Structural Fuse Concept for Bridges

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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 this concept have been rigorous in emphasizing replaceability of the sacrificial elements and absence of damage to the primary load-resisting structural system. Here the concept is applied to an innovative multicolumn 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 36 m (120 ft) and 9 m (30 ft) tall was designed according to AASHTO load and resistance factor design specifications. Its piers were designed with double-composite rectangular columns using Bi-Steel panels and structural fuses. Two corresponding ⅔-scale models were developed and tested. The two specimens were designed for a maximum horizontal force of 1,777 kN (400 kips). Three quasi-static tests were performed. For the first specimen, steel plate shear links 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 until 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 a bare frame cyclic test was performed until column failure.

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 in 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; it also provides hysteretic energy dissipation to the system. The idea of designing some sacrificial members, dissipating the seismic energy while preserving the integrity of other main components, is known as the structural fuse concept (*1–4*). Here, a structural fuse concept is proposed in which structural steel elements are added to the bridge bent to increase 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 Figure 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.

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 have been done on links by previous researchers, and it was found that shear links exhibit the most stable and ductile cyclic behavior. Kasai and Popov 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 (*5*). It was found that a well-detailed link can sustain a plastic rotation of 0.1 radian without failure. Engelhardt and Popov studied the behavior of flexural links (long links) and concluded that high bending strains at the ends develop to produce the inelastic deformation from which a flexural link was found to sustain a plastic rotation of 0.02 radian, which is about five times less than a shear link (*6*). Berman and Bruneau also studied the behavior of tubular links in eccentrically braced frames (*7–8*). Delaying the inelastic web shear buckling was also studied by Kasai and Popov by adding vertical stiffeners (*9*). Rules were 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 surrounded by a concrete encasement. An assumed stress distribution for a shear link is shown in Figure 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 is designed so that the wedge parts yield simultaneously in flexure, and therefore must vary linearly

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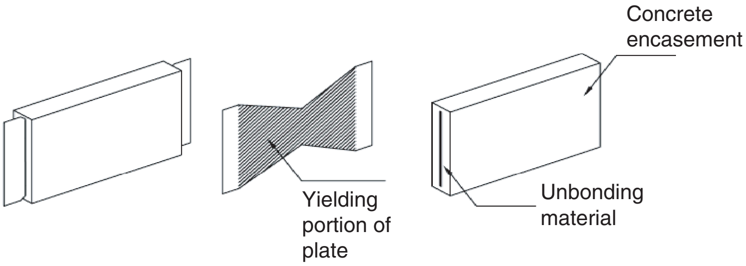

FIGURE 1 Proposed link sketch.

(like the moment diagram) to provide this plastic moment strength. From that basis, the plastic shear and reduced plastic moment can be calculated as

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

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

where

V_p = plastic shear strength at section A–A,
M_{pr} = reduced plastic moment in the presence of shear force for section B–B,
t = plate thickness, and
σ_y = 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

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

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

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

Second, buckling restrained braces (BRBs) are used 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, through 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 geometric properties have been proposed and studied extensively over the past 10 to 15 years (*10–17*). A summary of much of the early development of BRBs that use a steel core inside a concrete-filled steel tube is provided by Fujimoto et al. (*18*), and since the 1995 Kobe earthquake, these elements have been used in numerous major structures in Japan (*19*). The first tests in the United States were conducted in 1999 (*20*). Figure 3 shows a schematic mechanism of the BRB (*21*).

EXPERIMENTAL SETUP, INSTRUMENTATIONS, AND LOADING PROTOCOL

A three-span continuous bridge prototype having two twin-column pier bents with fixed base spaced at 36 m (120 ft) and 9 m (30 ft) tall, shown in Figure 4, was designed according to the AASHTO load and resistance factor design specifications (*22*). Two corresponding ⅔-scale models were developed and a series of quasi-static-cyclic

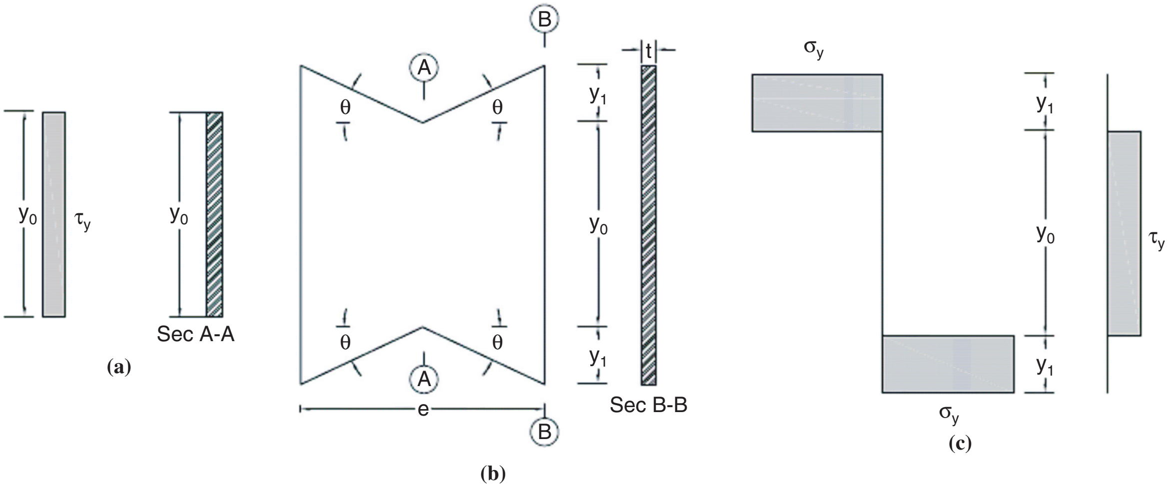

FIGURE 2 Assumed stress distribution in mid- and end plates at balanced link angle.

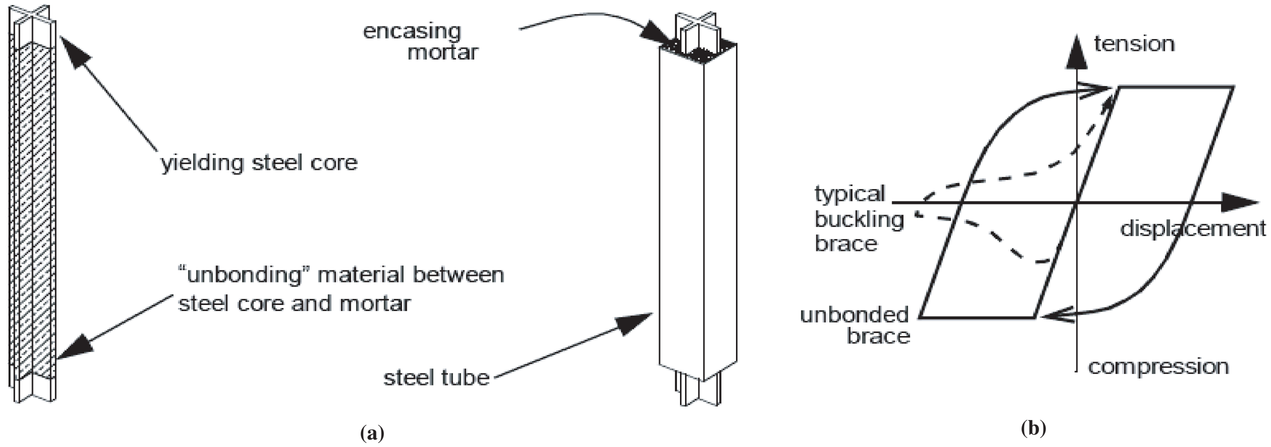

FIGURE 3 BRB: (*a*) schematic mechanism and (*b*) axial force–displacement behavior (*21*).

tests have been performed using the recommended Applied Technology Council (ATC) loading protocol of ATC 24 on a proposed twin column segmental bridge bent, using the balanced link angle type 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, which are double-skin steel-concrete high-performance rapid erect panels (*23*). These panels are composed of steel plates connected by an array of transverse friction–welded shear connectors and filled with concrete. The presence of these connectors was beneficial in reducing any local buckling effects that could occur along the columns as a result of adding the fuses. This system was also used because it could be beneficial when strength or speed of construction is vital. Note that the concept could be used for various types of columns including conventional cast-in-place columns and prefabricated concrete segmental columns taking into account the difference in the types of connections between the columns and the fuses.

The ⅔-scale for the geometric properties of the specimen was chosen based on the limitations of the Structural Engineering and Earthquake Simulation Laboratory (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 30 ft, so the maximum height of the specimen was set to be 25 ft. Two static actuators available at SEESL, each with a capacity of 400 kips, were used applying the horizontal force to a transfer beam from which the load is then transferred to the specimen. Figure 5 shows general views of the tests utilizing SPSLs, BRBs, and the bare frame, respectively.

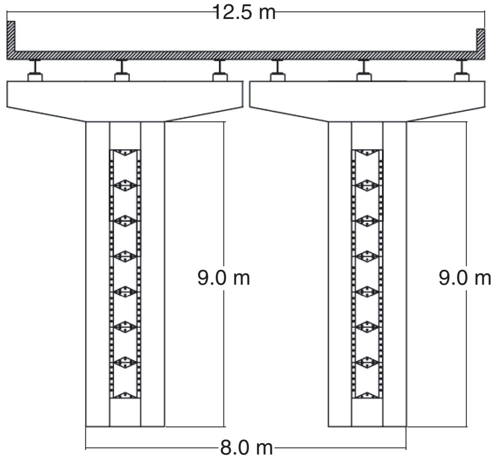

FIGURE 4 Prototype bridge.

Instrumentation for this experiment was 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 midheights (because of camera range limitations) to measure displacement response at specific points. Seismic response of the columns was obtained from strain gauges installed at critical points (top and bottom of each column) to determine whether these columns would 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- to 60-degree rosettes were installed at the midpoint of a few critical links. To ensure that no slippage or uplift occurred 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. Signs of local buckling started to occur at the west column at a drift level of 2.2%, and the same column fractured at a drift level of 2.7%, and the load dropped almost 33%. Figure 6 shows the hysteretic behavior of the specimen.

For the second specimen with the 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 there were no signs of plastic deformation for either column. The BRBs exhibited

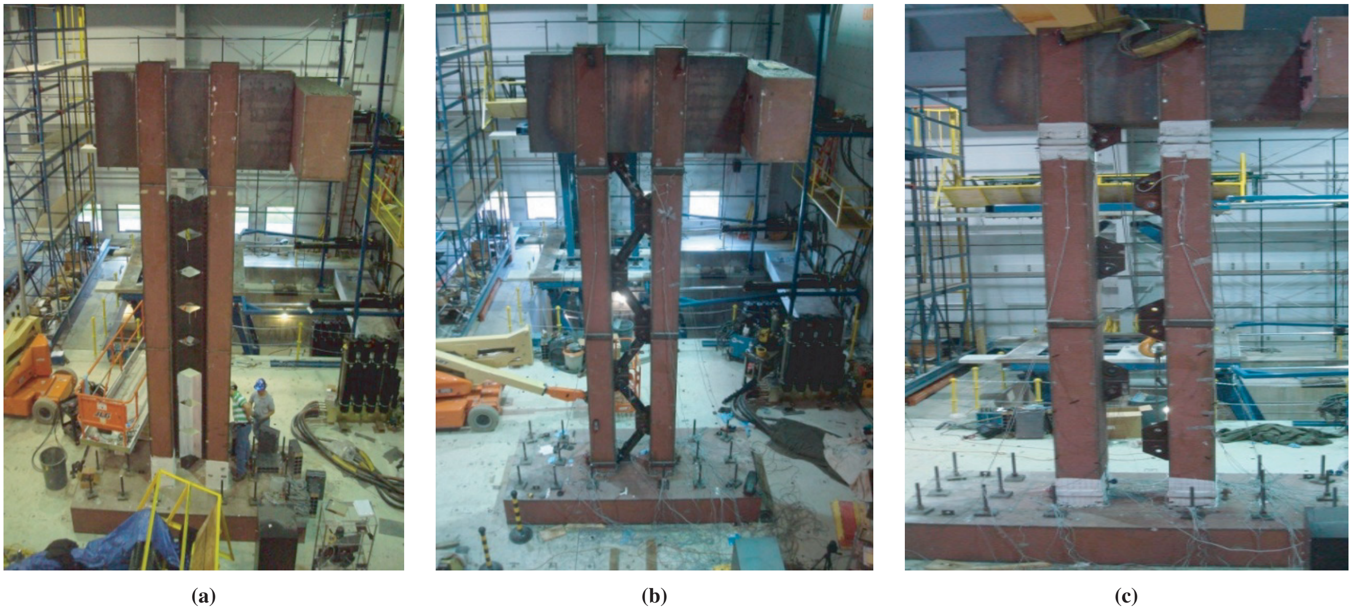
(a) (b) (c)

FIGURE 5 Experiment setup: (*a*) bridge pier with SPSLs, (*b*) bridge pier with BRBs, and (*c*) bare bridge pier.

stable hysteretic behavior. Figure 7 shows the hysteretic behavior of one of the BRBs (third from top) plotted against the total system force. A small amount of slippage occurred because of the pin connection of the BRBs. Hysteretic behavior for the specimen with BRBs is shown in Figure 8.

For the third test utilizing the bare frame, signs of local buckling were observed at 1.45% drift. Testing continued to 2.5% drift, where the lateral load resisted by the specimen dropped 44% due to a crack that started to develop at one of the bottom sides of the east column. At 4.35% drift, the west column had reached an extensive state of damage with 600-mm-long cracking along its base, and extensive local buckling, and concrete rubble started escaping from the cracks. Testing was then terminated. Figure 9 shows the hysteretic behavior of the bare frame.

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

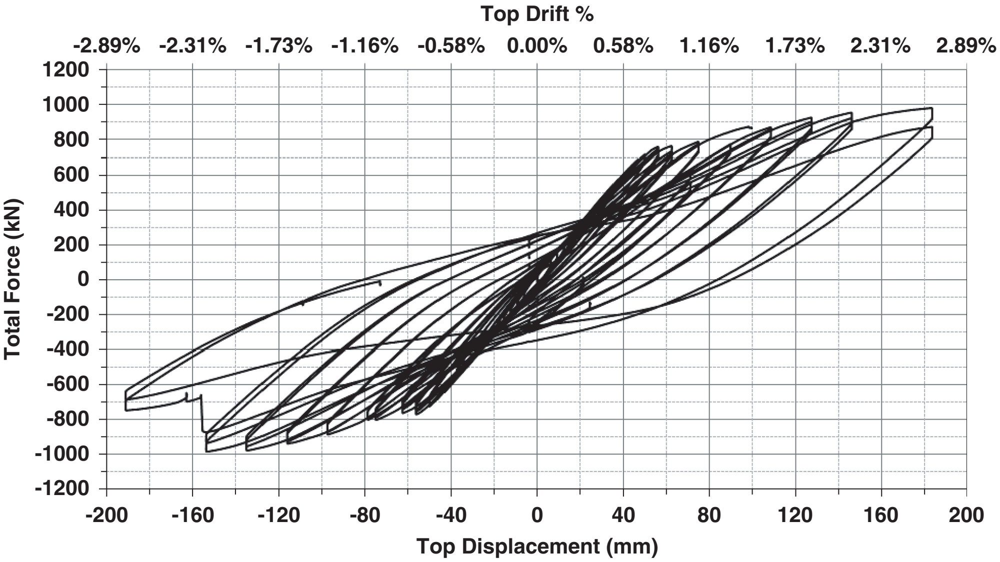

FIGURE 6 Hysteretic behavior for column using SPSLs.

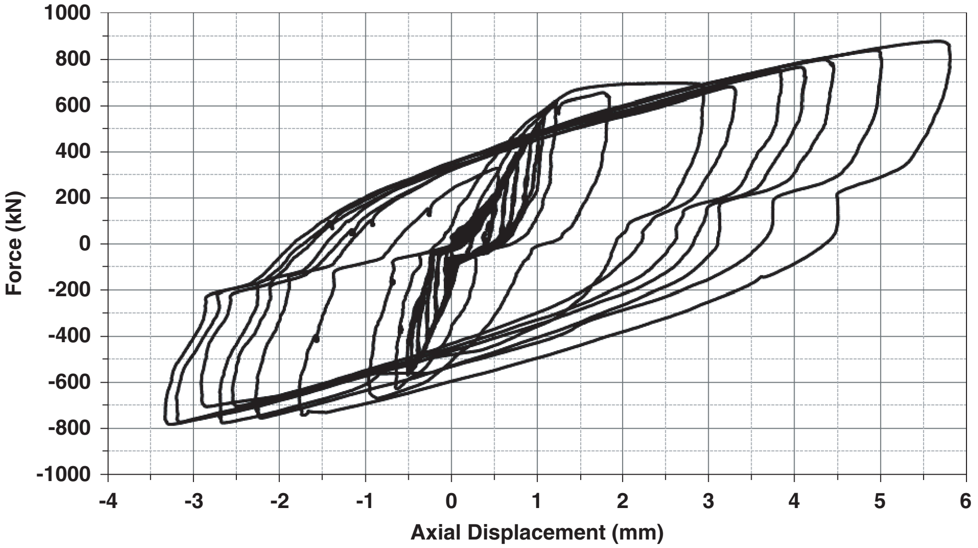

FIGURE 7 Hysteretic behavior for BRB.

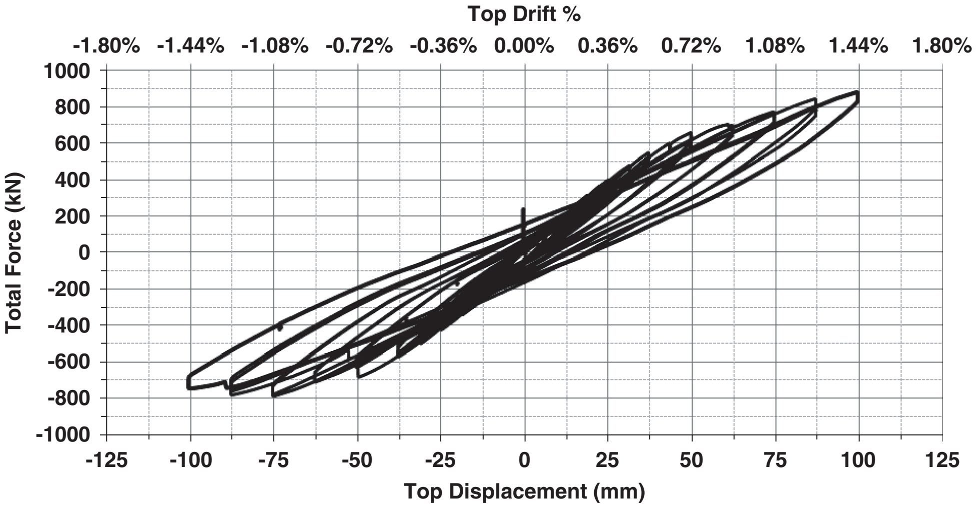

FIGURE 8 Hysteretic behavior for column utilizing BRBs at onset of column yielding.

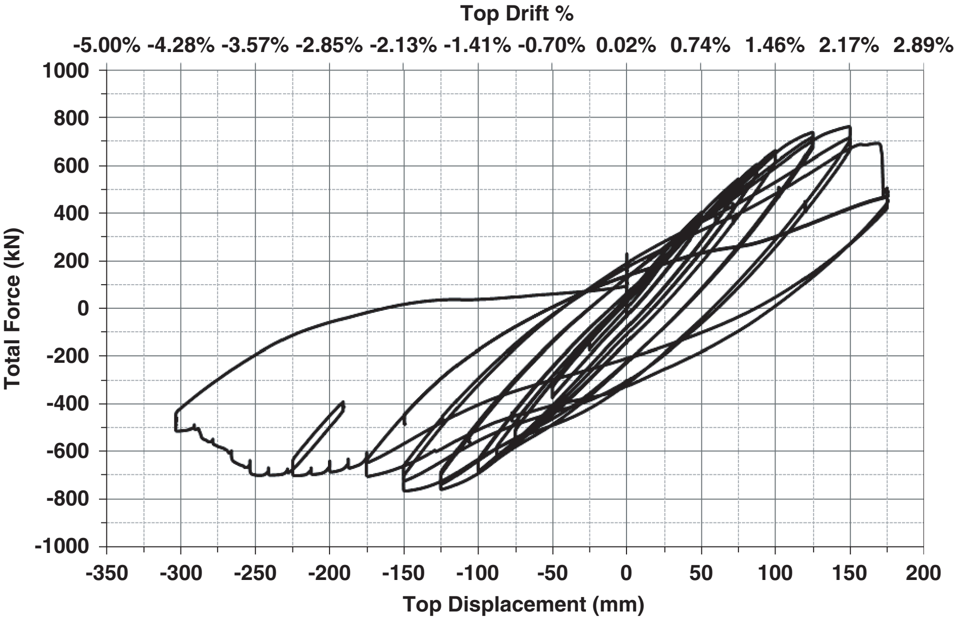

FIGURE 9 Hysteretic behavior of bare frame.

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 under way to investigate the results of this program.

CONCLUSION

The structural fuse concept for bridges has been investigated and validated through an experimental project for a ⅔-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 remains elastic. Results demonstrated the effectiveness of the proposed concept as an implementation of structural fuses in a bridge application.

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