Seismic performance of EBFs equipped with an innovative shape memory alloy damper

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Abstract. Given their unique characteristics, Shape Memory Alloys (SMAs) have significant potential for use in different areas of engineering. The phase shift characteristics of these alloys allow them to memorize a certain shape and, if deformed, they revert to that shape through a thermal process. Given the vast potentials of SMAs, they can be utilized to address the limitation of conventional Eccentrically Braced Frames (EBFs) with vertical links in order to achieve better residual and maximum interstory drifts. This paper introduced a vibration control system equipped with SMAs to achieve an improved operational domain. Compared to conventional EBFs, the proposed system named Recentering Damping Device (RDD) is easy to fabricate and implement and allows for redesigning fuse members. A numerical analysis of a 9-story steel frame building was performed using nonlinear analysis program, OpenSees, to evaluate the system performance. Results of time history analysis demonstrated better self-centering behavior and lower residual interstory drifts of the proposed system than EBF.

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1. Introduction

Eccentrically Braced Frames (EBFs) are lateral force-resisting systems that provide not only desirable elastic stiffness but also manageable inelastic behavior realized through controlled deformation of the link member under heavy loads such as earthquake motion. The history of research on the subject of controlled deformation under seismic loads can be traced back to the works published about three decades ago in [1–3].

The most important disadvantage of horizontal EBFs is the difficulty of repairing a deformed link member. To resolve this issue, researchers such as Aristizabal-Ochoa [4], Ghabarah and Abou Elfath [5], and Vetr et al. [6] proposed the application of vertical EBFs, in which a shear panel served as a vertical link between the story beam and the $\wedge$-shaped braces. This approach not only facilitates the repairing of damaged links but also makes the repairing easier in their horizontal counterpart. This approach also provides a convenient solution to the problematic cases where the presence of extensive gravity loads necessitates ensuring that floor beams remain in the elastic region. The disadvantage of this approach is the difficulty to provide lateral bracing for vertical links [7].

Shape Memory Alloy (SMA) is an alloy that can memorize a certain shape and, if deformed, recover the memorized shape when heated. SMAs have extensive potential for use in several industries, particularly in structures, automobiles, and aerospace vehicles [8]. Given the superelastic behavior, recentering ability, and damping capacity of SMAs, their potential use in the vibration control of structures has been the subject...
of many studies [9–26]. A comprehensive review of civil engineering applications of SMAs can be found in [27,28]. Regardless of their potential, applying these alloys to real structures needs an in-depth understanding of their mechanical behavior in different scenarios, which still requires further research [29]. This is also true in the case of EBFs, given that possible behaviors of SMAs in these frames are still under investigation [23].

In passive vibration control schemes, energy dissipation mechanisms are expected to reduce the demand on the primary structural members as well as any consequent plastic deformation. Meanwhile, the recentering mechanism attempts to return the structures to its original geometry, thereby preventing the aggregation of inelastic deformations [30]. The problem of applying SMAs to EBFs is the low energy dissipation capacity of recentering mechanisms, especially under high rate loadings, which is hard to reconcile with almost completely linear elastic behavior of SMAs. One approach to resolving this issue is the use of Nitinol-based devices proposed by Dolce et al. [31,32], which provides a good combination of recentering capability and energy dissipation. Some other researchers demonstrated that the combination of base isolation and SMA led to more structural integrity and concluded that recentering Lead Rubber Bearing (LRB) isolators enhanced the seismic performance in terms of energy dissipation and re-centering influence (e.g. [33]).

Haque and Alam [34] presented a piston-based bracing that could perform recentering after large deformation. DesRoches et al. investigated the application of SMA bars to the beam-to-column connections of steel moment-resisting frames and the seismic performance of the resulting system [35]. Ellingwood et al. studied the seismic demand of steel moment-resisting frames with SMA connections, but they used a probabilistic seismic demand assessment approach for this purpose [36]. The application of SMAs to the vibration control systems typical of other domains of civil engineering was also researched [23,37–41]. Moreover, several researchers have employed the special properties of SMAs to improve the response of structures. For example, in the references [16,23,41,42], it can be seen that the application of SMAs could significantly reduce the response of structures in terms of interstory drift ratios, residual drifts, and absolute acceleration of floors.

This paper proposes a recentering damper with enhanced self-centering and energy dissipation capabilities, which is simple to set up and can be utilized for the seismic design of new structures as well as retrofitting of existing structures. This paper also provides the results of the tests conducted to determine the impact of displacement amplitude and frequency on the mechanical behavior of the device, and the shaking table tests were carried out to evaluate its ability to control the seismic response.

2. SMA characteristics

2.1. Phase transformations

SMAs have two stable phases. The first phase, martensite, is the state where alloy has high stress and low temperature, and the second phase, austenite, is the state where alloy has low stress and high temperature. Martensite phase itself has two variants: twinned and detwinned. Therefore, a change in stress, temperature, or both can trigger phase transformation in the case of these alloys. The strain corresponding to the phase transformation is called transformation strain. In Figure 1, the transformation fronts are portrayed on the $T – \sigma$ plane. The phase transformation is the source of Shape Memory Effect (SME) and pseudoelasticity that make SMAs a fascinating and potentially rewarding subject of research. Researchers such as reference [43] have identified more phases for SMAs to model other effects, but this is beyond the scope of the present paper.

2.2. Shape Memory Effect (SME)

SME can be described as a process in which SMA memorizes a shape and, then, recovers that shape when heated. As shown in Figure 2, this effect is realized in the four following stages:

1. **Stress application**: Subjecting the alloy to stress rearranges the twinned martensite into detwinned martensite, but leaves a transformation strain;
2. **Stress removal**: Removing the stress eliminates the elastic strain, but not the transformation strain, as the alloy remains in the detwinned martensite phase;
3. **Heat application**: Once heated, the alloy undergoes a phase shift from martensite to austenite,
away from each other, the device will create a tension force and flag-shaped hysteresis which, alongside the hysteresis of the lead core, will result in significant energy dissipation. The plates moving toward each other will create no compression force in the bars, as they can slip into the slots embedded for this purpose. The SMA bars are connected to the steel plates using nuts. Some researchers conducted experimental tests equipped with the SMA bars in their model using nuts (e.g., [45, 46]).

4. Verification study

To ensure the accuracy of the modeling, all parts of the modeling have been verified by the experimental tests available in the literature. The verification study includes two different parts:

1. An Single-Degree-Of-Freedom (SDOF) vertical shear link studied by Bouwkamp et al. [47];
2. Modeling of the SMA material tested by Desroches et al. [48].

More details are addressed in the following.

4.1. Verification study of an SDOF vertical shear link

A one-story vertical shear link is subjected to cyclic loading in which two cycles are applied at displacement levels of ±1.5 mm, ±2.0, ±3.0, ±3.5, ±4.0, ±5.0, ±6.0, ..., ±10.0, ±12.0, ..., ±34.0. The details of the SDOF frame are shown in Table 1. Figure 4 illustrates good agreement between the results of the experimental test and OpenSees.

4.2. Verification study of SMA behavior

To evaluate the accuracy of the simulation of the SMA bar in OpenSees platform, the behavior of the material was verified by Desroches et al. [48]. Figure 5 shows a comparison between an SMA bar with 25.4 mm diameter and OpenSees, demonstrating that the parameters applied to the numerical model have been adopted accurately.
Table 1. The details of the SDOF frame tested by Boulkemp et al. [47].

| Specimen no. | Beam section | Vertical shear link section | Shear link length, e (mm) | Column section | Brace section |
|--------------|--------------|-----------------------------|--------------------------|----------------|---------------|
| 3            | HEA320       | HEA280                      | 300                      | 2UPN140        | 2UPN220       |

5. Frame design and modeling

The performance of the system was evaluated using the models of 9-story steel buildings designed for a seismically active site (Tehran) composed of soil type III with $V_s30 = 175 - 375$ m/s according to Iranian code of practice for seismic-resistant design of buildings [49]. Every story was assumed to have a height of 3.2 m. Buildings were designed using the gravity loads typically assumed for residential buildings in Iran. An image of the designed structures is shown in Figure 6. The specifications of the buildings are provided in Table 2. To ensure a reasonable comparison, the natural period of both systems should be almost the same. Attempts have been made to keep the natural period of the RDD system close to the conventional EBF by controlling the amount of SMA in the structure. The natural periods of the conventional structure and the RDD braced frame are 1.0 sec and 0.94 sec, respectively.

The buildings were modeled and analyzed by using OpenSees software. All models were simulated based on a verified model in OpenSees [47,50]. Internal frame of all structures was subjected to 2D nonlinear static and dynamic analyses. Steel behavior was modeled using OpenSees material library by assigning the elements with a desired bilinear kinematic stress-strain curve. To ensure that there would be no jump in local stiffness of elements or the transition between elastic and plastic regions, a transition curve was defined for the tangent moduli (the intersection of the first and second tangents). Beam and column cross-sections...
were modeled using a combination of displacement-based beam-columns and fiber sections. According to [51, 52], force-based elements are characterized by inherently lower stability than displacement-based elements. In the software, P-delta transformation of geometrical stiffness matrix was used to make sure that P-delta effects were incorporated into the analysis.

The details of the LRB used in the nine-story building are listed in Table 3.

| LRB-S     | V (kN) | $K_x$ (kN/mm) | $x_e$ (%) | $F_2$ (kN) | $F_1$ (kN) | $d_1$ (mm) | $d_2$ (mm) | $D_g$ (mm) | $t_e$ (mm) | $h$ (mm) | $H$ (mm) | $Z$ (mm) |
|-----------|--------|--------------|-----------|------------|------------|------------|------------|------------|------------|----------|---------|---------|
| 800/128-130 | 10310  | 3.2          | 29        | 267        | 155        | 10         | 83         | 800        | 128        | 223      | 283     | 850     |

Figure 6. Elevations and spans of building.

6. Performance assessment

The lateral load-carrying capacity was evaluated by applying lateral loads to the models both statically and dynamically.

6.1. Pushover curve

The lateral strength and post-yield behavior were assessed through static pushover analysis. Figure 7 presents the base shear versus maximum roof displacement pushover diagram obtained for the 9-story model. To ensure that the inherent response of the
building to lateral loading was accounted for, a load pattern based on the structure’s fundamental period was used to apply loading in a displacement-controlled state.

These results demonstrate that the proposed system has better performance due to its higher capacity.

### 6.2. Nonlinear time history analysis

Beyond the nonlinear static analyses, nonlinear response history analyses were carried out to further evaluate the inter-story drift responses of the system. This section discusses maximum inter-story drifts, maximum residual inter-story drifts, and residual displacement obtained from the nonlinear response history analyses of systems with and without the proposed damper.

To conduct the nonlinear time history analysis, ten far-field records were selected from FEMA P695 at magnitudes of 6.5–7.5. All the ground motion time histories were scaled to 0.55 g based on a method suggested by Iranian code of practice for the seismic-resistant design of buildings [49]. Figure 8 shows the scaling procedure according to Iranian seismic code. In addition, the considered soil type for Iran is D (stiff soils) based on Geomatrix soil class in USGS (US Geological Survey). The details of the used ground motions are specified in Table 4.

6.2.1. Maximum interstory drift ratio

Global and local interstory deformations are one of the causes of damage induced to the structure. Even elastic deformation of the structure may induce some damage to the nonstructural components. Therefore, greater deformation will cause not only nonstructural damage but also the series structural damage. Figure 9 shows that the maximum interstory drift has been reduced to 57%.

The response of the 9-story building subjected to one ground motion (record seq. no. 900 in Table 4) is shown in Figure 10 as an example.

### Table 4. Far-field ground motions from FEMA P695.

| Record seq. no. | \(V_{s30}\) (m/s) | NEHRP class | Year | Name | Recording station | Magnitude | PGA (g) |
|-----------------|-------------------|-------------|------|------|-------------------|-----------|--------|
| 933             | 3.66              | D           | 1994 | Northridge | Beverly Hills-Mulhol | 6.7       | 0.52   |
| 960             | 3.09              | D           | 1994 | Northridge | Canyon Country-WLC | 6.7       | 0.48   |
| 1602            | 3.26              | D           | 1999 | Durce, Turkey | Bolu | 7.1       | 0.82   |
| 106             | 2.75              | D           | 1979 | Imperial Valley | Delta | 6.5       | 0.35   |
| 174             | 1.96              | D           | 1979 | Imperial Valley | El Centro Array#11 | 6.5       | 0.38   |
| 1116            | 2.96              | D           | 1995 | Kobe, Japan | Shin-Osaka | 6.9       | 0.254  |
| 1158            | 2.76              | D           | 1999 | Kocaeli, Turkey | Durce | 7.5       | 0.36   |
| 900             | 3.54              | D           | 1992 | Landers | Yermo Fire Station | 7.3       | 0.21   |
| 848             | 2.71              | D           | 1992 | Landers | Coolwater | 7.3       | 0.42   |
| 752             | 2.89              | D           | 1989 | Loma Perieta | Capitola | 6.9       | 0.53   |
6.2.2. Residual drift
The inelastic deformation caused under earthquake loads may lead to significant residual deformation which increases the time and cost of the structure repair and, in some cases, leads to partial or total collapse or unsability of structure. As can be seen in Figures 11 and 12, the RDD device can significantly decrease the residual drift in the 9-story building. Figure 12 shows the residual drift of the two structures under Landers earthquake (see Table 4). The re-centering effect can be clearly seen in Figure 12. Based on this figure, the 9-story conventional building is not usable after the earthquake and will probably collapse, partially or totally. However, in the RDD braced frame, the maximum residual drift of the 9-story building is almost 0.2%; therefore, considering rehabilitation is reasonable and affordable.

6.2.3. Residual displacement
Residual displacement has an important role in judging the post-earthquake safety of buildings and in decision on the economic possibility of repair and reconstruction. Figure 13 illustrates the effect of the RDD device on mitigation of the residual displacement. As can be seen in Figure 13, the residual displacement has decreased. Moreover, residual displacement is more uniform in the case of both buildings. Time history response of the buildings is shown in Figure 14. It can be observed that the RDD device has a significant role in reducing the residual displacement of the structures. Uniform drift corresponds to uniform demand capacity stiffness ratios [55].

7. Conclusions
A Re-centering Damping Device (RDD) including an Eccentrically Braced Frame (EBF) equipped with
Shape Memory Alloy (SMA) that acts as a rapid repair fuse was proposed and numerically evaluated in this study. A nine-story steel frame was considered by using numerical models. A nonlinear time history analysis was conducted using 10 different ground motions simulated in the OpenSees platform. The main findings of the present study are summarized as follows:

1. The simulation results illustrated that RDD could reduce the maximum inter-story drift ratio by 57% in the nine-story building;
2. Compared to conventional EBFs, the RDD system effectively reduced residual drift by up to 86.99% for the nine-story buildings at different ground motion records;
3. The RDD system also produced minimal residual displacement for all of the ten ground motion records;
4. Considerably lower residual drifts observed in the proposed RRD system demonstrated that the repair costs of the steel buildings equipped with RRD were lower than those of the traditional steel frames after an earthquake;
5. The pushover curve showed that the RRD system had larger capacity than the conventional system;
6. Although SMA materials were expensive, their cost could be kept quite modest by using reasonably priced materials.

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