Damping Effect of Adjacent Structures Connected with Viscous Dampers Using Shaking Table Test

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ABSTRACT

The features of damper connection may affect the structural dynamic responses. In the current study, the shaking table test in a scale of 1/20 was used to investigate the damping effect of adjacent 15- and 7-storey frame-shear wall model structures connected with viscous dampers. The seismic intensity was 7 degree and four levels of seismic excitations (i.e. the frequent, basic, rare and large earthquake ones) were considered. The effects of the damper connection were examined under various levels of the seismic actions and waves. The results show that under the earthquake excitations, the decrease in frequencies and the increase in the damping ratios are relatively coincided; under the frequent and basic earthquake excitations, the acceleration amplification factors of the model structures with the damper connections were controlled in each floor of the main- and sub-structures; under the frequent, basic, and rare earthquake excitations, the displacements of the main- and sub-structures with the damper connections were controlled to some extent. ¹ ²

KEYWORDS

Adjacent Structure; Damper; Shaking Table Test; Vibration Control; Seismic Reaction; Damping Effect

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INTRODUCTION

After an earthquake, the vibrations of the adjacent buildings may be increased, even resulting in the collisions between these structures. These vibrations may be reduced to some extent if the dampers were setup between the structures.

To control vibrations between the adjacent structures in using the connections of hysteretic dampers, Bharti et al [1] and Lin et al [2] examined the adjacent structures connected with magneto-rheological (MR) dampers and controlling the relative displacements between buildings by using the instantaneous optimal semi-active control algorithm (TIOC); Kim and Kang [3] introduced a hybrid model combining skyhook and ground-hook control algorithm in a multi degree of freedom system to reduce seismic response of adjacent buildings; Uz et al [4] proposed an optimal design strategy based on GA (Genetic Algorithm) for nonlinear hysteretic control devices in preventing the pounding damage and obtained the seismic response mitigation of two adjacent structures; Guenidi et al [5] proposed a semi-active control device combining the classical TMD (Tuned Mass Damper) and MR dampers; Basili et al [6] carried out various shaking table tests on a physical model in a scale of 1/5 to represent two steel structures controlled by one MR damper and evaluated the passive and semi-active availability for the reduction in seismic responses.

In the current study, a shaking table test using adjacent 15-story of main-structure and 7-story of sub-structure with the frame-shear walls in a scale of 1/20 was designed. Four conditions (i.e. no damping connection and viscous dampers set in three various locations), four scales of seismic actions in the 7-degree earthquake (i.e. frequent, basic, rare and large earthquakes), and three seismic waves (i.e. El Centro, San Fernando and SHW2 waveforms) were considered. The dynamic influences of the damping parameters and locations on the damping effects of the main- and sub-structures were also examined.

TEST SITUATIONS

The earthquake response test of adjacent structure model was conducted in the shaking table room of the State Key Laboratory of Disaster Prevention for Civil Engineering in Tongji University, Shanghai. This shaking table may simulate the earthquakes with an area of 4 m × 4 m, a control system of 6 degrees of freedom in 3 directions with the waveforms in the frequency range of 0.1 to 50 Hz, and a maximum load capacity of 25 tons on the table with the maximum accelerations of 1.2, 0.8, and 0.7 g respectively in X, Y, and Z directions.

The 15-story main-structure was reinforced from the existing one in the shaking table test room, while the 7-story sub-structure was a newly-constructed model. The height of the lower building was designed as a 7-story one.
Model Structure And Similarity

To be convenient in setting the dampers between adjacent buildings, the plane layout, floor height, structural reinforcement, and materials used in the sub-structure were the same exactly to those in the lower 1 to 7 floors of the main-structure. The main- and sub- structures were the frame-shear-wall ones. The bolt was used to ensure the combination between the model structure and the shaking table. A concrete base was setup with the length, width, and the thickness of 1.95, 1.4, and 300 mm, respectively. The total heights of the main- and sub- structures were 3050 and 1450 mm, respectively. The height of the bottom layer was 230 mm, while that of other layers was 200 mm.

In the model structure, the particulate concrete with the strength grade of MC8.0 and the galvanized wire imitation steel bars of 26# were used respectively in shear-walls/floor-slabs and in the structural reinforcements. The double-layers of steel meshes were used in the walls with the grid spacing of 12.5 mm. The thicknesses of the shear-walls and floor-slabs were 15 and 10 mm, respectively. The steel frame parts in the beams and columns were constructed using red coppers. The structural height, material strength, and similarity were conducted. The influence of the live load was considered by using the setting counterweight method. The similarity of the model structure is listed in Table 1.

Design of Dampers

The selected viscous fluid dampers, produced by Shanghai Material Institute, have non-linear relations between damping force and velocity. The damping coefficient was 188.3 Ns/mm while the velocity index $\alpha$ was smaller enough ($\alpha = 0.338$) both to make the damping force to quickly approach into the designed one and to avoid the invalidation of the connections prior to the structure.

According to the analysis by Liu and Ye [7], the shock absorption effect as dampers located in the ends is better than that as more or uniformly-distributed dampers were used. The comparative tests were conducted both for two superior locations (i.e., dampers connected in the 7-story and in the 7- and 1-stories, respectively simplified as 7-d and 71-d) and for general ones (i.e., dampers connected in the 7-, 5-, 3-, and 1-stories, simplified as 7531-d). Two dampers were symmetrically setup in each story.

| Parameters | Length | Strain | Elasticity modulus | Stress | Density | Mass |
|------------|--------|--------|--------------------|--------|---------|------|
| Similarity | 1/20   | 1      | 2/7                | 2/7    | 1.90667 | 0.00024 |

| Parameters | Time | Velocity | Acceleration | Damping |
|------------|------|----------|--------------|---------|
| Similarity | 0.12910 | 0.38730 | 3 | 0.00185 |
Measurement Locations

A total of 27 accelerometers were assigned in two model structures. In the X direction, one accelerometer was assigned in the center of each floor. To measure the frequency changes of the structure in the Y direction, one accelerometer was assigned in each of the base, 7th, and top floors of the main-structure in the Y direction. One accelerometer was assigned in the X direction (or horizontally) in the center of the base floor of two structures to verify the measured data. The absolute acceleration in the table was measured by the shaking table system.

A total of 13 displacement gauges were assigned in the structures. One displacement gauge was assigned in the X direction both in the base-, 1-, 3-, 5-, 7-, and top- floors of the main-structure and in the base-, 1-, 3-, 5-, and top- floors of the sub-structure. One displacement gauge was assigned in the Y direction (or vertically) in the base- and top- floors of the main- and sub-structures.

A total of 10 resistance-style strain gauges were assigned in two adjacent structures. The gauges were assigned in the Y direction both in the outer- and inner-shoes of the main- and sub-structures and in the root of shear-wall.

Experiment Conditions

Table 2 shows the experimental conditions for a horizontal earthquake. In the table, the widely-used El Centro, San Fernando (respectively simplified as El and San), and SHW2 waveforms were considered as the excitations on the shaking table. Based on the 7 degree seismic fortification and the relations for the frequent, basic, and rare earthquakes, the input maximum accelerations on the table were respectively set as 0.1, 0.3, and 0.66 g. The large earthquake experiment with the input maximum accelerations of 1.0 g was also conducted.

The time interval was compressed to 0.002582 s. The excitation loads were input in the X direction. Before conducting the test, the white noises of sweep frequencies in the X and Y directions were performed for two model structures to independently obtain the natural vibration frequencies.

| Connections of dampers | Seismic Intensity | Peak Acceleration | Input Sequence of Seismic Waveform |
|------------------------|------------------|-------------------|-----------------------------------|
| No dampers             | Frequent, Basic  | 0.1g, 0.3g        | El to SHW2 to San                 |
|                        | Rare, Large      | 0.66g/1.0g        | El to San to SHW2/ El to San      |
| Two dampers in 7 story | Frequent, Basic  | 0.1g, 0.3g        | El to SHW2 to San                 |
|                        | Rare, Large      | 0.66g/1.0g        | El to San to SHW2/ El to San      |
| Four dampers in 7 and 1 stories | Frequent, Basic | 0.1g/0.3g | El to SHW2/ San |
| Four dampers in 7, 5, 3 and 1 stories | Frequent, Basic | 0.1g/0.3g | El to SHW2/ San |
Afterwards, a step-by-step loading mode was used to add earthquake excitations to both for independent models and for structural models with damper connections.

During the frequent and basic earthquakes before the large earthquake, the white noise of the sweep frequencies was conducted two times to the model structures to examine the damage process. The white noise measurement was conducted to obtain the dynamic features of the model structures after the excitations completely finished.

**EXPERIMENTAL RESULTS AND ANALYSIS**

**Phenomenon**

If no damper was connected after the excitation of the frequent earthquake, the model surface had no visible cracks. Nevertheless, the fundamental frequencies of the structures decreased a little and the stresses in concrete slightly exceeded the tensile strength, implying that the structure worked in an elastic state even though tiny crack occurred. According to the experimental results in various locations with damper connections under the basic and rare earthquakes, the fundamental frequencies of the structures declined continually and no obvious cracks appeared in this case. Nevertheless, after completing the excitation of the rare earthquake for the structures without damper connections, the fundamental frequencies of the structures declined greatly, and the obvious cracks and fall-offs occurred.

After completing the excitation of the large earthquake, the main- and sub-structures damaged seriously. In the main- structure, the concrete was greatly crushed or fall-off in the shear-wall root, the longitudinal reinforcements in the columns exposed, and the concretes between floors and frame columns destructed. In the sub- structure, obvious cracks occurred both in the shear-walls and in the floors of the root parts.

**Dynamic Features**

The transfer function was obtained by using the white noise sweep frequency and the spectrum analysis technique. The dynamic features for the frequencies and damping ratio of former two orders of the main- and sub- structures in the X direction are shown in Table 3.

It can be seen that the frequencies of the structures decreased gradually as the excitation was step-loaded. After some excitations of frequent and basic earthquakes, the first order frequencies of the main- and sub- structures decreased 10%, and the damage of the structures appeared. After the excitation of the rare
earthquakes, the first order frequencies of the main- and sub- structures decreased again and the damages extended in the structures.

### TABLE 3. MODEL TEST RESULTS OF MAIN- AND SUB- STRUCTURES IN X DIRECTION.

| No. of Load Conditions | Main- structure | Sub- structure |
|------------------------|-----------------|----------------|
|                        | First Order     | Second Order   | First Order     | Second Order   |
|                        | Frequency /HZ   | Damping Ratio  | Frequency /HZ   | Damping Ratio  |
|                        | Frequency /HZ   | Damping Ratio  | Frequency /HZ   | Damping Ratio  |
| 1                      | 3.756           | 0.052          | 12.770          | 0.046          | 9.014          | 0.039          | 9.014          | 0.020          |
| 2                      | 3.380           | 0.066          | 12.019          | 0.052          | 7.888          | 0.044          | 9.390          | 0.023          |
| 3                      | 3.005           | 0.114          | 10.892          | 0.064          | 7.512          | 0.143          | 7.512          | 0.057          |
| 4                      | 2.629           | 0.183          | 9.766           | 0.092          | 5.634          | 0.215          | 5.634          | 0.086          |

After the excitation of the large earthquakes, the frequencies of the structures decreased obviously, and the first order frequency of the sub- structures decreased about 40% with serious damages of the structures. At the same time, as the increase in the seismic excitations, the damping ratios of the main- and sub-structures tended to increase and the structures got gradually into the elasto-plastic state. In general, both the decrease in frequencies and the increase in the damping ratios of the model structures are relatively coincided during the development of the damages.

**Accelerations of Model Structures**

The acceleration responses was represented by acceleration amplification factor (AAF), or the ratio of the maximum acceleration of each floor to that on the table. Considering the space limit, only AAFs in main- and sub- structures under SHW2 wave of frequent earthquake were herein shown (see Figure 1).

![Figure 1. Acceleration amplification factor in main- and sub-structures under SHW2 wave of frequent earthquake.](image-url)
It can be seen that AAFs were controlled to some extent in each floor of the main- and sub-structures with the damper connections under the frequent and basic earthquake excitations, especially in the case of the basic earthquake excitations; AAFs for some floors increase both under the rare earthquake excitations and under part of the large earthquake excitations. The rapid attenuation in the structure stiffness obviously affects the damper effect. The damper effects were obviously better in the conditions of 7-d and 71-d than those in the condition of 7531-d.

Displacements of Model Structure

Considering the space limit, only the envelope diagrams of relative displacements in main- and sub-structures under SHW2 wave of frequent earthquake were herein shown (see Figure 2). It can be seen that the displacements of the main- and sub-structures were controlled to some extent with the damper connections under the frequent, basic, and rare earthquake excitations, especially in the case of the basic earthquake excitations; the displacements in top floor of the main structure increased under large earthquake excitations; the maximum inter story drift angle satisfy the requirements of the seismic capacity under frequent and rare earthquakes; the damper effects were better in the conditions of 7-d and 71-d than those in the condition of 7531-d.

CONCLUSIONS

The shaking table experiments in simulating earthquake effect were conducted for the frame-shear wall model structures with two adjacent 15- and 7-storey buildings. The dynamic features and seismic responses of the main- and sub-structures were examined. The following conclusions were concluded:
(1) Under the earthquake excitations, the decreases in frequencies and the increases in the damping ratios are relatively coincided during the damage evolutions of the model adjacent structures;

(2) Under the frequent and basic earthquake excitations, acceleration amplification factors of model structures with the damper connections were controlled to some extent in each floor of the main- and sub-structures, and the damper effect was affected by the attenuation in the structure stiffness;

(3) Under the frequent, basic, and rare earthquake excitations, the displacements of the main- and sub-structures with the damper connections were controlled to some extent, while the displacements in top floor of the main-structure increased under large earthquake excitations.

ACKNOWLEDGMENTS

Financial support for the study was provided by the Open Research Foundation of the State Key Laboratory of Disaster Prevention for Civil Engineering under Grant 2007-A-01. This support is gratefully acknowledged.

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