FUSE ELEMENTS FOR SPECIAL CONCENTRICALLY BRACED FRAMES

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ABSTRACT :

This paper explores the design of a fuse element for potential use in Steel Concentrically Braced Frames. The fuse element has lower axial strength and much greater toughness than the elements of the braced frame, and is designed to maintain its strength under repeated cycles beyond yield both in tension and compression. The use of this fuse element allows the braces to yield in a ductile manner while limiting the damage to the brace elements and the connections.

The proposed fuse element consists of metal bars embedded in a polymer matrix which is confined by a carbon fiber reinforced polymer. When loaded in tension and compression, the capacity of the element is controlled by yielding of the steel bars. When loaded in compression confinement provided by the FRP layer causes the polymer to restrain the lateral motion of the slender bars, increasing the buckling capacity so that there is no reduction in strength below the yield point.

A series of experiments were carried out to validate the conceptual design of the fuse element. Experimental results demonstrated that the proposed fuse element exhibited similar hysteretic behavior in tension and compression, and that it had the ability to dissipate energy without significant damage. Because the damage is concentrated on a relatively small element, this type of structural system has the added advantage that is easy to repair after a major earthquake.

KEYWORDS: fuse, composite, brace, steel

1. INTRODUCTION

Older seismic design provisions require that braces be proportioned to remain within their elastic range of response for the design earthquake [FEMA, NEHRP 1994], although it was expected that brace elements may deform beyond the buckling and yield displacements under severe dynamic excitations. Other limit states such as safety (collapse) and serviceability were addressed implicitly. New design provisions [AISC, 2005] are beginning to explicitly address critical parameters of structural response under severe earthquake motions such as inelastic deformations, and drift capacities. The current AISC design provisions [AISC, 2005] require that braces be proportioned to prevent fracture within the connection prior to significant yielding of the brace because that type of failure limits the drift capacity of the frame. In this paper the problem of limited deformation capacity of braced frames is addressed by concentrating inelastic deformations in fuse elements with reduced strength and increased toughness. Because the governing limit state is yielding over the reduced-strength region, braced frames yield in a ductile manner instead of having a brittle failure due to fracture at the connection. The fuse elements have the effect of maintaining demands on the other elements of the braced frame in the elastic range, while improving the deformation capacity of the bracing system.

2. FUSE ELEMENT

Some steel materials commonly used for braces have expected yield strengths significantly higher than their nominal yield strengths [AISC, 2005]. In the case of a knife-plate connection between round hollow sections and gusset plates, the over-slot of the brace required for erection leaves a reduced section that if left un-reinforced, may cause net-section fracture to become the governing limit state, significantly reducing the ductility of the brace [Korol, 1996; Cheng, Kulak, and Khoo, 1998]. Reinforcement may be provided in the form of steel plates welded to the tube to increase the effective area at the reduced brace section. The drawback of this approach is that such reinforcement adds significant cost and it does not address the damaging effects of buckling of the brace during compression cycles. Furthermore, recommended practices by seismic provisions for welding reinforcing plates around the tube may be difficult to implement in field conditions and may create potential stress risers that could lead to crack initiation.

An alternative solution to the reinforced connection is to reduce the strength of the brace section at a distance from the connection using fuse elements. The fuse elements are proportioned so that yielding over the reduced-strength section becomes the limiting state both in tension and compression, causing braces to yield in a ductile manner instead of having a brittle failure due to fracture at the connection or due to buckling during the compression phase. Although the commentary of the current AISC seismic design provision [AISC, 2005] states that “no significant reduction of the brace section is permissible”, this statement is intended to prevent weakening of the brace section at the connection so that gross-section yielding of the brace is the governing limit state in tension. Reducing the strength of the brace by introducing a fuse element with improved toughness at a distance away from the connection allows the brace to yield in a ductile manner and does not contradict the intent of the design norm.

The proposed fuse element consists of a high performance composite element made of metal bars embedded in a urethane polymer matrix that is confined by a thin layer of carbon fiber reinforced polymer. This composite element fuse can provide a significant improvement on the performance of steel special concentrically braced frames (SCBFs) under earthquake loads because it can undergo significant inelastic deformations without loss in strength. This type of fuse is designated by the letters “BCE”.

The BCE fuse capacity (in terms of force and deformation) and the characteristics of the confining system depend primarily on the material properties of the bars and the length of the fuse. The tensile strength of the fuse is essentially the same as that of the bars. Similarly, the buckling capacity is also controlled primarily by the buckling capacity of the bars. Depending on the slenderness of the bars the buckling capacity could be significantly less than the tensile capacity. Because the length of the fuse element is directly proportional to its deformation capacity, the most effective manner to increase the deformation capacity of the fuse requires increasing the slenderness of the bars. To limit the damaging effects of buckling when the bars are subjected to compression a buckling restraint system is provided by embedding the bars in a cylindrical urethane polymer matrix, which is encased in a cylindrical layer of fiber reinforced polymer intended to provide confinement to the urethane. When loaded in compression the urethane provides lateral restraint to the steel bars, increasing their buckling capacity and making it as high as their yield strength.

3. BCE BAR CONFIGURATION

An experimental study [Lambrecht, J., Matamoros, A. 2004] with small-scale specimens was carried out using Nickel-Titanium (Nitinol) Shape memory alloy rods. The SMA rods had a diameter of 0.197 in.(5 millimeters). These rods were anchored to steel plates through threaded ends. Each threaded end accommodated two nuts, one at each side of the steel plate, to transfer tension and compression loads from the plates to the Nitinol rods (Fig. 1). The goal of using Nitinol was to take advantage of the superelasticity property of SMA materials, which provides the ability to dissipate energy without loss in strength or residual deformations.

Experimental results [Lambrecht, J., Matamoros, A. 2004] showed that the fuse configuration was a promising system able to withstand large inelastic deformations under repeated load reversals. Unfortunately the inelastic capacity of the fuse was limited by premature fracture of the SMA rods at the threaded ends. Although the threads on the SMA rods were extruded (instead of being cut) in an attempt to improve the toughness of the thread region, and the section of the rods was reduced in the middle to provide a uniform yield zone, the inherent difficulty of machining small-diameter titanium rods proved to be a limiting factor in the experiments. This limitation would not exist when fabricating full-scale elements, in which better detailing of the thread region and the reduced-section region were possible due to the larger scale.

A second set of experiments was carried out using full-scale fuse elements. An alternative anchoring system was used in the full-scale specimens. The compression nut and threaded compression zone were replaced by an enlarged bar diameter or shoulder. Finite Element analyses showed that adding this shoulder reduced the magnitude of stress concentrations in the compression load transfer area. Finite element analyses also showed that the best alternative to reduce stress concentrations among several evaluated was to transition between the shoulder diameter and the yield zone using a circular arc shape (Fig. 1).

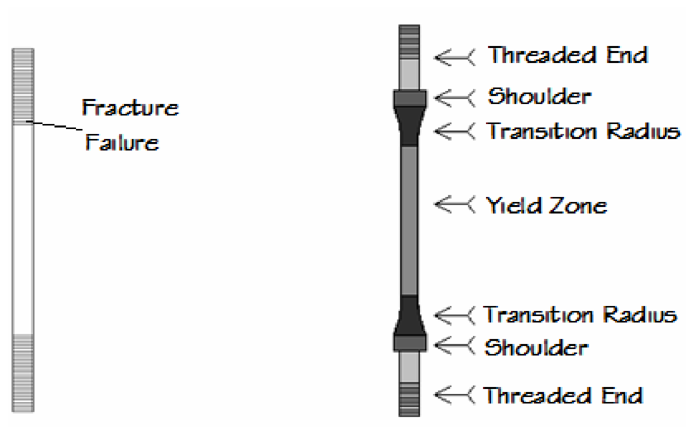

Fig.1 – Preliminary SMA Rod Configuration vs. Carbon Steel Bar Configuration.

Another consideration in optimizing the shape of the bar was that the threaded ends should be larger in diameter than the yield zone in order to avoid excessive stress concentration at the threaded end. In order to explore a more economical alternative and due to the difficulty of obtaining large-diameter SMA bars, carbon steel with high fracture toughness was selected for the fabrication of the full-scale fuses.

4. BCE FUSE MATRIX CONFIGURATION

A matrix with cylindrical shape was adopted in order to maximize the confining pressure provided by the layer of carbon fiber reinforced polymer. The matrix was intended to be re-used after the embedded bars had failed. For this reason the urethane matrix was cast so that it would not be in direct contact with the bars. Accordingly, individual urethane cores were cast around each bar and then embedded into the main urethane matrix. The urethane cores surrounding the bars served the purpose of protecting the main matrix from any deterioration caused by the bars during repetitive post-buckling deformations, and facilitating the repair of the system by replacing damaged bars with new ones after each experiment was concluded.

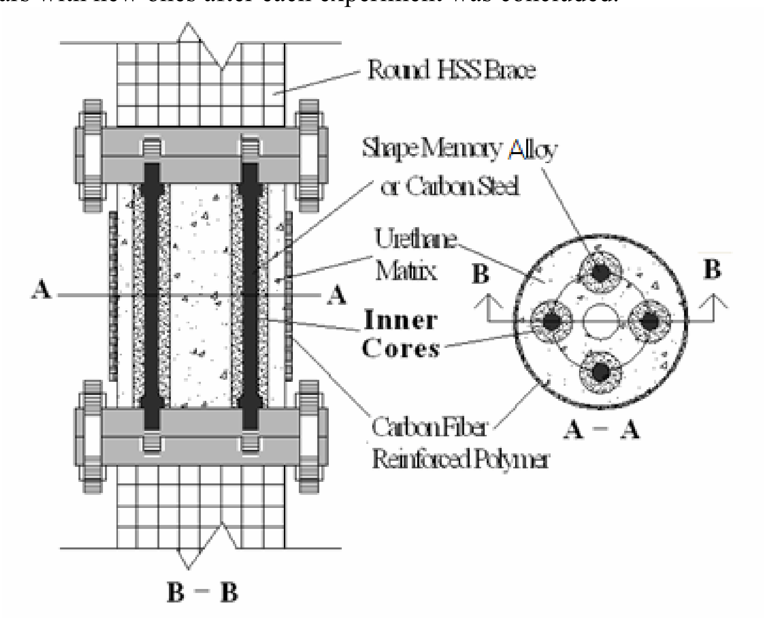

Fig. 2 – BCE Fuse Configuration with Inner Cores.

In addition to the bars and the matrix, the BCE fuse requires additional components for adequate load transfer between the brace and the fuse element. An example with a round HSS brace is presented in Fig. 2. A total of four steel plates are needed at the top and bottom of the fuse. The outermost plates are welded to the round HSS brace and the innermost are connected to the fuse element through the tension load transfer nuts and the bars enlarged shoulder. The assembly between the fuse element and the bracing system is made possible by bolting the outermost plates with the innermost plates.

5. BCE FUSE CFRP CONFIGURATION

The effectiveness of the confining system is strongly dependent on the height of the CFRP layer relative to the height of the urethane matrix, defined as the confinement ratio. The effect of the confinement ratio was investigated experimentally by testing in compression two urethane-CFRP assemblies with different confinement ratios. The first specimen consisted of a 5-in. (12.7 centimeters) tall and 5-in. (12.7 centimeters) diameter 80-durometer urethane matrix with a 1.5 in. (3.81 centimeters) confining layer, corresponding to a confinement ratio of 30%. The second test was carried out with a 3-in. (7.62 centimeters) confining layer over the same 5-in. (12.7 centimeters) tall matrix, corresponding to a 60% confinement ratio. The thickness of the CFRP confining layer was 0.08 in. (2 millimeters) for both tests. The experimental results were used to calibrate finite element models of the urethane-CFRP assemblies. A Mooney-Rivlin hyperelastic model proved adequate for simulating the behavior of the urethane matrix. (Fig. 3).

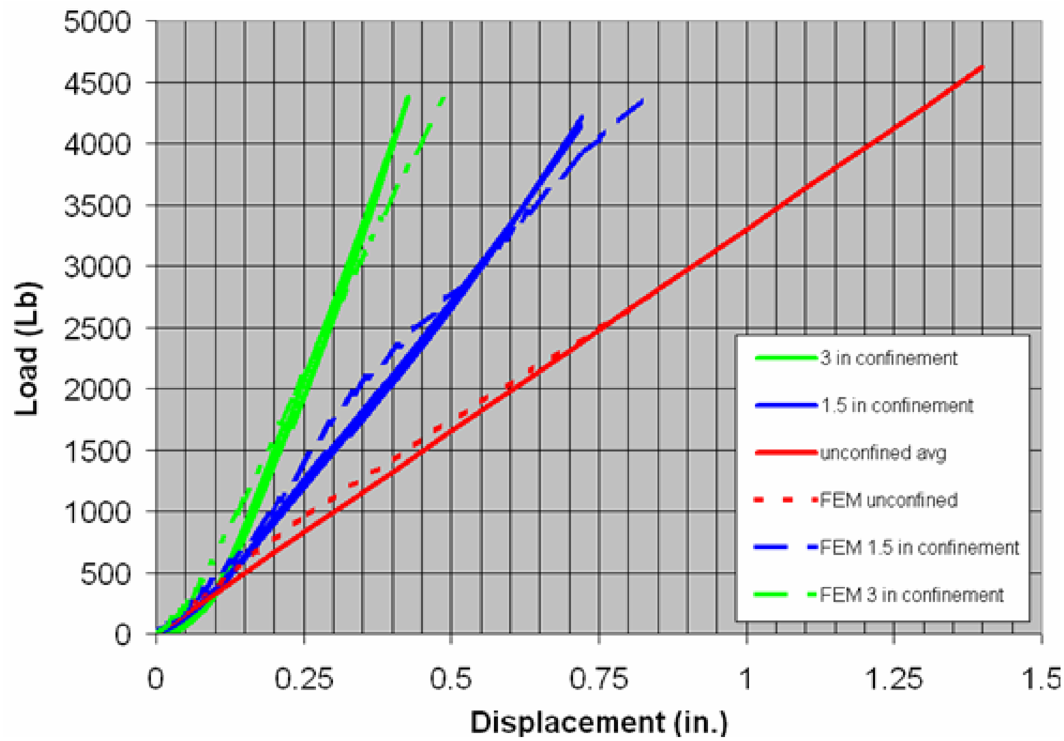

Fig. 3 - Experimental and Computational Load-Deformation Relationships for Urethane-CFRP Assemblies.

These experimental and computational results (Fig. 3) confirmed that the axial stiffness of the urethane matrix/CFRP confining layer system was directly proportional to the confinement ratio. For this reason it is recommended that the urethane matrix be almost completely confined by the CFRP layer. However, 100% confinement ratio is not desired because when loaded in compression the steel plates would transfer part of the load directly from the brace to the CFRP layer, which could increase the capacity of the fuse in compression beyond the yield strength of the bars, and may result in damage to the connection or the brace due to overstrength of the fuse. In order for the urethane to provide lateral restraint to the metal bars, the urethane matrix must be subjected to compressive loads. As the matrix is prevented from expanding by the CFRP layer, the urethane surrounding the bars acts as a buckling restraint system by preventing the lateral deformation of the bars, suppressing several of the lowest buckling modes.

The thickness of the CFRP layer is a function of the radial stresses induced by the urethane matrix as it tries to expand. Thicker CFRP layers have greater stiffness, although for the range of diameters that were investigated the thickness of the CFRP layer was found to have a negligible effect on the axial stiffness of the fuse. For that reason the primary consideration in determining the thickness of the CFRP layer was to maintain the hoop stress low enough to avoid failure of the CFRP.

6. BCE Fuse Buckling Capacity

When loaded in compression and restrained from buckling by the urethane the bars carried most of the axial load applied to the fuse. This was a result of a “softer” unconfined region near the end plates, which allows the urethane to deform without absorbing a significant fraction of the total load. As recommended above the urethane matrix should not be fully confined by the CFRP to avoid overstrength of the fuse when loaded in compression. Through the numerical and physical simulations it was found that the unconfined region of the urethane matrix should be at least 2% higher than the fuse height to pre-compress the urethane matrix during fuse-brace assembly. It was also found that when the unconfined length was too low bulging of the matrix in the unconfined region lead to damage of the urethane.

In order to understand the behavior of the proposed fuse it was essential to understand how it was that the urethane matrix affected the buckling capacity of the metal bars. If it is assumed that the buckling restraint system fully braces the bars against lateral buckling, the strength of the bars in compression is controlled by the yield strength of the metal. Furthermore deformations beyond the yield point will take place without a reduction in strength, as the buckling restraint system suppresses second order effects. Experimental results showed that the urethane did not provide perfect restraint to the bars. Removing the bars after testing showed that buckling of the bars had indeed taken place, but that the first, and in some instances higher, buckling modes were effectively eliminated. The observed deformations patterns of the bars were similar to a second or higher buckling mode, depending on the effectiveness of the confining system. Repetitive buckling deformations did not significantly deteriorate the bar or the inner core, and in all the experiments carried out significant inelastic deformations took place without fracture of any of the bars. As a result in most experiments the capacity of the bars in compression was nearly equal to the yield strength.

7. FULL SIZE BCE FUSE EXPERIMENTAL PROGRAM

The experimental program was intended to study the local hysteretic behavior of axially loaded steel braces with the BCE fuse. This experimental matrix was divided into a first series that examined the interaction between one bar and the urethane–CFRP confining system. A second series of experiments was intended to experimentally verify the behavior of a full size four-bar BCE fuse. The effect of the following parameters was investigated during the two testing series: bar slenderness, confinement ratio, fuse connection end conditions, axial load eccentricity, and number of bars embedded in the polymer matrix. In total twenty-one specimens were tested under monotonic and cyclic loading.

Previous studies have shown that the compressive strength of braces subjected to cyclic loads is reduced by more than half of its buckling capacity during post-buckling deformations [Popov, 1979]. Experimentally obtained hysteretic loops for all series 1 specimens (Fig. 4) demonstrated that there was negligible difference between the behavior of the specimens in tension and compression, and that the capacity of the fuse in compression remained nearly constant after it reached its critical buckling capacity. This is contrast to the typical behavior of bracing members [Jain, A.K., Goel, S. C., and Hanson, R. D., 1980]. Even in specimens with very low confinement ratios the compressive capacity of the fuse at displacement amplitudes beyond critical buckling did not decrease by more than 20% at average strain demands on the bars of 3%.

Comparing the nominal buckling capacity for the three unconfined bar types with experimentally measured values for the same bars embedded in the fuse it was found that all bars increased their capacity in compression to values near the yield stress of 56 ksi. (386 MPa). Bars type A doubled their buckling capacity when embedded in the fuse, and bars type B and C improved their compressive capacities by 42% and 21% respectively (Table 1).

Table 1 – 1-Bar BCE Fuse Experimental Capacity vs. Bar Nominal Capacity

Bar fuse type	Fuse height, in. (mm)	Length of yield zone, in. (mm)	Nominal buckling capacity, ksi (MPa)	BCE fuse buckling capacity ksi (MPa)	Fuse experimental / bar nominal buckling capacity
A	24 (610)	21.6 (523)	24 (162)	49 (335)	2.06
B	16 (406)	12.6 (320)	37 (252)	52 (358)	1.42
C	8 (203)	4.6 (117)	46 (317)	55 (382)	1.21

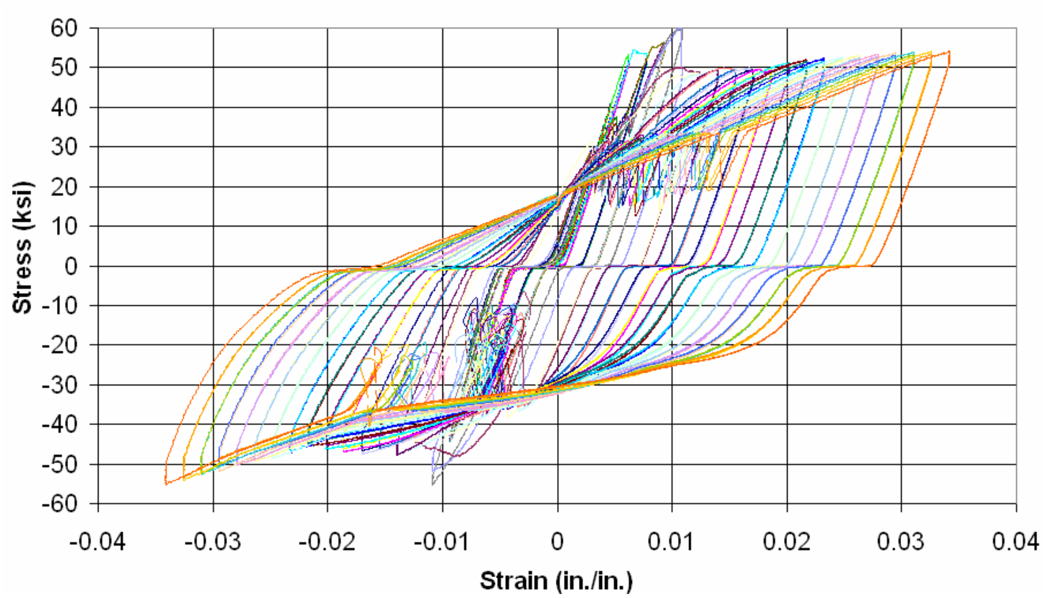

Fig. 4 – BCE Fuse 1-Bar Specimen Typical Hysteretic Behavior (Stress calculated as force divided by cross-sectional area of yield zone. Strain calculated as total deformation divided by the length of the yield zone of the bar).

The second series of experiments was intended to study the behavior of full-scale fuses with 4 bars when subjected to cyclic loads. This experimental series was composed of three groups, one per bar type, with 3 specimens per group, for a total of nine full-scale specimens. Each group included: one specimen with high CFRP confinement ratio subjected to concentric load, a second specimen with the same high confinement ratio but with the load applied at an eccentricity of 1.5 in. (3.81 centimeters), and a third specimen with a lower confinement ratio subjected to concentric load.

In an actual braced frame the connection between the fuse and the brace would have to be proportioned to resist bending moments induced by eccentricity of the load, and to resist the rotation demand during large inelastic deformations of the fuse. Using a moment-resisting connection for the experiments was not possible because such a configuration would result in the transfer of bending moments to the loading equipment. For this reason testing fixtures with pin end conditions were used for the tests. A comparison of bar nominal and fuse experimentally measured capacities showed that the fuse was able to improve the buckling capacity of the bars when subjected to both concentric and eccentric loads. Under concentric loading bars type A buckled at a compressive stress almost four times their nominal unconfined capacity, bars type B doubled their buckling capacity, and bars type C improved their compressive capacity by 22% when embedded in the fuse.

Under eccentric loading both a simple model and finite element analyses suggest that for an eccentricity of 1.5 in. approximately 90% of the load is resisted by two bars. Finite element models also showed that bending stresses improve the confinement of the bars that carry the highest load, and reduce the confinement on the bars subjected to lower loading. Accordingly, when the effects of bending are taken into account, bars type A tripled their buckling capacity when embedded in the fuse, and bars type B and C improved their compressive nominal capacities by 56% and 29% respectively.

The ability of the fuse to dissipate energy under large inelastic load reversals was significantly affected by large end rotations under eccentric axial loads. The magnitude of the end rotations was accentuated by the use of a pinned end condition during the tests, which is unlikely to exist in an actual braced frame.

10. CONCLUSIONS

The behavior of BCE fuses with two different types of bars was investigated. Small-scale specimens with SMA bars and full-scale specimens with steel bars were tested and studied using computer simulations. In all cases the BCE brace showed the ability to dissipate energy without loss in strength up to very large inelastic deformations. Under concentric loading the observed behavior in tension and compression was very similar. Full-scale tests under eccentric loading showed that the efficiency of the confinement system increased under eccentric loading, although the axial load capacity of the fuse decreased as a result of the bending moment. The BCE fuse exhibited great potential as an energy dissipation device. The biggest benefit of the composite fuse is its inherent toughness. The fact that the fuse bars can be easily replaced after large earthquakes is another significant advantage. Even though the fuse was subjected to large inelastic deformations, there was virtually no loss in strength in tension and compression, and there was no meaningful overstrength in compression. Damage to the BCE's under concentric loading was very light at unit deformations on the order of 3%, indicating that the fuse has remarkable toughness under load reversals. In the case of full-scale specimens, tests were stopped to prevent damage to the urethane matrix and the CFRP restraining layer, and in no case fracture of the steel bars was observed. Although they have a significantly higher cost, the use of shape memory alloy bars in small-scale specimens brought about the advantage of being able to dissipate energy without permanent deformations, providing an alternative to improve the performance of the system.

11. ACKNOWLEDGMENTS

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