Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Experimental Testing of Heavy Steel Moment Frames with Replaceable Shear Fuses

Paul W. Richards[1*] and Justin D. Marshall[2]

[1]Vice President, DuraFuse Frames, West Jordan, Utah, USA
[2]President, DuraFuse Frames, West Jordan, Utah, USA
[*]paul.richards@durafuseframes.com (Corresponding Author)

ABSTRACT

Steel special moment frames (SMFs) are designed with high ductility factors so significant inelastic behavior is expected under design earthquake shaking. Replaceable shear fuse (RSF) connections improve the functional recovery of SMF by reducing residual drifts (through enhanced post-yield stiffness) and making connections repairable (with the replaceable fuses). Past studies have demonstrated the experimental performance of RSF connection for typical beam sizes, and RSF connections are prequalified in Chapter 15 of AISC 358-22 for beams up to 464 kg/m (309 lb/ft).

Some projects require exceptionally heavy beams that are beyond the range of current RSF connection prequalification. Three specimens were tested to investigate the behavior of heavy beams with RSF connections. The specimens all had W1000×591 (W40×397) beams and heavy box columns. The fuses were made from 44 mm (1.75 in.) plate. The specimens were tested per the procedures in Chapter K of AISC 341. Finite element models were developed to complement the experiments and quantify the force transfer through the various connection elements.

The experiments and models indicated acceptable performance and some areas for improvement. The specimens had cyclic rotation capacity of 0.04-0.06 radians, meeting prequalification requirements. The force transfer results suggest an improved method for estimating the maximum force that can develop at the column face.

Keywords: Moment frame, connections, structural fuse, shear-yielding, functional recovery.

INTRODUCTION

Steel special moment frames (SMFs) are designed with high ductility factors so significant inelastic behavior is expected under design earthquake shaking [1]. This inelasticity may result in steel buildings that are difficult to repair after severe earthquakes [2].

One strategy for improving the repairability of SMF is to introduce structural fuses that can yield, rather than forming plastic hinges in the beams. Replaceable shear fuse (RSF) connections have a fuse plate at the beam bottom flange level that is configured to yield in shear to accommodate relative rotation between the beam and the column (Figure 1). The shear yielding mechanism is less susceptible to local buckling than beam plastic hinging, resulting in high post-yield stiffness at large inelastic deformations and lower residual drifts [3].

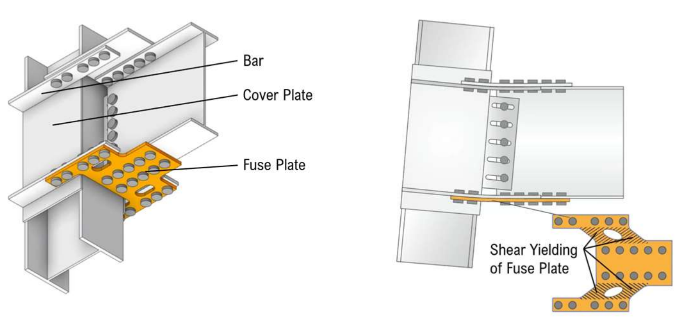


Figure 1. Replaceable Shear Fuse (RSF) connection.

Past studies have demonstrated the experimental performance of RSF connection for typical beam sizes [4], and RSF connections are prequalified in Chapter 15 of AISC 358-22 [5] for beams up to 464 kg/m (309 lb/ft). However, some projects require exceptionally heavy beams that are beyond the range of current RSF connection prequalification. This paper describes experiments and finite element simulations that were performed to quantify the performance of RSF connections with exceptionally heavy beams.

METHODS

Experimental Methods

Three specimens were tested to investigate the behavior of heavy beams with RSF connections. The test set-up is shown in Figure 2. Each sub-assembly specimen consisted of one column with one beam connected at mid-height via an RSF connection. The cantilevered end of the beam was attached to (2) hydraulic actuators via a corbel. The distance from the actuators to the column centerline was 4572 mm. The distance between column horizontal supports was 4877 mm. The actuators applied vertical loading to the beam per a displacement-based loading protocol (discussed later), which imposed relative rotation between the beam and the column. The actuator force and beam end displacement were used to compute the moment at the face of the column (actuator force multiplied by distance to column face) and the “rotation” of the sub-assembly joint (beam tip displacement divided by 4572 mm).

Figure 2. Experimental test setup.

All of the specimens had W1000×591 (W40×397) beams and heavy box columns. The connections were designed per the procedures in Chapter 15 of AISC 358-22 [5]. The design procedure began by selecting the design moment at the face of the column. All of the connection elements were designed based on the design moment and, at the end of the design procedure, the fuse was proportioned such that the fully yielded and strain-hardened fuse would produce the design moment at the column face. Some details of the beam-to-column connection are shown in Figures 3 and 4. In each specimen, the fuse was made from 44 mm plate.

The geometry of the fuse plate and the number of fuse plate bolts varied (Figure 4). K1.1 used (14) bolts per line, representing over-bolting that might occur if high drag loads were present at the top flange and the bolt pattern was copied down for the fuse. Specimens K2.1 and K2.2 used (10) bolts per line, based on the maximum force that could develop in the fuse plate. The bolts were 32 mm (A490) tension-control bolts.

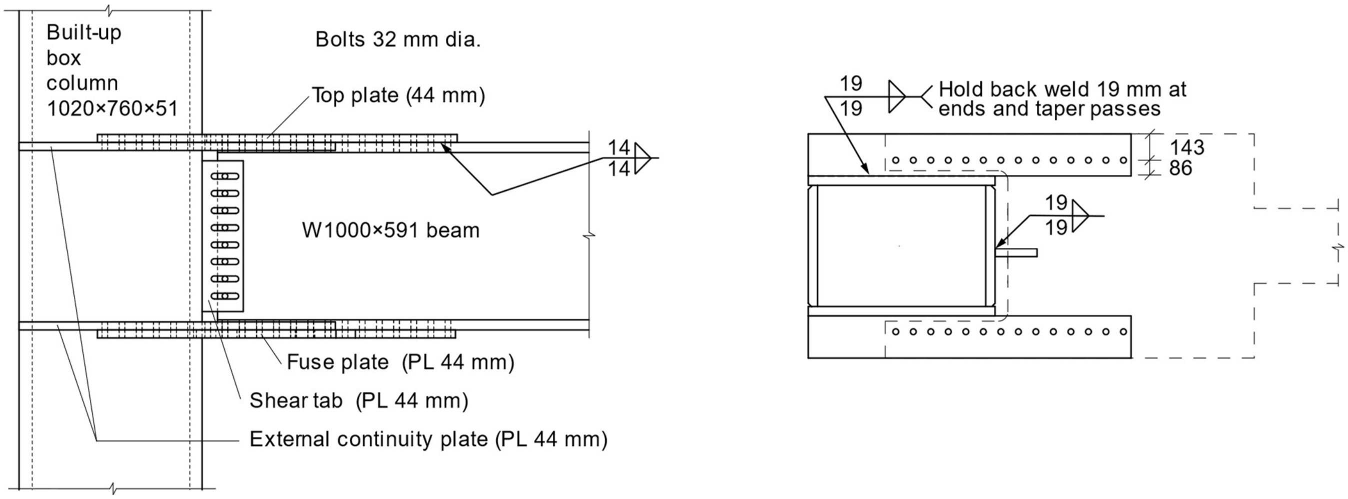


Figure 3. Connection details.

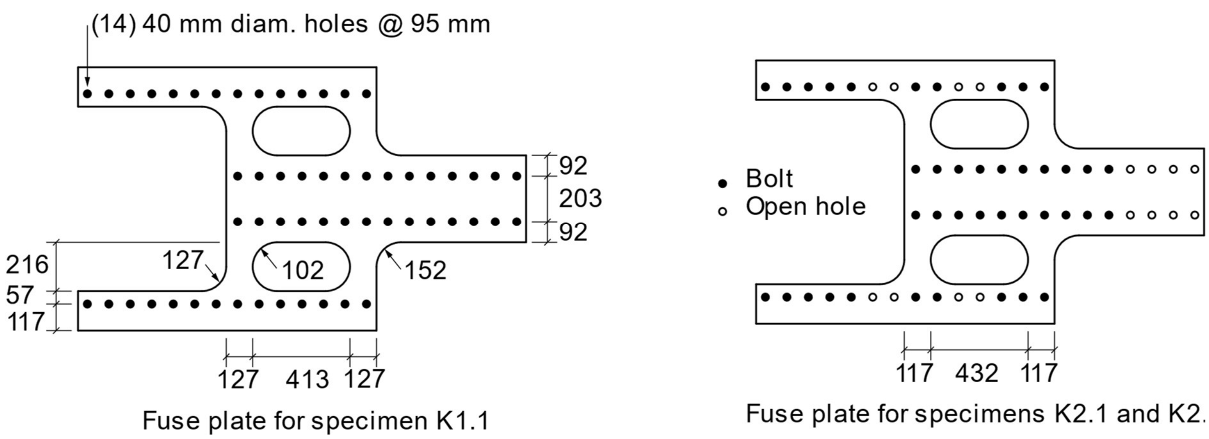


Figure 4. Fuse plate details.

The material for all the components had nominal strength of 345 MPa. The beams were A992 steel, and plates used for the built-up columns and the connections were A572 Gr. 50. Independent material testing for the 44 mm thick fuse plates indicated a yield stress of 384 MPa and tensile stress of 581 MPa, giving a tensile-to-yield ratio of 1.51.

The specimens were tested per the loading protocol and procedures in Chapter K of AISC 341 [6]. The loading protocol had six cycles at 0.0035, 0.005, and 0.0075 rad, followed by four cycles at 0.01 rad, and then two cycles at 0.015, 0.02, 0.03, 0.04 rad…until failure.

Finite Element Methods

Finite element simulations were performed with ANSYS Mechanical [7] to complement the experiments and quantify the force transfer through the various connection elements. Figure 5 shows the model used. A combination of element types were employed to efficiently represent the sub-assembly. The connection region was represented with higher-order hexahedral and tetrahedral elements, while the elastic regions of the beam and column away from the connection were modeled with beam elements to improve numerical efficiency. Symmetry was exploited.

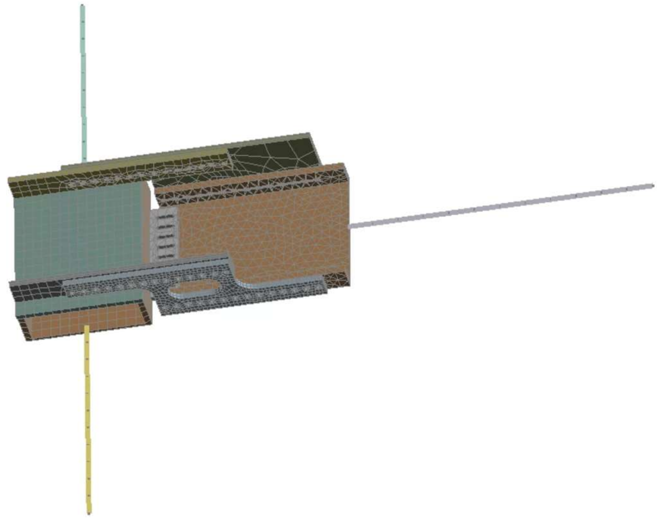


Figure 5. Finite element model of experiment.

Common material models were used in the FE simulations. Typical elastic material properties, E=200 MPa and ν=0.3, were used for the beam and column. A Voce-Chaboche material model was used to capture the non-linear response of the fuse. The values for the Voce-Chaboche parameters were: 370.7 MPa for the initial yield stress, 117.6 MPa for the exponential coefficient, 8 for the exponential saturation parameter, 13511 MPa for kinematic constant C1, 145.2 for kinematic constant $\gamma 1$, 1194 for kinematic constant C2, and 4.68 for kinematic constant $\gamma 2$.

In the FE model, the bolts were represented with spring elements. Each bolt was represented with two springs in parallel, a hysteretic spring that represented stick-slip behavior and a gap-elastic spring to represent bearing.

RESULTS

Experimental Results

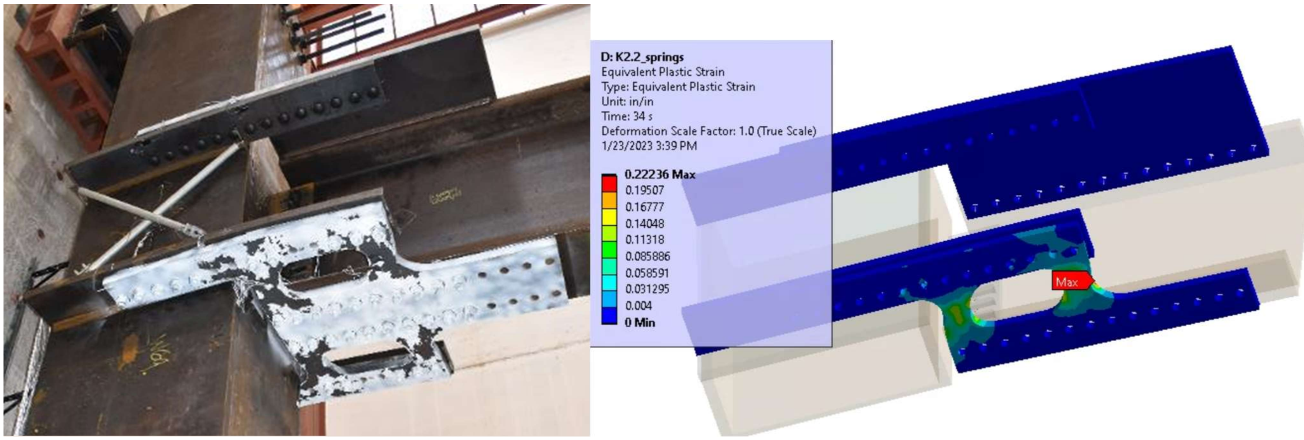
Figures 6 and 7 show Specimen K2.2 at various stages of loading. Throughout testing, significant yielding was confined to the fuse plate at the bottom flange level. Yielding was first observed in the center of the yielding regions during the 0.01 rad cycles, and expanded until the yielding regions were fully developed by the 0.03 rad cycles. The fuse plate started to experience low-cycle fatigue tearing during the first 0.06 rad cycle [Figure 6(a)], but the strength did not drop until the tear propagated during the second 0.06 rad cycle (Figure 7).

The other specimens had similar behavior but varying cyclic rotation, θ_{max}, capacity. Table 1 summarizes the different specimen responses. Specimen K1.1 had less bolt slip in the smaller cycles because of the additional bolts on the fuse plate. As a result, inelastic demands on the fuse plate were greater during the smaller cycles, as compared to K2.2, and the fuse experienced low cycle fatigue during the second cycle at 0.04 rad.

Specimen K2.1 re-used the same top plate bolts as K1.1 and had 10 bolts per line on the fuse plate like K2.2. Since the top flange bolts were re-used, they did not start the test centered in the oversized holes, and the available slip was all in one direction. As a result, the maximum positive moment for K2.2, $M_{f,pos}$, was substantially greater than the maximum negative moment, $M_{f,neg}$ (Table 1). Specimen K2.1 had more bolt slip in the smaller cycles than K1.1 and completed one cycle at 0.05 rad without fuse tearing. Testing of K2.1 was stopped after 0.05 rad, prior to fuse failure, to make sure that the final specimen could be tested. Prior to testing K2.2, all the bolts were replaced and centered. Specimen K2.2 was tested all the way to fuse tearing and completed cycles at 0.06 rad with balanced positive and negative moments.

Table 1. Test results.

Specimen	Bolts	θ_{max} (rad)	$M_{f,pos}$ (M_p)	$M_{f,neg}$ (M_p)
K1.1	14	0.04	0.83	0.85
K2.1	10	0.05	0.97	0.81
K2.2	10	0.06	0.92	0.91



(a) *(b)*

Figure 6. Fuse plate of Specimen K2.2 at 0.06 rad: (a) experiment, (b) finite element simulation.

Figure 7. Ductile tearing of fuse plate of Specimen K2.2.

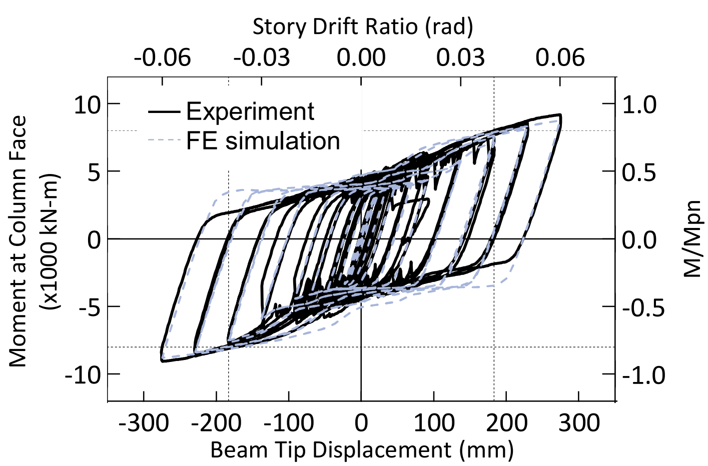


Figure 8. Hysteretic response of Specimen K2.2.

Figure 8 shows the hysteretic response for Specimen K2.2. The post-yield stiffness of the connection at 0.05 rad was 15% of the initial stiffness, whereas most SMF connections have negative stiffness at large inelastic rotations.

Finite Element Results

Figure 6(b) shows the plastic strains observed in the FE simulation, which were consistent with observations from testing. The ductile tearing observed in testing initiated at the location where the plastic strains in the FE simulation were the greatest. Figure 8 shows that the FE model did a reasonable job of simulating the overall hysteretic response of Specimen K2.2. Peak forces at 0.06 rad in the FE simulation were within 5% of those observed in testing.

The finite element simulation indicated that the maximum force that developed in the fuse was 3600 kN kips (each side). The yield capacity of the fuse (each side) was 2372 kN kips, based on the cross-sectional dimensions (Figure 3) and the measured yield capacity (384 MPa). Therefore, the strain hardening observed in the fuse was 3600/2372=1.52. This amount of strain hardening was essentially the same as what was observed from the coupon testing used to characterize the material (1.51). The strain hardening factor for the fuse plate is useful in estimating the maximum moment that can develop at the face of the column.

CONCLUSIONS

Three specimens were tested to investigate the behavior of heavy beams with replaceable shear fuse (RSF) connections. The specimens all had W1000×591 (W40×397) beams and heavy box columns. The fuses were made from 44 mm plate. The specimens were tested per the procedures in Chapter K of AISC 341 [6]. Finite element models were developed to complement the experiments and quantify the force transfer through the various connection elements.

The following conclusions are supported by the results that were presented:

- All of the specimens completed at least one cycle at 0.04 rad drift and could be used for special moment frames.
- The strain hardening in the fuse plate was equal to the ratio of tensile to yield stress observed in tension coupon testing.

These conclusions are helpful in refining the design procedures for moment frame connections with replaceable shear fuses and demonstrating that RSF connections can be used for exceptionally heavy beams.

ACKNOWLEDGMENTS

Experimental testing was funded by DuraFuse Frames, LLC (West Jordan, Utah, USA) and conducted at the University of California, San Diego (UCSD). The primary UCSD personnel involved with the project were Hooseok Lee (graduate student), Professor Chia-Ming Uang, and Andrew Sanders. The work of these individuals is gratefully acknowledged.

The RSF connection is proprietary, but licenses for use are granted on reasonable and non-discriminatory terms.

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