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AN INNOVATIVE BRACING MEMBER SYSTEM WITH SELF-CENTERING CAPABILITIES FOR IMPROVED SEISMIC PERFORMANCE

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ABSTRACT

An innovative bracing member that provides stable energy dissipation capacity and self-centering properties has recently been developed in Canada. The proposed system can be constructed from readily available structural steel members, Aramid tensioning elements, and friction energy dissipative mechanisms. Testing programs were performed to examine the cyclic response of the energy dissipation and tensioning components. The verification of the self-centering hysteretic behaviour of the new pre-tensioned brace assembly has been carried out through cyclic quasi-static axial tests and cyclic quasi-static and dynamic seismic tests on a full-scale frame system. The experimental results confirmed that the proposed pre-tensioned self-centering energy dissipative (PT-SCED) bracing member exhibits a repeatable flag-shaped hysteretic response with full re-centering capabilities, therefore preventing structural damage and eliminating residual deformations in braced frames to which it is connected.

Introduction

Building structures designed according to current seismic provisions are expected to sustain inelastic response during moderate and stronger earthquakes, implying structural damage along with residual deformations. The cost associated with the loss of business operation and to damage to structural and non-structural components following a moderately strong earthquake can be significant to modern society. Such cost is often comparable to, if not greater than the cost of the structure itself. While the objective of mitigating loss of life in a major earthquake still prevails, resilient communities expect buildings to survive a moderately strong earthquake with no disturbance to business operation, implying that no downtime be tolerated in small and moderately strong events, and that structural damage is minimized in case of a strong earthquake.

Figure 1a shows the idealized hysteretic response of a system representing a yielding structure. The response of equivalent elastic structure with equal initial stiffness and weight is also illustrated for comparison purposes. The maximum seismic force induced in the yielding system is significantly lower than that of the linear elastic system. The maximum displacement of the yielding system can be smaller, similar, or larger than that of the elastic system, depending on the characteristics of the ground motion and the natural period, strength, and energy dissipation properties of the yielding system. The shaded area in Fig. 1a represents the energy dissipated per cycle through hysteretic yielding. Designs aiming for

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an inelastic response of the structure may be appealing at first, particularly from the initial cost stand point. These designs have however two major drawbacks. First, the elements of the seismic force resisting system will need to be repaired due to yielding after moderately strong earthquakes and can be damaged beyond repair in strong earthquakes. Second, current seismic design approaches assume that large energy dissipation capacity is necessary to mitigate the effects of earthquakes. This premise has led to the notion that a good structural system should be characterized by full hysteresis loops, as shown in Fig. 1a, but this type of response can lead to significant residual displacements in a building after an earthquake, as also illustrated in the figure.

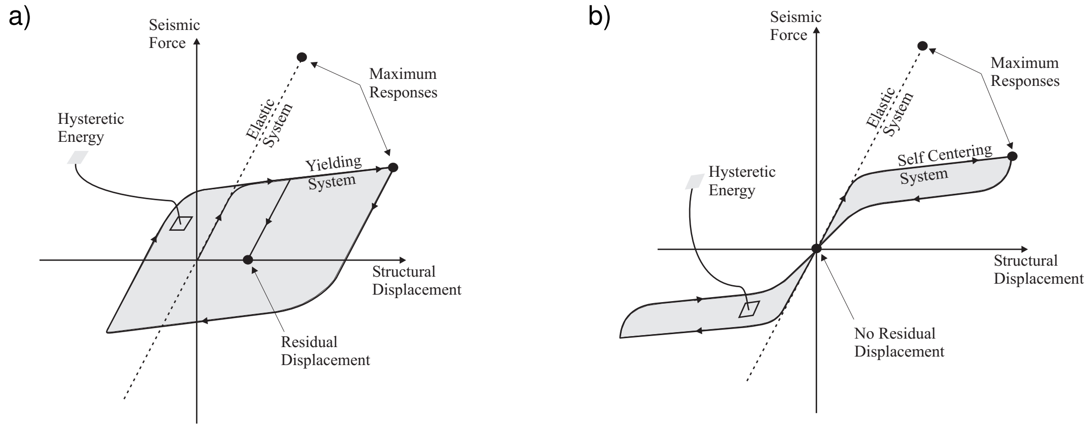

Figure 1. Nonlinear response to earthquake ground motions: a) Hysteretic system; b) Self-centering energy dissipating system.

Structural systems possessing self-centering characteristics that minimize residual deformations represent very promising alternatives to current lateral force resisting systems. Figure 1b shows the characteristic flag-shaped seismic response of such self-centering systems. The response has more frequent stiffness changes within one nonlinear cycle than the traditional elastic-plastic hysteresis. The amount of energy dissipation is reduced compared to that of the yielding system shown in Fig. 1a but, more importantly, the system returns to the zero-force, zero-displacement point at every cycle as well as at the end of the seismic loading. This characteristic eliminates residual deformations and prevents the progressive drifting response observed with traditional elastic-plastic hysteresis, thus mitigating the potential for large P-delta effects.

Self-centering behavior can be achieved with a number of structural configurations. Post-tensioned beam-to-column connections have been used to develop flag-shaped hysteretic response in precast concrete and steel moment-resisting frames (Priestley 1991; Ricles et al. 2001; Christopoulos et al. 2002). A similar concept has also been applied to rocking precast concrete shear walls (Stanton et al. 1993; Priestley et al. 1999). In wall systems, the re-centering force can be provided by the wall self-weight or by unbonded post-tensioning tendons connecting the wall to its foundation. Rocking response of braced steel frames has also been investigated for bridge applications (Dowdell et al. 2000; Pollino and Bruneau 2004) as well as for buildings (Azuhata et al. 2003; Uriz 2005; Roke et al. 2006).

Alternatively, self-centering response in braced steel frames can be effectively provided for by introducing specialized dampers exhibiting self-centering properties in the diagonal bracing members. Several systems of this kind have been developed and tested for seismic applications in the last decades. Some of these devices rely on mechanical or fluid spring systems (Nims et al. 1993; Aiken et al. 1993; Filiatrault et al. 1999; Soda 2004) while others make use of superelastic shape memory alloys (SMA) that possess inherent self-centering hysteretic response (Dolce et al. 2000; Sheliang et al. 2004; McCormick et al. 2006; Zhang and Zhu 2006). A new type of Self-Centering Energy Dissipative (SCED) bracing member has recently been developed in Canada. The system can be constructed with two structural steel members interconnected by a friction energy dissipative mechanism and equipped with a simple self-centering mechanism comprised of pre-tensioned fiber tendons. The mechanism is designed to bring the brace to its un-deformed state after the conclusion of a severe seismic event, without structural damage or residual deformations. This revolutionary apparatus can also be used for other extreme loading applications such as for the resistance to hurricanes or blast loads. This paper describes the proposed bracing member system. The behaviour under cyclic loading of the friction energy dissipation system and the tensioning elements is verified through testing. The performance of the SCED bracing system is then validated by means of full scale physical testing under cyclic quasi-static and dynamic seismic loading.

Description of the PT-SCED Bracing

PT-SCED Concept

Figure 2 shows a conceptual illustration of the PT-SCED system. The novelty lies in the combination of pre-tensioning elements and a source of energy dissipation along with a locking mechanism which allows the flag-shaped hysteretic response to be developed. The dissipative mechanism is connected to two structural members and is activated when relative longitudinal motion is induced between the members. In addition, abutting surfaces are provided at each end of the two structural elements that are configured to interact with the tensioning system. When tension is applied to the brace, and once the initial pre-tensioning (PT) force and resistance of the dissipative mechanism are overcome, the brace elongates resulting in an increase of the PT force while energy is dissipated through the dissipative elements. As shown in the figure, friction, yielding, viscous or visco-elastic assemblages can be used alone or in combination with each other as energy dissipation mechanisms. Alternatively, energy dissipation can be provided by specialized tensioning elements such as shape-memory alloys that inherently display an energy dissipation capacity when axially loaded. In the latter case, the tendons provide both the self-centering capacity and the energy dissipation.

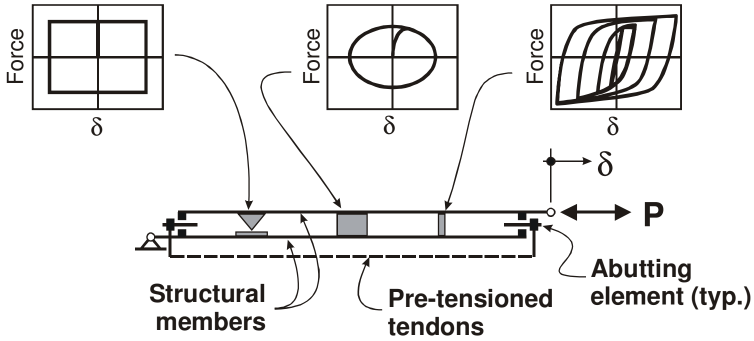

Figure 2. Schematic of the SCED bracing member.

The connections between the structural elements, the abutting elements and the tensioning elements are such that elongation of the tensioning elements is always induced when relative longitudinal motion takes place between the two bracing members. Figure 3 illustrates the hysteretic response when of a SCED bracing member with a friction energy dissipation located at one end of the brace (F in the figure). When a tension load P is applied, the pre-tension of the two structural elements reduces proportionally until it is overcome (Fig. 3a). Up to that point, the SCED member displays a high initial axial stiffness equal to the sum of the individual axial stiffness of the two structural members and the tensioning elements. When the initial pre-tensioning force and the force required to activate the energy dissipation system are surpassed, the two structural elements start moving relative to each other (Fig. 3b). The stiffness of the system is significantly reduced to that of the tensioning elements while sliding is activated in the friction dissipation mechanism. The tensioning elements elongate and provide a positive restoring force to the system.

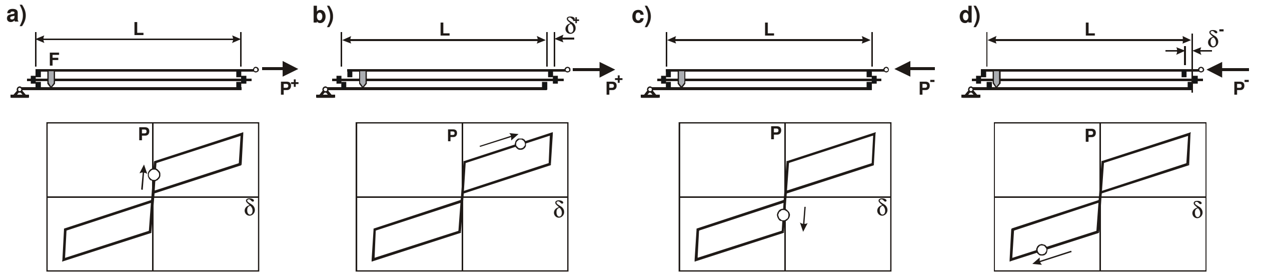

Figure 3. Behaviour of the SCED bracing member with friction energy dissipation.

When the load is reversed, the top structural member is pulled back towards its initial position. If the initial pre-tension force exceeds the force necessary to activate the dissipation mechanism, the system returns to its original position thus displaying a full re-centering property as illustrated in Fig. 3c. If the PT elements are chosen correctly relative to the resistance of the dissipative elements, the restoring force brings the system back to its initial position when the load is released. When compression is applied to the brace, a similar hysteretic behaviour is observed because of the locking mechanism that is present (Fig. 3d). When the load is once again reversed, the previously described hysteretic behaviour in tension can be repeated. The number of tensioning elements, their mechanical properties and their initial pre-tensioning force are selected to achieve the desired strength, post-elastic stiffness, deformation capacity, and the self-centering capacity of the SCED system. The level of pre-tension determines the force at which the relative movement initiates between the two steel members.

PT-SCED Prototype Design

The SCED concept can be achieved with a number of combinations of structural, tensioning, dissipative and blocking elements. The configuration that was used to construct the prototypes examined in this study is illustrated in Fig. 4. Square structural steel tubing is used for the two structural elements and one tube has smaller dimensions and is inserted inside the other tube of larger dimensions. The tubes are fitted concentrically and positioned with guiding elements. They are also cut at the same length and fitted with end plates. Neither the tubes nor the end plates are connected to each other. Pairs of back-to-back angles are welded to the outer tube and extend out to provide the connection of the SCED system at one end of the brace. At the other end, a connection component is fitted through a slot cut in the end plate and welded to the inner tube.

The tensioning elements are introduced in the space provided between the inner and outer tubes. The tensioning elements are anchored on the outer side of the two end plates. The outer tube is also slotted to allow for steel plates welded to the inner tube to protrude and to be bolted to back-to-back angles that are welded to the outer tube. The surface between the plate and the angles forms a friction interface that is activated by relative motion between the two structural members. These interfaces comprise the energy dissipation mechanism of the system. The tensioning elements are comprised of parallel lay Aramid tendons fitted with spike and barrel terminations. Details on the properties of the friction interfaces and on the tendons are given in the following paragraphs. To further clarify how the system works, Fig. 4 also illustrates the kinematics of the SCED system when tension and compression forces large enough to activate the relative motion between the two structural members are applied.

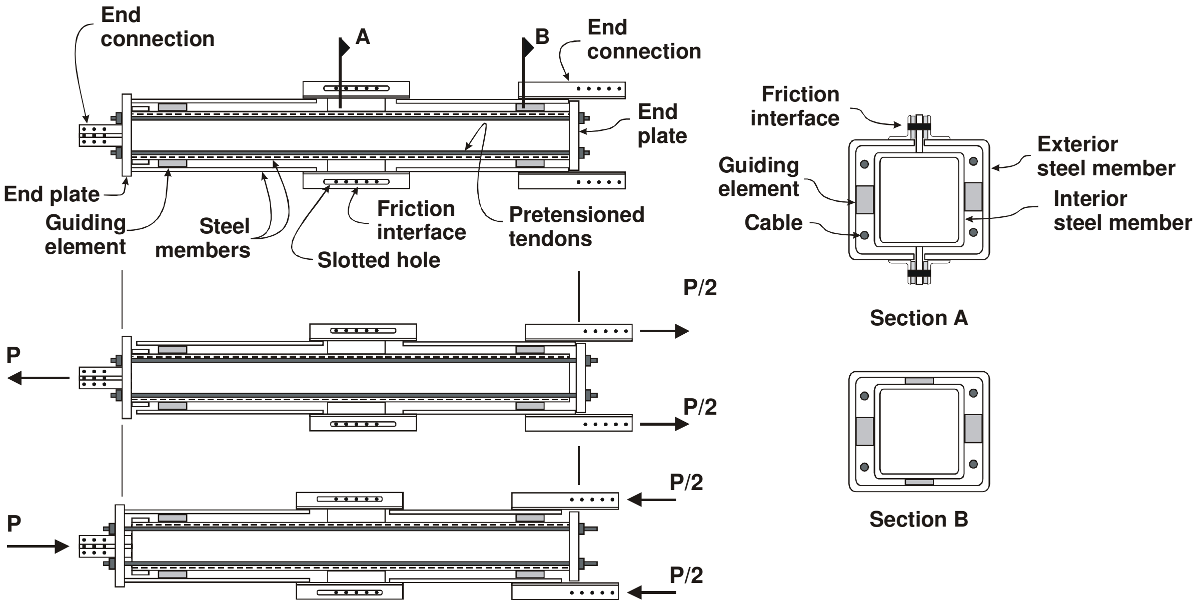

Figure 4. PT-SCED bracing member built with structural tubing members and friction energy dissipation mechanism.

Experimental Validation of the PT-SCED System

Validation of the SCED Brace Friction Energy Dissipative and Tensioning Components

An extensive validation of friction interfaces was first carried out to select an adequate dissipation mechanism for the bracing system. Non-Asbestos Organic (NAO) material commonly used in the automotive industry to stainless steel interfaces were examined. Details on the study that led to the choice of the most appropriate friction material can be found in Kim et al. (2004). The normal force on the interface was provided by pre-tensioned 19 mm (¾") ASTM-A325 bolts used in a double shear configuration to maximize the friction force produced by each bolt. The inner steel plate had a 2 mm thick sheet of stainless steel welded on each side while the outer plates were equipped with 3.3 mm thick NF-916 NAO pads of 70 mm x 30 mm produced by the Carlisle Group Inc. Figure 5a shows the force-deflection response obtained under harmonic loading consisting of 20 cycles at a loading frequency of 0.17 Hz. The material displayed a relatively low friction coefficient (0.12) but was selected as the final choice as it exhibited a very stable behaviour with almost no deterioration during the loading protocol.

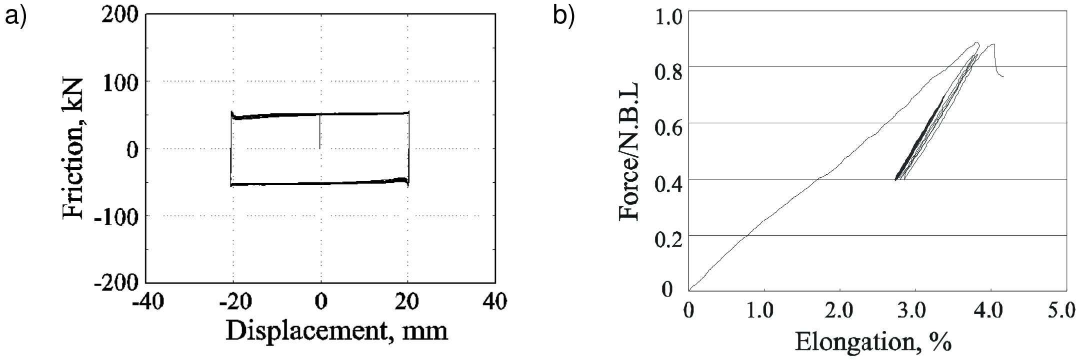

Figure 5. Cyclic test results on PT-SCED brace components: a) NAO-stainless steel friction interface; b) 17mm diameter Aramid based tendon.

Metallic tensioning elements such as high-strength steel do not possess sufficient elongation capacity to accommodate the required elongation in their elastic range. Therefore, a number of alternative tendons made of glass, carbon and aramid materials were examined. Aramid based tendons were found to be the most suitable because of their large elongation capacity and their reasonably high elastic modulus. Cyclic tests were performed on parallel lay tendons produced by Linear Composites Inc. and made of made of Kevlar 29, Kevlar 49, and Technora 200 Aramid fibers. Parallel lay tendons consist of small fibers that are run over the entire length of the tendon and anchored at each end with aluminum spike and barrel terminations. Figure 5b shows the load-deformation response of a 17 mm Technora tendon under monotonic loading up to 90% of nominal breaking load (NBL) and subsequent cyclic loading between 0.4 and 0.9 of the NBL. Aramid based tendons display different properties when the tendons are monotonically loaded to failure and when they are loaded cyclically as would be the case when they are incorporated in the SCED bracing system. As can be seen in the figure the initial stiffness of the system is substantially lower than the cyclic stiffness. For cyclic loading after initial preloading is applied, the available deformation range for the selected tendon was found to be 2.3%. The measured monotonic and cyclic moduli of this tendon were respectively equal to 65 GPa and 93 GPa.

Validation of the SCED Brace

A full-scale (reduced length) prototype PT-SCED brace was completed and subjected to a step-wise incremental quasi-static axial loading protocol at the University of Toronto Structures Laboratories. The prototype SCED system had interior and exterior square tubes of 254x254x8.0 and 305x305x6.4, respectively. The tensioning elements were comprised of four 17mm diameter Technora tendons while four friction dissipative mechanisms were included to produce an expected friction force of F = 276 kN. The SCED system was designed based on a building prototype with 9 m span and 4 m height and the loading protocol imposed a maximum brace elongation of 1.3% which corresponded to a 2% interstorey drift in the prototype structure.

The brace specimen mounted in the Universal testing machine is illustrated in Fig. 6a. Figure 6b shows the axial force-deflection response of the system. The brace performed as expected, reaching its design load of 800 kN at the target design drift and displaying a stable and repeatable full-centering response with good energy dissipation throughout the loading protocol. At the end of the entire loading protocol, the system sustained only a minor residual deformation of the order of a few millimeters, which disappeared when the bolts in the friction dissipative elements were unstressed. After the load capacity of the brace was reached, the full self-centering property of the system was still maintained, thus achieving the desired flag-shaped hysteresis.

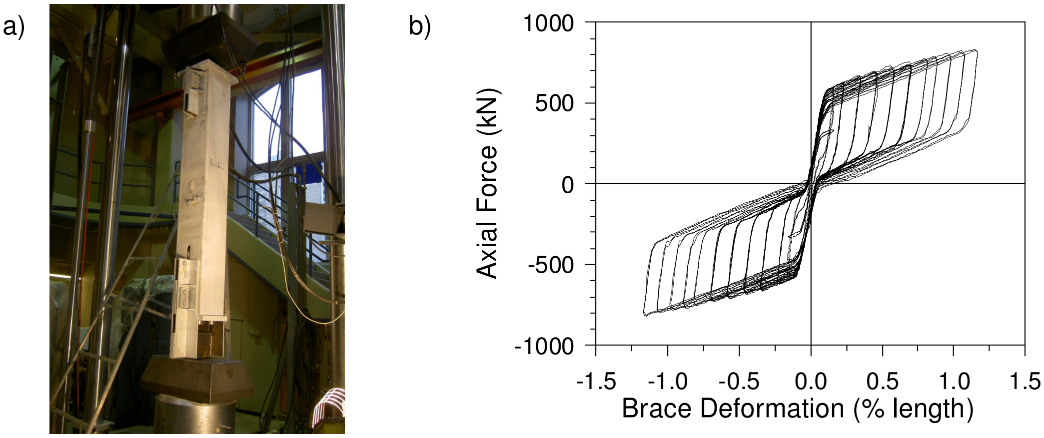

Figure 6. Cyclic quasi-static testing of a prototype SCED bracing member: a) Specimen mounted in the load frame; b) Measured hysteretic axial response.

Validation of the SCED Brace in Frame

Full-scale SCED braced frame testing was performed at the Structural Engineering Laboratory of École Polytechnique of Montreal using the 9 m x 3.75 m test frame depicted in Fig. 7a. The SCED brace specimen measured 6030 mm long and was made of the same HSS steel shapes as used for the individual brace tests. Figure 7b shows the brace components prior to assembly, including the four 17 mm tendons used for the tensioning elements. The friction energy dissipation mechanism was designed with four 19 mm A325 bolts. In the tests, the lateral displacement was applied with a high performance 1000 kN dynamic actuator and a loading arm transferring the load to the top beam. At the base, the beam was secured to the laboratory strong floor to transfer the horizontal reaction, reproducing storey shear transfer conditions found in actual building structures. Simple shear beam-to-column connections were used at both levels. At one end, the brace connection included a bolted connection with long slotted holes and the faying surfaces used in the friction energy dissipation mechanism. This fuse system was designed to slip at a predetermined load to prevent damage to the tensioning elements for storey displacements in excess of 2% interstorey drift angles.

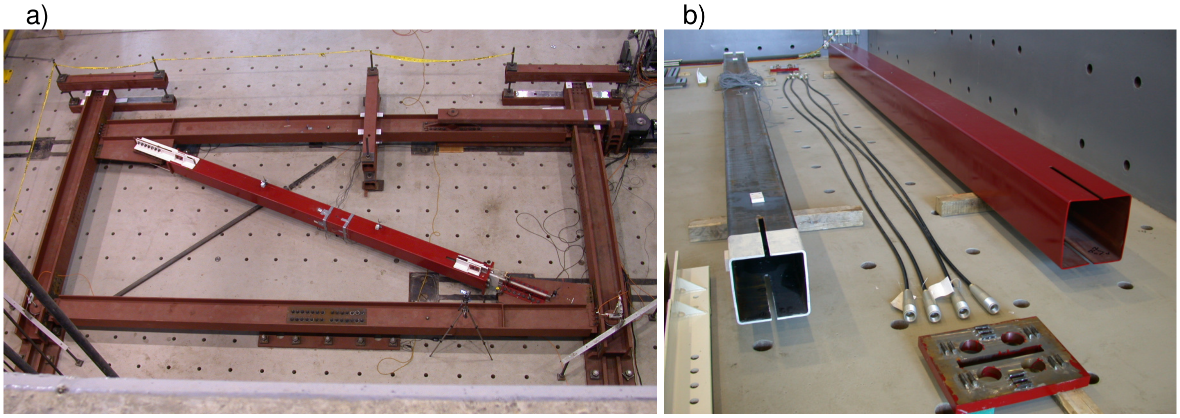

Figure 7. SCED brace prototype: a) Full-scale frame test setup; b) Upon assembling.

Several cyclic quasi-static and dynamic seismic tests were performed on the SCED braced frame. Figure 8a shows the storey shear-interstorey drift response measured when dynamically applying in real time the storey drift time history obtained from nonlinear dynamic analysis at the first level of an 8-storey SCED frame subjected to a ground motion record corresponding to 10% in 50 years hazard level. Figure 8b shows the same response parameters measured when imposing the interstorey drift time history computed at the first level of a 12-storey SCED frame subjected to a ground motion record corresponding to 2% in 50 years hazard level. Detail of the analytical study that was completed to determine these building responses can be found in Tremblay et al. (2007). The demand in the first test was nearly equally distributed in both directions while the higher level earthquake of the second test imposed large interstorey drift demand towards one direction only. In both tests, the SCED system displayed the intended flag shape hysteresis with stable energy dissipation and re-centering capability.

The response under cyclic quasi-static loading with stepwise incremental displacement amplitudes up to 3% interstorey drift is shown in Fig. 8c. The system exhibited stable and repeatable nonlinear behaviour with full re-centering response up to the target storey drift angle of 2.0%. Beyond that point, the end fuse protective system was activated, as anticipated, and the system started to act as a conventional friction brace system with additional deformation and energy dissipation capacity. In this particular test, the load dropped suddenly when the fuse was first actuated on the tension side but the frictional resistance was rapidly restored to the design level of 750 kN and remained uniform up to the applied 3% interstorey drift angle in both directions.

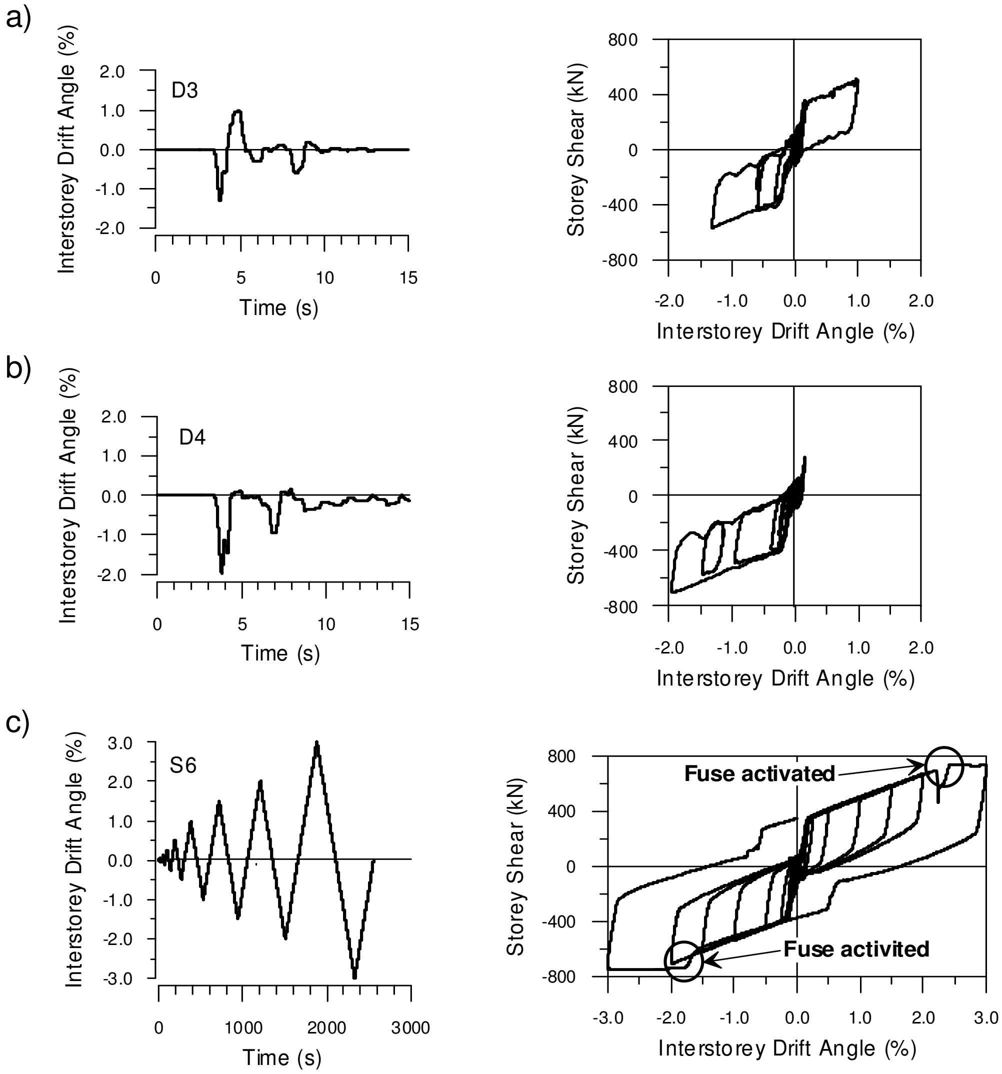

Figure 8. Storey shear-interstorey drift angle frame response under: a) Interstorey drift time history at Level 1 of an 8-storey structure under record LA18; b) Interstorey drift time history at Level 1 of a 12-storey structure under record LA28; and c) Cyclic quasi-static loading with stepwise incremental displacement amplitudes.

Conclusions

A new pre-tensioned self-centering energy dissipative (PT-SCED) bracing system is proposed as an alternative to conventional or buckling restrained bracing systems to achieve stable energy dissipative and self-centering response under seismic loading. The system can also be employed for other extreme and/or severe loading conditions due to winds, explosions or shocks. The mechanics of one possible embodiment of the PT-SCED design incorporating a friction energy dissipative mechanism combined with Aramid tensioning elements was presented. A test program was carried out to evaluate the behaviour under cyclic loading of the friction and tensioning components of the PT-SCED system. Full-scale validation of the system studied was performed both under axial loading and as part of a braced frame system subjected to interstorey cyclic quasi-static and dynamic shears. The experimental validations confirmed that the system performs as intended, with stable self-centering hysteretic response under cyclic loading protocols. When the deformations exceeded the tendon elongation capacities, the system lost its self-centering capacity and gradually transformed into a simple friction brace system with additional deformation capacity, due to the frictional fuse incorporated at one end of the brace. Alternative means are currently being studied to fully characterize the properties and performance of the tensioning elements as well as to enhance their deformation capacities.

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