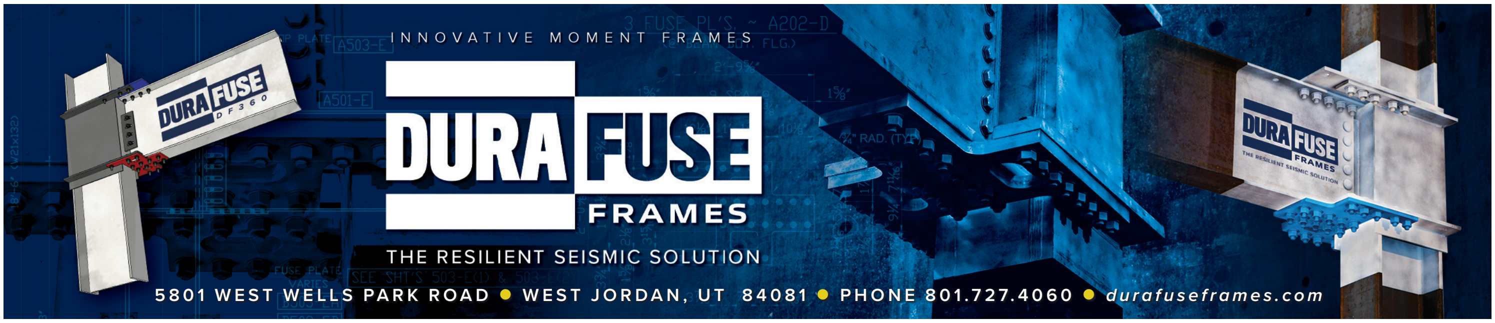

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08/21

# TECHNICAL BULLETIN 4

# Quantifying Connection Rigidity for DuraFuse Frames

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**Abstract:** Full-scale experiments were performed to evaluate the stiffness of connections in DuraFuse Frames. Sub-assemblies with beam depths ranging from 20.8 to 38.6 inches were subjected to initial cycles within the elastic range. The connection stiffnesses determined from the experiments were 2.2 to 4.6 times greater than the minimum connection stiffness required in order for the connections to be considered fully restrained (FR). Connections in DuraFuse Frames can be modeled as fully restrained (FR) connections for gravity and seismic loads.

## Introduction

In the design of moment frames, mathematical models are used to represent the stiffness of frames in order to check drifts and stability. Guidelines for such models are provided in ASCE 7 §12.7.3b (2016), AISC 360 §B3.4 (2016a), and in AISC 358 (2016b).

Connections can be considered fully restrained (FR) in the mathematical model if the connection transfers moment with negligible rotation between the connected members (AISC 2016a). This requirement is deemed satisfied for special moment frames when the rotational stiffness of the connection is greater than $18EI/L$, where $E$ is the modulus of elasticity, $I$ is the moment of inertia of the beam, and $L$ is the bay length (AISC 2016b).

This bulletin will first describe features of the DuraFuse Frames that influence connection stiffness. Then the connection stiffness from experiments will be quantified. Finally, the connection stiffness will be compared with the criterion for fully restrained (FR) connections.

## Features of the DuraFuse Connection

In DuraFuse Frames, plate material is added in the connection region to facilitate the connection. Some aspects of the plates tend to stiffen the beam-to-column connection by adding flexural stiffness in the connection region. Other aspects of the plates tend to add flexibility, by adding a transverse component to the load path.

Figure 1 illustrates how the connection plates increase the effective moment of inertia of the beam near the connection. Figure 1 shows cross-sections of the beam in the connection region. Relative values for the moment of inertia at each section in Figure 1 are from a design for a W30×99 beam. The average moment of inertia of the beam in the connection is more than double the moment of inertia of the beam.

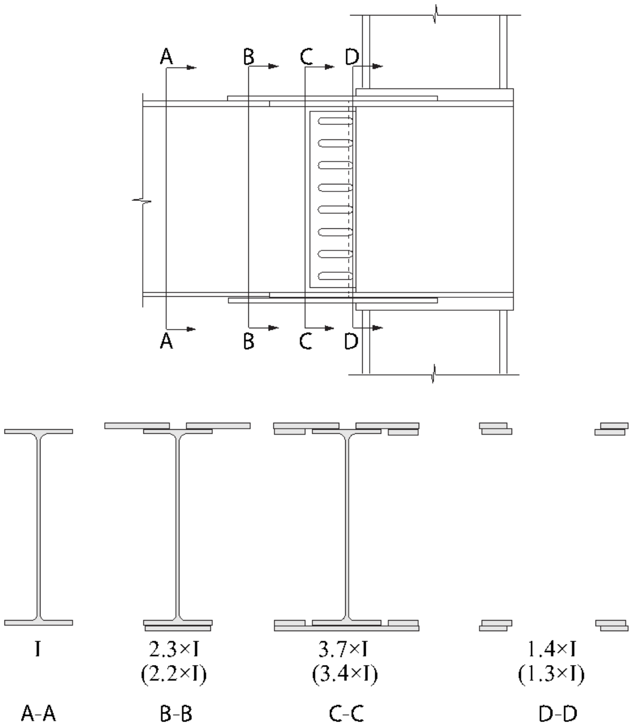

**Figure 1.** Increased moment of inertia for the beam in the connection region

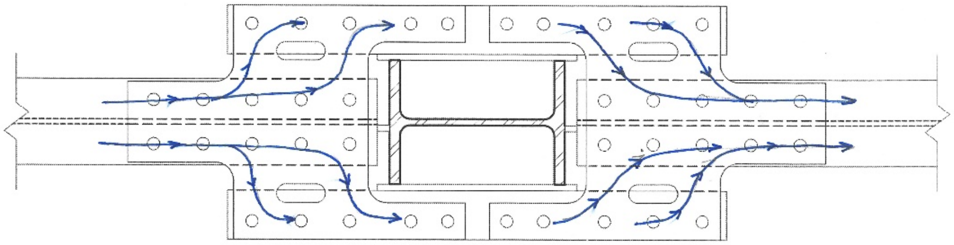

**Figure 2.** Transverse leg for load path as forces exit the beam through the fuse plate (similar for top plate).

However, Figure 2 illustrates how the fuse plate also introduces some flexibility by adding a transverse leg to the load path for the forces leaving the beam flanges. A similar path exists for the top plates. The elastic shear deformations in the top plates and fuse plate influence the stiffness of the connection.

## Quantifying Connection Stiffness

Full-scale sub-assemblies were tested to investigate connection stiffness and rotation capacity for the connections in DuraFuse Frames (Reynolds and Uang 2019a,b). Figure 3 illustrates the test set-up. The tests were deformation controlled, following the AISC moment connection testing protocol (AISC 2016c), with initial cycles of 0.00375 rad story drift. Full details of the experimental program are available in Reynolds and Uang (2019a,b).

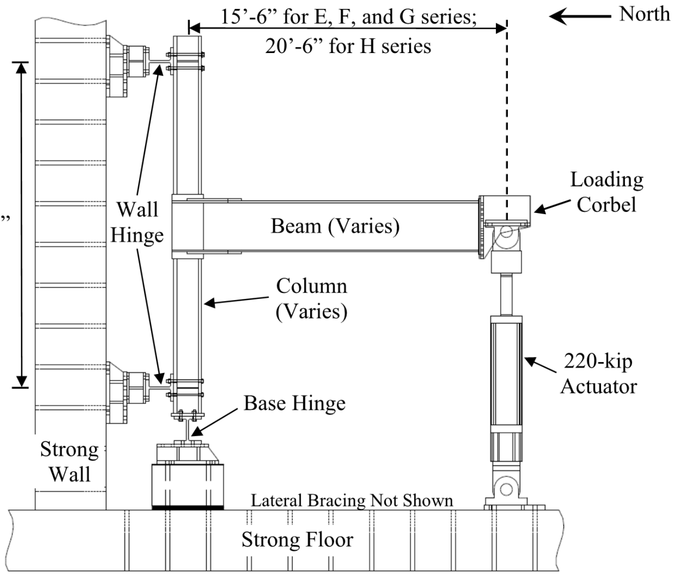

**Figure 3.** Full-scale experimental testing to investigate connection stiffness and rotation capacity (Figure from Reynolds and Uang 2019).

During testing the actuator force at the end of the beam, *F*, and the displacement at the end of the beam, $\delta$, were recorded. The beam displacement, $\delta$, was the sum of the displacement effects caused by beam deformations, $\delta_b$, column deformations, $\delta_c$, panel zone deformations, $\delta_{pz}$, and connection deformations, $\delta_{con}$.

For each test, the elastic stiffness of the connection was determined based on recorded forces and deformations from the first cycles of testing. Table 1 indicates actuator force, *F*, and total measured displacement, $\delta$, from the first cycle for each specimen. The components of the displacement due to beam deformations, $\delta_b$, and column deformations, $\delta_c$, were determined using Timoshenko beam theory and the applied force of the beam, *F*, and the calculated reaction forces on the column. Panel zone deformation effects, $\delta_{pz}$, were computed by multiplying the measured panel zone shear deformation by the distance from the column face to the actuator. The contribution from the connection rotation, $\delta_{con}$, was computed as:

$$\delta_{con} = \delta - \delta_b - \delta_c - \delta_{pz}$$

With the effects of the connection rotation determined, the rotational stiffness of the connection ($K_s$) was computed as:

$$K_s = \frac{M}{\theta} = \frac{(F)(g)}{\left(\frac{\delta_{con}}{g}\right)}$$

where *g* was the distance from the actuator line of action to the face of the column (Fig. 3).

**Table 1 – Results from full-scale testing of DuraFuse Frame sub-assemblies**

| Beam | I ($in^4$) | L (in) | g (in) | F (kips) | $\delta$ (in) | $\delta_b$ (in) | $\delta_c$ (in) | $\delta_{pz}$ (in) | $\delta_{con}$ (in) | $K_s$ (k-in/rad) | $K_s/(EI/L)$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| W21×50 | 984 | 372 | 179 | 10.0 | 1.069 | 0.694 | 0.214 | 0.080 | 0.081 | 3958884 | 52 |
| W30×99 | 3990 | 372 | 175.1 | 28.7 | 0.726 | 0.477 | 0.132 | 0.080 | 0.039 | 22725030 | 73 |
| W36×232 | 15000 | 492 | 234 | 55.0 | 0.865 | 0.581 | 0.123 | 0.075 | 0.085 | 35362334 | 40 |
| W40×167 | 11600 | 372 | 167.8 | 36.1 | 0.312 | 0.191 | 0.040 | 0.067 | 0.014 | 74008367 | 82 |

Moment frame connections are considered fully restrained (FR) for design purposes if the connection stiffness is large relative to the flexural stiffness (*EI/L*) of the beam. In the commentary to Chapter 13 of AISC 358 (2016b), a minimum stiffness of 18*EI/L* is discussed. In the commentary to B3 of AISC 360 (2016a), 20EI/L is discussed as a level of acceptability. Relative to these guides, the normalized values of $K_s$ shown in the last column of Table 1 were sufficient to classify the DFF connection as FR. For beams with depths ranging from 20.8 to 38.6, the connection stiffnesses were 2.2 to 4.6 greater than the minimum connection stiffness to be considered fully restrained (FR).

## Summary and Conclusion

In DuraFuse Frames, plate material is added in the connection region to facilitate the connection. Some parts of the plates tend to stiffen the beam-to-column connection by adding flexural stiffness to the beam in the connection region. Other parts of the plates tend to add flexibility, by adding a transverse component to the load path. The net effects of the plates on the connection stiffness was investigated through full-scale experimental testing.

The connection stiffnesses ranged from 40*EI/L* to 82*EI/L* for beams with depths of 20.8 to 38.6 inches. Since the connection stiffness exceeded 18*EI/L* by a significant margin for all cases, it is reasonable to consider the connections in DuraFuse Frames as fully restrained (FR).

## References

American Institute of Steel Construction (2016a). “Specification for Structural Steel Buildings,” AISC 360, Chicago, IL.

American Institute of Steel Construction (2016b). “Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications,” AISC 358, Chicago, IL.

American Institute of Steel Construction (2016c). “Seismic Provisions for Structural Steel Buildings,” AISC 341, Chicago, IL.

American Society of Civil Engineers (2016). “Minimum Design Loads and Associated Criteria for Buildings and Other Structures,” ASCE 7, Reston, VA.

Reynolds, M., and Uang, C.M. (2019a) “Cyclic Testing of DuraFuse (DF) Moment Frame Connections for SMF and IMF applications: Series E, F, and G Specimens.” Report No. TR-19/01, Department of Structural Engineering, University of California, San Diego, CA.

Reynolds, M., and Uang, C.M. (2019b) “Cyclic Testing of DuraFuse (DF) Moment Frame Connections for SMF and IMF applications: Series E, F, and G Specimens.” Report No. TR-19/02, Department of Structural Engineering, University of California, San Diego, CA.

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