Shaking table investigations on the seismic performance of a steel frame with optimized passive energy dissipation devices

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Abstract. In this study, the seismic responses of two kinds of optimized metallic energy dissipation devices (EDDs) are investigated by conducting shaking table tests on two storey full-scale steel frame model. The dampers are installed in pairs between the beams and corresponding cross bracings on each storey of the model. Then the whole setup, with and without dampers are subjected to different seismic waves with Peak Ground Accelerations (PGAs) of 0.14g, 0.40g, 0.62g and 0.90g with various configurations. In this paper, the dynamic properties, seismic responses and damage details of these distinct setups are recorded, analyzed and compared between controlled and uncontrolled structures. Thus obtained result shows that the effect of these kinds of dampers on acceleration and displacement are quite significant. This study lays down a firm foundation for the reliability of these kinds of passive energy dissipation devices on the basis of deeper research investigations.

1. Introduction

Different kinds of EDDs are widely used for the protection of civil engineering structures against the seismic waves [1,2]. Metallic Yield Dampers (MYDs) and Metallic Shear Dampers (MSDs) are the types of Passive Energy Dissipation Devices (PEDDs), which are made up of highly ductile hysteretic materials like mild steel that uses plastic deformation to dissipate the seismic energy. Since Kelly [3] first proposed the concept of MYD in 1972, there has been intensive research in these kinds of devices for the deeper understanding of mechanism and design methods [4,5]. These devices are proved to be highly efficient in improving the seismic performance of structures by increasing stiffness and damping ability of the structure [6-10]. Due to low cost, long term reliability, simple design, stable hysteretic behavior under repeated cyclic loading and convenience in replacement, PEDDs are widely used in engineering structures [11-13].

Teruna et al. [14] investigated various shaped hysteretic steel damper to evaluate the energy absorption capacity against earthquake load by applying in-plane cyclic loading. They derived stiffness, damping ratio, plastic strain ratio, ductility factor; and finally developed an approximate trilinear hysteretic model through the skeleton curve. The result showed that all the specimens exhibited excellent stable hysteresis under cyclic loading. Similarly, step-by-step time analysis conducted by Moreschi et al. [15] demonstrated that MYDs were a good option against the seismic loads due to their ability to dissipate a considerable amount of energy through hysteresis cycles.
In order to understand and verify the energy dissipation performance of the EDDs under actual earthquake action, this study designs the full-scale steel frame test model based on the optimized TJ metal energy dissipator developed by Shanghai Lanke Building Damping Technology Co., Ltd. The shaking table test is carried out to study the seismic performance of these dampers.

2. Models and Experiment

2.1. Shaking table
The Shaking Tables (Figure 1) used in this experiment is driven by a unique servo motor, and has two degrees of freedom in the X and Y directions. It consists of four 2 m × 2 m shaking table arrays, which can be spliced into single 4 m × 4 m square. This type of large-scale shaking table can carry out the seismic test of buildings, bridges, tunnels, etc. Its maximum overturning moment is 45t.m and the maximum load is 20t; but without any load, the excitation frequency range is 0.1-50Hz and the maximum acceleration is 2.6g; whereas, at full load (20 tons) the excitation frequency range is 0.1-50Hz and the maximum acceleration is 1.0g.

Figure 1. Shaking Tables in Shanghai Jiao Tong University

2.2. Test specimen and full-scale steel frame model
In this experiment two kinds of EEDs viz., TJM-type (Optimized MYD) and TJV-type (optimized MSD) made up of Q235 material are tested by installing in X and Y directions of a full-scale steel frame model with dimension of 1600 mm x 1600 mm x 2840 mm which is illustrated in figure 2(a) and 2(b).

The TJM dissipates energy by out-of-plane yield mechanism, which constitutes of three different vertical double-concave metallic plates connected in between two horizontal plates. Here, each vertical plates possess yielding displacement of 2.5 mm and yielding force of 0.35 kN; hence, altogether each damper set has a yielding force of 1.05 kN. This damper’s close-up view is illustrated in Figure 2(c).

On the other hand, the TJV dissipates energy by in-plane shear deformation mechanism. The yield force and yield displacement of these dampers are 9 kN and 0.22 mm respectively. This damper’s close-up view is illustrated in Figure 2(d).

Figure 2. (a) Steel frame model on shaking table, (b) Dimension of frame (c) TJM, ITI (d) TJV

2.3. Data acquisition and Sensors
In this experiment, DH5922N data acquisition system (4 sets; each with 32 channels) is used for data acquisition. All together 26 cable-type displacement sensors (DH801) are used, with a range of 0~±375 mm. Total of 7 three-way accelerometers (DH311E) are used, with a frequency response range of 0.3~200 Hz. For the measurement of strain, strain gauges (DH-120) with a range of 0~20000 με are used, whose resistances are 120 Ohms. In this study, ground micro-tremor test is carried out by
DEWE Soft’s SIRIUSi-ACC dynamic signal acquisition device with 941B ultra-low frequency detecting sensor. Additionally, to observe the temperature (energy) fluctuation in vertical (yielding) metallic plates in TJM dampers, M7500 Mikron Infrared Thermal Imager (ITI) is used whose temperature and spectral range are -40~120°C and 8.0~14.0 µm respectively.

Acceleration sensors are installed on the base of the test model in both directions, and the maximum measured acceleration value is the ground motion acceleration reference value. Acceleration sensors are placed on the base and each floor level. Under the same working condition, the acceleration amplification factor of each measuring point of the model is obtained by comparing the key parts of the model with the acceleration peaks in the corresponding directions on the base of the structure.

3. Results and Discussion

3.1. Macroscopic damage phenomenon and major seismic response characteristics

1. For the input ground acceleration of 0.14g, there is no damage in both the dampers. After the gradual increase in ground excitation, TJM damper exhibits large deformation at 0.40g; whereas, TJV damper shows large deformation at 0.62g. Hence, TJV damper exhibits very small deformation in comparison to the TJM damper. This implies that TJV is relatively a better choice from the perspective of deformation.

2. For the unidirectional ground motion, TJ damper in another direction is slightly out-of-plane.

3. During plastic yielding of TJM damper, the dissipation of energy (energy fluctuation) is captured by ITI, and the images have been presented below in Figure 3.

![Figure 3. ITI images of TJM (a) Before excitation (b) Initiation of excitation (c) Peak excitation (d) Gradual falling of temperature after decreasing seismic load (e) Shape of TJM.]

3.2. Natural vibration characteristics of the test model

3.2.1. Ground micro-tremor test. To determine the natural frequency of the full-scale test frame model, ground micro-tremor test is conducted before hoisting it onto the shaking table. Thus obtained test results are presented in Table 1.

| Serial Number | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|---------------|-----|-----|-----|-----|-----|-----|-----|
| Natural Frequency (Hz) | 7.63 | 8.69 | 18.66 | 32.66 | 35.10 | 38.88 | 44.78 |
| Damping Ratio (%) | 0.87 | 0.49 | 0.06 | 0.27 | 0.47 | 0.57 | 0.25 |

3.2.2. Sine wave sweep test. To determine the natural frequency of the structure, the shaking table is excited with sine waves of the different frequency range. All the sinusoidal excitations used here are unidirectional, with a peak acceleration of 0.07 g, and the sweeping frequency range of 5~60 Hz. Thus obtained summarized data are presented in Table 2.

| First order frequency | X-Direction |
|-----------------------|-------------|
|                        | At (0.14g)  | At (0.40g)  |
| Controlled Structure   | 9.89        | 9.71        |
| Uncontrolled Structure | 9.08        | 8.78        |

| First order frequency | Y-Direction |
|-----------------------|-------------|
|                        | At (0.14g)  | At (0.40g)  |
| Controlled Structure   | 9.89        | 17.09       |
| Uncontrolled Structure | 9.08        | 8.43        |

| First order frequency | At (0.62g)  |
|-----------------------|-------------|
| Controlled Structure   | 8.60        |
| Uncontrolled Structure | 8.30        |
From table 2, it is clear that the overall stiffness of the controlled structure is much greater than the uncontrolled one. However, with the gradual increase in acceleration the stiffness of both structures gradually decrease, and, at the same time, the damping ratio has gradually increasing trend. This indicates that the damage started from within the structure and gradually amplified.

3.3. Acceleration response

The Acceleration Amplification Factor (AAF) of each floor under the Imperial Valley wave for both the controlled and uncontrolled structure in X and Y-Direction are presented in Figure 4.

AAF in X and Y direction for the damped structure is much lower than the un-damped one during each peak acceleration of every seismic wave (with few exceptions). The results show that the acceleration control effect of both types of TJ dampers is excellent, but the response of TJV is comparatively better than the TJM. However, for the X & Y directions of US174 seismic wave and X direction of Imperial Valley seismic wave, the acceleration response is slightly worse. Increase in inter-storey stiffness due to the addition of dampers could be the possible cause for this anomaly.

Figure 4: AAF in both X and Y-Direction for First and Second Floor of controlled and uncontrolled model under Imperial Valley wave.

3.4. Displacement response

3.4.1. Relative displacement. Considering the Imperial Valley wave as an example, maximum relative displacement in each storey with different seismic intensities are compared in Figure 5.

The test results for displacement responses are summarized as follows:

1. Under earthquake loading, lateral displacement of the damped structure is much smaller than that of the un-damped structure; and the damping effect in Y-Direction is much better than X-Direction. The results show that these damper can effectively reduce the seismic response of the main structure. Therefore, installing TJV type shear metal damper in Y-Direction can better control the relative displacement of the structure.

2. From a statistical point of view, these dampers have significant control over the structural displacement response. However, in a few cases, the displacement of the damped structure is higher than the un-damped structure. This could be because of the additional damping to the structure after installing dampers.

3. The shear metal damper has better control over structural displacement response than the yield metal damper. Hence, TJVs are more suitable for seismic reinforcement of weak stories.

Figure 5. Maximum relative displacement due to minor, moderate and major earthquake (Imperial Valley wave) in each floor for controlled and uncontrolled model (X and Y-Direction).
3.4.2. **Inter-storey angular displacement.** Inter-storey displacement is a very important design parameter in most of the seismic codes. Maximum inter-storey displacement for both the controlled and uncontrolled structure under Imperial valley and its compressed wave are compared in Figure 6.

1. With the increase of input acceleration, the inter-storey drift is significantly increased; but the drift angle is within 1/250.
2. The drift angle of the damped structure is less than the un-damped one, which indicates that the dampers can better control and reduce relative displacement between the stories.

![Figure 6. Maximum angular displacement (X and Y-Direction) for controlled and uncontrolled structure under (a) Imperial valley and (b) Compressed Imperial valley wave.](image)

**4. Conclusions**

In this study, the simulated seismic shaking table test is carried out on the full-scale steel test frame model with TJ-type metallic Passive Energy Dissipation Devices. Based on the observation of experimental failure phenomena and analysis of a large number of experimental data, the following major conclusions are drawn:

1. The results of the shaking table tests show that the TJ-type metallic energy dissipator has remarkable overall stiffness increment and damping effect on the structure under seismic loading.
2. Regardless of numerous multi-directional seismic excitations, there is no damage in the structure. However, for the unidirectional ground motion, TJ-type metallic energy dissipator exhibits large in-plane deformation, but there is no out-of-plane deformation. This suggests that TJ-type metallic energy dissipators possess excellent in-plane deformation and energy dissipation ability.
3. These dampers can effectively minimize the inter-storey drifting within the permissible range. Therefore, they have better control over the relative inter-storey displacement.
4. Acceleration amplification factor in X and Y direction for the damped structure is much lower than the un-damped one during each peak acceleration of every seismic wave (with few exceptions). The results show that the acceleration control effect of both types of TJ dampers is excellent, but the response of TJV is comparatively better than the TJM.
5. These dampers can effectively reduce the lateral displacement of the main structure. Comparatively, installing TJV in Y-Direction can better control the relative displacement of the structure. Hence, TJVs are more suitable for seismic fortification.

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