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Dynamic response control of engineering structure equipped with smart compound damper

Meng Zhan PhD

Lecturer, College of Architecture Engineering, HuangHuai University,
Zhumadian, Henan, P. R. China (Orcid:0000-0001-8777-9245) (corresponding author: zhanyi313@163.com)

Lizhen Zhang BEng

Assistant Lecturer, College of Mechanical and Energy Engineering,
HuangHuai University, Zhumadian, Henan, P. R. China

Xiuyun Chen PhD

Professor, College of Architecture Engineering, HuangHuai University,
Zhumadian, Henan, P. R. China

Sheliang Wang PhD

Professor, College of Architecture Engineering, HuangHuai University,
Zhumadian, Henan, P. R. China

To better control engineering structures subjected to external disturbances, such as earthquakes of varying magnitudes, a smart compound damper is developed and its performance is investigated in this paper. Unlike devices for passive control systems without adjustable control force, the dynamic responses of the engineering structure can be more effectively suppressed under seismic excitation by using devices for active control systems that feature active input to the actuators. A compound damper designed in this vein consists of shape memory alloy (SMA) wires and a variable-friction damper that can provide an adjustable control force according to the level of ground motion by changing the voltage of piezoelectric ceramic (PZC) actuators. Numerical simulations of a seismically excited two-storey steel frame structure were implemented to evaluate the performance of the proposed SMA/PZC compound damper. A back-propagation neural network model was developed using experimentally obtained data to describe the hysteretic behaviour of the SMA wires. A Takagi–Sugeno (T-S) fuzzy controller was used to determine the command voltage of the PZC actuators, such that the compound damper could perform well when applied to structural control. The resulting solution, hybrid control modulated with a T-S fuzzy control strategy, was found to be more effective than passive control.

Notation

$\{1\}$	$3n$ -dimensional column vector whose elements are all one	M_f	martensite finish temperature
$\mathbf{0}$	zero matrix with dimensions mentioned in the subscript	M_s	martensite start temperature
A_f	austenite finish temperature	N_0	initial preload of the damper, set to 200 N
A_s	austenite start temperature	R_i	i th fuzzy control rule
$\mathbf{B}_s$	control force position matrix describing the coordinates of the structural motion, a $3n \times p$ matrix	$\text{sign}()$	symbolic function
$\text{BP}()$	predictive neural network model	U	input voltage, which was determined by the T-S fuzzy control strategy
$\mathbf{C}$	damping matrix of the structure, a $3n \times 3n$ matrix	$\mathbf{X}(t), \dot{\mathbf{X}}(t), \ddot{\mathbf{X}}(t)$	$3n$ -dimensional vectors of structural displacement, velocity and acceleration response relative to the ground, respectively
d_i	stationary inter-storey displacement of the i th floor	x_{20}	uncontrolled peak displacement of the second floor relative to the ground
$\mathbf{F} = [F_1, F_2, \dots, F_p]$	column vector of p -dimensional control forces	$\dot{x}_{a1}$	inter-storey velocity of the i th floor
F_p	control force of the p th damper	$\dot{x}_{a20}$	peak uncontrolled velocity of the second floor
F_U	friction supplied by the PZC actuators	$\ddot{x}_g$	seismic acceleration of the ground
$\mathbf{I}_{3n}$	a $3n \times 3n$ identity matrix	$\mathbf{Z}(t)$	state vector
j	number of fuzzy control rules	$\alpha_i (i = 1, 2, \dots, j)$	degree of membership of the i th rule activated by the input variable
$\mathbf{K}$	stiffness matrix of the structure, a $3n \times 3n$ matrix	μ	friction coefficient, set to 0.5 in the test
K_1, K_2	inter-layer stiffness values		
k_i	voltage value corresponding to i th fuzzy control rule		
$\mathbf{M}$	mass matrix of the structure, a $3n \times 3n$ matrix		

1. Introduction

Shape memory alloy (SMA) is a type of intelligent material that has been widely applied in engineering. When loaded/unloaded at a temperature exceeding that of the phase transition of austenite, it can provide a fully hysteretic curve and avoid residual

deformation after unloading (Iasnii and Junga, 2018). The material can thus absorb and dissipate a large quantity of energy in the process. Although SMA dampers designed using pseudo-elasticity have been widely applied to passive structural control in civil engineering (Xu *et al.*, 2015; Zhou and You, 2015), their application has been limited because the control force cannot be adjusted in real time. For the inverse piezoelectric effect, piezoelectric ceramics (PZC) can convert electrical energy into mechanical energy and obtain instantaneous electrical deformation. With a great amount of stress to restrict small deformation, PZC can be used as a good type of drive in the field of structural vibration. Friction dampers composed of PZC are a popular subject of research on structural control in civil engineering. Ng and Xu (2007) studied vibration control in the case of piezoelectric friction dampers installed between a main building and a podium. Ozbulut and Hurlebaus (2010) applied a piezoelectric friction damper for the seismic protection of the base isolation of a building, and proposed two fuzzy logic controllers to determine the control force of the damper. Etedali *et al.* (2013) used a proportional–derivative/proportional–integral–derivative (PD/PID) controller to benchmark base-isolated structures using piezoelectric friction dampers for seismic response control, where the controller was optimised based on a genetic algorithm to balance damping performance with the robustness of a closed-loop control system. In general, piezoelectric friction dampers require a large initial pressure to restrain the deformation of PZC to obtain a larger control force, where this mechanism is rendered invalid in the case of a small earthquake because sliding on the frictional surface is difficult. However, the smaller the preload is, the smaller the output force is, and this may also be less effective in the case of large earthquakes owing to insufficient energy dissipation.

Some researchers have combined piezoelectric friction dampers with other shock-absorbing elements to use the best of both. Dai (2012) designed a piezoelectric–SMA composite damper and applied it to the base isolation of a building to achieve a good suppression effect for the seismic response. The piezoelectric seismic isolation system (Lu *et al.*, 2010, 2011; Ozbulut *et al.*, 2011), cement-based piezoelectric compounds (Dong *et al.*, 2011, 2016) and active/passive hybrid control of a beam with weak vibration (Choi *et al.*, 1998; Yuvaraja and Senthilkumar, 2013) are among the applications to benefit from the unique combination of properties offered by the PZC actuator. Little research has been conducted on control devices composed of SMA and PZC compounds, which are promising because they are effective during seismic events.

In this paper, an SMA/PZC compound damper is designed and its control performance is tested on an engineering structure subjected to earthquakes of varying magnitudes. The compound damper consists of two subcomponents: superelastic SMA wires that exhibit excellent re-centring characteristics and a piezoelectric friction unit that can be intelligently controlled by adjusting the voltage. The structure and principle of the

SMA/PZC compound damper is described first. Then, a mechanical test is carried out on the SMA wires to establish the neural network constitutive model of the damper. A Takagi–Sugeno (T-S) fuzzy controller used to modulate the friction of the damper is then introduced. The paper concludes with a summary of a numerical analysis performed to investigate the effectiveness of the damper in terms of suppressing the earthquake response of a two-storey steel frame structure.

2. SMA/PZC compound damper

A three-dimensional rendering and front elevation of the SMA/PZC compound damper are shown in Figure 1. It contains seven main parts: two pressing plates, a connecting plate, a sliding plate, two split bolts, one fixed link, SMA wires and two, round piezoelectric actuators. The connecting plate is fixed by two pressure plates using the left split bolt. The middle of the upper and lower pressure plates are respectively set using sliding chutes for the link fixed to the sliding plate to slide. The right side of the sliding plate features a sliding chute for the free movement of the right split bolt, where this construction ensures that the slide plate moves along the axis. Two circular perforated piezoelectric actuators are inserted between the pressure plate and nuts to change the controlling force in real time by adjusting the electric potential of the piezoelectric actuators. The SMA wires are used to connect the split bolt and the fixed link by way of a special anchorage to provide an extrusion force. Two holes are machined at the end of the connecting plate and the sliding plate to connect them with the other structural components. The damper can self-centre, has few components, and is both light and stable.

Figure 1. SMA/PZC compound damper: (a) three-dimensional rendering diagram; (b) front elevation. Note: 1, split bolt; 2, pressing plate; 3, fixed link; 4, SMA wire; 5, PZC actuator; 6, sliding plate; 7, connecting plate; 8, sliding chute for fixed link; 9, sliding chute for shipping rod

When the vibrations occur, the sliding plate begins moving and generates friction with the pressure plates. At least one pair of the SMA wires is in a state of tension to produce the hysteretic energy, whether moving to the left or right. In addition, when voltage is applied to the piezoelectric actuators, the control system can cause more energy to dissipate because the deformation of the piezoelectric actuators owing to electric elongation increases the friction between the pressing plates and the connecting plate. The SMA wires can still consume seismic energy in a passive way as the power system fails.

3. Experiment on SMA wires

3.1 Testing equipment

Considering the size of the damper model and the fixed position of the SMA wires in the damper, Ti-51%atNi (the atomic percentage of nickel is 51.5% in nickel-titanium alloy) SMA wires with a diameter of 0.7 mm were used in the experiments. The phase transition temperatures of the SMA material were as follows: martensite finish temperature (M_f), -42°C ; martensite start temperature (M_s), -38°C ; austenite start temperature (A_s), -6°C ; and austenite finish temperature (A_f), -2°C . Thus, the SMA wires were austenite at room temperature (20°C). The test equipment consisted of a Taiwan Honda HT-2402 computer servo control material testing machine, and the data acquisition system was an automatic acquisition system. The axial force of the wire was measured by embedded force sensors of the test equipment, and the axial deformation was measured by a displacement extensometer with a gauge distance of 33.5 mm.

3.2 Experimental conditions

To establish the constitutive model of the back-propagation (BP) neural network of the SMA wires for simulation analysis based on the test data, experiments were performed to investigate the hysteretic curves and mechanical performance of the SMA wires under different loading rates and amplitudes of strain at room temperature.

The length of all SMA specimens under various conditions was 300 mm, and their effective length was 100 mm to eliminate the undesirable influences of different fixed lengths. A certain amount of prestress (10–30 MPa) was applied to the specimens to straighten and tighten the wires to ensure the accuracy of the tests. Three constant loading/unloading speeds were used in the experiments: 30, 60 and 90 mm/min. The axial force of the wire was 5 N and the maximum strain consisted of two triggers for the loading and unloading cycles. In general, the maximum strain of the SMA wires was 8–10% depending on the production environment. In this experiment, the maximum strain was set to 7%, and its specific values were 3, 4, 5, 6 and 7% according to the maximum value of 7–8% in previous tests reported in the literature. Moreover, 20 cyclic loadings were used for each case to stabilise the performance of the SMA wires.

3.3 Experimental results and analysis

The strain values of 4% and 7% were selected to evaluate the mechanical performance of the SMA wires. Figure 2 shows the stress–strain curves at 90 mm/min at strains with amplitudes of 4% and 7%. The performance of the SMA wires was stable after 20 cycles and the maximum stress was 700 MPa. Moreover, the wires exhibited hysteretic behaviour and recovered their shape completely after experiencing large strains.

With the SMA wires having reached a steady state, the stress–strain curves of the last lap at different loading/unloading velocities and amplitudes of strain are shown in Figures 3 and 4, respectively. It is clear that the loading/unloading rate had little influence on the mechanical properties of the SMA wires. With increasing amplitude of strain, the plateau of the martensitic transformation platform decreased, the accumulative residual deformation, ultimate stress and the area of the hysteretic curve increased, and the energy dissipation capacity improved continuously.

Figure 2. Stress–strain curve at 90 mm/min: (a) 4%; (b) 7%

Figure 3. Stress-strain curve at different loading speeds: (a) 4%; (b) 7%

Figure 4. Stress-strain curve at strains of different amplitudes: (a) 30 mm/min; (b) 90 mm/min

4. SMA neural network model

4.1 Structure of BP neural network

For shape memory alloy, the traditional constitutive model (Abeyartane and Knowles, 1993; Boyd and Lagoudas, 1996; Brinson, 1993) is complex and challenging to program. As a non-linear method of modelling, the neural network prediction model can avoid the inevitable error incurred by traditional modelling methods, which is a significant advantage in debugging and use. A three-layer BP network (input layer, output layer and an implicit layer) was used to establish the BP neural network model of the SMA wires, as shown in Figure 5.

The above material tests showed that the mechanical performance of the SMA wires was not significantly related to the loading and unloading velocities. Thus, the authors ignored the influence of the loading velocity, and considered only the direction of velocity to determine the stage of the testing process.

The input neurons of the BP networks were sign (v) and strain (ϵ), the output neuron was stress σ , and the hidden layer was determined by estimation and testing (Zhan *et al.*, 2016).

Fifteen working conditions were used for the results for the SMA wires, five with a loading/unloading velocity of 60 mm/min with strains of varying amplitudes (3, 4, 5, 6 and 7%) as testing data, and the other ten conditions were used as the training samples. All samples were normalised to prevent the absolute value of the input data from being too large to enter the saturation region.

4.2 Results of prediction

The data from the last lap of the above conditions were used as training samples for the prediction model of the BP neural network. trainlm was chosen as the training function, and the maximum number of training iterations was 1000, the target error was 10^{-5} and the learning rate was 0.3.

Figure 5. Structure of neural network

Figures 6 and 7 show the contrast curves of the stress–strain relation and sample error between the test and the prediction of the BP network at strain values of 4% and 7%. It is clear that the absolute value of the error in stress was mostly confined to within 20 MPa, and the BP network model accurately predicted the hyperelastic constitutive curves of the SMA wires under cyclic loading. Furthermore, the larger error points were mainly located in the initial loading stage and the end of the unloading stage because the data used for the training samples at this location exhibited a large fluctuation, but this did not affect the validity of the results of prediction and still met the engineering requirements.

5. Equation of motion of controlled structure

For the shear structure model with n degrees of freedom, p damping devices were installed on the structure. When

Figure 6. Stress–strain curve and sample error at 4%: (a) the contrast of stress–strain curves; (b) the sample error between test and prediction

Figure 7. Stress–strain curve and sample error at 7%: (a) the contrast of stress–strain curves; (b) the sample error between test and prediction

subjected to a one-dimensional earthquake, the equation for motion control is given by

$$1. \quad \begin{cases} \mathbf{M}\ddot{\mathbf{X}}(t) + \mathbf{C}\dot{\mathbf{X}}(t) + \mathbf{K}\mathbf{X}(t) = -\mathbf{M}\{1\}\ddot{x}_g + \mathbf{B}_s\mathbf{F} \\ \mathbf{X}(t_0) = \mathbf{X}_0 \quad \dot{\mathbf{X}}(t_0) = \dot{\mathbf{X}}_0 \end{cases}$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass matrix, damping matrix and stiffness matrix of the structure, respectively, where these are $3n \times 3n$ matrices. $\mathbf{X}(t)$, $\dot{\mathbf{X}}(t)$ and $\ddot{\mathbf{X}}(t)$ are $3n$ -dimensional vectors of the structural displacement, velocity and acceleration response relative to the ground, respectively. $\{1\}$ is a $3n$ -dimensional column vector whose elements are all one; $\ddot{x}_g$ is the seismic acceleration of the ground; $\mathbf{B}_s$ is the control force position matrix describing the coordinates of the structural motion, a $3n \times p$ matrix; and $\mathbf{F} = [F_1, F_2, \dots, F_p]$, is the column vector of p -dimensional control forces.

Introducing the state vector:

$$2. \quad \mathbf{Z}(t) = \begin{bmatrix} \mathbf{X}(t) \\ \dot{\mathbf{X}}(t) \end{bmatrix}_{6n \times 1}$$

The equation of motion described by Equation 1 can be expressed as

$$3. \quad \begin{cases} \dot{\mathbf{Z}}(t) = \mathbf{A}\mathbf{Z}(t) + \mathbf{D}\ddot{x}_g + \mathbf{B}\mathbf{F} \\ \mathbf{Z}(t_0) = \mathbf{Z}_0 \end{cases}$$

where $\mathbf{A} = \begin{bmatrix} \mathbf{0}_{3n} & \mathbf{I}_{3n} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix}_{6n \times 6n}$, $\mathbf{B} = \begin{bmatrix} \mathbf{0}_{3n \times p} \\ \mathbf{M}^{-1}\mathbf{B}_s \end{bmatrix}_{6n \times p}$, $\mathbf{D} = \begin{bmatrix} \mathbf{0}_{3n \times 1} \\ -\mathbf{M}^{-1}\mathbf{M}\{1\} \end{bmatrix}_{6n \times 1}$, $\mathbf{I}_{3n}$ is an identity matrix, and ' $\mathbf{0}$ ' is the zero matrix with dimensions mentioned in the subscript.

According to the structural characteristics of the compound damper, the control force F_p of the p th damper is composed of the SMA control force predicted by the BP network model and the adjustable piezoelectric control force

$$4. \quad F_p = \text{BP}[\text{sign}(\dot{\mathbf{X}}(t)), \varepsilon] + F_U$$

where $\text{BP}()$ is the predictive neural network model, $\text{sign}()$ is the symbolic function and F_U is the friction supplied by the PZC actuators, and derived from previous experiments by the authors' research group on the variable-friction damper (Zhan *et al.*, 2019). The hysteretic performance test of the variable-friction damper is shown in Figure 8, and the shake table test of the transmission tower with the variable-friction damper is shown in Figure 9.

(a)

(b)

Figure 8. Hysteretic performance test on variable-friction damper: (a) test device; (b) test result

The fitting relation between the control force and the input voltage is given Equation 5 according to experimental data.

$$5. \quad F_U = \mu(N_0 + 1.6U) \quad U \geq 0$$

where μ is the friction coefficient, set to 0.5 in the test, N_0 is the initial preload of the damper, set to 200 N, and U is the input voltage, which was determined by the T-S fuzzy control strategy.

A T-S fuzzy logic controller was developed to obtain the required voltage of the SMA/PZC compound damper. The absolute value of the velocity of the layer in which the compound damper was located is taken as the input to the fuzzy controller (He *et al.*, 2003; Zhan *et al.*, 2017). The boundary

Figure 9. Shake table test on variable-friction damper: (a) damper installation; (b) structure of transmission tower

Figure 10. Installation diagram of damper

of the theory field was the maximum absolute value of the relative velocity of the uncontrolled structure, and the voltage was taken as the output. The fuzzy field of the input variable was $[-2, 2]$, and, in total, six fuzzy subsets were selected in this paper with values m_{f1} , m_{f2} , m_{f3} , m_{f4} , m_{f5} and m_{f6} . The Gaussian function was selected as the membership function. If zero-step T-S fuzzy reasoning is used, the i th fuzzy control rule R_i can be expressed as

R_i : If v is m_{fi} , then $y_i = k_i (i = 1, 2, \dots, 6)$.

Then, k_i is determined by the following formula:

$$6. \quad k_i = \begin{cases} 0 & i = 1, 2, 3 \\ 150 \text{ V} & i = 4, 5, 6 \end{cases}$$

Assuming that ' j ' fuzzy control rules ($j \leq 6$) are activated by an input variable of inter-layer velocity, the output U of the fuzzy controller is the weighted average of the output of the j rules, and it can be expressed as

$$7. \quad U = \frac{\sum_{i=1}^j \alpha_i y_i}{\sum_{i=1}^j \alpha_i}$$

where α_i ($i = 1, 2, \dots, j$) is the degree of membership of the i th rule activated by the input variable.

6. Vibration control analysis

6.1 Introduction of controlled structure

A two-storey steel frame structure model was used as the control object. M_1 was 175 kg and M_2 was 165 kg. For inter-layer stiffness, K_1 and K_2 were both 1.2×10^5 N/m, and Rayleigh damping was used. The steel used was Q235, with an elastic modulus of 206 GPa, Poisson's ratio of 0.3, and density of 7800 kg/m³. Every layer was equipped with an SMA/PZC

Figure 11. Control process for structural seismic response

compound damper placed on the mounting plate. The split bolts and fixed link respectively passed through the mounting plate, and the compound damper was fixed to it by the split bolts, as shown in Figure 10.

The El Centro wave (NS) and Taft wave (EW) were selected as input seismic waves for structural vibration control. Through amplitude modulation, waves of the earthquakes were respectively tuned to 400 gal and 600 gal, and the excitation was carried along the X -direction of the structure. The duration was 20 s with a time step of 0.02 s; the coefficient of friction was 0.5 and the initial frictional force was 100 N. Each side of the damper was equipped with two SMA wires, and each was 0.2 m long.

6.2 Control process

When structures are subjected to seismic excitation, their displacement and speed-related response can be calculated using the vibration control equation, and strain is obtained by the displacement response. The BP neural network model with strain and sign of the velocity as input to the neurons could predict the tensile force of the SMA wires; the T-S fuzzy controller with the velocity response as input could export the required voltage value. By applying the control force provided by the SMA wires and friction provided by the variable friction unit to the equation of structural vibration control, the displacement and velocity responses of the structure can be solved for. A closed-loop system can then be formed to complete the

Figure 12. Simulink model for SMA/PZC hybrid control: (a) master model; (b) Simulink model for control force; (c) Simulink model for fuzzy control

process of vibration control. The control process is shown in Figure 11.

6.3 Results and analysis of control

A Matlab/Simulink simulation model of the SMA/PZC compound damper is shown in Figure 12. The displacement and the velocity responses were obtained directly from the simulation model, as shown in Figures 13 and 14. It is clear that the hybrid control method was more effective at suppressing the seismic response of the structure than passive control without inputting of voltage to the PZC actuators.

However, it is not sufficient to compare the displacement and velocity of the controlled structures. Other criteria were thus employed to evaluate the performance of the compound damper in terms of mitigating the effects of the earthquake

based on a reference (Spencer *et al.*, 1998). The formulae used to calculate the evaluation criteria are as follows:

$$8. \quad J_1 = \max_{\text{El Centro/Taft}} \left\{ \max_t \left[\frac{|d_1(t)|}{x_{20}}, \frac{|d_2(t)|}{x_{20}} \right] \right\}$$

$$9. \quad J_2 = \max_{\text{El Centro/Taft}} \left\{ \max_t \left[\frac{|\dot{x}_{a1}(t)|}{\dot{x}_{a20}}, \frac{|\dot{x}_{a2}(t)|}{\dot{x}_{a20}} \right] \right\}$$

where d_i is the stationary inter-storey displacement of the i th floor, and x_{20} is the uncontrolled peak displacement of the second floor relative to the ground. $\dot{x}_{a1}$ is the inter-storey velocity of the i th floor, and $\dot{x}_{a20}$ is the peak uncontrolled velocity of the second floor relative to the ground.

Figure 13. Curve of temporal history of dynamic response time of the second layer of the El Centro wave: (a) displacement at $0.4g$; (b) velocity at $0.4g$; (c) displacement at $0.6g$; (d) velocity at $0.6g$

Figure 14. Curve of temporal history of dynamic response time of the second layer of the Taft wave: (a) displacement at 0.4g; (b) velocity at 0.4g; (c) displacement at 0.6g; (d) velocity at 0.6g

Table 1. Peak response of the structure subjected to the El Centro wave at a peak ground acceleration of 0.4g

Working condition	Peak displacement: m		Peak velocity: m/s		Evaluation criteria	
	1	2	1	2	J_1	J_2
No control	0.0231	0.0367	0.3779	0.6370	0.6294	0.5934
Passive control	0.0141	0.0184	0.2812	0.4340	0.3842	0.4414
Hybrid control	0.0057	0.0086	0.1943	0.2078	0.1553	0.305

Table 2. Peak response of the structure subjected to the El Centro wave at a peak ground acceleration of 0.6g

Working condition	Peak displacement: m		Peak velocity: m/s		Evaluation criteria	
	1	2	1	2	J_1	J_2
No control	0.0347	0.0551	0.5669	0.9555	0.6298	0.5933
Passive control	0.0191	0.0283	0.3296	0.6621	0.3466	0.373
Hybrid control	0.0140	0.0199	0.2917	0.5067	0.2541	0.3053

Table 3. Peak response of the structure subjected to the Taft wave at a peak ground acceleration $0.4g$

Working condition	Peak displacement: m		Peak velocity: m/s		Evaluation criteria	
	1	2	1	2	J_1	J_2
No control	0.0280	0.0464	0.4986	0.8223	0.6034	0.6064
Passive control	0.0151	0.0210	0.2746	0.4051	0.3254	0.3339
Hybrid control	0.0076	0.0099	0.1554	0.1931	0.1638	0.1890

Table 4. Peak response of the structure subjected to the Taft wave at a peak ground acceleration of $0.6g$

Working condition	Peak displacement: m		Peak velocity: m/s		Evaluation criteria	
	1	2	1	2	J_1	J_2
No control	0.0420	0.0695	0.7480	1.2335	0.6043	0.6064
Passive control	0.0196	0.0316	0.3779	0.5332	0.282	0.306
Hybrid control	0.0153	0.0211	0.3111	0.4322	0.2201	0.2626

The peak displacement of the structure, peak velocity and associated evaluation criteria under different conditions are given in Tables 1–4. They show that the displacement and velocity responses of the structure were adequately suppressed under passive control using the proposed compound damper, and once voltage had been applied to the piezoelectric ceramic actuator, the control effect further improved. In addition, the effect of the passive control in terms of seismic reduction at $0.6g$ was better than that at $0.4g$, but was the opposite for the hybrid control method. This is because in passive control, the stronger the earthquake is, the more energy the controller consumes. On the contrary, in hybrid control, passive control plays a major role, and the capacity of the semi-active control for energy dissipation is insufficient, which in this case led to the weakening of seismic reduction capability at $0.6g$.

7. Conclusions

- The hysteretic curve of the SMA wires was affected little by the loading velocity. With an increase in the amplitude of strain, the platform for martensitic transformation decreased, accumulative residual deformation, ultimate stress and the area of the hysteretic loop increased, and the capacity for energy dissipation increased continuously.
- The absolute value of the error in stress was mostly confined to within 20 MPa, and large errors were mainly located in the initial loading stage and the end of the unloading stage, where the stress values were small. This shows that the BP neural network had acceptable precision and stability in predicting the stress–strain curves of the SMA wires under cyclic loading.
- The proposed SMA/PZT compound damper effectively restrained the dynamic response of the structure, and hybrid control reduced seismic vibrations better than passive control without a voltage input to the PZC actuators. Moreover, the seismic reduction accomplished

using passive control at $0.6g$ is better than that at $0.4g$, but the opposite held for hybrid control. This is because the capacity of semi-active control for energy dissipation is insufficient in the case of a strong earthquake when passive control plays a major role in the process.

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