Steel Structures Research Update

Self-Centering Column Base Connections with Friction Dampers

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INTRODUCTION

Recent work on a self-centering column base connection with friction dampers is highlighted. This research is a collaborative effort by Senior Researcher Massimo Latour and Professor Gianvittorio Rizzano from the University of Salerno, Italy, and Professors Aldina Santiago and Luis Simões da Silva of the University of Coimbra, Portugal. The work builds off the researchers' combined expertise on "free from damage" beam-to-column connections, friction materials for supplemental damping, and experimental testing and analytical modeling of a variety of connections.

Self-centering and rocking column bases have captured the interest of researchers across the globe. Some of the self-centering column base research in the past decade has originated from Japan, China, the United Kingdom, Taiwan, Canada, and the United States. Hayashi et al. (2018) developed a self-centering, rocking composite frame with post-tensioned (PT), concrete-filled tube (CFT) columns combined with a moment-resisting frame (MRF) with low-yield (LY) fuses. Kamperidis et al. (2018) proposed a partial-strength, self-centering steel column base with post-tensioning and replaceable, hourglass steel yielding devices. Freddi et al. (2017) and Chen et al. (2014) investigated rocking, PT column bases with friction devices to dissipate energy. PT column bases with yielding, buckling restrained steel (BRS) plates have been developed for CFT and wide-flange columns in MRFs (Wang et al., 2019; Chi and Liu, 2012, respectively). The PT column bases studied by Chi and Liu (2012) were part of a larger effort; Sause et al. (2010) conducted extensive design and validation of self-centering moment resisting frames and concentrically braced frames. Wiebe et al. (2013) investigated controlled rocking steel frames with configurations that implement rocking at upper sections to accommodate higher modes. Rocking steel-braced frames using post-tensioning and replaceable seismic fuses were developed by Eatherton et al. (2014).

The Salerno-Coimbra team has developed an alternative self-centering column base solution to minimize initial costs and economic losses. Specific objectives are to limit damage and residual drifts, with connection components that are easy to repair or replace if needed. The self-centering column base has been validated through quasi-static cyclic testing and pseudo-dynamic testing. The self-centering connection has also been investigated through numerical time-history analyses of moment-resisting frames comparing conventional, fixed column bases to self-centering column bases. Some highlights of the research are presented.

BACKGROUND AND MOTIVATION

The research is focused on design of steel moment-resisting frames (MRFs) to achieve seismic performance objectives while minimizing economic losses. The traditional design strategy is to develop plastic hinges in the beam ends and at the column bases with strong columns and full-strength connections. This strategy results in significant damage and residual drift due to the permanent, plastic deformations. Given the associated costs and questions related to reparability of the structure, the researchers sought alternative energy dissipation methods and connection designs.

With the goal of minimizing damage, the researchers explored partial strength connections with friction dampers. These types of connections were initially proposed by Grigorian et al. (1993). This work was followed by numerous other theoretical, experimental, and numerical studies (Latour et al., 2019). Specifically, in New Zealand, researchers developed the sliding hinge joint (SHJ) (e.g., Khoo et al., 2012; Ramhormozian et al., 2014) for a beam to column connection. The SHJ has a friction connection at the bottom beam flange, with friction pads made of mild steel, aluminum, brass, or abrasion-resistant steel. A European adaptation of this connection uses a bolted T-stub at the top flange and a shop-assembled friction damping device bolted to the bottom flange (Latour et al., 2018). As shown in Figure 1, the friction damping device consists of a slotted haunch; friction pads; L-stubs to connect the haunch to the column; and pretensioned bolts clamping the haunch, friction pads, and L-stubs. Energy dissipation is achieved through slip at the friction pads as the beam rotates about the stem of the T-stub. The same principles can be further adapted for use at a column base.

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The success with the adapted sliding hinge connection is tempered by residual drift issues. Although the friction connection does not experience the same damage as a plastic hinge, the connection experiences similar permanent deformations due to its high unloading stiffness. "Indeed, although these connections are very effective from the point of view of the damage avoidance, they still provide significant problems related to the low self-centering capacity." (Latour et al., 2019) To address this, the researchers also explored a supplemental self-centering solution for the column base.

As briefly described earlier, a number of researchers have proposed self-centering and rocking column base solutions. The Salerno–Coimbra team evaluated the various solutions in the development of their own column base. The team looked first to low-damage friction connections developed and tested by Borzouie et al. (2015) and shown to avoid problems with axial shortening of columns due to yielding and local buckling (MacRae et al., 2009). Then, for self-centering solutions, the researchers acknowledged the benefits of using long PT bars extending into the basement level to avoid yielding of those PT bars (e.g., Chi and Liu, 2012), but they suspected difficulties in repair and replacement. The researchers also noted a related objective to avoid any connection of the PT bars to a concrete foundation. Meanwhile, the researchers found promise in a study utilizing a tension-limiting base level hinge. The base hinge consisted of prestressed Ringfeder springs and vertical friction plates. The Ringfeder springs were prestressed by a tightened bolt through their center, and the friction plates did not engage until the gravity load and Ringfeder spring prestress was exceeded (Gledhill et al., 2008). These and additional studies are described in more detail in Latour et al. (2019). From those studies, the researchers proposed to "keep the layout of the connection as simple as possible providing, other than the self-centering capacity, additional benefits such as the absence of interaction with the concrete foundation and the limited size of the connection which is, overall, similar or lower than the size of the cover plates employed to realize a traditional column splice connection" (Latour et al., 2019).

THE PROPOSED COLUMN BASE CONFIGURATION

For their self-centering column base, the researchers propose a column-splice with friction pads and threaded bars with Belleville disk springs, located just above a traditional full-strength base plate connection, as shown in Figure 2(a). The benefits of the proposed connection follow the researchers' objectives of providing a simple, self-centering connection detail that is not larger than a conventional column splice connection and does not have any attachment to the concrete foundation. As such, damage and residual drifts are limited, and the connection components are expected to be easy to repair or replace if needed.

In the proposed self-centering column base, the moment-rotation response is at the column splice and is governed by the component behavior. As shown in Figure 2(a), there is a stiffened base plate connection and a column stub. The column stub is spliced to the rest of the column with flange and web plates and friction pads with pretensioned bolts. Slotted and oversized holes in the column flanges and web above the splice are used to accommodate the rotation—that is, gap opening—at the column flanges. Threaded bars on each side of the column web are anchored to stiffener plates above and below the column splice, with a system of Belleville disk springs between the nuts and stiffener plates. The contributions of the friction pads, threaded bars, and Belleville disk

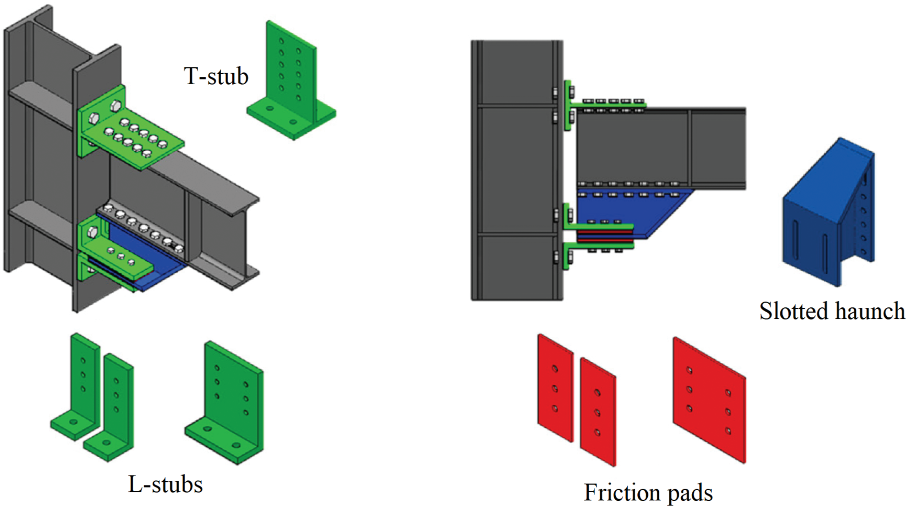
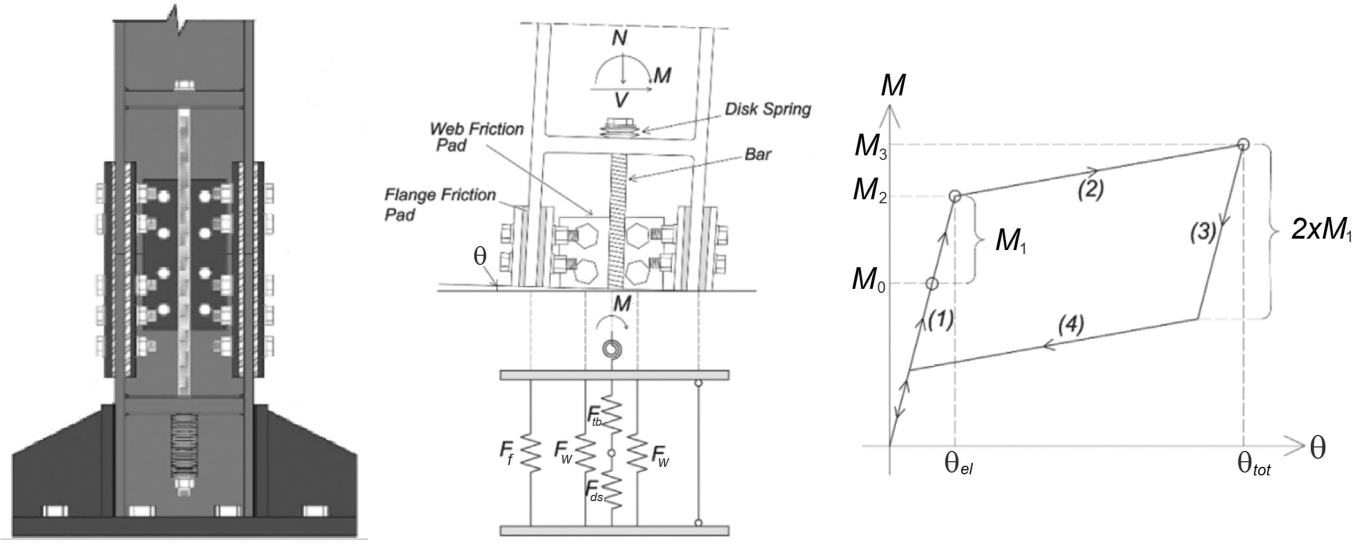


Fig. 1. Beam-to-column connection with friction damping device (based on Latour et al., 2018).

springs to the moment-rotation behavior can be idealized in a mechanical model of equivalent springs, as shown in Figure 2(b). Springs F_w and F_f represent the friction pads on the column web and flanges. The F_w and F_f springs have infinite stiffness up until the slip force and zero stiffness after slip. The translational spring F_{tb} models the axial behavior of the threaded bars, which work in series with the system of disk springs, F_{ds}. The force deformation behavior of the F_{tb} and F_{ds} springs are dependent on the number and properties of the threaded bars and the number and properties of the disk springs working in series and in parallel.

As shown in Figure 3, the disk springs can be stacked to work in parallel or in series, and in this manner, the system of disk springs can be tuned to the desired stiffness. Using the equations developed by Latour et al. (2019) for the equivalent springs, the typical moment-rotation behavior of the connection is shown to follow a flag shape hysteresis, as shown in Figure 2(c). At the bending moment M_0, the initial axial load in the column and the prestress of the threaded bars have been offset, and the bending moment M_1 is the contribution to the bending moment due to the friction pads. At the top of loading branch 1, the moment M_2 represents the decompression moment corresponding to slip in the friction pads and gap opening (i.e., rotation) at the column splice. Loading branch 2 corresponds to slip in the friction pads and loading governed by the stiffnesses of the threaded bars, disk springs, and column in bending. Unloading branches 3 and 4 are governed by the same behavior as the loading branches 1 and 2. The connection returns to zero moment and zero rotation—that is, no residual plastic deformation.



(a) *(b)* *(c)*

Fig. 2. (a) Connection assembly; (b) mechanical model; (c) theoretical moment-rotation relationship.

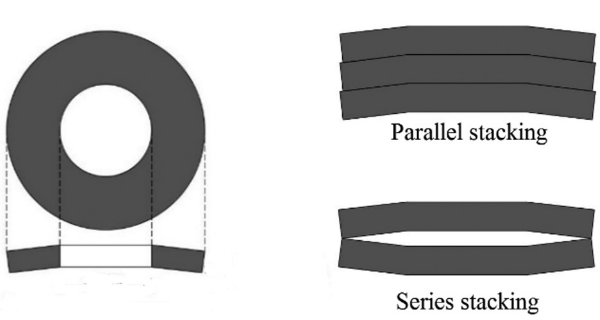


Fig. 3. Belleville disk spring stacking methods.

EXPERIMENTAL INVESTIGATION

The proposed self-centering column base connection has been validated through quasi-static cyclic testing and pseudo-dynamic testing. A cantilever specimen representing the bottom half of a first-story column was designed using the principles outlined in Latour et al. (2019). The column was a 9.44-in.-deep, 9.44-in.-wide H-section (HEB240) with a yield stress of 40 ksi (S275 steel). The connection plates were also S275 steel. The friction pads were S275 steel plates with a 0.012-in. thermal spray aluminum coating. Prior to the cyclic and pseudo-dynamic testing, the friction pads were tested and characterized by Silva (2016).

The test specimens were subjected to axial and lateral loads. As shown in Figure 4, an actuator placed on top of the specimen was used to apply the axial load under load control. A displacement-controlled actuator applied increasing, cyclic lateral displacements at the top of the specimen. Given the limitations of the test equipment, the axial load was limited to 25% of the squash load; from the applied lateral load, the bending moment at the column splice was limited to 95% of the plastic bending moment of the column. Figure 5 shows the test frame, the connection being assembled, and the complete column base before the test.

Cyclic Testing

Four cyclic tests with and without the threaded bars, and with different axial loads, were conducted. Axial loads of 25% or 12.5% of the squash load were applied and held constant for the duration of the test. The test specimens therefore represented an internal moment frame column that does not experience large changes in axial force during an earthquake. For the lower applied axial force, the axial force in the threaded bars, F_{tb}, was increased but could not be increased to the level needed to ensure recentering of the column (Latour et al., 2019).

The cyclic tests validated the design of the self-centering column base connection, highlighting the importance of the recentering bars and the total axial load in the column. Figure 6 compares moment-rotation response—with and without the threaded, recentering bars—for an applied axial load of 25% and 12.5% of the squash load. Both tests with the 25% axial load ratio exhibited self-centering behavior, with residual rotations of 2.1 mrad and 4.1 mrad with and without the recentering bars, respectively. These rotations were both lower than common construction tolerances on the order of 5 mrad (Latour et al., 2019). Figure 6(a) qualitatively shows the improvement in self-centering behavior

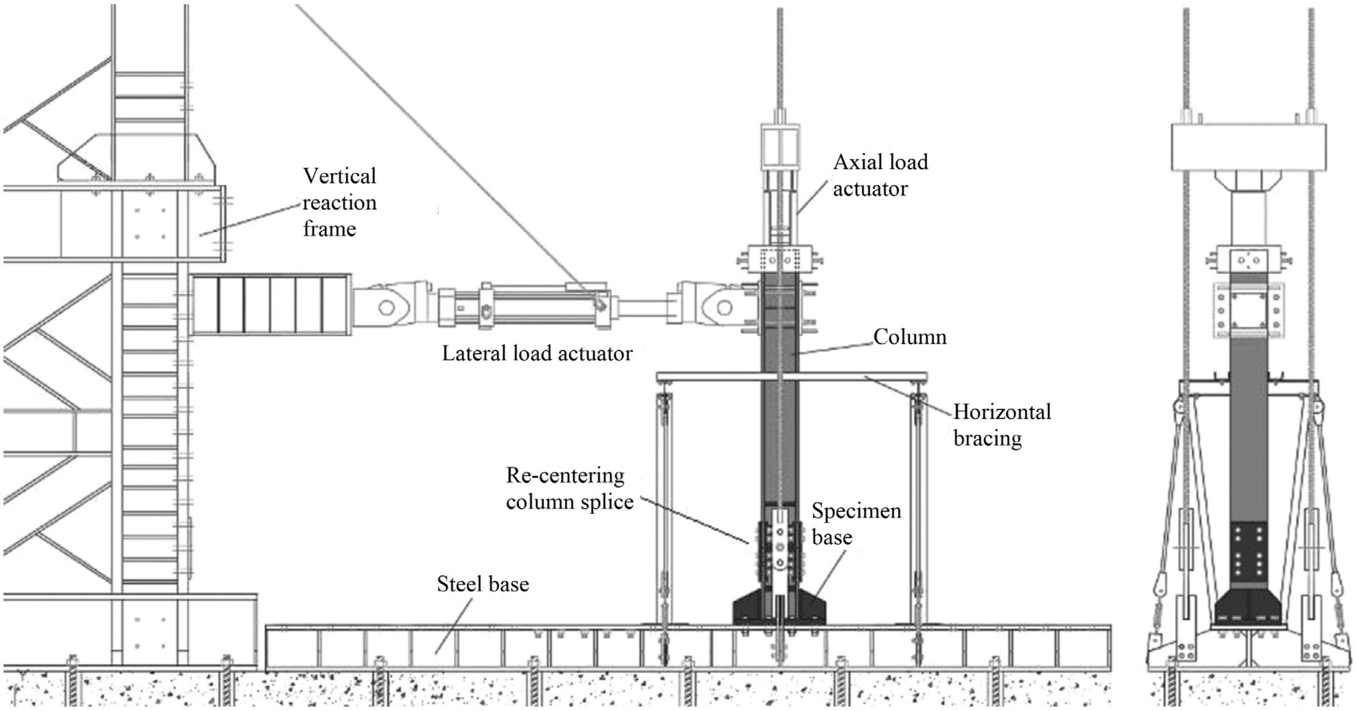


Fig. 4. Front and side views of the test setup.

with the bars. The test specimens with 12.5% axial load ratio exhibited much higher residual rotations. The recentering bars reduced the residual rotations from almost 50 mrad to 31 mrad. However, higher-capacity bars were needed to provide recentering behavior. Additional details for the cyclic tests can be found in Latour et al. (2019).

Pseudo-Dynamic Testing

The proposed self-centering column base connection was further validated with pseudo-dynamic tests. For a more realistic dynamic-response history, a computer simulation was used to account for damping and inertial effects, and the physical test provided restoring force and displacement data for the structure. The structure was idealized as a discrete-parameter system with one degree of freedom. With this idealization, the pseudo-dynamic tests could be conducted with the same test setup used for the cyclic testing. Two ground motions, Kobe (Japan, 1995) and Spitak (Armenia, 1988), were selected to compare results for ground motions with different characteristics. "Kobe is a seismic event inducing a high number of large amplitude cycles, Spitak is characterized mainly by two large reversal and many low amplitude cycles. The scale factor of the seismic events was selected in order to achieve in the connection, approximately, a rotation of 40 mrad" (Latour et al., 2019). An axial load ratio of 25% was used for all tests. Specimens with and without the recentering bars were tested for the Kobe ground motion. The results for the Kobe tests [scale factor 1.4 (PGA = 0.35g)] will be briefly presented. Results for the Spitak test can be found in Latour et al. (2019).

The pseudo-dynamic test results highlighted the role of the recentering bars. Figure 7 shows the moment-rotation responses for the Kobe ground motion and the improvement in the self-centering behavior of the column base with the recentering bars. The bars reportedly reduced the residual rotation from 5.2 mrad to 1.7 mrad. The improved self-centering behavior can also be seen in the reduction of residual drift in the displacement time history plots in Figure 8.

NUMERICAL SIMULATIONS

The proposed self-centering column base connection was further investigated through numerical time-history analyses of moment-resisting frames. Two four-bay, six-story MRFs were designed, one with conventional, fixed column bases and one with self-centering connections. The MRFs had 20-ft bays and 10.5-ft story heights with the exception of the 11.5-ft first story. Preliminary beam sizing was based on dead and live loads of 84 psf and 42 psf. The MRF members were designed for a region of high seismicity (PGA = 0.35g) and dense sand, gravel, or stiff clay.

The self-centering column base connections were represented with a mechanical model, an assembly of springs and gap elements. The mechanical model was able to capture the moment-rotation responses from the experimental tests. Four bilinear springs in parallel with gap elements simulated the hysteretic response of the friction dampers.

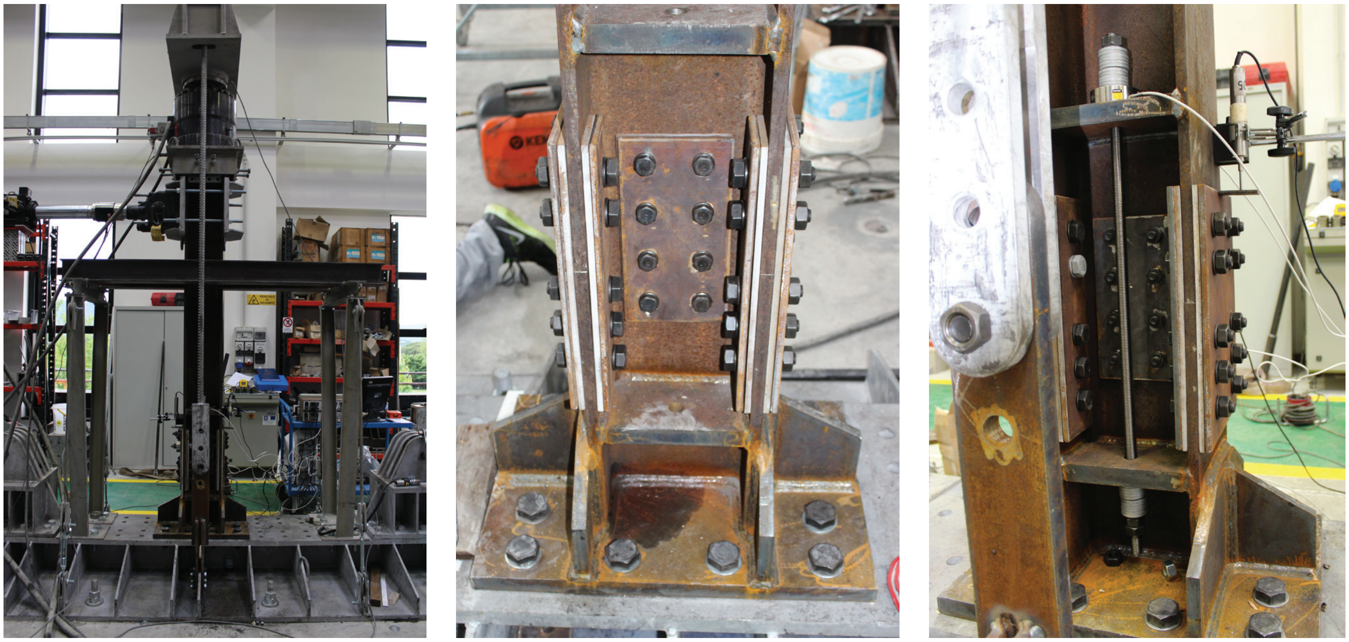
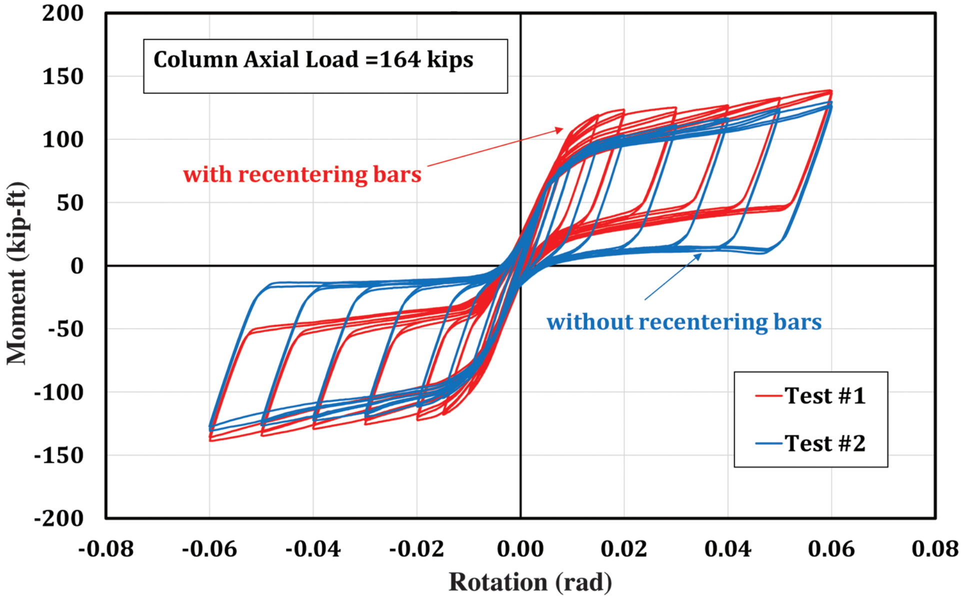
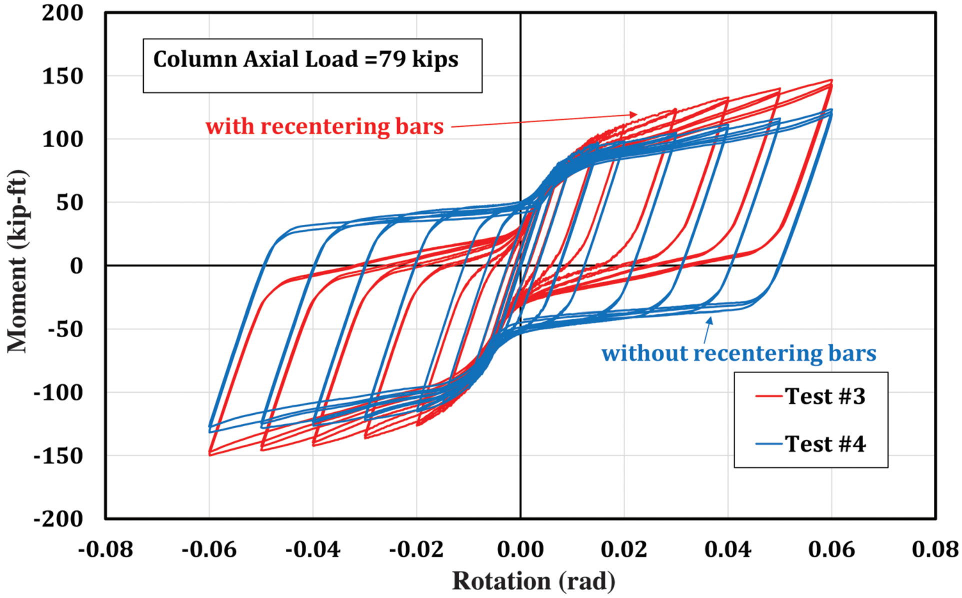

(a) (b) (c)

Fig. 5. (a) Test setup; (b) connection being assembled; (c) column base connection.



(a) 25% axial load ratio



(b) 12.5% axial load ratio

Fig. 6. Moment-rotation responses.

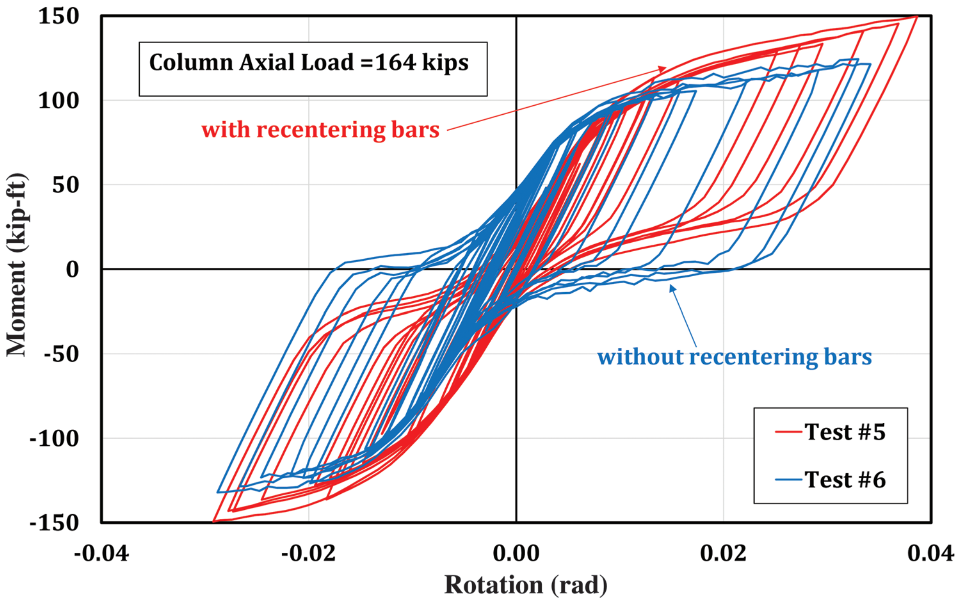


Fig. 7. Moment-rotation responses for the Kobe ground motion.

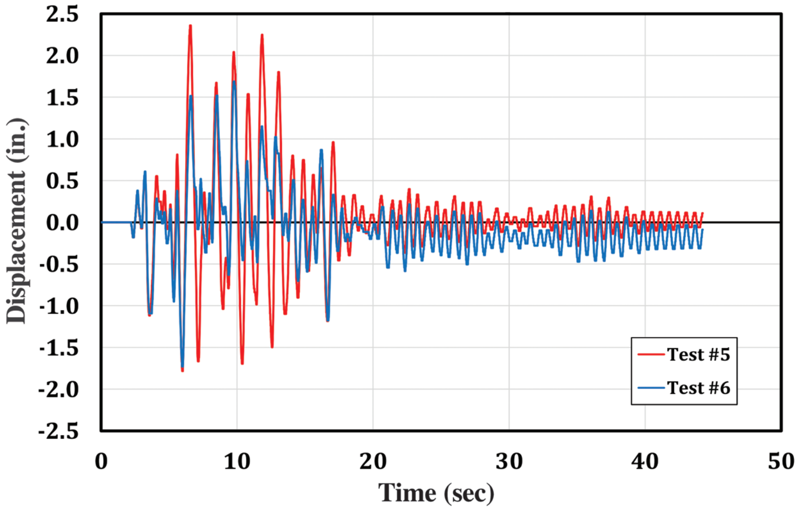


Fig. 8. Displacement time histories for Kobe ground motion.

A central bilinear spring simulated the initial prestress and the hysteretic response of the recentering bars. Properties of the springs were calibrated to the experimental data. Meanwhile, the bolted beam-to-column connections with friction dampers (Figure 1) were modeled according to Latour et al. (2018). A damping ratio of 5% was used.

The time-history analyses were conducted for a simulated seismic event. That simulated event was based on eight natural ground motions. Figure 9 compares the roof displacement time histories for the conventional and self-centering column base MRFs. For the conventional full-strength column base connections, the residual roof displacement at the top of the building was 13.8 in., corresponding to 18 mrad of drift. Use of self-centering column base connections reduced the residual displacement by 85%, to 2.4 in., or 3 mrad drift, well within acceptable levels.

SUMMARY AND FUTURE WORK

The Salerno-Coimbra team has proposed a self-centering column base connection designed to minimize initial costs and economic losses. The proposed connection is a column-splice with friction pads and threaded bars with Belleville disk springs, located just above a traditional full-strength base plate connection. With the self-centering column base connection, damage and residual drifts are limited, and the connection components are expected to be easy to repair or replace if needed. The self-centering column base has been validated through quasi-static cyclic testing and pseudo-dynamic testing. The self-centering connection was further investigated through numerical time-history analyses of moment resisting frame (MRFs) comparing conventional, fixed column bases to self-centering column bases. The experimental and numerical results are promising. The research team looks to extend the work to other configurations to more broadly validate their self-centering column base concept.

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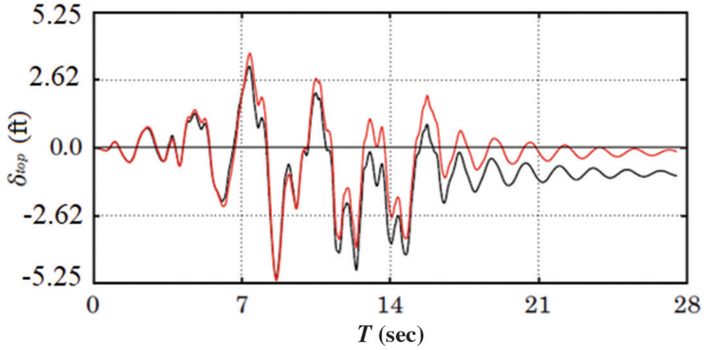

Fig. 9. Roof displacement time histories for simulated ground motion.

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