CABLE DAMPER BRACING FOR PARTIAL SEISMIC REHABILITATION

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ABSTRACT :

A seismic rehabilitation method which involves minor on-site construction work without requiring the use of heavy equipment and disruptive noise is developed. The system consists of eccentrically connected elastic cables and a central energy dissipater (CED), where all cables are intended to be in tension under lateral loads so that the system dissipates energy through a bi-linear hysteresis curve. The CED dissipates energy through the cyclic bending of steel plates which are replaceable after severe earthquake event. The system cab be assembled onsite and is easily connected to existing framing using high strength bolts, turnbuckles and padeyes.

KEYWORDS: Cable Bracing, Seismic Rehabilitation, Steel Damper, Retrofit

1. INTRODUCTION

For steel structures, a large number of supplemental energy-dissipating systems and rehabilitation techniques have been proposed since the late 1990's, motivated mainly by the severe damage observed in both the 1994 Northridge and 1995 Kobe earthquakes [Bertero et al. 1994, AIJ Reconnaissance 1995, FEMA Interim 1997, Nakashima et al. 1998.] The addition of seismic isolation, supplemental bracing, concrete or steel shear walls, and damping devices are among the techniques that have been successfully implemented into existing buildings. However, because of the high cost and disruption during construction, seismic rehabilitation projects are still limited to critical or essential facilities such as hospitals, schools, and historical structures despite the existence of a huge stock of seismically vulnerable buildings.

A multi-staged seismic rehabilitation strategy recently proposed by FEMA provides an option for building owners to reduce their initial investment and disruption due to construction [FEMA 2002, FEMA 2003.] This incremental rehabilitation divides a rehabilitation project into a series of discrete actions implemented over a period of several years. These actions can be made to coincide with regularly scheduled building repairs, maintenance or capital improvement so that both investment and losses due to business interruptions are minimized. The underling philosophy of the incremental rehabilitation goes within the strategies of sustainable development and provides the community with the opportunity to enhance its value by having an improved and healthier building stock that are rehabilitated using the latest building codes [ASCE-41 2006, ASCE-7 2005.]

Considering this status, further development of rehabilitation methods which involve minor on-site construction without requiring the use of heavy equipment and disruptive noise is extremely desirable. Utilizing elastic cables and a central energy dissipater, an innovative supplemental lateral-load-resisting system suitable for a discrete rehabilitation action is developed. The system is easily connected to existing frames through conventional construction techniques such as high-strength bolts, turnbuckles and padeyes. The research work consists of both analytical and experimental tasks. This paper presents the results of the preliminary analytical work which has been performed to study the feasibility of the devices and to optimize the damper or structural elements. The experimental part of study will be performed in Fall 2008.

2. CABLE DAMPER BRACING WITH CENTRAL ENERGY DISSIPATER

2.1. Cable Damper Bracing

For the rehabilitation of steel structures, the most common strategies to increase the capacity of system are the addition of supplemental bracing and shear walls. Other techniques, such as introduction of isolation or damping devices, are also common to reduce seismic demands. Design criteria for these new and existing structural members includes consideration of global buckling, local buckling, low cycle fatigue, and fracture in addition to simple yielding. For supplemental systems where stiffness and strength demands are relatively small compared to those in primary systems, buckling in compression is the dominant design criterion for some elements. Since rehabilitation schemes following current guidelines apply a strict capacity design approach that does not allow strength overdesign of supplemental elements, elements with proper compact sections and small strength are not always available. In such a case, an approach to design them as tension-only elements becomes a rational option. Cable, tension-only rods, and slender angles are well known example of these elements. Cables with various sizes are available in the market with pre-qualified end connectors and adjustable turnbuckles. An example of a cable installation to existing framing is illustrated in Figure 2-1.

Cable bracing systems, where all cables are intended to be in tension under lateral loads, dissipate energy through a bi-linear hysteresis curve. Figure 2-2 shows several cable bracing systems proposed previously [Pall 1983, Mualla and Bellev 2002, Phocas and Pocanschi 2003.] Pall proposed a friction device with a slip joint for cross bracing and an inverted V-bracing. Mualla and Bellev conducted dynamic tests of a scaled steel frame with friction damper devices installed in inverted cable V-bracing system. Phocas and Pocanschi proposed a system where diagonals of the system are fixed at the bottom of the columns and are able to move at the top corners of the frame through rotations of the connecting eccentric discs. These systems showed stable hysteresis analytically or in small scale experiments.

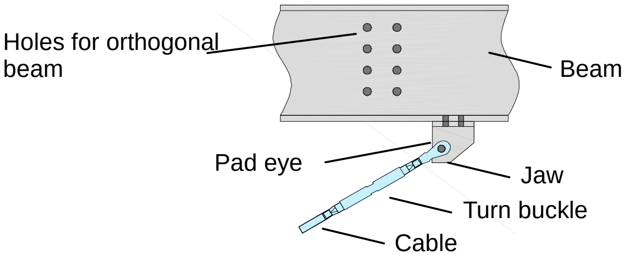
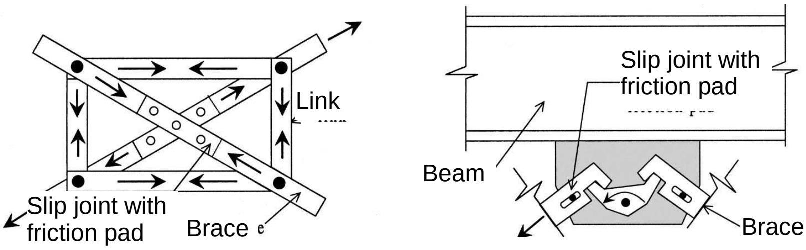
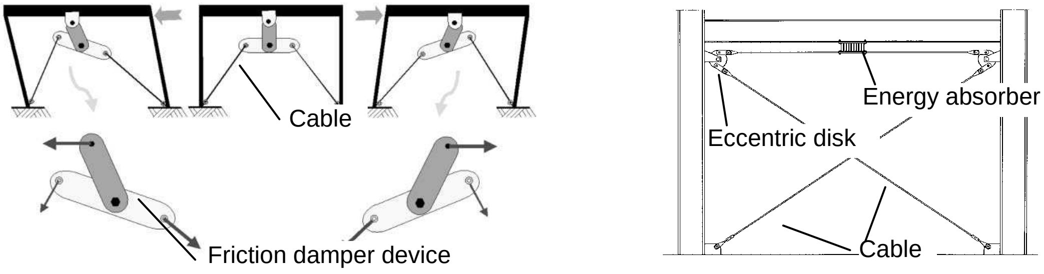


Figure 2-1 Cable with hanger connection



(a) Friction device for tension-only bracing by Pall (1983)



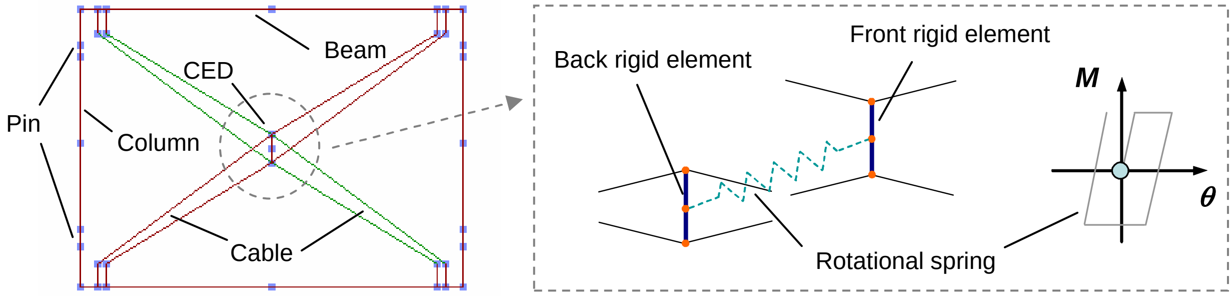
(b) Tension-only concentric bracing by Mualla and Bellev (2002)

(c) Hysteretic damper system with eccentric disc by Phocas and Pocanschi (2003)

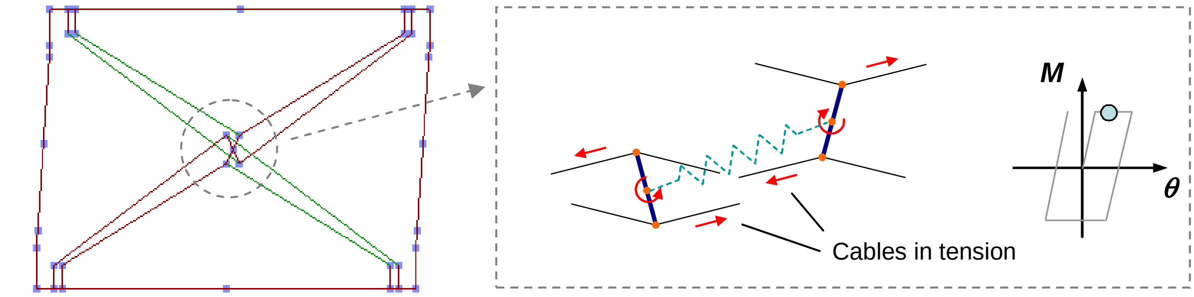
Figure 2-2 Example cable damper bracing mechanism proposed in past

2.2. Prototype Geometry

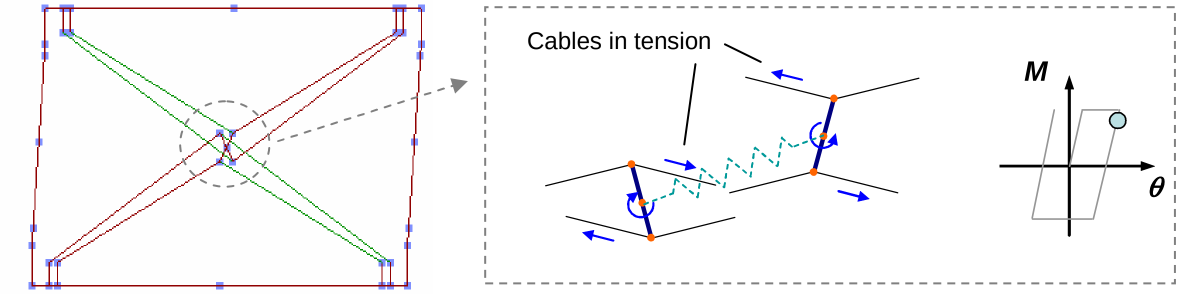
The proposed cable cross bracing system consists of eight tension-only elastic cables and one central energy dissipater (CED). Details of the CED design and operation will be given in the next section. Figure 2-3(i) shows the entire assembly installed to a portal frame with pins at its four corners which represents experimental setup to be used for proof-of-concept testing. The CED consists basically of two front and back rigid elements connected by a rotational spring. When the earthquake load begins to deform the frame, four cables in tension begin to resist the deformation and rotate the front and back rigid elements in opposite directions while tied together by a rotational spring as shown in Figure 2-3(ii). Note that the other four cables, which connect across the shortened diagonal, are not slack when the loading direction changes because of the permanent rotation of rigid elements. As shown in Figure 2-3(iii), the other cables start to resist immediately after the change of loading direction, resulting in a system that exhibits bi-linear load displacement behavior instead of the typical slip type curve associated with tension-only diagonal systems.



i) Initial phase, Analysis model (left), central energy dissipater (right)



ii) Loading phase

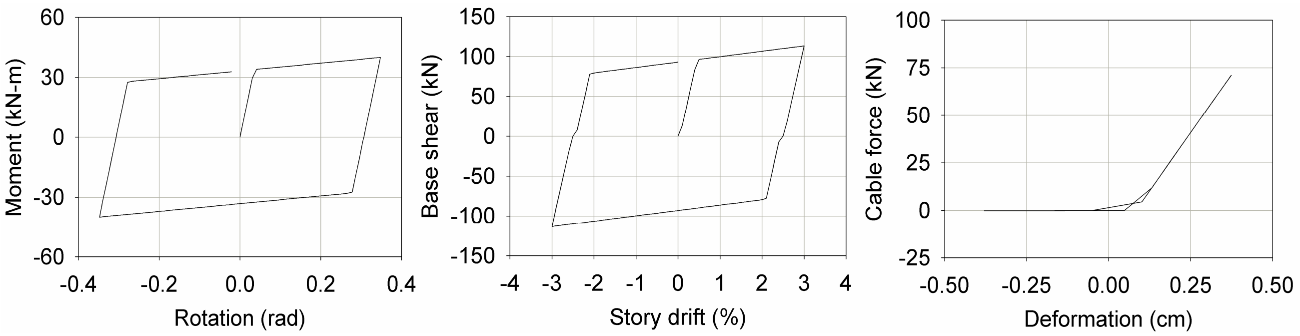


iii) Unloading phase

Figure 2-3 Concept of cable damper bracing with CED by Kurata (2008)

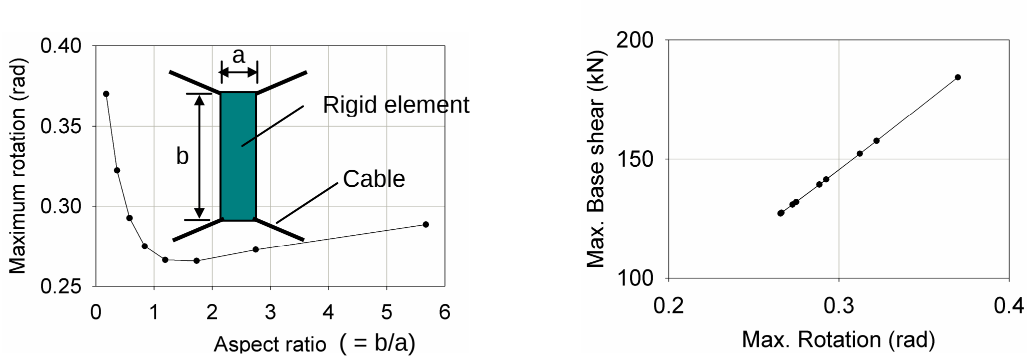
2.3. Preliminary Analysis in OpenSees

Figure 2-4 shows the results from preliminary analysis of this system using OpenSees for a prototype of this system. If the rotational spring can deliver a stable bi-linear curve (Figure 2-4(a)), then the behavior of the entire subassmeblage, as characterized by its force vs. story drift curve (Figure 2-4(b)), is also stable and bi-linear. As seen in Figure 2-4(c), the cables resist load only in tension. Using this analysis model, a parametric study was conducted to determine an approximate optimal shape for the central energy dissipater. The main parameter studied was the aspect ratio of the rigid element to which cables are connected. For these studies, the diagonal length of rigid element is fixed. As seen in Figure 2-5, the rotation of the spring is smallest when the aspect ratio is between 1 and 2 and gradually increases at aspect ratios greater than 2. The relationship between base shear and rotation of the spring is linear. It can be concluded that the best shape for the rigid element is either a square or slight oblong in order to limit rotational demand.



(a) Rotational spring hysteresis (b) System base shear (c) Cable hysteresis

Figure 2-4 Preliminary analysis results from OpenSees model



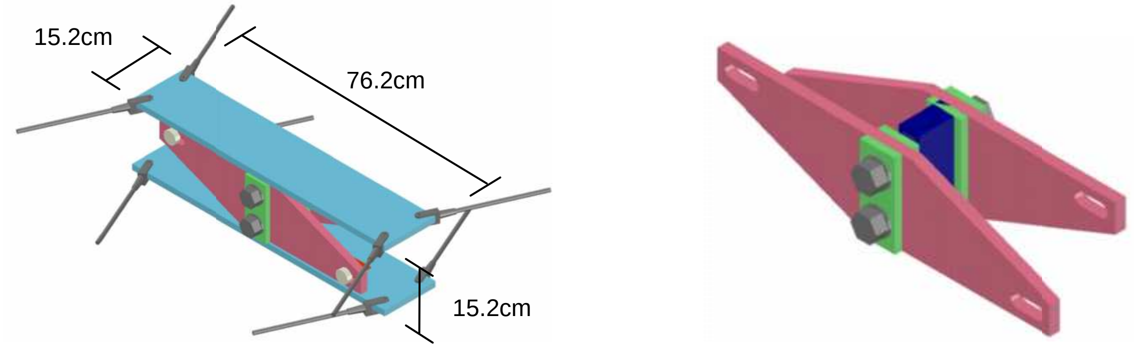
(a) Aspect ratio vs. maximum rotation (b) Base shear vs. rotation

Figure 2-5 Parametric study to geometry of CED

3. FINITE ELEMENT ANALYSIS OF CENTRAL ENERGY DISSIPATER

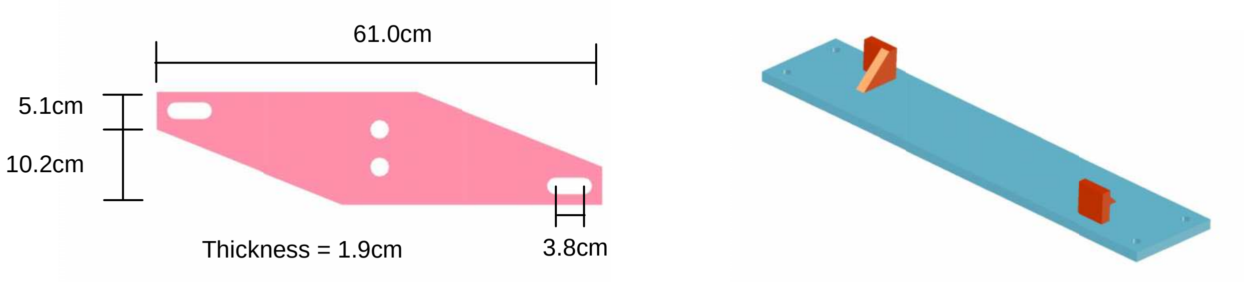
The central energy dissipater (CED) for the proposed cross cable system was developed by using a general purpose finite element analysis program, ABAQUS. Figure 3-1 shows the geometry and dimensions of a prototype with a performance goal intended to achieve a stable hysteresis curve up to 0.3 to 0.4 radian rotation with a yielding moment of approximately 33.9kN-m (300kip-in). In this device, the torsional moment induced by the rotation of the top and bottom rigid steel plates is resisted by the bending moment of two lozenge steel plates of which each end is transversely connected to the top and bottom rigid plates, respectively. As Whittacker and Tsai reported, mild steel plates possess stable energy dissipation capacity under cyclic bending until very large deformations are reached [Whittacker 1991, Tsai 1993.]

The prototype CED has dimensions of 15.2cm x 76.2cm x 15.2cm (6” x 30” x 6”) and is compact and light enough to be carried by two construction workers with a small wheelbarrow or similar moving device. It is also possible to assemble it on site since all the components are connected through high-strength bolts. The plastic deformation of the device is limited only to the steel plate energy absorber (SPEA) which is replaceable after an earthquake event. The assembly of the CED proceeds as follows. A steel HSS is placed between two SPEAs and a post tensioning force is applied to the outer surface of the SPEAs by high strength bolts. This subassembly is then connected to the top and bottom cover plates with high strength bolts; the bolts are not pre-tensioned. To prevent the development of undesirable axial forces in the SPEA, these bolts are allowed to slip along a long slotted hole. Once the top and bottom cover plates start to rotate in opposite directions due to the coupled cable forces, the SPEAs deform inward and outward against each other.



(a) Isometric view

(b) Without top and bottom plates



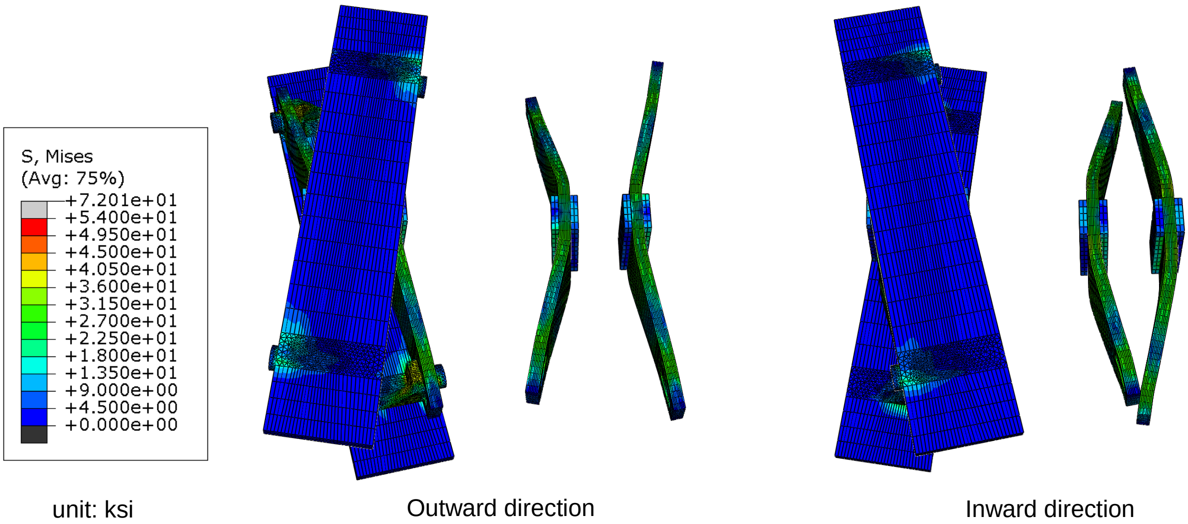
(c) Steel plate energy absorber (SPEA)

(d) Steel cover plate

Figure 3-1 Assemblage and components of CED by Kurata (2008)

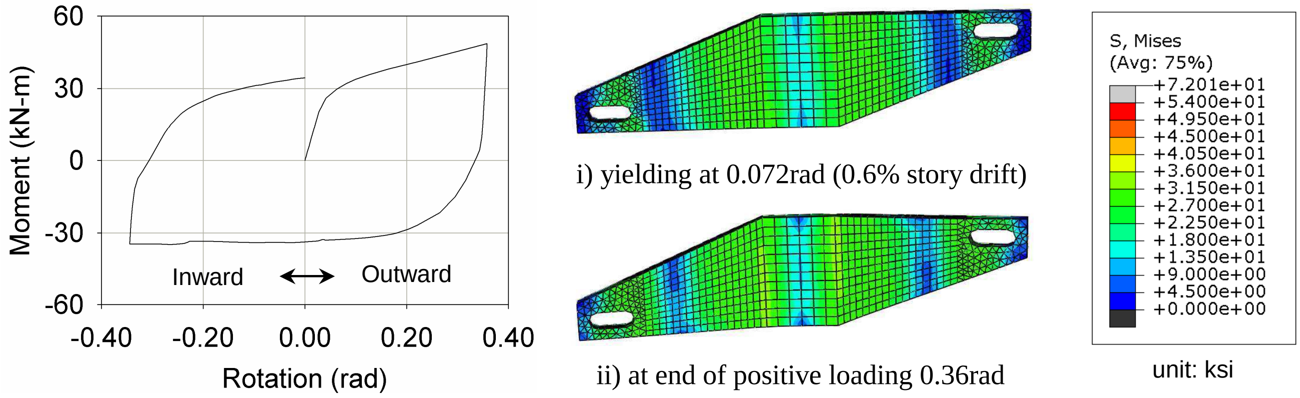
The deformed shape and hysteresis behavior of the CED obtained from a finite element analysis are presented in Figure 3-2. For illustrative purposes, the deformed shape is also shown without cover plate and HSS. In these analyses, a cyclic rotation is applied to the top and bottom cover plates with the amplitude of 0.18rad. The relative rotation between two plates is 0.36rad which corresponds to 3% story drift from a preliminary OpenSees analysis. The SPEA deforms cyclically without developing severe kinks in the middle. The SPEAs placed in parallel do not touch, even under severe deformation because of its lozenge shape.

In the hysteresis curve (Figure 3-3(a)), the CED yields approximately at 0.6% story drift (0.072rad) and shows post-yielding stiffness slightly higher in the outward direction than in inward direction, primarily because of the bolt slip at the loading point of the SPEA. The stress contours for the SPEA (Figure 3-3 (b)) shows that stress distributes uniformly at the center part of plate without severe stress concentration. In the figure, stress is also high at the loading area around the long slotted holes. For further loading, the stress exceeds the yield stress of 36ksi (235N/mm) only at the center of the SPEA.



i) at 3% story drift; w/t and w/o cover plate ii) at -3% story drift; w/t and w/o cover plate

Figure 3-2 Deformed shape and stress contour



i) yielding at 0.072rad (0.6% story drift)

ii) at end of positive loading 0.36rad

(a) Hysteresis behavior (b) Stress contour in SPEA

Figure 3-3 Finite element analysis results

4. Conclusion

An innovative rehabilitation method suitable for a discrete rehabilitation action has been developed. The proposed supplemental lateral-load-resisting system consists of eight tension-only elastic cables and one central energy dissipater (CED). The preliminary analysis results in OpenSees showed stable bi-linear hysteresis of the system if CED can deliver stable bi-linear curve. The optimal shape of CED was determined by a parametric analysis using the OpenSees analysis model. The prototype CED was designed using a general purpose finite element analysis program, ABAQUS and successfully achieved the target deformation capacity as well as target design strength with stable bi-linear hysteresis. The designed CED is compact and light enough to be carried by two construction workers with a small wheelbarrow or similar moving device and cab be assembled on-site. The poof-of-concept testing of the proposed system is scheduled at the Georgia Tech structural laboratory in Fall 2008.

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