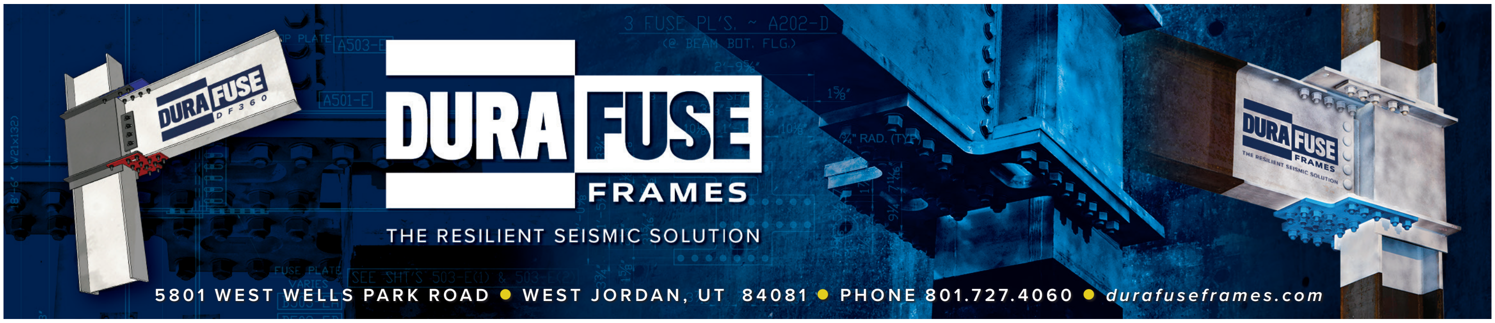

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TECHNICAL BULLETIN 21

Repair Requirements for Welded and Bolted SMF Connections

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Abstract: For small earthquakes, special moment frames (SMFs) will respond elastically. For moderate and severe earthquakes some amount of inelastic behavior is expected. Welded moment frames are susceptible to damage that is the most difficult to repair. For moderate earthquakes that require repairs, bolted SMFs, including DuraFuse Frames (DFF), might be repaired without replacing any steel. For severe earthquakes, DuraFuse Frames offers better repairability than other SMFs because beam yielding is prevented and the fuse is accessible. Experimental testing has demonstrated that DFF fuses have sufficient energy dissipation capacity to handle multiple, maximum considered events (MCEs). DFF fuses will only require replacement after severe events that result in large residual drifts.

Introduction

Special moment frames (SMFs) are expected to experience significant inelastic deformations during large seismic events (AISC, 2016). SMF connections are qualified based on tests that demonstrate the connection can sustain a story drift angle of at least 0.04 rad (AISC, 2016). The required 0.04 rad drift angle is greater than the 0.01 to 0.025 rad drift limits used for design, compensating for the fact that the MCE is not used in design (ASCE, 2016) and the C_d factor is known to be non-conservative for some cases (Medina and Krawinkler, 2005).

In SMF design, inelastic story drifts are estimated using a C_d factor to scale results from elastic analysis (ASCE, 2016). This approach is crude, but convenient for design. Response history analysis of low- to mid-rise buildings show greater inelastic story drifts than those estimated with C_d (Karavasilis et al., 2007; Medina and Krawinkler, 2005; Richards and Thompson, 2009; Uang and Maarouf, 1994).

Whenever buildings experience inelastic deformations, there is the possibility for residual drift. If residual drifts are greater than 0.5%, some sort of repair action will be required to return the building to service (Erochko et al., 2011).

For small earthquakes, it is not anticipated that SMFs will require structural repairs. Most SMFs will respond elastically for drifts up to around 1%. The precise drift depends on the beam and column depth and the slip capacity of bolts when the connection is bolted. Moment frames with heavy W36× beams and deep columns have an elastic limit of about 0.75% (Gharibans et al., 2003), while moment frames with W21× beams and W14× columns have an elastic limit of about 1.25% (Reynolds and Uang, 2019a).

For moderate to severe earthquakes, SMFs are expected to experience inelastic deformations through yielding and/or bolt slip at the connections and are expected to require repair (AISC, 2016). This technical bulletin reviews repair procedures for welded and bolted SMF connections for moderate and severe earthquakes.

Moderate Earthquakes

Welded Connections

SMFs with welded connections will be challenging to repair, even at relatively small drifts. Fig. 1 shows the experimental response of an RBS connection with a W36×150 beam. The inelasticity at 2% drift [point A in Fig. 1(a)] is due to yielding in the reduced section of the beam [Fig. 1(b)]. If the connection were unloaded from this point [red line in Fig. 1(a)], the residual drift would be about 1%. This residual drift would be challenging to repair. Proposed procedures entail shoring the beam, cutting out the yielded section, re-plumbing the building (while

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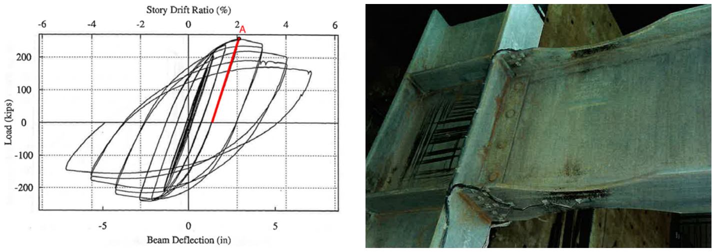
shoring the beams), and remaking the beam-to-column and beam-to-beam connections. If beams were yielded throughout an entire building, repair may be impractical.



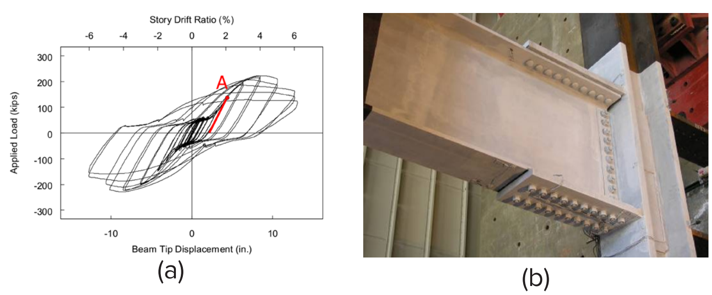
(a) (b)

Fig. 1 *Results from experimental testing of RBS connection with W36×150 beam: (a) hysteretic plot, (b) beam yielding between 1 and 2% drift (Gilton, Chi, and Uang, 2000)*

Bolted Connections

Compared with welded SMF connections, the prospects of repairing bolted SMF connections after drifts of 1 to 2% are much better. In bolted SMF connections, the bolt holes are oversized in the connection plates. Thus, drifts in the 1 to 2% range are largely accommodated by bolt slip.

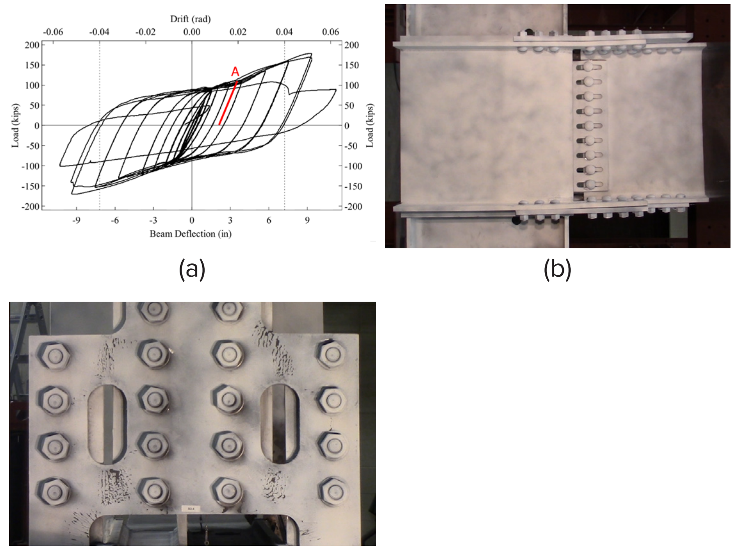
For example, Fig. 2 shows the experimental response of a bolted flange plate (BFP) connection with a W36×150 beam (Sato et al., 2007). The inelasticity at 2% drift [point A in Fig. 2(a)] is mostly due to bolt slip. If the connection were unloaded from this point [red line in Fig. 2(a)], the residual drift would be about 1%. *Bolt slip still results in residual drift, but this type of residual drift would be easier to repair since the beam has not been damaged.* A proposed procedure would be removing bottom flange bolts, replumbing the building as much as possible, and replacing the bottom flange bolts. A similar procedure would apply for SMFs with bolted SidePlate (SP) connections.



(a) (b)

Fig. 2 *Results from experimental testing of BFP connection with W36×150 beam: (a) hysteretic plot, (b) minor beam damage near 2% drift (Sato, Newell, and Uang, 2007)*

Fig. 3 shows the response of a DuraFuse Frames (DFF) connection with a W36×150 beam (Richards, 2021). The hysteretic response [Fig. 3(a)] is similar to the BFP connection for low drifts and, at 2% drift, most of the inelasticity is from bolt slip (on the flat portion of the hysteretic curve). Fig. 3(c) shows the fuse plate at between 1 and 2% drift. Minor yielding is localized and the fuse plates would not require replacement (see further discussion in next section). If there are no residual drifts, no repair is needed. If residual drifts needed to be addressed, the bottom flange bolts could be removed, the building replumbed, and the bottom flange bolts replaced; *similar to any other bolted SMF connection. DFF fuse plates do not require inspection, repair, or replacement for small or moderate earthquakes.*



(a) (b)

(c)

Fig. 3 *Results from experimental testing of BFP connection with W36x150 beam: (a) hysteretic plot showing drift from bolt slip in small cycles, (b) connection at 2% drift, (c) localized fuse yielding between 1 and 2% drift (would not require repair)*

Severe Earthquakes

Welded Connections

Severe earthquakes will result in larger drifts and welded SMF connections will experience higher inelastic strains and local buckling in the beam plastic hinge region. Fig. 4 shows an RBS connection at 3% and 4% drift. Flange and web local buckling result in a drop of strength, and negative stiffness on the backbone curve [see Fig. 1(a), strength loss after 2% drift]. Proposed repair procedures entail shoring the beam, cutting out the yielded section, re-plumbing the building (while shoring the beams), and remaking the beam-to-column and beam-to-beam connections. If beams were yielded throughout an entire building, repair may be impractical.

(a) (b)

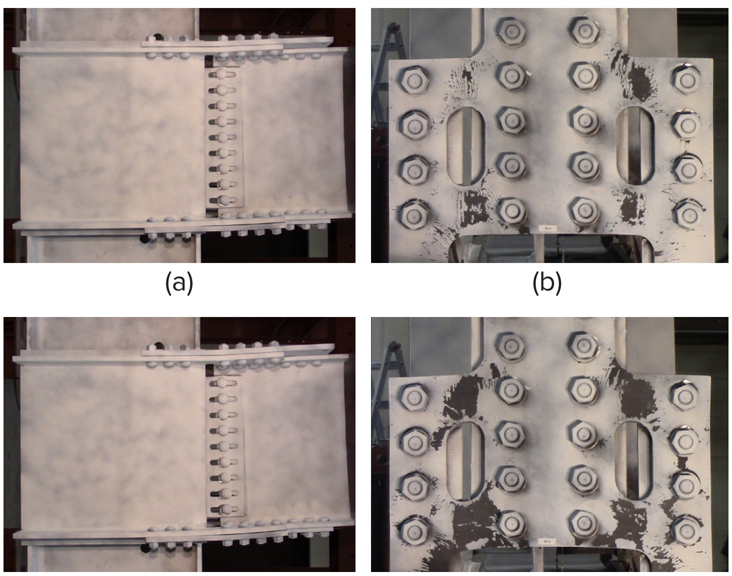
Fig. 4 *Results from experimental testing of RBS connection with W36×150 beam: (a) 3% drift; (b) 4% drift (Gilton, Chi, and Uang, 2000)*

Bolted Connections that Rely on Beam Yielding

Most bolted SMF connections rely on beam yielding to achieve the required 0.04 rad drift angle. For a bolted SidePlate (SP) connection with a W36×150 beam, a full plastic hinge forms at 3% drift, followed by flange and web local buckling at 4% drift (SidePlate, 2016); similar to Fig. 4. This type of damage results in strength loss and negative backbone stiffness. The proposed procedure to repair this beam damage entails shoring the beams, cutting out the yielded sections, replacing the yielded sections, and remaking the beam-to-column and beam-to-beam connections. If beams were yielded throughout an entire building, repair may be impractical.

Bolted Connections that Rely on Fuse Plate Yielding

DFF connections are designed to prevent beam yielding during severe earthquakes. Fig. 5 shows a DFF connection at 3 and 4% drift (Richards, 2021). There is no beam yielding and all damage has been confined to the fuse plate. Experimental testing has shown that a fuse plate can dissipate the energy from three or more MCE level events (see next section). Thus, replacement of the fuse plates is only necessary if it is required to address residual drifts.



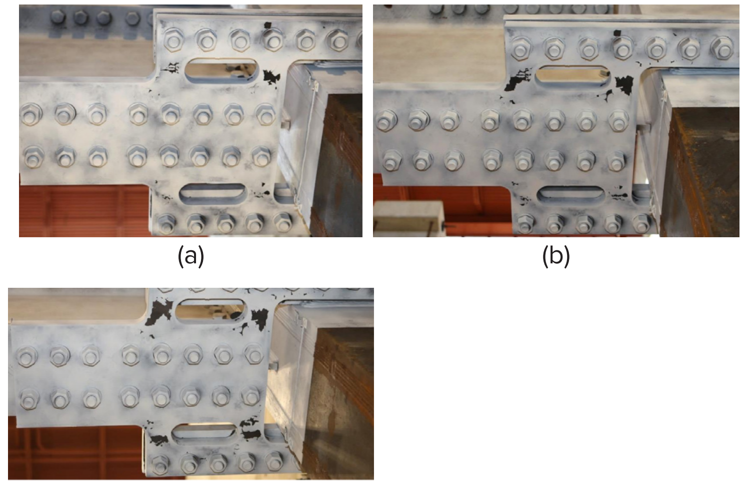
(a) (b) (c) (d)

Fig. 5 *Results from experimental testing of DFF connection with W36×150 beam: (a) 3% drift, (b) fuse at 3% drift, (c) 4% drift, (d) fuse at 4% drift (Richards, 2021)*

When Do DFF Fuse Plates Require Replacement?

In general seismic design, there are two criteria that dictate the need to replace structural fuses in a building. The first criteria is if the energy dissipating capacity of the fuse is used up. The second criteria is if residual drifts cannot be fixed without a new fuse. DFF fuse replacement will be discussed in the context of these two criteria.

Experimental testing has quantified the energy dissipation capacity of DFF connections. DFF connections generally complete three to five large displacement cycles beyond those required for qualification using the standard loading protocol (Reynolds and Uang, 2019a). This represents two to four times the energy dissipation demand for a severe earthquake. DFF testing has also been conducted using loading protocols more representative of actual earthquake shaking. Specimen H1.2 was tested under three MCE level events, back-to-back, without fuse replacement (Reynolds and Uang, 2019b). Fig. 6 shows that the H1.2 fuse had additional capacity even after the three consecutive MCE events. Based on the experimental testing that has been conducted, it is unlikely that the first criteria (exhausted energy dissipation capacity) will ever dictate the replacement of a DFF fuse.



(a) (b) (c)

Fig. 6 *Experimental testing of a DFF connection with a W36×232 beam subjected to three consecutive MCE events without replacing fuse plate: (a) after Northridge scaled to MCE, (b) after Loma Prieta scaled to MCE, (c) after Kobe scaled to MCE.*

The second criteria for fuse replacement relates to residual drift. After a severe earthquake that causes extensive fuse plate yielding, there may be residual drifts that need to be addressed. If the fuse plate is distorted, it will need to be replaced in order to fit in the re-plumbed frame.

So when will DFF plates require replacement? Only after severe earthquakes that result in large residual drifts.

Summary and Conclusions

Special moment frames (SMFs) are expected to experience significant inelastic deformations during large seismic events (AISC, 2016). The required 0.04 rad drift angle for SMFs is greater than the 0.01 to 0.025 rad drift limits used for design, compensating for the fact that the MCE is not used in design and the C_d factor is known to be non-conservative for some cases.

For moderate and severe earthquakes some amount of inelastic behavior is expected in all SMFs. Welded moment frames are susceptible to damage that is the most difficult to repair. For moderate earthquakes that require repair, bolted SMFs, including DuraFuse Frames (DFF), might be repaired without replacing any steel.

For severe earthquakes, DuraFuse Frames offer better repairability that other SMFs because beam yielding is prevented and the fuse is accessible. Experimental testing has demonstrated that DFF fuses have sufficient energy dissipation capacity to handle multiple MCE events. DFF fuses will only require replacement after severe events that result in large residual drifts.

References

AISC (2016). "ANSI/AISC 341-16: Seismic Provisions for Structural Steel Buildings." American Institute of Steel Construction (AISC), Chicago, IL.

ASCE (2016). "ASCE/SEI 7-16, Minimum Design Loads and Associated Criteria for Buildings Structures." American Society of Civil Engineers, Reston, VA.

Erochko, J., Christopoulos, C., Tremblay, R., and Choi, H. (2011). "Residual Drift Response of SMRFs and BRB Frames in Steel Buildings Designed according to ASCE 7-05." Journal of Structural Engineering, 137(5), 589-599.

Gharibans, E., Lou, K., Gupta, B., Uang, C.-M., and Richards, P. W. (2003). "Seismic design of steel moment frames with deep columns and reduced beam sections: a case study." Structural Engineers Association of California (SEAOC) 72nd Annual Convention, SEAOC, Squaw Creek, CA.

Karavasilis, T. L., Bazeos, N., and Beskos, D. E. (2007). "Estimation of seismic drift and ductility demands in planar regular X-braced steel frames." Earthquake Engineering & Structural Dynamics, 36(15), 2273-2289.

Medina, R., and Krawinkler, H. (2005). "Evaluation of Drift Demands for the Seismic Performance Assessment of Frames." Journal of Structural Engineering, 131(7), 1003-1013.

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." University of California San Diego, La Jolla, CA.

Reynolds, M., and Uang, C.-M. (2019b). "Cyclic Testing of DuraFuse (DF) Moment Frame Connections for SMF and IMF Applications: Series H Specimens." University of California San Diego, La Jolla, CA.

Richards, P. W. (2021). "Cyclic Hardening Factor for Replaceable Shear Fuse Connections." Journal of Constructional Steel Research, In Press.

Richards, P. W., and Thompson, B. (2009). "Estimating Inelastic Drifts and Link Rotation Demands in EBFs." Engineering Journal (AISC), 46(3), 123-135.

Sato, A., Newell, J., and Uang, C.-M. (2007). "Cyclic Testing of Bolted Flange Plate Steel Moment Connections for Special Moment Frames." University of California San Diego, La Jolla, CA.

SidePlate (2016). "SidePlate Bolted SMF Test U3 Close up." YouTube, https://www.youtube.com/watch?v=vwxF8GoRq0Q.

Uang, C. M., and Maarouf, A. (1994). "Deflection Amplification Factor for Seismic Design Provisions." Journal of Structural Engineering, 120(8), 2423-2436.

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