Research Article

Seismic Performance Evaluations of Mega-Sub Isolation System

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This paper presents mega-sub isolation system. Shaking table test of the mega-sub isolation system is carried out in this paper. Three test models have been developed. One is called aseismic model, in which all the substructures are fixedly connected with the megastructures. The second one is known as isolated model, where the substructures are connected with the megastructures with isolators, and the last one is called the lower substructure consolidated (LSC) model, in which all the substructures except for the substructures at the lowest level, in other words, substructures at the second mega floor, are isolated from the megastructures. Nonlinear dynamic time analysis of the test models is conducted by SAP2000. Acceleration responses of the megastructure, story drift responses of the megastructure and the substructure, and the deformations of the isolation layer are compared between experimental and numerical simulation results. The results show that the experimental results and numerical simulation results agree well with each other, and the isolated model and LSC model perform better than the counterpart aseismic model. The structures with isolation devices can reduce the structural responses effectively and are much safer than the structure without isolation devices.

1. Introduction

Traditionally, architects and engineers have been interested in constructing structurally sound, functionally efficient, and esthetically elegant high-rise buildings. Remarkable advances made over recent years in engineering science including materials, geotechnical, and structural engineering and control technologies [1, 2] have benefited the analysis, design, and construction of tall buildings. The population growth of large cities has led to an increased demand for building construction sites, whose availability is limited. This has resulted in a corresponding rise in the land value of such sites and the related trend of constructing tall or supertall buildings on them, in order to ensure that such building projects are economically viable. Many of the high-rise buildings in metropolis such as Tokyo, Hong Kong, and Shanghai exemplify this situation.

For buildings with modest height, implementation of passive control devices offers a potential improvement in structural safety and human comfort. But the structural

characteristics common to most tall and supertall buildings, such as high shear rigidity, tend to prevent the application of the traditional control devices. A new method for controlling the response of tall buildings or supertall buildings under severe external loads was first introduced by Feng and Mita [3]. Feng and Mita first proposed to release the connections between the megabuilding and the substructures in a mega-sub structure, but without installing dampers between the megabuilding and the substructures. Using a simple analytical model, a preliminary investigation of the interaction between the megaframe and the substructures in suppressing the vibrations of the entire mega-sub structure system was carried out. The results show that the substructures in this structural configuration have a strong TMD function. Chai and Feng subsequently improved this configuration and presented a MSCS based on a conventional mega-sub controlled frame and undertook a study of its dynamic response to random wind load excitations [4]. Recently, some studies about the optimal parameters between the substructure and megastructure have been done in order to

FIGURE 1: Analytical model of mega-sub isolation system.

(a) Aseismic model

(b) Isolated model

(c) LSC model

FIGURE 2: Experimental models.

achieve the best performance by Tian [5]. Lan et al. proposed a multifunction mega-sub controlled structure, which has the function of the mass dampers and base isolation as well as damping energy dissipation [6]. Qin et al. [7–9] and Zhang et al. [10, 11] have investigated the control performances of the mega-sub controlled structure with different control strategies. A new connection form between the substructures and megastructure was put forward by Pei and Wang, in which the top substructure was connected with the megastructure by dampers. And the studies showed that this new connection form can achieve better damping effect and also can prevent collisions between the top substructures and the megastructure [12]. Seismic responses of the mega-sub controlled frame with friction damper were analyzed by Lian et al. [13, 14]. Limazie et al. have investigated the dynamical characteristics and controlling performances of the mega-sub controlled structure when subjected to strong earthquake

motion by designing a reasonable and realistic scaled model [15].

Although many studies have investigated the performances of mega-sub controlled structure by theoretical analysis, the mega-sub isolation system has not been investigated systematically. In this study, shaking table test of the mega-sub isolation system is carried out. The performances of three experimental models have been tested under a set of ground motions with different PGAs. Numerical simulation analysis on mega-sub isolation system has been conducted for comparison.

2. Mega-Sub Isolation System

In the mega-sub isolation system, the substructures are connected with the megastructure by isolation devices. Theoretical analysis shows that this system can achieve good

FIGURE 3: Plan view of the experimental model.

FIGURE 4: Bearings.

FIGURE 5: Test of bearing.

performances under seismic excitations. Isolation devices can reduce the earthquake responses of both the substructure and megastructure effectively. In the theoretical analysis process, the isolation devices are usually simulated with Kelvin model, and the megastructure is simplified as a series of pointed models, while each substructure is simplified to a lumped mass. Figure 1 shows the simplified analysis model of the mega-sub isolation system. Based on this analytical model, Tan et al. have investigated the work mechanism of the

mega-sub isolation system by systematically investigating its dynamic characteristics corresponding to various structural parameters [16]. Results show that, with increase in substructure mass, the working mechanism of the mega-sub isolation system is changed from tuned vibration absorber, energy dissipation to seismic isolation. Then, based on the theoretical studies on the mega-sub isolation system and the convenience in the test, three experimental models subjected to a series of shaking table tests were accordingly designed in this paper.

FIGURE 6: Hysteretic curve of bearing under case 3.

FIGURE 7: Hysteretic curve of the damper under case 3.

3. Experimental Setup

3.1. Experimental Models. To investigate the seismic performance of the mega-sub isolation system, three steel frame structure models with 1/25 scale are designed according to “code for seismic design of buildings” (GB50011-2010) and “code for design of steel structures” (GB50011-2010), as shown in Figure 2. According to the “code for seismic design of buildings” (GB50011-2010), the limits on story drift of steel structure under frequent and rare earthquakes are taken as 1/250 and 1/50, respectively. All these three experimental models are composed of four megastories and seven-story substructures that are attached to megastructure from the second floor to the fourth floor. There is no substructure installed at the first floor of the megastructure because the bottom story of substructure is supported on the ground, and its movement will not directly influence the structural responses. Among these three steel frame models, one is called aseismic model, in which all the substructures are

(a) First mode

(b) Second mode

(c) Third mode

FIGURE 8: The vibration modes of the megastructure.

fixedly connected with the megastructures. The second one is known as isolated model, where the substructures are

FIGURE 9: Comparison of the peak accelerations of each megastructure between aseismic structure and isolated structure (0.125 g).

FIGURE 10: Comparison of the peak accelerations of each megastructure between aseismic structure and LSC structure (0.275 g).

connected with the megastructures with isolators, and the last one is called LSC model, in which all the substructures except for the substructures at the lowest level are isolated from the megastructures. In general, the bottom story of megastructure is 0.996 m high, and the other three stories are each 1.02 m high. Therefore, the total height of this experimental model is 4.056 m with attached substructures of total height 0.84 m and story height 0.12 m. Figure 3 shows the plan view of the experimental model.

3.2. Isolation Bearings. The bearing used in this test consists of guide for providing vertical stiffness, spring for providing restoring force, and small viscous damper for providing

damping force, as shown in Figure 4. The main material of the viscous damper is silicone, which can provide full viscous damping energy, and the equivalent damping ratio level can reach 0.5 or higher. Performance test of the bearing has been conducted under sinusoidal wave, and displacement control was adopted, where the amplitude of the sinusoidal wave was scaled to 5.5 mm. Due to the small surface pressure of a single bearing, four bearings were tested together (Figure 5).

Four cases were included in the test, as shown in Table 1. Each loading case was composed of three cycles. Figure 6 shows the hysteretic curve of bearing under case 3.

For the loading frequency of 0.005 Hz, the force of the viscous dampers can be neglected. Thus, the elastic stiffness

FIGURE 11: Comparison of the peak accelerations of each megastructure between isolated structure and LSC structure (0.125 g).

FIGURE 12: Comparison of the acceleration time history curves of the top megastructure between aseismic structure and isolated structure (0.125 g).

TABLE 1: Test cases.

	Surface pressure (kN)	Loading frequency (Hz)
Case 1	32	0.005
Case 2	32	0.05
Case 3	32	0.2
Case 4	32	0.5

of the bearing (four bearings) can be obtained which is 0.5064 kN/mm. Then, the force of the dampers can be calculated by the bearing's total force subtracting the elastic force. The third-cycle hysteretic curve of the dampers under case 3 is shown in Figure 7.

According to the formula $v = 2\pi fA$ (A represents the maximum stroke of the damper), the maximum output force of the dampers and the corresponding velocity values can be obtained under cases 2, 3, and 4, respectively, which are listed in Table 2. The relationship between the damper force and the stroke velocity can be fitted as $F = 1.4187v^{0.275}$.

4. Test Results and Analysis

This experiment adopts one artificial wave and three real strong natural earthquake records, that is, the records of El Centro ground motion, Taft ground motion, and Tangshan ground motion. The original earthquakes are scaled by 0.125 in magnitude and 0.179 in time, so the peak accelerations of

FIGURE 13: Comparison of the acceleration time history curves of the top megastructure between isolated structure and LSC structure (0.275 g).

FIGURE 14: Comparison of the story drift of megastructure between aseismic structure and isolated structure.

TABLE 2: The maximum output force and velocity values of the dampers.

	F (kN)	v (mm/s)
Case 2	1.6075	1.6372
Case 3	2.355	6.0275
Case 4	2.9603	14.7423

the seismic earthquakes under, frequently, fortification and, rarely, earthquakes are taken as 0.04375 g, 0.125 g, and 0.275 g, respectively.

4.1. Modal Characteristics. The structural dynamic characteristics of the models were tested by inputting white noise, the

peak acceleration of which was taken as 0.05 g. The first three modes of the megastructure of isolated modal in X direction are shown in Figure 8. Table 3 lists the fundamental periods of the structural models obtained from the shaking table test and numerical simulation.

4.2. Response Analysis of the Models. Figures 9–11 present the comparison of the peak accelerations of the megastructure in X direction among the aseismic structure, isolated structure, and LSC structure. It can be seen that the peak accelerations of each floor of the megastructure are reduced significantly in isolated structure model and LSC structure model compared to that of the aseismic structure model.

The peak accelerations of the megastructure of the isolated model are almost the same as those of the LSC model.

FIGURE 15: Comparison of the story drift of substructure between isolated structure and LSC structure.

FIGURE 16: Hysteretic curves of bearing.

TABLE 3: Experimental period and numerical simulation period of the structural models.

Structural models	Experimental (s)	Theoretical (s)	Error (%)
Aseismic model	0.42	0.365	13.09
Isolated model	0.488	0.563	15.36
LSC model	0.485	0.560	15.52

However, the peak accelerations of the megastructure of the isolated model are smaller than that of the LSC model, as shown in Figure 11. Thus, the control effectiveness of the isolated model whose substructures are all isolated with the megastructures is better than that of the LSC model, in which the lower substructures are fixedly connected with

the megastructure while the others are connected with the megastructures with isolators.

Figures 12 and 13 compare the acceleration time history curves of the top megastructure among the aseismic structure model, the isolated structure model, and the LSC structure model, respectively. The acceleration time histories of the top megastructure of isolated structure model are significantly reduced, especially for the aseismic structure model. The acceleration time histories of the top megastructure of LSC structure are similar to that of the isolated structure, whereas the peak accelerations are larger than that of the isolated structure, as shown in Figure 13. Therefore, the isolated model outperforms the LSC model. In the practical engineering applications, the substructures should be all connected with

TABLE 4: Comparison of peak accelerations of the megastructure in X direction between the experimental and numerical simulation results of the isolated structure (unit: g).

Cases		Artificial (0.125 g)	El centro (0.125 g)	Taft (0.125 g)	Tangshan (0.125 g)	Artificial (0.275 g)	El centro (0.275 g)	Taft (0.275 g)	Tangshan (0.275 g)
1	Experiment	0.1278	0.1411	0.1237	0.127	0.2696	0.2478	0.2217	0.3597
	Simulation	0.0988	0.1071	0.0994	0.1157	0.2384	0.2053	0.1905	0.3013
	Error (%)	17.91	24.10	19.64	8.89	11.57	17.15	14.07	16.24
	Experiment	0.1457	0.1494	0.1105	0.1652	0.2635	0.2483	0.267	0.3312
2	Simulation	0.0992	0.1148	0.0976	0.1442	0.2002	0.1609	0.2326	0.257
	Error (%)	24.25	23.16	11.67	12.71	24.02	35.19	12.88	22.40
	Experiment	0.1223	0.0848	0.06905	0.084	0.1981	0.1414	0.1735	0.204
	Simulation	0.091	0.0749	0.0599	0.072	0.1561	0.122	0.1426	0.1654
3	Error (%)	25.69	11.67	13.22	14.29	21.20	13.72	17.81	18.92
	Experiment	0.146	0.1843	0.1013	0.1419	0.2495	0.3203	0.3079	0.3138
	Simulation	0.113	0.1605	0.0972	0.1406	0.2393	0.2665	0.2845	0.3291
	Error (%)	22.54	12.91	4.05	0.92	4.09	16.80	7.59	2.58

Floor

TABLE 5: Comparison of story drift responses of the substructure in X direction between the experimental and numerical simulation results (unit: mm).

Cases		Aseismic Floor			Isolated Floor			LSC Floor		
		1	2	3	1	2	3	1	2	3
Artificial (0.125 g)	Experiment	2.85	2.89	3.83	2.20	2.72	3.49	2.64	2.82	3.72
	Simulation	2.95	3.30	3.91	3.26	3.26	3.60	2.48	2.87	3.86
	Error (%)	3.51	13.79	2.36	19.98	19.98	3.08	6.15	1.68	3.72
El centro (0.125 g)	Experiment	2.59	3.12	3.55	1.86	1.86	2.69	1.52	2.01	2.73
	Simulation	2.29	2.86	3.60	1.50	1.50	2.23	1.76	0.34	2.34
	Error (%)	11.58	8.33	1.69	19.29	19.29	17.0	15.79	16.29	14.38
Taft (0.125 g)	Experiment	2.74	1.79	1.01	1.05	1.05	1.58	2.49	1.13	1.89
	Simulation	2.77	1.99	1.02	0.95	0.95	1.20	2.08	1.12	1.96
	Error (%)	1.46	11.17	0.99	9.81	9.81	24.10	16.37	0.74	3.18
Artificial (0.275 g)	Experiment	5.91	5.11	7.65	4.72	4.80	6.96	5.15	4.98	7.14
	Simulation	6.17	4.71	7.67	4.85	5.36	8.18	6.65	6.30	8.44
	Error (%)	4.58	7.84	0.26	2.73	11.73	17.57	29.08	26.48	18.24
El centro (0.275 g)	Experiment	4.90	5.45	6.52	4.78	4.22	5.27	3.20	4.47	5.37
	Simulation	4.09	5.14	6.46	3.84	4.06	4.98	4.07	4.65	5.21
	Error (%)	16.53	5.51	0.92	19.81	3.70	5.50	27.04	4.04	2.97
Taft (0.275 g)	Experiment	4.56	3.40	4.53	3.46	3.03	3.89	5.17	2.93	4.20
	Simulation	3.95	3.54	4.58	3.12	2.84	3.24	3.99	2.89	4.52
	Error (%)	13.45	4.19	1.33	9.93	6.21	16.65	22.89	1.41	7.68

FIGURE 17: Finite element model of mega-sub structure.

the megastructures with damping devices in order to achieve the best performance.

The story drift responses of the megastructure between aseismic structure and isolated structure in X direction are compared in Figure 14. It can be seen that the story drift of the megastructure of the isolated structure is smaller than that of the aseismic structure. That is because the control devices installed between the substructure and megastructure can not

only provide stiffness but also offer additional damping to the entire system.

Figure 15 shows the contrast plots about the story drift of the substructure between isolated structure and LSC structure in X direction. It can be observed that the story drift of the substructures on the second floor and the third floor of the LSC structure is similar to that of the isolated structure, while the story drift of the first floor of the LSC structure is larger than that of the isolated structure. This is because the first floor substructure is fixedly connected with the megastructure in the LSC structure, which further illustrates the effectiveness of the isolation device installed in this experiment.

Figure 16 presents the hysteretic curves of the isolation bearings installed between the top megastructure and substructure in isolated structure. Horizontal axis and vertical axis in the figures represent the relative displacement and relative acceleration of isolators, respectively. From Figure 16, it can be seen that a lot of earthquake energy was dissipated by the isolation bearings. The energy dissipated by both megastructure and substructure is reduced simultaneously; thus, the safety of the megastructure and the substructure, especially the substructure, can be ensured.

5. Finite Element Models of Mega-Sub Structure

The finite element models of aseismic structure, isolated structure, and LSC structure have been developed by

FIGURE 18: Comparison of acceleration time history curves of the top megastructure between the experimental and numerical simulation results of isolated model.

SAP2000. Figure 17 shows the numerical simulation model of mega-sub structure established in SAP2000. The isolation devices used in the isolated structure and LSC structure are simulated by the Rubber Isolator element and damper element, where the Rubber Isolator element is simulated as the spring and the damper element is modeled as the viscous damper, respectively. The horizontal stiffness of the Rubber Isolator element was taken as 31.65 N/mm, and the damping coefficient and velocity index of the damper element were taken as 1.4187 and 0.275, respectively, which are determined by the performance test of bearings. The slabs were modeled by shell elements in these three finite element models and Q235 steel is used as the material of the test models, whose yield strength is 235 MPa. The sections of the beams and columns of the megastructure and substructure are both box sections. The sizes of columns and beams of the megastructure are taken as 40 mm * 40 mm * 1.2 mm and 20 mm * 20 mm * 0.9 mm, respectively, and the sizes of

columns and beams of the substructure are taken as 16 mm * 16 mm * 0.6 mm and 20 mm * 20 mm * 0.9 mm, respectively.

6. Comparison of the Numerical Simulation and Experimental Results

6.1. Acceleration Response of the Megastructure. Table 4 compares the peak accelerations of the megastructure in X direction between the experimental and numerical simulation results of the isolated structure. Figure 18 shows the comparison of acceleration time history curves of the top megastructure in X direction under some cases between the experimental and numerical simulation results.

6.2. Story Drift of the Megastructure. Figures 19 and 20 present the comparison of story drift of the megastructure between the experimental and numerical simulation results of the aseismic structure and LSC structure in X direction.

FIGURE 19: Comparison of story drift of the megastructure between the experimental and numerical simulation results of the aseismic model.

FIGURE 20: Comparison of story drift of the megastructure between the experimental and numerical simulation results of the LSC model.

6.3. Story Drift of the Substructure. Comparison of story drift responses of the substructure between the experimental and numerical simulation results of the aseismic structure, isolated structure, and LSC structure is tabulated in Table 5.

6.4. Isolation Layer Displacement. Figures 21 and 22 show the comparison of the isolation layer displacements between the experimental and numerical simulation results of the isolated structure and LSC structure in X direction.

It can be observed that the trends of numerical simulation results and the experimental results under different earthquake records agree well with each other. There are some differences between the numerical simulation results and the experimental results. That is because the performance of isolation devices will be influenced by the velocity of isolation level when subjected to different ground motions.

In the numerical simulation analysis, the velocity correlation of isolator is not considered and the stiffness of the isolation bearings is chosen as a determined value in SAP2000. On the other hand, there are some deviations existing between the experimental models and the numerical simulation models due to the manufacturing errors in the factory. As a whole, the trends of the numerical simulation results and experimental results are consistent with each other; thus, the accuracy of these shaking table tests is verified.

Both the numerical simulation results and the experimental results show that the story drift of the substructures is larger than that of the megastructures of these three different structural models. That is, under the strong ground motions, the substructures are out of work earlier than the megastructures.

As different earthquake records have different spectral characteristics, the control effectiveness of the isolated

FIGURE 21: Comparison of the isolation layer displacement between the experimental and numerical simulation results of the isolated model.

structure and the LSC structure compared with the aseismic structure varies with the selected ground motions.

The structural responses of the isolated model and LSC model are greatly reduced compared with that of the aseismic model, which can be illustrated by both the numerical simulation results and experimental results. Isolation bearings installed between the megastructure and substructure can reduce the structural responses effectively, and the novel structure is safer than the traditional structure without isolation devices.

7. Conclusions

The shaking table test of the mega-sub isolation system has been carried out in this paper in order to study the seismic performance of the mega-sub isolation system. The seismic

performances of the aseismic structure, isolated structure, and the LSC structure have been studied. The finite element models have been established by SAP2000. Numerical simulation results were compared with the experimental results on some structural responses such as the acceleration response and story drift response of the megastructure, the story drift response of the substructure, and the deformation of the isolation layer. The following conclusions can be obtained.

The acceleration and story drift of megastructure and the story drift of the substructure in isolated structure and the LSC structure are greatly reduced compared with those of the aseismic structure, which can be illustrated by both the numerical simulation results and experimental results. That is because some isolation bearings are placed on the isolated structure and the LSC structure, and these damping devices can not only provide stiffness but also offer additional

FIGURE 22: Comparison of the isolation layer displacement between the experimental and numerical simulation results of the LSC model.

damping to the structure. The analysis of the story drift of substructure further illustrates the effectiveness of the isolation device used in this experiment.

The structural responses of the LSC structure are similar to that of the isolated structure, and the responses are larger than that of the isolated structure. Therefore, the damping effect of the isolated structure is better than that of the LSC structure. So in the practical engineering applications, the substructures are suggested all to connect with the mega-structures by damping devices in order to achieve the best control effectiveness.

The trends of the numerical simulation results and experimental results are consistent with each other; thus, the accuracy of these shaking table tests is verified.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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