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CAST STEEL YIELDING FUSE FOR CONCENTRICALLY BRACED FRAMES

M. G. Gray[1], C. Christopoulos[2] and J. A. Packer[3]

ABSTRACT

Since the construction of the distinct cable net roof structure of the 1972 Munich Olympic Stadium there has been a renaissance in the use of structural cast steel connections in buildings and bridges in Europe. More recently, the movement has crossed the ocean to North America. Although castings have been employed primarily in architecturally exposed structures where the cast elements and the structural members they are connected to are designed to remain elastic under all loading conditions, researchers have recently demonstrated that the freedom to control geometry and material properties makes steel castings an attractive solution for more severe loading conditions such as seismic-resistant connections for steel structures. This paper presents a new cast steel connector that acts as the energy dissipating element in a concentrically braced frame. Seismic energy is dissipated through inelastic flexural yielding of specially designed yielding elements of the cast connector. The cast connector concept is first introduced, the cast steel material used for a device prototype is then discussed and finally full-scale proof-of concept laboratory test results are presented.

Introduction

The use of structural steel castings has grown immensely in the last forty years. Since the construction of the Olympic Stadium in Munich in 1972, steel castings have been employed more frequently by European architects and engineers. This popularity of steel castings has recently made its way to North America. To date, the primary motivation for the use of steel castings in North American building projects has been the aesthetic appeal created by the freedom of geometry offered by the casting process. However, there has been increased awareness in the research community of the potential of using steel castings to simplify the design and detailing of complex structural problems such as the design of seismic resisting steel structures.

Researchers at the University of Toronto recently developed a new cast steel connector that replaces complex reinforcement details in the connections of brace members in Type MD and Type LD Concentrically braced frames, as per CAN/CSA S16-09 (similar to a SCBF and OCBF as per ANSI/AISC 341-05) (de Oliveira et al., 2008). This connector is designed to remain completely elastic during cyclic tensile yielding and inelastic compressive buckling of the brace member. It uses the freedom of geometry available through the casting process to create a virtually shear lag free welded connection. Also, through careful detailing of the nose of

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[1] Ph.D. Candidate, Dept. of Civil Engineering, University of Toronto, 35 St. George St., Toronto, ON, M5S 1A4
[2] Associate Professor, Dept. of Civil Engineering, University of Toronto, 35 St. George St., Toronto, ON, M5S 1A4
[3] Professor, Dept. of Civil Engineering, University of Toronto, 35 St. George St., Toronto, ON, M5S 1A4

the casting, the proposed connectors were designed to accommodate all commonly available circular braces with a given outer diameter but with variable wall thickness, thus maximizing the mass production advantages that are inherent to the steel casting process. More recent research at the University of Arizona has lead to the development of several cast steel connectors that are designed to act as the ductile yielding element of seismically loaded moment resisting frames (Fleischman et al., 2007; Sumer et al., 2007). These assorted components use different yielding mechanisms to dissipate energy (shear yielding of the panel zone in a cast steel beam-column joint in one case and flexural yielding of cast steel brackets that connect the beam flanges to the column face in another). These studies have demonstrated that it is possible to produce sound castings of a ductile steel alloy that can adequately dissipate seismic energy through controlled plastic deformations.

As an extension of this work in functional steel castings designed for seismic resistant steel structures, the research presented in this paper introduces a new, ductile cast steel connector for concentrically braced frames: the Cast Steel Yielding Fuse (CSF).

Cast Steel Yielding Fuse (CSF) Concept

The CSF is a new seismic device for concentrically braced frames, which is designed to achieve a stable symmetric inelastic response through the flexural yielding of specially designed fingers. It is intended to eliminate the cyclic tensile yielding and inelastic compressive buckling (and the resulting pinched hysteresis) of traditional braces. The hysteretic response of a CSF-brace assembly is similar to a buckling restrained brace (BRB) (Christopoulos and Filiatrault, 2006). However, unlike a BRB, the CSF is a connector that fits to the end of a standard structural shape (W-section or hollow structural section) and is intended to be a readily available, off-the-shelf component. The CSF-brace assembly would be fabricated and installed by the same steel fabricator/erector that is constructing the rest of the structure. In a structural system that employs the CSF as part of the lateral force resisting system, earthquake induced storey shears cause axial forces in the brace members, thereby engaging the CSF device. Seismic energy is dissipated through the flexural yielding of the yielding fingers. The deformed shape of a CSF-brace assembly is illustrated in Fig. 1. Fig. 2 illustrates the brace to corner gusset plate connection of a CSF-brace member assembly. The eccentric arms of the CSF are welded with fillet welds to the brace member on one side and the yielding fingers of the CSF are connected by means of a specially designed bolted connection to a pair of splice plates The welds to the brace, the elastic arms of the CSF, the bolted connection to the splice plates, and the splice plates themselves, are designed to remain fully elastic during the plastic deformation of the yielding fingers. In particular, the freedom of geometry that is inherent to the casting process enables the geometry of the elastic arms to be dictated solely by the loads that they must resist.

In order to maximize the ductility of the yielding elements of the device, the fingers have been shaped to induce flexural yielding along most of their length. Similar to the TADAS system (Tsai et al., 1993), the bending moment and shear force diagrams of the yielding fingers are similar to those of a basic cantilever. The yielding fingers have a nearly rectangular cross section (some variation from a true rectangle was required to meet castability constraints), with a width that varies linearly along the length of the finger and a thickness that is held constant. This gives the yielding fingers the general shape of a triangular prism and results in nearly constant curvature along their length when the fingers are deformed, which in turn results in an even distribution of the plasticity along nearly the full the length of the finger when it yields.

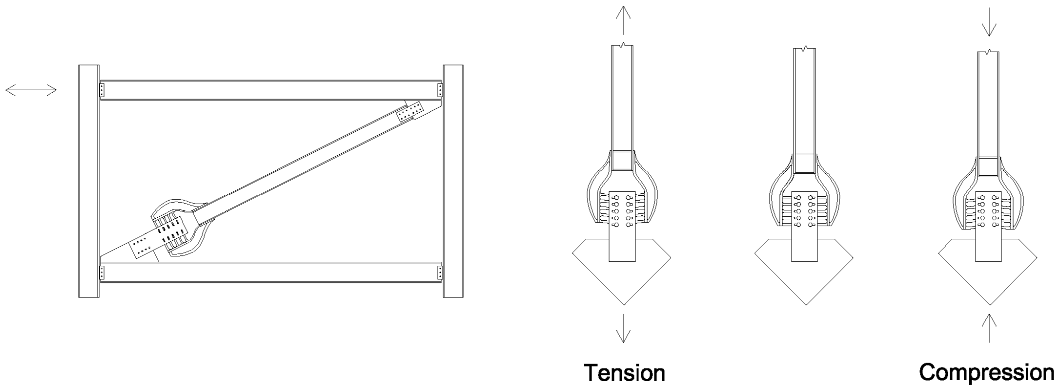


Figure 1. Deformed shape of a yielding CSF-brace assembly in tension and compression

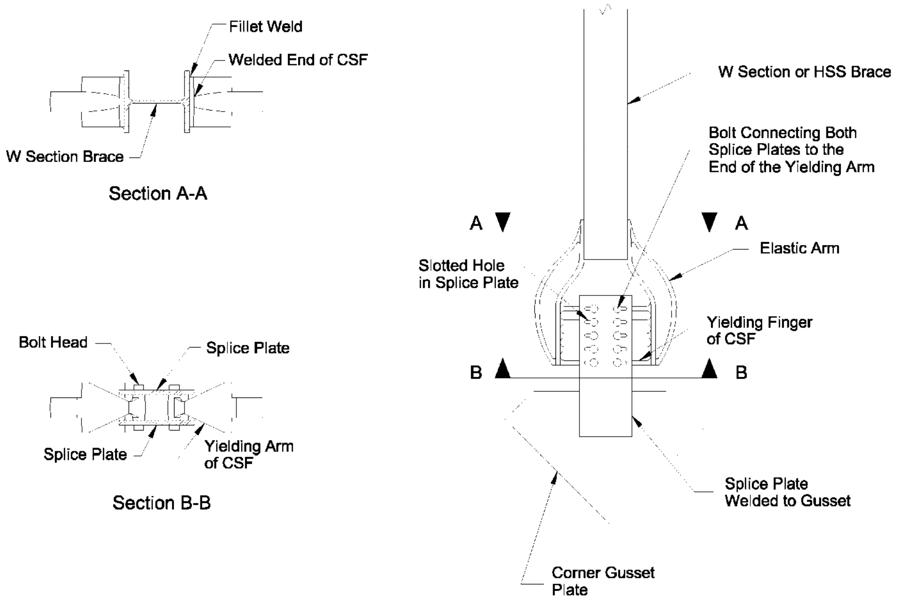


Figure 2. CSF-brace assembly connection to a typical corner gusset plate

The ends of the yielding fingers are equipped with a cylindrical boss that has a hole drilled in the centre to accommodate a standard high strength bolt. The bolt transfers the shear force from the end of the yielding finger to two splice plates through bearing in long slotted holes that are oriented perpendicular to the brace axis. If the bolts were received by standard, round holes, the yielding fingers would develop a large, second-order catenary force at the large displacements that would be expected in a design level earthquake. To reduce this catenary effect, the splice plates have been detailed with long slotted holes that allow for the lateral translation (δ’) that is induced in each finger as it deforms in the direction of the brace axis. The contact force between the bolt and the slotted holes is always normal to the direction of the slot. As illustrated in Fig. 1, at large displacements, the bolted ends of the yielding fingers experience a significant rotation. Thus, in spite of the use of long slotted holes, a component of the bearing reaction will still induce an axial force in the yielding finger at very large displacements. This behaviour also results in a post-yield stiffening of the system which can be tuned to become more pronounced at a given brace displacement through careful design of the system.

Prediction of the CSF Response

Based on the regular geometry of the yielding fingers, the elastic stiffness of the CSF, *k*, and the brace axial force that causes plastification of the yielding fingers, P_P, are derived from first principles:

$$k = \frac{nb_o Eh^3}{6L^3} \tag{1}$$

$$P_P = \frac{nb_o h^2 F_y}{4L} \tag{2}$$

In these equations, *n* is the number of yielding fingers in the CSF-brace assembly, b_o is the width of an individual yielding finger at its base, *E* is Young's modulus for the cast steel material, *h* is the thickness of an individual yielding finger and *L* is the height of an individual yielding finger. (see Fig. 3 for an illustration of the yielding finger geometric parameters).

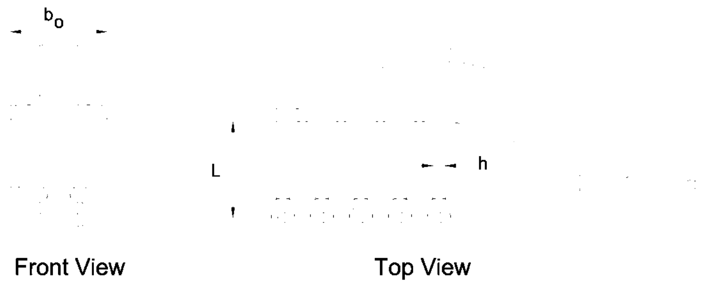
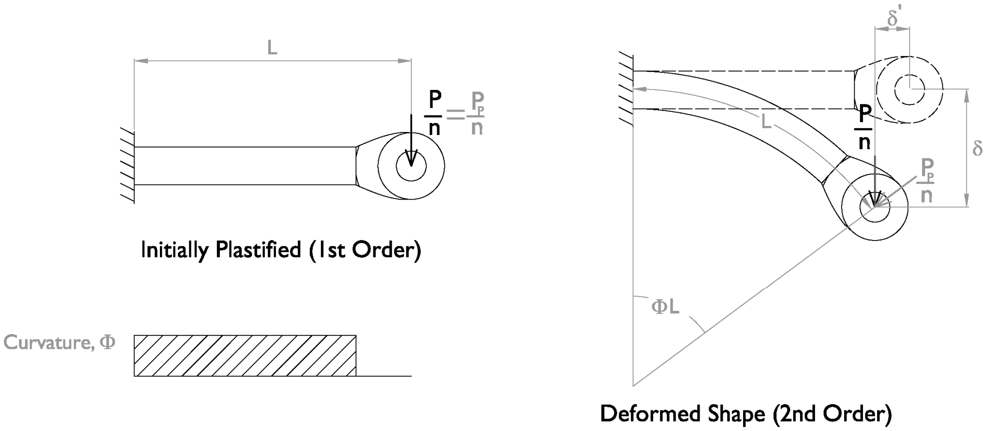


Figure 3. Geometric Parameters of the CSF yielding fingers

As previously described, during the design level earthquake, second-order effects in the yielding fingers are expected to be significant and therefore must be considered in examining the response of the CSF. The second-order axial force that develops in each yielding finger when they are subjected to large bending deformations results in a post-yield stiffening that can be observed in the load displacement response of a CSF brace assembly. This post-yield stiffening of the yielding fingers is relevant to the capacity design of the remaining elements of the CSF-brace assembly and the other structural elements of the lateral load resisting frame.

The post-yield axial response of a CSF-brace assembly can be approximated by examining the second-order displaced shape of an individual yielding arm (Fig. 4).



Initially Plastified (1st Order)

Deformed Shape (2nd Order)

Figure 4. Second-order displaced shape of a yielding finger

As illustrated in Fig. 4, in the initially plastified (i.e. first-order) state the yielding finger is in constant curvature (due to its triangular shape). If it is assumed that the yielding finger is still in constant curvature (the finger has reached its plastic moment along its entire length) after significant bending deformation, then the component of the bolt load, P/n , that induces flexure is equal to the first-order plastic force, P_P/n . With the knowledge of the flexural component of the applied load that is required to maintain flexural yielding in the finger, P_P , the applied bolt load corresponding to any brace displacement, δ, can be obtained :

$$P = \frac{P_P}{\cos(\frac{2\delta}{L})} \tag{3}$$

With Eqs. 1, 2, and 3, a designer can predict the backbone static load displacement response of a CSF and thus capacity design the fuse, its connections, and the remainder of the lateral force resisting elements. The validity of these response prediction equations is later checked against results from a full-scale CSF assembly test.

Properties of the Cast Steel Material

The selection of an appropriate cast steel material grade is central to developing a CSF that can achieve the required cyclic inelastic demands that would be imposed to the CSF-brace assembly during seismic loading. Through a close interaction with steel casting specialists it was determined that the use of ASTM-A352 LCB was the most suitable cast steel grade for the CSF prototypes. ASTM-A352 is a low carbon, notch tough steel that is suitable for low temperature applications. The minimum yield strength specified by the standard for the LCB grade is 240 MPa and the notch toughness is achieved through quenching and tempering. The results of the destructive testing of test bars that were cast from the same material as the full-scale prototypes are summarized in Tables 1.

It should be noted that in past tests of the A352 LCB material, it has been observed that the yield and tensile strengths of the test bar exceed the results from in situ coupons cut directly from test specimens. This is a result of the different thermal properties (i.e. thickness of the material and shape of the component) of the test bar and the cast part and therefore slightly different microstructures.

Table 1. Results of foundry destructive testing of the CSF prototype material.

Yield Strength MPa (ksi)	**Tensile Strength MPa (ksi)**	**Elongation %**	**Reduction of Area %**	**Avg. CVN @ 46C Joules**
365 (52.9)	523 (75.8)	32	76.2	46

In an effort to characterize the low-cycle fatigue life of the A352 LCB cast steel material 40 small-scale cast plates that resembled the yielding fingers of a CSF were tested in an apparatus that simulated the elastic arms and splice plates of the CSF system. The test setup and a sample hysteretic response are illustrated in Fig. 5. The first 30 of the specimens were tested in cycles of constant strain amplitude with the goal of finding the relationship between strain and low-cycle fatigue life of ASTM A352 LCB. The remaining 10 small-scale specimens were tested with variable displacement protocols. These test results were then compared with the fatigue life prediction that was made using the strain-life model calibrated with the first 30 test results and Miner's rule. Once the strain-life model was validated it was used to design the full-scale prototypes that are discussed in the next section.

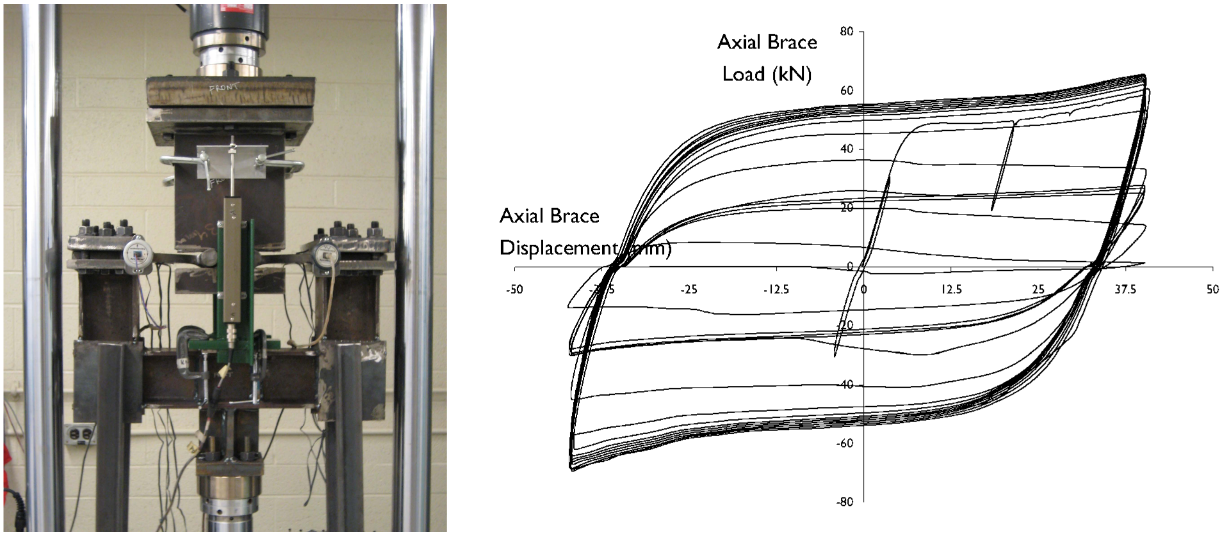


Figure 5. Small-scale low-cycle fatigue test setup (left) and a typical hysteretic response (right)

Full-Scale CSF Prototype Tests

In order to validate the CSF concept, a full-scale prototype was designed, manufactured and tested under cyclic, quasi-static axial loading with a universal testing machine at the University of Toronto. This CSF prototype was designed for a yield load of 1113 kN (250 kips) and a CSF-brace assembly axial stiffness of 140 kN/mm (800 kips/in) which is similar to the stiffness of a buckling restrained brace designed for the same yield load and frame geometry. The prototype was designed to represent the second floor brace of a six storey steel building located in Los Angeles. The design was carried out in accordance with ASCE/SEI 7-05 and ANSI/AISC 341-05. The guidelines and seismic response parameters for buckling restrained braced frames were adopted for the CSF, as the two systems have very similar responses. The full-scale CSF prototype was designed using the previously described first principles equations and further validated with non-linear finite element analyses. After iterations with foundry engineers a castable geometry was selected that also met all the performance requirements that had been defined for this device. The final prototype is illustrated in Fig. 6.

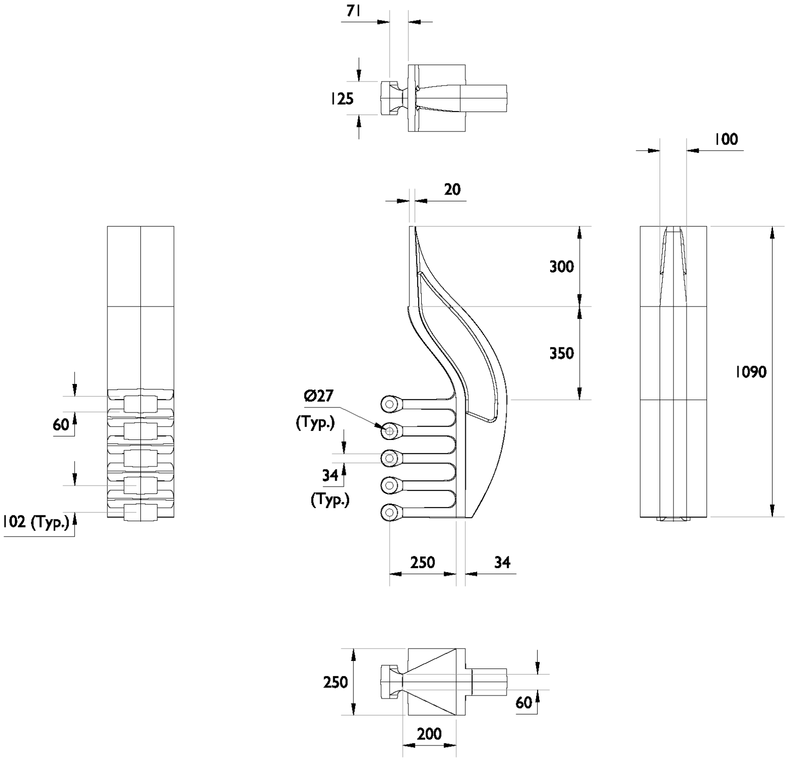


Figure 6. Full-scale CSF prototype design (all dimensions in mm)

The assembly that was used for the full-scale validation of the CSF is illustrated in Fig. 7. The test included two castings (required for one CSF-brace assembly) welded to a short length of W310x158 that simulated the end of the brace member, and a plate assembly that simulated the splice plates that connect the CSF-brace assembly to the corner gusset. In addition to the axial load and machine head displacement that are output by the testing machine, the test specimen is instrumented with a linear variable displacement transducer on each side of the setup and with 22 LED targets for a 3D camera measuring system.

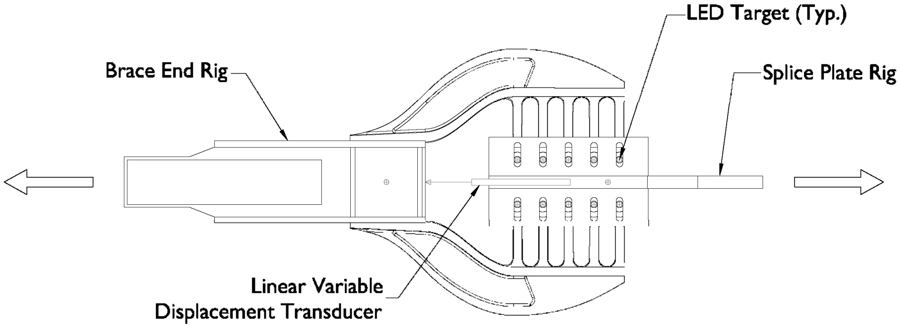


Figure 7. Full-scale CSF axial test setup and instrumentation

The specimen was tested in quasi-static, cyclic loading based on the qualifying protocol for buckling restrained braces described in Appendix T of ANSI/AISC 341-05. This protocol is derived from the design storey drift calculated based on the design structure. Based on an iterative capacity design and elastic spectral analysis of the sample structure and an assumed deflection amplification factor, C_d, of 5.5 (as prescribed by ASCE/SEI 7-05 for buckling restrained braced frames) the design storey drift of the second floor CSF-brace assembly was determined to be 51.5mm (or 1.4 % of the height). This drift is equivalent to an axial deformation in the CSF- assembly that was tested of 39.7mm.

Based on this design storey drift and using the displacement protocol defined by (in Appendix T of ANSI/AISC 341-05) it was determined that the specimen would be subjected to 2 cycles at 9mm, 2 cycles at 20mm, 2 cycles at 40mm, 2 cycles at 60mm, 2 cycles at 80mm and 2 cycles at 60mm. Based on an estimated yield displacement of 9mm this protocol exceeds the cumulative plastic displacement requirement of 200 times the yield displacement (ANSI/AISC 341-05). After the protocol was successfully completed the specimen was cycled at 80mm until the welds between the brace stub and one of the castings began to fail. None of the yielding fingers showed any visible signs of low-cycle fatigue fracture at the end of the test.

Photographs of the test specimen in the testing machine before and during the test at a displacement of +80mm mm are shown in Fig. 8. The recorded force-deflection response of the CSF assembly is shown in Fig. 9. The SCF-assembly met and exceeded the applied loading protocol and displayed a very stable and symmetric cyclic yielding response. The small slackness that is observed in the hysteretic response at zero load is caused by the oversized holes in the castings where the bolts are installed. Fig. 9 also contains the static backbone curve that is predicted using Eqs. 1, 2, and 3. From the graph it is apparent that these first principles calculations are a good representation of the experimental response. The difference in the load calculated from first principles and the load observed in the repeated cycles of the experimental protocol are attributed to cyclic strain hardening of the cast steel material that is not accounted for in the equations that have been developed. The cyclic strain hardening of the yielding fingers was considered in the capacity design of the sample building's lateral force resisting system.

The preliminary results of this full-scale CSF prototype test demonstrated the significant energy dissipation capacity of this system. It is acknowledged that the purely axial load test described above was not a perfect representation of the boundary conditions that would be experienced by a CSF-brace assembly in a real building frame. Ongoing research on the CSF technology is focused on the full-scale testing of a CSF-brace assembly in a single storey steel braced frame.

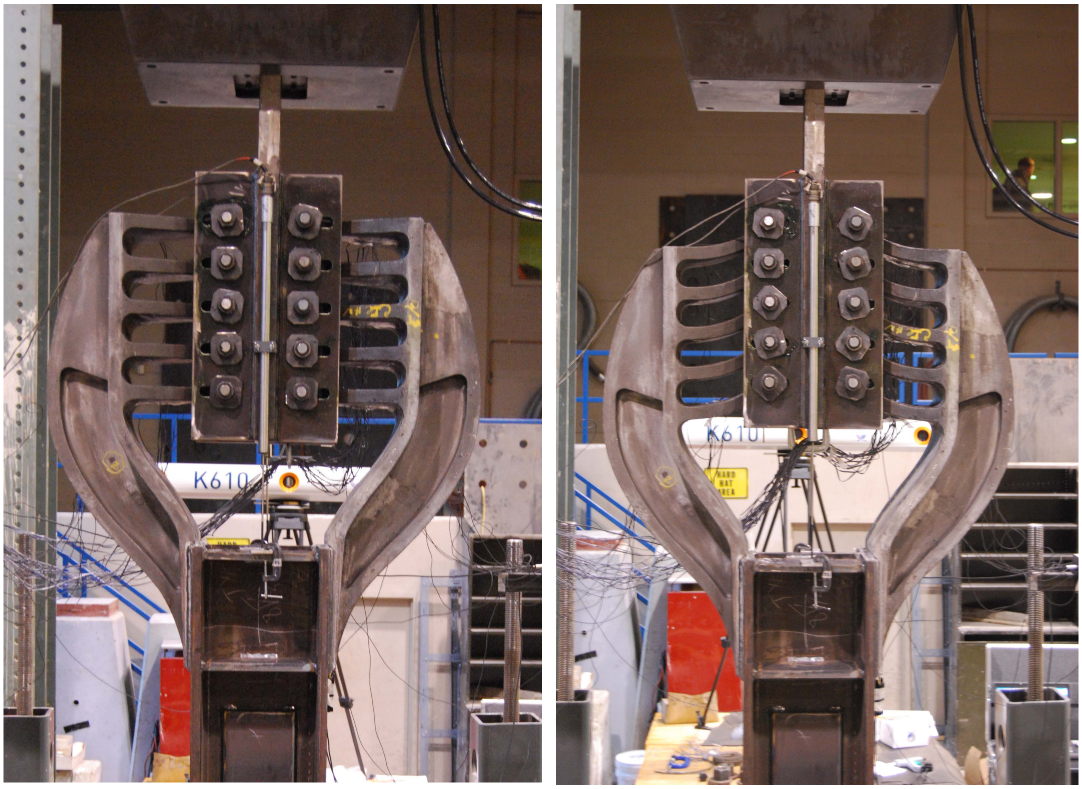


Figure 8. Test specimen before testing (left) at a displacement of 80 mm (right)

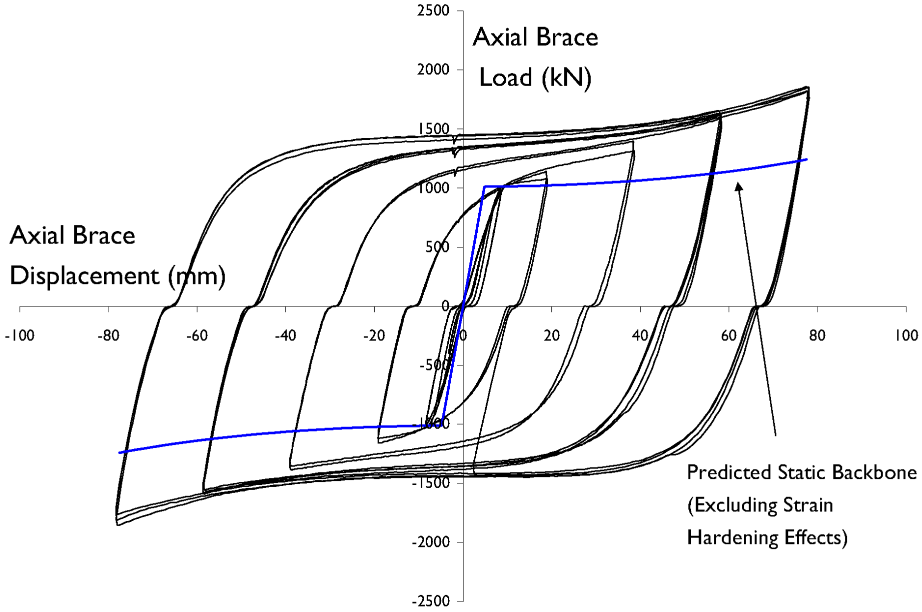


Figure 9. Force-Deflection response of the CSF prototype

Conclusions

The cast steel yielding fuse concept was presented as a new seismic energy-dissipative device for concentrically braced frames. The use of a CSF device eliminates the cyclic tensile yielding and inelastic compressive buckling of traditional braces and replaces it with a stable symmetric hysteretic response. A brief analytical derivation of the behaviour of the CSF was presented as well as a brief summary of the material properties of the cast steel grade that was used for the full-scale prototype tests. In addition, experimental results of an axial test of the CSF-brace assembly prototype confirmed the expected stiffness, strength and ductility response of the device and showed that the behaviour closely matched the analytically predicted response.

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