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Re-centering variable friction device for seismic control of structures

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Abstract: This paper investigates the seismic response control of a nonlinear benchmark building with a new re-centering variable friction device (RVFD). The RVFD consists of three parts: (i) a friction generation unit, (ii) a piezoelectric actuator, and (iii) shape memory alloy wires. The friction unit and piezoelectric actuator compose the first subcomponent of the hybrid device that is a variable friction damper (VFD). The clamping force of the VFD can be adjusted according to the current level of ground motion by adjusting the voltage level of piezoelectric actuators. The second subcomponent of this hybrid device consists of shape memory alloy (SMA) wires that exhibit a unique hysteretic behavior and full recovery following post-yielding deformations. In general, installed SMA devices have the ability to re-center structures upon end of the motion and VFDs can increase the energy dissipation capacity of structures. The full realization of these devices into a singular, hybrid form which complements the performance of each device is investigated. A neuro-fuzzy model is used to capture rate- and temperature-dependent nonlinear behavior of the SMA components of the hybrid device. A fuzzy logic controller is developed to adjust voltage level of VFDs for favorable performance in a RVFD hybrid application. Numerical simulations of seismically excited nonlinear benchmark building are conducted to evaluate the performance of the hybrid device. Results show that the RVFD modulated with a fuzzy logic control strategy can effectively reduce interstory drifts without increasing acceleration response of the benchmark building for most cases.

Keywords: shape memory alloys, friction device, re-centering, benchmark building

1 Introduction

Protection of civil structures against natural hazards such as earthquakes and strong winds constitutes a significant task for structural engineers. Over past two decades,

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numerous control devices and strategies have been proposed to provide structural integrity with the goal of improving the safety and performance of civil engineering structures.

Shape memory alloys (SMAs) have attracted a great deal of attention as a smart material that can be used in seismic protection systems for energy dissipating and re-centering purposes [Ozbulut *et al.*, 2011]. SMA behaves similarly to linear-elastic materials for small magnitude events, but for moderate and more severe strain levels, SMAs display superelastic behavior from which it can fully recover its original elastic shape. SMAs also exhibit self-centering capability when permanent deformations in surrounding assemblies afflict the SMA installation; thus, the overall integrity of neighboring structural systems can be maintained. Because of their re-centering capability, SMAs can serve as a valuable component in a seismic control device. Although the hysteretic behavior of SMAs provide some level of damping, 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.

Friction dampers rely on the resistance developed between two solid interfaces sliding relative to one another. They add energy dissipation capacity to structures and limit the force and acceleration in the system, improving their ability to withstand against extreme event, but they lack re-centering capacity [Ribakov 2004]. The energy dissipated by a friction damper is the product of normal contact force and drift of the damper. Hence, for a friction damper, if a small normal force is available, the energy dissipation of the damper may not be substantial during severe earthquakes. On the other hand, a large normal force results in small deformation of the damper (i.e., less energy dissipation) during moderate and weak ground motions. Therefore, a controllable normal force is favorable in order to ensure sufficient energy dissipation for various levels of ground motions [Gaul *et al.* 2008].

This paper proposes a novel re-centering variable friction device (RVFD) for control of civil structures that are subjected to various levels of earthquakes. The first subcomponent of this hybrid device consists of shape memory alloy (SMA) wires which exhibit excellent re-centering characteristics but have limited energy dissipation capability. The second subcomponent of this hybrid device consists of a variable friction damper (VFD) that can be intelligently controlled to enable desired level of energy dissipation through friction. Here, first, a detailed description of the hybrid device and its modeling technique are discussed. Then, a heuristic fuzzy controller that is employed to modulate the normal contact force of the RVFD is introduced. Next, a numerical study is performed to investigate the effectiveness of the proposed device in suppressing the response of a seismically excited three-story nonlinear benchmark structure.

2 Description of Re-centering Variable Friction Device

The RVFD proposed in this study consists of three parts: (i) a friction generation unit, (ii) a piezoelectric actuator, and (iii) shape memory alloy wires. Figure 1 shows a schematic diagram and a 3D rendering of the RVFD. In the design of the hybrid device, friction unit simply consists of two steel plates rubbing against a friction pad material and clamped together with high strength bolts and a piezoelectric actuator. Since piezoelectric materials cannot endure large strains that can be induced in the hybrid device during a seismic event, piezoelectric actuators are oriented perpendicular to the sliding surface of a RVFD. Four piezoelectric actuators are used in the device. The clamping force of a RVFD can be adjusted according to the current level of ground motion by adjusting the voltage level of piezoelectric actuators. The energy dissipation capacity of the hybrid device is a function of the friction material chosen and the contact force. For a given structural system subjected to seismic loading, the desired level of energy dissipation can be obtained by a proper selection of the coefficient of friction between two bodies and varying the contact force of the device.

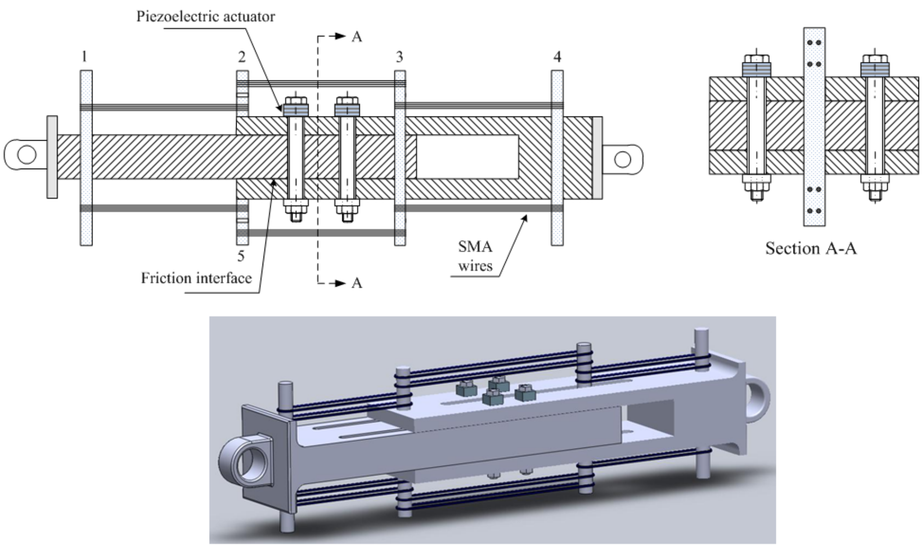

Figure 1: Schematic illustration and 3D rendering of hybrid device for Configuration I.

Superelastic shape memory alloys are employed in the hybrid device to realize re-centering ability for the device. A total of five studs are inserted into plates as shown in Figure 1. Studs 1 and 3 are inserted into the inner steel plate and mutually move with this plate. In order to enable the movement of stud 3, the outer plate has a longitudinal slot in the middle of its top and bottom surfaces. Stud 4 is similarly inserted into the outer plate, while two short studs (2 and 5) are attached to the edges of the outer plate. The SMA wires are wrapped around the studs connected to the inner and outer plates. The arrangement of the wires and studs is such that either the wires in the middle group or the outer SMA wire groups are subjected to the tension. By setting the number of SMA wires in the middle group to twice as many as in the outer group, the hybrid device will exhibit symmetrical response.

3 Modeling of Re-centering Variable Friction Device

A neuro-fuzzy model is used to characterize the behavior of the superelastic SMA wires that is employed in the RVFD. A fuzzy inference system is a simple scheme that maps an input space to an output space using fuzzy logic. Adaptive neuro-fuzzy inference system (ANFIS) is a soft computing approach that combines fuzzy theory and neural networks. Specifically, the ANFIS employs neural network strategies to develop a Sugeno-type fuzzy model whose parameters (membership functions and rules) cannot be predetermined by user's knowledge. One of the main advantages of the ANFIS is that it does not require a complex mathematical model to compute the system output. The ANFIS uses a hybrid algorithm to learn from the sample data from the system and can adapt parameters inside its network. Here, the ANFIS is used to create a model of superelastic SMAs considering temperature and loading rate effects. Details in regard to the neuro-fuzzy model of the NiTi wires can be found in Ozbulut and Hurlebaus [2010].

A continuous hysteretic model proposed by Constantinou *et al.* [1990] is used to define the frictional force of the RVFD as follows

$$F_f = \mu N(t)Z \tag{1}$$

where μ represents the coefficient of friction;N is the contact force; and Z is a hysteretic dimensionless quantity expressed as

$$u_y Z + \gamma|\dot{u}|Z|Z|^{n-1} + \beta\dot{u}|Z|^n - A\dot{u} = 0 \tag{2}$$

where u_y is the yield displacement; $\dot{u}$is the slip velocity of the damper; and γ, β, A and n are dimensionless parameters that control the shape of the hysteresis loop. The recommended values of these parameters to provide typical Coulomb friction behavior are u_y= 0.5mm, γ = 0.5, β = 0.5, A= 1 and n=2. Note that the hysteretic quantity Z is bounded by $\pm 1$and accounts for occurrence of the stick phase of the damper.

4 Three Story Nonlinear Benchmark Structure

In this study, the SAC Los Angeles 3-story structure, designed for the SAC Phase II Steel Project is selected for numerical investigations. This structure has been used as a benchmark building for nonlinear seismic control design [Ohtori *et al.* 2004]. The lateral load resisting system of the building consists of two steel perimeter moment resisting frames (MRFs) with simple framing in between. The seismic masses of the first and second levels are 9.57×10^5 kg, and the mass of the third level is 1.04×10^6kg. The structure is modelled using two dimensional frames that represent half of the structure in the north-south direction. It is assumed that the model of the structure has a Rayleigh damping with 2% damping ratio for the first two modes. The first three natural frequencies of the 3-story benchmark building are 0.99, 3.06, and 5.83 Hz. A detailed description of the building can be found in Ohtori *et al.* [2004].

The ground motions used to evaluate the performance of the RVFDs includes two far-field earthquakes (El Centro and Hachinohe) and two near-field earthquakes (Northridge and Kobe). In the benchmark study, various levels of each of the earthquake records including: 0.5, 1.0 and 1.5 times the magnitude of El Centro and Hachinohe; and 0.5 and 1.0 times Northridge and Kobe. The cross-sectional area and the length of the SMA wires in each RVFD are set to be 141 mm^2 and 1.5 m. A preload of 15 kN is set on each device, corresponding to a force equal to 10% of the total frictional force of the RVFD. The RVFD are installed at each story level using a chevron brace configuration. The number of control devices connected between the ground and first story, the first and second stories, and the second and third stories are 15, 10 and 10, respectively.

5 Fuzzy Controller for Re-centering Variable Friction Device

In this study, a heuristic fuzzy controller is developed to adjust the contact force of the RVFD. Acceleration measurements of each story are used for feedback in the control system. Three sensors are used to measure absolute accelerations at each story level. The fuzzy controller employs the accelerations of the adjacent floors as input variables and outputs the command voltage for the RVFD. One controller is designed for the first and second level control devices and uses the acceleration measurements of the first and second floor, and another fuzzy controller that employs second and third floor accelerations as input variables is designed for the RVFDs installed in the third floor. Seven triangular membership functions are defined for each input variable of the fuzzy controller and four triangular membership functions are defined to cover the universe of discourse of the output variable voltage that varies from 0 V to 10 V. After the fuzzification of input and output variables, a fuzzy rule base is defined for the fuzzy controller. The rule base adopted for the developed fuzzy controller is given in Table 1.

Table 1: Fuzzy rule base of the fuzzy controller

	First input						
Second input	**NL**	**NM**	**NS**	**ZR**	**PS**	**PM**	**PL**
NL	L	L	M	M	L	M	M
NM	L	M	S	S	M	M	S
NS	M	S	S	ZR	M	S	S
ZR	M	S	S	ZR	S	S	M
PS	S	S	M	ZR	S	S	M
PM	S	M	M	S	S	M	L
PL	M	M	L	M	M	L	L

6 Nonlinear Time History Analyses

In this section, nonlinear time history analyses of the three-story benchmark building are conducted to evaluate efficacy of the RVFD in mitigating the seismic response of structures. A total of 12 evaluation criteria that are defined in the benchmark control problem statement are computed for the benchmark structure subjected to various levels of earthquakes. The evaluation criteria $J_1 - J_3$ evaluate the peak response while $J_4 - J_6$ is based on normed building response. The evaluation criteria $J_7 - J_{10}$ is related to the building damage and the evaluation criteria next category $J_{11} - J_{12}$ assesses the performance of the control device.

Table 2 presents performance evaluation criteria $J_1 - J_{12}$ for the 3-story benchmark building with RVFDs under the 10 ground motion records specified in the control problem. It can be seen that the peak interstory drift ratio $J_1$is reduced for nine earthquake cases by up to 69%, while the response is increased by 6% for one record. The results also show that the peak story acceleration J_2 is decreased by up to 53% for six records and increased only 2% and 12% for two records. For the peak base shear J_3, there is an increase between 8-25% for six records, while the peak base shear response is reduced up to 43% for four cases. Also, note that there is a significant reduction in the norm values of the building response $(J_4 - J_6)$ for most of the excitation cases.

Table 2: Performance evaluation criteria for three-story benchmark building

Evaluation Criteria	El Centro (0.5/1.0/1.5)	Hachinohe (0.5/1.0/1.5)	Northridge (0.5/1.0)	Kobe (0.5/1.0)	Maximum value
J_1 Peak drift ratio	0.4191	0.3084	0.5991	1.0613	1.0613
	0.6951	0.5025	0.8140	0.6734	
	0.9046	0.6155			
J_2 Peak level accel.	0.6937	0.4650	0.9746	1.0225	1.1153
	0.9952	0.7298	0.9939	0.7606	
	1.1153	0.9937			
J_3 Peak base shear	0.6212	0.5658	0.9481	1.0807	1.2456
	1.1524	0.9449	1.1105	1.1266	
	1.2456	1.1591			
J_4 Norm drift ratio	0.3831	0.1303	0.1076	1.3105	1.3105
	0.5710	0.2140	0.9818	0.4599	
	0.4925	0.3215			
J_5 Norm level accel.	0.5512	0.2658	0.5812	0.5866	0.7810
	0.7810	0.3263	0.6428	0.6909	
	0.7461	0.4428			
J_6 Norm base shear	0.6100	0.3054	0.6763	0.6267	0.8225
	0.8225	0.3650	0.7260	0.7594	
	0.7736	0.4857			
J_7 Ductility	0.4112	0.3244	0.3251	1.1099	1.1099
	0.5989	0.4258	0.7276	0.9431	
	0.8432	0.6447			
J_8Dissipated energy				0.6651	1.1539
	0.0136	0	0.6242	1.1539	
	0.5575	0.0387			
J_9 Plastic connection				1	1
	0.1818	0	0.9091	0.8438	
	1	0.667			
J_{10} Norm ductility	0.3694	0.1372	0.0575	1.6699	1.6699
	0.3594	0.1883	1.1759	0.6087	
	0.6186	0.4880			
J_{11} Control force	0.0607	0.0549	0.1068	0.1063	0.1204
	0.1090	0.0883	0.1204	0.1323	
	0.1107	0.1089			
J_{12} Device stroke	0.1667	0.1183	0.2622	0.4344	0.4344
	0.2747	0.1969	0.3004	0.3176	
	.3571	0.2694			

In terms of building damage criteria, the installed RVFDs have the ability to reduce the ductility index J_7 by up to 60% and norm ductility $J_{10}$by up to 94% but increased J_7 11 % for one case and J_{10} 18% and 67% for two cases. For dissipated energy J_8, the response of the structure remains in the linear range for four records, it is reduced by up to 96% for five cases and increased by 15% for one case. The occurrence of plastic connection J_9 is also decreased in all cases except two cases which are at par with the uncontrolled case for the structure controlled with RVFD. The control force and device stroke requirements of the RVFD are appears to be acceptable.

7 Conclusions

This study explores the effectiveness of a re-centering variable friction device for protection of seismically excited nonlinear benchmark building. A fuzzy controller is developed to determine the voltage to send to the variable friction device. Nonlinear time-history analyses of the benchmark building with installed hybrid device are conducted under various levels of earthquakes. Results show that the RVFD is capable of effectively mitigating peak displacement response of the structure, while producing a modest amelioration in the acceleration response for most cases.

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