SHAKING TABLE TESTS ON STEEL FRAME BUILDING WITH INNOVATIVE HYBRID SMA FRICTION DEVICES

H. Qian[1], H. N. Li[1], G. Song[2], L. Sun[1]

[1] *State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, China*
[2] *Dept. of Mechanical Engineering, University of Houston, Houston, TX 77204-4006, USA*
Email: chansteed@126.com, hnli@dlut.edu.cn, gsong@uh.edu

ABSTRACT :

This paper presents an extensive experimental program and main results of shaking table tests performed on reduced-scale steel frame model with and without passive energy dissipation devices. The goal of this work was to assess the effectiveness of the proposed energy dissipation devices in reducing dynamic response of structures subjected to strong seismic excitations. Innovative re-centering hybrid shape memory alloy friction devices (HSMAFD) which consist of pre-tensioned superelastic shape memory alloy (SMA) wires and friction devices (FD) were considered. The most important property of the SMA-based hybrid friction device is integration with stable large energy dissipation capacity and re-centering feature. In the shaking table tests, several representative seismic signals as well as white noise motion were used as input energy. The comparisons of dynamic behaviors, i.e. storey displacements, interstorey drifts and storey accelerations, of structural model with and without SMA-based RCD under seismic loading were conducted. The results show that HSMAFD were effective in suppressing the dynamic response of building structures subjected to strong earthquakes by dissipating a large portion of energy through their hysteretic loops. Moreover, the structures were able to undergo strong earthquakes without remarkable residual drift due to the re-centering feature of the devices.

KEYWORDS: shape memory alloys, shaking table test, passive seismic control, energy dissipation

1. INTRODUCTION

It is widely accepted that passive vibration control is a promising design strategy to enhance structural functionality and safety against natural hazard, such as earthquake. Current passive control applications are mainly based on the following three techniques: seismic isolation, energy dissipation and dynamic resonance absorption (Soong and Spencer 2002). Among them, energy dissipation technique, relying on the absorption and dissipation of large amount of energy by damping devices, provides a very effective passive method of protecting structures from earthquakes (Soong et al. 1997).

Generally, current damping devices operate on principles such as yielding of metals, sliding friction, deformation of viscoelastic (VE) solids or fluids and extrusion of fluid through orifice. Recently, a class of special alloys, i.e. shape memory alloys (SMAs), which dissipate energy through martensitic phase transformation in material, attract extensive attentions in the application of earthquake engineering (Song et al. 2006).

SMAs (Duerig et al. 1990) exhibit some unique properties, including shape memory effect, superelasticity effect, extraordinary fatigue and corrosion resistance, high damping characteristic and temperature-dependent Young's modulus, which make them particularly suited for seismic applications in structural engineering.

In the past decade, some passive energy dissipation devices based on shape memory alloys have been presented (e.g. Wilde et al. 2000; Dolce et al. 2000; Dolce et al. 2005; DesRoches et al. 2002; Han et al. 2003; Li et al. 2004; Li et al. 2006; Zhu and Zhang 2007; Ren and Li 2007; Li and Qian 2007). Among these outcomes, the most substantial effort in the area of seismic applications of SMA has been from the research project named MANSIDE (Memory Alloys for New Seismic Isolation and Energy Dissipation Devices) conducted by the European Union. As results of this project, Dolce et al. (2000) developed two families of SMA-based energy dissipating and re-centering braces for seismic vibration control of buildings and bridges. To assess the effectiveness of SMA braces to reduce the seismic response of reinforced concrete (RC) framed structures, shaking table tests of a 1/3.3-scale, three-story, two-bay RC plane frame, which was designed for low seismicity and low ductility according to the European seismic code, were carried out by Dolce et al.(2005). Their experimental results show that the SMA braces can enhance seismic performances at least comparable to those provided by steel braces, while having an additional self-centering feature.

An innovative hybrid SMA friction device (HSMAFD) combining friction damper (FD) with pre-tensioned superelastic shape memory alloy (SMA) wires was also developed in previous works by the authors (Li and Qian 2008). HSMAFD shows satisfying hysteresis properties, including both recentring and the energy dissipating features. The main aim of this paper is to assess the effectiveness of the HSMAFD in reducing the seismic response of structures through shaking table tests. A 1/4-scale, 3-story steel frame building was tested. The comparisons of dynamic behaviors, i.e. storey displacements, interstorey drifts and storey accelerations, of structural model with and without HSMAFD under various seismic loading were conducted.

2. INNOVATION ENERGY DISSIPATION DEVICES

In this study, innovative hybrid SMA friction device (HSMAFD) (Li and Qian 2008) as energy dissipation device was considered. HSMAFD consists of recentering device based on pre-tensioned superelastic NiTi wires and friction device (FD), as shown in Figure 1. The superelastic NiTi wires mainly perform a function of recentering due to large restoring force, as well as additional energy dissipation owing to their hysteretic damping property. The friction devices are utilized to dissipate most seismic energy by relative sliding between the friction plants impacted by high strength bolts. By properly combining the number and the pre-tensioning level of the superelastic SMA wires and the friction force, the device exhibits supplemental recentering capacity and energy dissipating feature, which can be exploited to reduce structural seismic response and return the building to the initial position after earthquakes. Figure 2 presents a HSMAFD fabricated based on the design.

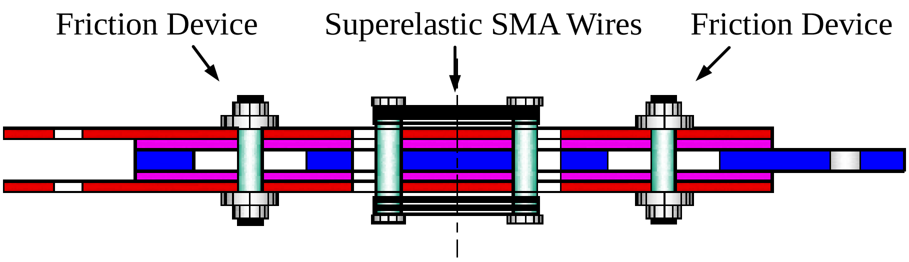


Figure 1 Scheme diagram of a HSMAFD

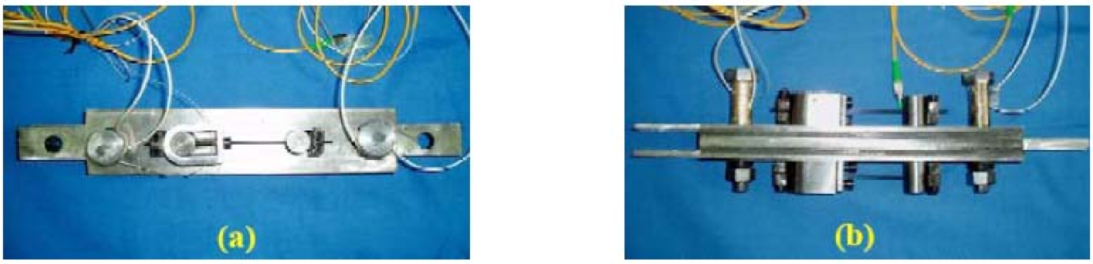


Figure 2 Photos of HSMAFD

Figure 3 shows hysteretic behavior of a HSMAFD under sinusoidal cyclic displacements of increasing amplitudes with loading frequency of 0.05Hz, 0.1Hz, 1.0Hz and 2.0Hz, respectively. As we can see, satisfying hysteretic loops, including both recentring and the energy dissipating features, were obtained under various conditions. With the increase of the displacement amplitude, the energy dissipation per cycle increases almost linearly, while the secant stiffness and the equivalent damping decrease. Moreover, the performance is not highly sensitive to frequencies of loading in the range of which earthquake engineering concerns.

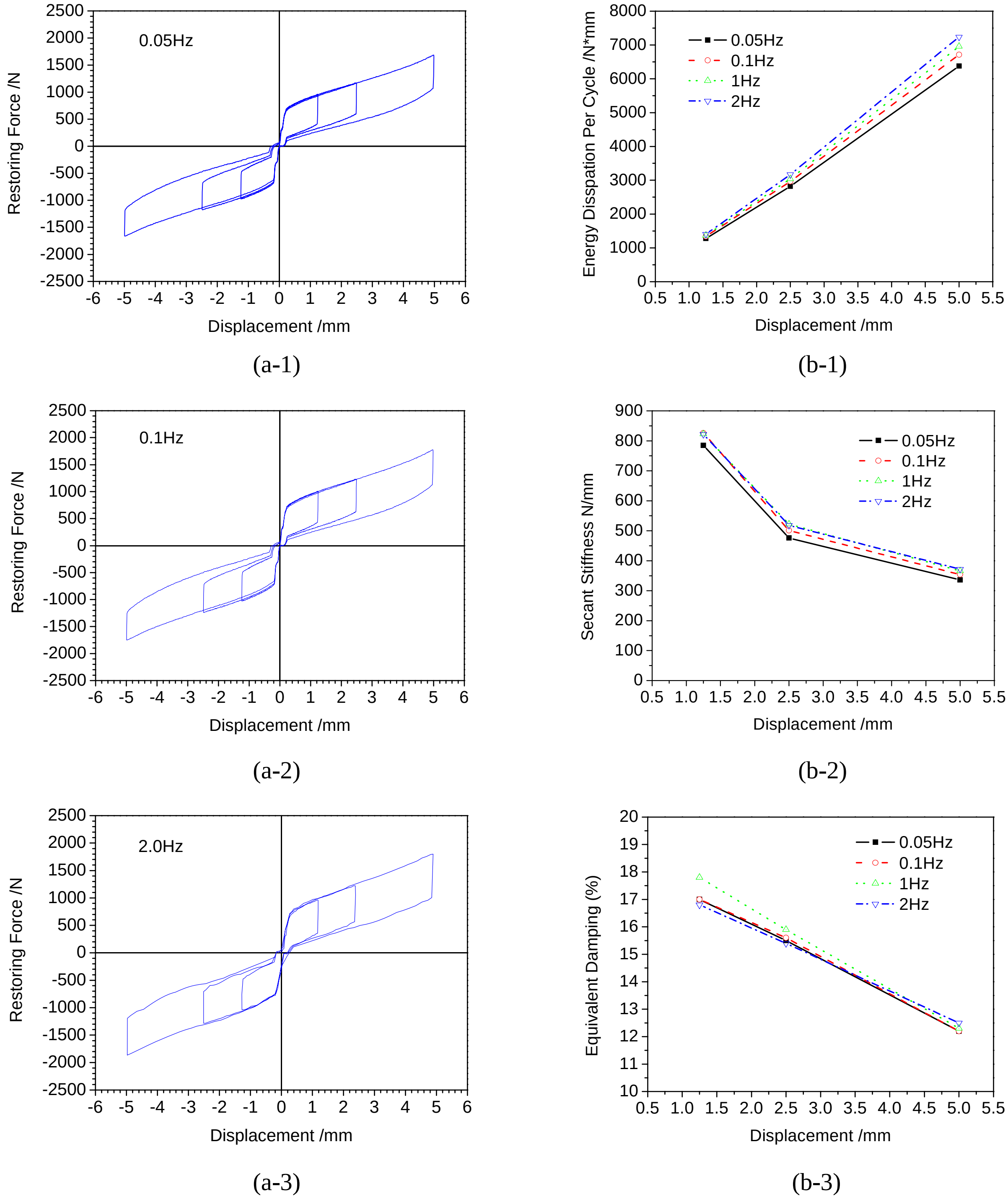


Figure3 Hysteretic behaviour of HSMAFD under various loading frequency and displacement amplitudes: (a) Force-displacement curves; and (b) Mechanical quantities.

3. SHAKING TABLE TESTS

3.1. Shaking table

The experimental tests were carried out on the earthquake simulator shaking table of the State Key Laboratory of Coastal and Offshore Engineering in Dalian University of Technology. It included a 3m×4m steel platform, with three degree of freedom, driven by servo-hydraulic actuators which were numerically controlled by a MTS analogue electronic control system. The shaking table has about 10 tons payload capacity with frequency band of 0.1~50Hz.

3.2 Structural model

The structural model in the tests is a 1/4 scaled three-story steel frame. Its overall dimension is 1.5×1.5m in plane and 2.4m in elevation. All the columns in the model have constant cross section (30mm×30mm×3mm angle iron). Similarly, all the beams have the same cross section (60mm×40mm×3mm rectangle iron). The main geometrical characteristics of the steel frame model are shown in Figure 4. The yield stress and Young's modulus of the material are 215MPa and 206GPa, respectively. Masses added to the structure are 300.6kg for the first floor, 300kg for the second floor and 318.5kg for the third floor.

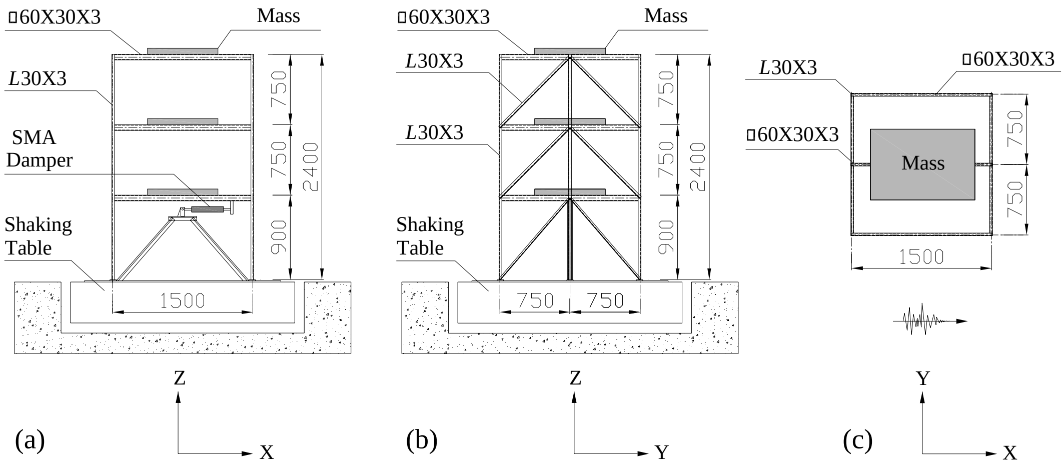


Figure 4 Geometrical characteristics of the steel frame model (unit: mm):
(a) X direction elevation; (b) Y direction elevation; and (c) typical floor plan.

3.3 Earthquake historical records

In the tests, the flowing three earthquake historical records were selected: (i) El Centro. The N-S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of May 18, 1940; (ii) Taft. The S69E component recorded at Taft Lincoln School Tunnel, Kern County, California earthquake of August 31, 1976; (iii) Tianjin. The N-S component recorded at the Tianjin hospital, Ninghe, Tangshan aftershock of November 15, 1976. The absolute peak acceleration of the earthquake records are adjusted to 0.15g. Additionally, the equally-spaced intervals of El Centro, Taft and Tianjin are 0.01s, 0.01s and 0.005s, respectively. Additionally, random white noise tests were conducted to identify the fundamental frequency of vibration and assess the damage suffered by the structure subjected to the seismic records.

3.4 Shaking Table Tests Results

Fig.5 shows the frequency spectrum of the structure with and without damping device. As can be seen, the fundamental frequency of the structure increases from 2.02Hz to 3.06Hz, up more than 50%, after HSMAFD was installed, which indicates that the energy dissipation system provides supplemental stiffness into the original structure.

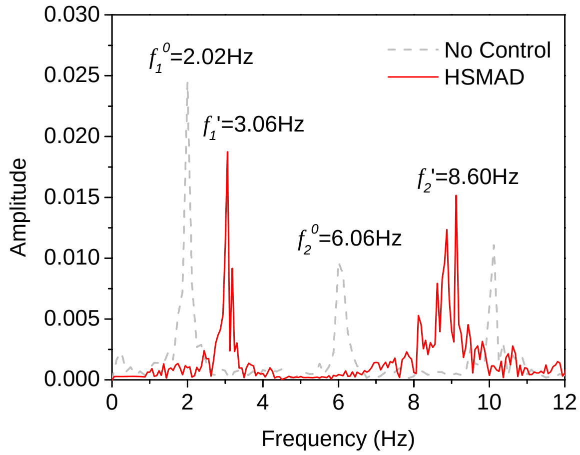
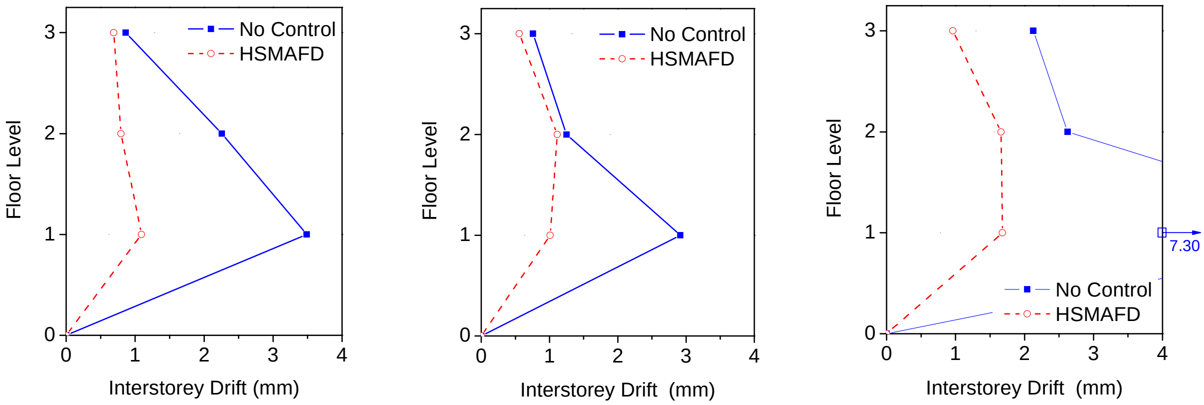
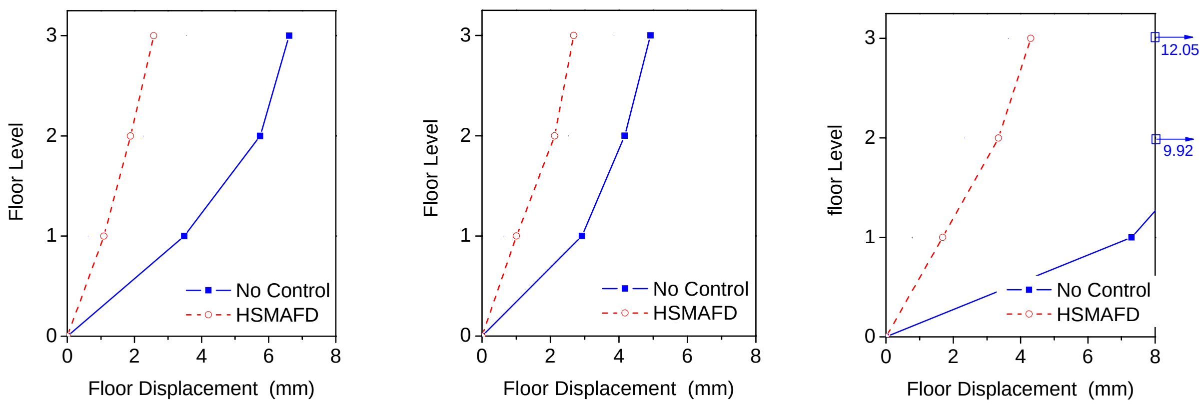


Fig. 5 Frequency spectrum of the free and controlled structures



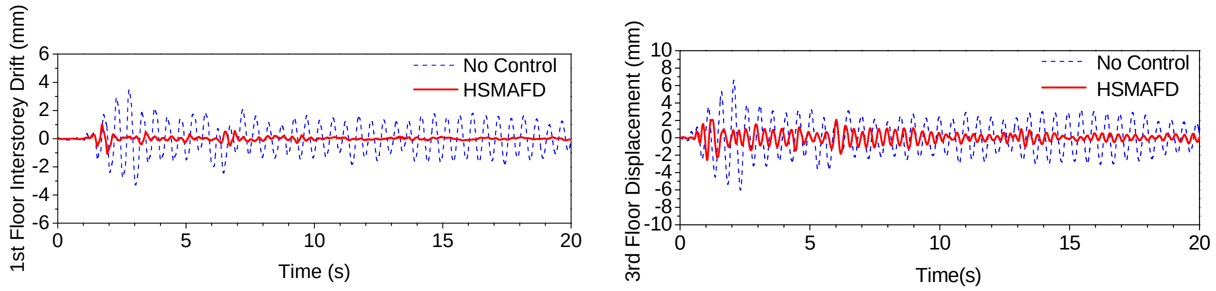
(a) El Centro (b) Taft (c) Tianjin

Fig.6 Profiles of maximum interstorey drifts for the free and controlled structures

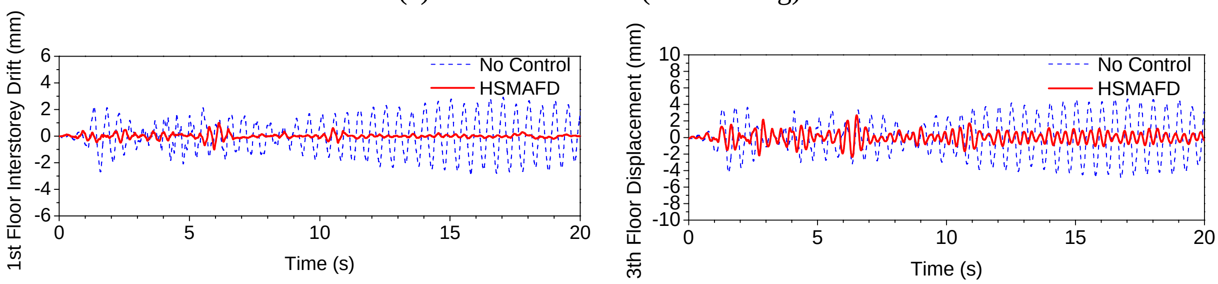


(a) El Centro (b) Taft (c) Tianjin

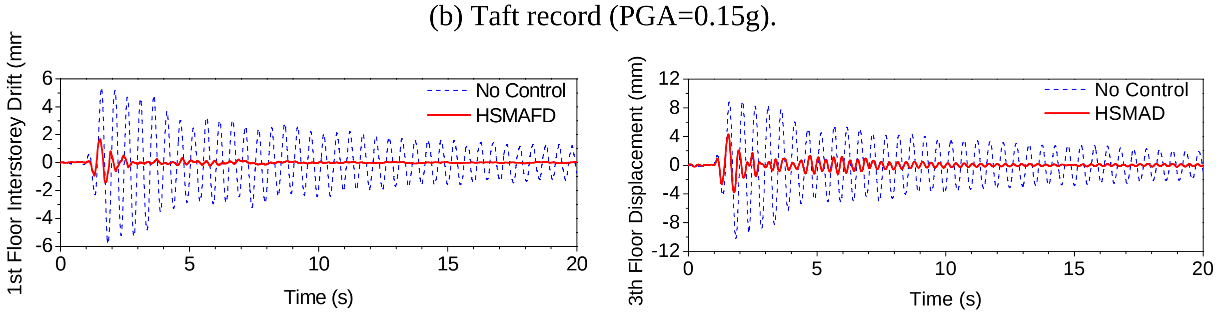
Fig.7 Profiles of maximum absolute displacements for the free and controlled structures



(a) El Centro record (PGA=0.15g).



(b) Taft record (PGA=0.15g).



(a) Tianjin record (PGA=0.15g).

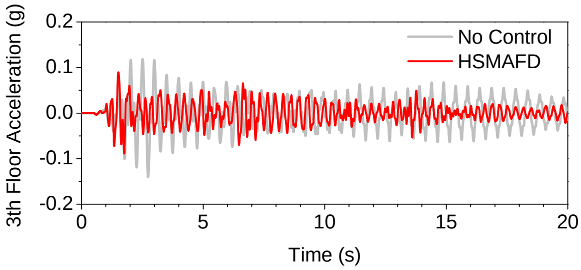
Fig. 8 Time history of (a) interstorey drift of the 1st floor, and (b) absolute displacement of the 3rd floor

Fig. 6 shows the profiles of maximum interstorey drifts for the free and controlled structures under different earthquakes with 0.15g PGA. As seen from the Figure, interstorey drifts of the building have been non-identically reduced. Especially, compared with the two upper floors, the first floor has a more significant effect, decreasing by 69.1% for El Centro, by 65.5% for Taft and by 77.1% for Tianjin, respectively. This is because the damping device was only installed in the first floor of the building.

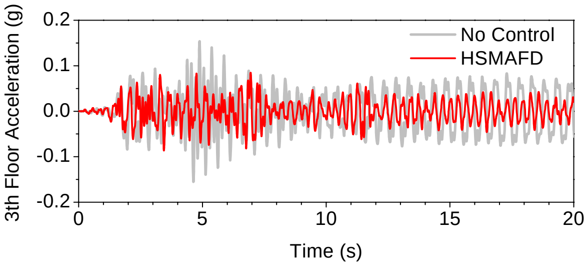
Fig.7 shows the profiles of maximum absolute displacements relative to the table for the free and controlled structures under different earthquakes with 0.15g PGA. As can be seen, the maximum absolute displacements relative to the table of the top floor of the building decrease by 61.0% for El Centro, 45.7% for Taft and 65.6% for Tianjin, respectively.

Fig.8 shows the time history of the 1st floor interstorey drifts and the 3rd floor absolute displacement of structure with and without energy dissipation system under different seismic records. In the figures, the blue dashed lines and the red solid lines represent the seismic response of the free and controlled structures, respectively. As we can seen, the seismic response of the structure have been significant reduced by the SMA damper.

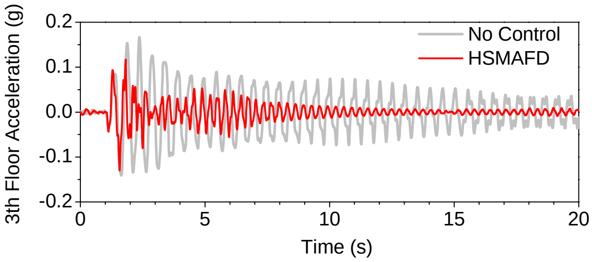
Fig.9 shows the time history of the 3rd floor acceleration of the free and controlled structure. As can be seen, the accelerations of the 3rd floor have been reduced, but no significant control effects are found because the energy dissipation system adds supplemental stiffness into the original structure.



(a) El Centro, PGA=0.15g



(b) Taft, PGA=0.15g



(c) Tianjin, PGA=0.15g

Fig. 9 Time history of acceleration of the 3th floor

4. CONCLUSIONS

To assess the effectiveness of an innovative energy dissipation system (HSMAFD) in reducing the seismic response of structures, shaking table tests on a 1/4-scale, 3-story steel frame building with were carried out. The comparisons of dynamic behaviors, i.e. storey displacements, interstorey drifts and storey accelerations, of structural model with and without HSMAFD under various seismic loading were conducted. The fundamental frequency of the structure increases by about 50% after HSMAFD was installed due to its supplemental stiffness. The interstorey drifts and the absolute displacements relative to the table of the building have been non-identically reduced by HSMAFD. The first floor has a more significant effect than the other two floors because the arrangement of the HSMAFD in the first floor. The results show that HSMAFD were effective in suppressing the dynamic response of building structures subjected to different earthquakes by dissipating a large portion of energy through their hysteretic loops.

ACKNOWLEDGEMENTS

The research reported in this paper was supported by the Outstanding Young Scientist Award of National Science Foundation of China (NSFC) through Grant No. 50025823 and the Overseas Outstanding Young Scientist Award of NSFC through Grant No. 50328807. These supports are greatly appreciated.

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