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STRUCTURAL FUSE CONCEPT FOR BRIDGES

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ABSTRACT

The concept of designing sacrificial elements to dissipate seismic energy while preserving the integrity of the structure's other main components is known as the structural fuse concept. Few implementations of the structural fuse concept have been rigorous in emphasizing easy and complete replaceability of the sacrificial elements and absence of damage to the primary load-resisting structural system. Here, the concept is applied to an innovative multi-column accelerated bridge construction (ABC) pier concept. Different types of structural fuses are investigated to compare the effect of each on ABC bridge bents. A three span continuous bridge Prototype having two twin-column pier bents with fixed base spaced at 36m (120 ft) and 9m (30 ft) tall, was designed according to the AASHTO LRFD bridge design specifications (AASHTO 2008). Its piers were designed using double composite rectangular columns using Bi-Steel panels and structural fuses. Two corresponding 2/3 scale models were developed and were tested at the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University at Buffalo. The two specimens were designed for a maximum horizontal force of 1777 kN (400kips). Three quasi-static tests were performed. For the 1st specimen Steel Plate Shear Links (SPSLs) were installed between the columns as a series of structural fuses. Testing was performed up to a drift corresponding to the onset of column yielding to investigate the effectiveness of adding the fuses in dissipating the seismic energy, then testing continued till column failure. Then, the other specimen was installed and tested utilizing Buckling Restrained Braces (BRBs) as a series of structural fuses. The BRBs were then removed and bare frame cyclic test was performed until reaching failure of the columns.

INTRODUCTION

Earthquakes can cause significant damage to bridge substructures which may cause collapse and loss of life. The ability of a system to deform inelastically without significant loss of strength or stiffness can improve its seismic response avoiding catastrophic collapses. Providing reliable mechanisms for dissipation of the destructive earthquake energy is key for the safety of structures against intense earthquakes. The benefit of the inelastic deformation is that it can limit the forces in the members allowing reasonable design dimensions; also it provides hysteretic energy dissipation to the system. The concept of designing some sacrificial members dissipating the seismic energy while preserving the integrity of other main components is known as the structural fuse concept (Fellow et al. 1997; Huang et al. 1994; Vargas and Bruneau 2009a; Vargas and Bruneau 2009b). Here, a structural fuse concept is proposed in which structural steel elements are added to the bridge bent to increase

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its strength and stiffness, and also designed to sustain the seismic demand and dissipate all the seismic energy through hysteretic behavior of the fuses, while keeping the bridge piers elastic. Several types of structural fuses can be used and implemented in bridges; the focus in this paper will be on using two types of structural fuses.
First, an innovative Steel Plate Shear Link (SPSL) is introduced, The proposed SPSL shown in Fig.1 consists of a steel plate restrained from out of plane buckling using a concrete encasement and an unbonding material. The steel plate is designed to yield in shear, at a stress equal to $0.6F_y$ dissipating the seismic energy.

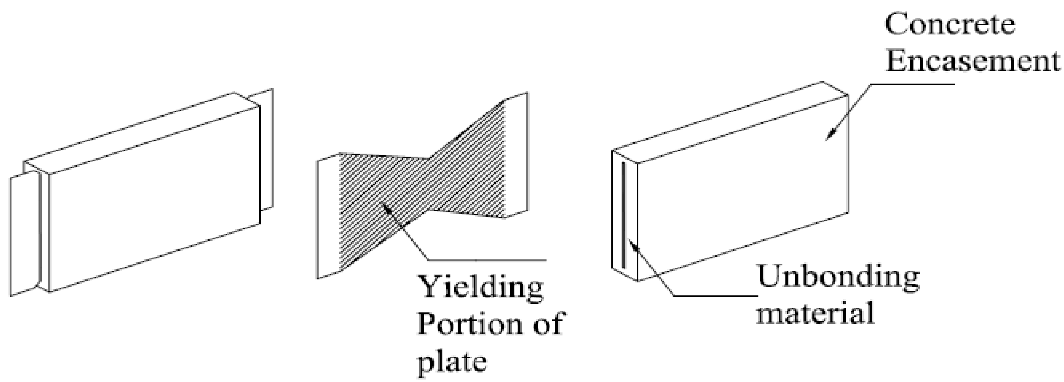


Figure 1. Proposed Link Sketch

Three types of plastic mechanisms can develop in laterally restrained links regardless of the shape of the cross section. The plastic mechanism that can develop depends mainly on the link length, and can be categorized as follows:

- Flexural links (pure flexural yielding) developing full plastic moment hinges, M_p, at the ends of the links and a corresponding shear force less than the full plastic shear force, V_p. These links dissipate energy by flexural plastic rotation.
- Shear links (pure shear yielding) developing full plastic shear force, V_p, over the entire length of the link, with corresponding moments at their ends less than the plastic moment reduced to account for the presence of shear, M_p^r. These links dissipate energy by shear plastic rotation.
- Intermediate links, which are links yielding in both flexure and shear where, one yielding mode develops after the other mode strain hardens.

Various experimental studies has been done on links by previous researchers and it was found out that shear links exhibits the most stable and ductile cyclic behavior. (Kasai and Popov 1986b) studied the behavior of shear links (short links) and concluded that the inelastic shear strains are fairly uniformly distributed over the entire length of the link which permits the development of large inelastic deformations without the presence of high local strains. It was found out that a well detailed link can sustain a plastic rotation of 0.1 radian without failure. (Engelhardt and Popov 1989) studied the behavior of flexural links (long links) and concluded that high bending strains at the ends develops to produce the inelastic deformation from which a flexural link was found to sustain a plastic rotation of 0.02 radian which is about 5 times less than a shear link. (Berman and Bruneau 2007) also studied the behavior or tubular links in eccentrically braced frames.

The ultimate failure mode for shear links is inelastic web shear buckling, delaying that failure mode was also studied by (Kasai and Popov 1986a) by adding vertical stiffeners, simple rules where developed to calculate the stiffeners spacing according to the maximum inelastic link rotation.

For the proposed link, the web shear buckling is overcome by wrapping the steel plate with unbonding material and surrounding it by a concrete encasement. An assumed stress distribution for a shear link is shown in Fig.2. In this approach, shear yielding is assumed to occur over a depth of y_o over the entire length of the link. Since the link is in double curvature, the wedge parts of the link should develop moments to be in equilibrium with the developed shear force. The slope, θ, of the link edges are designed so that the wedge parts yields simultaneously in flexure, and therefore must vary linearly (like the moment diagram) to provide this needed plastic moment strength. From that basis, the plastic shear and reduced plastic moment can be calculated as:

$$V_p = \frac{\sigma_y}{\sqrt{3}} t y_0 \tag{1}$$

$$M_{pr} = \sigma_y y_1 t (y_0 + y_1) \tag{2}$$

where V_p is the plastic shear strength at section A-A, M_{pr} is the reduced plastic moment in the presence of shear force for section B-B, and σ_y is the yield stress of the plate.

The balanced link length, e^* , from which the transition of behavior occurs from flexural to shear can be calculated as:

$$e^* \le \frac{1.6 y_o}{\sqrt{3}\tan^2\theta}\left(1-\sqrt{3}\tan\theta\right) \tag{3}$$

while the balanced link angle, θ^*, at which shear yielding of the web and flexural yielding of the wedge parts occur simultaneously can be calculated as:

$$\tan^2\theta^* + \frac{2y_0}{e}\tan\theta^* - \frac{2y_0}{e\sqrt{3}} = 0 \tag{4}$$

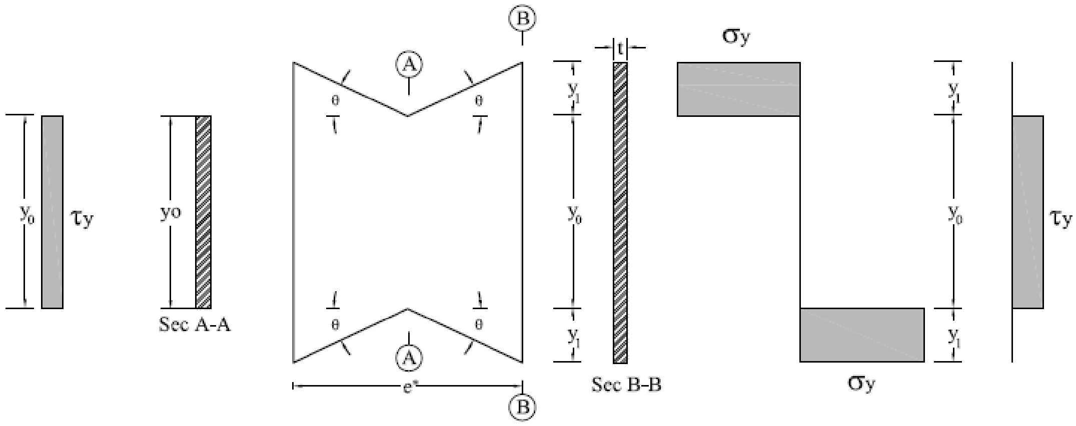


Figure 2. Assumed Stress Distribution in Mid and End plate at Balanced Link Angle

Second, BRBs are utilized as structural fuses. The BRB consists of a steel core encased in a steel tube filled with concrete. The steel core carries the axial load while the outer tube, via the concrete provides lateral support to the core and prevents global buckling. Typically a thin layer of material along the steel core/concrete interface eliminates shear transfer during the elongation and contraction of the steel core and also accommodates its lateral expansion when in compression (other strategies also exist to achieve the same effect). This gives the steel core the ability to contract and elongate freely within the confining steel/concrete-tube assembly. A variety of these braces having various materials and geometries have been proposed and studied extensively over the last 10-15 years (Black et al. 2002; Hasegawa et al. 1999; Iwata et al. 2000; Lopez et al. 2002; López and Sabelli 2004; Mamoru Iwata 2006; Sabelli et al. 2003; Saeki et al. 1995). A summary of much of the early development of BRBs which use a steel core inside a concrete filled steel tube is provided in (Fujimoto et al. 1988), and since the 1995 Kobe Earthquake, these elements have been used in numerous major structures in Japan (Reina and Normile 1997). The first tests in the United States were conducted in 1999 (Aiken et al. 2002). Fig.3 shows a schematic mechanism of the BRB.

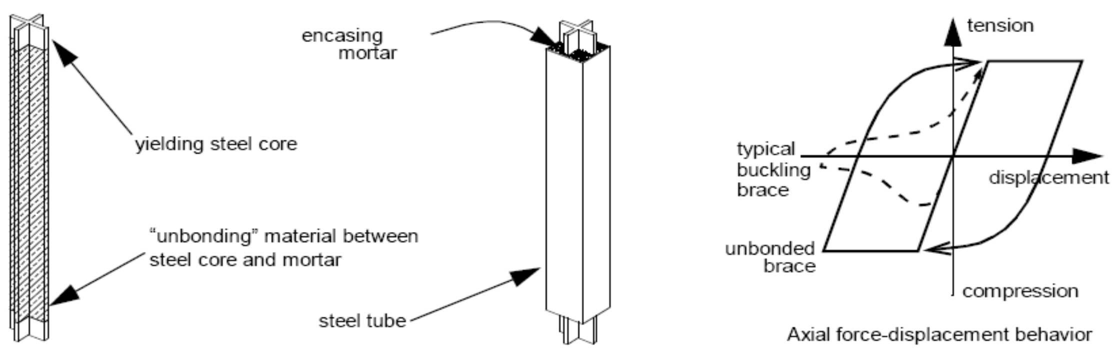
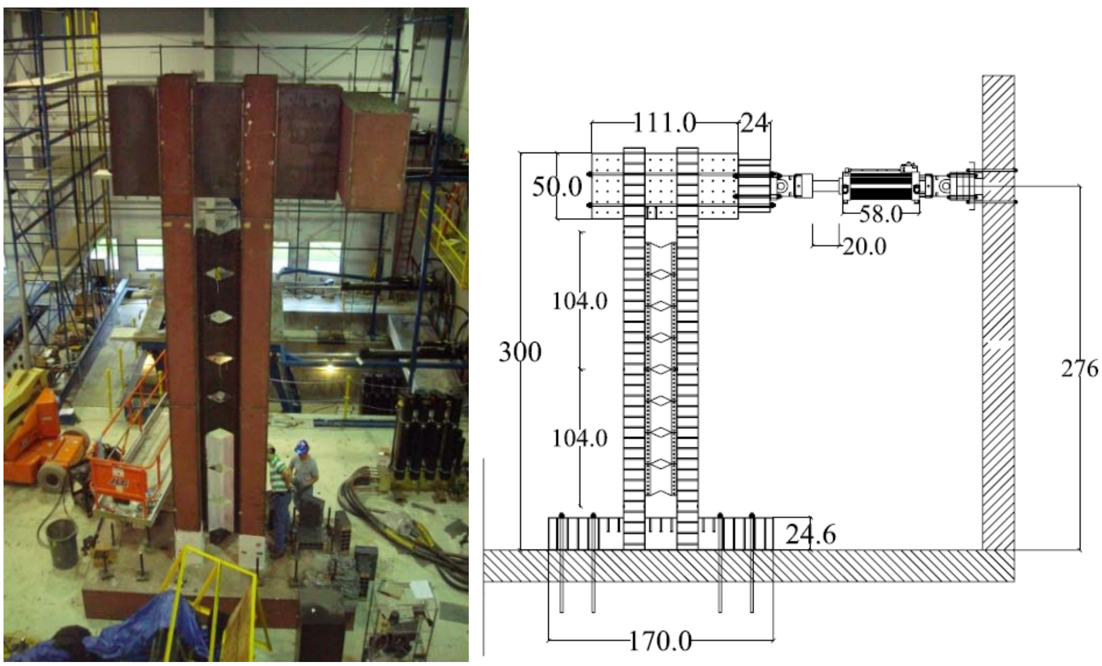


Figure 3. Schematic Mechanism of the BRB (Clark et al. 2000)

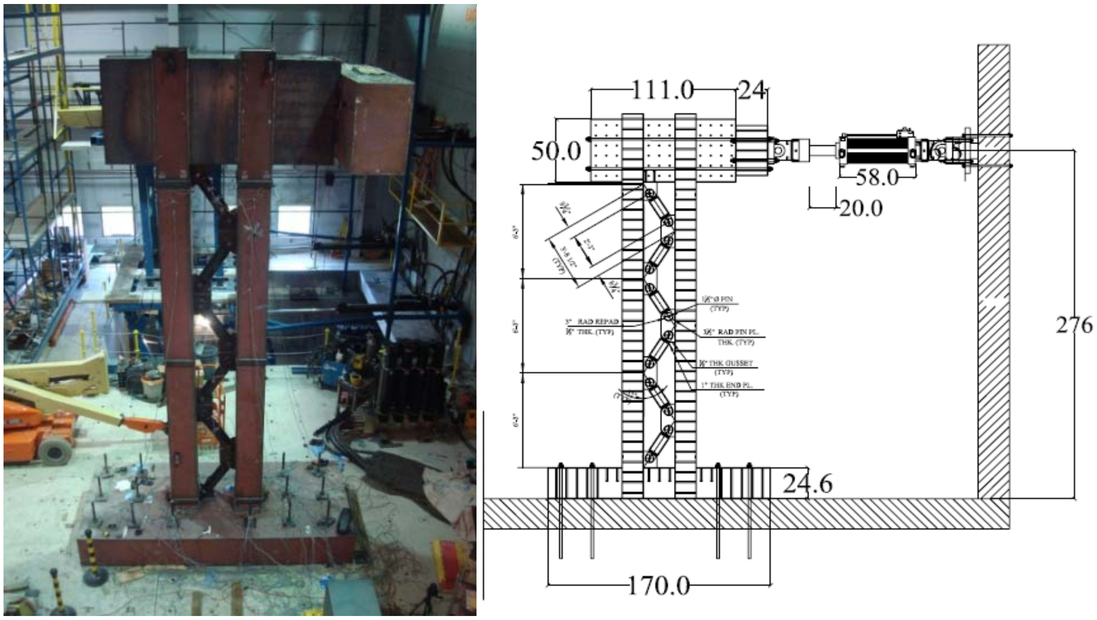
Experimental Setup, Instrumentations, and Loading Protocol

A series of quasi-static cyclic tests has been performed using the recommended Applied Technology Council (ATC) loading protocol of ATC 24 (ATC, 1992) on a proposed twin column segmental bridge bent, utilizing the SPSLs and BRBs as a series of structural fuses between the columns. The columns used for the experiment consisted of segments of Bi-Steel sections (Bowerman et al. 1999) which is a system of double skin steel–concrete–steel high performance rapid erect panels. These panels are composed of steel plates connected by an array of transverse friction welded shear connectors and filled with concrete. This system could be beneficial when strength or speed of construction is of vital importance. Column sections were stacked over each other and connected by welding. A 2/3 scale for the geometric properties of the specimen was chosen based on the limitations of the SEESL at the University at Buffalo and other considerations regarding the availability of the Bi-steel sections in particular, the maximum height of the SEESL strong wall is 30ft, so the maximum height of the specimen was set to be 25ft. Two static actuators available at SEESL each with a capacity of 400kips were used applying the horizontal force to a transfer beam from which the load is then transferred to the specimen. Figs. 4, 5, and 6 show general views of the tests utilizing SPSLs, BRBs and the bare frame respectively.



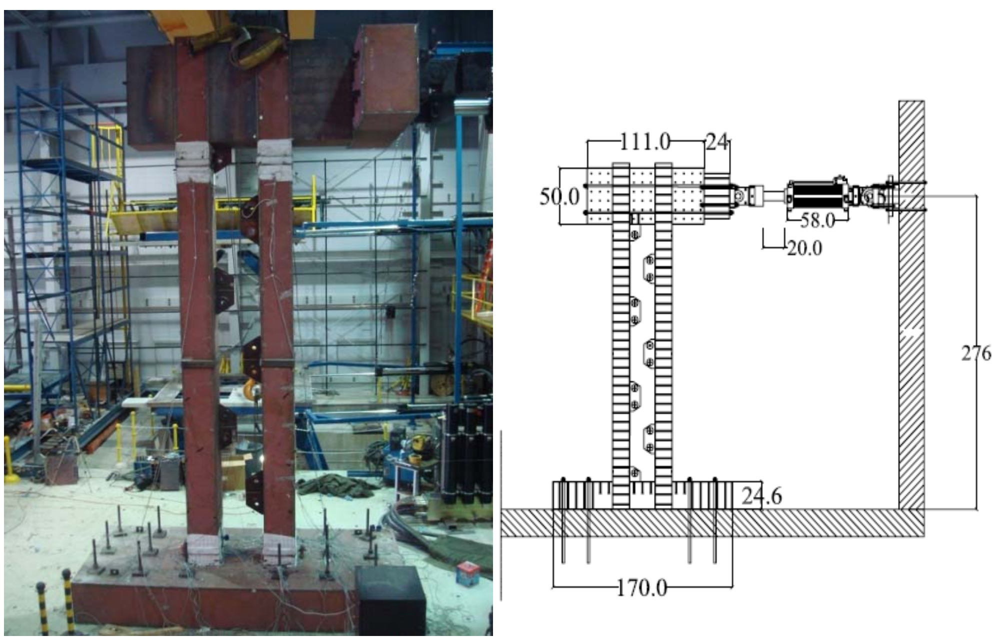
(a) (b)

Figure 4. Experiment Setup (a) General View of the Experiment, (b) Bridge Pier with SPSLs



(a) (b)

Figure 5. Experiment Setup (a) General View of the Experiment, (b) Bridge Pier with BRBs



(a) (b)

Figure 6. Experiment Setup (a) General View of the Experiment, (b) Bare Bridge Pier

Instrumentation for this experimental project has been designed to measure global response of the frame, and local performance of the links and braces. Global response of the structure in terms of displacements was obtained from string-pots installed at different levels from the base to the top of the frame. Optical coordinate tracking probes (Krypton sensors) were also distributed on the columns up to their mid heights (due to camera range constrains) to measure displacement response at specific points. Seismic response of the columns was obtained from strain gages installed at critical points (top and bottom of each column), to determine whether these columns remain elastic during the test, recalling that one of the objectives of this experiment is to assess the effectiveness of the structural fuse concept to prevent damage in columns. Axial deformations of the BRBs were measured with String-Pots installed in parallel with the braces and connected to the gusset-plates. To measure strains in the SPSLs, 30-60 degree rosettes were installed at the midpoint of a few critical links. To ensure that no slippage or uplift occurs in the base, horizontal and vertical transducers were installed at its four corners.

Experimental Results

For the first specimen with the SPSLs, loading was performed up to a drift level corresponding to the onset of column yielding to ensure that energy dissipation was through the SPSLs, then testing continued until fracture occurred at the base of both columns. This specimen reached a ductility ratio of 4 and drift of 1.5% without any sign of plastic deformation in the columns, Fig.7 shows the hysteretic behavior at that level of drift. Signs of local buckling started to occur at the west column at a drift level of 2.2% as shown in Fig.8, and the same column fractured at a drift level of 2.7% and the load dropped almost 33% as shown in Fig.9.

For the second specimen with BRBs, loading was performed up to a drift level corresponding to the onset of column yielding (1.5%); also a ductility of 4 was reached, and no signs of plastic deformation were observed for both columns. The BRBs exhibited stable hysteretic behavior. Fig.10 shows the hysteretic behavior for one of the BRBs installed (3^{rd} from top) plotted against the total system force. A small amount of slippage occurred due to the pin connection of the BRBs. Hysteretic behavior for the specimen with BRBs is shown in Fig.11.

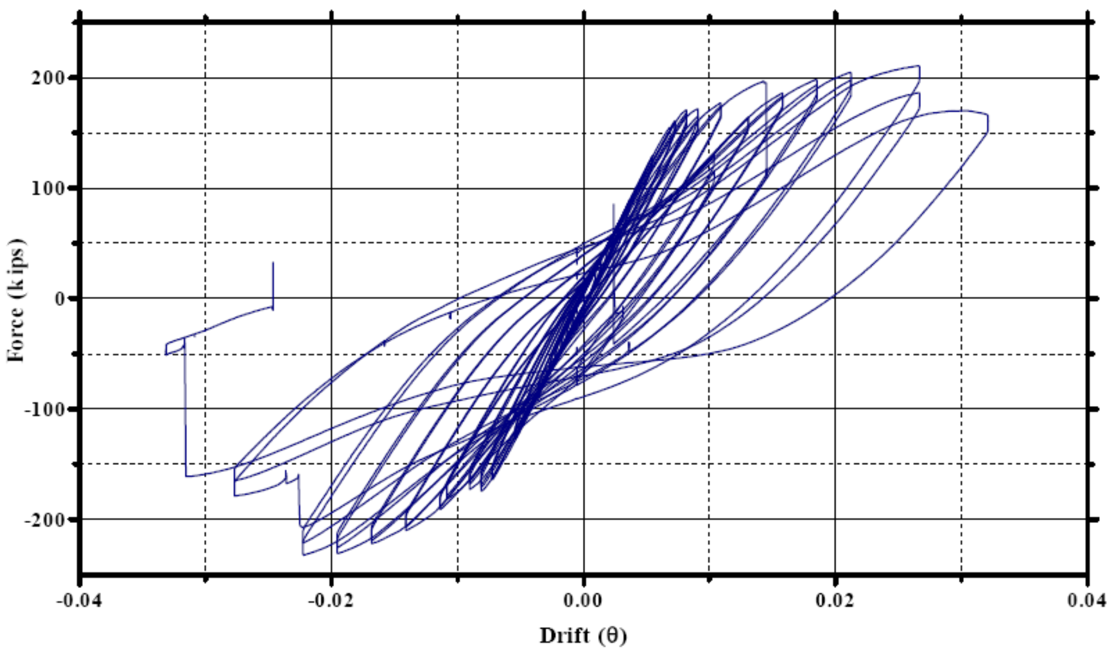


Figure 7. Hysteretic Behavior for Column utilizing SPSLs at the Onset of Column Yielding

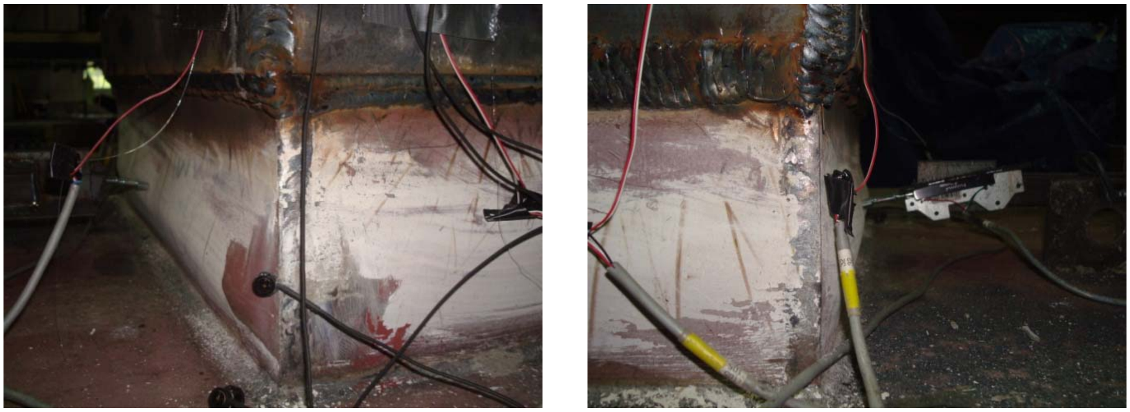


Figure 8. Local Buckling of West Column (West Side) at 2.2% Drift

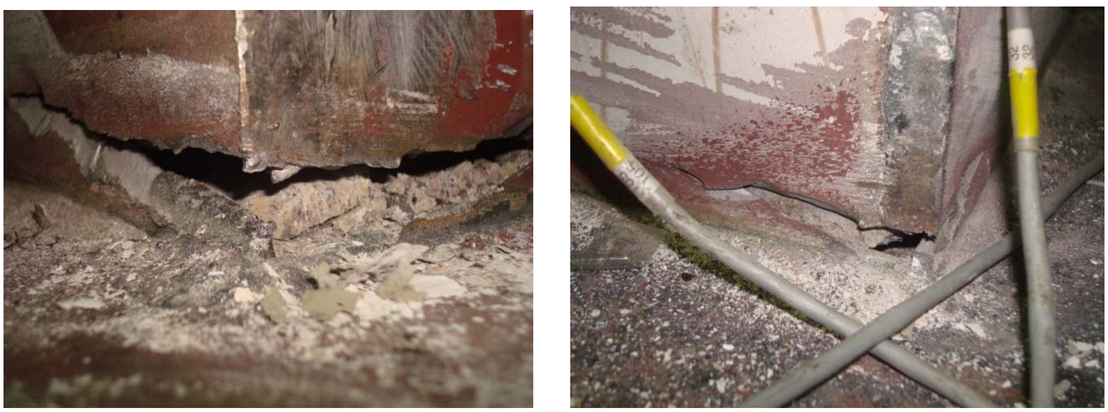


Figure 9. Fracture of West Column (North West Corner) at 2.7% Drift

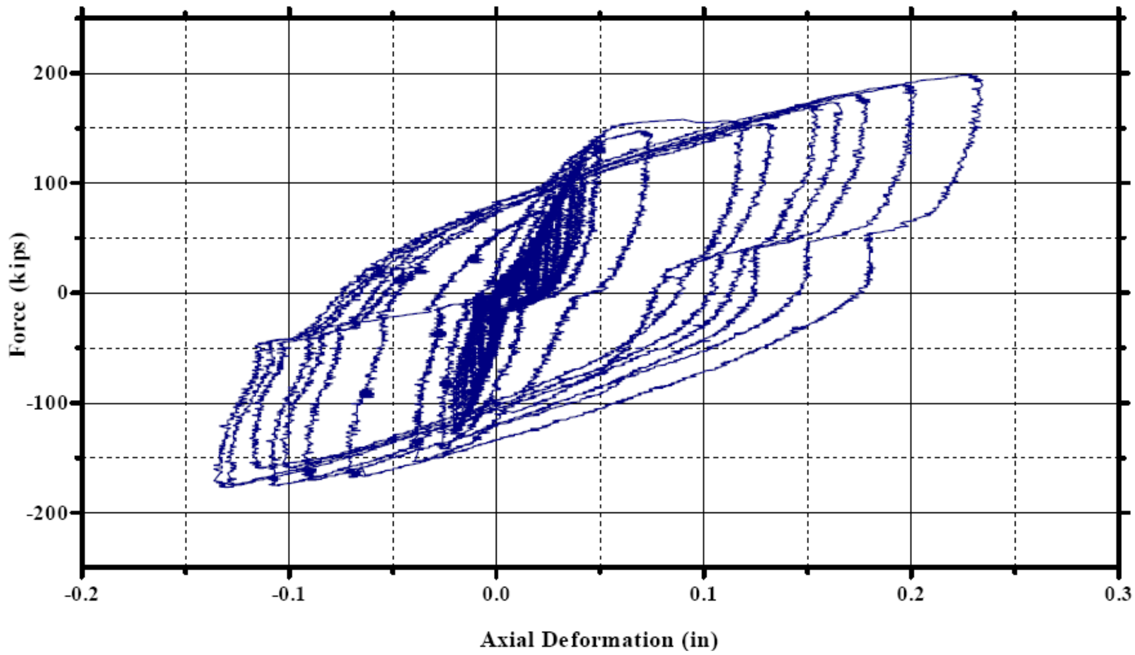


Figure 10. Hysteretic Behavior for BRB (3rd from top)

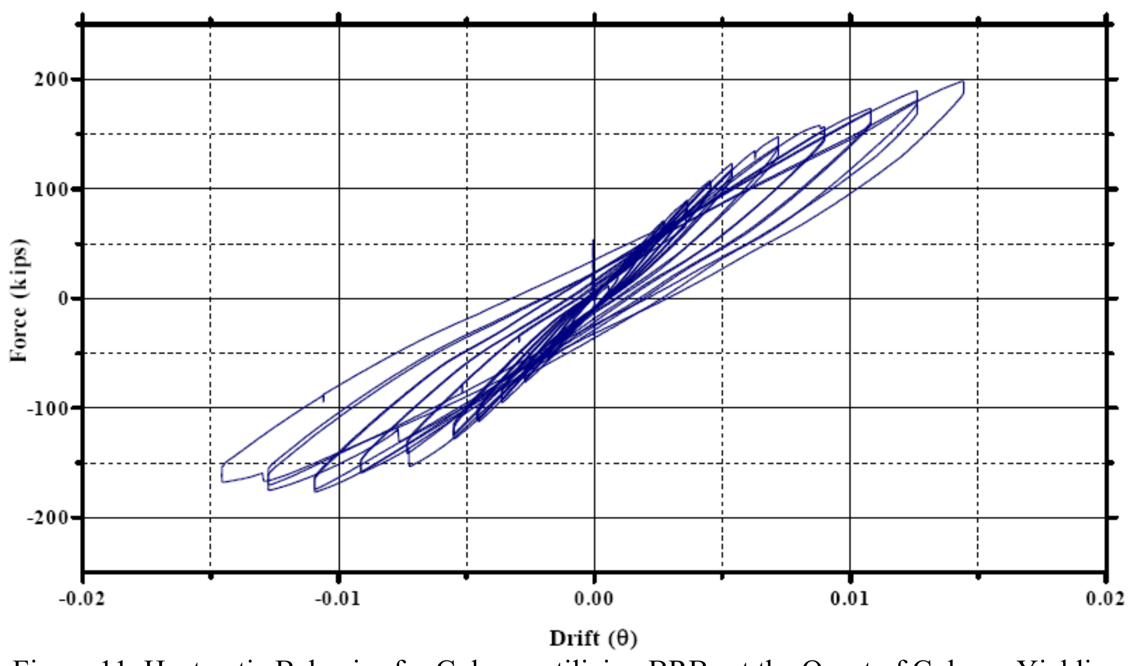


Figure 11. Hysteretic Behavior for Column utilizing BRBs at the Onset of Column Yielding

Observations

All specimens tested in this experimental program exhibited stable force-displacement behavior, with little pinching of hysteresis loops until the significant accumulation of damage at large drifts. All specimens performed well, behaving elastically at small displacements and exhibiting stable hysteretic behavior as the seismic energy was dissipated through the structural fuses. Adding the fuses increased both the stiffness and strength of the bare frame about 40% and increased the amount of energy dissipated by the frame. Further analysis is underway to investigate the results of this experimental program.

Conclusion

The structural fuse concept for bridges has been investigated and validated through an experimental project for a 2/3 scale proposed twin column bridge pier bent concept using SPSLs and BRBs as a series of structural fuses. Quasi-static tests were performed to investigate the effectiveness of adding the structural fuses on the overall performance of the bent by increasing its strength and stiffness, also dissipating the seismic energy through them while the bridge pier remain elastic. Results obtained demonstrated the effectiveness of the proposed concept as an implementation of structural fuses in a bridge application.

Acknowledgments

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