Experimental tests and finite element simulations of a new SMA-steel damper

Canxing Qiu¹, Hongyang Wang², Jiawang Liu¹, Jian Qi² and Yanming Wang²

¹ Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing 100124, People’s Republic of China
² School of Civil Engineering, Shandong University, Jinan 250061, People’s Republic of China

E-mail: qiucanxing@bjut.edu.cn

Received 30 March 2019, revised 19 November 2019
Accepted for publication 13 January 2020
Published 29 January 2020

Abstract
Owing to their outstanding recentering capability, shape memory alloy (SMA) dampers are emerging as promising passive dampers for seismic applications. However, compared to typical seismic dampers, the inherent energy dissipation capability of SMAs is often deemed barely satisfactory. To enhance the damping capacity of SMA dampers, this study suggests combining SMA elements with steel dampers based on bending steel plates. In this new SMA-steel damper, the steel dampers are mainly responsible for absorbing seismic energy, whereas the SMA bars primarily play the role of recovering inelastic deformation. Experimental tests were conducted at room temperature to verify the cyclic behavior of the proposed damper. The hysteretic parameters, such as strength, stiffness, equivalent damping ratio, and residual deformation, are of particular interest and quantified as a function of the loading amplitude. According to test results, the new damper is confirmed to possess desirable recentering capability and high damping. To further understand the damper, numerical simulations were carried out in the finite element (FE) analysis software ABAQUS. The numerical results validated the experimental data. Based on the calibrated FE model, the thickness of the bending steel plate of the steel damper and the diameter of the SMA bars were varied in the parametric analysis to examine its effect on the recentering tendency and damping mechanism.

Keywords: passive damper, shape memory alloy, finite element simulations, cyclic loading tests

(Some figures may appear in colour only in the online journal)

1. Introduction
In the past decades, great progress has been achieved in seismic vibration control in the research field (Soong and Dargush 1997, Soong and Spencer 2002). According to the working principle, vibration control strategy includes active control, semi-active control, and passive control. In earthquake engineering, passive control is the most favorable strategy owing to the combined merits of reliable control efficacy and cost-effectiveness (Housner et al 1997). Passive control is achieved by installing passive dampers at the designated locations of the protected structure. The dampers are mainly responsible for absorbing the input seismic energy and shifting the damage away from major structural elements to protect the structure. In practice, seismic energy can be dissipated by the yielding process of metals, friction mechanisms, viscous fluids, and viscoelastic materials etc, all of which have been reported to be very effective in controlling the peak seismic responses of structures (Soong and Dargush 1997). Recently, with the increasing concern regarding seismic resilience (Bruneau et al 2003), post-earthquake residual deformation has received increased attention. However, several studies have implied that conventional dampers are inadequate for controlling residual deformation after moderate or severe earthquake scenarios.
Consider buckling-restrained braces (BRBs) that were widely used in seismically resistant structures as an example. Several studies (Sabelli et al. 2003, Tremblay et al. 2008, Zhu and Zhang 2008, Qiu and Zhu 2016, Qiu et al. 2018) indicated that using BRBs may lead to excessive deformations after design-basis and maximum-considered earthquakes. A recent investigation (McCormick et al. 2008) pointed out that large residual deformations are often associated with substantial economic loss owing to downtime and huge restoration efforts. In light of this, self-centering (SC) structures and dampers were developing rapidly over the past years with the special purpose of suppressing the accumulation of post-event residual deformations.

Among active advances in developing SC structures, shape memory alloys (SMAs) are considered as a promising solution (Graesser and Cozzarelli 1991, DesRoches and Smith 2004, Song et al. 2006, Ozbulut et al. 2011, Li et al. 2018). SMAs are a class of alloys that have high fatigue life, excellent corrosion resistance, good damping behavior, and exhibits remarkable superelastic property at room temperature (DesRoches et al. 2004, Qiu and Zhu 2014, Choi et al. 2018, Wang, Zhu 2018b). When SMAs are introduced, the corresponding structural systems or elements are endowed with significantly improved recentering capability due to the inherent superelastic nature of such metals. In the early stages, most studies used SMA wires, which included the SC dampers, restrainers, and braces (Dolce et al. 2001, Zhang and Zhu 2007, Li et al. 2008, Padgett et al. 2010, Qiu and Zhu 2017). With the development of heating treatments and manufacturing technology, it was found that SMA bars also exhibited desirable superelastic properties under cyclic loadings as SMA wires (Dolce and Cardone 2001, DesRoches et al. 2004, Fang et al. 2015a, 2015b, 2016, Wang and Zhu 2018a). Compared to wires, bars can cater better to the strength demand caused by seismic actions. Additionally, bars can be more conveniently exploited in practice than wires through reliable connecting techniques, such as bolting connection (Speicher et al. 2011, Fang et al. 2014). Typical examples of using SMA bars have been demonstrated in prior cases (Speicher et al. 2011, Fang et al. 2014, Araki et al. 2015, Youssef et al. 2015, Wang et al. 2016, 2017). Hence, SMA bars will be utilized as the kernel element in developing the current SMA-based damper.

Although SMA-based structures or dampers successfully demonstrated their SC capability under cyclic loadings or realistic earthquakes in earlier studies (Zhang and Zhu 2007, Li et al. 2008, Zhu and Zhang 2008, Miller et al. 2012, Qiu and Zhu 2017, Wang et al. 2017, Li et al. 2018), the inherent damping of SMAs is not large, as shown in figure 1, which compares simplified hysteretic curves of SMAs and mild steel. The ‘yielding’ plateau of SMAs essentially corresponds to the austenite to martensite phase transformation, which starts when the applied stress reaches $\sigma_{AM}$. For easier understanding, $\sigma_{AM}$ can be analogous to the yielding stress of steel $\sigma_y$. The parameters, $\zeta_{eq,SMA}$ and $\zeta_{eq,Steel}$, represent the equivalent damping ratio of SMA and steel, respectively. Thus, a frequently raised common concern for SMA-based dampers is to enhance their energy dissipation capacity. Researchers made various attempts by adding external damping sources along with SMA components. Dolce et al. (2000) used martensite SMAs as an added damping (AD) mechanism. Zhu and Zhang (2008) combined SMA wires with friction dampers and achieved full-flag-shape (FS) hysteresis. Miller et al. (2012) adopted a BRB core in SMA-based SC braces. Li et al. (2018) developed an SMA-lead damper and found that the shearing behavior of the lead well increased the total damping capacity. However, there were some critical issues that needed to be addressed for these damping sources; for example, martensite SMAs are not an economical option, the friction mechanism may lose stability during long-term service, BRB tends to exhibit unsymmetrical cyclic behavior, and lead is deemed non-eco-friendly.

Metallic yielding dampers seems to be a potential choice for increasing the damping of SMA dampers. Metallic yielding dampers utilize metals with low yielding stress and high ductility, and exhibit stable and substantial energy dissipation capability (Whittaker et al. 1989, Nakashima et al. 1996, De la Llera et al. 2004). During the past decades, various types of metallic yielding dampers were proposed, such as AD and stiffness (ADAS) elements (Whittaker et al. 1989, Qiu et al. 2019), triangular ADAS elements (Tsai et al. 1993), J-shaped steel damper (Kato et al. 2005) and U-shaped steel damper (Kishiki et al. 2008, Qiu et al. 2019). The seismic capacity of steel dampers has been validated experimentally and numerically (Nakashima et al. 1996, Chan and Albermani 2008, Hao et al. 2018). Therefore, this study adopted steel dampers as the AD element in the proposed damper.

According to the above literature review, it is recognized that SMA elements have excellent SC capability, but offered insufficient damping. There remains a pressing need to enhance the damping capacity of SMA-based dampers to help the protected structures meet the seismic demands. Considering the merits of SMA bars and steel dampers, this study combines these two elements in parallel and proposes a new SMA damper, denoted as the SMA-steel damper. The cyclic behavior of the new damper is expected to be a suitable combination of recovering deformation and dissipating energy. To prove this concept and have a preliminary understanding of the seismic properties, this study conducted cyclic loading tests and FE simulations on the proposed SMA-steel damper.
2. SMA-steel dampers

2.1. Basic configuration

The damper consists of three parts: the SC element, the AD element, and the framing element, as shown in figure 2(a). To describe the damper, all the subassemblies are listed from 1 to 9: 1—the force transmission steel plate; 2—the SMA bar with threaded ends; 3—the top cover block; 4—the bending steel plate; 5—the steel frame; 6—the triangular steel block; 7—the bottom cover block; 8—the driving stud; and 9—the clamp plate. The different parts are connected through bolting or welding. Steel ribs are welded to some steel plates to enhance bending stiffness. The red components in the figure are the steel dampers. As observed, both the SMA bars and bending steel plates are bolted to the steel frame, and accordingly, they deform simultaneously when the damper is subjected to external loads. The deformed shape of the damper upon tension and compression are respectively shown in figures 2(b), (c). As the SMA bars are always elongated when the damper is deformed, the buckling induced instability problem is avoided. This design also allows convenience in repairing and replacing the SMA bars and steel dampers in case of excessive deformation or damage caused by severe seismic events.

The working principle of the SMA-steel damper is described as follows: upon tension action, as shown in figure 2(b), the external load is directly transferred through the force transmission plate to the base plate of the steel damper, which causes out-of-plane bending of the steel plates. Meanwhile, the top cover block is pulled away from the steel frame forming a deformation gap, while the bottom cover block is restrained by the triangular steel block that causes the elongation of the SMA bars. Upon compression action, as shown in figure 2(c), the corresponding behavior is similar to that triggered by tension action. A deformation gap is formed between the bottom cover block and the triangular steel block that induces out-of-plane bending of the steel plates and elongation of the SMA bars. During both loading actions, the SMA bars and steel damper cluster are subjected to the same vertical deformation demand and would concentrate inelastic deformations, while other parts of the damper are designed adequately strong to stay elastic.

2.2. Damping force model

For SMA bars, the damping force model can be simplified as linear piecewise FS model, as suggested by prior studies (Li et al 2004, Andrawes and DesRoches 2007, Zhu and Zhang 2013). The model is shown in figure 3(a), and expressed numerically in equation (1).

\[ F_{SMA} = \begin{cases} k_A x \\ (1 - \alpha)k_A x_y + \alpha k_A x \\ (1 - \alpha)k_A (x - x_m) + k_A x \end{cases} \]

\[ \begin{aligned} & (1 - \beta) x_y + \alpha k_A x \ \\
 & \quad (1 - \beta) x_y < |x| < x_m - \alpha k_A x < 0 \end{aligned} \]

where \( x \) is the axial displacement of the SMA bars; \( \dot{x} \) is the corresponding velocity; \( x_y \) is the ‘yielding’ displacement corresponding to the commencement of forward phase transformation; \( x_m \) is the maximum displacement; \( \alpha \) and \( \beta \) are dimensionless parameters that measure ‘post-yielding’ stiffness ratio and width of hysteresis; \( k_A \) is the axial stiffness of the SMA bars related to austenite phase and calculated...
using equation (2)

\[ k_A = E_A A / L, \quad F_{MA} = \sigma_M A, \]

where \( E_A \) is the elastic modulus of the austenite SMA material; \( A \) and \( L \) are the cross-sectional area and effective length of the SMA bar. For convenience, the stiffness in the martensite phase is given as:

\[ k_{AM} = \alpha k_A = E_{AM} A / L, \]

where \( E_M \) is the modulus of martensite SMA material.

As aforementioned, the steel damper is essentially similar to the ADAS proposed by Whittaker et al. (1989). The shape of the bending steel plate will be shown later on. For simplified consideration, the bilinear elastoplastic model is used to describe the nonlinear behavior of the steel damper, as shown in figure 3(b). The model is characterized by the initial stiffness \( k_e \) and post-yielding stiffness ratio \( r \). For the X-shaped bending steel plates, the bending curvature generated by a transverse load applied at the end is uniform over the full length of the plate without concentrating curvature. Thus, the yielding behavior will be activated simultaneously over the full height of the steel plates. Assuming the shear deformation is small compared to that induced by bending action, the theoretical elastic lateral stiffness, \( k_e \), the yielding displacement, \( x_y \), and the yielding strength, \( F_y \), of each single bending steel plate are given by equation (4)

\[ k_e = \frac{2B^3}{3H^3 E} ; \quad x_y = \frac{H^2}{2E f_y} ; \quad F_y = \frac{Bt^2}{3H f_y}, \]

where \( H \), \( B \) and \( t \) are length, width, and thickness of the bending steel plate, respectively; \( E \) and \( f_y \) are the elastic modulus and yielding stress of steel, respectively.

The corresponding damping force model for the SMA-steel damper is expressed as:

\[ F = M \cdot F_{SMA} + N \cdot F_{Steel}, \]

where \( F \) is the total force of the damper, \( F_{SMA} \) and \( F_{Steel} \) are the forces offered by one SMA bar and one bending steel plate, respectively; \( M \) and \( N \) are the numbers of the SMA bars and steel plates, respectively. In the derivation of the hysteretic model of the SMA-steel damper, it is assumed that the SMA bars and steel plates deform simultaneously into their nonlinear stages, i.e. when the steel dampers yield, the SMA bars start to undergo forward phase transformation. This assumption is based on the following considerations: if the yielding displacement of steel damper is larger, its damping contribution will be delayed; and if the steel damper yields earlier, according to equation (5), for the steel damper with sufficient strength capacity, a small yielding displacement implies a high initial stiffness that consequently leads to large initial stiffness of the SMA-steel damper. For dampers, a high initial stiffness is usually not favorable from the perspective of suppressing seismic induced vibration. Owing to the symmetrical behavior shown in figure 3(c), only the first quadrant is described. The critical points on the hysteretic curves are derived below:

At stage \( o \sim a \), the damper is elastic and begins to yield at point \( a \). The corresponding displacement and force are given as:

\[ x_a = x_y, \]

\[ F_{o \sim a} = (M \cdot k_A + N \cdot k_e) x. \]

The yielding force is calculated by:

\[ F_a = M \cdot F_{MA} + N \cdot F_y. \]

At stage \( a \sim b \), both the SMA bars and steel dampers are in nonlinear state. The corresponding force is given by:

\[ F_{a \sim b} = (M \cdot k_M + N \cdot r k_e)(x - x_a) + F_a, \]
At stage \( b-c \), the SMA bars and steel dampers are recovering elastic deformation. The corresponding force is given:

\[
F_{b-c} = (N \cdot k_e + M \cdot k_A)(x_b - x_a) + F_b.
\]  

At point \( c \), the SMA bars start the martensite to austenite phase transformation; the corresponding displacement and force are given as:

\[
x_c = x_b - \beta x_y, \quad F_c = M \cdot [(1 - \alpha - \delta)F_{M_b} + \alpha k_A x_b] + N \cdot [(1 - \beta)F_p + r k_e (x_b - x_a - F_p)].
\]  

At \( c-d \) stage, the SMA bars continue the martensite to austenite phase transformation and the steel damper yields at point \( d \). The force in this stage is given by:

\[
F_{c-d} = (N \cdot k_e + M \cdot \alpha k_A)(x - x_c) + F_c.
\]  

The displacement and force at point \( d \) are given by:

\[
x_d = x_b - 2x_y, \quad F_d = M \cdot \{(1 - \alpha)(1 - \beta - 2\alpha)F_{M_b} + \alpha k_A x_b\} + N \cdot [r k_e (x_b - x_a) - F_p].
\]

At \( d-e \) stage, the SMA bars complete the martensite to austenite phase transformation while the steel damper is still in plastic state and leaves a residual deformation when the force is removed. The corresponding force is given by:

\[
F_{d-e} = (M \cdot \alpha k_A + N \cdot r k_e)(x - x_c),
\]

where \( x_e \) is the residual displacement, given as:

\[
x_e = \frac{(1 - r)F_p - (1 - \alpha)(1 - \beta)F_{M_b}}{\alpha k_A + r k_e}.
\]

### 3. Experimental tests

As the SMA-steel damper depends on the behavior of SMA bars and steel dampers, both of which are critical to the ultimate performance. Reliable performance of the SC and AD elements is the premise of generating desirable behavior of the SMA-steel damper. Hence, prior to the test on the SMA-steel damper, the SMA bars and steel dampers were tested individually. This helps in understanding the mechanical properties of each subassembly and in adjusting the initial design if necessary. The steel frame and the force transmission plate are made of steel plates of 16 and 10 mm thickness, respectively. The thickness is selected large enough to make sure they remain elastic during the tests.

All the tests were carried out on the MTS machine. The test procedure is a displacement-based one, and the damper force is recorded by the internal data acquisition system of the MTS machine. The loading scheme is shown in figure 4, which consists of stepwise incremental amplitudes with a frequency of 0.01 Hz. The loading amplitudes were gradually increased during the tests to 3.1, 6.2, 9.3, 12.4, and 15.5 mm, corresponding to the strain levels of 1%, 2%, 3%, 4%, and 5% generated in the SMA bars, respectively. All loading amplitudes were repeated once to observe the stability of the cyclic
behavior. In this experimental study, dynamic loading test was not carried out, because the loading rate effect has been addressed by several prior studies (Dolce and Cardone 2001, DesRoches et al. 2004). However, the loading rate effect on SMA materials should be always well recognized. As reported earlier (DesRoches et al. 2004), a higher loading rate would lead to an increase in both the loading and unloading stress. The increase in unloading stress is often more significant and accordingly result in a narrowing of the hysteresis.

3.1. SMA bars

Commercial NiTi SMA bars were chosen in this study because of their superiority over other types of SMAs (DesRoches and Smith 2004). The NiTi bars were purchased from Xi’an Saite Metal Material company Ltd. The raw bar had a diameter $D = 12$ mm. According to the material supplier, the chemical composition of the NiTi SMA is approximately 56% Ni and 43% Ti in weight. The austenite finish temperature is $A_f = 0^\circ C$. The raw bar was machined to dog bone-shaped samples shown in figure 5. The lengths of the raw bar and reduced part were 400 and 310 mm, respectively. The threaded part was 45 mm long at both ends to permit the bolting connection. The threaded ends were gradually deformed to the reduced section to avoid stress concentration as per Chinese Standards (GB/T 228-2010 2010). The test was conducted in an indoor environment at a temperature of 24$^\circ$C–26$^\circ$C, which is well above the austenite finish temperature. As suggested by prior studies (Qiu and Zhu 2014, Wang et al. 2016), training treatment was conducted prior to the formal tests. After several trial-and-error attempts, the training treatment included two steps: in the first step, the specimen was subjected to one loading cycle with 7% strain, and in the second step, the specimen was heated at 400 $^\circ$C in a muffle furnace for 15 min followed by water quenching. To

![Figure 7. Steel damper: (a) bending steel plate; (b) base plate; (c) physical product.](image)

![Figure 8. Cyclic behavior of the steel damper using bending steel plate with a thickness of 5 mm.](image)

**Table 1. Mechanical properties of the steel damper.**

| Parameters         | $F_y$ (kN) | $\Delta_y$ (mm) | $K$ (kN mm$^{-1}$) |
|--------------------|------------|-----------------|-------------------|
| Theoretical calculations | 1.92       | 4.71            | 0.41              |
| Test results       | 2.10       | 4.83            | 0.43              |
| Error              | $-8.6\%$  | $-2.4\%$       | $-4.7\%$         |

Smart Mater. Struct. 29 (2020) 035016 C Qiu et al
be consistent with the configuration of the final damper, a pair of SMA bars were installed by bolting them to the steel frame and then tested.

Figure 6 plots the hysteretic curve of the tested SMA bars. The force was generated by two samples. Overall, the SMA bars exhibited stable and symmetrical FS cyclic behavior within the applied loading amplitude. Initially, the SMA bars were in the austenite state and performed linear elastically. When the applied displacement was raised to approximately 6 mm, the specimen began to 'yield' due to the activation of forward phase transformation. Later, the force level gradually increased at a much lower rate associated with the phase transformation process. As the applied load was removed, the deformation fully recovered to zero associated with backward phase transformation. For all loading amplitudes, the second cyclic loop perfectly overlapped with the first one, implying a very stable cyclic property. Thus, the SMA bars successfully exhibited desirable SC capability as expected.

### 3.2. Steel damper

As shown in figure 7, the steel damper consists of the bending steel plate and base plate, both of which are made of Q235B steel as defined by Chinese code (GB 50017-2003 2003). Figure 7(a) shows the dimension of the bending steel plate, which was $130 \times 100 \times 5$ mm$^3$, and a diamond hole was cut in the center of the plate. The steel damper is essentially an X-shaped ADAS. The diamond hole was cut for running through the SMA bars. To facilitate the transfer of shear force inside the damper and to minimize stress concentration, the corner of the diamond hole was laser cut with arc transition and shifted 5 mm away from the plate edge. The base plate, as shown in figure 7(b), had a dimension of $100 \times 110 \times 10$ mm$^3$. The thick base plate offered fixed restraint for the bending steel plate and avoided generating excessive deformation when the damper was deformed. A total of four holes with a diameter of 12 mm were slotted for bolt connections.

Figure 8 shows the cyclic behavior of the steel damper. The steel damper exhibits fat hysteresis without strength or stiffness degradation, and in particular, it had perfect symmetrical behavior under tension and compression actions. Stable mechanical properties can be observed by the overlapped hysteretic loops in all loading amplitudes. In the SMA-steel damper, a total of four such steel dampers were installed to match the strength capacity of the SMA bars. To validate the strength estimation in the initial design, the test results were compared with the theoretical calculations using equation (3), as listed in table 1. In terms of the parameters of interest, the error is found to be less than 9%. The theoretical calculations constantly underestimated the test results because theoretical calculations cannot consider the material hardening effect induced by the welding procedure.

### 3.3. Hysteretic parameters of the SMA bars and steel damper

To highlight the hysteretic characteristics of the SC and AD elements, the SMA bars and steel damper are compared in terms of residual deformation and equivalent damping ratio as a function of applied displacement, as shown in figure 9. Figure 9(a) indicates that the residual deformation generated in the SMA bars is much smaller than that in the steel damper. Considering the results corresponding to the maximum
loading amplitude for example, the residual deformations of the SMA bars and steel damper were approximately 0.14 and 11 mm, corresponding to 1% and 70% of the applied displacement, respectively. In terms of the equivalent damping ratio plotted in figure 9(b), the steel damper performed much better than the SMA bars, the performance of the former was approximately eight times higher than that of the latter during the maximum loading cycle. Therefore, the direct comparison reveals the hysteretic features of these two elements. Further, it supports the intention of using SMA bars to recover deformation and using steel dampers to improve damping.

4. SMA-steel damper

The SMA-steel damper assembled to make use of the merits of SMA bars and steel dampers while maintaining a concise configuration is shown in figure 10. A pair of SMA bars and four steel dampers were newly fabricated and installed into the damper. The corresponding hysteretic parameters have been obtained through the above-mentioned tests. In addition to serving as a proof-of-concept, the study experimentally examined the effects of varying the contribution of the AD element on the final behavior of the SMA-steel damper by increasing the thickness of the bending steel plate. The damper specimens with 5 and 10 mm thick bending steel plates are denoted as S1 and S2, respectively. Prior to the formal tests, the properties of the new SMA bars were also stabilized by the same training treatment suggested earlier. Besides, the SMA bars were prestressed slightly by fastening the bolts to counterbalance the gaps between the interface of different parts.

4.1. Test results

To have a direct understanding of the typical deformation characteristics of the SMA-steel damper, the deformed shapes
which is clearly demonstrated by increased noticeably when the steel damper was engaged, the SMA-steel damper. It was observed that the damping is enhanced at the cost of partially deformation increased simultaneously. Thus, it can be hysteresis curve widened remarkably while the unrecoverable of the bending steel plate increased from 5 to 10 mm, the

| Specimen | $F_a$ (kN) | $F_b$ (kN) | $F_c$ (kN) | $F_d$ (kN) |
|----------|------------|------------|------------|------------|
| S1 Test  | 38.63      | 60.61      | 47.32      | 29.11      |
| Prediction | 44.09      | 64.64      | 55.30      | 33.61      |
| Error (%) | 14.13      | 6.65       | 16.86      | 15.46      |
| S2 Test  | 62.65      | 98.68      | 66.26      | 29.52      |
| Prediction | 65.62      | 115.24     | 87.02      | 30.81      |
| Error (%) | 4.74       | 16.78      | 31.33      | 4.37       |

Figure 13. Comparisons between hysteretic curves: (a) S1 versus SMA bars; (b) S1 versus steel damper. Figure 14 plots the cyclic behavior of the tested SMA-steel dampers. The specimens exhibited stable and symmetrical behavior without strength or stiffness degradation, which is in conjunction with the observations in the aforementioned tests. When the applied loading was increased gradually, the damper showed remarkable nonlinear characteristics. As the complete behavior is contributed together by SMA bars and steel dampers, the hysteretic behavior was observed in both the recentering tendency and high damping. Comparison between S1 and S2 indicate that, as the thickness of the bending steel plate increased from 5 to 10 mm, the hysteresis curve widened remarkably while the unrecoverable deformation increased simultaneously. Thus, it can be observed that damping is enhanced at the cost of partially losing SC capability.

To measure the contributions made by SMA bars and steel dampers, figure 13 compares their behavior with that of the SMA-steel damper. It was observed that the damping increased noticeably when the steel damper was engaged, which is clearly demonstrated by figure 13(a). At the maximum loading loop, the equivalent damping ratio of the SMA-steel damper was approximately three times that of the SMA bars. Compared to the steel damper, the activity of the SMA bars remarkably reduced the residual deformation from 11.0 to 1.2 mm in the last loading loop, as shown in figure 13(b).

The accuracy of the developed damping force model is examined by comparing the predicted strength capacity with the test results. Table 2 shows the comparison results in terms of strength corresponding to the points $a$, $b$, $c$, and $d$ illustrated in figure 3. Overall, the equation tends to overestimate the predictions by 4.37% and 31.33%. The major assumption made in the derivation of the model is that the SMA bars and steel dampers yield simultaneously. However, comparing figures 6 and 8 shows that the SMA bars ‘yield’ at approximately 6.5 mm, while the steel dampers yield at approximately 3.8 mm. This is the primary reason causing the damper to exhibit a reduced strength capacity than expected.

As shown in figure 14, strain gauges were used to measure the local behavior of the steel bending plates. Strain gauges were not glued on the surface of SMA bars, because the measuring range is up to $1 \times 10^4$ micro-strain. Most strain gauges were damaged by severe bending actions. To demonstrate the results, the data measured by L3 is selected. Figure 14(b) plots the time history of the strain value. As can be seen, it follows the rule of the input displacement loadings in the initial cycles. However, when the strain is up to $8 \times 10^3$ micro-strain, the strain gauge was damaged, leading to the value drastically dropped and remained to be around $1 \times 10^3$ micro strain permanently.

4.2. Hysteretic parameters

This section aims to quantify the hysteretic properties of the SMA-steel damper. The hysteretic parameters that interested by seismic applications are measured or calculated. To observe the trend in deformation, these parameters were plotted as a function of the loading amplitude. The results are presented in figure 15.

Figure 15(a) shows that residual deformation gradually accumulated with the increase in loading amplitude. The performances along both loading directions were given, which demonstrates the symmetry of the cyclic behavior. For both specimens, the residual deformations show an almost
linear relationship with the loading amplitude. The constantly larger residual deformation generated in S2 compared to S1 is attributed to the unrecoverable deformation of the steel damper. When the applied displacement was 15.5 mm, the residual deformation of S2 was approximately 6 mm, which indicates that over 60% of deformation was recovered.

Figure 15(b) plots the secant stiffness of the damper along both loading directions. With the increase in loading displacement, the secant stiffness decreases. This is because, upon large deformations, SMA bars enter austenite to martensite phase transformation process while the steel dampers are in the yielding plateau. The nonlinear behavior of both subassemblies capped the generated strength in the damper. In this case, when the thickness of the bending steel plate was doubled, the secant stiffness rose by approximately 50%.

Figure 15(c) exhibits the generated peak strength in the specimens. Both loading directions show an identical trend with the loading amplitude. The peak strength of S1 and S2 reached approximately 60 and 90 kN, respectively, in the last loading loop. The difference in strength is attributed to the variation in thickness of the bending steel plate and the changing degree matches with that found in the secant stiffness.

Figure 15(d) calculates the dissipated energy in each tension-compression loading cycle. Both specimens started to dissipate energy when the deformation exceeded 3.1 mm, which deformed the SMA bars by 1% strain elongation. The effect of increasing the thickness of the bending steel plate is remarkable on the finally AD. Compared to the 522 J dissipated by S1, the amount of dissipated energy by S2 drastically increased to 1600 J, which corresponds to approximately 200% improvement.

Figure 15(e) indicates the development of equivalent damping ratio. The trend of equivalent damping ratio is affected by secant stiffness and dissipated energy. The general trend kept increasing throughout the entire loading history. Initially, both the specimens had a 4% equivalent damping ratio. A large gap could be found between them when the displacement deformed the steel damper into plastic stage. At the maximum loading cycle, the equivalent damping ratio of S1 and S2 reached up to 9% and 18%, respectively. Thus, recalling the differences between S1 and S2 in terms of strength and stiffness, the difference in equivalent damping ratio seems more significant.

5. FE simulations

5.1. FE model

To enable a further understanding of the cyclic behavior of the proposed damper and to cross validate the test results, a numerical study was carried out using the general nonlinear FE analysis package ABAQUS (2017). Based on the numerical model, the stress states within each subassemblies can be conveniently accessed as well. As shown in figure 16, the three-dimensional FE model includes the force transmission plate, cover blocks, steel frame, steel dampers and SMA bars. To save the computational effort and avoid convergence problems, all the fastened bolts and welded conjunctions were not explicitly modeled but simplified as ‘tie’ interaction. For general contact pairs, ‘hard contact’ behavior with no penetration in the normal direction was assumed. The contact interfaces include those built between up cover block and steel frame, bottom cover block and steel triangle, and steel studs and cover blocks. The eight-node linear brick element (C3D8 elements) was used to create a mesh for the SMA bars. The meshing size was 10 mm, leading to 62 elements over the cross section of the SMA bar. For the bending steel plate and other steel components, the ten-node modified quadratic tetrahedron elements C3D10M were used. To achieve a balance between computational efficiency and simulation accuracy, the meshing size for the bending steel plate was redefined sufficiently to capture the plastic behavior, while other steel components were relatively coarse as they remained constantly elastic. A static displacement-controlled point load was applied on the loading position to simulate the loading cycles. The loading protocol was identical to that used for the tests.
5.2. Material properties

A built-in material model for SMA in ABAQUS using Auricchio’s approach (1997) was employed to simulate the superelastic behavior of the NiTi SMA under isothermal conditions. The associated critical material parameters, as shown in figure 16(d), include Young’s Modulus at the austenite and martensite phases \( (E_A \text{ and } E_M) \), forward and backward phase transformation stresses \( (\sigma_{Mf}, \sigma_{Ms}, \sigma_{As} \text{ and } \sigma_{Af}) \), Poisson’s ratio at the austenite and martensite states \( (v_A = v_M = v) \), and maximum transformation strain \( \varepsilon_L \). It should be noted that ABAQUS cannot define a rate dependent constitutive model for SMA material. The values of these parameters are based on the tensile results of the SMA coupons that are listed in table 3.

For the bending steel plate, the steel material used the model for metals subjected to cyclic loadings. The current model adopts Von Mises yield criterion and considers both isotropic and kinematical hardening effect based on the constitutive model proposed by Chaboche (1968). The back stress and isotropic hardening stress are shown in equations (18) and (19), respectively. The back stress indicates the movement of

Figure 15. Hysteretic parameters of the SMA-steel damper: (a) residual deformation; (b) secant stiffness; (c) peak strength; (d) dissipated energy; (e) equivalent damping ratio.
the yield surface, and isotropic hardening stress indicates the increase in radius of the yield surface as given below:

\[ \alpha = \sum_{k=1}^{g} C_k \gamma_k (1 - e^{-\gamma_k \sigma^0}), \]

\[ \sigma^0 = \sigma_{00}^s + Q_\infty (1 - e^{-\gamma_k \sigma^0}). \]

In the above equations, \( \sigma^0 \) is the equivalent plastic strain; \( C_k \) and \( \gamma_k \) are the parameters of the model; \( Q_\infty \) represents the limit of the isotropic hardening stress and \( \nu \) represents the speed of steel hardening; \( \sigma_{00}^s \) represents the initial yield stress. According to the steel coupon test results, the initial yield stress is approximately 280 MPa. The elastic module is 2.06 GPa and the Poisson’s ratio is 0.33. Based on the suggested parameters by Deng et al. (2013), the final calibrated parameters for this study are listed in Table 4.

### Table 4. Coefficients used in the constitutive model of the bending steel plate.

| \( C_1 \) | \( \gamma_1 \) | \( C_2 \) | \( \gamma_2 \) | \( C_3 \) | \( \gamma_3 \) | \( Q_\infty \) | \( \nu \) |
|---|---|---|---|---|---|---|---|
| 9000 | 173 | 7000 | 120 | 5000 | 32 | 21 | 1.2 |

5.3. Simulation results

Employing the above modeling technique, the cyclic loading tests were repeated by FE simulations. Figure 17 compares the hysteretic curves between experimental data and simulation results for the steel dampers, SMA bars and SMA-steel dampers S1 and S2. The numerical method generated coherent predictions with the test results. Both the SC and energy dissipation characteristics were well captured. Figure 17(a) shows that the unloading stiffness of the steel damper was overestimated to a certain degree, which is due to the difficulty in considering the material and geometric deficiencies of steel. A similar problem was detected in the simulation of S2 shown in Figure 17(d). Slight discrepancy was noted in the tension behavior of the SMA bars, as shown in Figure 17(b). This is attributed to the gap between the driving stud and top cover steel block, which slightly consumes the loading displacement in the tests. This gap was later eliminated by filling a thin aluminum sheet in the tests for SMA-steel dampers. The simulations for dampers S1 and S2 are plotted in Figures 17(c), (d), respectively, showing reasonable agreement with the test results. A quantitative evaluation of the FE model is made by comparing some
critical hysteretic parameters. The corresponding values are listed in table 5 and the associated errors are calculated. The numerical errors are similar in all parameters and the maximum error is found to be approximately 10%. This validates the FE model and simulation technique.

An in-depth insight in the behavior of the SMA-steel damper can be revealed by plotting the Von Mises stress contour, as shown in figure 18. For comparing the different components, the stress state corresponding to the maximum loading cycle was generated. At this loading displacement, the deformed shapes of the bending steel plates and SMA bars were consistent with the experimental observations. A deformation gap between the up cover block and steel frame can be clearly noticed as that observed during the tests. According to the Von Mises stress contour, the cover blocks and steel frame had a stress level lower than 200 MPa thus remained elastic. The force transmission plate kept plumb without buckling tendency. The bending steel plates showed nearly identical stress state at each cross section over the entire length. The SMA bars suffered from perfect uniform stress in the reduced section with a stress level of approximately 500 MPa, which exceeded the forward phase transformation stress threshold. The stress was less than 200 MPa at both ends of the SMA bar. Thus, it remained in austenite stage. Based on the examination of stress states, the performance of each component was checked and found to meet the expectation.

5.4. Parametric analysis

The validated FE model enables a further parametric study to investigate the influence of some key parameters that were challenging in the physical tests. Considering that the research is focused on the damping and recentering capability of the SMA-based dampers, the parameters of interest are determined to be the thickness of the bending steel plate and diameter of the SMA bar. This section selects steel plates with a wide range of thickness ranging from 0 to 25 mm with an interval of 5 mm and SMA bars with diameters ranging from 4 to 10 mm with an increment of 2 mm in each test. The case of 0 mm thick steel plate refers to pure SMA bars that were included for comparison purpose.

Figure 19 presents the numerical results of the dampers using different bending steel plates. As shown in figure 19(a), for cases with thickness less than 10 mm, the hysteresis was getting plump with the increase in plate thickness but was dominated by the SC capability due to the contribution of SMA bars. As the plate thickness increased further to be larger than 10 mm, as shown in figure 19(b), the hysteresis shape tended to be characterized by the elasto-plastic behavior attributed to the high proportion of the steel dampers. Unrecoverable deformation was generated because the yielding strength of the steel dampers became much higher than the forward phase transformation strength offered by the SMA bars. This can be understood by assessing the working mechanism of the SC energy dissipative steel brace developed...
Table 5. Comparisons between experimental data and numerical results upon the maximum loading cycle.

| Components | Peak strength (kN) | Secant stiffness (kN mm\(^{-1}\)) | Equivalent damping ratio (%) | Residual displacement (mm) |
|------------|-------------------|----------------------------------|-----------------------------|---------------------------|
|            | Test   | FE     | Error (%) | Test   | FE     | Error (%) | Test   | FE     | Error (%) |
| Steel      | 14.99  | 13.57  | -9.47     | 0.92   | 0.86   | -6.52     | 30.96  | 32.91  | 6.30      | 10.99  | 11.23  | 2.18      |
| SMA        | 54.40  | 50.36  | -7.43     | 3.38   | 3.24   | -4.14     | 3.48   | 3.59   | 3.16      | 0.14   | 0.13   | -7.14     |
| S1         | 60.61  | 64.05  | 5.68      | 4.03   | 4.11   | 1.99      | 8.59   | 9.55   | 11.18     | 1.15   | 1.16   | 0.87      |
| S2         | 98.68  | 99.91  | 1.24      | 6.18   | 6.53   | 5.66      | 17.23  | 19.19  | 11.43     | 5.94   | 6.02   | 1.35      |
by Christopoulos et al (2008). In the case of 15 mm, the yielding strength of the steel damper was over three times that of the SMA bars. An additional plot for this case is given in figure 20(a) that shows the residual deformation reduced from 14.2 to 10.5 mm corresponding to 26% reduction. In the utmost case of 25 mm, as shown in figure 20(b), the behavior was nearly identical to pure steel dampers. Although the SC capability deteriorates by increasing the thickness of the bending steel plate, the role of SMA bars in recovering deformation is clearly demonstrated.

Figure 21 shows the development of equivalent damping ratio and residual deformation with the loading displacement. This figure clearly demonstrates that both parameters were effectively raised, but the tendency becomes saturated as the cyclic behavior gradually approached a bilinear elasto-plastic shape. In other words, the SC capability is consumed by adding damping capacity. Compared to pure SMA bars with a damping ratio of 3.5%, the total damping significantly increased to over 40%; i.e. a tenfold enhancement when 25 mm bending steel plate was used in the steel damper. Less
than 10% deformation can be recovered in the utmost case, which implies that the SC capability was lost by over 90%.

Figure 22 examines the effect of varying the diameter of SMA bars on the cyclic behavior of the damper. The damper utilizing the 8 mm diameter SMA bars serves as the baseline. As expected, when the diameter was reduced, the strength and stiffness decreased accordingly. More importantly, the residual deformation became fairly noticeable. When the 4 mm diameter SMA bars were installed, the unrecoverable deformation constituted over 30% of the maximum deformation. Using large size SMA bars increases strength and stiffness, but imposes a higher strength demand to the adjacent members. As indicated in figure 22(b), slackness is found in the hysteretic curve that is caused by the yielding behavior of the bottom cover block, as shown in figure 23.

6. Conclusions

To enhance the damping capability of SMA-based dampers, this study suggested adding steel dampers made of bending steel plates in parallel. By combining the SMA bars and steel dampers, this study proposed a new damper named SMA-steel damper. Experimental loading tests were carried out to prove the design concept and to obtain the hysteretic characteristics of the damper. The relationship between the performance indices interested by seismic applications was built as a function of the loading amplitude. For further investigation, the high-fidelity three-dimensional FE model was established in ABAQUS. According to this study, the following conclusions can be drawn:
The proposed SMA-steel damper possesses stable and symmetrical cyclic behavior upon tension and compression; this damper features both, good deformation-recovering capability and high damping ratio; the configuration of the damper is concise, permitting convenient assembling and repairing in case of damage caused by severe earthquakes.

The experimental data shows that by combining the steel dampers made of 5 and 10 mm thick bending steel plates with SMA bars having a diameter of 8 mm, an equivalent damping ratio of approximately 10% and 20% can be achieved, respectively. The applied deformation can be recovered by approximately 90% and 60%, respectively.

The established FE model reflected the cyclic behavior of the damper and captured the hysteretic characteristics. The error of the estimated parameters is around 10%; the parametric study based on the FE model indicated that the SC capability will be consumed by adding damping, but the tendency will be finally saturated.

Increasing the thickness of the bending steel plate may be detrimental to the SC capability of the SMA-steel damper, but the effect on the dynamic behavior under realistic earthquake excitations is not necessarily fully predictable. Thus, the seismic performance of the proposed damper needs further investigation by installing it into structures and subjecting the damped structures to an earthquake environment.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (No.: 51808317) and Beijing Postdoctoral Research Foundation, China (Grant No. ZZ2019-104). However, any opinions, findings, conclusions and recommendations presented in this paper are those of the authors and do not necessarily reflect the views of the sponsors. Finally yet importantly, the authors wish to thank the anonymous reviewers for their careful evaluations and insightful comments that helped improve the paper.

ORCID iDs

Canxing Qiu https://orcid.org/0000-0001-5323-7229
Hongyang Wang https://orcid.org/0000-0002-0382-4203

References

ABAQUS 2017 Analysis User’s Manual (Providence, RI: ABAQUS, Inc)
Andrawes B and DesRoches R 2007 Effect of hysteretic properties of superelastic shape memory alloys on the seismic performance of structures Struct. Control Health Monit. 14 301–20
Araki Y, Shrestha K C, Maekawa N, Koetaka Y, Omori T and Kaunuma R 2015 Shaking table tests of steel frame with superelastic Cu–Al–Mn SMA tension braces Earthq. Eng. Struct. Dyn. 45 297–314
Auricchio F, Taylor R L and Lubliner J 1997 Shape-memory alloys: macromodelling and numerical simulations of the superelastic behavior Comput. Methods Appl. Mech. Eng. 143 175–94
Brunae M, Chang S E, Eguchi R T, Lee G C, O’Rourke T D, Reinhorn A M and Von Winterfeldt D 2003 A framework to quantitatively assess and enhance the seismic resilience of communities Earthq. Spectra 19 733–52
Chaboche J L 1968 Time-independent constitutive theories for cyclic plasticity Int. J. Plast. 2 149–88
Chan R W and Albermann F 2008 Experimental study of steel slit damper for passive energy dissipation Eng. Struct. 30 1058–66
Choi E, Mohammadzadeh B and Kim H S 2018 SMA bending bars as self-centering and damping devices Smart Mater. Struct. 28 025029
Christopoulos C, Tremblay R, Kim H J and Lacerte M 2008 Self-centering energy dissipative bracing system for the seismic resistance of structures: development and validation J. Struct. Eng. 134 96–107
Deng K L, Pan P and Wang C Y 2013 Development of crawler steel damper for bridges Constr. Steel Res. 85 140–50
DesRoches R, McCormick J and Delenmont M 2004 Cyclic properties of superelastic shape memory alloy wires and bars J. Struct. Eng. 130 38–46
DesRoches R and Smith B 2004 Shape memory alloys in seismic resistant design and retrofit: a critical review of their potential and limitations J. Earthq. Eng. 8 415–29
Dolce M and Cardone D 2001 Mechanical behaviour of shape memory alloys for seismic applications 1. Martensite and austenite NiTi bars subjected to torsion Int. J. Mech. Sci. 43 2631–56
Dolce M, Cardone D and Marnetto R 2000 Implementation and testing of passive control devices based on shape memory alloys Earthq. Eng. Struct. Dyn. 29 945–68
Dolce M, Cardone D and Marnetto R 2001 SMA recentering devices for seismic isolation of civil structures Smart Mater. Struct. 4330 238–50
Fang C, Yam M C H, Lam A C C and Xie L K 2014 Cyclic performance of extended end-plate connections equipped with shape memory alloy bolts J. Constr. Steel Res. 94 122–36
Fang C, Yam M C, Lam A C and Zhang Y 2015a Feasibility study of shape memory alloy ring spring systems for self-centering seismic resisting devices Smart Mater. Struct. 24 075024
Fang C, Yam M C H and Ma H 2015b Tests on superelastic Ni–Ti SMA bars under cyclic tension and direct-shear: towards practical recentring connections Mater. Struct. 48 1013–30
Fang C, Zhou X, Osofore A I, Shu Z and Corrida M 2016 Superelastic SMA Belleville washers for seismic resisting applications: experimental study and modelling strategy Smart Mater. Struct. 25 105013
GB 50017-2003 2003 Code for Design of Steel Structures (Beijing: China Architecture & Building Press) (in Chinese)
GB/T 228-2010 2010 Standardization Administration of the People’s Republic of China (Beijing: China Architecture & Building Press) (in Chinese)
Graesser E J and Cozzarelli F A 1991 Shape memory alloys as new materials for seismic isolation J. Eng. Mech. 117 2590–608
Hao L, Zhang R and Jin K 2018 Direct design method based on seismic capacity redundancy for structures with metal yielding dampers Earthq. Eng. Struct. Dyn. 47 515–34
Housner G W, Bergman L A and Caughey T K 1997 Structural control: past, present, and future J. Eng. Mech. 123 897–971
Kato S, Kim Y B and Nakazawa S 2005 Simulation of the cyclic behaviour of J-shaped steel hysteresis devices and study on the efficiency for reducing earthquake responses of spatial structures J. Constr. Steel Res. 61 1457–73
Kishiki S, Ohkawara Y and Yamada S 2008 Experimental evaluation of cyclic deformation capacity of U-shaped steel dampers for base-isolated structures J. Struct. Constr. Eng. 624 333–40
Li H, Liu M and Ou J 2004 Vibration mitigation of a stay cable with one shape memory alloy damper Struct. Control Health Monit. 11 21–36
Li H, Mao C X and Qu J P 2008 Experimental study and theoretical study on two types of shape memory alloy device Earthq. Eng. Struct. Dyn. 37 402–26
Li H N, Liu M M and Fu X 2018 An innovative re-centering SMA-lead damper and its application to steel frame structures Smart Mater. Struct. 27 075029
De la Llera J, Esquerra C and Almanzal J L 2004 Earthquake behavior of structures with copper energy dissipators Earthq. Eng. Struct. Dyn. 33 329–58
McCormick J, Aburano H, Ikenaga M and Nakashima M 2008 Permissible residual deformation levels for building structures considering both safety and human elements Proc. 14th World Conf. on Earthquake Engineering (Beijing, China)
Miller D J, Fahnstock L A and Eatherton M R 2012 Development and experimental validation of a nickel–titanium shape memory alloy self-centering buckling-restrained brace Eng. Struct. 40 288–98
Nakashima M, Saburi K and Tsuji B 1996 Energy input and dissipation behaviour of structures with hysteretic dampers Earthq. Eng. Struct. Dyn. 25 483–96
Ozbayr D E, Hurlebaus S and DesRoches R 2011 Seismic response control using shape memory alloys: a review J. Intel. Mater. Syst. Struct. 22 1531–49
Padgett J E, DesRoches R and Ehlinger R 2010 Experimental response modification of a four-span bridge retrofit with shape memory alloys Struct. Control Health Monit. 17 694–708
Qiu C, Zhang Y, Li H, Qu B, Hou H and Tian L 2018 Seismic performance of concentrically braced frames with non-buckling braces: a comparative study Eng. Struct. 154 93–102
Qiu C, Zhang Y, Qu B, Dai C, Hou H and Li H 2019 Cyclic testing of seismic dampers consisting of multiple energy absorbing steel plate clusters Eng. Struct. 183 255–64
Qiu C and Zhu S 2014 Characterization of cyclic properties of superelastic monocrystalline Cu–Al–Be SMA wires for seismic applications Constr. Build. Mater. 72 219–30
Qiu C and Zhu S 2016 High-mode effects on seismic performance of multi-story self-centering braced steel frames J. Constr. Steel Res. 119 133–43
Qiu C and Zhu S 2017 Shake table test and numerical study of self-centering steel frame with SMA braces Earthq. Eng. Struct. Dyn. 46 117–37
Qu B, Dai C, Qiu J, Hou H and Qiu C 2019 Testing of seismic dampers with replaceable U-shaped steel plates Eng. Struct. 179 625–39
Sabeli R, Mahin S and Chang C 2003 Seismic demands on steel braced frame building with buckling-restrained braces Eng. Struct. 25 655–66
Song G, Ma N and Li H N 2006 Applications of shape memory alloys in civil structures Eng. Struct. 28 1266–74
Soong T T and Dargush G F 1997 Passive Energy Dissipation Systems in Structural Engineering (New York: Wiley)
Soong T T and Spencer B F 2002 Supplemental energy dissipation: state of the art and state of the practice Eng. Struct. 24 243–59
Speicher M S, DesRoches R and Leon R T 2011 Experimental results of a NiTi shape memory alloy (SMA)-based recentering beam-column connection Eng. Struct. 33 2448–57
Tremblay R, Lacerte M and Christopoulos C 2008 Seismic response of multistory buildings with self-centering energy dissipative steel braces J. Struct. Eng. 134 108–20
Tsai K C, Chen W H and Hong C P 1993 Design of steel triangular plate energy absorbers for seismic-resistant construction Earthq. Spectra 3 505–28
Wang B and Zhu S 2018a Cyclic tension–compression behavior of superelastic shape memory alloy bars with buckling-restrained devices Constr. Build. Mater. 186 103–13
Wang B and Zhu S 2018b Superelastic SMA U-shaped dampers with self-centering functions Smart Mater. Struct. 27 055003
Wang W, Fang C and Liu J 2016 Large size superelastic SMA bars heat treatment strategy, mechanical property and seismic application Smart Mater. Struct. 25 075001
Wang W, Fang C and Liu J 2017 Self-centering beam-to-column connections with combined superelastic SMA bolts and steel angles J. Struct. Eng. 143 04016175
Whittaker A, Bertero V V and Alonso J 1989 Earthquake Simulator Testing of Steel Plate Added Damping and Stiffness Elements (UC Berkeley, CA: Earthquake Engineer Research Center)
Youssef M A, Alam M S and Nehdi N 2015 Experimental investigation on the seismic behavior of beam-column joints reinforced with superelastic shape memory alloys J. Earthquake Eng. 12 1205–22
Zhang Y and Zhu S 2007 A shape memory alloy-based reusable hysteretic damper for seismic hazard mitigation Smart Mater. Struct. 16 1603
Zhu S and Zhang Y 2008 Seismic analysis of concentrically braced frame systems with self-centering friction damping braces J. Struct. Eng. 134 121–31
Zhu S and Zhang Y 2013 Loading rate effect on superelastic SMA-based seismic response modification devices Earthq. Struct. 4 607–27