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BEHAVIOR OF A SMA-BASED PARTIALLY RESTRAINED BEAM-COLUMN CONNECTION

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ABSTRACT

A half-scale interior beam-column connection incorporating superelastic nickel titanium shape memory alloy tendons was designed, fabricated, and tested in order to assess the feasibility of such a connection in a partially restrained lateral moment resisting system. The superelastic connection was compared to three other connections utilizing steel, martensitic nickel titanium, and superelastic nickel titanium paralleled with low strength aluminum tendons. Pretests showed the effect of the friction resistance in the shear tab in all the connections tested. The moment-rotation response path of the superelastic connection was investigated and relates the connection behavior to the mechanical behavior of the tendons. After being subjected to a cyclic loading protocol, the connection showed no degradation in strength but some degradation in stiffness due to the accumulation of residual deformations at larger drift demands. Even with this accumulation of residual deformations, the connection maintained significant recentering capabilities. This novel connection is intended as a proof-of-concept to be further developed in terms of practicality, ease of installation, and cost.

Introduction

Since the 1994 Northridge and the 1995 Kobe earthquakes exposed previously unknown deficiencies in fully retrained moment connections, numerous researchers have looked at ways to create improved moment resisting systems. One such method is to reduce the beam flange, effectively predetermining the plastic hinge location and protecting the integrity of the joint. Another method is to use partially restrained bolted connections, which eliminated the need for field welding. Both of these methods have been shown to be effective in creating enhanced seismic performance (Engelhardt et al., 1998; Jones et al., 2002; Leon, 1995; Sumner and Murray, 2002; Swanson and Leon, 2000). With these methods in mind, this research looks at the experimental results of a SMA-based beam-column connection in which the predetermined "hinge" is formed about a superelastic NiTi-tendon couple at the face of the joint. The NiTi's superelastic properties enable the connection to dissipate energy and recenter after large drift

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demands, creating a robust lateral load resisting system.

Several researchers have investigated recentering systems as an alternative to fully restrained connections, many of which are based on post-tensioning (PT) schemes (Cheok et al., 1993; Chou et al., 2009; Christopoulos et al., 2002; Garlock et al., 2005; Priestley and MacRae, 1996; Ricles et al., 2002; Wolski et al., 2009). The PT systems use the elastic stretch of "long" cables or bars to create a flag-shaped recentering behavior, showing reasonable success in experimental and analytical studies. However, PT systems require larger beams to handle the added axial loads and a somewhat cumbersome overall arrangement. A simpler system is envisioned by obtaining recentering from SMA material behavior.

Numerous researches have looked at creating various recentering systems out of SMA wires and bars (DesRoches et al., 2004; Dolce et al., 2000; McCormick et al., 2007; Tyber et al., 2007; Wilson and Wesolowsky, 2005). Of particular interest to this research, SMA beam-column connections were investigated in work by Ocel et al. (2004), Penar (2005), and Sepulveda et al. (2008). However, none of these studies used SMA-bars with good superelastic properties, thus these connections didn't display good spontaneous recentering. Furthermore, though there have been many advances field of SMA research in terms of material properties, widespread use has not occurred. The goal of this study was to create a proof-of-concept connection with good recentering, energy dissipation, and ductility.

Connection Details

The connection was designed to concentrate the deformations primarily in the tendon "fuse" elements while the rest of the connection remains elastic. A picture of the connection, joining W12x14 beams to a W8x67 column, is shown in Figure 1. This connection transfers the moment primarily through the coupled forces resulting from the HSS element bearing against the column face (compression) and the tendons pulling against the stiffened bracket (tension). The anchor bracket and transfer element were made from a stiffened 152x102x9.23 mm (6x4x3/8 in.) L-shape and a 102x76.2x6.35 mm (4x3x1/4 in.) HSS section. The L-shape was stiffened with three 9.23 mm (3/8 in.) triangular plates, one in the middle and one on each side.

A shear tab was installed to transfer the shear from the beam to the column. A 203x127x6.35 mm (8x5x0.25 in.) plate was welded to both sides of the column face using 9.5 mm (3/8 in.) beveled groove welds with E7018 electrodes. The shear tabs had 17.5 mm (11/16 in.) holes slotted 25.4 mm (1 in) to accommodate the relative rotation expected between the beam and column. The beam was connected to the shear tab with three 16 mm (5/8 in.) bolts tightened using a torque wrench to 81 N-m (60 ft-lbs) for *Test C*. The effect of the bolt torque is discussed in the Results-Pretests section.

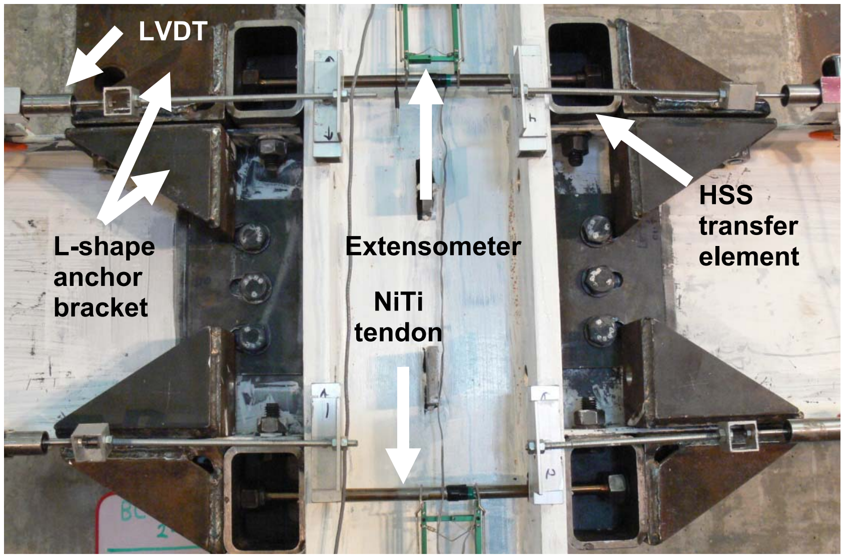

Figure 1. Close-up view of the beam-column connection tested in this study

Testing Scheme

The connection was subjected a cyclic test based on the protocol developed as part of the SAC Joint Venture (SAC, 1997). The loading protocol consists of 6 cycles at 0.375%, 0.50%, and 0.75% drift, followed by four cycles of 1% drift, and finishes with two cycles of 1.5%, 2%, 3%, 4%, and 5% drift. The SAC protocol was originally developed after the 1994 Northridge Earthquake to investigate the behavior of fully restrained welded moment connections, and has since become a standard protocol for cyclic connection testing.

The drift angle was selected as the governing parameter for this protocol. The load was applied in a quasi-static manner, at a rate of 50.8 (2.0) mm (in.) per minute. This protocol was implemented by manually inputting points into the ramp generator of a MTS 407b controller, giving the operator step-by-step control of the loading. Further details of the test setup can be found in the dissertation work by Speicher (2009).

The connection was tested with several different tendon "fuse" elements. The details of each connection are shown in Figure 2. *Tests A* and *B* were conducted as benchmark tests utilizing steel tendons and martensitic NiTi (recover shape after heating) tendons, respectively. *Tests C* was conducted with superelastic NiTi tendons. Finally, *Test D* was conducted with the same superelastic NiTi tendons combined in parallel with low strength annealed aluminum tendons. This paper focuses on the response of *Test C*; therefore the results of *Tests A, B,* and *D* are not presented herein.

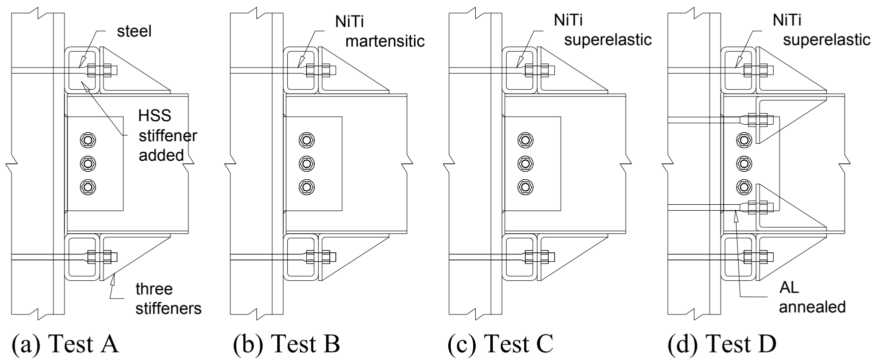

Figure 2. Connection details for each test.

Results

Pretests

A set of pretests were conducted to assess the resistance of the shear tab with varying levels of bolt torque. This was done primarily because the shear tab contribution could not be gleaned directly from the connection test data. The results of these tests are shown in Figure 3. As the connection was pushed to the right (positive drift), the beam pivoted around the exterior HSS transfer element, causing a considerable amount of moment resistance. When the drift was reversed, the moment resistance was significantly less as the beam rotated about the center shear tab bolt rather than the HSS corner. As the connection was cycled completely to the left, the moment resistance spiked up because the HSS section began to bear against the face of the column flange.

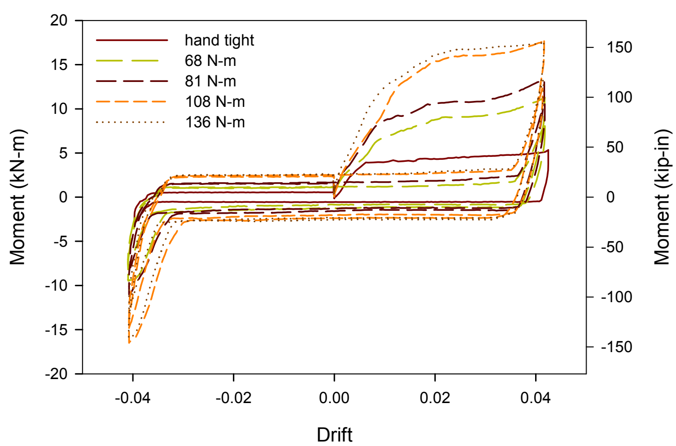

Figure 3. Moment vs. drift for shear-tab-only tests

Because of this behavior, the shear tab friction is much more significant for the connection with the superelastic tendons because the tendons will consistently pull the beam back into contact with the column. This will result in the response seen on the positive-drift-side of the first cycle. Once the beam has been forced away from the column face and there is nothing to pull it back (i.e. superelastic tendons), the shear tab's contribution to strength and stiffness is significantly decreased. Additionally, as expected, the shear tab had more moment resistance as the bolt torque was increased.

Superelastic NiTi Test

Superelastic NiTi tendons were installed in the connection for *Test C*. The tendons were prestrained 0.5% to ensure good initial stiffness and help reduce residual deformation accumulation as the connection was cycled. A picture of the connection at 5% is shown in Figure 4. The resulting connection moment vs. concentrated rotation behavior of *Test C* is shown in Figure 5 (the sign convention is illustrated in the upper left side of the figure). The connection moment is the averaged moment calculated from the strain gauges mounted one beam depth away from the L-shape brackets of each beam. The concentrated rotation is the averaged rotation calculated from the LVDT readings attached between the beam flanges and the column face (see Figure 1).

The connection had good ductility throughout the range of testing. The connection fully recentered at small drift levels. For drift levels of 3% and above, the connections did not obtain full recentering, but it did recover approximately 80% of its rotation. The reason for the reduced recentering can be seen in Figure 6, in which the top-left tendon moment-strain behavior and the connection gap opening (LVDT reading) are shown, respectively. Figure 6 indicates that at the larger drift levels the gap doesn't fully close until the column has passed the centered positions (zero). This is a product of the tendons not being able to fully pull the beams into contact with the column.

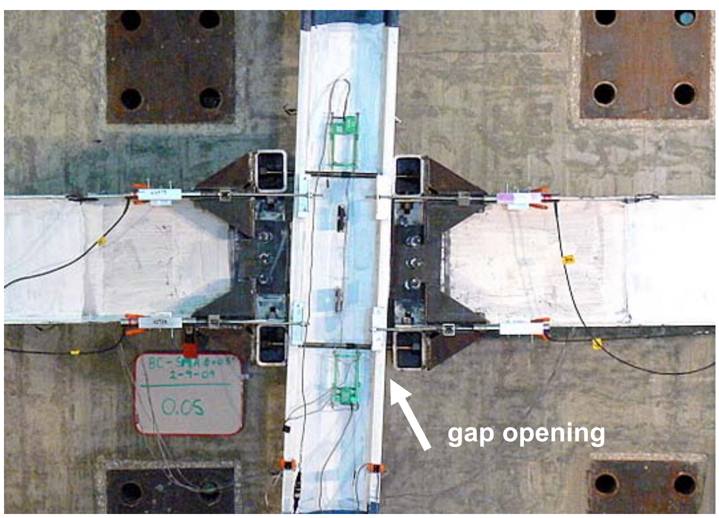

Figure 4. Connection deformation at 5% drift for *Test C*.

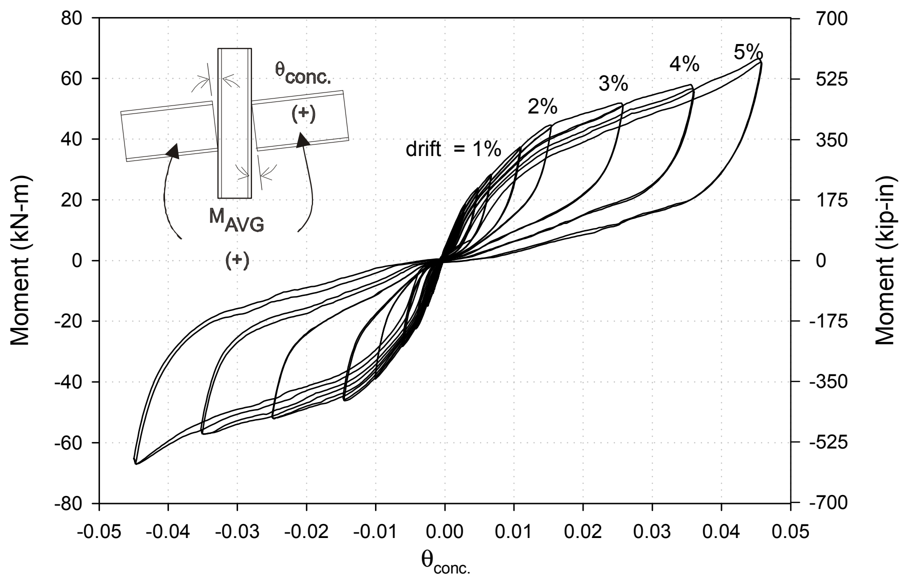

Figure 5. Connection moment-rotation response for *Test C*

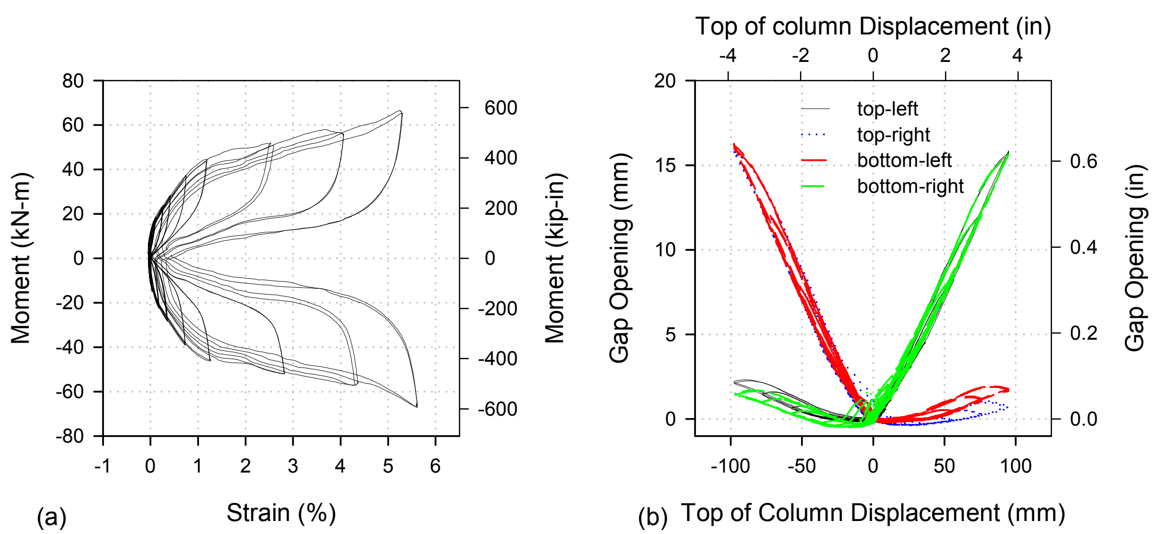

Figure 6. (a) Tendon moment-strain and (b) gap opening (LVDT) between beam and column.

Discussion of Results

Response Path

To gain a better understanding of the response of the SMA-based connection, it is helpful to look at an individual cycle. Figure 7 shows the moment-rotation curve for the first 5% drift cycle, selected because it exhibited all of the different transition points observed in the testing. The transition points (*a* through *g*) are labeled to help delineate the different phenomena that were occurring as the connection was cycled.

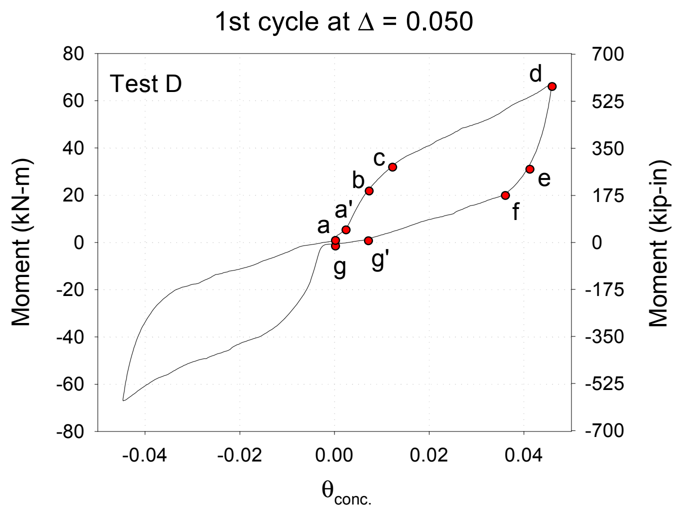

Figure 7. Response path for superelastic connection (*Test C*)

During small rotations levels on loading portion, the connection was prone to lose stiffness due to the accumulating residual strains in the tendons (*a* to *a'* in Figure 7). From point *a'* to *b*, the combined tension in the tendons and the friction in the shear tab resulted in an approximate linear stiffness. After point *b* was reached, the NiTi began to transition into its phase transformation region. At point *c*, the SMA had presumably reached the stress in which the austinite begins to transform into detwinned martensite, which allowed an increased accommodation of strain with smaller changes in stress. At point *d*, the austinite had almost fully transformed to martensite, and there was some indication of the stiffer martensitic behavior.

For the unloading portion, the tendons remained in the detwinned martensite phase until the transition started to happen at point *e* and was completed at point *f*. At point *f*, the detwinned martensite began to revert back into the austinite phase (it is more stable at the lower stress levels). From point *f* to *g'*, the NiTi tendons attempted to pull back the connection. Because of the shear tab friction resistance and residual strain accumulation in the NiTi tendons, point *g'* falls somewhere to the right of point *g*. This distance is defined as the residual rotation in the connection. Further cycling resulted in this path being followed all over again, with the previous cycle affecting the current cycle. It should be noted that if both points *a-a'* and *g-g'* are at the same coordinates, then full recentering would be obtained. Additionally, when the frame is loaded and unloaded in the opposite direction (frame moves to the left for the loading), the resulting response path is the same.

Cyclic Progression

Figure 8 shows the connection moment-rotation progression over the range of drift levels. This figure helps highlight some of the observations made in the results section. For small drift levels, the connection behaved elastic with very small hysteretic loops and full recentering. At a drift of 0.75%, a hysteresis becomes more apparent. The majority of this hysteresis is the result of fiction in the connection rather NiTi tendons superelasticity because the tendons were only being stretched to strain levels much less than that required to induce a phase transformation (i.e.

“yielding”). This friction-based hysteresis continued to grow until the tendons began to yield during 3% drift cycle. After this, the hysteresis was the result of the combined friction and SMA mechanical behavior.

Figure 8 also demonstrates that the connection experiences essentially no strength degradation. For increasingly higher levels of drift, the connection consistently maintained its strength. However, the connection did lose some effective stiffness as cycling progressed. This was mainly due to the accumulation of residual strains in the NiTi tendons. The accumulation of residual strains was expected due to the known mechanical behavior of superelastic SMAs and the counteracting friction resistance of the shear tab. To help improve this behavior, it is suggested that the tendons either be trained or given higher levels of prestraining, depending on the performance requirements.

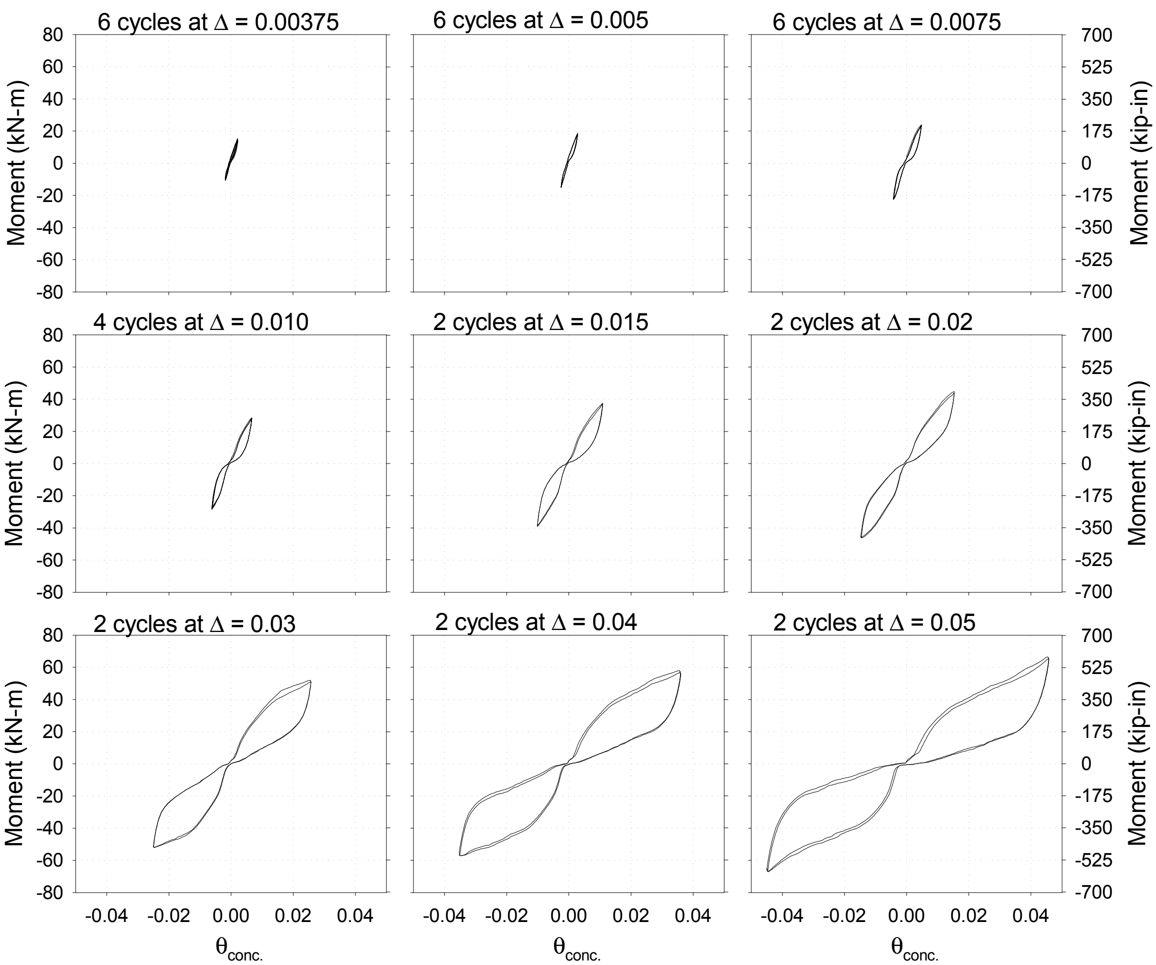

Figure 8. Detailed connection moment-rotation response for *Test C*

Conclusions

A cyclic test was conducted on a beam-column connection in order to assess the viability of creating a recentering connection using superelastic NiTi tendons. It was shown that the friction resistance of the shear tab contributed greatly to the connection’s damping behavior, though the shear tab resistance could not be gleaned directly from the connection tests. The test results showed that a connection can be created with good recentering, energy dissipation, and ductility. Through an investigation of the response path, the relation between the connection moment-rotation and the NiTi tendons strains was highlighted. Finally, by looking connection's cyclic progression over the entire drift range, it was seen that the SMA-based connection exhibited essentially no degradation in strength and moderate degradation in stiffness (due to the residual deformation accumulation in the tendons). Improvements in recentering and stiffness are suggested by either training the NiTi tendons to reduce the residual accumulation or increasing the prestrained applied to overcome the residual accumulation. Since this connection was exploratory in nature, the results motivate further development and investigation of such a system.

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