



Local and lateral torsional buckling of 36 in. deep beams with IMF end-plate moment connections

Maria A. Mercado-Celin¹, Matthew R. Eatherton², Thomas M. Murray³

Abstract

Previous testing has shown that four-bolt extended unstiffened end-plate moment connections can be used with beams up to 24 in. deep and develop sufficiently ductile performance to satisfy seismic qualification. It is desirable to extend this depth limit to allow deeper beams for intermediate moment frames. Three moment connection specimens using built-up 36 in. deep beams with a four-bolt extended unstiffened end-plate moment connection, were tested to determine if they satisfy the intermediate moment frame qualification criteria given in AISC 341. The web of the specimens satisfied the moderately ductile section criteria for web slenderness, which is required for intermediate moment frames, but not highly ductile section criteria required for special moment frames.

All three specimens passed qualification criteria for intermediate moment frames (IMF) as given in AISC 341-16 by retaining at least 80% of the nominal plastic moment strength through 2% story drift. The observed failure modes included lateral torsional buckling of the specimen, flange local buckling, fracture of the flanges, and failure of the flange-to-web fillet weld. The results of these tests support current moderately ductile limits associated with lateral bracing and cross-section slenderness given that the associated specimens reached IMF qualification criteria, but not special moment frame (SMF) criteria. It was concluded that four-bolt extended unstiffened end-plate moment connections satisfy intermediate moment frame requirements with a beam depth of 36 in. and that a modification is needed for beam web to flange welds in built-up sections near the moment connection.

1. Introduction

Previous cyclic testing on four-bolt extended unstiffened (4E) end-plate moment connections with beams deeper than 24 in. have failed to satisfy the intermediate or special moment frame (IMF or SMF) qualification criteria given in AISC 341 Seismic Provisions for Structural Steel Buildings ANSI/AISC 341-16 (AISC 2016). Ryan and Murray (1999) tested one 4E specimen with 55 in. deep beam that resulted in bolt fracture at 0.01 rad rotation and Blumenbaum and Murray (2004) tested two 4E specimens with 60 in. deep rafters that resulted in bolt fracture and out of plane buckling at 0.01 rad to 0.02 rad. of inelastic rotation. Conversely, tests by Sumner et. al. (2000) and Meng and Murray (1996) reported successful SMF qualification tests of 4E moment connection specimens with W24x68 and W24x76 sections.

¹ Graduate Research Assistant, Virginia Polytechnic Institute and State University, <mariamercado@vt.edu>

² Professor, Virginia Polytechnic Institute and State University, <meather@vt.edu>

³ Emeritus Professor, Virginia Polytechnic Institute and State University, <thmurray@vt.edu>

To facilitate longer spans, it is desirable to allow the use of 4E connections in IMF or SMF with beams deeper than 24 in. For that reason, a testing program was conducted to determine the required connection detailing such that the connection has sufficient ductility to achieve IMF qualification criteria with 36 in. deep beams. The testing program utilized specimens with webs satisfying moderately ductile, but not highly ductile criteria and lateral bracing that satisfied either IMF or SMF criteria. This study, therefore, represents a unique opportunity to investigate the distinction between IMF and SMF in terms of inelastic lateral torsional buckling and local buckling behavior.

2. Experimental Program

2.1 Test Specimens

The specimens were designed according to the design procedures in AISC 358s2-20 (AISC 2020). The test beams were built-up sections with 5/8 in. by 8 in. flanges and 1/2 in. thick webs. The flanges satisfy highly ductile section criteria, per AISC 341-16 (AISC 2016), and the webs satisfy moderately ductile section criteria. The detailing of the moment connection satisfied requirements of AISC 358s2-20. The built-up beams were fabricated using A572 Grade 55 steel for the flanges, HSLA55 steel for the webs, and A572 Grade 50 for the end plates. Table 1 is the text matrix, Figure 1 shows beam and end-plate details, and Table 2 and Table 3 give specific dimensions.

The specimen identification is given with the bolt configuration (4E for four-bolt extended unstiffened), bolt diameter (1.5 for the 1.5 in. A490 bolts), end-plate thickness (1.75 in.), beam depth (36 in.) and then a letter to distinguish between the three specimens. The specimens are therefore labeled, 4E-1.5-1.75-36a, 4E-1.5-1.75-36b, and 4E-1.5-1.75-36c.

In accordance with Section 6.3.1(1) of AISC 358s2-20, the beam web-to-beam flange weld was specified to be 3/8 in. double-sided fillet with a minimum required length of 24 in., which was used for Specimen 4E-1.5-1.75-36a and 4E-1.5-1.75-36b. The length of double-sided fillet weld was increased to 48 in. for Specimen 4E-1.5-1.75-36c.

To make efficient use of the steel beams, both ends of each beam had end-plates attached so that two unique specimens could be created with one beam. A set of four holes in the beam flange were included in all specimens, centered at a distance, L2, from the outside face of the end-plate (See Figure 1 and Table 3). The holes in the beam flange facilitate connection to the actuator when testing the far side end-plate connection. The distance from outside face of end plate to centerline of the bolt holes, L2, was extended for Specimens 4E-1.5-1.75-36b and 4E-1.5-1.75-36c.

Table 1: Test Matrix

Specimen Identification	Beam Depth, d (in.)	Bolts	End-Plate Thickness (in.)	Double Fillet Weld Length (in.) ¹	Lines of Lateral Bracing
4E-1.5-1.75-36a	36	1-1/2 in. A490	1-3/4	24	2
4E-1.5-1.75-36b	36	1-1/2 in. A490	1-3/4	24	3
4E-1.5-1.75-36c	36	1-1/2 in. A490	1-3/4	48	3

1. Length of double-sided fillet weld at the beam web-to-beam flange, measured from the outside face of the end-plate (see dimension L3 in Figure 1)

Table 2: Specimen Thicknesses, all units are inches

Specimen	Web Thickness		Lower Flange Thickness		Upper Flange Thickness		End Plate thickness	
	Nominal	Measured	Nominal	Measured	Nominal	Measured	Nominal	Measured
4E-1.5-1.75-36a	0.50	-	0.625	0.628	0.625	0.624	1.75	1.781
4E-1.5-1.75-36b	0.50	0.535	0.625	0.64	0.625	0.625	1.75	1.765
4E-1.5-1.75-36c	0.50	0.535	0.625	0.625	0.625	0.64	1.75	1.765

Table 3: Specimen Dimensions, all units are inches

Specimen	Length, L1	Length, L2	Length, L3
4E-1.5-1.75-36a	20'-2-7/8	5'-0	24
4E-1.5-1.75-36b	23'-8-7/8	8'-6	24
4E-1.5-1.75-36c	23'-8-7/8	8'-6	48

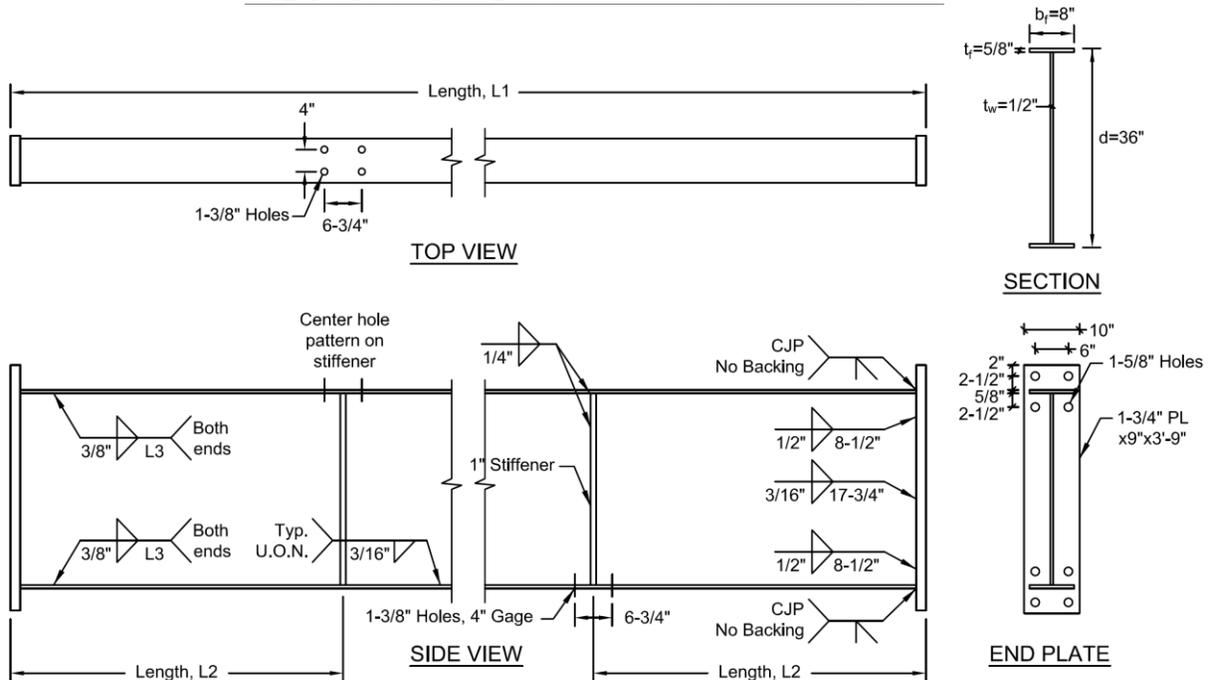


Figure 1: Details of the Beam

2.2 Test Setup

Three tests were conducted, in accordance with AISC 341-16 Chapter K, at the Thomas M. Murray Structural Engineering Laboratory at Virginia Tech. A schematic of the test setup is shown in Figure 2 and a photograph is in Figure 3. The setup used in this study simulated an exterior moment connection in a structure with 32 ft. wide bays and a 12 ft. story height. The reaction column was a W14x398. Force was applied by an MTS 201.70 servo hydraulic actuator with ± 10 in. stroke and a tension capacity of 220 kips.

Lateral bracing for specimen 4E-1.5-1.75-36a, was provided at the end of the plastic hinge and near the point of loading as shown in Figure 2. This lateral bracing satisfies IMF requirements in AISC 341-16 Section D1.2a.1, but not SMF requirements in Section D1.2b. An additional line of lateral bracing was added for specimen 4E- 1.5 – 1.75-36-2 and specimen 4E- 1.5 – 1.75-36-3 (See Figure 3), to meet the unbraced length required for SMF.

Lateral bracing consisted of steel frames with adjustable steel angles that were moved until the face of the angle was approximately 1/16 in. away from the flange tips. Lithium grease was applied to the face of the angles to reduce friction during the test. An example of the lateral bracing is shown in Figure 4.

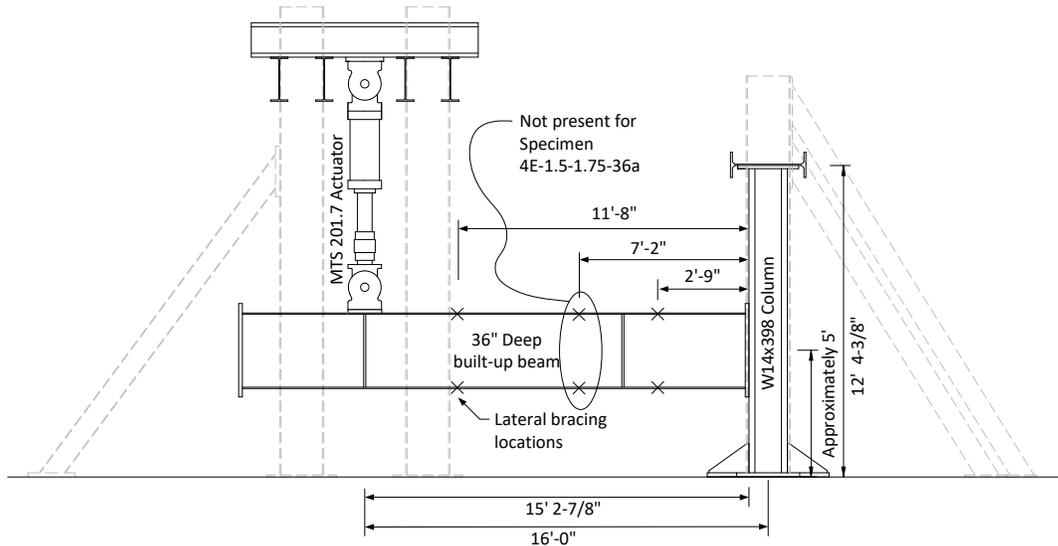


Figure 2: Schematic of Test Setup



Figure 3: Photograph of the Test Setup

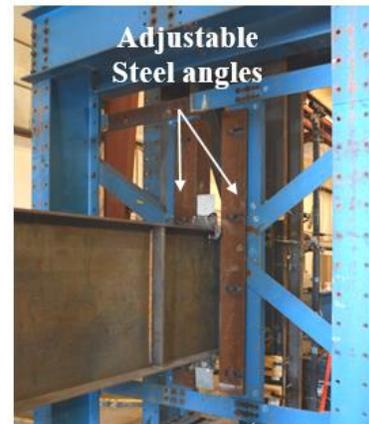


Figure 4: Beam Lateral Bracing

2.3 Instrumentation plan

The instrumentation plan is shown in Figure 5. String potentiometers SP_01, SP_02, SP_03 and SP_08 were used to measure column movement. String potentiometers SP_04 and SP_05 measured beam vertical movement and SP_06, SP_07 and SP_09 measured end-plate movement with respect to the beam flanges. Two instrumented spring calipers, CLP_01 and CLP_02 were used to measure the end-plate separation from the column flange. Linear potentiometers LP_01 and LP_02 measured panel zone shear deformations. The applied force and displacement were measured by the actuator's internal load cell and displacement transducer. All sensors were connected to a National Instruments data acquisition system which was managed using National Instruments Signal Express software. Measurements from all sensors were recorded at 3 Hz.

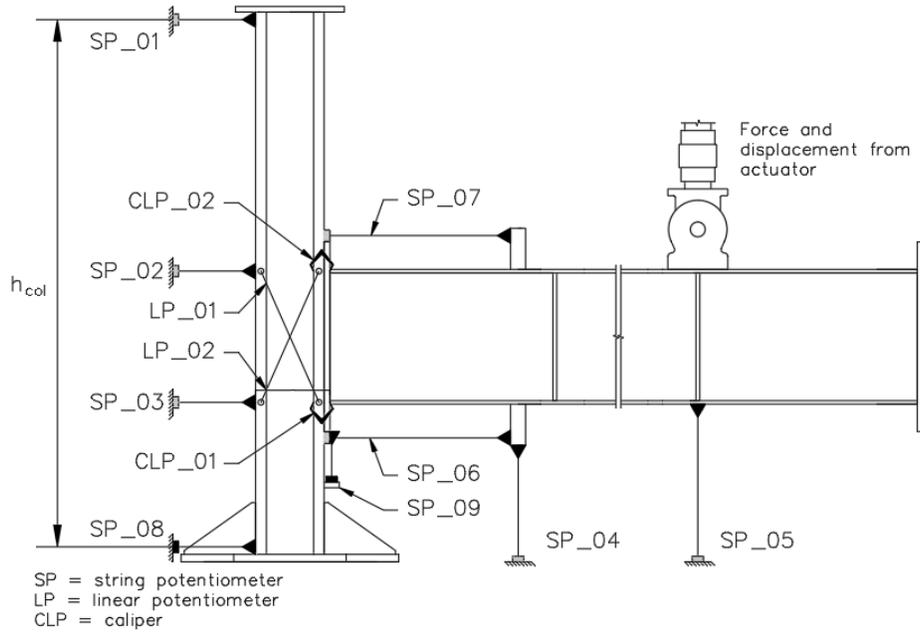


Figure 5: Instrumentation plan for tests

2.4 Displacement Protocol and Qualification Criteria for IMF and SMF

The cyclic displacement protocol from AISC 341-16 Chapter K for qualification testing of IMF and SMF moment connections was used and is given in Table 4. The maximum displacement that could be applied corresponded to 4.5% story drift based on the location and maximum stroke of the actuator. The displacement rate was 0.00025 radians/second which corresponds to a vertical displacement at the actuator of approximately 2.88 in./min.

Table 4: AISC 341-6 Displacement Protocol for Moment Connection Tests

Story Drift Target		Number of Cycles
Radians	Percent	
0.00375	0.375	6
0.005	0.5	6
0.0075	0.75	6
0.01	1	4
0.015	1.5	2
0.02	2	2
0.03	3	2
0.04	4	2
0.045	4.5	Until fracture

The story drift was calculated real-time within the MTS control software using external feedback, and then used to control the actuator displacement to produce the story drifts given in Table 4. The applied story drift, θ_{APP} , was calculated in the MTS MultiPurpose Testware calculations module using Eq. 1.

$$\theta_{APP} = \frac{-\delta_{SP-05}}{L_{cl}} - \frac{\delta_{SP-01} - \delta_{SP-08}}{h_{col}} \quad (1)$$

where:

h_{col} = distance between SP_01 and SP_08, 137 in.

L_{cl} = distance from the actuator centerline to column centerline, 192 in.

δ_{SP-01} = displacement measured by SP_01, in.

δ_{SP-05} = displacement measured by SP_05, in.

δ_{SP-08} = displacement measured by SP_08, in.

The qualification criteria for intermediate moment frame connections in AISC 341-16 states that the connection must maintain a moment strength at the face of the column of at least 80% of the nominal beam plastic moment strength through the first cycle of 2% story drift. The moment at the face of the column was calculated as the applied load multiplied by the distance from the actuator to the face of the column, 15.23 ft. Based on the beam cross-section shown in Figure 1 with plastic section modulus, $Z_x=328 \text{ in}^3$, and a nominal yield stress of $F_y=55 \text{ ksi}$, the nominal plastic moment strength of the beam is, $M_p=18,040 \text{ k-in}$.

3. Results

3.1. IMF Qualification

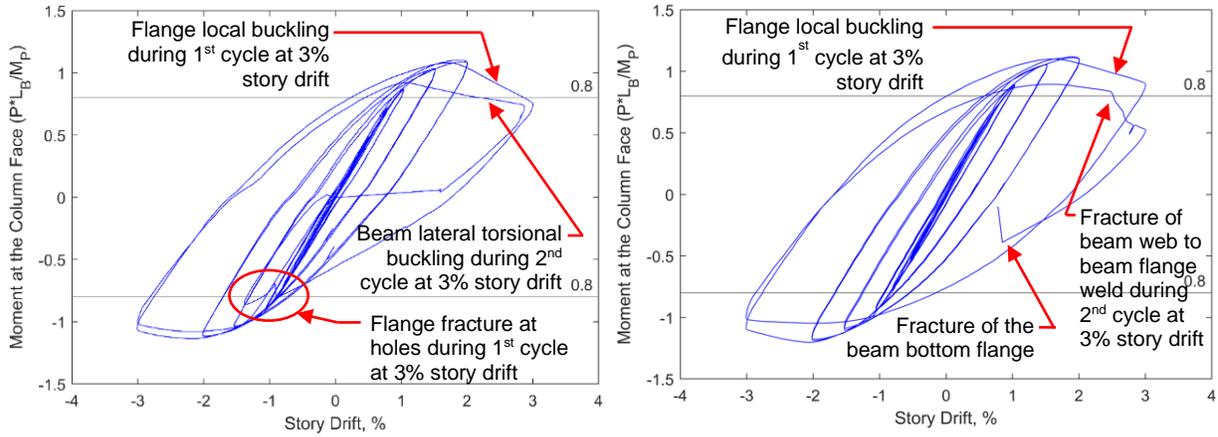
All three specimens passed qualification criteria for intermediate moment frames (IMF) as given in AISC 341-16 by retaining at least 80% of the nominal plastic moment strength through 2% story drift. Table 4 gives the moment strength for each specimen at the positive and negative peak during the first cycle at 2% story drift, values significantly larger than $0.8M_p = 1202 \text{ k-ft}$. The three specimens had almost identical behavior through the 2% story drift cycles, as shown in Figure 6, with no observable flange local buckling or strength degradation while the flanges yielded. Specimen 4E-1.5-1.75-36c survived to the 4% story drift cycles, but as shown in Table 4, due to local buckling of the section, the moment strength dropped to approximately 95% of the required moment strength to reach special moment frame (SMF) qualification (1149 k-ft compared to the required 1202 k-ft). The end-plate separation remained small for all tests with a maximum value of approximately 0.12 in. for one specimen, and was less than 0.06 in. for the other two specimens. There was no observed yielding or damage to the end-plates or bolts during any of the tests. This suggests that the design procedures in AISC 358 for the end-plate and bolts were sufficient for this connection.

Table 4: Summary of Qualification Status for Each Specimen

Specimen	First Cycle at Story Drift of	Moment at Positive Peak ¹	Moment at Negative Peak ¹	Qualification ²
4E-1.5-1.75-36a	2%	1656 k-ft	1619 k-ft	IMF
4E-1.5-1.75-36b	2%	1650 k-ft	1755 k-ft	IMF
4E-1.5-1.75-36c	2%	1711 k-ft	1712 k-ft	IMF
	4%	1214 k-ft	1149 k-ft	

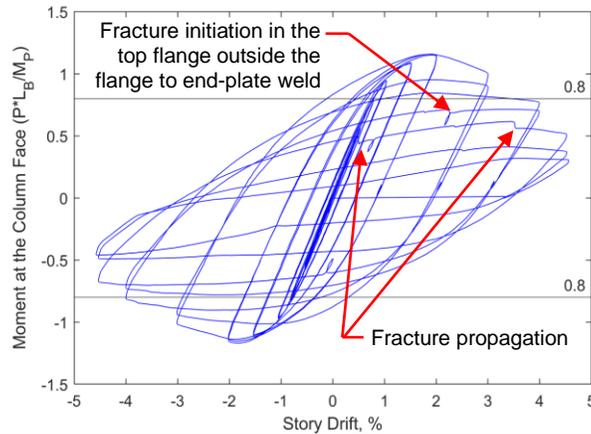
¹ Moment calculated at the column face

² Qualification is reached if moment strength is greater than $0.8M_p = 1202 \text{ k-ft}$



(a) Specimen 4E-1.5-1.75-36a

(b) Specimen 4E-1.5-1.75-36b



(c) Specimen 4E-1.5-1.75-36c

Figure 6: Hysteretic Behavior of the three Specimens

3.1. Specimens Response

The first two specimens experienced several undesirable limit states that were progressively mitigated until the third specimen for which all these limit states were prevented. As shown in Table 5, Specimen 4E-1.5-1.75-36a and 4E-1.5-1.75-36b survived to the 3% story drift cycles, while Specimen 4E-1.5-1.75-36c exhibited excellent fracture resistance and ductility surviving multiple cycles at 4.5% story drift before the test was stopped. The individual limit states for Specimens 4E-1.5-1.75-36a and 4E-1.5-1.75-36b are discussed in the subsequent paragraphs. Figure 7 shows the final condition of each specimen. Greater deformations were achieved as the specimens and test setup were retrofitted based on the failure modes observed.

Table 5: Summary of Failure Mode for Each Specimen

Specimen	Peak Story Drift Attained	Failure Mode
4E-1.5-1.75-36a	2 Cycles at 3%	Lateral torsional buckling
4E-1.5-1.75-36b	2 Cycles at 3%	Fracture of beam web-to-beam flange weld, then flange fracture
4E-1.5-1.75-36c	3 Cycles at 4.5%	Flange local buckling, fracture of the flange outside the CJP weld at the end-plate



(a) Specimen 4E-1.5-1.75-36a (b) Specimen 4E-1.5-1.75-36b (c) Specimen 4E-1.5-1.75-36c
 Figure 7: Final State at the Connection of each Specimen

Beam Net Section Fracture of Specimen 4E-1.5-1.75-36a (Not Related to Qualification)

Specimen 4E-1.5-1.75-36a experienced a net section fracture of the beam at the location of a set of holes approximately 4.75 ft from the face of the column, as shown in Figure 8. AISC 360-16 Section F13 provides a way to check for such a limit state based on a ratio of the flange net area to the flange gross area. The required moment strength at the location of the bolt holes associated with the beam developing the maximum probable moment strength, M_{pr} , at the column face is calculated as, $M_u=1229$ k-ft. The nominal moment strength calculated in accordance with AISC 360-16 Section F13 is found to be $M_n=1037$ k-ft, which is less than the required moment strength, M_n , and therefore suggests that the beam flange is susceptible to beam net section fracture. It is noted that at the time of fracture, the moment at the face of the column was approximately 65% of M_{pr} which was used in the calculation, but during the previous cycle, the moment at the column face was close to M_{pr} . It is possible that net section fracture initiated during the previous cycle but was not noticed. The specimen was repaired by welding a flange plate to the outside of the bottom flange as shown in Figure 9, in an effort to continue the test.



Figure 8: Bottom Flange Fracture at Bolt Holes of Specimen 4E-1.5-1.75-36a



Figure 9: Bottom Flange Repair with Welded Plate of Specimen 4E-1.5-1.75-36a

For Specimens 4E-1.5-1.75-36b and 4E-1.5-1.75-36c, the distance from the column face to the first set of bolt holes was increased to approximately 8.25 ft which was selected so that the required moment strength, $M_u=750$ k-ft was less than the design moment, $\phi M_n=778$ k-ft. Neither of these specimens experienced net section fracture of the beam suggesting that the requirements of AISC 360 Section F13 were effective in preventing this limit state.

Lateral Torsional Buckling of Specimen 4E-1.5-1.75-36a

After the bottom flange repair, Specimen 4E-1.5-1.75-36a also underwent lateral torsional buckling in the unbraced length equal to 107 in, as shown in Figure 10. According to AISC 341-16, the maximum unbraced length for moderately ductile, $L_{b,Mod}$, and highly ductile, $L_{b,High}$, are given by Eq. (2) and Eq. (3).

$$L_{b,Mod} = 0.19r_y E / (R_y F_y) = 128 \text{ in.} \quad (2)$$

$$L_{b,High} = 0.095r_y E / (R_y F_y) = 64 \text{ in.} \quad (3)$$

The provided unbraced length for Specimen 4E-1.5-1.75-36a was 107 in., meeting the requirements for moderately ductile section requirements for IMF, but not highly ductile section requirements for SMF. This is consistent with the results obtained where Specimen 4E-1.5-1.75-36a experienced lateral torsional buckling after passing 2% story drift cycles (IMF), but before reaching 4% story drift (SMF).

The unbraced length for Specimen 4E-1.5-1.75-36c, was 54 in. which satisfied highly ductile section and thus SMF design requirements. This is also consistent with the resulting behavior in that the specimen reached and exceeded 4% story drift without experiencing lateral torsional buckling.



Figure 10: Lateral Torsional Buckling of the Beam of Specimen 4E-1.5-1.75-36a

Buckling and Fracture Behavior of Specimen 4E-1.5-1.75-36b

Specimen 4E-1.5-1.75-36b underwent flange and web local buckling, shown in Figure 11 and Figure 12, with associated reduction in moment strength. In addition, Figure 13 shows the weld fracture at the beam web to the beam flange joint where the weld transitioned from 3/8 in. double-sided fillet weld to 3/16 in. single-sided fillet weld. The requirement for the double-sided fillet weld comes from AISC 358s2-20 Section 6.3.1(1) which requires that at moment-connected ends of welded built-up sections, within at least the depth of beam or three times the width of flange, whichever is less, the beam web and flanges shall be connected using either a complete joint penetration (CJP) groove weld or a pair of fillet welds each having a size 75% of the beam web thickness but not less than 1/4 in. For the specimens in this study, the requirement results in a 3/8

in. double-sided fillet weld (or CJP weld) that extends for 24 in. Beyond this region, the beam web to flange weld is designed for shear transfer, which for these specimens allows the use of a 3/16 in. single-sided fillet weld.



Figure 11: Flange local buckling during the first cycle at 3% story drift



Figure 12: Beam flange local buckling extending approximately 3 ft to 4 ft from the face of the column



Figure 13: Fracture of Beam Web to Beam Flange Weld of Specimen 4E-1.5-1.75-36b



Previously tested 4E specimens that satisfied SMF requirements used sections satisfying highly ductile section criteria (e.g., Meng and Murray 1996) and generally resulted in local buckling confined to a length of the beam that was the lesser of the depth of the beam or three times the flange width. It is also noted that other previous end-plate moment connection tests (configurations other than 4E) with built-up beam sections satisfying highly ductile section criteria did not experience this type of beam web to flange weld fracture (e.g., Szabo et al. 2017, Zarat-Basir et al. 2020). Specimen 4E-1.5-1.75-36b in the current test series had a beam web that satisfied moderately ductile section criteria, but not highly ductile section criteria, and experienced local buckling that extended over a length of approximately 4 ft (Figure 12). The larger zone of local buckling either caused or was exacerbated by the fracture of the weld joining the beam web and flange.

It appears that the larger web slenderness, compared to previous SMF qualification tests, contributed to the local buckling extending over a longer length and the observed weld fracture. Therefore, it is concluded that moment connections with moderately ductile section classification designed for IMF require longer length of the larger beam web to flange weld. Based on the successful test results of Specimen 4E-1.5-1.75-36c where the beam web to flange weld did not fracture, a weld length double that currently required in AISC 358s2-20 Section 6.3.1(1) is recommended with beams satisfying moderately ductile section classification.

4. Conclusions and Recommendations

Three specimens were tested to evaluate whether four-bolt extended unstiffened moment connections with 36 in. built-up deep beams can satisfy IMF qualification criteria in AISC 341-16. All three specimens satisfied IMF qualification criteria by retaining a moment strength at the face of the column flange greater than 80% of the nominal plastic moment strength of the beam through a cyclic displacement protocol up to 2% story drift. The specimens exhibited excellent behavior though the 2% story drift cycles with only yielding of the section, no observed local buckling, and no undesirable limit states.

The test results support the beam net section fracture requirements in AISC 360-16 Section F13 which successfully predicted net section fracture of the beam in the first specimen and the lack of net section fracture in the following two specimens. The test results also verified the difference in requirements for IMF and SMF in two ways. First, the first specimen, which satisfied moderately ductile lateral bracing requirements, but not highly ductile requirements, experienced lateral torsional buckling after reaching 2% story drift (IMF), but before reaching 4% story drift (4%). Second, the beam webs satisfied moderately ductile section classification, but not highly ductile section classification. Local buckling of the beam in the third specimen occurred after satisfying the qualification requirements for IMF, but led to a severe reduction in moment strength at 4% story drift which was less than required for SMF qualification.

Based on the results of this study, the following recommendations are made for modifying the requirements in AISC 358s2-20:

1. Table 6.1 in AISC 358s2-20 should be modified to allow a beam depth up to 36 in. for the four-bolt unstiffened (4E) connection configuration for use in intermediate moment frames.
2. Section 6.3.1(1) should be modified to extend the length of the larger weld (CJP or double-filled weld) to a length that is double the current requirement, i.e., two times the depth of the beam or six times the flange width, whichever is less, when the beam section satisfies moderately ductile section classification but not highly ductile section classification.

Acknowledgments

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