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EXPERIMENTAL VALIDATIONS AND DESIGN OF SELF-CENTERING ENERGY DISSIPATIVE (SCED) BRACED STRUCTURES

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ABSTRACT

The self-centering energy dissipative (SCED) brace is an advanced cross-bracing system that has recently been developed in Canada. Its self-centering capability reduces or eliminates residual building deformations after major seismic events and prevents progressive drifting to occur under long duration strong ground motion inducing inelastic cyclic structural response. The system can be utilized in new structures as well as for the seismic retrofit of deficient structures. A description of the bracing system is presented, together with possible applications where SCED braces are used in braced steel frames or in combination with other seismic force resisting systems. Time-history responses of sample structures are presented and discussed. Hysteretic responses from full-scale SCED braced frame tests are presented. An ongoing shake table test program carried out on a 1/3 scaled three-story SCED braced frame is described and preliminary results are presented.

Introduction

Seismic force resisting systems designed according to current code seismic provisions are expected to respond beyond the elastic limit and develop yielding ductile inelastic response under strong ground shaking. Figure 1a shows the idealized force-displacement response of a system representing a yielding structure. The shaded area in Figure 1a represents the energy dissipated per cycle through hysteretic yielding. Designs aiming for an inelastic structural response may appear very appealing at first, particularly from the initial cost stand point. These designs have however two major drawbacks. First, elements of the seismic force resisting system will likely require repair due to yielding after moderately strong earthquakes and may be damaged beyond repair in strong earthquakes. Second, full hysteresis loops as shown in Fig. 1a can lead to significant residual displacements in a building after an earthquake, as also illustrated in the figure.

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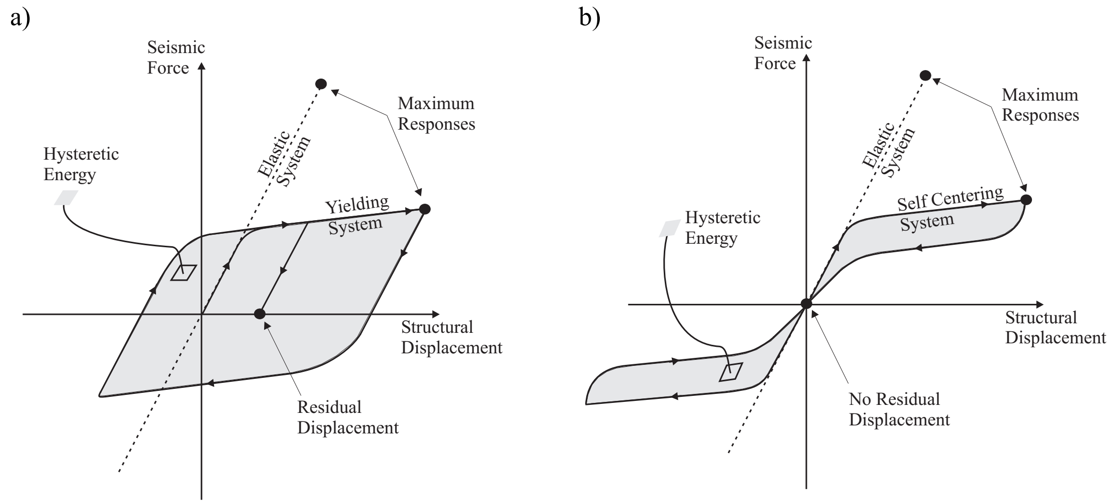

Figure 1. Nonlinear hysteretic response to earthquakes: a) Yielding systems; b) Self-centering energy dissipation systems.

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 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 potential for large P-Δ effects.

Self-centering behavior can be achieved with a number of structural configurations (Filiatrault et al. 2004). A self-centering energy dissipative (SCED) bracing member has recently been developed in Canada for use in braced frame structures or in combination with other framing systems (Tremblay et al. 2008, Christopoulos et al. 2008). Unlike other comparable advanced bracing systems that dissipate energy, the SCED brace system has a self-centering capability that reduces or eliminates residual building deformations after major seismic events. This paper briefly presents the SCED bracing member. Past analytical studies comparing the seismic response of SCED and buckling restrained braced (BRB) frames for multi-story buildings are reviewed, together with quasi-static and cyclic seismic dynamic frame tests. Braced frame and wall systems incorporating SCED braces are presented and discussed. An ongoing shake-table test program on one-third scale SCED braced frame is introduced. Results from these tests will be used to validate modeling techniques that have been developed to numerically predict the response of structures incorporating SCED braces.

SCED Bracing Member

A schematic of the SCED bracing member is illustrated in Fig. 2a. It is built with two structural steel members interconnected by an 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 SCED concept can be achieved with a number of combinations of structural, tensioning, dissipative and blocking elements. The configuration with a friction energy dissipation mechanism is examined in this study. As shown in Fig. 2b, square structural steel tubing can be used for the two structural elements. 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 cut to the same length and fitted with end plates. The tensioning elements are comprised of parallel lay Aramid tendons fitted with spike and barrel terminations. They are introduced in the inner tube tubes and anchored on the outer side of the right and left end plates. Figure 2c shows the assembled SCED brace in a full-scale test frame. Pairs of back-to-back angles are welded to the outer tube and extend out to provide the connection of the SCED system on the upper left-hand end. The outer tube is slotted to allow for steel plates welded to the inner tube to protrude and to be bolted to back-to-back angles 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. A similar design is used at the opposite end, the connection component being fitted through a slot cut in the end plate and welded to the inner tube. The friction mechanism developed for use with the SCED system consists of thin friction Non-Asbestos-Organic (NAO) pads sliding over a stainless steel surface. The normal force on the interface is provided by pre-stressed bolts.

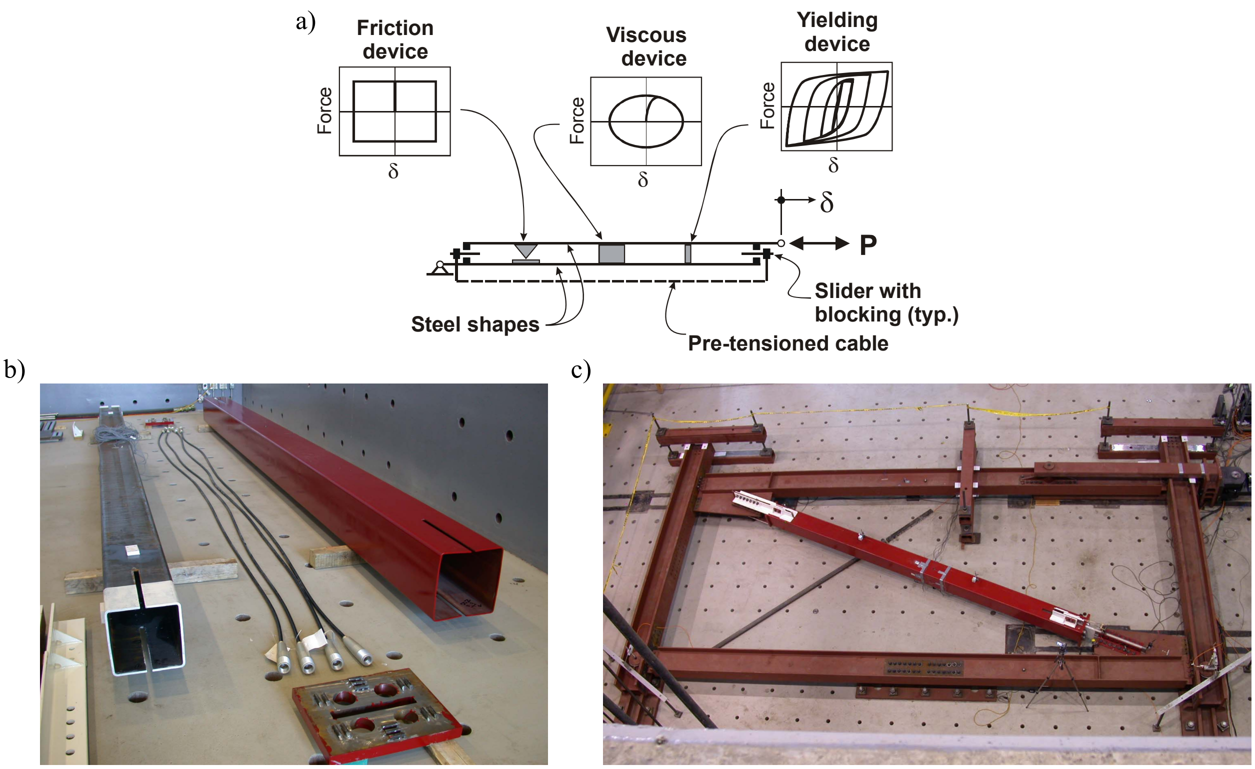

Figure 2. a) Schematic of the SCED bracing member system; b) Components of a SCED brace prior to assembly; and c) SCED brace in a full-scale frame test setup.

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. Detail of the connection between the structural elements, the abutting elements and the tensioning elements is done in such a way as to assure that when relative longitudinal motion is induced between the two bracing members, it always results in an elongation of the tensioning elements. Once this movement is initiated, the energy dissipation mechanism is activated by this relative motion between the two structural elements and the stiffness of the system changes from the initial elastic stiffness, determined by the sum of the elastic stiffness of the two structural members, to the post-elastic stiffness, determined by the stiffness of the tensioning elements. The level of pre-tension also governs the re-centering capability of the system: full re-centering behavior being achieved by providing sufficient pre-tension to overcome the force required to activate the energy dissipation mechanism. Additional information on the design of the system components can be found in Christopoulos et al. (2008).

Structural Configurations with SCED Braces

Figure 3 shows possible structural configurations with SCED braces. In Fig. 3a, SCED members are used as bracing members to form concentrically braced steel frames with superior inelastic response, with no brace yielding or buckling and no permanent deformations. Tremblay et al. (2008) performed an extensive numerical simulations were performed on 2- to 16-story braced frames of this type. The structures were located in the Los Angeles region and designed using the seismic loads specified in ASCE 7 (ASCE 2005). The SCED frames sustained no residual deformations under the design base earthquake (DBE) level and collapse was prevented in all cases under the maximum credible earthquake (MCE).

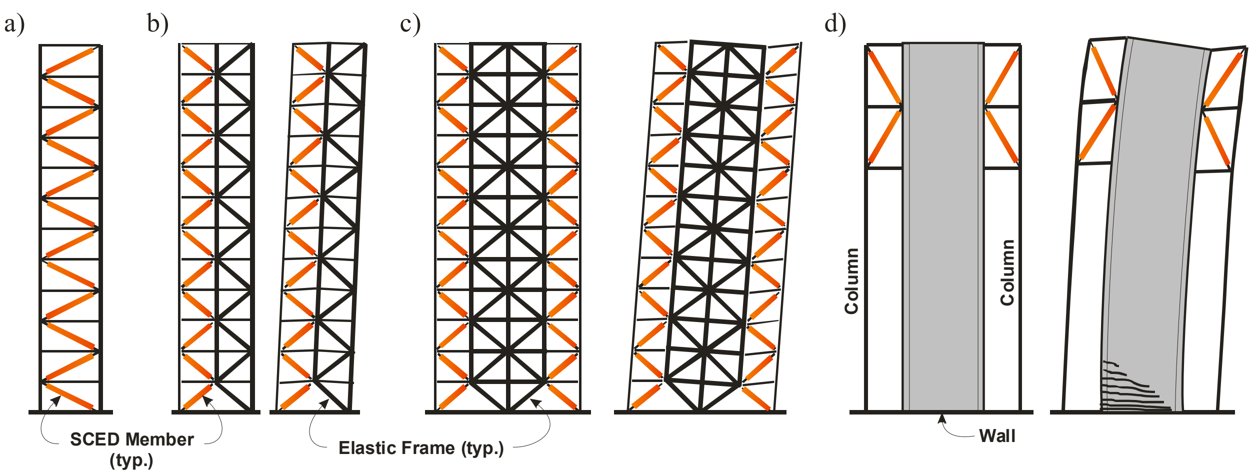

Figure 3. a) SCED braced frame; b) and c) Dual SCED braced frame; and d) SCED bracing acting in parallel with a reinforced concrete shear wall.

This analytical study also compared the response of SCED braced frames to that of buckling restrained braced (BRB) frames. The lateral displacement time histories at the roof and first levels, as well as the first story shear-story drift hysteretic responses at the first level, under a DBE ground motion are illustrated in Fig. 4 for the two 8-story frames. Both structures experienced similar peak deformation demand, as was expected due to the similitude in backbone load-deformation characteristics exhibited by the two bracing systems. Beyond that point, the SCED frame oscillates about the zero deformation position, whereas the BRB frame exhibits an offset with respect to the initial undeformed frame geometry.

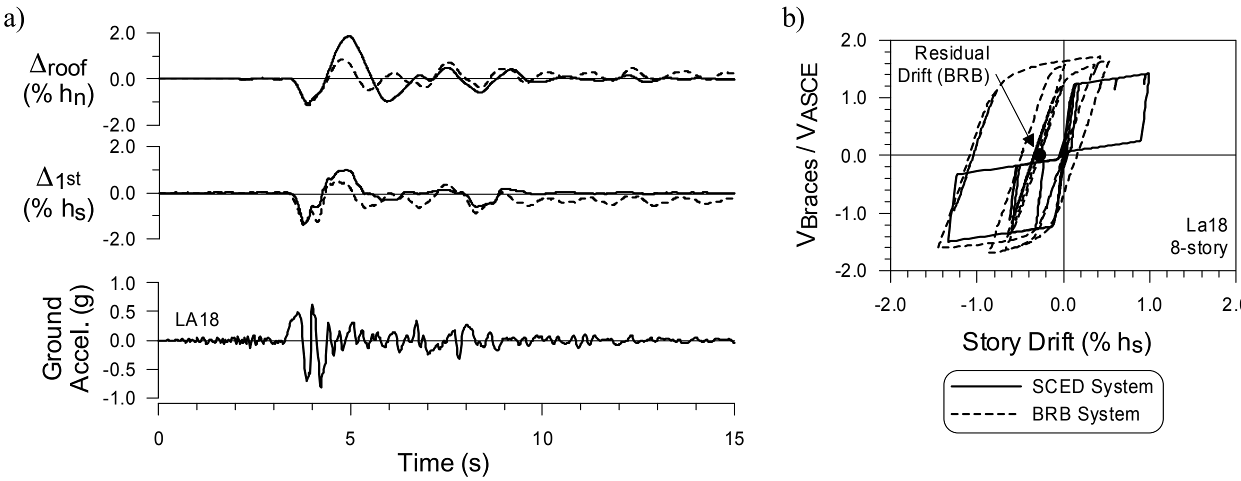

Figure 4. Computed responses of 8-story SCED and BRB frames under a DBE ground motion record: a) Roof displacement and first story drift time histories; b) Story shear-story drift response at Level 1.

Cyclic quasi-static and dynamic seismic tests have been performed on individual SCED members and SCED bracing member used in braced frames. Figure 5a shows the measured story shear response of the test frame in Fig. 2c when subjected to the first story drift time history shown in Fig. 4a. The displacement signal was applied in real time and the system displayed the intended flag shape hysteresis with stable energy dissipation and re-centering capability. The response of the same frame under cyclic quasi-static loading with stepwise incremental displacement amplitudes up to 3% story drift is shown in Fig. 4b. The system exhibited stable and repeatable nonlinear response up to 2% interstory drift. Beyond that point, a friction fuse protective system that was introduced at one end of the SCED brace was activated and the system started to act as a conventional friction brace system with additional deformation and energy dissipation capacity. A shake table test program has also been undertaken on SCED braced frame, as discussed later in this paper.

SCED braces can also be implemented in dual braced steel frames that comprise a vertical trussed frame designed to remain essentially elastic under strong ground motions (Figs. 3b and 3c). The elastic frame distributes the hysteretic response over the building height and help achieving uniform story drift demand. The benefits of dual braced frames have been examined in past analytical studies with buckling restrained bracing members (Tremblay 2003; Merzouq and Tremblay 2006; Tremblay and Poncet 2007). When the BRB members are replaced by SCED braces, the frame also possesses self-centering capabilities, which can improve further the structure seismic performance. For instance, one-sided response with progressive drifting of the structure due to P-Δ effects and successive yielding excursions under long duration earthquakes can be eliminated when using SCED members. This is illustrated in Fig. 6 for a 12-story dual braced frame designed with BRB and SCED members subjected to Cascadia subduction earthquakes along the Pacific coast of North America.

In dual braced steel frames, the elastic truss forces first mode inelastic response and preliminary design of the SCED bracing members can be easily performed using methods prescribed in current building codes. Forces in the elastic truss members are strongly influenced by inelastic higher mode response that develops once the SCED behaves in the response range. Empirical expressions have been proposed by Merzouq and Tremblay (2006) to preliminary size the elastic truss members. The design is then finalized by adjusting the SCED and elastic truss components until the desired performance obtained from nonlinear time-history analyses is achieved.

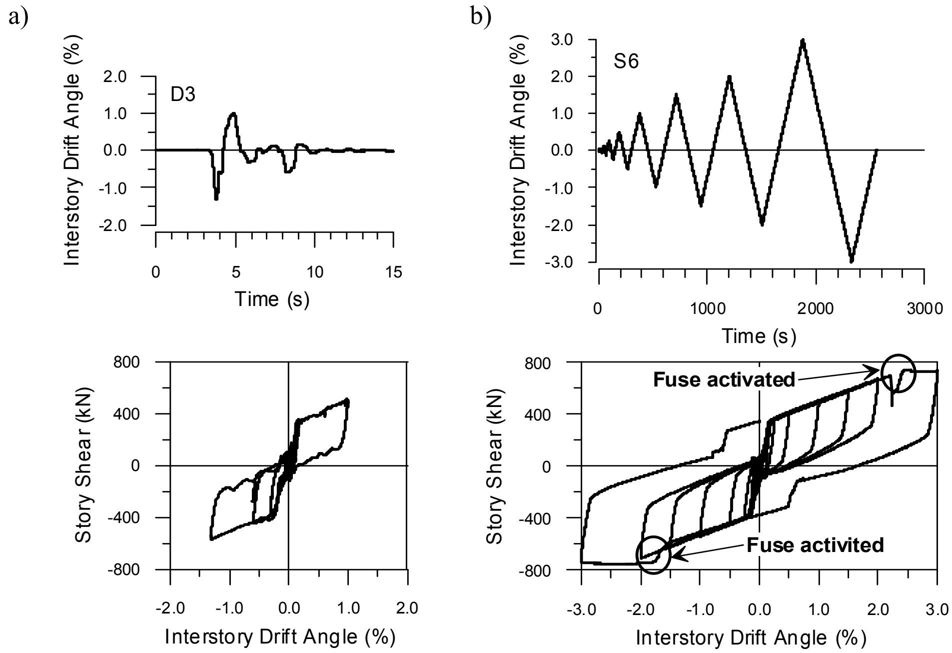

Figure 5 Story shear-drift response of the braced SCED frame in Fig. 2c under: a) Story drift time history at Level 1 of the 8-story structure under DBE ground motion (see Fig. 4); b) Cyclic quasi-static loading with stepwise incremental displacement amplitude.

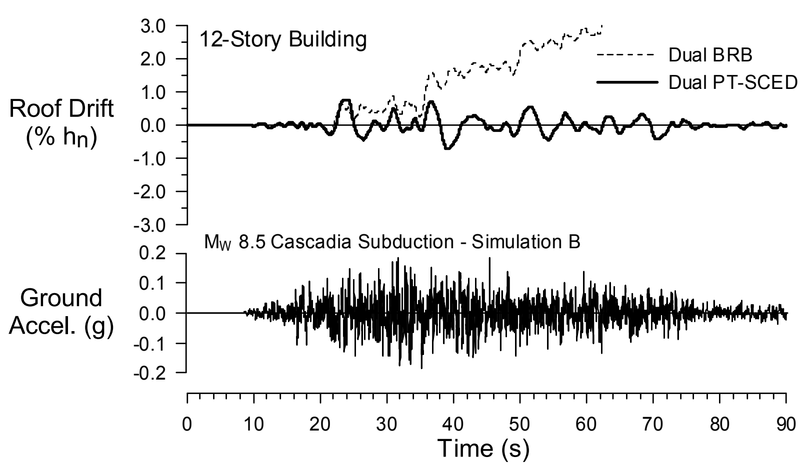

Figure 6. Roof displacement time history of 12-story dual braced frames with BRB and SCED bracing members under a Cascadia subduction earthquake ground motion.

SCED members can be used in conjunction with reinforced concrete structures to control drifts and mitigate permanent deformations after strong ground shaking. One such application is illustrated in Fig. 3d where for a gravity steel frame laterally braced by a reinforced concrete shear wall. In that configuration, SCED braces are introduced in the upper floors, on each side of the wall, and act as outriggers connected to adjacent gravity columns. Wall tip deflections and rotations can then be reduced and residual deformations are controlled. This behavior is illustrated in Fig. 7a for a 15-story R/C wall equipped with pairs of SCED members in the upper 4 stories. The bare shear wall without self-centering members exhibits unsymmetrical response with a permanent shift. More symmetrical response can be achieved with SCED members, with oscillations centered on the undeformed position. Contrary to an elastic outrigger system, the nonlinear response of the SCED members (shown in Fig. 7b) bounds the forces that will be imposed on the wall and gravity columns.

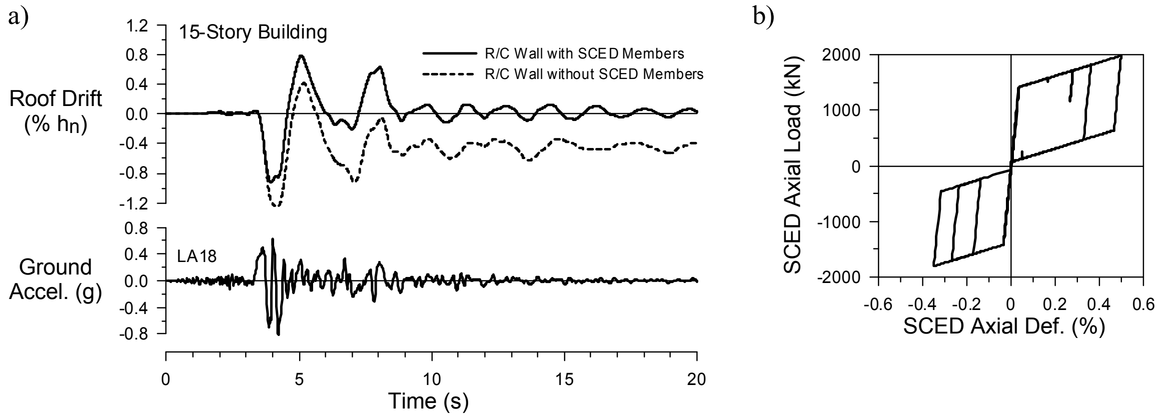

Figure 7. Seismic response of a 15-story R/C wall with and without SCED members: a) Roof displacement time histories; b) SCED member hysteretic response.

Shake Table Test Program

A shake table test program has been initiated to examine the response of a multi-story SCED braced frame under dynamically applied earthquake ground motions. The plan view of the prototype building is shown in Fig. 8. This is a three-story office steel building with four SCED perimeter braced frames acting in the N-S direction and two perimeter moment-resisting frames acting in the E-W direction. An elevation of the studied braced frame is shown in the figure. The structure was assumed to be located on a site type D in the Los Angeles area and was designed according to ASCE 7-05. Design gravity loads and seismic data are given in Fig. 8. In the N-S direction, the design and actual periods are 0.43 s and 0.46 s, respectively.

A 1/3 scaled model with artificial mass simulation was selected for the shake table test program. The model includes one braced frame and its tributary seismic weight. The test frame is 2845 mm wide x 3962 mm tall and the seismic weight at each floor is obtained by means of four 2438 mm x 3658 mm, 51 mm thick, steel plates, leading to 118 kN. At each floor, the plates are bolted together and connected to the test frame by means of a stiff strut equipped with a load cell such that inertial loads can be directly measured. The plates are vertically supported on an independent three-story gravity frame designed with pin-ended columns, allowing P-Δ effects to be included in the response. The resulting mass and time scaling factors are 1.0 and 0.58, respectively, and the test model has periods of 0.26, 0.10 and 0.08 s in the first three modes of vibration. Prior to assembling the test frame, the hysteretic properties of the model SCED braces were validated through individual quasi-cyclic tests (Fig. 9a). Test results are shown in Fig. 10.

In a first series of tests, the braces were examined without the friction energy dissipation mechanism in place (first row of plots in Fig. 10). The hysteretic response is therefore characterized by a bi-linear elastic response resulting from elongation of the tendons in both directions. Energy dissipation is obtained by activating the friction mechanism, as illustrated in Fig. 10 (second row of plots).

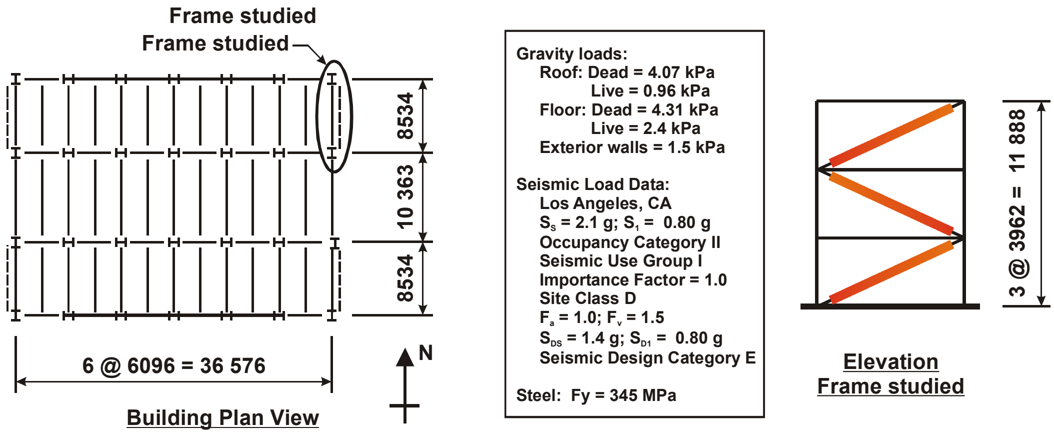

Figure 8. Three-story prototype building and design loads for the shake table test program.

a) b)

Figure 9. Shake table test program: a) SCED brace specimen subjected to quasi-cyclic characterization test; b) Test SCED braced frame upon assembly.

The response of the three-story test frame under the DBE level 1966 Parkfield, California (cs08) record is illustrated in Fig. 11. The time-history of the roof displacement and the hysteretic response of the first story brace are plotted. As shown, the frame behaved as intended, with no structural damage, a self-centering response and no permanent deformations. The full shake-table testing program is currently underway and includes both DBE and MCE level earthquakes.

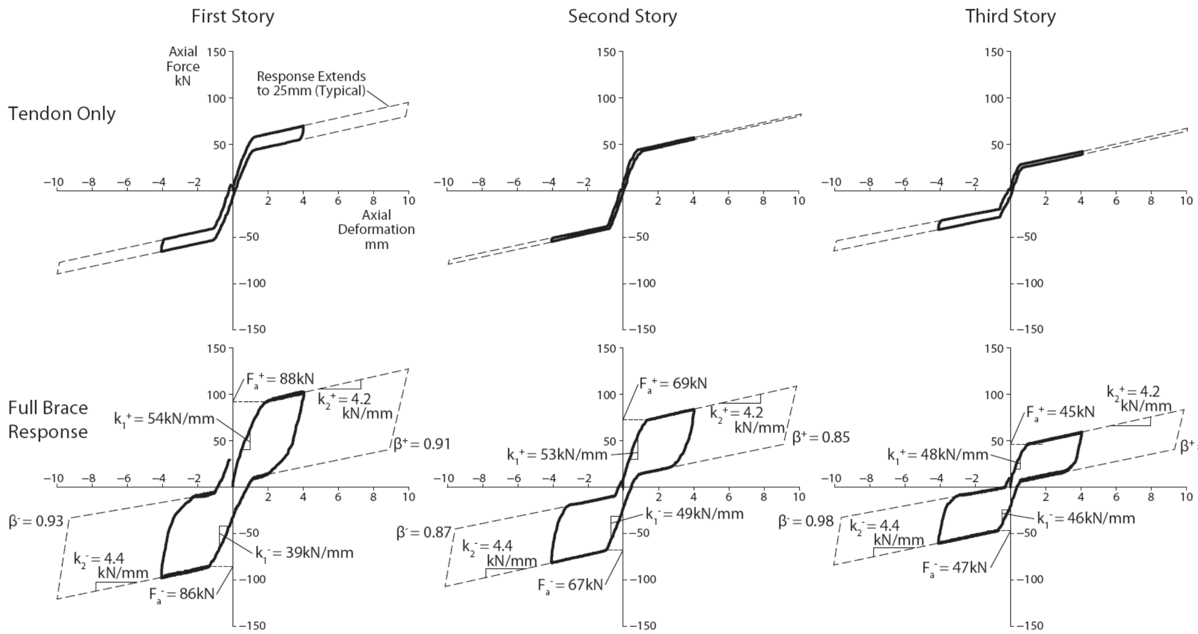

Figure 10. Hysteretic responses of the SCED brace specimens from the characterization tests performed without and with the brace's internal energy dissipation mechanisms.

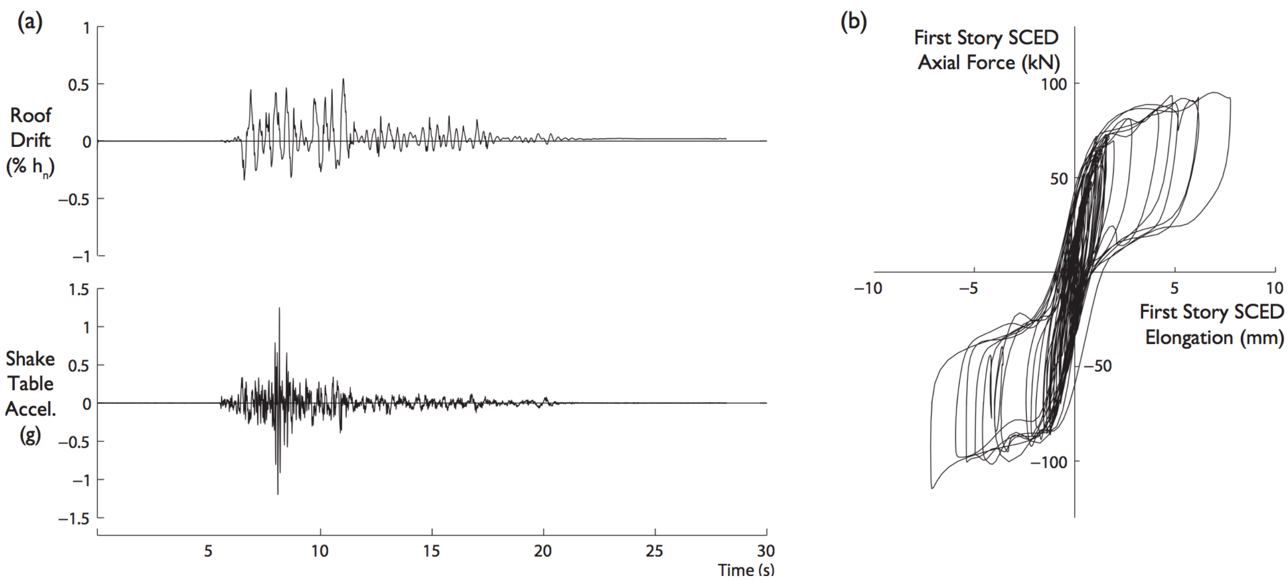

Figure 11. Response from shake table experiments under a DBE record 1-4: 1966 Parkfield - cs08: a) Roof displacement time history and shake table acceleration record b) First-story shear-story drift response.

Conclusions

A new pre-tensioned self-centering energy dissipative (PT-SCED) bracing system has been proposed as an alternative to conventional or buckling restrained bracing systems to achieve stable energy dissipation and self-centering response under severe seismic loading. The mechanics of the SCED design incorporating a friction energy dissipative mechanism combined with Aramid tensioning elements was presented. Various possible applications of the SCED members were illustrated. Design methodologies for these systems were briefly introduced and their expected seismic performance as obtained from numerical simulations was presented and discussed. The performance of SCED braced frames was verified through full-scale seismic dynamic and quasi-static cyclic tests. A shake table test program on a 1/3 scaled three-story test frame was described. The shake table test program also included quasi-cyclic tests performed on individual SCED braces. The model braces and test frame were found to perform as expected under different levels of earthquake ground motions and provided a basis for the validation of the models that have been developed to capture the response of structures incorporating SCED bracing members.

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