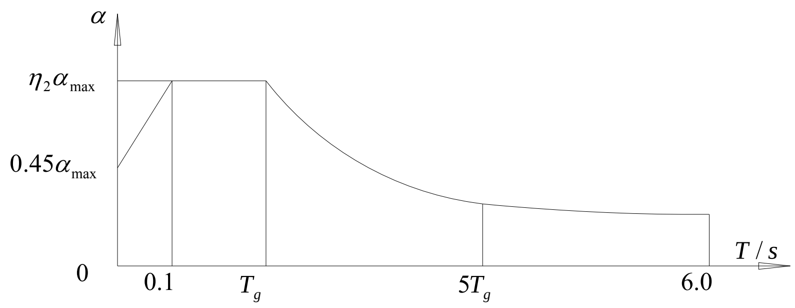


Figure 6 Curve of seismic influence coefficient

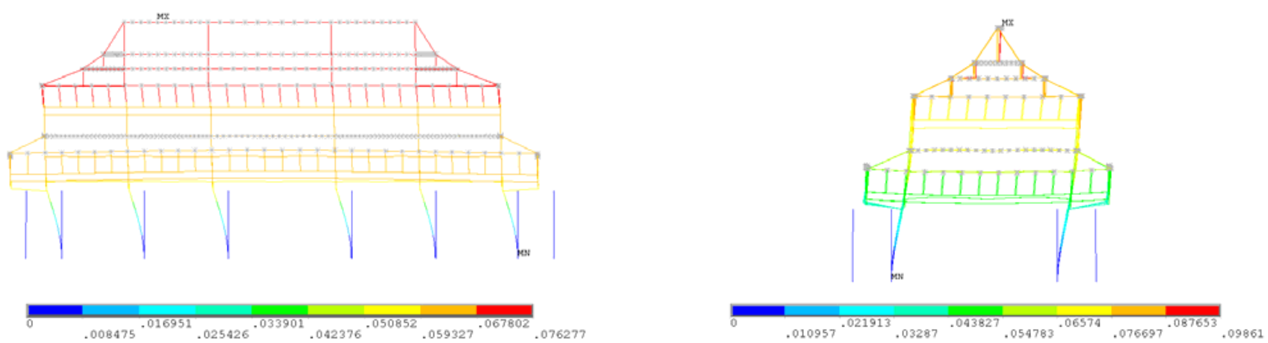
The curve in figure 6 is composed of 4 parts,as shown in the following equation:

$$\alpha = \begin{cases} [0.45 + (10\eta_2 - 4.5)T]\alpha_{max} & (0 \le T < 0.1) \\ \eta_2\alpha_{max} & (0.1 \le T \le T_g) \\ (T_g / T)^{\gamma}\eta_2\alpha_{max} & (T_g < T \le 5T_g) \\ [\eta_2 0.2^{\gamma} - \eta_1(T - 5T_g)]\alpha_{max} & (5T_g < T \le 6.0) \end{cases} \tag{3.5}$$

In equation (3.5), α represents the seismic influence coefficient; T represents the natural period of vibration of the structure; α_{max} represent maximum value of seismic influence coefficient,considering the 8-degree intensity of seldomly occurred earthquake, $\alpha_{max} = 0.9$; T_g represents design characteristic period of the structure,the site classification of the Forbidden City is Ⅲ and design seismic group is Ⅰ,so $T_g = 0.45$; η_2 represents adjustment coefficient of damping, $\eta_2 = 1$; γ represents attenuation index of decrease stage of the curve, $\gamma = 0.9$; η_1 represents adjustment coefficient for slope coefficient of decrease stage, $\eta_1 = 0.02$.

3.3. Spectrum Analysis

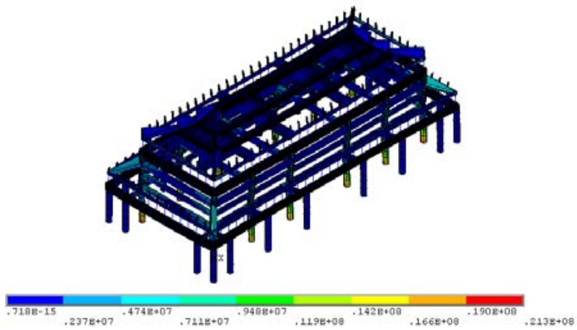
Single-point response spectrums of 8-degree intensity of seldomly occurred earthquake in x and z directions are applied on the Shen-Wu Gate.Results of deformation are shown in figure 7,of inner forces are shown in 8-10,the correspondly positions for maximum inner force and displacement are shown in figure 5.



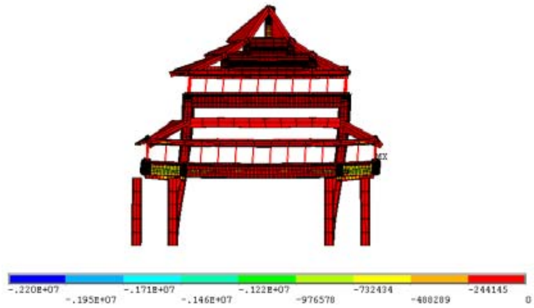
(a)Lengthwise direction (b)Cross direction

Figure 7 Deformation of the structure

From figure 7 it is clear that under level seismic forces the structure produces large deformation,whose maximum value reaches 0.076m in lengthwise direction(node 19225) and 0.099m in cross direction(node 19210).Both values meet the demand of Chinese Wood Design Code(H/120).



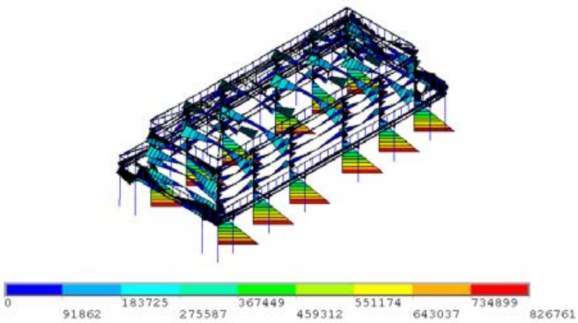
(a)1st principal stress



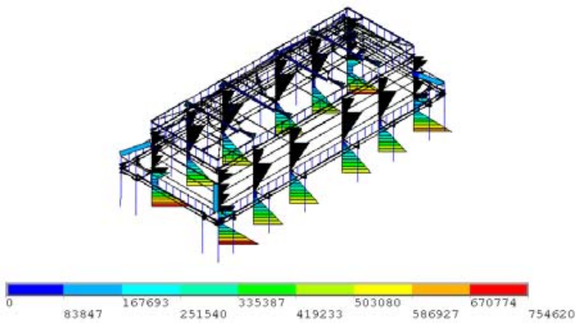
(b)3rd principal stress

Figure 8 Principal stress distribution

From figure 8 it is obtained that the maximum value of 1st principal stress is 21.3MPa<37MPa,the position is at element 7097;The maximum value of 3rd principal stress is 2.2MPa<19.8MPa,which is at element 3716.



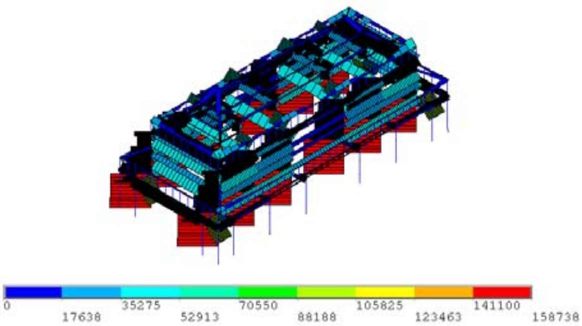
(a) My



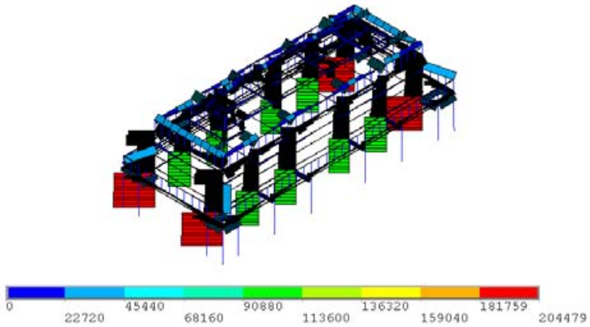
(b)Mz

Figure 9 Flexural torque of the structure

From figure 9 it is obtained that the maximum value of flexural torque round y axis is 8.27x105N·m,round z axis is 7.55 x105N·m.After combination according to Chinese Seismic Design Code,it is obtained that the maximum value is 1.18 x106N·m at element 7097,the accordingly bend stress is 28.5MPa<29.6MPa.



(a)Sfy



(b)Sfz

Figure 10 Shear force distribution of the structure

From figure 10 it is clear that the maximum shear force in y direction is 1.59x105N,in z direction is 2.04 x105N,both positions are at element 7097.After combination according to Chinese Seismic Design Code,maximum value reaches 2.59x105N,the accordingly shear stress is 0.44MPa<3.85MPa.

4.CONCLUSION

(1)The Shen-Wu Gate in the Forbidden City in China has aseismic Constitutions.

(2)Under 8-degree intensity of seldomly occurred earthquake,the Shen-Wu Gate produces large displacement,but as maximum displacement and inner forces are all within the allowance values,the structure will not be destroyed.

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