Design and Testing of an Enhanced-Elongation Telescoping Self-Centering Energy-Dissipative (T-SCED) Brace

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SUMMARY:
The self-centering energy-dissipative brace (or SCED brace) is a new steel bracing member that provides both damping to a structure and a re-centering capability, reducing or eliminating residual building deformations after major seismic events. Previous SCED brace designs exhibited full self-centering capability over frame lateral deformations on the order of 1.5% to 2.0% of a typical building storey height. To overcome this limitation, a new enhanced-elongation telescoping SCED (or T-SCED) brace has been designed that allows for self-centering response over two times the range achieved with the original SCED bracing system. This design was fabricated and tested dynamically in a full-scale vertical steel frame. It exhibited full self-centering behaviour in a single storey frame that was laterally deformed to 4% of its storey height. Additionally, the testing program satisfied both the ASCE 7 and AISC 341 testing protocols for buckling restrained braces.

Keywords: Self-Centering Systems, Residual Drifts, Steel Frames, High-Performance Systems

1. INTRODUCTION

With the emergence of performance-based design as the dominant philosophy for the seismic design of structures, owners and engineers have become increasingly concerned about the state of structures following an earthquake. Post-earthquake structural resilience is of particular importance to governments, which are concerned with the post-disaster operation of critical structures such as schools and hospitals. In addition, private-sector businesses that require constant up-time, even after moderate-sized earthquakes, can clearly benefit from a performance-based design approach. For a business that would lose millions of dollars for every day or hour of down-time, an 'immediate occupancy' level of performance is not only desirable but may be necessary for the survival of the business.

Recent studies have shown that the amount that a building is leaning after an earthquake is a critical measure of performance (Pampanin et al. 2003, Ruiz-Garcia and Miranda 2006). This lean is generally referred to as 'residual drift'. In fact, a study of structures that have experienced earthquakes in Japan has concluded that for structures that have residual storey drifts greater than 0.6% of the storey height, it is likely less expensive to rebuild the structure than to repair it (McCormick et al. 2008).

The most common high-performance seismic force resisting systems that are used for building design today use steel yielding or friction activation to dissipate energy. These types of systems exhibit a full-cycle hysteretic response as shown on the left side of Fig. 1. These systems are effective at limiting design forces in the system and at dissipating energy; however, they are prone to residual drifts after earthquakes. A study by Erochko et al. (2011) suggests that even under design-level excitations, buildings that use ductile steel yielding systems are likely to experience residual drifts that exceed the level of 0.6% discussed above. To attempt to deal with this residual drift problem, which affects the post-event performance of these structures, a number of different self-centering systems have been developed in the last decade (Filiatrault et al. 2004). Self-centering systems use various design strategies to achieve the flag-shaped hysteretic response as shown on the right side of Fig. 1. These systems exhibit half of the full-cycle energy dissipation of yielding or friction systems, but they re-center the displacement response after each cycle, eliminating residual drifts in the structure. Even though the full-cycle energy dissipation is lower for these systems, studies have shown that buildings that use self-centering systems experience similar peak displacement and drift responses as those that use yielding or friction systems (Christopoulos et al. 2002, Choi et al. 2008, Tremblay et al. 2008).

Self-centering systems have one other important benefit over traditional ductile yielding systems: since self-centering structures constantly return to zero deformation after every cycle of loading, they avoid progressive collapse due to P-Delta effects. Studies have shown that under the influence of P-Delta effects, structures may experience residual drifts after each cycle of loading that bias the response of the structure, causing successive cycles to pull the structure further in the same direction (MacRae and Kawashima 1997). This type of progressive collapse mechanism is particularly of concern for parts of the world that are at risk of long duration subduction fault earthquakes.

Many proposed self-centering systems require a significant modification to the way that buildings are constructed. For example, rocking wall systems require special details to accommodate rocking at the base and the upwards movement of the walls at each floor where the wall interfaces with the gravity supporting system. In Canada, a self-centering system has been developed that fits within the form factor of an axial steel brace (Christopoulos et al. 2008). The major benefit of this system is that it has the versatility to be used in buildings anywhere that a traditional steel brace or damper could previously have been used. This system is called the self-centering energy-dissipative (or SCED) brace.

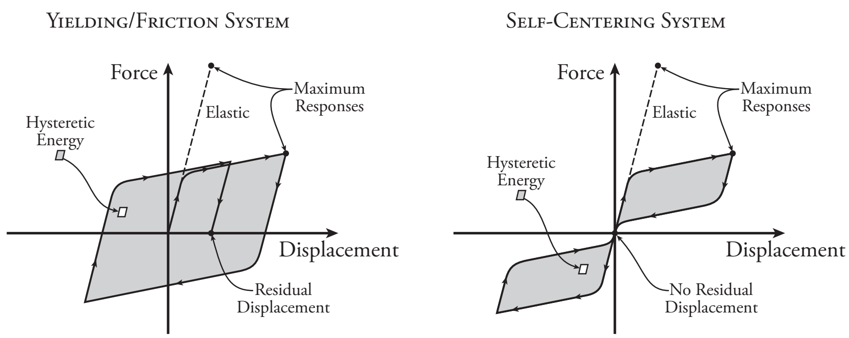

Figure 1. Nonlinear hysteretic response to earthquakes:
Yielding/Friction Systems vs. Self-Centering Systems

A number of SCED brace prototypes have been constructed and tested, including the two that are described by Christopoulos et al. (2008). A three storey SCED-braced frame has also been tested on a shake table (Tremblay et al. 2010). These previous tests have shown that the SCED brace concept is feasible, works both statically and dynamically, performs well dynamically within the context of a full steel system, and is able to be accurately represented by computer models.

The deformation range over which SCED braces can exhibit self-centering response is limited by the length of the body of the brace and by the material that is selected for the pretensioned tendons (as will be explained below). For typical building storey geometries, this self-centering axial deformation range generally results in storey drifts of ±1.5% to ±2.0% times the storey height. To accommodate larger storey drifts, the SCED braces in previous test programs were equipped with an external friction fuse in series with the main brace. This fuse allowed the system (brace plus fuse) to deform as much as necessary to accommodate extreme earthquake scenarios. The addition of an external fuse meant that for drift demands greater than the self-centering deformation range of the brace, the system experienced some residual drift; however, this residual drift would only occur under maximum considered earthquakes (MCE level, with a 2% probability of exceedence in 50 years) in high seismic zones, and the residual drifts that did occur were much smaller than they would be for yielding- or friction-type systems. For moderate and low seismic zones, or for more frequent but moderate level earthquakes in high seismic zones, SCED braces have previously been able to provide full self-centering capability with no residual drifts.

To enhance the self-centering deformation range of SCED braces for high seismic applications, the SCED concept was extended by using a telescoping configuration that doubles the brace deformation over which full self-centering response can be achieved. This telescoping configuration has been applied to the SCED prototype described in this paper. This telescoping SCED configuration, or T-SCED brace, was designed, built at full scale, and tested statically and dynamically in a full scale, single-storey steel frame. This paper describes the mechanics of the extended SCED system and presents results from the laboratory testing program.

2. TELESCOPING SCED BRACE MECHANICS AND DESIGN

The mechanics of the original SCED brace are explained in Christopoulos et al. (2008) and depicted in Fig. 2. The brace mechanism consists of four main elements: (1) an inner steel member (usually an I-beam section or a steel tube), (2) an outer steel member (usually a steel tube), (3) an energy dissipating device that activates based on the relative movement of the inner and outer members, and (4) a set of tendons that are pretensioned and which axially clamp both the inner and outer members at both ends via a pair of free end plates. Although Fig. 2 shows the inner and outer members adjacent to one another, in reality, the inner member is usually smaller in cross-section and is located within the outer member. The inner member is connected to the structure at one end of the brace and the outer member is connected to the structure at the other end of the brace.

The flag-shaped hysteretic behaviour is achieved through the interaction of these four elements as shown in Fig. 2. The tendons are pretensioned during assembly and, therefore, provide a restoring force that constantly pulls all of the elements back to their initial positions. The tendons elongate regardless of whether the brace is in tension or compression. When the brace is in tension, the right end plate abuts the outer member which separates from the inner member; however, the left end plate remains stationary because it abuts the inner member. When the brace is in compression, the opposite case occurs: this time the left end plate abuts the outer member and separates from the inner member while the right end plate remains stationary because it abuts the inner member. The initial stiffness in the hysteretic response is a result of all of the elements deforming together until the tension or compression force overcomes the pretension in the tendons, allowing the right or left end plate to separate from the inner member. In addition to the pretension force, the axial force in the brace must also overcome the slip or yield force in the energy dissipater before the end plates can move. After the pretension force plus the slip or yield force is exceeded, the SCED brace has ‘activated’ and the stiffness of the brace is approximately equal to the stiffness of the tendons alone. The energy dissipating device provides the width of the flag hysteresis. This width is equal to $2F$ in Fig. 2 where F is the slip or yield force in the energy dissipating device. In order for the brace to be fully self-centering, the only criterion is that the pretension in the tendons (T) must be greater than the activation/yield force for the energy dissipater (F).

In order to increase the elongation capacity of the SCED system, a telescoping SCED (or T-SCED) has been designed. This system relies on the basic mechanics of the original system, except that it adds an extra element. As shown in Fig. 3, one or more new ‘floating’ intermediate steel members are added that are parallel to the existing inner and outer members. This new intermediate member allows the addition of a second set of tendons. In this revised configuration, the two sets of tendons and the intermediate member are effectively in series, allowing the two sets of tendons to share the brace deformation equally between them. Therefore, if the strain capacity of each individual set of tendons is the same as it was for the original SCED (δ), the T-SCED will have double the total elongation capacity. Although only one intermediate member is shown in Fig. 3, the concept may easily be extended to include two or more intermediate members.

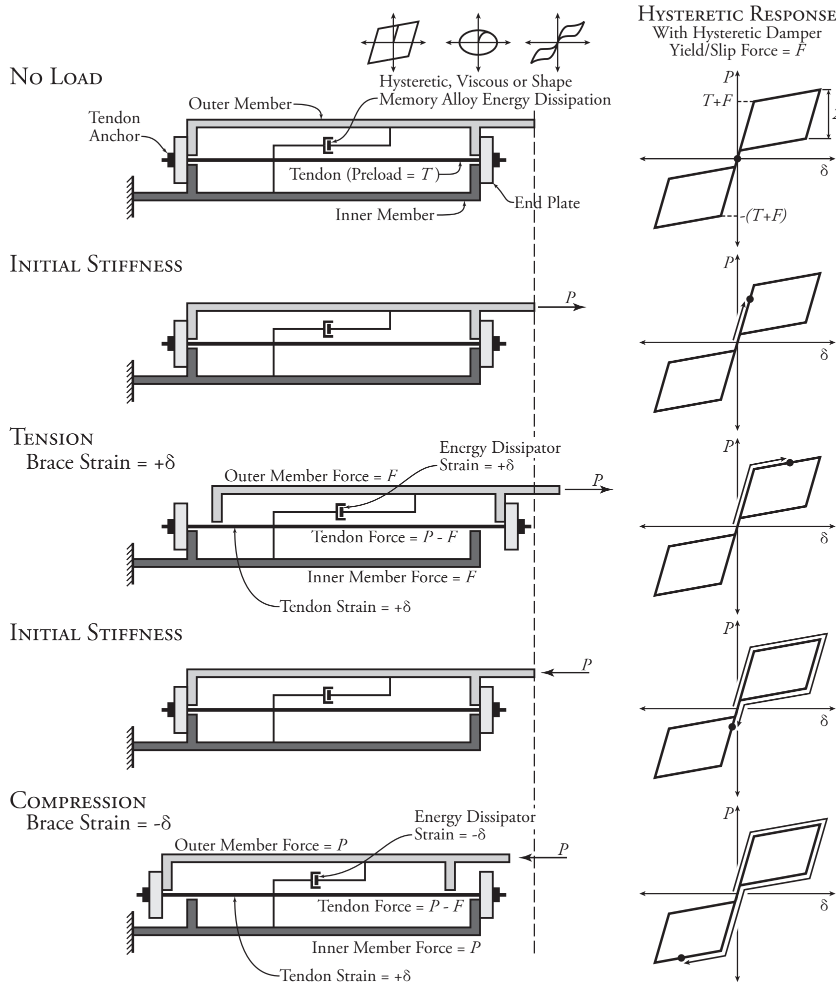

Figure 2. Mechanics of the SCED brace

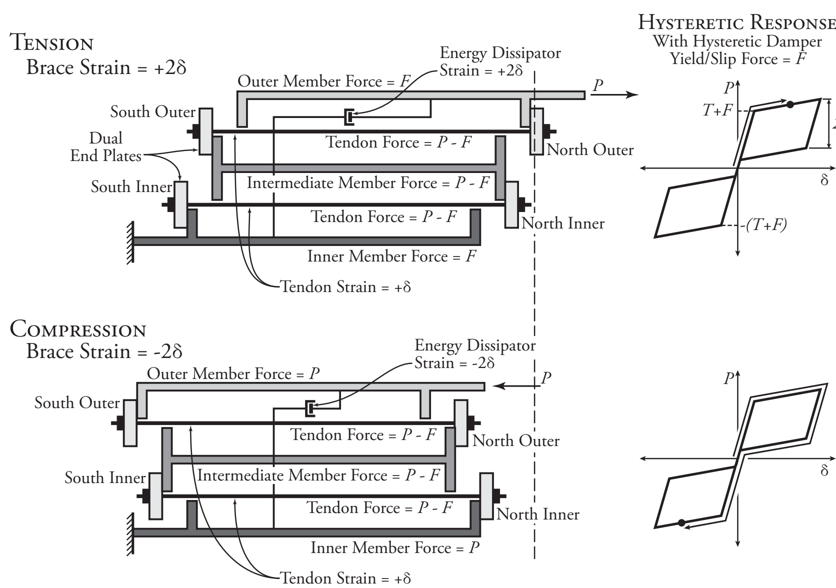

Figure 3. Mechanics of T-SCED brace providing enhanced elongation capacity

A prototype of the T-SCED system with one intermediate member was designed and fabricated. A schematic showing the layout of the major elements of the brace is shown in Fig. 4. In this design the outer member is an HSS508x305x12.7, the intermediate member is an HSS356x254x9.5 and the inner member is a W200x59. The tendons are made of straight aramid polymer fibres and the friction mechanism uses non-asbestos friction pads with a normal force provided by ¾” steel bolts. As shown in the figure, there are four thick steel end plates, two at either end of the brace, one inner end plate and one outer end plate. When the brace is at rest and fully closed, the inner end plate abuts the inner and intermediate members and the outer end plate abuts the intermediate and outer members. Each set of end plates is pretensioned against the members using six tendons, resulting twelve tendons total. Plastic pads are used as guides to keep the members in place.

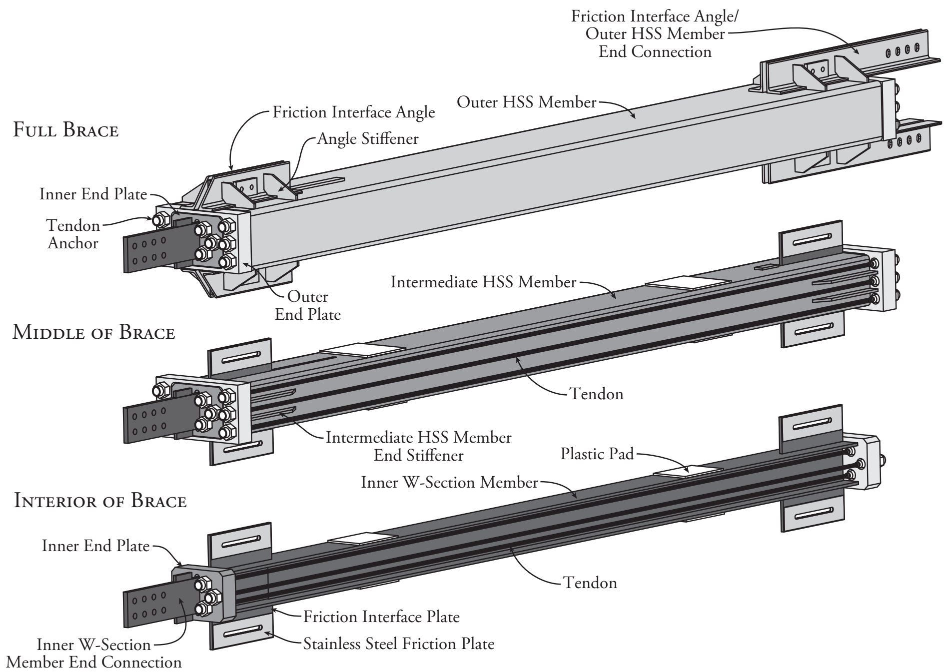

Figure 4. T-SCED Brace Design

3. TEST FRAME

The T-SCED brace was tested in a full-scale reusable steel test frame at the University of Toronto. A frame test was chosen for this prototype test program to simulate realistic end conditions and rotations in the brace. The full test setup is shown in Fig. 5 and Fig 6.

The test setup consisted of a single storey steel braced frame with a storey height of a 2.74m (9 ft) and a bay width of 7.32m (24ft). The actuators that displace the frame were connected to the middle of the beam and anchored to a strong wall. The bases of the columns were pinned. The beam to column connection consisted of a double angle header with slotted holes in the beam to accommodate rotation. The brace was connected to the frame via a straight bolted connection at the top (south end) and a true pin connection at the bottom (north end). Beam and column lateral restraints were constructed to restrain the motion of the frame out of plane.

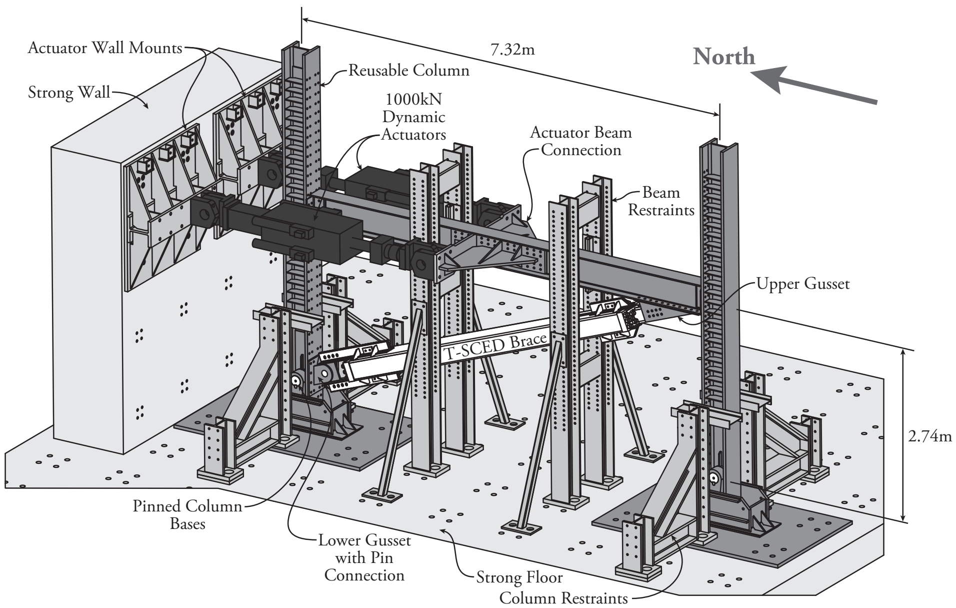

Figure 5. Test Frame Assembly

Figure 6. Test Frame Photo

4. T-SCED BRACE CALIBRATION

Before the brace was tested, the friction slip force of the internal friction mechanism in the brace was progressively increased in two steps to reach the desired slip force. This was done in place so that the hysteretic response of the brace at different friction force levels could be observed by displacing the test frame a small amount in either direction. The slip force of the internal friction mechanism depends on the axial force in the steel bolts that provide the normal force to the friction interfaces. This axial force was applied using a combination of bolt torque and direct bolt length measurements.

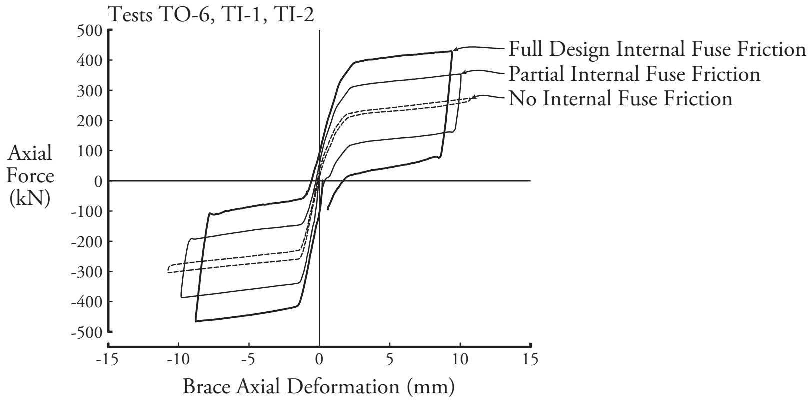

Figure 7. T-SCED Brace Calibration

The resulting brace hysteresis at varying levels of friction slip force is shown in Fig. 7. The response labelled 'No Internal Fuse Friction' represents the hysteretic response of the brace when the axial load in the normal force bolts was zero. This bilinear elastic response represents the behaviour of the inner, intermediate and outer members with the tendons only. The load at which this bilinear curve changes stiffness is equivalent to the total pretension force in six tendons. This bilinear curve has some thickness due to the small inherent friction between the moving parts of the brace mechanism. After half of the normal force bolts were tightened to their design axial force, the brace was tested again and is shown in the figure as 'Partial Internal Fuse Friction'. The added friction widened the hysteresis around the bilinear response by an amount on each side that is equal to the friction slip force in the internal friction interfaces, thereby increasing the brace activation force. Then all of the bolts were tightened to their final level, increasing the activation load of the brace up to its full target design level, which is shown as 'Full Design Internal Fuse Friction' in the figure.

5. TEST RESULTS AND DISCUSSION

The T-SCED specimen was subjected to over fifty static and dynamic tests of varying amplitude and frequency. In addition to these, thirty hybrid simulation tests were performed. Cyclic protocol testing was performed to satisfy both the ASCE 7 and AISC 341 testing protocols for the design of buckling restrained braces (ASCE 2005 and AISC 2005). For these protocols, the design level drift was selected to be 1.3% storey drift (Δ_{bm} in AISC 341). This value was chosen based on a mean-plus-one-standard-deviation drift demand for a 12-storey building equipped with SCED braces subjected to twenty 10% probability of exceedence in 50 years earthquakes as modelled by Choi et al. (2008).

The results from one dynamic protocol test that demonstrate the full hysteretic behaviour of the T-SCED brace are shown in Fig. 8 and Fig. 9. In Fig. 8, the thick grey line shows the total brace deformation with respect to time. The deformation demand in this test was applied in the form of a sinusoid with increasing amplitude at each successive cycle. The maximum brace deformation in this test was 100mm which is equivalent to 3.9% storey drift or three times the design drift. Fig. 9 shows the full hysteretic behaviour of the T-SCED brace under the applied sinusoidal deformation. The hysteresis is stable and symmetric with respect to force and deformation. In that particular test, the compression side of the hysteresis (the lower left quadrant) is wider than the tension side because of additional inherent friction caused by one brace component in the compression direction.

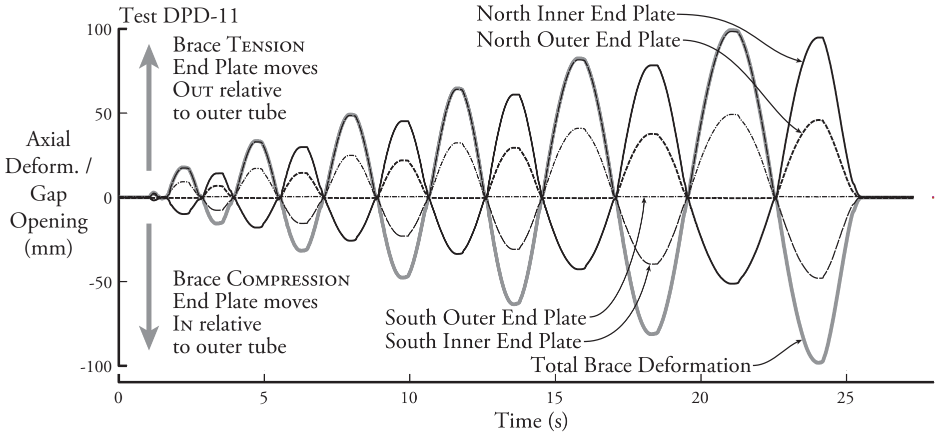

Figure 8. Dynamic Protocol Test Results – Brace Deformation and End Plate Gap Opening

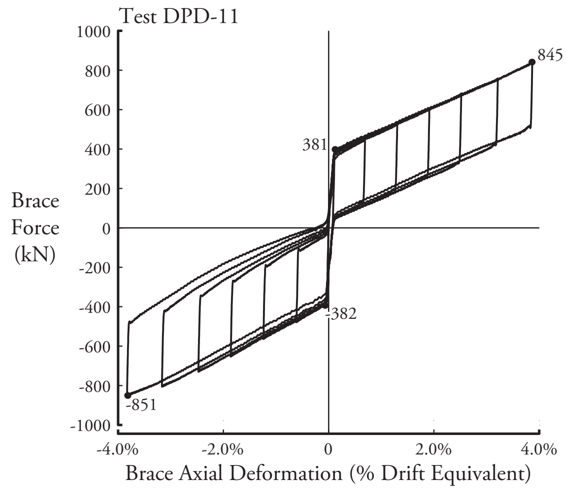

Figure 9. Dynamic Protocol Test Results – Brace Hysteresis

The plot of the gap openings in Fig. 8 demonstrate that the telescoping mechanism of the T-SCED brace was functioning as it was designed to. With reference to Fig. 3, where the left and right sides of the figure are respectively the south (upper) and north (lower) brace ends in the test, when the brace is in tension, the south inner end plate moves two units out with respect to the outer member with a magnitude equal to the applied deformation, and the south outer end plate moves one unit out with respect to the outer member. This is identical to the behaviour shown in Fig 8. Meanwhile, the north inner end plate moves one unit in with respect to the outer member, and the north outer end plate does not move at all with respect to the outer member. In compression, the situation is reversed north-to-south. In addition, if the intermediate member is properly floating, equilibrium dictates that the deformation demand in both sets of tendons should be equal. For this to be true, the two unit movement should be twice the one unit movement. Figure 8 shows this to be true, confirming that the T-SCED brace behaved as intended.

In addition to the static and dynamic protocol testing, a selection of dynamic earthquake deformation records was applied to the frame. The hysteretic behaviour of the T-SCED brace subject to these excitations is shown in Fig. 10. The first drift history that was used (Test EQR-1) was taken from the dynamic response of one storey in a twelve storey simulated SCED braced frame from Tremblay et al. (2008). The excitation earthquake that was used for this model was a simulated Cascadia subduction zone earthquake created for a study performed by Tremblay and Atkinson (2001). This record has a long duration of 100s and produced a large number of cycles of activation in the brace. The T-SCED brace showed no degradation in the response and prevented any residual drift. For a yielding or friction braced frame system, this type of earthquake would likely result in a progressive P-Delta mechanism, biasing the response in one direction.

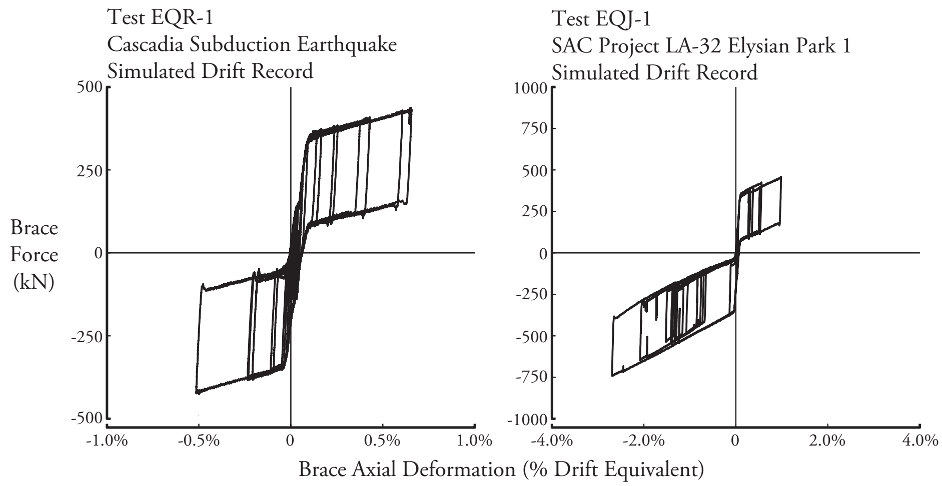

Figure 10. Dynamic Earthquake Simulation Test Results

The second drift history (Test EQJ-1) was taken from the dynamic response of the first storey in a twelve storey simulated braced frame as modelled by Choi et al. (2008). The earthquake record that was used for the model was from the SAC Joint Venture Report (Somerville et al. 1997). It is a simulated maximum considered earthquake hazard level (2% probability of exceedence in 50 years) record for Los Angeles. The demand from this drift history approaches 3% drift in the brace. Even at this extreme level of demand, the T-SCED brace fully self-centers the frame, avoiding any residual drift.

6. CONCLUSION

The new telescoping self-centering energy-dissipative (T-SCED) brace extends the self-centering deformation range of the original SCED brace by allowing it to deform twice as far as previous designs. This extends its applicability in structures and removes the need for an external fuse in series with the brace in high seismic applications. The T-SCED brace prototype was capable of accommodating 3.9% drift in the test frame, equivalent to over 100mm of axial brace deformation. In addition, the brace easily satisfied both the ASCE and AISC test protocols for buckling-restrained braces.

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