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EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF BRIDGE PIERS HAVING STRUCTURAL FUSES AND BI-STEEL COLUMNS

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ABSTRACT

Bridges are built in a variety of locations, many of which are susceptible to earthquakes. These bridges must be built to achieve the objectives of both accelerated bridge construction (ABC) and rapid return to service following a disaster. 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. The structural fuse concept considered here for seismic resistance was developed and experimentally validated for implementation in a composite multi-column pier using double composite rectangular columns of Bi-Steel panels. 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. 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 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.

1. INTRODUCTION

The emergence of new design objectives in bridge engineering always provides new opportunities to re-examine past design practices and explore the potential benefits of various alternative design solutions. The need for Accelerated Bridge Construction (ABC) solutions intended to minimize construction time and thus the inconvenience to the users of the road network, given that traffic congestion (due to construction delays or other sources) have been conclusively demonstrated to translate into major losses to modern economies. This paper presents recent research on structural fuses developed for the purpose of meeting the above performance requirements for bridges. The structural fuse concept considered here for seismic resistance was developed and experimentally validated for implementation in a composite multi-column pier using double composite rectangular columns of Bi-Steel panels.

2. STRUCTURAL FUSE FOR SATISFACTORY SEISMIC PERFORMANCE

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 2006a; Vargas and Bruneau 2006b). However, for a true structural fuse analogy (e.g Vargas and Bruneau 2006a, 2006b), the sacrificial elements should be easily replaceable, allowing the rest of the structure (that remained

elastic) to return to its plumb condition after the fuses are removed. Here, in that perspective, 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 an encasement and an unbonding material, the steel plate is designed to yield in shear reaching (0.6Fy) dissipating the seismic energy.

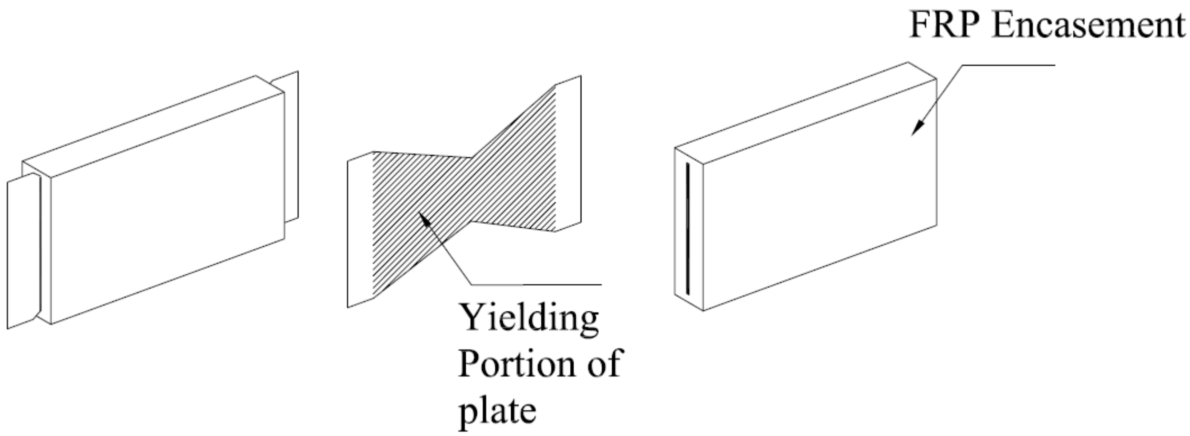


Figure 1. Proposed link sketch

Three types of plastic mechanisms can develop in links regardless of the shape of the cross section. The type of the plastic mechanism developed depends mainly on the link length in which links can be categorized into:

- Flexural links (pure flexural yielding) developing full plastic moment hinges M_p at the ends of the links and shear force less than the full plastic shear force V_p and dissipating 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 moments at the ends less that the plastic moment reduced to account for the presence of shear M_p^r and dissipating energy by shear plastic distortion.
- Intermediate links which are links yielding in both flexure and shear using the Von Mises yield criteria assuming that 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 (Berman and Bruneau 2007; Engelhardt and Popov 1989; Kasai and Popov 1986). The ultimate failure mode for shear links is inelastic web shear buckling, which can be delayed by adding vertical stiffeners (Kasai and Popov 1986). For the proposed link, the web shear buckling is overcome by wrapping the steel plate with unbonding material and surrounding it by an encasement.
An assumed stress distribution for a shear link is shown in Figure 2 from which the plastic shear and plastic moment can be calculated as:

[1] $V_p = \tau t y_0$

[2] $M_p^V = \sigma_y y_1 t(y_0 + y_1) + \sigma_y \frac{t y_0^2}{4}$

where V_p is the plastic shear force in presence of moment for section A-A, M_p^v is the plastic moment in presence of shear force for section B-B, and σ_y is the yield stress of the plate.

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

$$[3]\quad e^* \le \frac{\sqrt{3}y_0}{2\left(1-\frac{\sqrt{3}}{2}\tan\theta\right)}$$

while the balanced link angle, θ^*, can be calculated as:

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

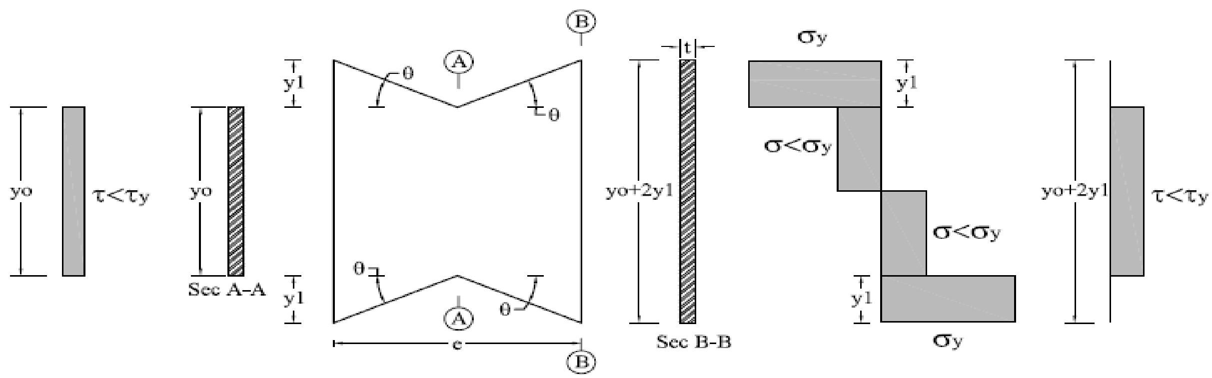


Figure 2. Assumed stress distribution in mid and end plate

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. (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). Figure 3 shows a schematic mechanism of the BRB.

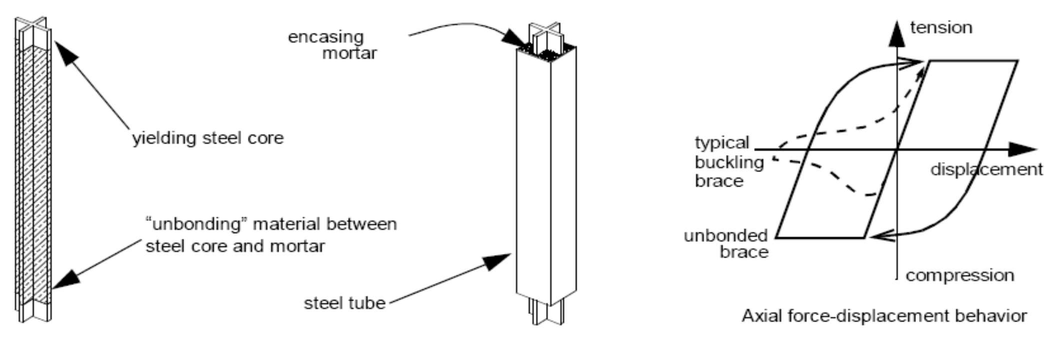
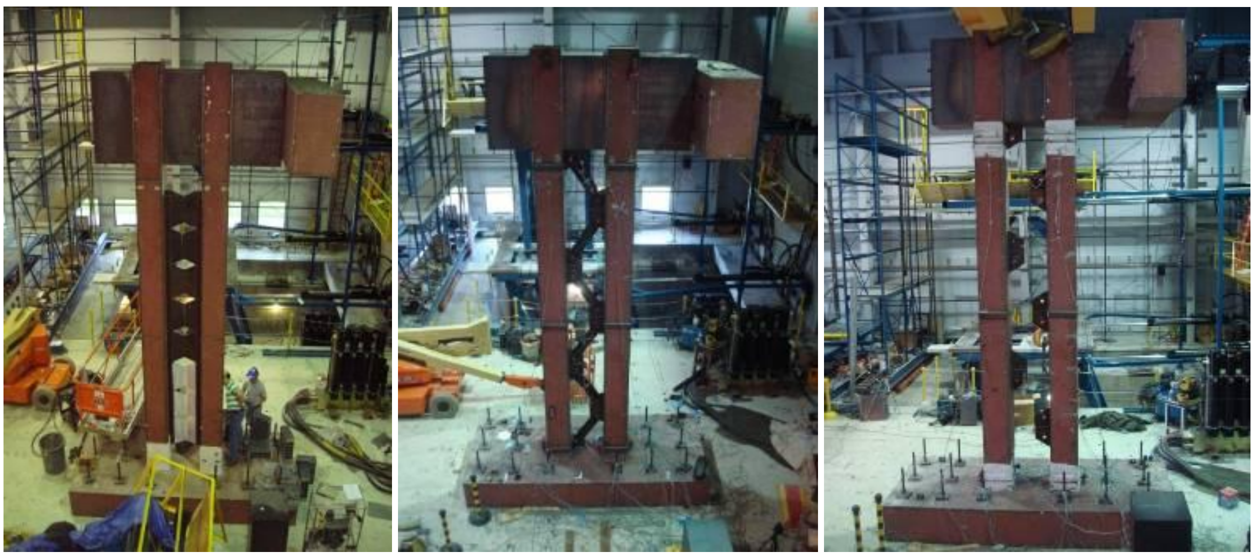


Figure 3. Schematic mechanism of the BRB (Clark et al. 2000)

3. 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 1.5 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. Figure 4 shows a general view of the tests utilizing SPSLs, BRBs and the bare frame respectively.



(a) SPSLs (b) BRBs (c) Bare bridge pier

Figure 4. General view of the experimental setup for the 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.

4. 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 100mm top displacement (1.5% drift) without any sign of plastic deformation in the columns, Figure 5 shows a comparison between the experimental and analytical hysteretic and pushover results obtained from the ABAQUS model at that level of drift. Signs of local buckling started to occur at the west column at 125mm top displacement (1.8% drift), and the same column fractured at 160mm top displacement (2.3% drift) as shown in Figure 6, and the load dropped almost 33%.

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. Figure 7 shows the hysteretic behavior for one of the BRBs installed (3rd from top) plotted against the total system force. A small amount of slippage occurred due to the pin connection of the BRBs. A comparison between the experimental and analytical hysteretic behavior and pushover is shown in Figure 8.

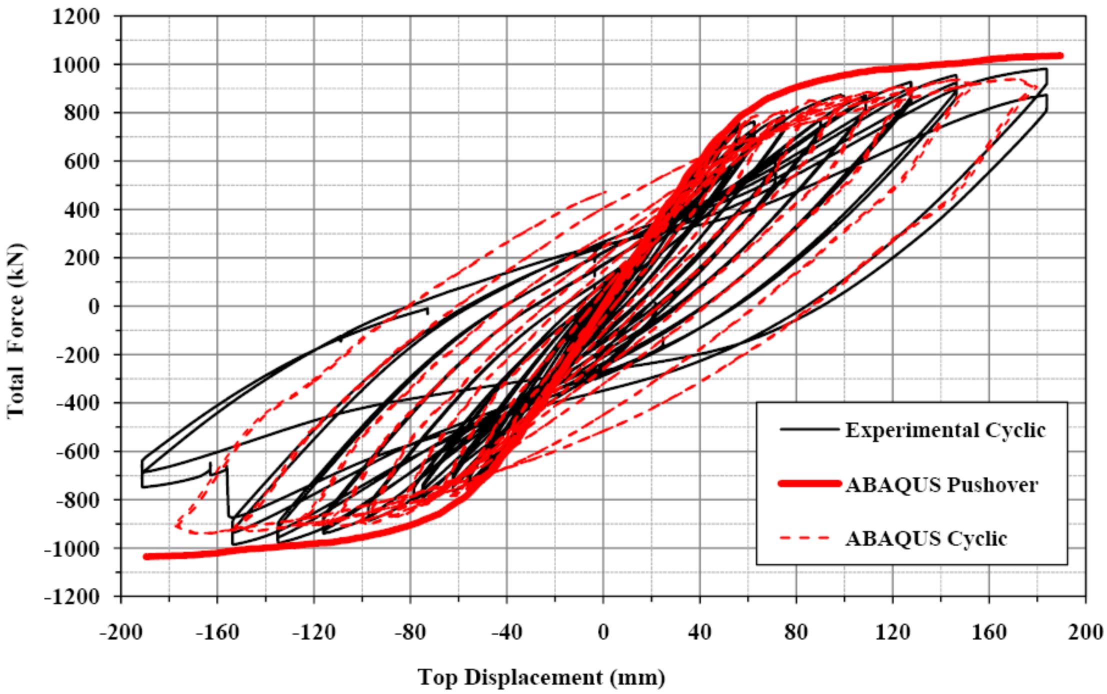


Figure 5. Comparison between experimental and analytical results for the bridge pier with SPSLs

(a) 1.8% drift (b) 2.3% drift

Figure 6. West column damage

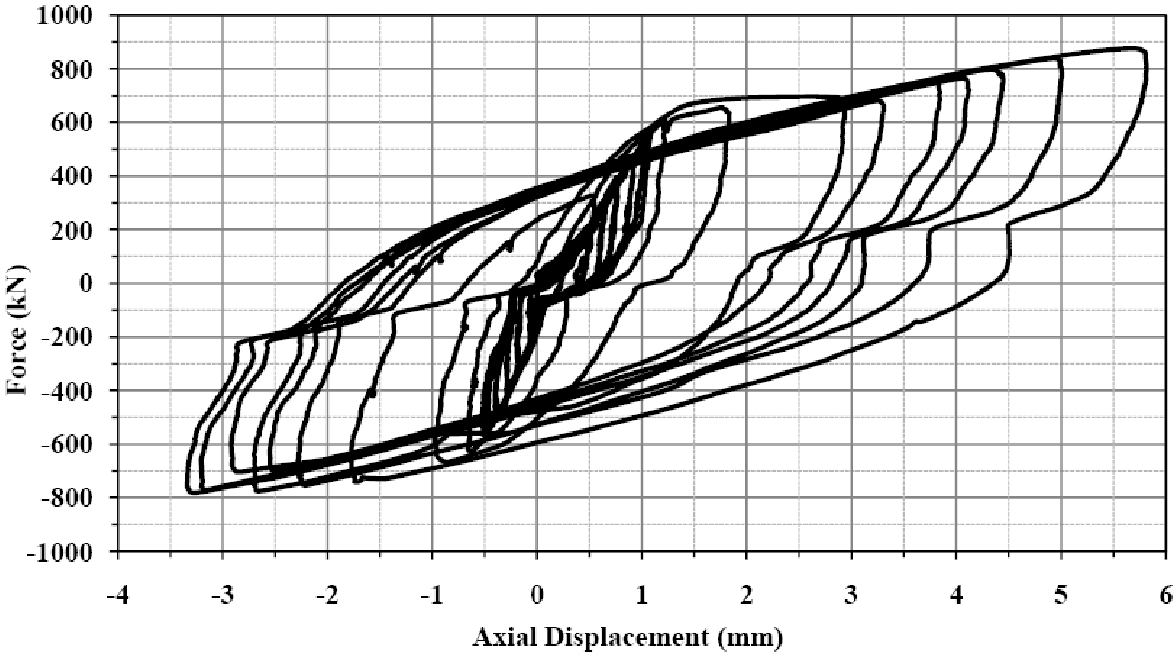


Figure 7. Total lateral force vs. axial BRB displacement hysteretic curve for BRB3 (3rd from top)

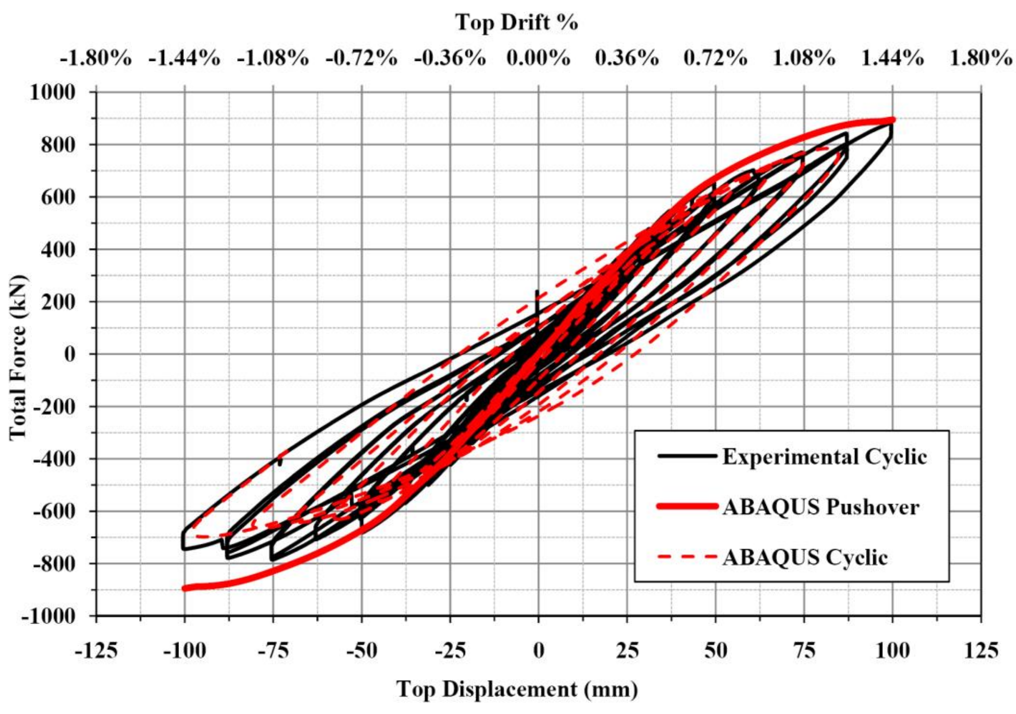


Figure 8. Comparison between experimental and analytical results for the bridge pier with BRBs

5. 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. Figure 9 shows the pushover results comparison for all specimens. A stiffness increase of 80% with a 30% increase in strength is observed between the bare frame and the frame with the SPSLs in between the columns. While a 20% increase in strength is observed between the bare frame and the frame with BRBs in between the columns. Using the BRB structural fuse system could be more beneficial in the case where the distance between the columns is large (as would be the case for conventional multi-column bridge bents) as the length of the BRB could be increased, while using the SPSL fuse system, whose performance depends on the aspect ratio of the SPSL, would be likely limited to special columns having close spacings of the type considered here.

6. 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. Although an increase in seismic demand is imposed on the system due to the addition of the fuses as they increase the strength and stiffness of the system, the gained ductility will result in dissipating the seismic energy through yielding of the fuses while keeping the columns elastic. Results obtained demonstrated the effectiveness of the proposed concept as an implementation of structural fuses in a bridge application.

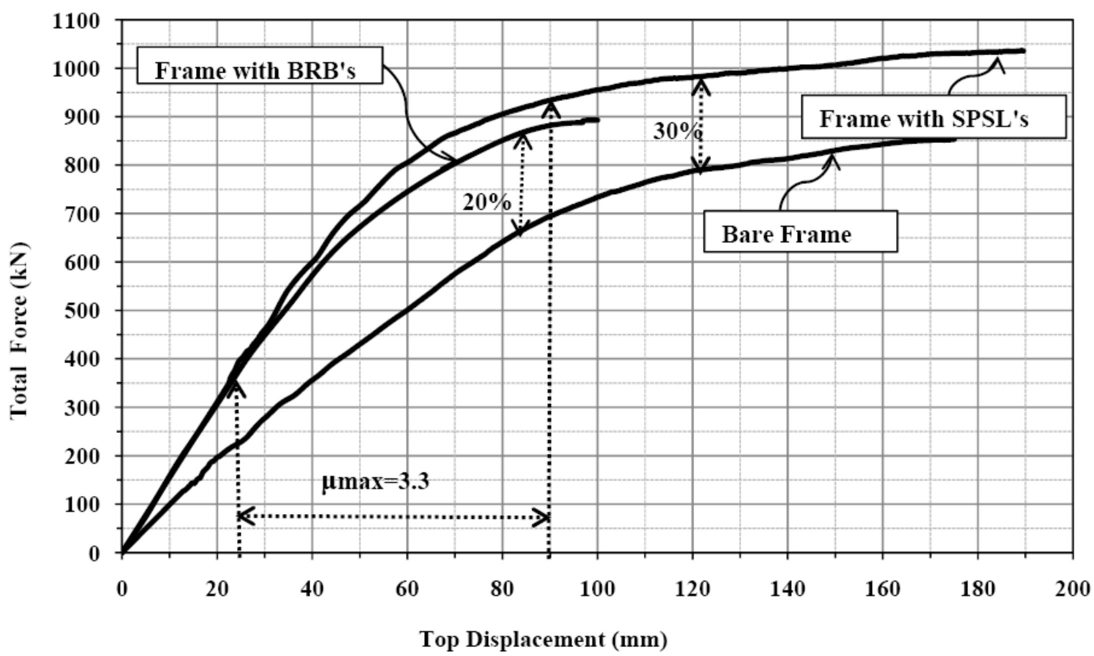


Figure 9. Pushover results comparison

7. ACKNOWLEDGMENTS

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