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Application of Intelligent Passive Devices Based on Shape Memory Alloys in Seismic Control of Structures

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ABSTRACT

In this study, seismic application of an innovative control device called self-centering hybrid damper (SCHD) is investigated. Two main characteristics of the SCHD result in structural response mitigation. Steel pipe as a vertical link and two transverse pairs of Shape Memory Alloy (SMA) wires are used as energy dissipation and recentering components, respectively. Adjustable design parameters including design load, incorporation percentage of SMA, pipe height and wire inclination angle provide desirable structural responses. A numerical parametric study revealed the effect of each parameter on device performance. Besides, an optimum incorporation percentage of SMA in design load was obtained from the parametric study. The results also indicated that in addition to ideal energy dissipation capability, SCHDs can effectively reduce the permanent displacement. Nonlinear time-history analysis of a 5-story building equipped with the SCHD was conducted to evaluate the effectiveness of the device. The results indicated that utilization of the proposed innovative damper is an effective way in reduction of roof acceleration, peak interstory drift and permanent displacement.

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1. Introduction

In recent years, various design philosophies have been developed to reduce the economical losses and inelastic deformations of structures under strong ground motions. After the 1994 Northridge earthquake, supplemental energy dissipation devices have been introduced to improve the resistance of structures. A wide range of materials can be used in passive energy dissipation systems to improve the structural responses [1, 2]. Examples of such systems are viscoelastic devices, buckling-restrained braces (BRB) and friction dampers. In spite of several advantages of energy dissipation devices, relatively large residual displacement is the major deficiency in these systems. Moreover, current technologies demonstrate some restrictions including problems related to temperature dependence performance, serviceability and resilience and complications related to installation and substitution.

Application of SMA-based self-centering systems received significant attention from scholars and designers recently. SMAs are unique class of alloys with capability to recover their original shape upon unloading (Superelastic Effect-SE) and heating above a transformation temperature (Shape Memory Effect-SME) [3]. The striking characteristics of SMAs can be attributed to thermal effect or stress-induced phenomenon. Considering its exclusive properties, SMA wire is used as a core recentering component in the SCHD.

Several numerical and experimental studies have shown the workability of SMAs in vibration mitigation of structural systems. Desroches and Delemont [4] have investigated the effectiveness of SMA bars to hinder unseating of the bridge deck from the pier. A modern base isolation system composed of steel-teflon flat sliding bearings was proposed by Jalali et al. [5]; they used SMA truss elements to provide a proper restoring capability. Besides, Cardone et al. [6] conducted an experimental investigation of the Smart Restorable Sliding Base Isolation System (SRSBIS) using superelastic Shape Memory Alloy (SMA) wires, and the outcomes revealed that the SRSBIS can be reliably used in passive control of structures. Dolce et al. [7] evaluated the effectiveness of SMA braces in reinforced concrete structures, results from shaking table test demonstrated that SMA bars can provide favorable self-centering capability. In addition to the mentioned applications, SMAs gained widespread popularity in framed structures. Dolce et al. [8] tested special types of braces using promising properties of SMA during the 'Memory Alloys for New Seismic Isolation and Energy Dissipation Devices' project, the working mechanisms of the device verified the new design concept. Ozbulut and Hurlebaus [9] introduced a recentering variable friction device for vibration limitation of structures subjected to near-field excitations. Simulation results demonstrate that the proposed device has the capability to reduce the peak structural response. Zhu and Zhang [10] investigated the seismic response of a concentrically braced frame (CBF) with reusable hysteretic damping brace made of energy-dissipating SMA wires, results show that the proposed system has a potential to eliminate the residual interstory drift. In another study, Zhu and Zhang [11] suggested a type of bracing element

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named self-centering friction damping brace for utilization in CBF systems, recentering characteristic of the device is satisfied with stranded superelastic SMA wires while energy dissipation procedure is complemented by means of friction. Yang et al. [12] proposed an innovative hybrid device that combined energy dissipation and recentering components. According to the presented formula of force distribution between the components, the hybrid damper showed recentering capability with maximum energy dissipation capacity. Motahari et al. [13] implemented a damper using different phases of SMA to produce a reasonable behavior which is efficient for both energy dissipation and recentering capabilities. Asgarian and Moradi [14] evaluated the seismic performance of steel frames equipped with SMA braces. The results indicated that SMAs are favorable materials which lead to reduction in residual displacement and peak interstory drift. Jalaeefar and Asgarian [15] developed and tested a hybrid damping device with energy-dissipating and recentering characteristics using steel and SMA bars, respectively. Besides, the optimum proportion of SMA and steel was obtained in various analyses. Ma and Yam [16] examined a self-centering damper with recentering and energy dissipating components group. Their studies show that the controlled structure vibrates around its initial position. Salari and Asgarian [17] investigated seismic performance of steel braced frames using SMA-based hybrid damper. Results proved the efficiency of the device in seismic response mitigation.

McCormick et al. [18] evaluated a novel CBF to compare its seismic performance with traditional systems. They applied rigid bracing members with continuous SMA in whole brace. Krumme et al. [19] have proposed a SMA-based damper for passive control of structures. The success of the proposed damper was revealed through the experiments conducted by Clark et al. [20].

The favorable concept behind the SCHD is the parallel use of the two different sub-components that slightly increases the preliminary building design cost and markedly mitigates the cost related to seismic events. Functional simplicity, moderate encumbrance under installation condition and great durability are the most important features of SCHDs. The main concentration of previous studies was on the reduction of structural responses such as interstory drift. However, similar trend was not observed in time history of acceleration, especially during the earthquake. This response has effectively reduced using the proposed SCHD.

1.1. Shape memory alloys

The dual-phase microstructure of SMAs displays two distinct crystal structures: the austenite phase stable at higher temperatures with body-centered cubic structure, and the martensite phase which is the weaker SMA stable at lower temperatures with parallelogram structure. The presence of stress and temperature changes triggers the transformation between the two crystallographic phases. External stress and temperature have mutual effects on the transformation mechanism. In other words, higher stress leads to higher transition temperatures. There are four critical temperatures that pinpoint the start and final of the straight and reversal transformation. M_s and M_f indicate the martensite start and finish temperatures, respectively. While A_s and A_f denote the austenite start and finish temperatures. Fig. 1 illustrates a stress-strain diagram of SMA under isothermal transformation when $T > A_f$. A considerable strain of 8%-10% will be fully recovered at the end of the applied load [21]. A plump hysteresis loop with zero residual strain will be produced under this unique behavior (SE). A small number of parameters are required to compose the constitutive model which represents the mechanical properties of SMAs. σ_S^{AS} and σ_F^{AS} are starting and final stresses in martensite forward transformation which equal to 525 MPa and 600 MPa, respectively. Similarly, σ_S^{SA} and σ_F^{SA} are martensite to austenite starting and final stresses which equal to 250 MPa and 100 MPa, respectively. E_{SMA} is the elasticity modulus of SMA which equals to 21,500 MPa in austenite and martensite phases [15].

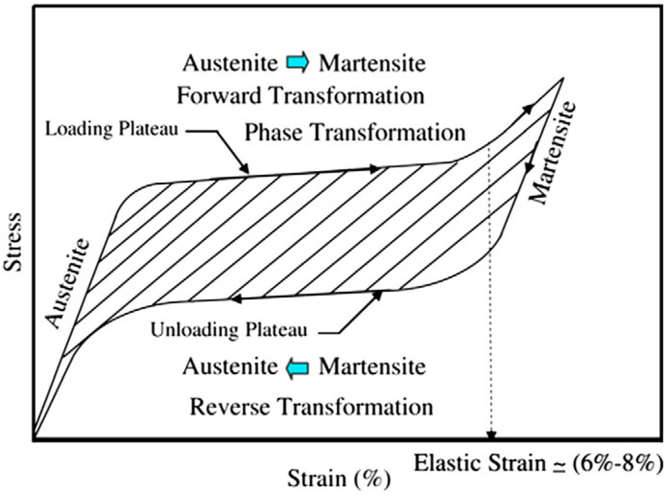

Fig. 1. Stress-strain relationship of superelastic SMA wires [21].

Some different types of SMAs are evaluated based on their mechanical and durability properties. Among them, NiTi is considered as the most popular alloy in vibration control of structures. The main reasons include its extraordinary fatigue and corrosion resistance, preferable superelastic behavior and great durability.

In order to evaluate the effectiveness of SMA wires, cyclic performance of 16 different SCHDs is compared with similar dampers in the absence of SMA wires. Residual displacement and dissipated energy of dampers with different incorporation of SMA are determined to obtain an optimum loop shape. First, a detailed specification of SCHD and its modeling procedure are presented.

2. Description of SCHD mechanism

The schematic of the SCHD for use between the beam and braces is indicated in Fig. 2(a). As can be seen in Fig. 2(b), the device is fabricated of two subcomponents: two pairs of identical transverse SMA wires and a steel pipe. Two plates are installed at both ends for exerting boundary conditions. The benefits of using steel pipe come from its excellent energy dissipation capacity upon yielding and its low cost. Besides, due to being independent from loading rate and surrounding temperature, energy dissipation through steel yielding is a trustworthy method. The hysteretic behavior of SCHD is determined using superposition of flag-shaped hysteresis loop of SMA wires and rectangular curve obtained from yielding of steel pipe. The combined hysteresis loop shows a self-centering behavior accompanied by favorable energy dissipation capability. Owing to high fatigue life of NiTi wires, SCHD can be designed to withstand several intense aftershocks without workability deterioration. For recentering group upon loading, the relative displacement between the two plates will induce tension in one of the two transverse SMA wires, while the wires in another direction simply go slack. Each wire is comprised of several SMA wires with submillimeter diameters to provide the required cross sectional area. Therefore, due to the probability of buckling, compression section of the stress-strain curve is ignored. Furthermore, this movement triggers the energy dissipation process through the deformation of steel pipe. It should be noted that the end plates need to be thick enough to remain elastic under lateral loading.

2.1. Steel and SMA wire modeling

Cyclic loading analyses of SCHDs were carried out using ABAQUS finite element program [22]. The steel used in this study was tested by Maleki and Bagheri to evaluate the shear pipe damper performance, and yield stress of the material is assumed to be equal to 250 MPa [23].

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