Shaking Table Test and Numerical Analysis on Terminal Building 2 in Pudong International Airport

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ABSTRACT :

The seismic performance of terminal building 2 in Pudong international airport subjected to various earthquake inputs was investigated. A 1:35 scaled model structure was built and tested in the shaking table using a series of horizontal and vertical motions with gradually increasing amplitude. In addition, a 3D finite element analysis was carried out to gain a better understanding of the structural behavior. The model responses and numerical analysis showed that the building can sustain relatively high dynamic excitations without severe damage.

KEYWORDS: Hybrid structure, scaled model, shaking table test, seismic performance

1. INTRODUCTION

Pudong International Airport, Shanghai, China has total floor area of 400 thousand square meters and constitutes a terminal building, a boarding hall and mass transit stations (Figure 1). Terminal building 2 consist of 25 planar frames with 18m spacing. 3 hybrid columns (in 0/1A, A and G axis) and 1 pin-pin supported steel column (in K axis) serve as horizontal resistance together with beam string system. In addition, it is a hybrid structure, in which the Upper steel roof and lower RC frame are assembled with Y-shaped hybrid columns. Terminal building 2 could be classified as a vertically irregular structure due to SRC column, Y-shaped steel column and steel roof along the height. The unique design of its RC frame and Y-shaped steel column make it become an exceptional structure. Up to now, no Chinese Design Code can be applied efficiently to this type of structure.

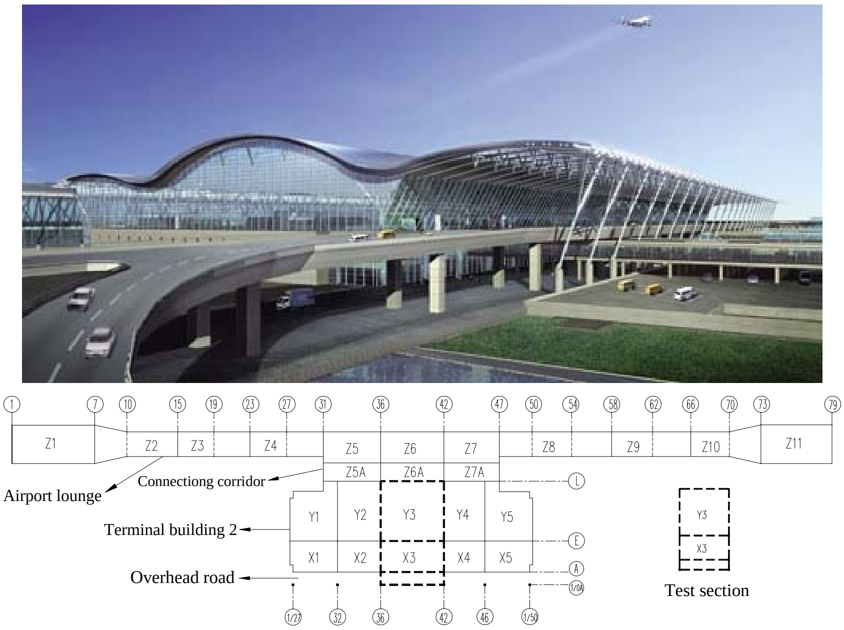

Figure 1 Panorama of Pudong international airport and illustration for test section

Thus, it is significant to completely understand the overall structural behavior under moderate and strong earthquakes when designing this structure. In this regard, shaking table model test plays an important role in obtaining the overall dynamic characteristics, seismic responses and failure mechanism of targeted structure [1–3]. It should be noted that a relatively small number of shaking table tests on tall buildings are executed and published due to the difficulties in modeling scaled material properties, the cost restrictions and limitations of specimen size and capacity of available shaking tables, especially for this type of large span hybrid structure. This paper presents a detailed shaking table test of scaled model on the terminal building 2. The study attempts to provide some insights into the overall dynamic behavior of the new structural system and accumulates the experimental evidence for establishing related design guidelines for such complex hybrid structures in the future.

2. MODEL EXPERIMENT

2.1. Description of the shaking table

Shaking table model test is carried out using MTS shaking table facility at the State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China. The table can input three-dimensional and six degree-of-freedom motions. The dimension of the table is 4m×4m, and the maximum payload is 25 000 kg. The shaking table can vibrate with two maximum horizontal direction accelerations of 1.2g and 0.8g, with a maximum acceleration of 0.7g vertically. Its frequency ranges from 0.1 to 50Hz and there are 96 channels available for data acquisition during testing progress.

2.2. Model similitude and materials

The model is designed by scaling down the geometric and material properties from prototype structure. Steel structural elements were modeled with iron sheets, and those of reinforced concrete elements were modeled with fine-aggregate concrete with fine wires. The basic model similitude rules are established from the scaling theory. Considering the capacity and the size of the shaking table to be used at Tongji University, the dimension scaling parameter is chosen as $1/35$.Subsequently, the stress scaling parameter is chosen as 0.2, and the acceleration scaling parameter is selected as 1.0 in order to investigate the seismic response of this large span structure subjected to vertical excitations. The main scaling parameters are presented in Table I.

Table I. Similitude scale factors for the test model.

Parameter	Length	Young's module	Acceleration	Frequency	Mass	Density
Model/Prototype	1/35	0.2	1.0	5.92	1.63E-04	7.0

2.3. Test set-up and procedure

To ensure an effective transmission of the table motion to the base of the test structure, the model base plate was firmly mounted on the shaking table through bolt connections. Figure 2 demonstrates an overview of the model structure after the test set-up. The instrumentation is organized so that both overall and local responses of interest could be measured, including accelerations measured by accelerometers, displacements measured by LVDTs and strains measured by strain gauges. Total of 33 accelerometers and 12 LVDTs are placed at reinforced concrete frame, Y-shaped steel column and steel roof, respectively. In addition, total of 20 strain gauges are placed on Y-shaped column and curved steel beam in steel roof. All the test data are collected by a computer-controlled data acquisition system and can be transferred to other PC computers for further analysis. Condition of site soil is one of the important factors to determine the earthquake inputs for dynamic test. Considering the spectral density properties of Type-IV site soil, El Centro wave, Pasadena wave and SHW2 wave were selected. Additionally, Sim-T2 wave which simulated according to the construction site was selected during the test. Figure 3 shows the time history and power spectral density of X direction of Sim-T2 wave. Except that SHW2 is 1-D wave, the other three waves are all 3-D wave.

Figure 2 Model panorama

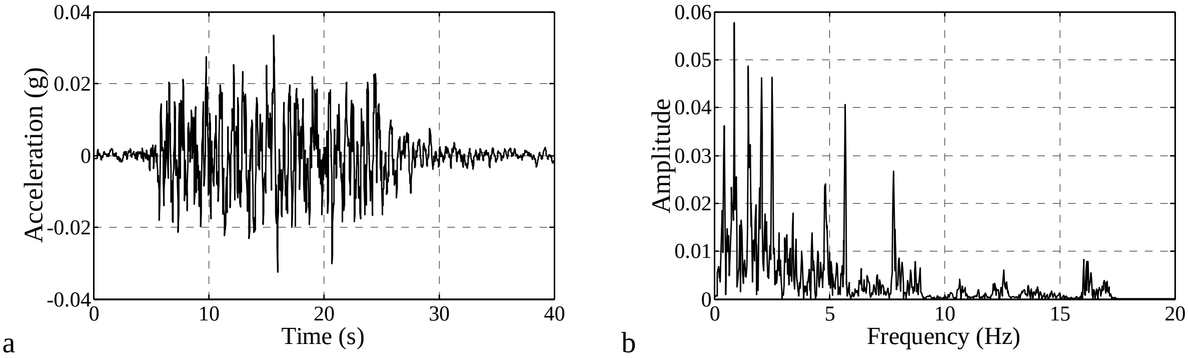

Figure 3. (a) Time history of Sim-T2 wave; and (b) power spectra of Sim-T2 wave.

According to China code, frequent, basic and seldom occurrences represent three peak levels of ground motions with intensity less than, equal to and higher than the design intensity, respectively. Three different requirements related to the three levels, are set to evaluate the overall capacity of structure under corresponding intensity. Since the design intensity in Shanghai is specified as 7, the test is carried out in four phases representing frequent, basic and seldom occurrences of design intensity 7, and seldom occurrence of design intensity 8, respectively. The last phase is utilized for further investigation of dynamic responses of the targeted structure under extremely strong earthquakes. During the test, the gradually increasing amplitudes of base excitation are inputted successively in a manner of time-scaled earthquake waves. After different series of ground acceleration are inputted, white noise is scanned to determine the natural frequencies and the damping ratios of the model structure.

2.4. Test results

2.4.1. Cracking and failure pattern

The test model survived from frequent intensity 7 to seldom intensity 7 without visible damage. Nevertheless, the gradual decreases of the natural frequencies of the model structure measured indicate that the intrinsic damage within the structure progressively developed during the phases of basic intensity 7 and seldom intensity 7. Major damages eventually occurred and propagated under seldom-occurred earthquake intensity 8, which are demonstrated in Figure 4. The main failure patterns under seldom intensity 8 are described as follows:
1, A large amount of curved beam located in steel roof ruptured or buckled.
2, Major cracks spread at the joint between the SRC column and the Y-shaped steel column.

3, Major cracks occurred on the RC beam or column.

Figure 4 Failure pattern of test model

2.4.2. Dynamic characteristics

Table 2 Natural frequencies, damping ratios and vibration modes

Excitation	Frequency (Hz)	Period (s)	Damping ratio	Vibration mode
Initial	3.517	0.284	0.038	Translation of X
	5.275	0.190	0.036	Torsion & Warp
	6.029	0.166	0.032	Translation of Y
Frequent 7	3.517	0.284	0.035	Translation of X
	5.275	0.190	0.029	Torsion & Warp
	6.029	0.166	0.029	Translation of Y
Basic 7	3.517	0.284	0.040	Translation of X
	5.275	0.190	0.029	Torsion & Warp
	5.778	0.173	0.030	Translation of Y
Seldom 7	3.014	0.332	0.059	Translation of X
	4.773	0.201	0.054	Torsion & Warp
	5.024	0.199	0.048	Translation of Y
Seldom 8	2.512	0.398	0.066	Translation of X
	2.763	0.362	0.086	Torsion
	3.768	0.265	0.071	Translation of Y

The natural frequencies of the structure are obtained from white-noise scan tests. The variations of frequencies at the end of each occurrence phase are presented in Table 2. The first four order vibration mode and the trend of natural frequency are given in Figure 5-6. The frequencies remained constant during the first series of tests, which revealed that almost no damage occurred in the structure. The first natural frequency decreased slightly after the model withstood the second series of tests referring to basic intensity 7, which suggested that the structure was still behaving in elastic state. In the third stage, the structure was subjected to the stronger earthquake inputs resulting in 14.29% and 16.67% decrease of the X and Y direction natural frequencies, which demonstrated that the intrinsic damage occurred even though no visible crack was observed on the model surface. After the input of seldom-occurred earthquake intensity 8, the natural frequencies dropped faster, which indicated that the model structure is now severely damaged.

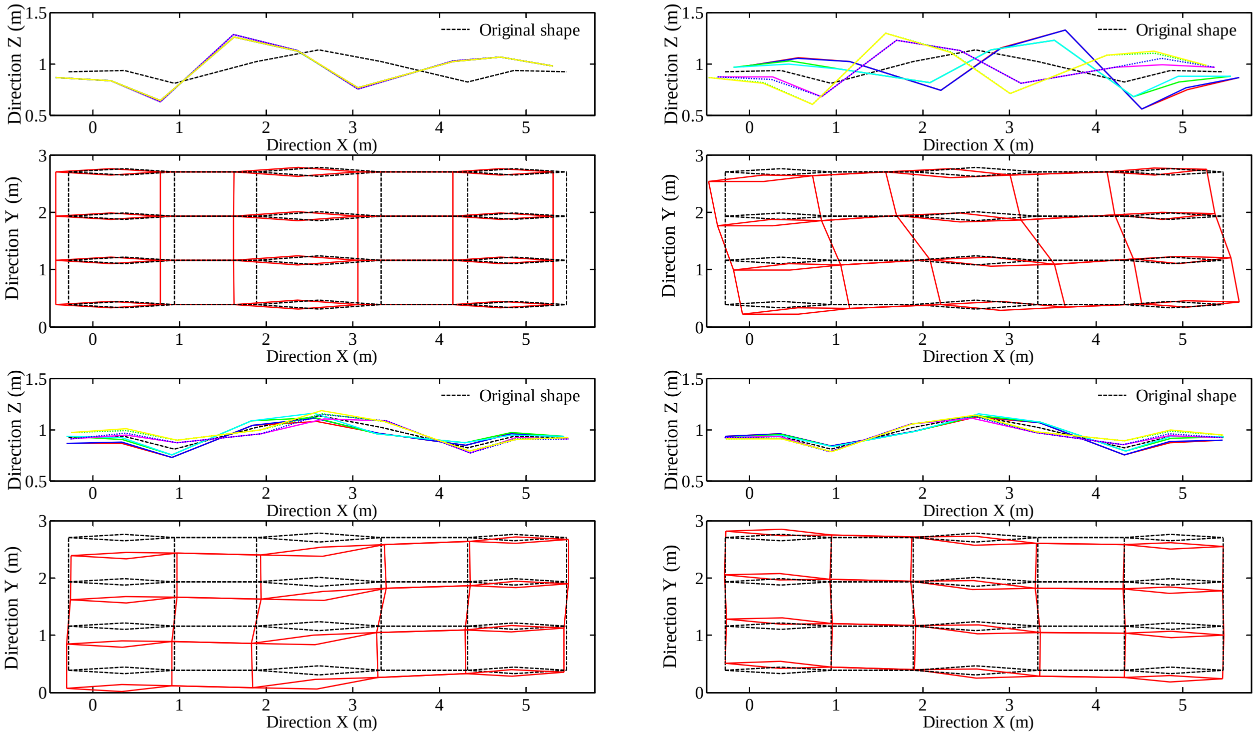

Figure 5 The first four order vibration modes

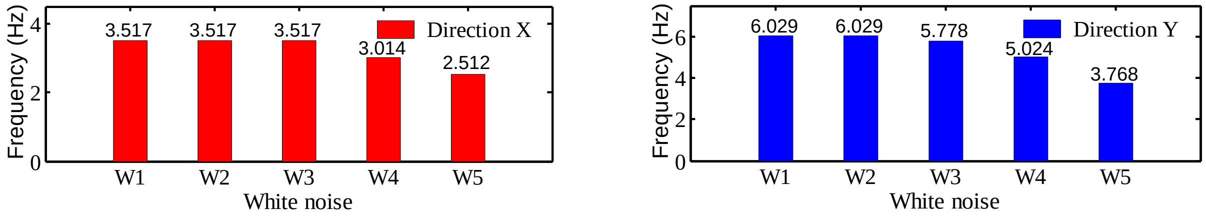

Figure 6 The trend of natural frequency during the whole test

3. FINITE ELEMENT ANALYSIS

To gain a better understanding of the dynamic behavior of the structure, 3D finite element analysis software ABAQUS were used to analyze the prototype structure. This part includes the results of: (i) structural dynamic characteristics, (ii) time history analysis.

3.1 Analytical model of the prototype structure

3D beam elements were selected for the beams and columns, shell elements and link elements were used for the floor slab and brace, respectively. Detailed information of the analytical model is listed in Table 3. Figure 7-8 shows the panorama and elevation of the analytical model.

Table 3. Information of the finite element model

FE Model information	Number
Beam elements	8785
Link elements	764
Shell elements	4576
Nodes	11957

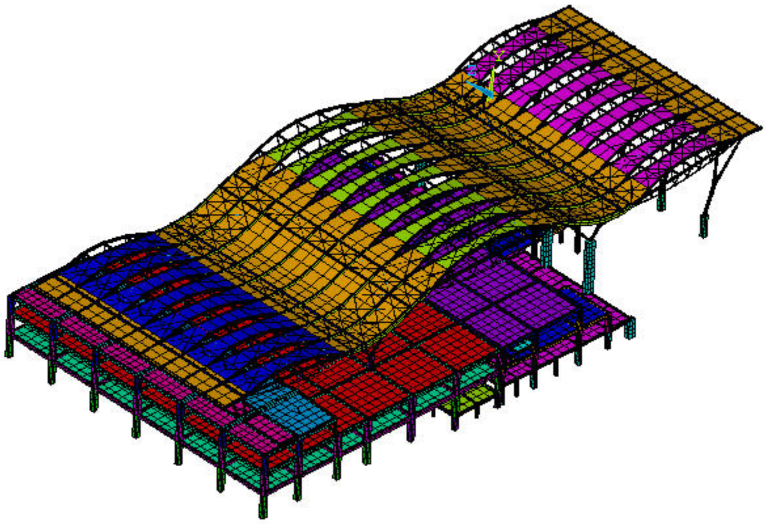

Figure 7 Finite element model panorama

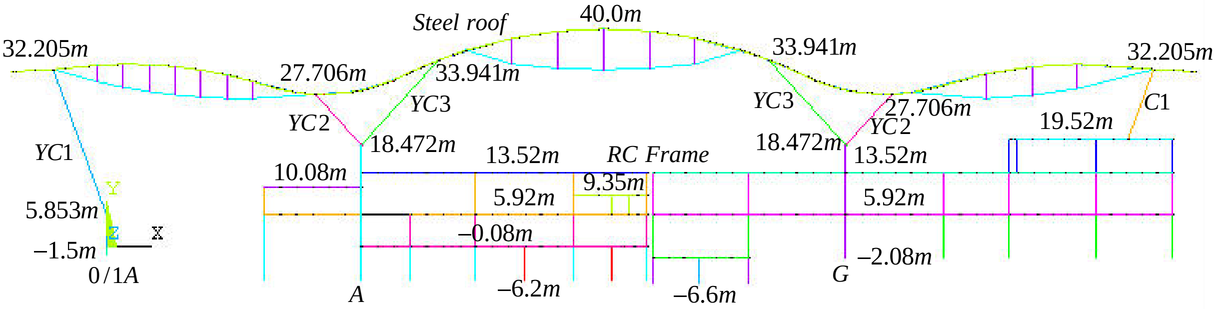

Figure 2

Figure 8 The elevation illustration for terminal building 2

3.2 Analytical dynamic characteristic of the prototype structure

Table 4 compares the analytical and test results on dynamic characteristic, they are agree with each other well.

Table 4. Experimental and analytical results of the prototype structure

Mode	Experiment (Hz)	Numerical analysis (Hz)	Error
1	0.594	0.574	3.37%
2	0.891	0.801	10.1%
3	1.018	0.984	3.34%

3.3 Time-history analysis (THA) of the prototype structure

The prototype structure was also analyzed using the SHW2 wave discussed above. The ground motion input was one-dimensional and peak acceleration was set to be 0·035g and 0.22g corresponding to frequent intensity 7 and seldom intensity 7. In the analysis, the slab was assumed to be elastic and the damping ratio set to be 0·03.

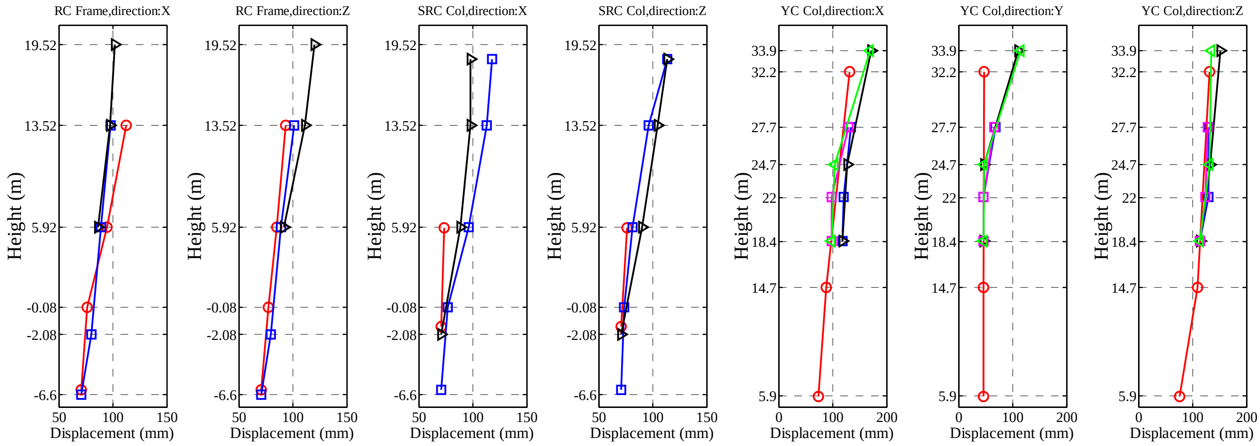

Figure 9 Maximum displacements of major part when subjected to frequent 7 excitation

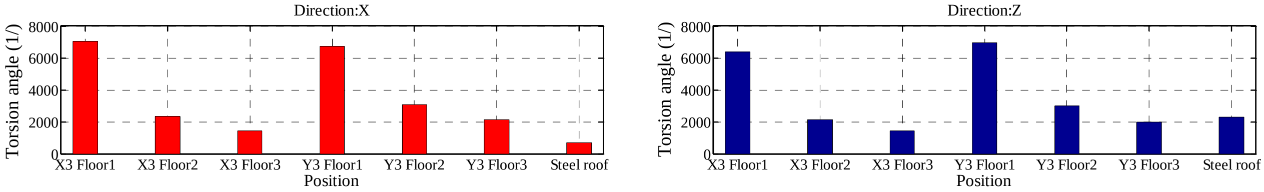

Figure 10 Maximum torsion response of each section when subjected to frequent 7 excitation

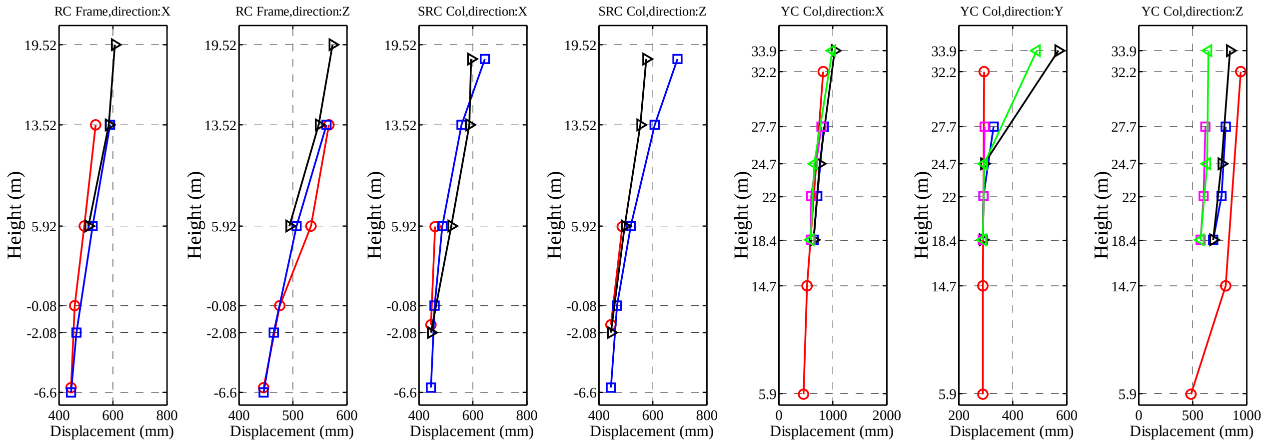

Figure 11 Maximum displacements of major part when subjected to seldom 7 excitation

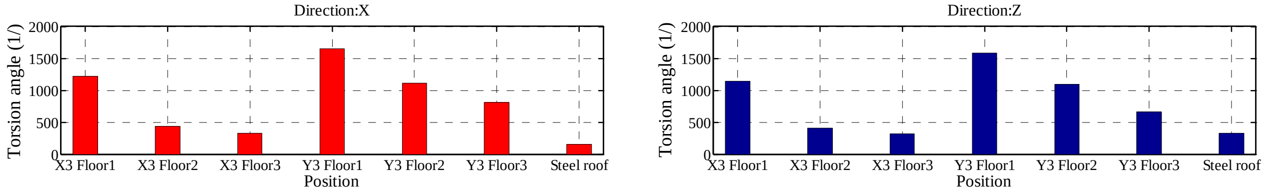

Figure 12 Maximum torsion response when subjected to seldom 7 excitation

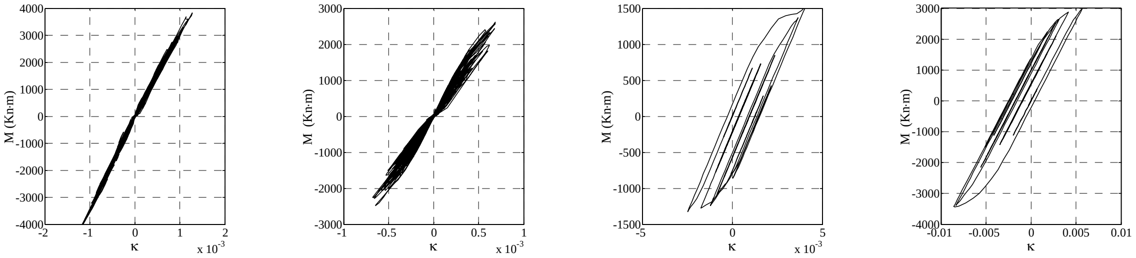

Figure 13 Typical hysteretic response of SRC column and YC column when subjected to seldom 7 excitation

The maximum displacement and torsion response when subjected to frequent 7 and seldom 7 level ground motions are pictured in Figure 9-12. In addition, the typical hysteretic responses of columns are plotted in Figure 13. Some conclusions and discussions can be drawn as follows:

(1) Displacement and torsion response become larger with the increase of ground motion inputs;
(2) Compared to the SRC column and RC frame, the Y-shaped steel column and steel roof can produce the larger displacement response;
(3) The YC column can have a bigger vertical displacement response;
(4) Steel roof have an apparent torsion response compared to the RC frame.
(5) Some SRC column and Y-shaped column maybe get into the plastic state when the structure subjected to seldom 7 excitations.

4. CONCLUSIONS

Seismic behavior of terminal building 2 in Shanghai Pudong international airport has been experimentally and numerically investigated. A 1/35 scaled model of a hybrid structure, which consists of RC frame structure, Y-shaped steel column and steel roof, is tested on a shaking table by subjecting it to a series of ground motions with increased intensity of shaking in each successive test run. The following conclusions can be drawn from the test and finite element analysis:

(1) The model test results indicate that the prototype structure is able to withstand frequent occurred, basic intensity and seldom-occurred earthquakes of intensity 7 without sever damage. The structural system in this building demonstrates good quality in resisting earthquakes.

(2) The natural frequencies and equivalent rigidities decrease very slightly after the basic intensity earthquake, which indicates that the prototype structure still remains in elastic stage.

(3) After the seldom-occurred earthquake of intensity 7, visible cracks occur and the natural frequencies and equivalent rigidities decrease apparently.

(4) Under seldom occurrence of intensity 8, curved steel beam ruptures or buckles in steel roof, and fine crack spread in the joint between SRC column and Y-shaped steel column. These damages indicate that the curved beam and the joint is a weak position. Design measures to increase the ductility are needed to avoid extensive deformations.

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