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A superelastic viscous damper for enhanced seismic performance of steel moment frames

Baikuntha Silwal [a], Robert J. Michael [b], Osman E. Ozbulut [a,*]

[a] Department of Civil and Environmental Engineering, University of Virginia, Charlottesville, VA, USA
[b] Department of Mechanical Engineering, Gannon University, Erie, PA, USA

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ABSTRACT

This study proposes a hybrid passive control device and investigates its performance in improving response of steel frame structures subjected to multi-level seismic hazards. The proposed superelastic viscous damper (SVD) relies on shape memory alloy (SMA) cables for re-centering capability and employs a viscoelastic (VE) damper that consists of two layers of a high damped (HD) blended butyl elastomer compound to augment its energy dissipation capacity. First, experimental tests are conducted to characterize behavior of SMA cables and VE damper and to assess the influence of various parameters such as displacement amplitude and loading frequency on their mechanical response. Then, an analytical model of a six-story steel special moment frame building with the installed SVDs is developed to determine the dynamic response of the structure. Nonlinear response history analyses are conducted to evaluate the behavior of controlled and uncontrolled buildings under 44 ground motion records. Results shows that SVDs can effectively mitigate dynamic response of steel frame structures at different seismic hazard levels and enhance their post-earthquake functionality.

1. Introduction

Passive energy dissipation systems can favorably affect the dynamic response of civil structures in retrofit scenarios as well as new design. These devices, which require no additional energy to operate, generate a control force or provide improved energy dissipation in structural systems. A number of passive energy dissipation systems have been proposed and developed to mitigate damaging effects of natural hazards on structures [1]. Passive energy dissipation devices can be grouped into two main categories: displacement-dependent and rate-dependent devices. Examples of displacement-dependent devices include metallic yielding devices and friction devices. Energy dissipation in hysteretic devices depends primarily on relative displacements within the device. These devices add initial stiffness until yielding or slip occurs and dissipate energy especially at large deformations. Metallic devices usually have a limited number of working cycles and may require replacement after a strong event. Friction devices may lead to permanent deformations if no restoring force mechanism is provided. Examples of rate-dependent devices include fluid viscous dampers and viscoelastic dampers. These devices can dissipate energy at all levels of vibration and may provide some stiffness [2]. The energy dissipation capacity of rate-dependent devices depends on the velocity across the device.

Viscoelastic (VE) dampers consist of viscoelastic layers, which are typically copolymers or glassy substances, bonded with steel plates. Damping is produced via hysteresis or relative motion of polymer molecules. Some materials, such as butyl and silicone, have inherently high damping and are quite common for VE dampers. Other materials such as natural rubber and neoprene are compounded to produce high damping via fillers (oil, carbon black, etc.), but this may compromise other properties such as tensile strength and elongation. A number of researchers examined the performance of VE dampers in reducing seismic response of structures. Chang et al. [3] conducted shake table tests on scaled three-story steel frames with and without VE dampers. They found that the VE dampers can effectively reduce the structural response and ductility demand on the test structure under strong earthquakes. Xu [4] carried out shake table tests to evaluate the dynamic response of 1/5-scale reinforced concrete structure with VE dampers. Xu et al. [5] also assessed the performance of eight-story reinforced concrete frame structure with VE dampers through numerical simulations. Another group of researchers developed simplified design procedures for seismic design of reinforced concrete structures [6] and steel frame structures [7] with the installed VE dampers.

Viscoelastic dampers have also been combined with a displacement-dependent device to produce a hybrid damping

* Corresponding author. Tel.: +1 434 924 7230; fax: +1 434 982 2951.
E-mail address: ozbulut@virginia.edu (O.E. Ozbulut).

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system, which can effectively control the response of structures over a wide range of displacement amplitudes. VE dampers can provide energy dissipation at low-level vibrations while the displacement-dependent devices do not provide sufficient damping at small vibrations. On the other hand, the displacement-dependent devices dissipate significant energy during large magnitude earthquakes and can augment the damping capacity of VE dampers during strong earthquakes. Tsai et al. [8] proposed the combination of a metallic yielding device in parallel with a VE damper. Marshall and Charney [9] studied the performance of hybrid passive control systems, which combine a VE damper or viscous damper with a buckling restrained braces (BRBs) in mitigating seismic response of steel frame structures. Yamamoto and Sone [10] conducted both numerical and experimental studies on three different hybrid passive control systems. They considered the combination of a VE damper with a steel shear panel and a BRB as diagonal or inverted-V type connection. Note that in all above-mentioned hybrid control systems, the displacement-dependent device needs to be replaced after a strong earthquake.

Shape memory alloys (SMAs) are metallic alloys that can fully regain their original shape upon being deformed [11]. These materials are of particular interest primarily due to their unique re-centering ability and energy dissipating capacity, excellent corrosion resistance, and high fatigue resistance. However, previous studies on SMAs indicate that the quantity of equivalent viscous damping provided by superelastic SMA wires or bars is not sufficient to render the use of SMAs as the sole damping device implemented in a tall structure subjected to severe dynamic loadings [12,13]. Therefore, several researchers have explored the development of SMA-based control devices with supplemental energy dissipation capabilities. Yang et al. [14] and Zhu and Zhang [15] adopted a hybrid strategy by combining SMA wires with traditional hysteretic devices; the former used energy absorbing struts while the later utilized a sliding friction-based configuration. Both devices were successful in improving structural response to dynamic loading while providing excellent re-centering capabilities. Ozbulut and Hurlebaus [16,17] proposed an SMA-based semi-active device that combines a variable friction damper and SMA wires, and evaluated the performance of the hybrid device through numerical simulations. Miller et al. [18] developed and tested a self-centering buckling restrained brace (BRB) that combines a typical BRB component with pre-strained SMA rods. Luo et al. [19] proposed an SMA damper that consists of two components. Superelastic SMA wires are used as re-centering component and martensite SMA sheet or low yield steel sheet is used for energy dissipation.

This paper proposes a conceptual design for an innovative SMA-based damper and illustrates its efficiency through numerical simulation of a case study. The superelastic viscous damper (SVD) combines the energy-dissipating capacity of a conventional viscoelastic damper with the excellent re-centering properties of SMA cables in a single device, which demonstrates an improved, hybrid response. In what follows, the experimental studies on the individual components of the hybrid damper, namely SMA cables and a high damped (HD) butyl elastomer, are described first. Then, the design and behavior of the proposed superelastic viscous damper are introduced. Next, the modeling of SVD and a six-story steel frame building is discussed. Finally, nonlinear response history analyses are conducted to explore the effectiveness of the SVD in suppressing the response of the steel building.

2. Shape memory alloy cables

Shape memory alloy cables have been recently developed as an alternative and new structural element [20]. They leverage the superior mechanical characteristics of small diameter SMAs into large-size structural tension elements. Besides, they have considerable cost advantages over same size monolithic SMA bars [21]. In this study, SMA cables are considered for the development of a hybrid seismic device. The SMA cable is made of Nickel Titanium (NiTi) and obtained from Fort Wayne Metals, Research Products Corp. The SMA cable, which was produced in a helix configuration, is composed of 7 strands and each strand had 7 wires. Each wire had a diameter of 0.885 mm providing outer cable diameter of 8 mm and total cross sectional area of 30.14 mm^2.

The uniaxial tensile tests are conducted at various loading rates and strain amplitudes to characterize the superelastic properties of the SMA cable and study the rate-dependent mechanical response of the SMA cable under dynamic loads. Fig. 1 shows the schematic drawing of the SMA cable cross-section, longitudinal section of the cable and test set up. The test samples are obtained by cutting the cable into pieces with a length of 150 mm. Before formal tests, a training test procedure that consists of 20 load cycles at a strain amplitude of 5% at 0.01 Hz was applied. The displacement and force data was recorded using MTS data acquisition system. The strains were also measured using a laser extensometer.

In order to investigate the cable behavior under different strain amplitudes, the cable was cycled, with a frequency of 0.05 Hz, to obtain target strains of 2%, 3%, 4%, 5%, 6%, 7%, 8%, and 9%. All the tests lasted for 3 cycles. Fig. 2(a) represents stress–strain curves for experimental tests at measured strain amplitudes varying from 1.5% to 7.7%. It can be observed that the material exhibits well-known flag-shaped cycles, which is a common behavior of SMAs. The SMA cable recovers almost all of its deformations upon unloading when it is loaded up to strain amplitude of 6.5%. On the other hand, recorded residual strains at strain amplitudes of 7.2% and 7.7% are only about 0.2%. It can be also seen that the strength of the cable decreased at high strain amplitudes possibly due to the failure of individual wires at the gripping region.

Tests matrix was then extended to include the behavior of the cable under higher frequency cyclic loads. The tensile loads were applied to the cable in a displacement controlled test to obtain 6% target strain using test frequencies of 0.1, 0.5, 1.0, and 2.0 Hz. Fig. 2(b) shows the hysteresis loop at each loading frequency. It can be observed that both the forward and reverse transformation stresses increase with the increasing test frequency. However, the increase in the reverse transformation stress level is more pronounced. Therefore, the area under the hysteresis loop, which signifies the energy dissipation, slightly decreases for the higher loading rates.

3. High damped butyl elastomer

The HD butyl series is compounded specifically to produce high damping at moderate to low stiffness. These elastomers are currently in use in various VE dampers and in a new base isolation system used to isolate storage racks from seismic events [22–24]. For these devices, the HD butyl has resulted in an increase in damping by more than a factor of two over traditional elastomers. In this study, the HD butyl compounds are considered for use in an SMA-based hybrid damper.

Butyl rubber is a synthetic rubber produced by polymerization of about 98% isobutylene with about 2% of isoprene. Butyl rubber is also known as polyisobutylene or PIB. It has excellent impermeability, inherently high damping and its long polymer chains give it excellent flex properties. The first major application of butyl was tire inner tubes because of its excellent impermeability to air. Butyl is also used extensively in vibration isolators due to its high damping. Other favorable properties include a low glass transition