

# **Application of pushover analysis in estimating seismic demands for large-span spatial structure**

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## **Abstract**

Pushover analysis has been widely adopted in the seismic analysis of low- and medium-rise structures. It needs to be studied whether it is accurate for large-span spatial structure. In this paper, pushover analysis of a large-span spatial structure, Beijing A380 hangar structure at Capital International Airport is introduced. The modal load pattern is adopted to perform pushover analysis for the hangar structure. The pushover analysis results are compared with nonlinear response history analysis results. It is concluded that pushover analysis is accurate enough for large-span spatial structure, provided the modal participating mass ratio is larger than about 0.65.

**Keywords:** pushover analysis, nonlinear response history analysis, large-span spatial structure, Beijing A380 hangar, earthquake response

## **1. Introduction**

Estimating seismic demands at low performance levels, such as life safety and collapse prevention, requires explicit consideration of inelastic behavior of the structure. While nonlinear response history analysis (NLRHA) is the most rigorous procedure to compute seismic demands, it is impractical for routine use. It is now common to estimate seismic demands in a simplified manner by nonlinear static analysis or pushover analysis, which seems to be the preferred method in structural engineering practice[1]. Pushover analysis has been widely adopted in the seismic analysis of low- and medium-rise structures, however, few research references about pushover analysis of the long-span spatial structures have been reported till now [2]. Whether it is accurate for large-span spatial structure, it needs to be studied by practical engineering projects. This paper introduces the application of pushover analysis of Beijing A380 hangar structure at Capital International Airport. The results produced by pushover analysis are compared with the associated ones produced by NLRHA.

## **2. Description of the structure**

### 2.1. Structural model

Beijing A380 hangar is located near 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[3], a tri-layer steel space frame and a front truss are adopted for the roof structure (Fig.1). The height of the space frame is 8.0m and the height of the front truss is 11.5m. Grid is arranged to be oblique quadrangular pyramid. The middle chord grid size is 6.0m×6.0m. Steel tube filled concrete columns are used for the supporting structure. The column space is 12.0m for side walls and 18.0m for rear wall. A rectangular hollow reinforced concrete column with section dimensions of 5400mm×7000mm is adopted at the middle of the front side. The seismic fortification intensity of the structure is 8, the design basic acceleration of ground motion for the structure is 0.2g.

Three-dimensional modeling of the hangar structure is performed using SAP2000 program. All members are simulated by the beam element. The FE model includes the steel roof structure and its supporting structure. The total number of elements is 22533. All columns are fixed on the top of foundation and are pinned to the roof space frame structure.

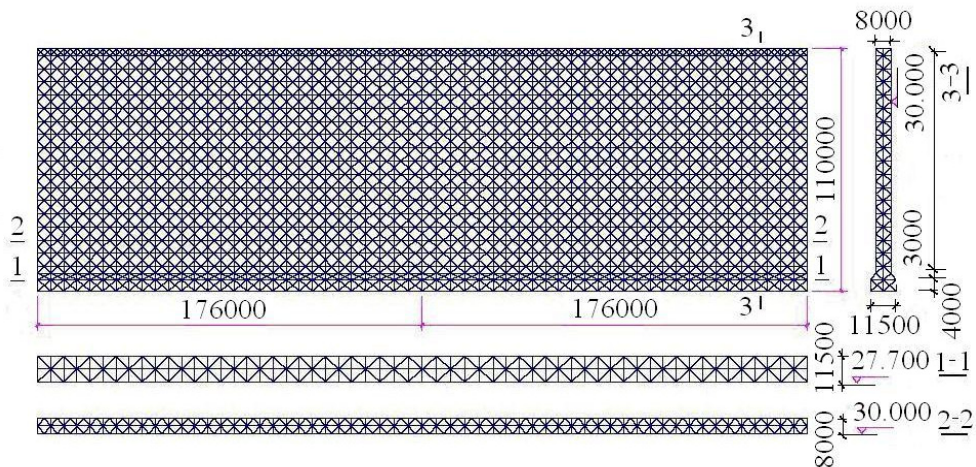


Figure1 Structural scheme for Beijing A380 hangar roof

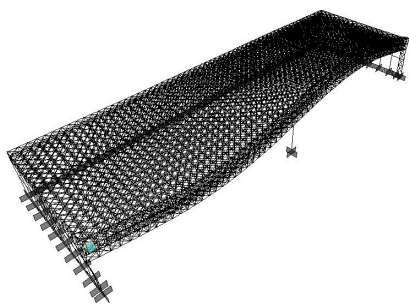
### 2.2. Free vibration behavior

The first step in earthquake analysis must always be the solution of the free vibration problem. This is necessary to get a first important insight into structural dynamic properties. The first five modes of the hangar structure are presented in Table 1. As can be seen, the frequencies of the hangar are dense. In addition, two and above vibrations are contained in the most shapes (see Figure 2). The fundamental vibration mode is vertical deformation, the

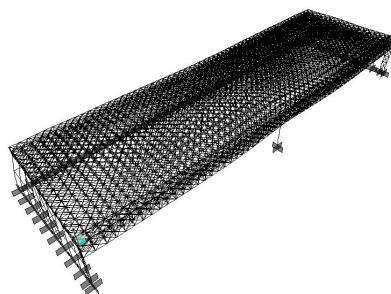
second and third modes are primary horizontal deformations and is the first mode in y direction (the short direction in plan) and the first mode in x direction (the long direction in plan), respectively.

Table 1. Modal periods and frequencies of the hangar

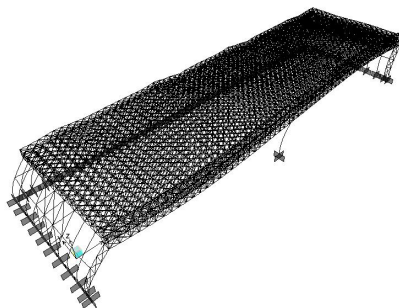
Mode	Period $T/s$	Circular frequency $\omega/\text{rad}$	Cyclic frequency $f/\text{Hz}$
1	1.5904	3.9507	0.6288
2	1.3097	4.7976	0.7636
3	1.1594	5.4193	0.8625
4	1.1324	5.5485	0.8831
5	0.9333	6.7323	1.0715



(a) Mode 1



(b) Mode 2



(c) Mode 3

Figure 2. Mode shapes of first three modes of the hangar structure

### 3. Methodology of pushover analysis

#### 3.1 Plastic hinge model and its parameters

Concentrated plastic hinges are employed to represent elasto-plastic behaviors of members. The curve of generalized force  $Q$  (axial force or bending moment) versus generalized displacement  $\Delta$  (axial deformation or rotation) of the plastic hinge models is shown in Figure 3.

In calculating of the yield axial force and 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. Default hinge properties which based on FEMA 356[4] criteria are used for the P hinge, Interaction surface of P-M-M hinge are defined through the combination of axial force and bending moments as shown in Figure 4, which followed the statement in “Code for Design of Steel Structures” GB50017-2003[5]. Parameters of P-M-M hinges are defined according to Table 5-6 and Table 5-7 in FEMA 356.

Based on the elastic analysis results and the importance of structure members, 1106 plastic hinges are assigned to some members of the steel roof frame structure and to all members of the supporting structure.

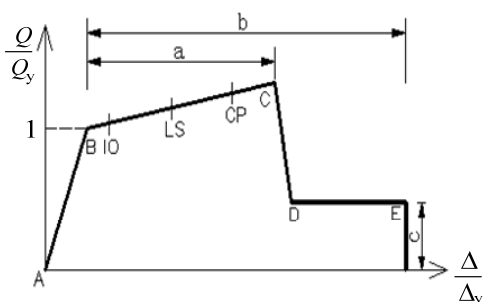


Figure 3 General force-general displacement relationship curve of plastic hinges

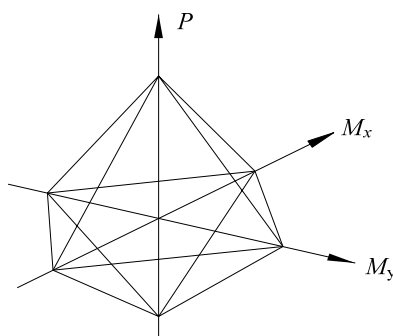


Figure 4 Sketch of yield surface of P-M-M hinges

#### 3.2 Determination of Performance Point

Prior to the pushover analysis, static analysis of the structure under vertical loads is performed. P- $\delta$  effects are taken into account. By pushover analysis the capacity curve of the structure is obtained. Then the capacity curve is converted to the capacity spectrum curve. The elastic acceleration response spectrum curve (spectrum acceleration  $S_a$  versus period  $T$ ) for severe earthquakes can be obtained from “Code for Seismic Design of Buildings” GB50011-2001[6]. The elastic acceleration response spectrum curve is

converted to demand spectrum curve (spectrum acceleration  $S_a$  versus spectrum displacement  $S_d$ ) [7]. 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. Analysis results

### 4.1 Pushover analysis results

Pushover analysis of A380 hangar is performed in both x and y direction. The modal load pattern is adopted under displacement control in the pushover analysis. Modal load is a pattern of forces on the joints that is proportional to the product of a specified mode shape times its circular frequency squared ( $\omega^2$ ) times the mass tributary to the joint. The first mode shape in x and y direction is taken for the lateral load pattern and the modal participating mass factor is 0.88 and 0.64, 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 Fig.5. From the figure, it can be seen that the structure is almost in elastic under severe earthquakes. Response values are listed in Table 2.

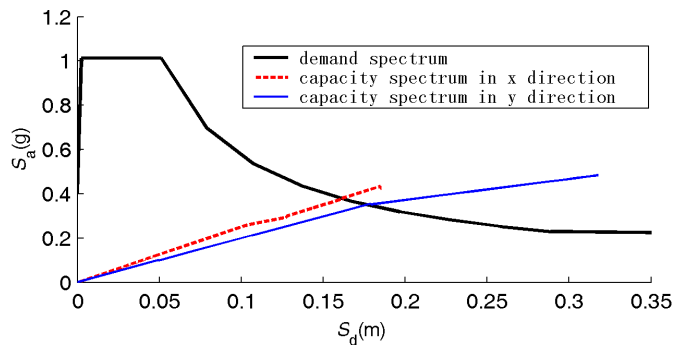


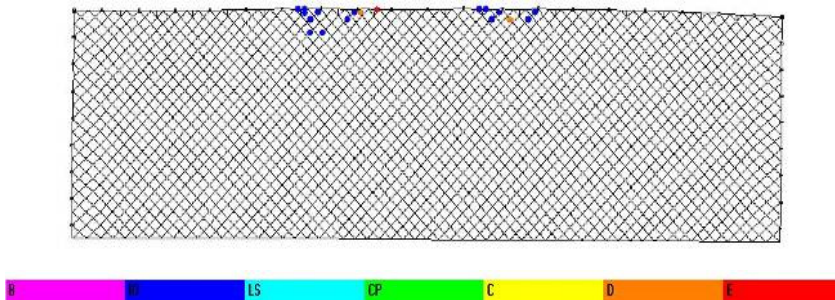
Figure 5. Determination of performance point for A380 hangar

Table 2. Response of A380 Hangar under Severe Earthquake Motions

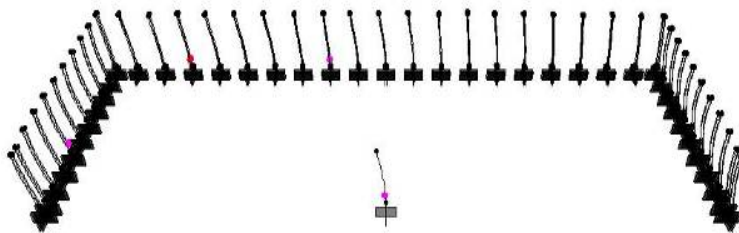
Direction	Performance point		Lateral displacement				Base shear force			
	$S_d/m$	$S_a/g$	$(\Delta_c)_{max}/m$		$(\Delta_c)_{max}/H$		$F/kN$		$F/W$	
			Pushover	Dynamic	Pushover	Dynamic	Pushover	Dynamic	Pushover	Dynamic
x	0.1618	0.378	0.168	0.132	1/185	1/235	63350	50184	0.332	0.263
y	0.1772	0.351	0.200	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 top,  $F$  is the base shear force,  $W$  is the representative value of gravity loads, “Pushover” means the results of pushover analysis, “Dynamic” means the average of the maximum response under three sets of earthquake records.

Figure 6 shows plastic hinge locations at the bottom chords of the steel frame and plastic hinge locations at the columns from pushover analysis in  $x$  direction. Plastic hinges also appear in 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

Figure 6. Plastic hinge locations from pushover analysis in  $x$  direction

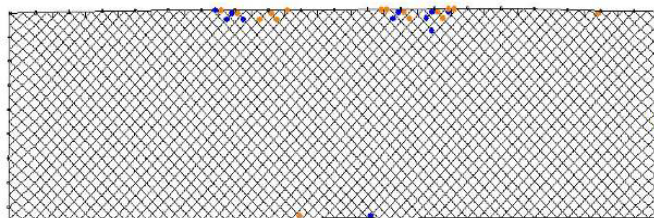
#### 4.2 Comparison with dynamic analysis results

To examine pushover analyses results, non-linear response history analysis of the hangar structure is performed. Three sets of three-dimensional earthquake motions have been used.

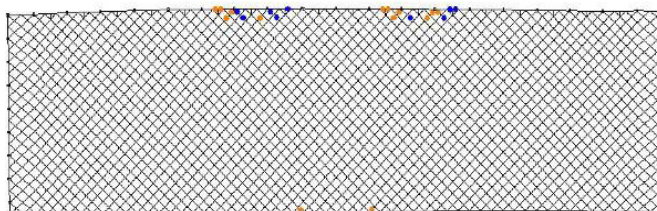


They are Corralit earthquake motion, Lwd-Del earthquake motion and Tianjin Hospital motion. The peak acceleration is scaled up to 0.4g for the main input horizontal direction, and it is scaled up to  $0.85 \times 0.4g$  for another horizontal direction and to  $0.65 \times 0.4g$  for the vertical direction. The damping ratio of 3.5% is adopted.

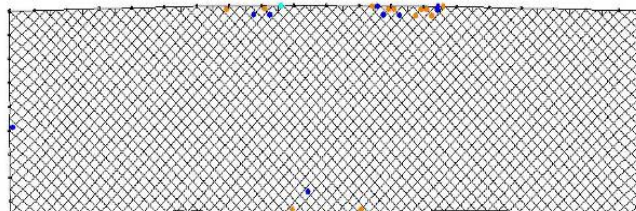
The average values of the peak responses under three sets of earthquake motions are listed in Table 2. The pushover analysis results are about 20% larger than those of dynamic analysis. Plastic hinge locations at the bottom chords of the steel frame due to Corralit earthquake motion, Lwd-Del earthquake motion and Tianjin Hospital motion are shown in Figure 7. The locations of plastic hinges are almost the same as those of pushover analysis results. General speaking, the results of pushover analysis and non-linear response history analysis are close.



(a) Under Corralit earthquake motion



(b) Under Lwd-Del earthquake motion



(c) Under Tianjin hospital motion

Figure 7. Plastic hinge locations at bottom chords due to strong earthquake motions

## 5. Conclusions

This investigation aimed to study accuracy of pushover analysis of large-span spatial structure, it has led to the following conclusions:

- 1) Pushover analysis results of Beijing A380 hangar indicate that plastic hinges would appear at few members and the whole structure remains essentially elastic under severe earthquakes.
- 2) When the modal participating mass factor is larger than approximately 0.65, the pushover method may lead to results in good agreement with those obtained by dynamic analyses.
- 3) For complex larger-span structures with huge numbers of members, pushover analysis has high efficiency to find out the weak part of the structure, while non-linear response history analysis takes a great deal of time.

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