A NOVEL CONFINED SUPERELASTIC DAMPER FOR EARTHQUAKE-RESILIENT DESIGN AND RETROFIT OF CIVIL STRUCTURES

A.M. Asfaw\textsuperscript{1}, F. Shi\textsuperscript{2}, and O.E. Ozbulut\textsuperscript{3}

ABSTRACT

Conventional earthquake resisting structural systems are deemed to provide adequate safety without significant damage for design level earthquake intensities. However, these systems significantly depend on inelastic deformations to resist strong ground shakings. Thus, high repair costs and associated business downtime are inevitable. This paper introduces an innovative Confined Superelastic Damper (CSD) that dissipates seismic energy while providing a self-centering capability to minimize damage to structural elements. The CSD is made up of a superelastic Nickel-Titanium (NiTi) shape memory alloy (SMA) bar restrained by a steel tube filled with grout. The SMA bar can accommodate large deformations without significant accumulation of residual strain and also dissipate energy due to its typical flag-shaped hysteretic behavior. The outer steel tube will restrain the SMA bar from buckling as the damper undergoes significant cyclic stresses in compression. As a step towards the development of the CSD, a detailed experimental investigation into the complex buckling and post-buckling behavior of large diameter superelastic SMA bars is discussed in this paper. In particular, compressive testing of NiTi rods with different slenderness ratios are conducted. Stress-strain curves are plotted and buckling response is discussed. Based on test results, an anti-buckling system for the development of CSD is suggested. Successful implementation of CSD is demonstrated as a seismic retrofit of non-ductile RC beam-column joints through numerical simulations. Compared with the original non-ductile RC joints, the joints retrofitted with CSDs exhibited improved performance in terms of re-centering and energy dissipation capacity.

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A.M. Asfaw¹, F. Shi², and O.E. Ozbulut²

ABSTRACT

Conventional earthquake resisting structural systems are deemed to provide adequate safety without significant damage for design level earthquake intensities. However, these systems significantly depend on inelastic deformations to resist strong ground shakings. Thus, high repair costs and associated business downtime are inevitable. This paper introduces an innovative Confined Superelastic Damper (CSD) that dissipates seismic energy while providing a self-centering capability to minimize damage to structural elements. The CSD is made up of a superelastic Nickel-Titanium (NiTi) shape memory alloy (SMA) bar restrained by a steel tube filled with grout. The SMA bar can accommodate large deformations without significant accumulation of residual strain and also dissipate energy due to its typical flag-shaped hysteretic behavior. The outer steel tube will restrain the SMA bar from buckling as the damper undergoes significant cyclic stresses in compression. As a step towards the development of the CSD, a detailed experimental investigation into the complex buckling and post-buckling behavior of large diameter superelastic SMA bars is discussed in this paper. In particular, compressive testing of NiTi rods with different slenderness ratios are conducted. Stress-strain curves are plotted and buckling response is discussed. Based on test results, an anti-buckling system for the development of CSD is suggested. Successful implementation of CSD is demonstrated as a seismic retrofit of non-ductile RC beam-column joints through numerical simulations. Compared with the original non-ductile RC joints, the joints retrofitted with CSDs exhibited improved performance in terms of re-centering and energy dissipation capacity.

Introduction

In the current state-of-the-art seismic design philosophy, most structures are designed to behave in the inelastic range under design-basis earthquakes [1]. Although this design strategy can guarantee “life-safety” by controlling structural damage and preventing collapse, noticeable permanent deformation is frequently observed in conventional seismic-resisting structures according to post-earthquake reconnaissance.

Following the 1994 Northridge and 1995 Kobe earthquakes, a number of structures had to be demolished [2-3] although they were still standing. This was primarily because of large residual deformations observed in these structures, which prevented an economic repair. There have been significant research efforts to overcome the limitations of conventional seismic resisting systems by implementing passive control devices. One such earlier effort led to the development of

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buckling restrained braces (BRBs). BRBs have proved efficiency in providing structures with stable hysteretic behavior, significant ductility, and large energy dissipation capacity [4]. However, past studies have shown that steel BRBs commonly have large residual deformations after an earthquake because of the accumulation of plastic deformations [5]. Consequently, structures designed with BRBs can experience excessive residual story drifts. The post-earthquake residual story drift ratio is a critical index that determines whether repairing the damaged structure or rebuilding a new one is a more effective strategy. A study conducted in Japan after 1999 Kobe earthquake suggested that the threshold of residual inter-story drift ratio in determining the reparableabiliy is 0.5% [6], raising the urgency of developing high-performance braces or energy dissipation devices to control peak seismic demands and meet the stringent requirement on the residual inter-story drift ratio. In response to this, research efforts continued investigating methods that may reduce or eliminate residual deformations, leading to the development of self-centering systems [7-10].

There are several different mechanics for creating a restoring force to return a civil structure to plumb after an earthquake. One approach is to allow structure to undergo controlled rocking at discrete locations such as column-base joint or beam-column joints. These systems usually involve the use of unbonded post-tensioned tendons to provide bilinear elastic self-centering behavior and a dissipating system to produce sufficient energy dissipation. Rocking precast concrete walls [7-8] and post-tensioned precast concrete special moment frames [9] are examples of such systems. Another approach is to employ braces or seismic control devices with self-centering capabilities [10].

Due to its inherent nonlinear elastic behavior, shape memory alloys (SMAs) have also been considered for self-centering systems. Many studies have been conducted to study self-centering steel frame structures that incorporate either SMA-based dampers [11-12] or short-segment SMA braces [13-16]. McCormick et al. [13] investigated the use of short-segment SMA braces in three and six-story frames. Results pointed out that the re-centering nature of superelastic SMA braces is efficient in reducing the maximum story drifts and the residual drifts under earthquake loading. Youssef et al. [14] studied the use of short-segment SMA bracing in strengthening low-rise RC frames. The seismic performance of the SMA braces was compared with that of steel BRBs. The results revealed that the use of superelastic SMA braces in RC frames led to significant reductions in seismic residual deformations. Asgarian and Moradi [15] used short-segment SMA bracing as a replacement to steel BRBs. The seismic responses of the frames with SMA braces were compared to the ones with steel BRBs. The results indicated that implementing the SMA braces can provide considerable reduction in residual roof displacement and peak inter-story drift compared to those of buckling restrained braced frames. Vafaei and Eskandari [16] studied the seismic performance of steel mega braced frames equipped with short segment SMA braces under near-fault earthquakes. They concluded that implementing of SMA braces can significantly reduce the residual displacements in comparison to the case of steel BRBs.

This paper introduces a novel seismic energy dissipating element, termed Confined Superelastic Damper (CSD). The CSD consists of a superelastic Nickel-Titanium (NiTi) SMA bar restrained by a grout-filled steel tube. The primary purpose of the CSD is to serve as a fuse element to prevent damage to main structural elements and provide both re-centering capability and reliable energy dissipating capacity for the whole structure. Potential applications of CSD include but not limited to their use as knee braces in the seismic retrofit of reinforced concrete moment resisting frames, as an external damper in post-tensioned self-centering connections, and as a component in ductile end cross frames in steel plate girder bridges. This study first presents an experimental
investigation on the complex buckling and post-buckling behavior of SMAs as a step toward the development of CSD. First, the conceptual design of CSS is described. Then, experimental testing of SMA bars with different slenderness ratios under compression loads is discussed. Subsequently, the implementation of CSDs for seismic retrofit of non-ductile reinforced concrete beam-column joints is illustrated. In particular, numerical analyses of representative non-seismically designed beam-column joints with and without CSD is presented.

Conceptual Design of CSD

The design concept of confined superelastic damper is similar to a buckling restrained brace or metallic tension-compression yielding dampers [17]. CSD consists of an SMA core encased in a steel tube filled with grout (or epoxy). The SMA core carries the axial load while the outer tube, via the grout, provides confinement to the core and prevents global buckling in compression. The damper is designed to exhibit superelastic hysteretic loops both in tension and compression. The SMA bar milled to a reduced diameter to create a controlled fuse action; an external part with threaded ends provides a connection for the brace and has a larger diameter to avoid damage to the connection. A thin layer of debonding agent along the SMA core at the grout interface eliminates shear transfer during elongation and contraction of the core. It also accommodates lateral expansion of the core when in compression. By minimizing friction, the unbonding material allows the SMA bar to freely contract and elongate within then confining steel tube-grout assembly. The cross-sectional area of the SMA bar gradually increases at the ends to ensure that it remains elastic. Fig. 1 illustrates the 2D view and 3D rendering of the CSB.

![Figure 1. 2D view and 3D rendering of Confined Superelastic Damper](image)

The global stability of the confined superelastic brace is ensured by properly designing the outer steel tube. Stability analysis based on Euler theory of buckling indicates, to guarantee that the brace does not buckle in the first mode, the CSB must satisfy the following condition:

\[
\frac{\pi^2 EI}{L^2} \geq \alpha P_D
\]

where \( E = \) Young’s Modulus, \( I = \) moment of inertia of the outer confining tube, \( L = \) damper length, \( \alpha = \) global buckling factor of safety, and \( P_D = \) design axial load.

When the conditions of the above equation are met, the external structural tube will provide the necessary global buckling resistance and enable the SMA core to undergo compressive loading instead of global brace buckling in the first mode. The effectiveness of CSD can be increased by preventing local buckling of SMA core along the restrained length. Thus, the casing is designed to provide the required lateral restraint against buckling of SMA core. The suggested design idea, as illustrated in Fig. 2, is based on estimating the buckling force to crush the grout at the ultimate
strain.

When an SMA bar is subjected to axial compression, the bar shortened longitudinally and expanded transversely. The horizontal expanding stresses ($P_{SMA}$ and $P_g$) as well as the displacement ($\Delta_{SMA}$ and $\Delta_g$) of the SMA bar and grout respectively, are the same at any critical points around the surface of SMA bar. The relationship can be given as:

$$P_{SMA} = P_g$$  \hspace{1cm} (2)

$$\Delta_{SMA} = \Delta_g$$  \hspace{1cm} (3)

Therefore, the displacement of grout $\Delta_g$ at the critical point can be determined by the definition of the strain in the SMA bar. Due to the grout restraining the SMA bar from expansion, a horizontally unknown strain which is induced by the confining pressure of grout is assumed $\beta \varepsilon_{SMA}$:

$$\Delta_g = \Delta_g = (\nu \varepsilon_{SMA} + \beta \varepsilon_{SMA}) D_{bar}$$  \hspace{1cm} (4)

Where $\nu$ is poisons ratio, and $D_{bar}$ is the diameter of SMA bar. Assume the steel tube used to confine the grout to be not deformed. According to Hooke’s Law, $P_{SMA} = P_g$ cab be written as:

$$\beta \varepsilon_{SMA} E_{SMA} = \frac{\Delta_g}{(D_{tube} - D_{SMA})} E_g$$  \hspace{1cm} (5)

Then the unknown ratio $\beta$ can be solved by substituting $\Delta_g$ in Eq. (2) into Eq. (3). Once $P_g$ reach the value of grout strength $f_g'$ with a certain brace axial force, the grout cannot provide horizontal resistance anymore, and the buckling occurs. In this critical situation, the brace critical axial stress $P_{critical}$ can be computed as:

$$P_{critical} = \varepsilon_{SMA} E_{SMA} = \frac{f_g'}{\beta}$$  \hspace{1cm} (6)

Therefore, the buckling force of the CSD can be obtained by $A_f P_{critical}$ where $A_f$ present the reduced cross-section area of the CSD.

Through understanding of the buckling behavior of isolated SMA bars is necessary to validate the previously discussed conceptual design and develop a reliable design procedure and detailing requirements for CSD. While many uniaxial tension experiments of SMAs have been reported in the literature [18,19], very few experimental studies address buckling behavior of isolated SMA bars. SMAs exhibit complex buckling behavior due to the coupled effect of material nonlinearity as a result of stress induced martensite transformation (SIMT) along with geometric nonlinearity.

Unlike steel and other engineering materials, buckled SMA bars can recover their shape after the removal of the load, and continue serving their intended purpose for repeated loading-unloading cycles. Hence, it is essential to understand well this behavior to expand SMAs applications in structural engineering. Theoretical predictions of critical buckling loads cannot fully take into account the effects of material and geometric nonlinearities, which leads to
overestimation of the actual buckling load. Especially in the case of SMAs, the effect of phase transformations needs to be considered while estimating the critical buckling load. Therefore, here, an experimental campaign was carried out to study buckling behavior of SMAs directly from experimental tests.

Experimental Testing of SMA Bars under Compression

The purpose of the experimental testing program was to investigate the cyclic compression behavior of superelastic NiTi SMAs. A series of experimental tests were performed with superelastic Nickel-Titanium (Ni-Ti) bars subjected to cyclic compression loads. The NiTi specimens were cold-drawn and obtained from Fort Wayne Metals, Research Products Corp. The austenite ($A_s$ and $A_f$) and martensite ($M_s$ and $M_f$) transformation temperatures were determined from Differential scanning calorimetry (DSC) test. DSC test result, as shown in Fig. 3, shows that the “as-received” bars are initially in the austenite phase at room temperature.

![Figure 3. Material characterization test results: (a) DSC (b) tension test](image)

Mechanical properties for the numerical simulation and other design purpose have been obtained from a direct tensile test at a room temperature. As shown in Fig. 3, the bar did not completely recovered its deformation. To improve the superelastic behavior of SMA bars, all the specimens were heat treated at a temperature slightly above the austenite finish temperature.

All testing was performed on specimens that are 9.53 mm in diameter, variable in length, with a gauge length of 101.6mm. The testing apparatus consisted of a MTS 55-kip hydraulic testing machine fitted with circular MTS 647 hydraulic wedge grips. To provide an effective fixing condition, each ends of the specimens were inserted 19 mm deep into the grips. The free length, $L$ was determined as: $L_{total} = 2 \times 19$. Specimens are identified by their slenderness ratio, computed as $\lambda = 4 \times \text{Unsupported length/diameter}$. Slenderness ratio ranging from 60 to 90 was considered. A total of 9 bars were tested. The loading protocol used consist of increasing strain cycles of 1-6% by increments of 1% followed by three cycles at 6%. The loading was performed at a frequency of 0.025Hz, which corresponds to a maximum strain rate of approximately 0.3%/s.

Experimental Results

Fig. 4 shows cyclic compression test results of Ni-Ti bars for different slenderness levels. The results are generally consistent with similar test results reported in literature [20]. Unlike the typical tensile stress-strain curve, there is no distinct plateau during the SIMT process for the
compressive stress-strain curve. Rather the initiation of the SIMT process may be marked by slight and smooth decrease in the material stiffness. In all the cases, stress at instability point was below that which correspond to the start of phase transformation. Hence, instability occurred in the austenite phase. As expected, stress at instability point and the corresponding strain decrease as the slenderness ratio increase. The post-peak branch uniformly fell in all cases. The bars presented small residual strain values.

![Stress-strain curves for various slenderness ratios](image)

(a) \( \lambda = 60 \)  
(b) \( \lambda = 75 \)  
(c) \( \lambda = 90 \)

Figure 4. Cyclic compression stress-strain curves of SMA bars for various \( \lambda \) slenderness

The axial compressive load \( (P) \) versus the end shortening \( (\Delta) \) curves at 6% strain are shown in Fig. 5. The bars were able to exhibit almost the same pattern of P-\( \Delta \) curves for a few repeated loading-unloading cycles especially for high slenderness ratios (\( \lambda = 75 \) and 90) where the buckling occurs at early times of phase transformations.
Numerical Simulation of non-ductile RC beam-column joints retrofitted with CSD

The proposed confined superelastic damper discussed in this paper is herein utilized as a retrofit solution for existing under-designed RC frame systems. The main goal of applying this retrofit solution to existing RC frame buildings designed without capacity design considerations is to eliminate the damage in the beam-column panel zones while enhancing global response. Local CSDs, as illustrated in Fig. 6, are introduced in the vicinity of beam-column connection to protect the panel zone region from excessive damage by redirecting the stress-flow around the joint area and forcing the development of plastic hinge in the beam. The design of CSD retrofit includes proper selection of geometric parameters (distance from the column interface, \( L \), and inclination angle \( \theta \)) and axial stiffness. The design target is to control the moment developed in the beam at the face of the column in such a way that undesirable brittle failure mechanisms within the joint panel zone are avoided. Furthermore, the reversal of the strength hierarchy must be assured during the design process by forcing a flexural plastic hinge in the beam close to damper connection points.

![Figure 6. Proposed CSD retrofit configuration for (a) exterior (b) interior joints](image)
A feasibility study on the efficacy of the proposed CSD retrofit solution was conducted. The seismic responses of representative non-ductile RC beam-column subassemblies, selected from literature [21,22], were evaluated using analysis software OpenSees [23]. Geometric properties and reinforcement details of exterior and interior joints are shown in Fig. 7. The existing joint analytical model in OpenSees was employed to numerically model interior and exterior joint assemblages. The beam and columns in the joint assemblage are modeled using the force-based beam-column element with fiber sections, which are divided into the unconfined and confined zones to incorporate the effect of hoops. The constitutive relationship used to describe concrete follows the “Concrete 02” model in OpenSees. Fig. 8 shows validation of the numerical model of the original RC joints using experimental data [21, 22]. As can be seen from the figure, reasonable agreement was observed between the numerical prediction and experimental results.

The design of the CSD elements was carried out following the conceptual procedure outlined in the previous paragraphs with the intention of protecting the joint region from excessive damage while forcing a plastic hinge in the beam outside from the column interface. Beam and column members need also to be protected against excessive shear demand and brittle failure by controlling the damper’s design parameters. The CSDs were modeled as pin connected truss element using self-centering material model. The model parameters were calibrated with experimental results conducted as part of this study. Table 1 summarizes the final design iteration output and SMA properties used for simulation.

Figure 7. Geometric properties and reinforcement details of RC beam-column joints (a) exterior (b) interior [21,22]

The numerical results of the original and CSD retrofitted joints are illustrated in Fig. 9. It can be seen from the numerical results that the CSDs show promising behavior for relocating the plastic hinge in the beam and protecting the joint panel zone from brittle shear failure. It is also observed that dampers provide re-centering capacity to the joint and increase the energy dissipation capacity of the joint.
Figure 8. Comparison of numerical prediction and experimental results (a) exterior joint Force-displacement (b) Interior joint column shear-drift

Table 1: Parameters used for CSD modeling

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<th>Exterior Joint</th>
<th>Interior Joint</th>
<th>SMA mechanical properties</th>
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<tr>
<td>$L$</td>
<td>140 mm</td>
<td>180 mm</td>
<td>$E_{\text{SMA}}$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>50°</td>
<td>45°</td>
<td>$\sigma_s^{\text{AS}}$</td>
</tr>
<tr>
<td>$L_{\text{SMA}}$</td>
<td>466.46 mm</td>
<td>565.69 mm</td>
<td>$\sigma_f^{\text{AS}}$</td>
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<tr>
<td>$A_{\text{SMA}}$</td>
<td>798 mm$^2$</td>
<td>548 mm$^2$</td>
<td>$\sigma_s^{\text{SA}}$</td>
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<td></td>
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Figure 9. Force-displacement response of the RC joints with and without CSDs

Conclusions

A novel confined superelastic damper (CSD) is described in this paper. The CSD is composed of Ni-Ti SMA bar that deforms axially while a restraining tube filled with grout prevents the bar from buckling in compression. Conceptual design of the damper was first presented. Then, experimental tests conducted to investigate the cyclic behavior of SMAs under compression was described. Based on experimental results, an anti-buckling system was designed to ensure stable behavior of
CSD under cyclic tension-compression loading. Numerical analyses of two CSD retrofitted non-ductile RC beam-column joints were conducted and the response of the joints with and without CSDs were examined. The results indicates that CSDs can effectively improve response of RC joints.

References

23. OpenSees version 2.5.0 [Computer software]. Univ. of California, Berkley, CA