APPLICATION OF PUSHOVER ANALYSIS ON EARTHQUAKE RESPONSE PREDICATION OF COMPLEX LARGE-SPAN STEEL STRUCTURES

J.R. Qian[1] W.J. Zhang[2] and X.D. Ji[3]

[1] *Professor,* [3] *Postgraduate Student, Key Laboratory for Structural Engineering and Vibration of Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing, China*
[2] *Associate Professor, College of Architecture and Civil Engineering, Beijing University of Technology, Beijing, China*
Email: qianjr@tsinghua.edu.cn zhangweijing@bjut.edu.cn jixd@mails.tsinghua.edu.cn

ABSTRACT :

Pushover analysis has been widely used on earthquake response predication of building structures under severe earthquakes. It needs be studied whether it is applicable for complex large-span steel structures or not. In this paper, pushover analysis of two practical engineering projects, Beijing A380 hangar at Capital Airport and the National Stadium for 2008 Beijing Olympic Games, are introduced. The first mode lateral loading pattern for the hangar structure and twelve cases for the stadium steel structure are adopted to perform the pushover analysis respectively. The pushover analyses results are compared with nonlinear time history analyses results. It is concluded that pushover analysis is applicable for certain types of complex large-span steel structures, providing the total modal mass participation factor is larger than about 0.65.

KEYWORDS: Complex large-span steel structure, Pushover analysis, Beijing A380 hangar, the National Stadium, Earthquake response

1. INTRODUCTION

Pushover analysis has been widely used on predicting response of building structures subjected to severe earthquakes. But it has not been used for complex large-span steel structures. Whether it is applicable for complex large-span steel structures or not, it needs be studied by practical engineering projects. This paper introduces application of pushover analysis of two projects, namely, Beijing A380 hangar at Capital Airport and the National Stadium for 2008 Beijing Olympic Games. The seismic fortification intensity of both structures is 8, and the design basic acceleration of ground motion for both structures is 0.2g.

2. DESCRIPTION OF THE TWO STRUCTURES

2.1. Beijing A380 hangar

Beijing A380 hangar is located at the North of Terminal 3 of Capital International Airport. It is one of the largest hangars in the world. The hangar hall has a length of (176m+176m) and a depth of 110m. The bottom chord elevation is 30m, and the allowable maximum height of the hall is 40m. After performing structure analysis and comparison, a three-layer steel space frame together with a truss at the door-side is adopted for the roof of the hangar hall (Zhu and Pei, et al., 2008). The height of the space frame is 8.0m. Grid is arranged to be the oblique quadrangular pyramid. The grid size of middle chords is 6.0m×6.0m. The roof is supported by the four-leg concrete-filled steel tube columns at three sides of the perimeter and a rectangular hollow reinforced concrete column with section dimension of 5.4m×7.0m at the middle of the door-side. The column space is 12.0m for side walls and 18.0m for rear wall.

2.2. The National Stadium

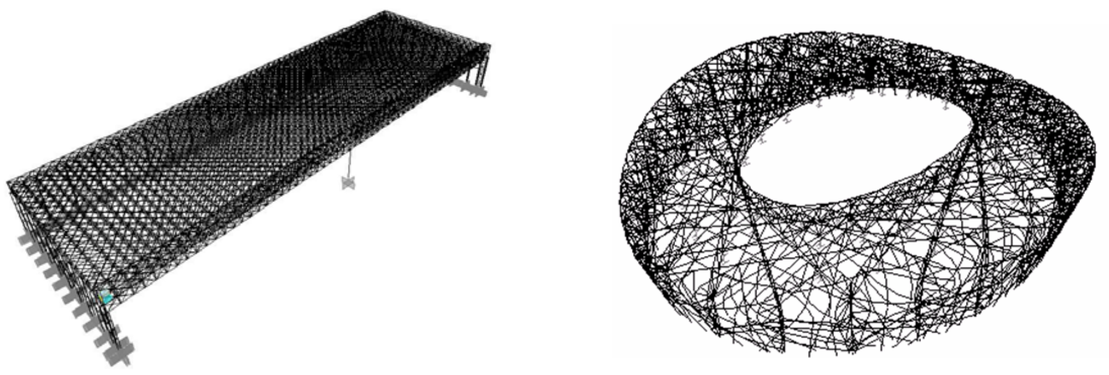
As the main venue for the Beijing 2008 Olympic Games, the National Stadium is composed of a concrete bowl and a steel roof, and these two parts are absolutely independent. The overall architectural form of the steel roof is described as a “bird nest”, with the plan shape of ellipse and the top surface of saddle. In plan, the ellipse is 332.3m in the long axis, and 296.4m in the short axis. The saddle surface which is created by the bi-directional arcs has the height of 68.5m at the peak, and the height of 40.1m in the valley. The middle part of the top surface is a hole with the length of 185.3m and the width of 127.5m (Fan and Liu, et al., 2007).

The steel roof is a complex large-span structure. It can be sub-divided into the primary structure and the secondary structure. The primary structure consists of truss girders and 24 truss columns. The truss girder is comprised of upper chords, lower chords and diagonals. Truss columns are located around the perimeter of the stadium with an equal distance of 37.958m to support truss girders and transfer vertical loads to the foundations. The truss column is comprised of two square columns and a rhombic column, which are connected by diagonals. The secondary structure consists of roof secondary structure and facade secondary structure. Members of the primary structure and the secondary structure are all of fabricated steel rectangular tube sections.

3. METHODLOGY OF PUSHOVER ANALYSIS

3.1. Analytical model

A three-dimensional FE model of each structure is built respectively using SAP2000 software (CSI, 2002). All members are simulated by the beam element. For Beijing A380 hangar, the FE model includes the steel roof structure and its supporting structure. The number of elements is 22533. All columns are fixed on the top of foundation and are pined to the roof space frame structure. For the National Stadium the number of elements is 9522, including 3922 elements of the primary structure and 5600 elements of the secondary structure. Since all connections are formed by welding, they are regarded as rigid connections in the FE model. The bases of truss columns are fixed on the top of pile foundations, so they are assumed to be fixed in the FE model. The bases of other members in the elevation facade are assumed to be pinned. Figure 1 shows the FE models of the two structures.



(a) Beijing A380 hangar (b) The National Stadium

Fig.1 Analytical model of the two structures

3.2 Plastic hinge model and its parameters

Concentrated plastic hinges are employed to represent elasto-plastic behavior of members. The curve of generalized force Q (axial force or bending moment) versus generalized displacement Δ (axial deformation or rotation) of the plastic hinge models is shown in Figure 2.

In calculating of the yield axial force and the yield moment of plastic hinges, the standard value of strength of materials is used, and the influence of local buckling and global buckling of associated members is considered. According to the mechanical behavior of members, two types of plastic hinges are employed, namely, P hinge and P-M-M hinge. The P hinges are assigned at the middle of members which resist mainly axial force, while the P-M-M hinges are assigned at the ends of members which are subjected to axial force and bending moments. Yield surface of P-M-M hinge is obtained through the linear combination of axial force and bending moments as shown in Figure 3, which follows the statement in “Code for Design of Steel Structures” (GB50017-2003). Parameters of hinge plastics are defined and values refer to Table 5-6 and Table 5-7 in FEMA 356 (ASCE,2000).

Based on the elastic analysis results and the importance of structure members, in total 1106 plastic hinges are assigned to certain members of the steel roof frame and to all columns for A380 hanger, and 9037 plastic hinges are assigned to members of the National Stadium.

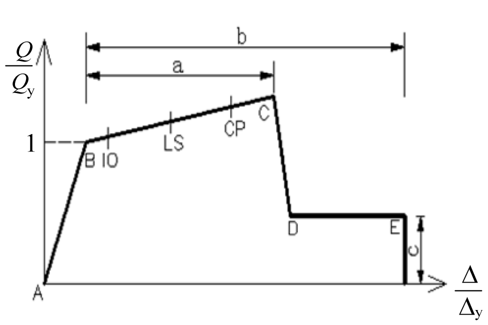


Fig.2 Generalized force-generalized displacement relationship curve of plastic hinges

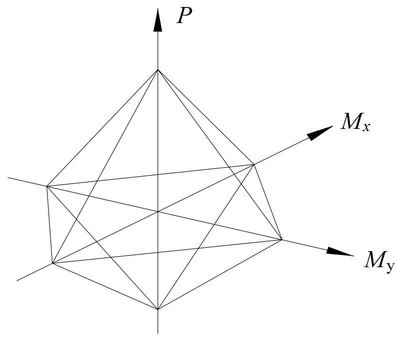


Fig.3 Sketch of yield surface of P-M-M hinges

3.3. Determination of performance point

Prior to pushover analysis, static analysis of A380 hangar under the vertical load and nonlinear stage construction analysis of the stadium is performed, respectively. P-Δ effect is automatically taken into account by software SAP2000 in the construction analysis and pushover analysis. By pushover analysis the capacity curves of two structures are obtained. Then the capacity curves are transformed to the capacity spectrum curves. The elastic acceleration response spectrum curve (S_a versus T) for severe earthquakes can be obtained from “Code for Seismic Design of Buildings” (GB50011-2001). The elastic acceleration response spectrum curve can be transformed into demand spectrum curve (S_a versus S_d) (ATC, 1996) for both structures. Then the capacity spectrum curve is superimposed on the demand spectrum curve and the intersection point is considered to be the performance point. From values of S_a and S_d of performance point, responses of the structure under severe earthquakes are obtained.

4. PUSHOVER ANALYSES RESULTS

4.1. Beijing A380 hangar

Pushover analysis of A380 hangar is performed in x direction (the long direction in plan) and in y direction (the short direction in plan), the first mode shape of x and y direction is taken for the lateral load pattern, respectively. For A380 hangar most of weight is contributed by the steel frame roof. The first modal mass participation factor is 0.88 and 0.64 for x and y direction respectively. The damping ratio of the structure is taken as 3.5% to establish the response spectrum for severe earthquakes. Determination of performance point of A380 hangar is shown in Figure 4. From the figure, it can be seen that the structure is elastic in general under severe earthquakes. Response values are listed in Table 1.

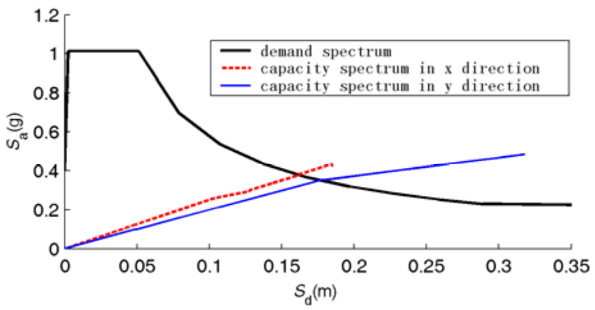


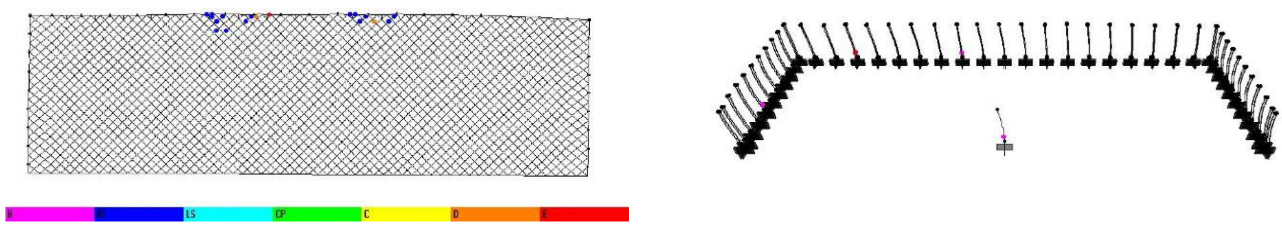
Fig.4 Determination of performance point for A380 hanger

Table 1 Response of A380 hanger under severe earthquakes

Direction	Performance point		Lateral displacement				Base shear			
	S_d/m	S_a /g	$(\Delta_c)_{max}$ /m		$(\Delta_c)_{max}$ /H		F/kN		F/W	
			Pushover	Dynamic	Pushover	Dynamic	Pushover	Dynamic	Pushover	Dynamic
x	0.1618	0.378	0.168	0.132	1/185	1/235	63350	50184	0.332	0.263
y	0.1772	0.351	0.200	0.155	1/155	1/200	42907	38735	0.225	0.203

Notes: S_d and S_a are spectrum displacement and spectrum acceleration respectively, $(\Delta_c)_{max}$ is the maximum displacement at the column top, H is the height of column, F is the base shear, W is the representative value of gravity loads, "Pushover" means the results of pushover analysis, "Dynamic" means the average of the maximum response of non-linear time history analysis.

Figure 5 shows plastic hinge distribution of bottom chords of the steel frame and plastic hinge distribution at columns from pushover analysis in x direction. Plastic hinges also appear at the top chords of the steel frame. Several concrete-filled steel tube columns and the reinforced concrete column yield. In y direction the plastic hinges are mainly formed at the bottom chords of the steel frame near the concrete column. All the hinges are in the phase of B-IO, means the member need not be repaired after earthquakes.



(a) Plastic hinges at the bottom chords of the steel frame (b) Plastic hinges at columns

Fig.5 Plastic hinge distribution diagram from pushover analysis in x direction

4.2 The Nation Stadium

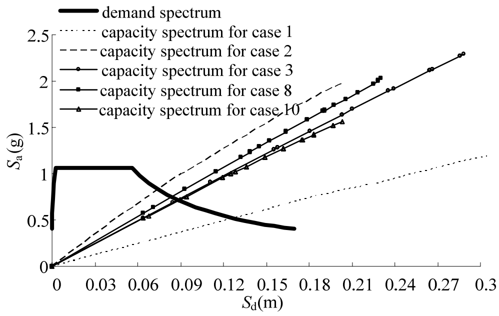
12 pushover analysis cases, as listed in Table 2, are performed. The modal pushover analysis (Chopra and Goel, 2002, 2004) is performed through the SRSS combination of the effects of case 1 and case 2.

Table 2 Loading direction and pattern for each pushover analysis case

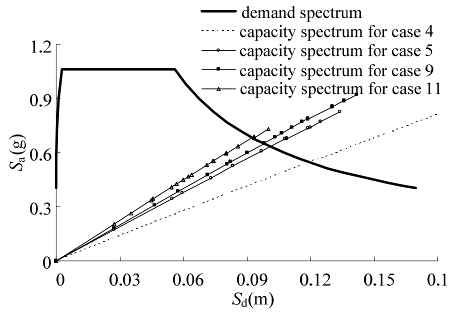
Analysis case	Loading direction	Loading pattern
1	x	The first mode shape in the x direction
2	x	The second mode shape in the x direction
3	x	Acceleration load
4	y	The first mode shape in the y direction
5	y	Acceleration load

6	*z*	The first mode shape in the *z* direction
7	*z*	Acceleration load
8	*x* and *y*	Acceleration load (a_x:a_y=1:0.85)
9	*x* and *y*	Acceleration load (a_x:a_y =0.85:1)
10	*x*, *y* and *z*	Acceleration load (a_x: a_y : a_z =1:0.85:0.65)
11	*x*, *y* and *z*	Acceleration load (a_x: a_y : a_z =0.85:1:0.65)
12	*x*	Modal pushover analysis

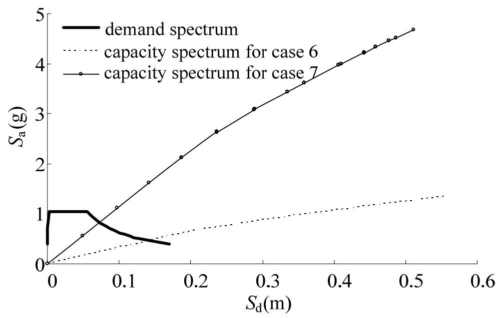
The damping ratio of the stadium is taken as 3% to establish the response spectrum for severe earthquakes. The performance point for each analysis case is obtained from Figure 6. The main results from pushover analysis of the stadium under severe earthquakes are listed in Table 3.



(a) In *x* direction



(b) In *y* direction



(c) In *z* direction

Fig.6 Determination of performance point for the stadium

Table 3 Response of the National Stadium under severe earthquakes by pushover analysis

Analysis case	Performance point		Displacement of control node		Base reaction force	
	S_d (m)	S_a (g)	Δ (m)	Δ/*H* or Δ/*L*	*F* (kN)	*F*/*W*
1	0.1280	0.516	0.0664	1/614	80237	0.172
2	0.0742	0.829	0.0508	1/802	165808	0.352
3	0.0880	0.715	0.0457	1/892	117004	0.236
4	0.1191	0.550	0.1448	1/463	178753	0.379
5	0.1005	0.635	0.1222	1/549	217265	0.438
6	0.1410	0.462	0.1442	1/437(1/134)	62432	0.132
7	0.0727	0.825	0.0744	1/849(1/157)	111486	0.237
8	0.0837	0.745	0.0434	1/887	115846	0.246
9	0.0980	0.652	0.1192	1/563	211980	0.450
10	0.0890	0.712	0.0462	1/882	116512	0.235
11	0.0933	0.683	0.1135	1/592	233688	0.471
12	—	—	0.0836	1/487	184202	0.392

Notes: H is the height of control node, L is the overhanging span of control point, Δ/L for case 6 and 7 is only calculated by vertical pushover analysis; values in the brackets are calculated by combination of gravity loads and vertical pushover analysis; vertical reaction weight ratio does not include the proportion produced by gravity loads.

For all analysis cases, the amount of plastic hinges and corresponding percentage are listed in Table 4. Most of plastic hinges are in the phase of B-IO or IO-LF. The amount of plastic hinges formed in the 11th analysis case is the maximum among the 12 analysis cases, and they are shown in Figure 7.

Table 4 Statistics of plastic hinges obtained by pushover analyses

Analysis case	Primary structure		Secondary structure	
	Number	Percentage (%)	Number	Percentage (%)
1	—	—	15(2)	0.29
2	15	0.38	18(2)	0.32
3	—	—	1	0.018
4	—	—	90(6)	1.61
5	—	—	74(5)	1.32
6	12	0.31	3	0.054
7	—	—	—	—
8	—	—	11(1)	0.20
9	2	0.051	136(6)	2.43
10	—	—	10(1)	0.18
11	12	0.31	233(9)	4.16

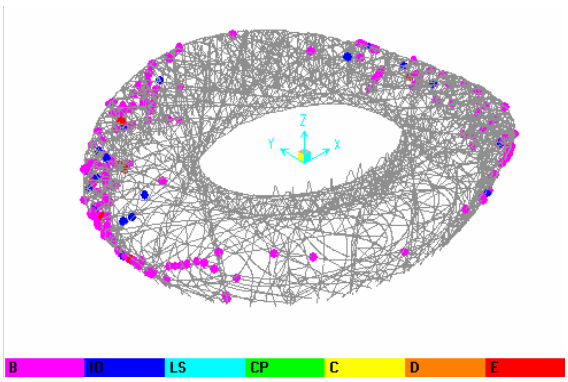


Fig.7 Plastic hinge location for pushover analysis case 11

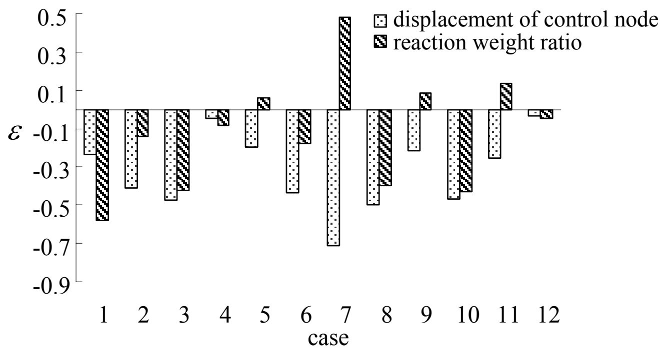


Fig.9 Relative errors between results of pushover analysis and dynamic analysis

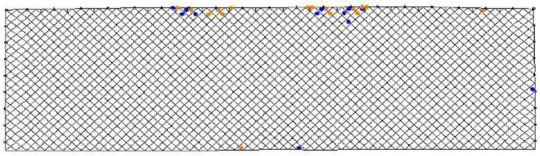
5. COMPARISON BETWEEN RESULTS OF PUSHOVER ANALYSIS AND DYNAMIC ANALYSIS

To examine pushover analyses results, non-linear time history analysis of both structures is performed. The ground motion selected is 3 sets of three-dimensional earthquake records for the hangar, and 4 sets of three-dimensional earthquake records and 1 set of artificial wave for the stadium. The peak acceleration is adjusted to 0.4g for the main input horizontal direction, and it is adjusted to 0.85×0.4g for another horizontal direction and to 0.65×0.4g for the vertical direction. The damping ratio is 3.5% and 3% for the hangar and the stadium, respectively.

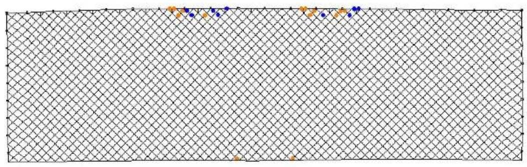
5.1 Beijing A380 hangar

The average values of the peak responses under three sets of earthquake records are listed in Table 1. The dynamic responses are about 20% smaller than the pushover analysis results. Plastic hinges distribution at the bottom chords of the steel frame under Corralit earthquake record, Lwd-Del earthquake record and Tianjin

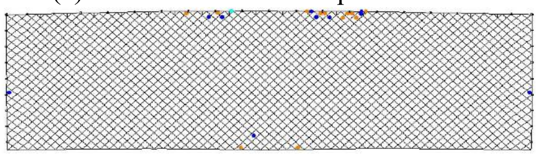
Hospital record are shown in Figure 8. The distribution of plastic hinges is almost the same as that of pushover analysis results. General speaking, the results of pushover analysis and non-linear time history analysis are close.



(a) Under Corralit earthquake record



(b) Under Lwd-Del earthquake record



(c) Under Tianjin Hospital record

Fig.8 Plastic hinge distribution diagram of bottom chord members under severe earthquakes

5.2 The National Stadium

Results of pushover analysis are compared with those of non-linear time history analysis, as shown in Figure 9. In the figure, ε of y-axis denotes relative errors of earthquake responses for each pushover analysis case comparing with the average of peak responses of all non-linear time history analyses. Figure 9 indicates that (1) for the cases of acceleration load, displacement of control node obtained by pushover analysis is much smaller than the average of non-linear time history analysis, and the averages of relative errors in the x, y and z directions are -47.8%, -22.3% and -71.0%, respectively; base shear (reaction) weight ratios by these two methods also have considerable discrepancy, and the averages of relative errors in the x, y and z directions are -41.7%, 9.4% and 48.1%, respectively. (2) the results of case 4 (lateral forces are proportional to the production of mass and the first modal shape in y direction) and case 12 (the modal pushover analysis in x direction) are in good agreement with the results of dynamic analysis; relative errors of displacement of control node are -3.2% and -4.9%, respectively, and relative errors of base shear are -4.4% and -8.5%, respectively. The total modal mass participation factor of the first two modes in x direction is 0.754, and the modal mass participation factor of the first mode in y direction is 0.69. (3) For case 6 (forces are proportional to the production of mass and the first modal shape in z direction) the responses are far smaller than the average of non-linear time history analyses. The modal mass participation factor of the first mode in z direction is only 0.287. For most of large-span space structure, modes in the vertical direction are considerably dense, and the total modal mass participation factor of combined modes is difficult to reach a large value. Therefore, the modal pushover analysis in the vertical direction may be not applicable.

6. CONCLUSIONS

This research investigation of pushover analysis of two complex large-span steel structures has led to the following conclusions.

1) Pushover analyses results of the two complex large-span steel structures, namely, Beijing A380 hangar and the National Stadium indicate that plastic hinges appear at few members and the whole structure is within elastic under severe earthquakes.

2) For certain types of complex large-span steel structure, when the total modal mass participation factor is larger than about 0.65, results of pushover analysis will be close to those of dynamic analysis. In this case, pushover analysis appears to be accurate for predicating responses of complex large-span steel structures under severe

earthquakes.

3) For complex larger-span steel structures with huge numbers of members, pushover analysis has high efficiency to find out the weak part of the structure, while non-linear time history analysis is time consuming.

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REFERENCES

American Society of Civil Engineers (2000). Pre-Standard and Commentary for the Seismic Rehabilitation of Buildings. FEMA-356, Washington D.C.: Federal Emergency Management Agency.

Chopra A.K. and Goel R(2002). A modal pushover analysis procedure for estimating seismic demands for buildings. *Earthquake Engineering and Structural Dynamics*, **31:5**, 561-582.

Chopra A.K. and Goel R(2004). A modal pushover analysis procedure to estimate seismic demands for un-symmetric-plan buildings. *Earthquake Engineering and Structural Dynamics*, **33:8**, 903-927.

GB50017-2003(2003). Code for Design of Steel Structures. China Architecture & Building Press, Beijing.

GB 50011-2001(2001).Code for Seismic Design of Buildings. China Architecture & Building Press, Beijing.

Computer and Structures Inc. (2002). SAP2000 Three Dimensional Static and Dynamic Finite Element Analysis and Design of Structures: Analysis Reference, Computer and Structures, Inc., Berkeley.

Fan Z., Liu X.M. and Fan X.W., et al. (2007). Design and research of large-span steel structure for the National Stadium. *Journal of Building Structures*, **28:2**,1-16.

Applied Technology Council (1996). Seismic Evaluation and Retrofit of Concrete Buildings. ATC 40, Redwood City, California.

Zhu D., Pei Y. ZH., Xu R., et al. (2008). Design and research on the long-span structure of Beijing A380 hangar. *China Civil Engineering Journal*, **41:2**, 1-8.