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M-Factors for the DuraFuse Frames Arrow Connection

Paul Richards, PhD, PE¹

Abstract: Most pre-Northridge buildings with steel special moment frames (SMF) do not meet current seismic performance standards. When engineers evaluate such buildings and consider retrofit options, they often perform linear analysis and use m-factors to account for nonlinear effects. This bulletin describes the development of m-factors for the DuraFuse Frames Arrow connection. Data from full-scale experimental testing were used to develop a general backbone curve for the connection. The m-factors obtained from the curve were 4.7 for life safety (LS) and 5.9 for collapse prevention (CP). These m-factors are higher than those for welded haunch retrofits and reflect the excellent performance of the DuraFuse Frames Arrow connection.

Introduction

The 1994 Northridge earthquake revealed unacceptable performance of steel special moment frames (SMF). Fractures of SMF beam-to-column welds, that were observed in buildings after Northridge (Youssef et al. 1995), were replicated in laboratories (Sabol et al. 1996; Uang et al. 1998; Yang and Popov 1995) and found to be related to inherent problems with the prescriptive pre-Northridge connection detail. Design requirements for new construction address these issues, but many pre-Northridge buildings have SMF connections with limited/no ductility. Most pre-Northridge buildings will not have life safety (LS) performance for the design earthquake unless they have been retrofitted.

To assist engineers with seismic evaluation and retrofit, the American Society of Civil Engineers (ASCE) developed ASCE 41 (2017). This standard describes a variety of analysis procedures that can be used to evaluate capacities and demands on components in existing buildings or retrofit designs. The linear analysis procedures in ASCE 41 are the easiest to use since they employ relatively simple elastic models like those used for the majority of new building designs.

When linear analysis procedures are used for seismic design, factors are used to account for the non-linear response that would actually occur during severe earthquake shaking. In ASCE 41 (2017), the expression below

is used to check components when the strength demand, Q_{UD} , comes from a linear analysis.

$$m\kappa Q_{CE} > Q_{UD} \quad \text{Eq. 7-36 in ASCE 41}$$

In EQ. 7-36, m is a factor that reflects connection ductility (conceptually similar to an R factor) and amplifies the capacity. The other terms on the capacity side (left side of the equation) are a knowledge factor, κ , and the expected strength of the component, Q_{CE} . The m -factor is based on the deformation associated with a particular performance level. For a life safety (LS) performance level, the m -factor is based on deformations associated with life safety. For a collapse prevention (CP) performance level, more deformation is acceptable, and the m -factor will be higher.

M-factors for older connections can be read from a table in ASCE 41 and m -factors for new connections can be calculated from experimental test results. Table 9-6 in ASCE 41 (2017) provides m -factors for connections and retrofit strategies that were in the literature at the time the standard was developed. For newer alternatives, Section 7.6 of ASCE 41 provides a method for determining m -factors. The method involves developing a general backbone curve from testing data and calculating the ratios of different deformation values on the backbone.

1. Vice President, DuraFuse Frames, 5801 West Wells Park Road, West Jordan, UT 84081. Email: paul.richards@duraFuseframes.com

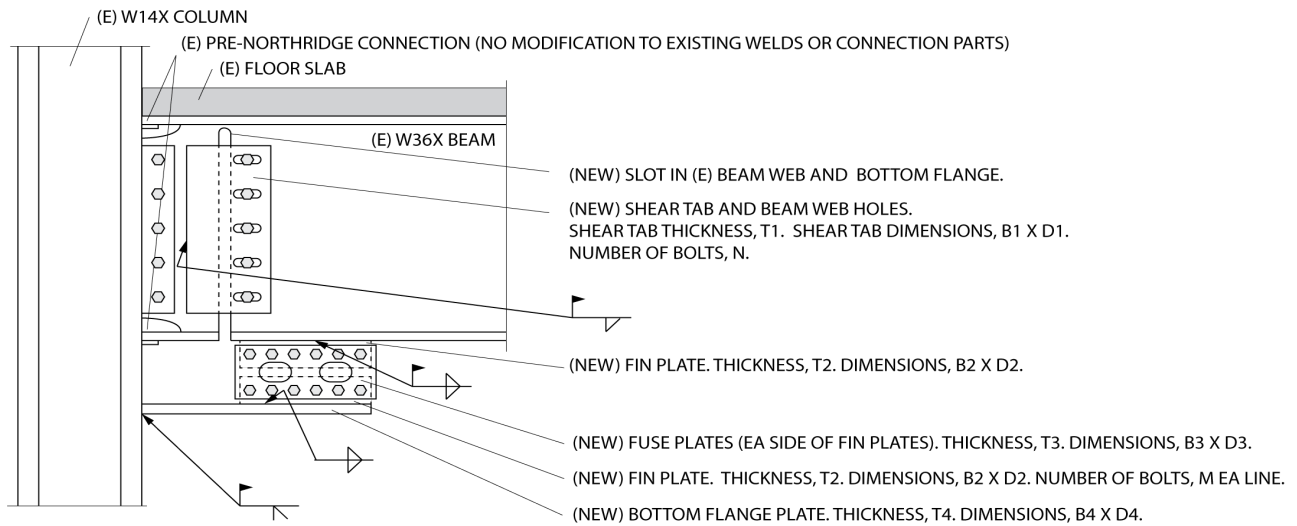


Fig. 1. *DuraFuse Frames (DFF) Arrow Retrofit*

One of the newest alternatives for SMF retrofit is the DuraFuse Frames (DFF) Arrow configuration (Richards 2020). The DFF Arrow has fuse plates, installed in a haunch configuration, that prevent yielding in the beam and column during severe earthquake shaking (Fig. 1). The DFF Arrow configuration has been experimentally validated at full-scale (Lee and Uang 2021) and is pre-qualified for use in new construction (UES 2020). It can also be applied in retrofit applications (Fig. 1). Since the DFF Arrow is an attractive retrofit option, it is useful to have m-factors for the connection.

This bulletin presents the derivation of m-factors for the DFF Arrow configuration following the procedure in ASCE 41 (2017).

M-Factor Derivation

This section presents the derivation of the m-factors for the DuraFuse Frames Arrow retrofit. The first step for m-factor derivation was to summarize back-bone curves from the experiments. Fig. 2 shows the backbone curves from three specimens J1.1, J2.1, and J3.1 (Lee and Uang 2021). Specimens J1.1 and J2.1 were tested cyclically with the protocol in AISC 341 (2016). Specimen J3.1 was tested monotonically. It is common for monotonic tests to get to larger deformations (see J3.1 in Fig. 2)

because there is less fatigue as compared to cyclic testing. Specimen J3.1 had higher moment at lower deformations because there was less bolt slip (Lee and Uang 2021).

The next step was to construct a simplified backbone based on the experiments. It is permitted to construct the simplified backbone from a combination of cyclic and monotonic test data (ASCE 2017). The dashed line in Fig. 2 shows the simplified backbone. Point E in Fig. 2 matches the maximum displacement attained in the monotonic test.

With the simplified backbone constructed, the calculation of the m-factors for life safety (LS) and collapse prevention (CP) limit states was straightforward. For LS, the m-factor was 0.75 times the ratio of 0.75 times the displacement at point C to the displacement at point B (ASCE 2017):

$$m = (.75)[0.75(0.05)/(0.006)] = 4.7$$

For CP, the m-factor was governed by 0.75 times the ratio of 0.75 times displacement at point E to the displacement at point B (ASCE 2017):

$$m = (.75)[0.75(0.063)/(0.006)] = 5.9$$

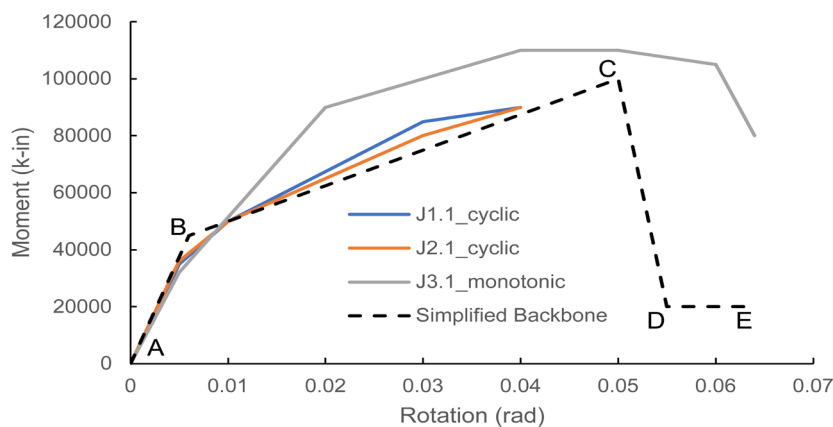


Fig. 2. *Backbone curves from experimental testing of DFF Arrow*

M-factor Comparison

Table 1 compares the m-factors for DFF Arrow with those for a welded bottom haunch retrofit (ASCE 2017). The m-factors for the DFF Arrow connection were significantly greater, primarily because the DFF Arrow qualification testing included a monotonic test, while welded haunch did not, resulting in a more favorable general backbone curve. The practical conclusion of the comparison was that the DFF Arrow retrofit can be used in place of a welded bottom haunch retrofit in all circumstances.

Table 1. *M-factor comparison of DFF Arrow and bottom haunch retrofit*

Retrofit	m-Factors for Linear Procedures	
	LS	CP
Bottom haunch in WUF with slab	2.7	3.4
DFF Arrow with Slab	4.7	5.9

Independent Review

When m-factors are derived from experimental test results, Section 7.6 of ASCE 41-17 requires independent review of the process by a reviewer that is experienced with the use of test data in the design and analysis of structures.

The suggested method for complying with this process for DuraFuse Arrow is:

1. EOR independently determines m-factors based on experimental results (DuraFuse Frames LLC can provide information from experiments; this technical bulletin can function as a guide for determining m-factors).
2. DFF LLC provides an independent review of the EOR's parameter derivation. Dr. Paul Richards at DFF has 20+ years of experience in the use of test data in the design and analysis of structures. If the EOR chooses to use a backbone curve and m-factors similar to those discussed herein, DuraFuse Frames can provide a stamped letter describing the independent review as required by AISC 341-17 Section 7.6.

Conclusion

Many existing buildings with special moment frames (SMF) do not meet life-safety requirements and need retrofit. Since m-factors are commonly used for retrofit design, the m-factors for the DuraFuse Frames Arrow connection were derived. Results from experimental testing were used for the derivation, following the procedures in Section 7.6 of ASCE 41 (2017). The m-factors obtained from the results were 4.7 for life safety (LS) and 5.9 for collapse prevention (CP). These m-factors are greater than other connection retrofit options, making the DFF Arrow connection the top-performing solution for SMF connection retrofits.

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