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CYCLIC TESTING OF BOLTED FLANGE PLATE STEEL MOMENT CONNECTIONS FOR SPECIAL MOMENT FRAMES

by

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Final Report to American Institute of Steel Construction, Inc.

June 2007

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ABSTRACT

To expand the experimental database for prequalifying the bolted flange plate (BFP) moment connection for special moment frames (SMFs), cyclic testing of three full-scale BFP steel moment connection specimens has taken place at the University of California, San Diego. One-sided moment connection specimens, without a concrete structural slab were fabricated and tested in accordance with Appendix S of the AISC *Seismic Provisions for Structural Steel Buildings*. Specimens were designed using the procedure developed by the BFP Committee of AISC's Connection Prequalification Review Panel (CPRP). Beam sizes for these specimens (W30×108, W30×148, and W36×150) were larger than previously tested to extend the range of available experimental results; W14 columns were used.

All three specimens met the Acceptance Criteria of the AISC *Seismic Provisions for Structural Steel Buildings* for beam-to-column connections in special moment frames. Specimens achieved an interstory drift angle of 0.06 radians before failure. All three specimens experienced necking in the beam flange at the outermost row of bolts. Specimens BFP-1 and BFP-3 eventually failed by beam flange net section fracture. The tensile strain on the net section where fracture occurred was further increased by lateral-torsional buckling (LTB) of the beam. On large drift cycles (5% and 6%) column twisting was observed in addition to beam LTB. The specimens did not include a concrete structural slab, which would limit LTB and column twisting. However, column twisting has not previously been observed in testing of moment connection specimens with W14 columns without a concrete structural slab. Bolt-slip occurred early during testing of all three specimens. The BFP connection differs from welded moment connections in that the additional component of bolt slip-bearing contributes to overall inelastic deformation of the connection. Slip-bearing deformation contributed a significant amount to the total deformation (approximately 30% of the total deformation at an interstory drift angle of 0.04 radians).

ACKNOWLEDGEMENTS

Funding for this project was provided by the American Institute of Steel Construction; Mr. Tom Schlafly was the project manager. Design of the test specimens was provided by Professor Linda Hanagan of Pennsylvania State University. Materials and fabrication were donated by Schuff Steel Company and Nucor Fastener. Technical assistance from the staff at the Powell Structures Laboratory at the University of California, San Diego was greatly appreciated.

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LIST OF SYMBOLS

F_u	Specified minimum tensile strength
F_y	Specified minimum yield stress
H	Column height
L_b	Beam clear length
L_c	Clear bay width
M	Moment of the beam
M_{pa}	Actual plastic moment of the beam
M_{pn}	Nominal plastic moment of the beam
M_u	Ultimate moment of the beam achieved at assumed plastic hinge location (outermost row of bolts)
a	Panel zone width
b	Panel zone depth
d_b	Beam depth
d_c	Column depth
d_i	Distance between displacement transducers δ_5 and δ_6
α	Overstrength factor accounting for cyclic strain hardening
δ_1, δ_2	Column displacement transducer (see Figure 2.20)
δ_3, δ_4	Panel zone displacement transducer (see Figure 2.20)
δ_5, δ_6	Slip-bearing displacement transducer (see Figure 2.20)
δ_b	Beam component of δ_{total}
δ_c	Column component of δ_{total}
δ_{pz}	Panel zone component of δ_{total}
δ_{SB}	Slip-bearing component of δ_{total}
δ_{total}	Total beam tip displacement
θ_c	Column rotation
θ_{SB}	Slip-bearing rotation
$\bar{\gamma}$	Average panel zone shear strain

1. INTRODUCTION

1.1 General

Steel moment connections in high seismic regions typically use welded beam flange to column flange joints. Field welding and the associated inspection of these connections has significant economic impact on the overall cost of the building. A moment connection that could eliminate field welding in favor of field bolting and shop welding could result in a more economical seismic moment frame connection.

One type of bolted moment frame connection consists of plates that are shop welded to the column flange and field bolted to the beam flange and is known as the bolted flange plate (BFP) moment connection. As a part of the SAC Joint Venture Phase II Connection Performance Program, eight full-scale BFP moment connection specimens were tested (Schneider and Teeraparbwong, 2000). Tested connections exhibited predictable, ductile behavior and met established acceptance criteria. However, beam sizes were limited to W24×68 and W30×99.

The AISC Connection Prequalification Review Panel (CPRP) is in the process of reviewing the bolted flange plate moment connection for inclusion in the next edition of the AISC *Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications* (ANSI/AISC 358-05). To expand the experimental database for prequalifying the BFP moment connection for special moment frames, cyclic testing of three full-scale BFP steel moment connection specimens has been conducted. Beam sizes for these specimens (W30×108, W30×148, and W36×150) were larger than previously tested to extend the range of available experimental results.

1.2 Scope and Objectives

To expand the experimental database for prequalifying the bolted flange plate (BFP) moment connection for special moment frames (SMFs), three full-scale, one-sided BFP steel moment connection specimens, without a concrete structural slab were subjected to cycling testing in accordance with Appendix S of the AISC *Seismic Provisions for Structural Steel Buildings* (AISC, 2005b) at the University of California, San Diego.

2. TESTING PROGRAM

2.1 Test Setup and Connection Details

The overall specimen geometry and test setup are shown in Figures 2.1 and 2.2. The beam length varied for the three specimens in order to maintain the target clear beam span-to-depth ratio (L_c/d_b=12). In accordance with the AISC *Seismic Provisions*, the required lateral bracing distance for Specimens 1, 2, and 3 was 107, 113, and 123 in., respectively. For Specimens BFP-1 and BFP-2 lateral bracing of the beam was provided 105 in. from the centerline of the column, as shown in Figures 2.1 and 2.3. The only change in the test setup between Specimens BFP-1 and BFP-2 was to move the actuator position outward approximately 6 in. for Specimen BFP-2. The same lateral bracing at a distance of 105 in. from the column was also used for Specimen BFP-3. But since testing of both Specimens BFP-1 and BFP-2 showed column twisting, it was decided to add a second lateral bracing location at 177 in. from the column centerline (see Figures 2.2 to 2.4). The lateral bracing consisted of steel bracing columns provided on both sides of the beam. These columns were connected to each other above and below the specimen with either a cross beam or threaded rod, depending on the location. Mounted on the guide columns were short lengths of W-shapes or steel plates that were greased to minimize friction forces and adjusted to meet the beam flanges.

To simulate inflection points in the actual building, the ends of the specimen columns were mounted on short sections of W14×370 positioned to experience weak axis bending (Figure 2.5). A steel corbel piece was bolted to the end of the beam for attachment of the servo-controlled hydraulic actuator to the specimens.

Beam-to-column connection details are shown in Figures 2.6 to 2.8 for Specimens BFP-1, BFP-2, and BFP-3, respectively. Shop drawings for the specimens are included in Appendix A. Bolt holes in the beam shear tab were short-slotted with the slot length oriented parallel to the beam span and bolt holes in the beam web were standard holes. Bolt holes in the flange plate were oversized holes (1-1/4 in. dia. for 1 in. dia. bolts) and bolt holes in the beam flange were standard holes (1-1/16 in. dia. for 1 in. dia. bolts). As indicated in Table 2.1, Specimens BFP-1 and BFP-2 had 1 in. continuity plates and Specimen BFP-3 did not have continuity plates. Specimen BFP-1 did not have a panel zone doubler plate and Specimens BFP-2 and BFP-3 had a 3/4 in. doubler plate. The doubler plate for these specimens was unintentionally offset 3 in. towards the bottom of the beam during fabrication. Table 2.2 summarizes the required shear strength and the design strength of the panel zone for each specimen.

2.2 Fabrication and Erection

Two different welding processes were used to complete the flange plate to column flange complete joint penetration (CJP) groove welds. Flange plates were welded to one flange of the column using the electroslag welding (ESW) process and to the other flange of the column using the flux-cored arc welding (FCAW) process. For each specimen, plates were welded with both process, i.e., two flange plates were welded with the ESW process to one column flange and the other two flange plates were welded with the FCAW process to the opposite column flange. In the testing program these welded joints did not fracture and, therefore, only one welding process was tested per specimen. Otherwise, the beam would have been removed and re-connected to the opposite side of the column for re-testing.

Fabrication services were provided by Schuff Steel Company at their Gilbert, AZ facility. Electroslag welding of the flange plates to the column was tested for both Specimens BFP-1 and BFP-2. Figure 2.9 shows the ESW setup and welding process. As shown in the figure the sides of the weld were formed by water-cooled copper shoes. Two Arcmatic 105-VMC 3/32 in. dia. electrodes were used inside a consumable guide tube. This electrode has a specified minimum Charpy-V Notch Toughness of 15 ft-lbs at -20°F. Flux (FES72) was added by hand per the fabricator's standard procedure. It took approximately 15 minutes to weld each flange plate. Welding Procedure Specifications (WPSs) for this process are included in Appendix B.

Flux-cored arc welding of the flange plates to the column was tested for Specimen BFP-3. Figure 2.10 shows the FCAW setup and welding process. Welding was done with an E70T-1 gas-shielded flux-cored electrode (Hobart Brothers TM-11, 3/32 in. dia.) and 100% CO_2 shielding gas. This electrode has a specified minimum Charpy-V Notch Toughness of 20 ft-lbs at 0°F.

Welding of continuity plates and panel zone doubler plates for all specimens was completed with the FCAW process. Welding was done with an E70T-1/E70T-9 gas-shielded flux-cored electrode (Lincoln Outershield 70, 3/32 in. dia.) and 100% CO_2 shielding gas. This electrode has a specified minimum Charpy-V Notch Toughness of 20 ft-lbs at -20°F. WPSs for these welds are included in Appendix B.

Schuff Steel Company provided quality control inspection of the fabricated specimens. Welds were subjected to a combination of visual, magnetic particle, and ultrasonic inspection.

Specimens were erected at UCSD by laboratory staff. The column was first placed in position in the test setup, followed by installation of the beam to simulate the field erection process. Beam web to shear tab bolts were F1852 (A325TC) tension control bolts. Flange plate to beam flange bolts were F2280 (A490TC) tension control bolts. A Tone shear wrench supplied by Schuff Steel Company was used to tension the bolts (Figure 2.11). Bolts were initially brought to the snug-tight condition with connected plies in firm contact followed by systematic tensioning of the bolts. For the beam web to shear tab connection the middle bolt was tensioned first and then bolts were tensioned outward from the middle progressing in an alternating up and down pattern. Flange plate to beam flange bolts were tensioned, starting with the most rigid portion of the connection near the face of the column and then working progressively outward. Bolt pretension verification was conducted at UCSD, as shown in Figure 2.12. The average value of pretension was consistently observed to be 69 kips for the 1 in. dia. F2280 bolts when tested in a Skidmore-Wilhelm Bolt Tension Calibrator. This erection process and the bolt tensioning procedures were discussed with Schuff Steel Company field personnel prior to work.

For all specimens, two 1/8 in. finger shim plates (total 1/4 in.) were installed between the top flange plate and beam top flange, as shown in Figure 2.13. No shims were used between the bottom flange plate and beam bottom flange.

2.3 Material Properties

A992 steel was specified for all beam and column sections. A572 Gr. 50 steel was specified for all plate material. The values shown in Table 2.3 are the material properties obtained from tensile coupon testing conducted by Colorado Metallurgical Services (CMS) and Certified Mill Test Reports.

2.4 Loading History

The loading sequence for beam-to-column moment connections as defined in the 2005 AISC *Seismic Provisions* was used for testing. This loading sequence is presented in Figure 2.14. Displacement was applied at the beam tip and was controlled by the interstory drift angle. The loading began with six cycles each at 0.375%, 0.5%, and 0.75% drift. The next four cycles in the loading sequence were at 1% drift, followed by two cycles each at 1.5%, 2%, 3%, 4%, 5% drift, etc., until the specimen failed.

2.5 Instrumentation

A combination of displacement transducers, strain gage rosettes, and uniaxial strain gages were placed in specific locations on the specimens to measure global or local responses. The applied load was measured with a load cell mounted on the actuator. Figures 2.15 and 2.16 show the location of displacement transducers. Displacement transducer L1 measured the overall vertical displacement of the beam tip, located 10-3/4 in. from the centerline of the actuator. L2, L3, and L4 monitored movement of the column ends, which was intended to be negligible. L5 and L6 measured column movement (L15 and L16 used in BFP-3 only). L7 and L8 measured the slippage between flange plate and beam flange (L11 and L12 used in BFP-2 and BFP-3 to measure slippage at the shear tab). L9 and L10 measured the average shear deformation of the column panel zone. For Specimen BFP-3, which did not require continuity plates in accordance with the AISC *Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications* (ANSI/AISC 358-05), L13 and L14 measured the local deformation of the column flange. The various rosette and uniaxial strain gages were used to measure the strain throughout the connection region (see Figures 2.17 to 2.19).

2.6 Data Reduction Procedure

To determine the contribution of panel zone, column, slip-bearing, and beam deformation to the overall beam tip deformation the following four step data reduction procedure was used. Figure 2.20 shows the displacement transducer naming convention used in the data reduction procedure.

(1) Panel Zone Component: Use Eq. 2.1 to compute the average panel zone shear strain, $\bar{\gamma}$ and Eq. 2.2 to compute the panel zone deformation contribution, δ_{pz} to total beam tip displacement, δ_{total}.

$$\bar{\gamma} = \frac{\sqrt{a^2 + b^2}}{2ab}\left(\delta_3 - \delta_4\right) \tag{2.1}$$

$$\delta_{pz} = \bar{\gamma} L_b \tag{2.2}$$

(2) Column Component: The column rotation, θ_c, can be computed from Eq. 2.3 and the column deformation contribution, δ_c to δ_{total} from Eq. 2.4.

$$\theta_c = \frac{\left(\delta_2 - \delta_1\right)_{total}}{d_b} - \bar{\gamma}\left(1 - \frac{d_b}{H}\right) \tag{2.3}$$

$$\delta_c = \theta_c\left(L_b + \frac{d_c}{2}\right) \tag{2.4}$$

(3) Slip-Bearing Component: The slip-bearing rotation, θ_{SB}, and slip-bearing beam tip displacement component, δ_{SB} can be computed from Eqs. 2.5 and 2.6 respectively.

$$\theta_{SB} = \frac{\left(\delta_5 - \delta_6\right)}{d_i} \tag{2.5}$$

$$\delta_{SB} = \theta_{SB} L_b \tag{2.6}$$

(4) Beam Component: The beam component, δ_b of δ_{total} can be computed from Eq. 2.7.

$$\delta_b = \delta_{total} - \delta_{pz} + \frac{\bar{\gamma} d_b}{H}\left(L_b + \frac{d_c}{2}\right) - \delta_c - \delta_{SB} \tag{2.7}$$

Table 2.1 Member Sizes and Connection Details

(a) Member Sizes

Specimen Designation	Column	Beam	L_c (in.)	L_c/d_b [a]
BFP-1	W14×233	W30×108	355-3/4	11.94
BFP-2	W14×233	W30×148	367-1/2	11.97
BFP-3	W14×311	W36×150	426-7/8	11.89

[a]Clear bay width-to-beam depth ratio, L_c/d_b (target ratio = 12)

(b) Connection Details

Specimen Designation	Flange Plates (in.)	Flange Plate Welding	Row of Bolts	Panel Zone Doubler Plate (in.)	Continuity Plates (in.)
BFP-1	1-1/2	ESW	7	NA	1
BFP-2	1-3/4	ESW	11	3/4	1
BFP-3	1-3/4	FCAW	10	3/4	NA

Table 2.2 Panel Zone Shear

Specimen Designation	Required Strength (kips)	Design Strength (kips)	Demand-Capacity Ratio
BFP-1	658	643	1.02
BFP-2	980	997	0.98
BFP-3	944	1297	0.73

Table 2.3 Steel Mechanical Properties

(a) Specimen BFP-1

Member	Steel Grade	Yield Strength[a] (ksi)	Tensile Strength[a] (ksi)	Elongation[a,b] (%)	Heat No.	Steel Mill
Column (W14×233)	A992	51.5 (57.0)	76.5 (75.5)	28 (25)	263579	Nucor-Yamato
Beam (W30×108)	A992	52.0 (57.0)	77.5 (75.0)	30 (24)	263312	Nucor-Yamato
BFP (1-1/2 in. Plate)	A572 Gr. 50	60.5 (63.0)	87.5 (85.3)	25 (22)	M04958	Oregon Steel Mills
Continuity Plate (1 in. Plate)	A572 Gr. 50	(56.7)	(80.3)	(20)	6103833	Nucor

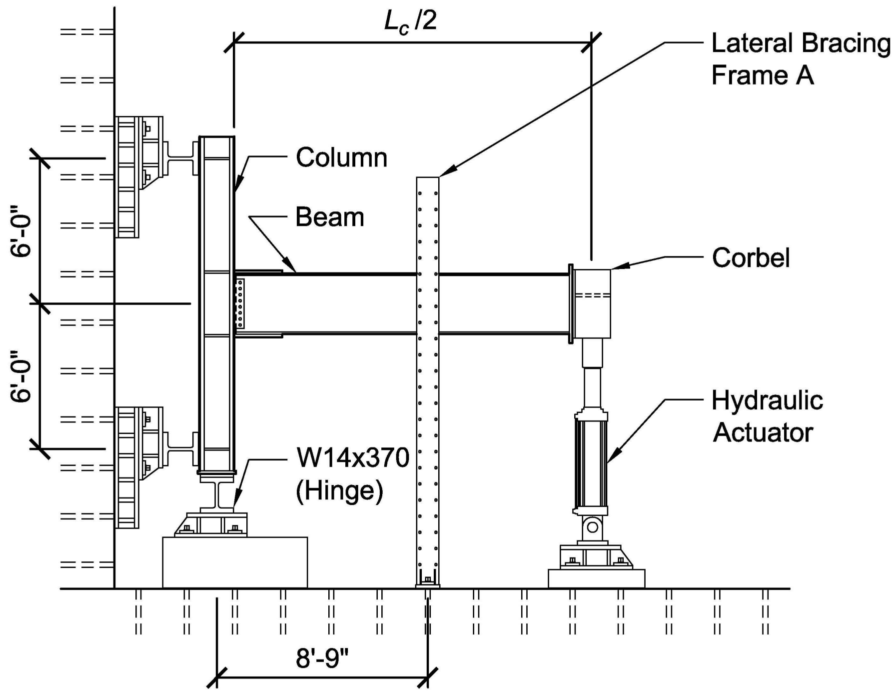
(b) Specimen BFP-2

Member	Steel Grade	Yield Strength[a] (ksi)	Tensile Strength[a] (ksi)	Elongation[a,b] (%)	Heat No.	Steel Mill
Column (W14×233)	A992	51.5 (57.0)	76.5 (75.5)	28 (25)	263579	Nucor-Yamato
Beam (W30×148)	A992	58.5 (60.0)	80.0 (79.0)	27 (22)	232698	Nucor-Yamato
BFP (1-3/4 in. Plate)	A572 Gr. 50	54.5 (60.1)	81.5 (84.6)	27 (17)	4106491	Nucor
Doubler Plate (3/4 in. Plate)	A572 Gr. 50	(57.0)	(78.0)	(20)	W3L775	Ipsco
Continuity Plate (1 in. Plate)	A572 Gr. 50	(56.7)	(80.3)	(20)	6103833	Nucor

(c) Specimen BFP-3

Member	Steel Grade	Yield Strength[a] (ksi)	Tensile Strength[a] (ksi)	Elongation[a,b] (%)	Heat No.	Steel Mill
Column (W14×311)	A992	55.0 (56.0)	78.0 (76.0)	27 (25)	263447	Nucor-Yamato
Beam (W36×150)	A992	- (58.0)	- (75.0)	- (26)	255565	Nucor-Yamato
BFP (1-3/4 in. Plate)	A572 Gr. 50	54.5 (60.1)	81.5 (84.6)	27 (17)	4106491	Nucor
Doubler Plate (3/4 in. Plate)	A572 Gr. 50	(57.0)	(78.0)	(20)	W3L775	Ipsco

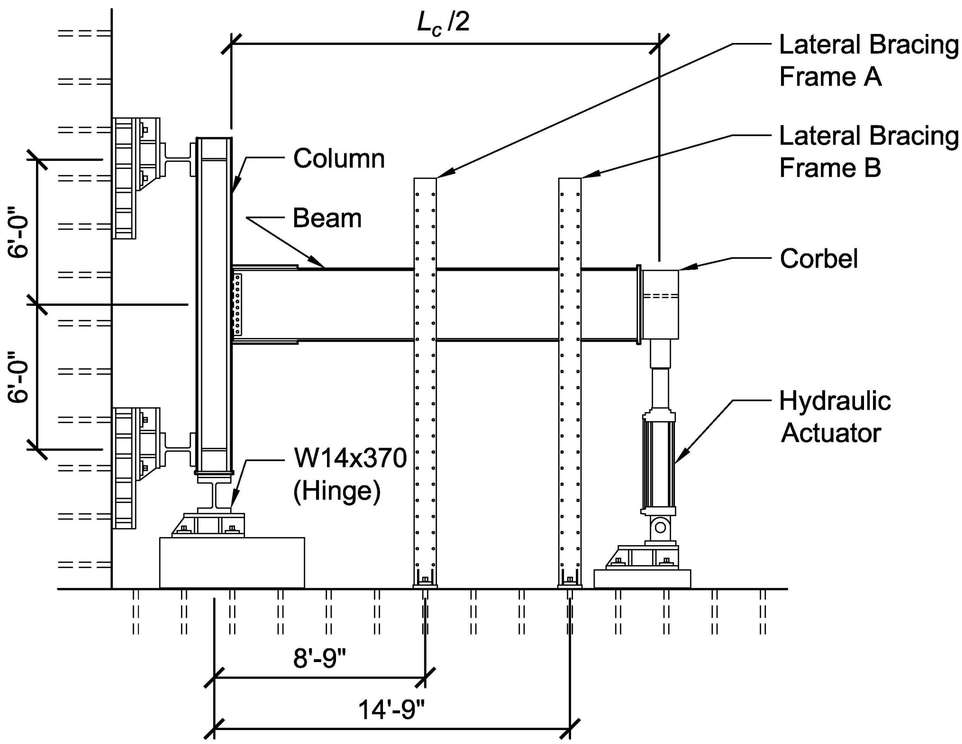
[a]Values in parentheses are based on Certified Mill Test Reports, others from testing by CMS.
[b]Certified Mill Test Report elongation in parentheses based on 8 in. gauge length, others based on 2 in. gage length.



(a) Schematic

(b) Photo

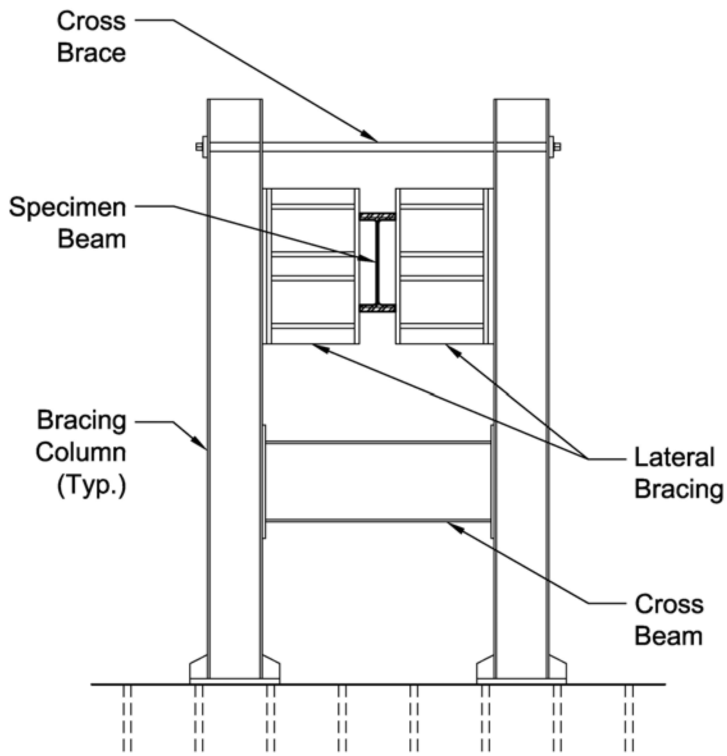
Figure 2.1 Test Setup for Specimens BFP-1 and BFP-2



(a) Schematic

(b) Photo

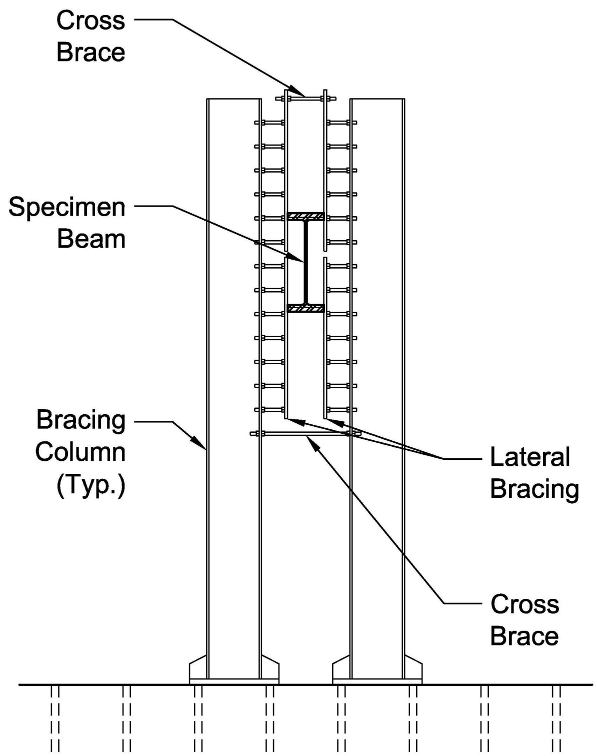
Figure 2.2 Test Setup for Specimen BFP-3



(a) Schematic

(b) Photo

Figure 2.3 Lateral Bracing Frame A



(a) Schematic

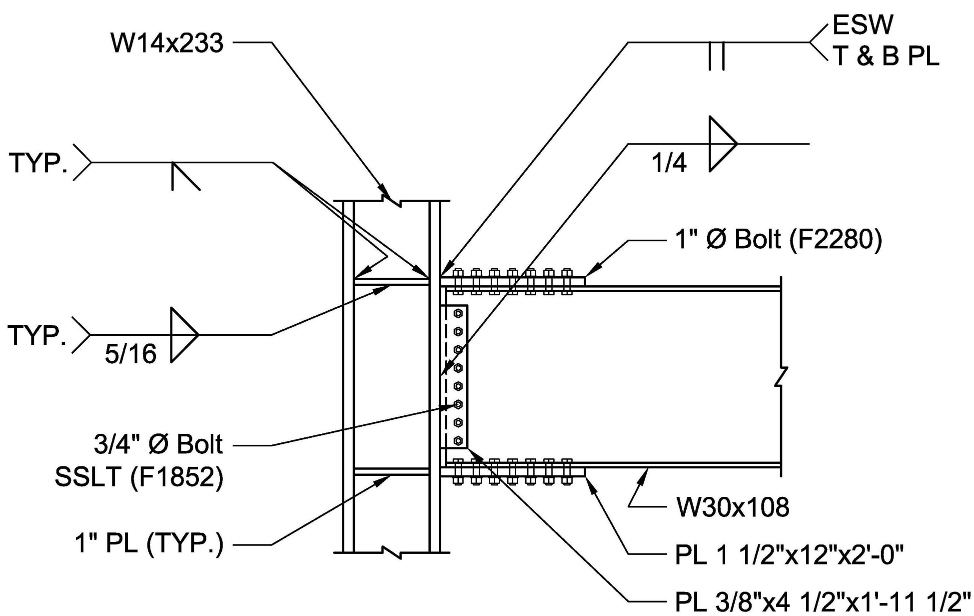
(b) Photo

Figure 2.4 Lateral Bracing Frame B (Specimen BFP-3)

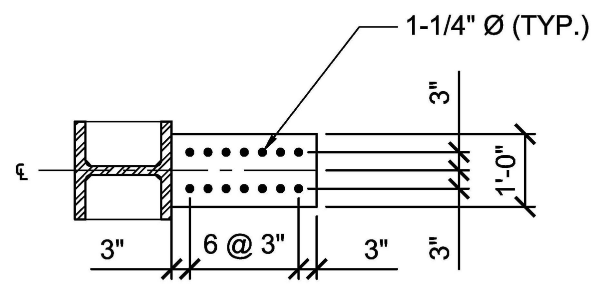
(a) Top Hinge

(b) Bottom Hinge

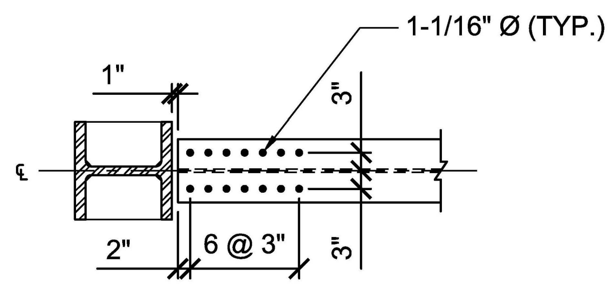
Figure 2.5 Close-up of Column Supports



(a) Moment Connection

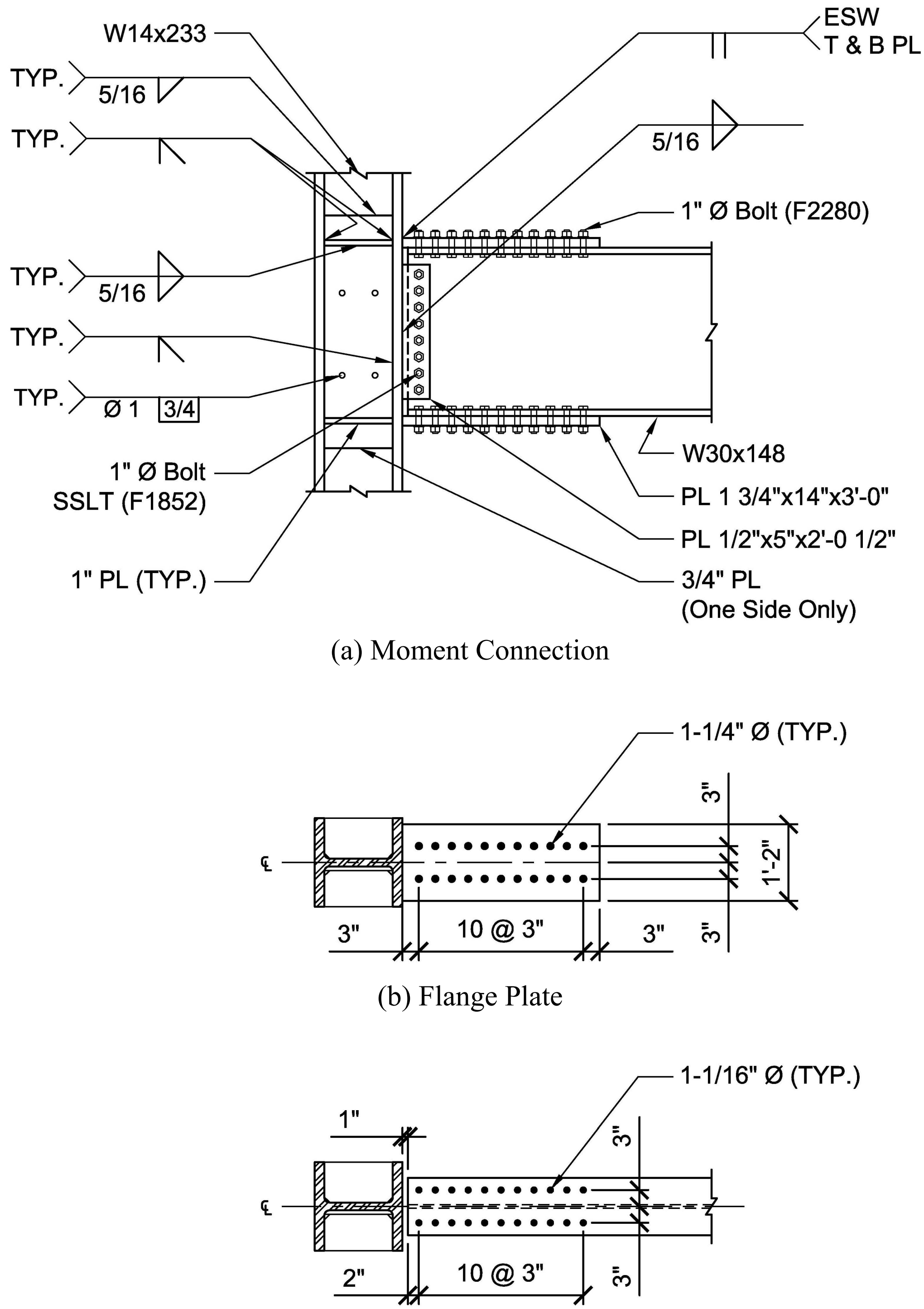


(b) Flange Plate



(c) Beam Flange

Figure 2.6 Specimen BFP-1: Connection Details

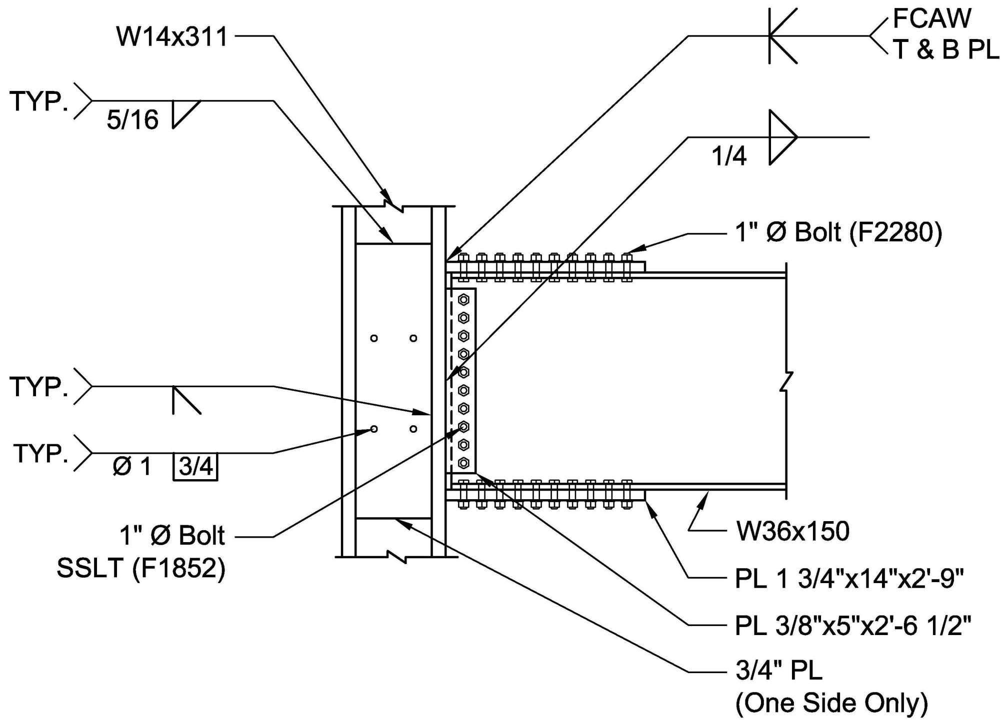


(a) Moment Connection

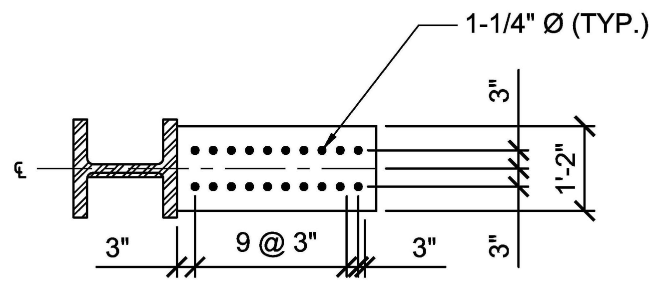
(b) Flange Plate

(c) Beam Flange

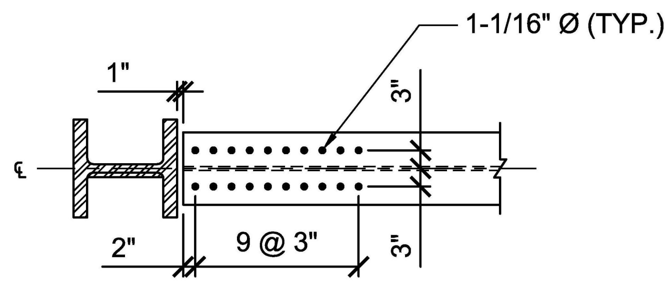
Figure 2.7 Specimen BFP-2: Connection Details



(a) Moment Connection



(b) Flange Plate



(c) Beam Flange

Figure 2.8 Specimen BFP-3: Connection Details

(a) Setup

(b) Close-up of Setup

(c) Welding Process

Figure 2.9 Electroslag Welding

(a) Setup

(b) Welding Process

Figure 2.10 Flux-cored Arc Welding

Figure 2.11 Bolt Tensioning

Figure 2.12 Tension Control Bolt Pretension Verification

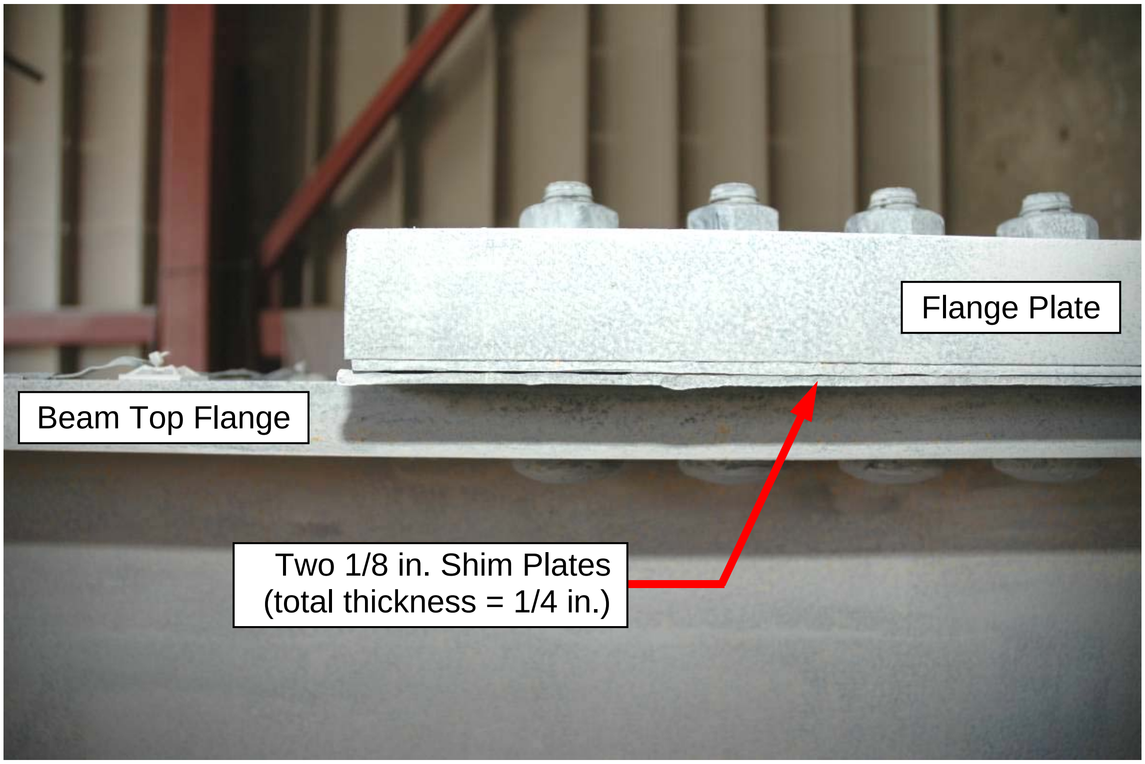


Figure 2.13 Shims Between Beam Flange and Flange Plate

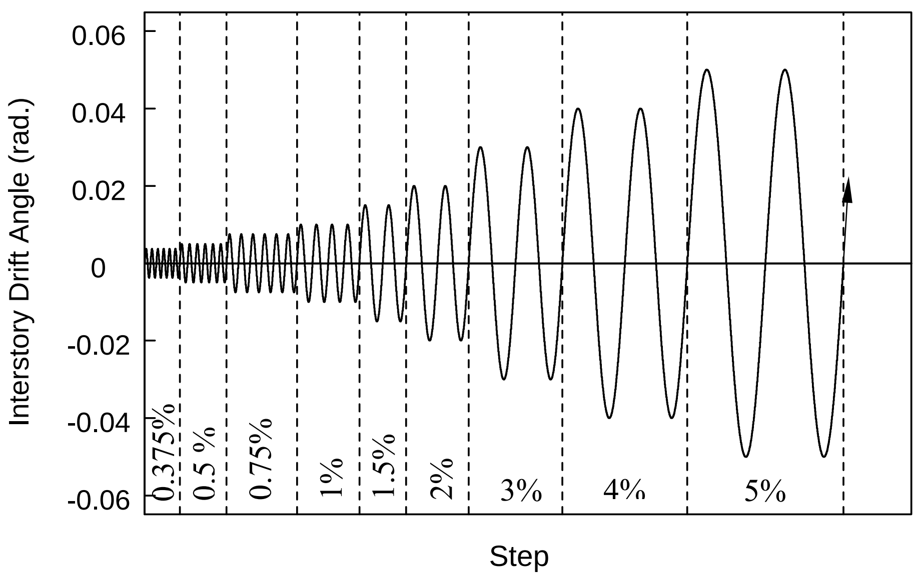


Figure 2.14 AISC Loading Sequence

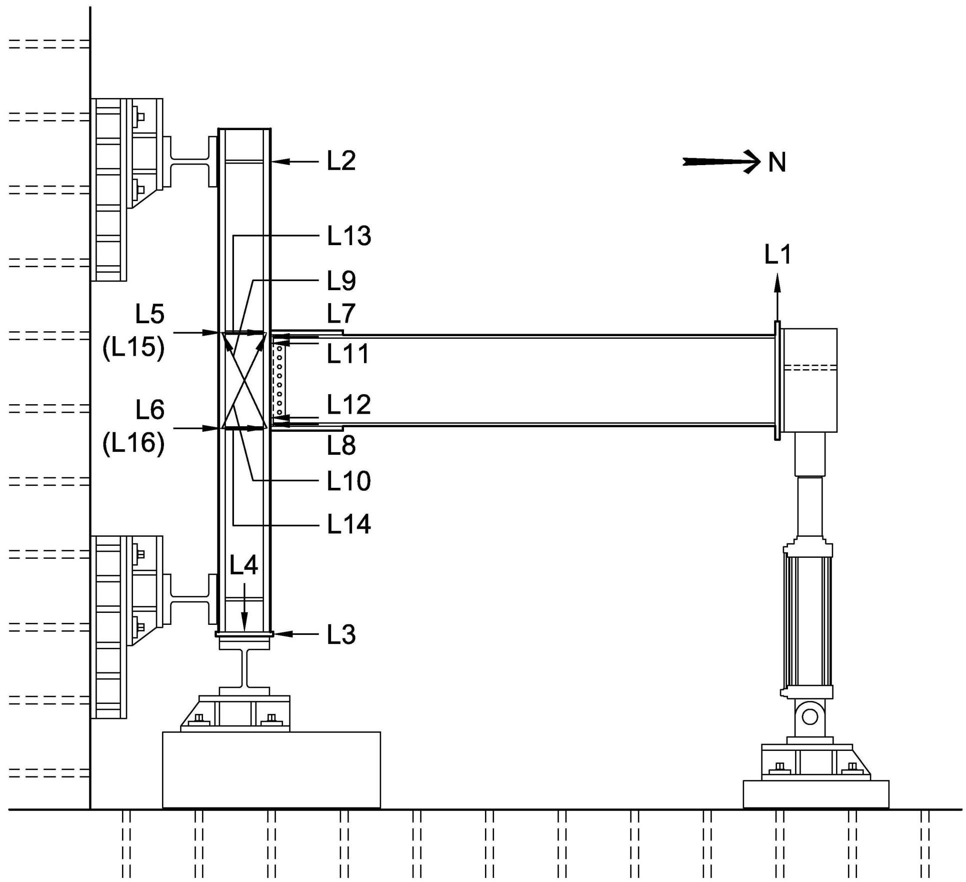
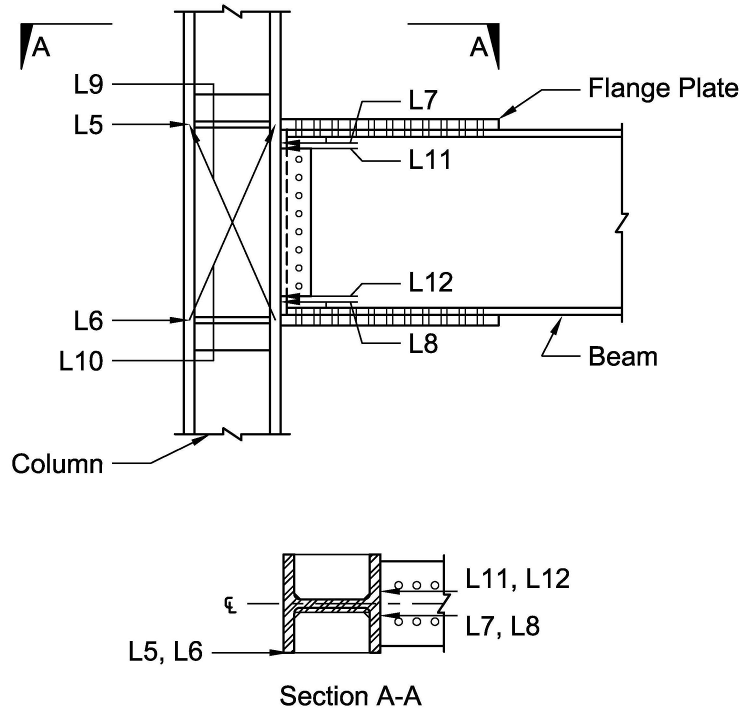
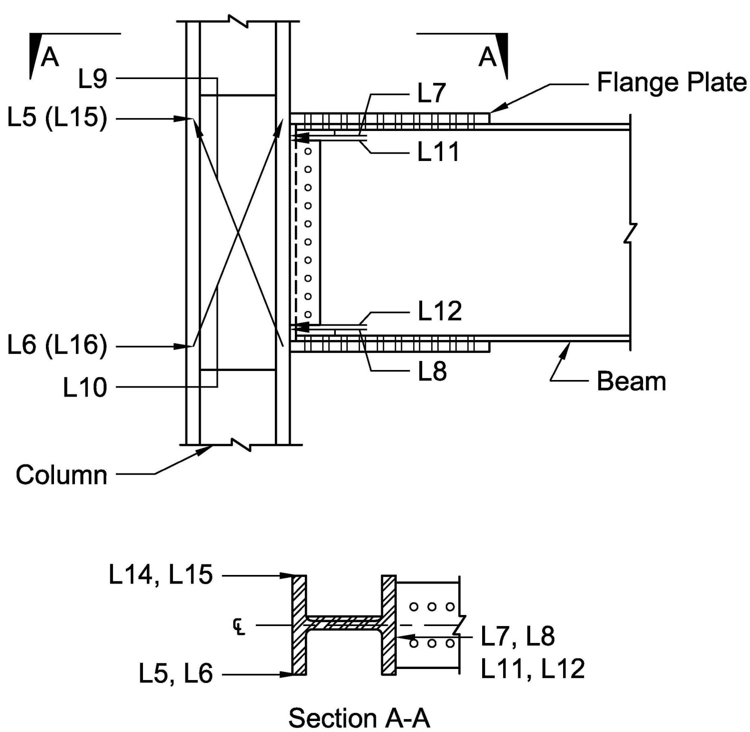


Figure 2.15 Displacement Transducer Locations

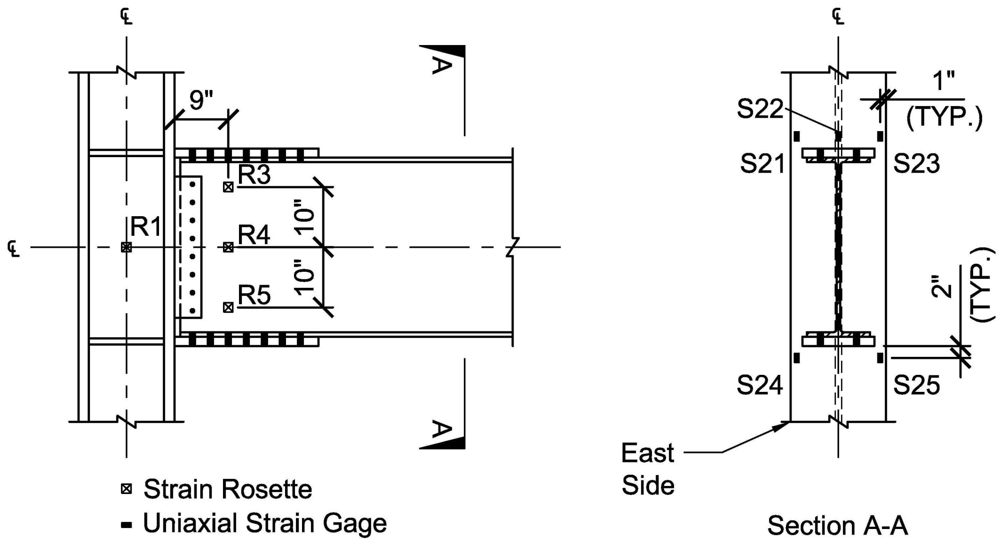


(a) Specimens BFP-1 and BFP-2

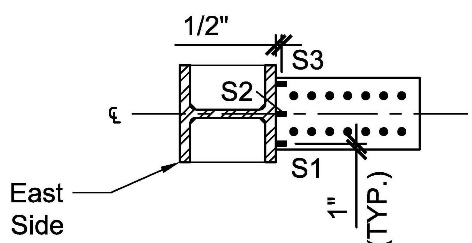


(b) Specimen BFP-3

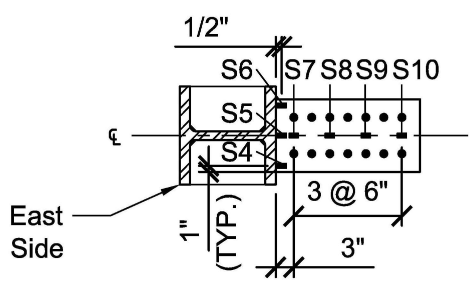
Figure 2.16 Displacement Transducer Locations Detail at Connection



(a) Elevation and Section

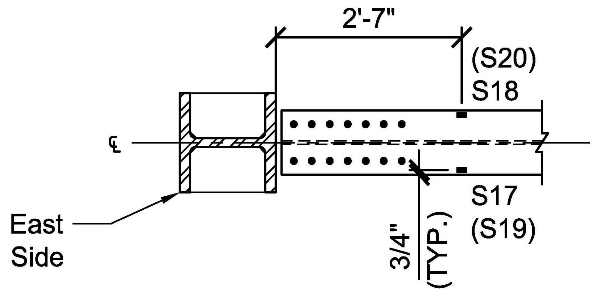


(b) Top Flange Plate

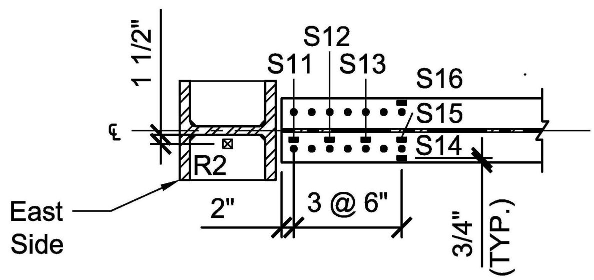


(c) Bottom Flange Plate

Figure 2.17 Specimen BFP-1: Uniaxial and Rosette Strain Gage Location

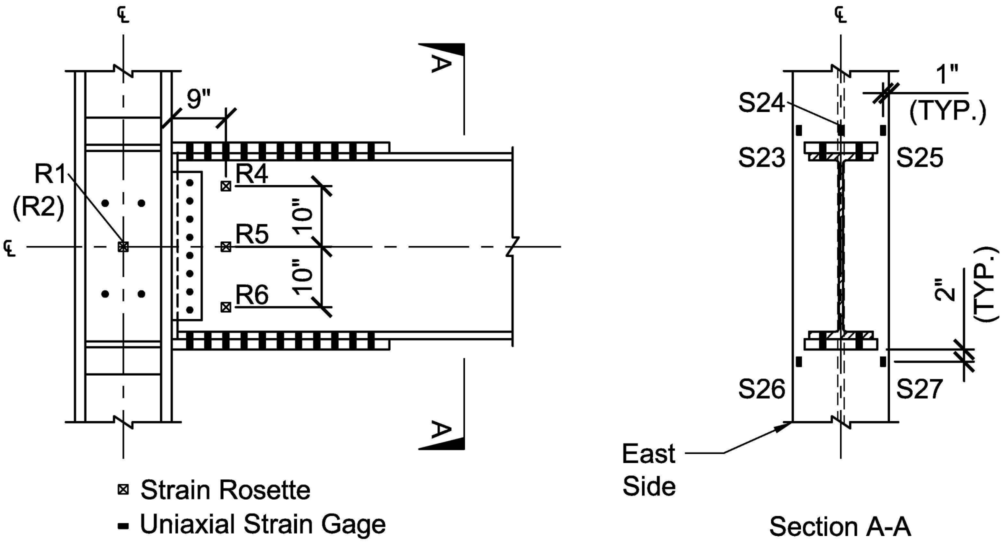


(d) Top (Bottom) Beam Flange [Outer Side]

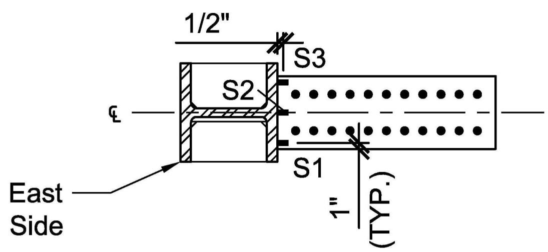


(e) Bottom Beam Flange [Inner Side]

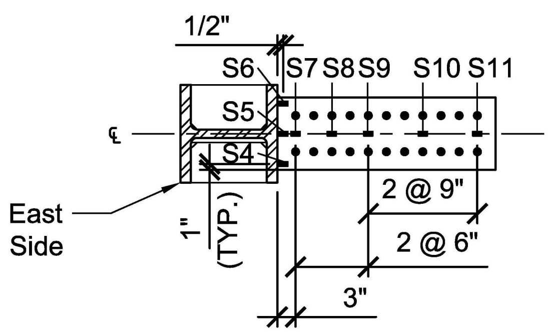
Figure 2.17 Specimen BFP-1: Uniaxial and Rosette Strain Gage Location (cont.)



(a) Elevation and Section

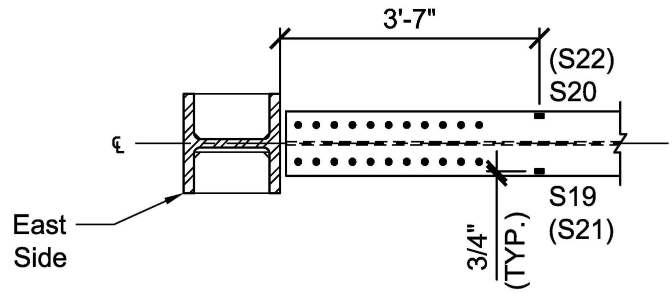


(b) Top Flange Plate

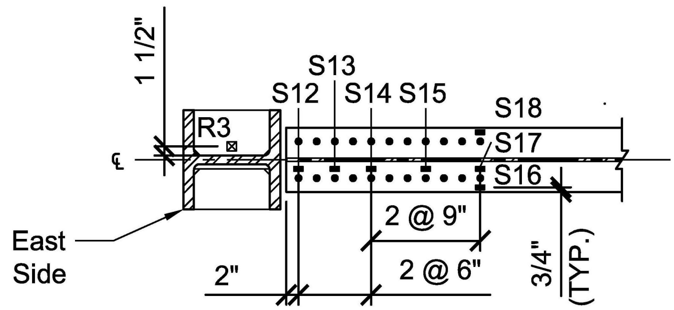


(c) Bottom Flange Plate

Figure 2.18 Specimen BFP-2: Uniaxial and Rosette Strain Gage Location

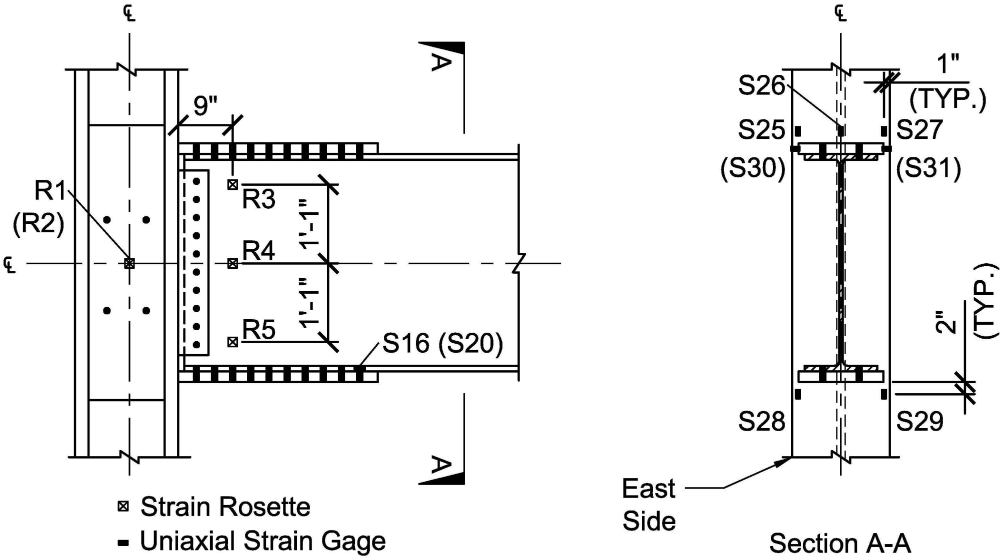


(d) Top (Bottom) Beam Flange [Outer Side]

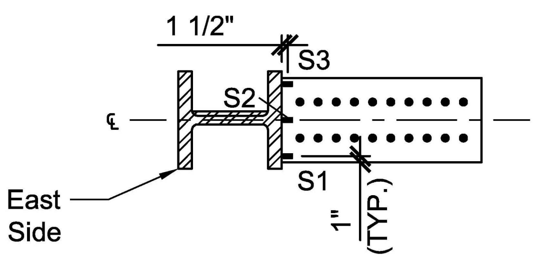


(e) Bottom Beam Flange [Inner Side]

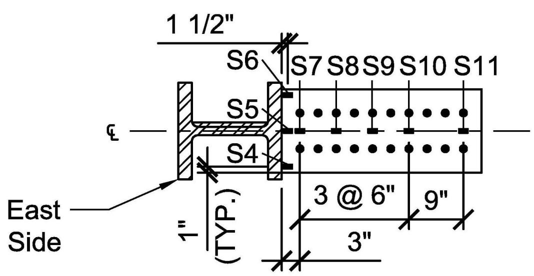
Figure 2.18 Specimen BFP-2: Uniaxial and Rosette Strain Gage Location (cont.)



(a) Elevation and Section

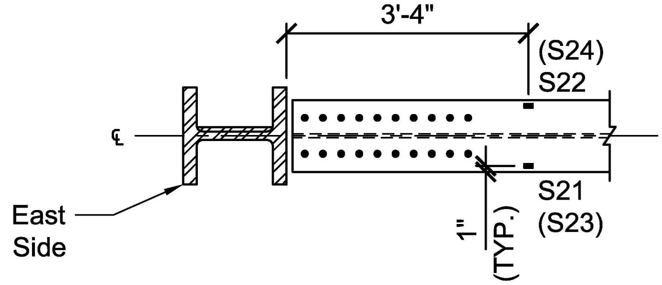


(b) Top Flange Plate

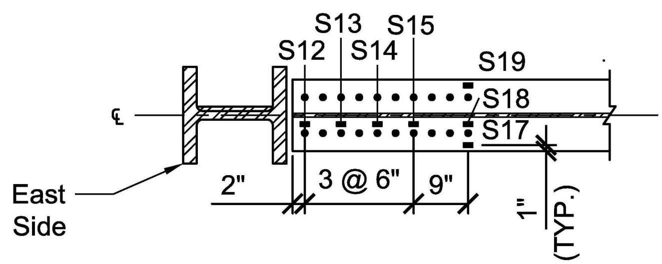


(c) Bottom Flange Plate

Figure 2.19 Specimen BFP-3: Uniaxial and Rosette Strain Gage Location



(d) Top (Bottom) Beam Flange [Outer Side]



(e) Bottom Beam Flange [Inner Side]

Figure 2.19 Specimen BFP-3: Uniaxial and Rosette Strain Gage Location (cont.)

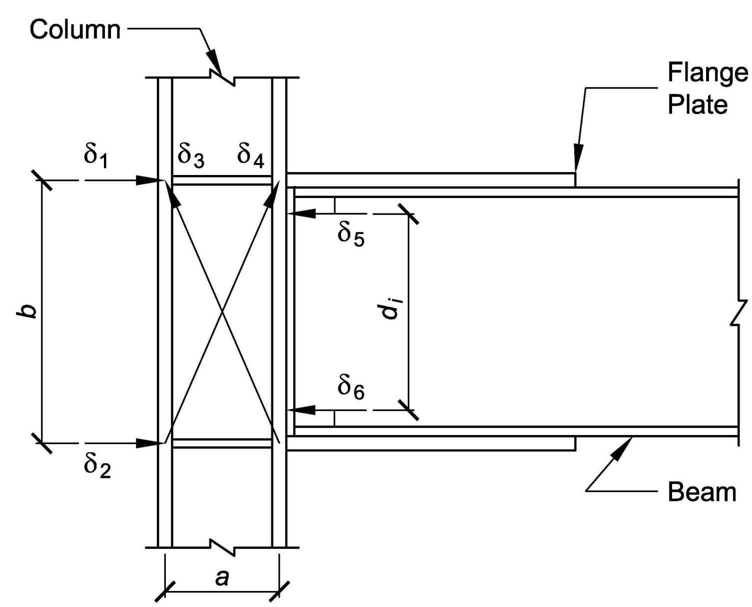


Figure 2.20 Data Reduction Procedure Instrumentation Plan

3. TEST RESULTS

3.1 Introduction

This chapter presents the observed performance and recorded response for the three bolted flange plate beam-to-column moment connection specimens. Figures are included which show the progression of yielding, flange local buckling, and overall deformation with increasing drift. Also included, where appropriate, are figures showing specimen fracture. Plots of applied load versus beam tip displacement (and story drift ratio) and moment versus beam tip displacement illustrate specimen global behavior. Plots of moment versus the contributing components of beam tip displacement (panel zone shear deformation, column rotation, slip-bearing deformation of the bolted flange plate joint, and beam rotation) are provided to evaluate the relative contribution of each individual component to overall specimen displacement. (The data reduction procedure for determination of these displacement components is described in Chapter 2.) Also, selected plots of specimen strain versus applied load are included to illustrate specimen panel zone, flange plate, beam flange, and column flange strain demand.

3.2 Specimen BFP-1

Specimen BFP-1 (W30×108 beam, W14×233 column, and flange plate to column flange weld by ESW process) was tested on February 15, 2007 using the loading sequence for beam-to-column moment connections as defined in the 2005 AISC *Seismic Provisions* (see Figure 2.14). Test results showed that this specimen satisfied the Acceptance Criteria of the AISC *Seismic Provisions* for beam-to-column connections in special moment frames. Specimen BFP-1 failed by beam flange net section fracture on the second excursion to +6% drift.

3.2.1 Observed Performance

Figure 3.1 shows an overall view of the specimen and a close-up of the connection region before testing. Bolt slip, which was accompanied by very loud noise, occurred during the first cycle at 0.375% drift and on all subsequent cycles. Minor yielding in the panel zone, as evidenced by the flaking of the whitewash, was observed at 2% drift. Obvious yielding in the panel zone and minor yielding in the beam flanges was observed at 3% drift. Flange and web local buckling initiated at 4% story drift, and lateral-torsional buckling (LTB) was observed at 5% drift simultaneously with twisting of the column. Photos of the overall deformed configurations are shown in Figure 3.2. Figure 3.3 shows the yielding pattern in the beam at 2% to 6% drift. Figure 3.4 shows the progression of panel zone yielding. The significant LTB of the beam at 6% drift resulted in skewing of the actuator to the east side, as shown in Figure 3.5. The specimen failed on the second excursion to +6% drift by net section fracture of the beam bottom flange at the outermost bolt row. Figure 3.6 shows the location and a close-up view of the fracture. Ductile fracture was accompanied by the occurrence of necking at the net section.

3.2.2 Recorded Response

A plot of the load versus beam tip displacement relationship is shown in Figure 3.7 and moment (at column face) versus beam tip displacement relationship is shown in Figure 3.8. The Interstory Drift Angle (i.e., total rotation) achieved by Specimen BFP-1 was 0.06 radian, where the beam flexural strength at the column face did not degrade below 80% of the nominal plastic moment (M_{pn}) of the beam. Figure 3.9 shows the relationship between the moment and the total plastic rotation. Deformation of the beam, column, panel zone, and bolt slippage and bearing contributed to the total rotation of the specimen. Figure 3.10 shows the relationship between moment and shear deformation at the panel zone, Figure 3.11 shows the relationship between moment and column total rotation, and Figure 3.12 shows the relationship between moment and beam slip-bearing rotation at the bolted flange plate connection. (The slip-bearing rotation resulting from relative slip and bolt bearing deformation between the flange plates and beam flanges was calculated as described in Chapter 2.) Figure 3.13 shows the relationship between moment and beam rotation. As shown in Figures 3.10 and 3.12, shear deformation in the panel zone and slippage between the bolted flange plate and beam flange made significant contributions to the total rotation. The column response remained in the elastic range (Figure 3.11). Figure 3.14 shows the relative contribution of the beam, panel zone, column, and slippage-bearing to the overall beam tip displacement at 1% to 6% drift.

Figure 3.15 shows the shear strain in the panel zone. Significant yielding in the panel zone can be observed. Figure 3.16 shows the strain in the flange plate near the ESW CJP groove weld; strains of up to about 5 times the yield strain were observed. Figure 3.17 shows the strain at the net section of beam flange, and Figure 3.18 shows the strain in the column flange.

3.3 Specimen BFP-2

Specimen BFP-2 (W30×148 beam, W14×233 column, and flange plate to column flange weld by ESW process) was tested on February 21, 2007 using the loading sequence for beam-to-column moment connections as defined in the 2005 AISC *Seismic Provisions*. Test results showed that this specimen satisfied the Acceptance Criteria of the AISC *Seismic Provisions* for beam-to-column connections in special moment frames. Specimen BFP-2 completed one cycle at 6% drift before testing was suspended due to excessive lateral-torsional buckling (LTB) of the beam.

3.3.1 Observed Performance

Figure 3.19 shows an overall view of the specimen and a close-up of the connection region before testing. Bolt slip occurred during the first cycle at 0.375% drift and on all subsequent cycles. Minor yielding in the panel zone, as evidenced by the flaking of the whitewash, was observed at 3% drift. Obvious yielding in the panel zone, yielding in the beam flanges, and minor yielding of the flange plates were observed at 4% drift. Also at 4% drift, minor local buckling of the beam web was observed. LTB of the beam and associated column twisting were observed at 5% drift. Photos of the overall deformed configurations are shown in Figure 3.20. Figures 3.21 and 3.22 show the yielding pattern in the beam and progression of panel zone yielding, respectively. Figure 3.23(a) and (b) shows beam LTB and column twisting at 5% drift. The deformation became more significant at 6% drift. The test was stopped after one complete cycle at 6% drift due to excessive column twisting [see Figure 3.23(c)]. Figure 3.24 shows the actuator skewed to one side at +5% and +6% drift. Figure 3.25 shows ovalization and necking of the beam top flange bolt hole at the outermost row of bolts.

3.3.2 Recorded Response

A plot of the load versus beam tip displacement relationship is shown in Figure 3.26, and moment (at column face) versus beam tip displacement relationship is shown in Figure 3.27. The specimen achieved an Interstory Drift Angle of 0.06 radian. Figure 3.28 shows the relationship between the moment and the total plastic rotation. Figure 3.29 shows the relationship between moment and shear deformation in the panel zone. The shear deformation plotted in Figure 3.29 should be viewed with caution because column twisting affected the measurements of displacement transducers L9 and L10 (see Figure 2.16). Figure 3.30 shows the relationship between moment and column total rotation. Figure 3.31 shows the relationship between moment and beam slip-bearing rotation at the bolted flange plate connection, and Figure 3.32 shows the relationship between moment and beam rotation. Shear deformation in the panel zone and slippage at the bolted flange plate made significant contributions to the total rotation (Figure 3.29 and Figure 3.31). The column response remained in the elastic range (Figure 3.30). Figure 3.33 shows the relative contribution of the components to the overall beam tip displacement at 1% to 4% drift. (Components for 5% and 6% drift are not shown because column twisting affected the measurements.)

Figure 3.34 shows the shear strain in panel zone. Significant yielding in the panel zone can be observed. Figure 3.35 shows the strain in the flange plate near the ESW CJP groove weld; strains of up to about 7 times the yield strain were observed. Figure 3.36 shows the strain in the beam flange at the net section of the outermost row of bolts. As shown in Figure 3.36(c), significant yielding was observed at the net section. Figure 3.37 shows relatively minor yielding in the column flange.

3.4 Specimen BFP-3

Specimen BFP-3 (W36×150 beam, W14×311 column, and flange plate to column flange weld by FCAW process) was tested on March 7, 2007 using the loading sequence for beam-to-column moment connections as defined in the 2005 AISC *Seismic Provisions*. Test results showed that this specimen satisfied the Acceptance Criteria of the AISC *Seismic Provisions* for beam-to-column connections in special moment frames.

Specimen BFP-3 failed by beam flange net section fracture on the first excursion to +7% drift.

3.4.1 Observed Performance

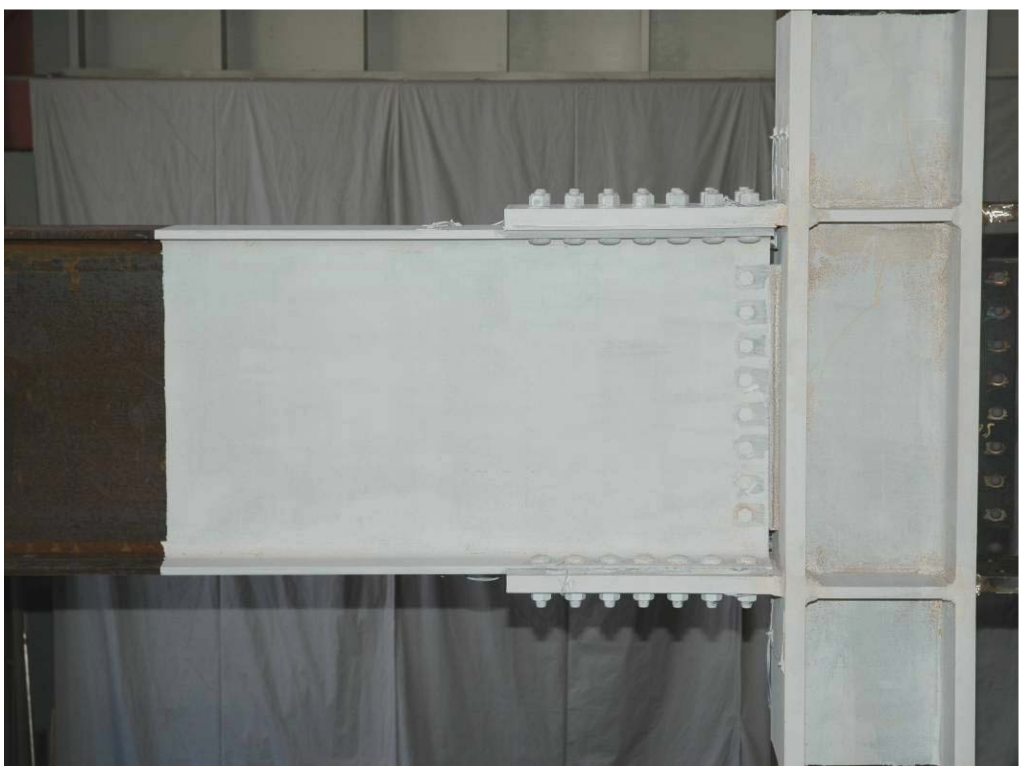
Figure 3.38 shows an overall view of the specimen and a close-up of the connection region before testing. Bolt slip occurred during the first cycle at 0.5% drift and on all subsequent cycles. Minor yielding in the beam flange was observed at 2% drift. Beam flange and web local buckling was observed at 4% drift. At 5% drift, necking of the beam flange at the net section of outermost bolt row was observed for both the top and bottom flanges. Beam LTB and associated column twisting were observed at 6% drift. Photos of the overall deformed configurations are shown in Figure 3.39. Figure 3.40 shows the yielding pattern in the beam. Panel zone yielding was very limited (Figure 3.41). Recall that the panel zone shear demand-capacity ratio (DCR) was 0.73 for Specimen BFP-3, compared with a DCR of approximately 1.0 for Specimens BFP-1 and BFP-2 (see Table 2.2). Beam flange and web local buckling at 5% drift is shown in Figure 3.42. As shown in Figure 3.43, obvious LTB and column twisting were observed at 6% drift level. The unusual yielding pattern of the column shown in Figure 3.44 might have been caused by column twisting (i.e., warping stress), flange local bending, and/or web local yielding of the column. The failure mode of this specimen was similar to Specimen BFP-1. On the first excursion to +7% drift net section fracture of the beam bottom flange at the outermost bolt row was observed. Figure 3.45 shows the location and a close-up view of the fracture.

3.4.2 Recorded Response

A plot of the load versus beam tip displacement relationship is shown in Figure 3.46, and moment (at column face) versus beam tip displacement relationship is shown in Figure 3.47. The specimen achieved an Interstory Drift Angle of 0.06 radian. Figure 3.48 shows the relationship between the moment and the total plastic rotation. Figure 3.49 shows the relationship between moment and shear deformation at the panel zone. Figure 3.50 shows the relationship between moment and column total rotation. Figure 3.51 shows the relationship between moment and beam slip-bearing rotation at the bolted flange plate connection, and Figure 3.52 shows the relationship between moment and beam rotation. The column panel zone remained in the elastic range (Figure 3.49). Panel zone yielding was very limited, although the column flange experienced significant yielding due to column twisting, flange local bending, and web local yielding. Figure 3.53 shows the relative contribution of the components to the overall beam tip displacement at 1% to 6% drift.

Figure 3.54 shows the shear strain in the panel zone, which remained essentially elastic. Figure 3.55 shows the strain in the flange plate near the FCAW CJP groove weld; strains of up to about 15 times the yield strain were observed. Figure 3.56 shows the strain in the beam flange at the net section of the outermost row of bolts. Significant yielding at the net section can be observed from Figure 3.56. Minor yielding can be observed in the column flange (see Figure 3.57).

(a) Overall View



(b) Close-up of Connection Region

Figure 3.1 Specimen BFP-1: Before Testing

Positive Drift Negative Drift

(a) 4% Drift

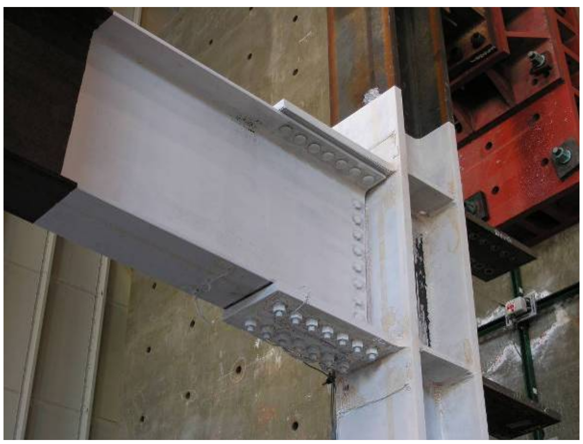
(b) 5% Drift

(c) 6% Drift

Figure 3.2 Specimen BFP-1: Overall Deformed Configuration

(a) 2% Drift

(b) 3% Drift



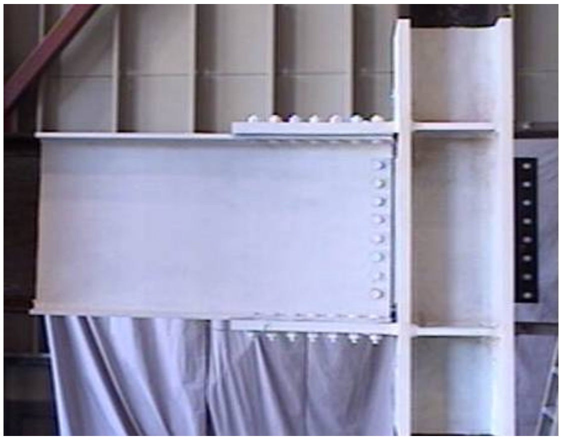
(c) 4% Drift

(d) 5% Drift

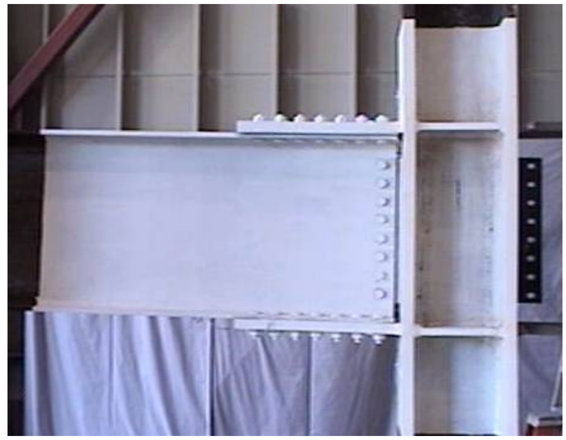
(e) 6% Drift (1st Cycle)

(f) 6% Drift (2nd Cycle)

Figure 3.3 Specimen BFP-1: Yielding Pattern and Beam Local Buckling

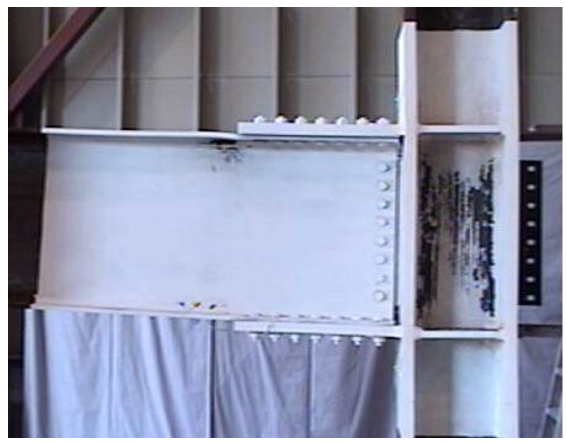


(a) 2% Drift

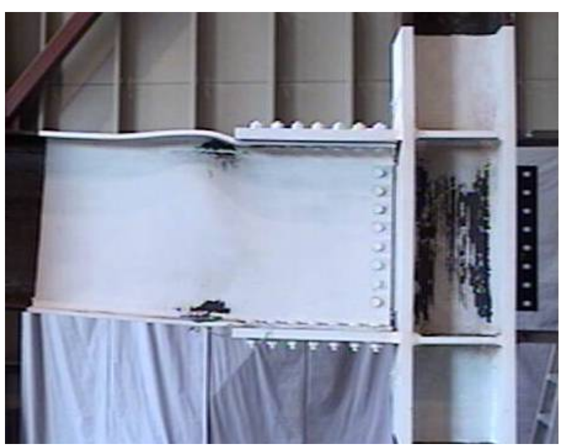


(b) 3% Drift

(c) 4% Drift



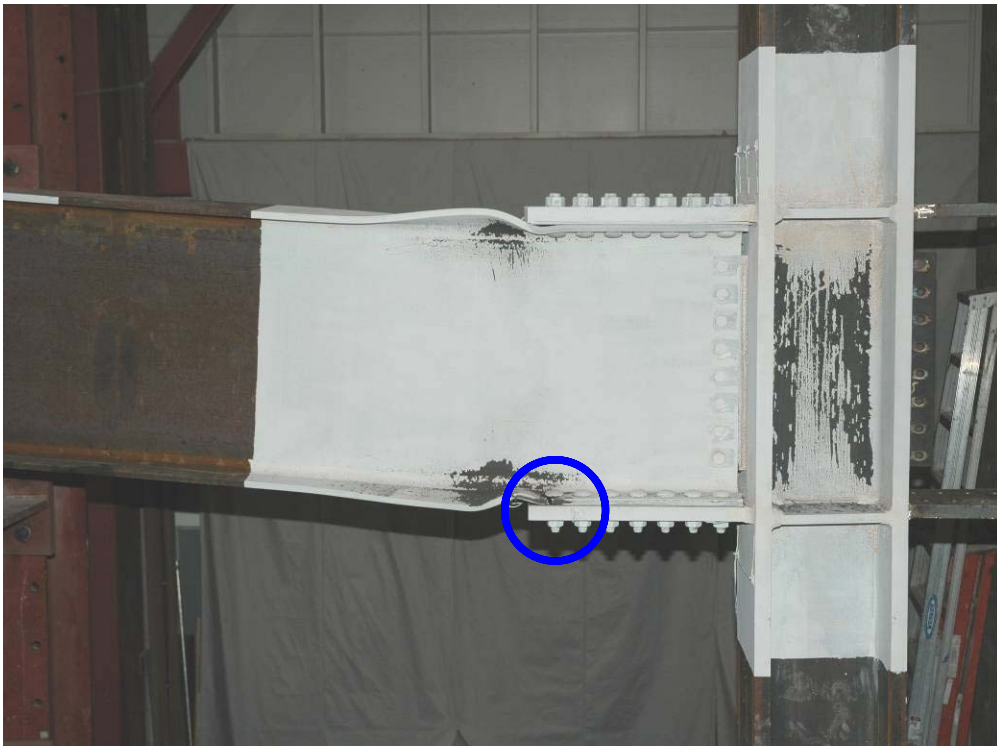
(d) 5% Drift



(e) 6% Drift

Figure 3.4 Specimen BFP-1: Panel Zone Yielding Pattern

Figure 3.5 Specimen BFP-1: Actuator Skewed to East Side at +6% Drift (2nd Cycle)



(a) Fracture Location

(b) Close-up

Figure 3.6 Specimen BFP-1: Beam Bottom Flange Net Section Fracture on 2nd Cycle at +6% Drift

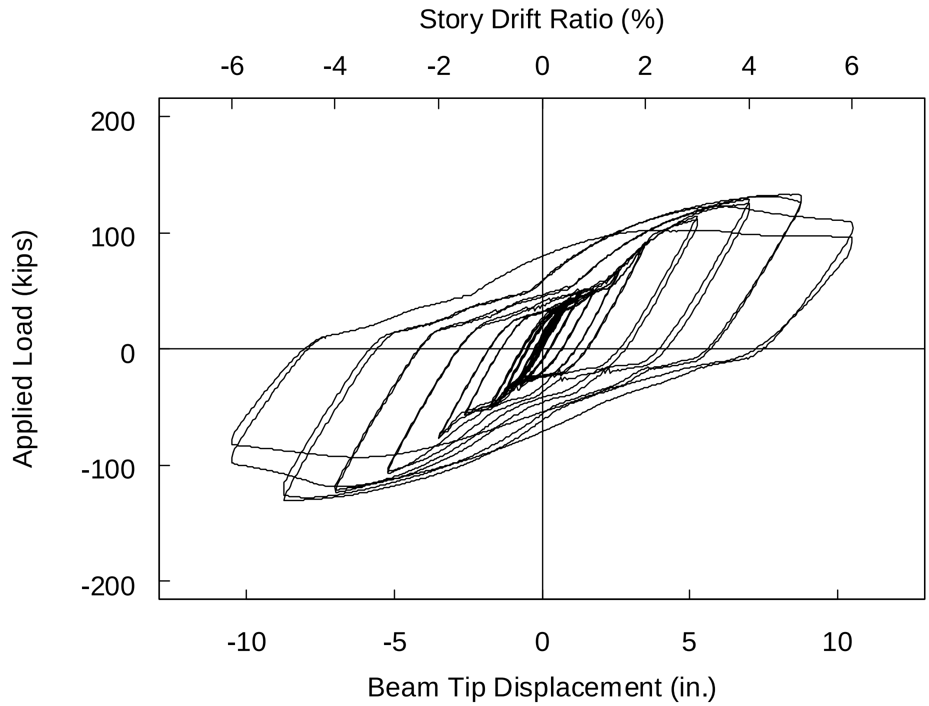


Figure 3.7 Specimen BFP-1: Load versus Beam Tip Displacement

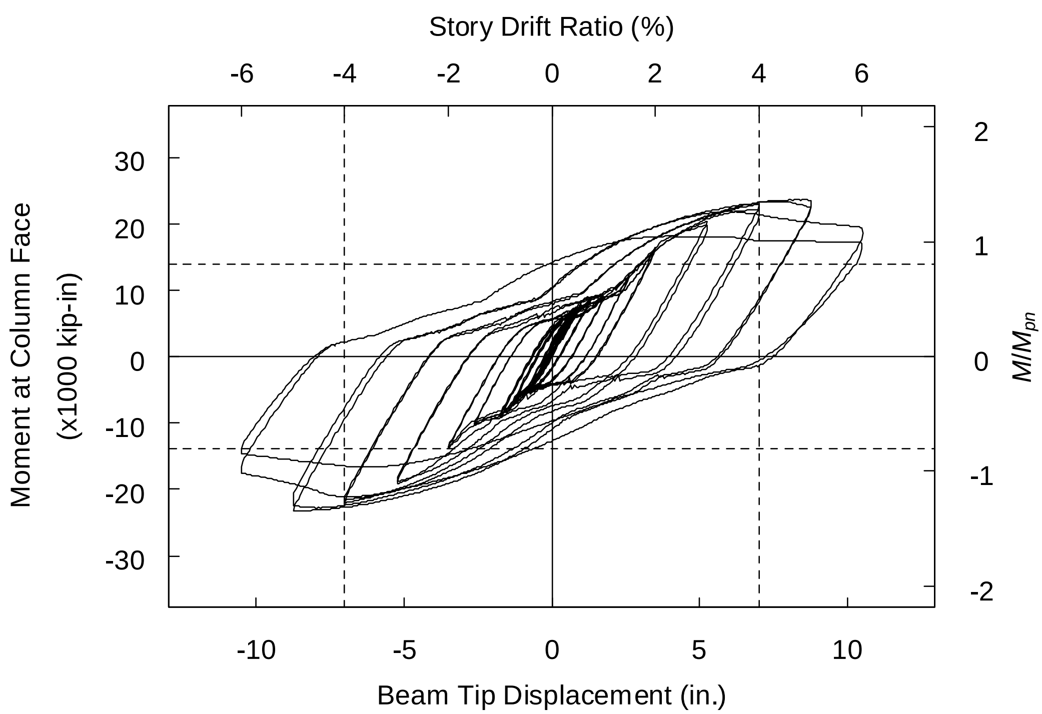


Figure 3.8 Specimen BFP-1: Beam Moment versus Beam Tip Displacement

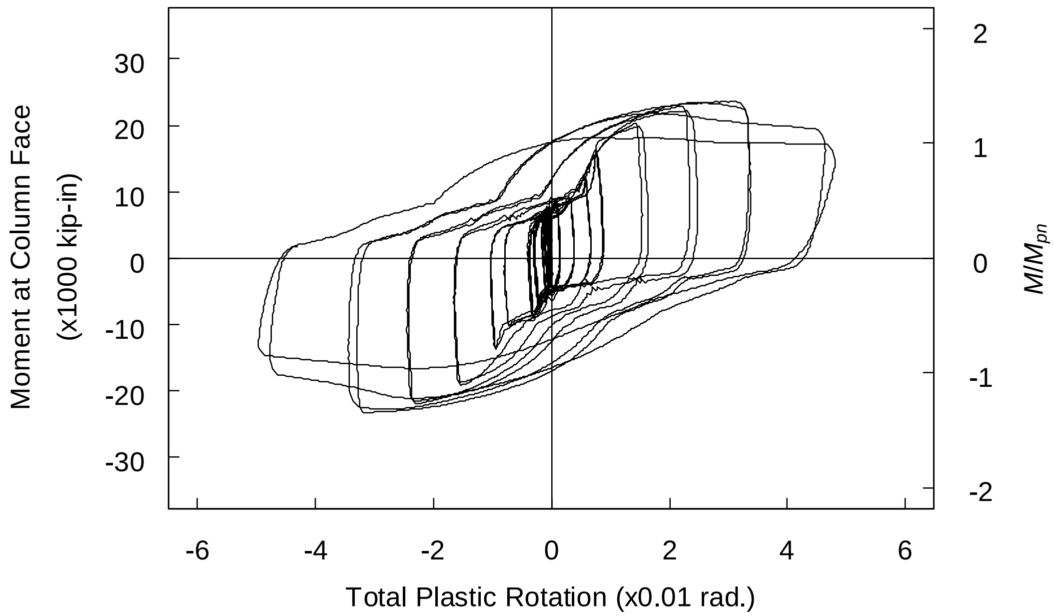


Figure 3.9 Specimen BFP-1: Beam Moment versus Total Plastic Rotation

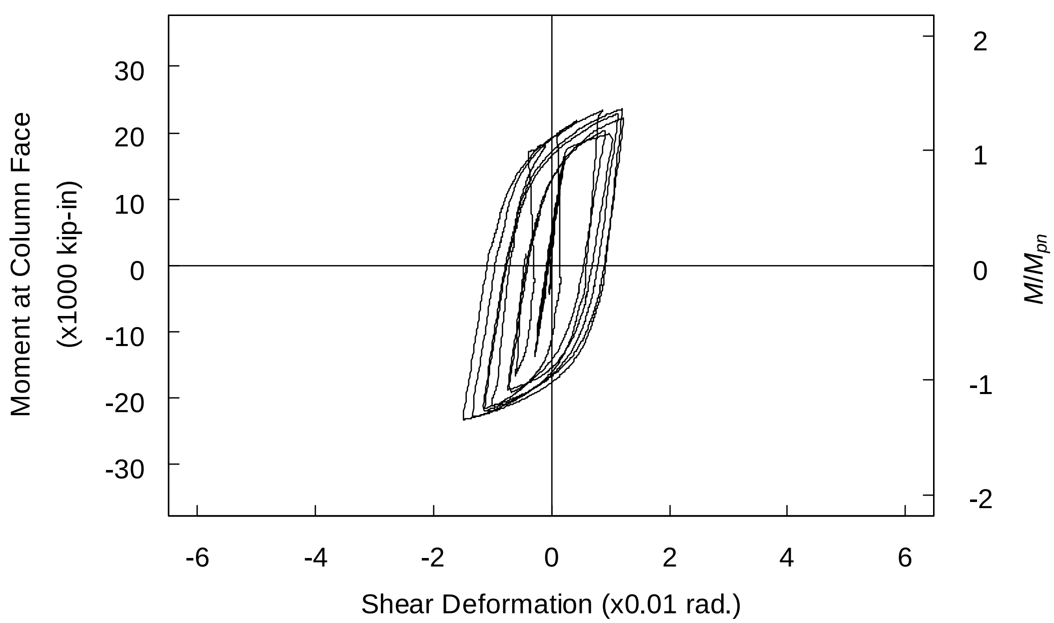


Figure 3.10 Specimen BFP-1: Beam Moment versus Panel Zone Deformation

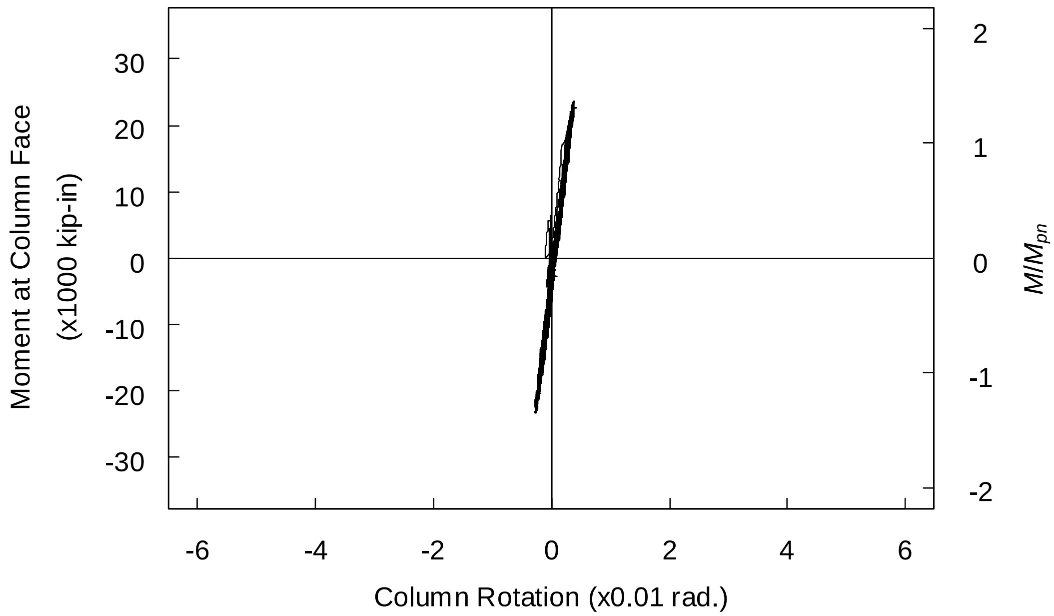


Figure 3.11 Specimen BFP-1: Beam Moment versus Column Total Rotation

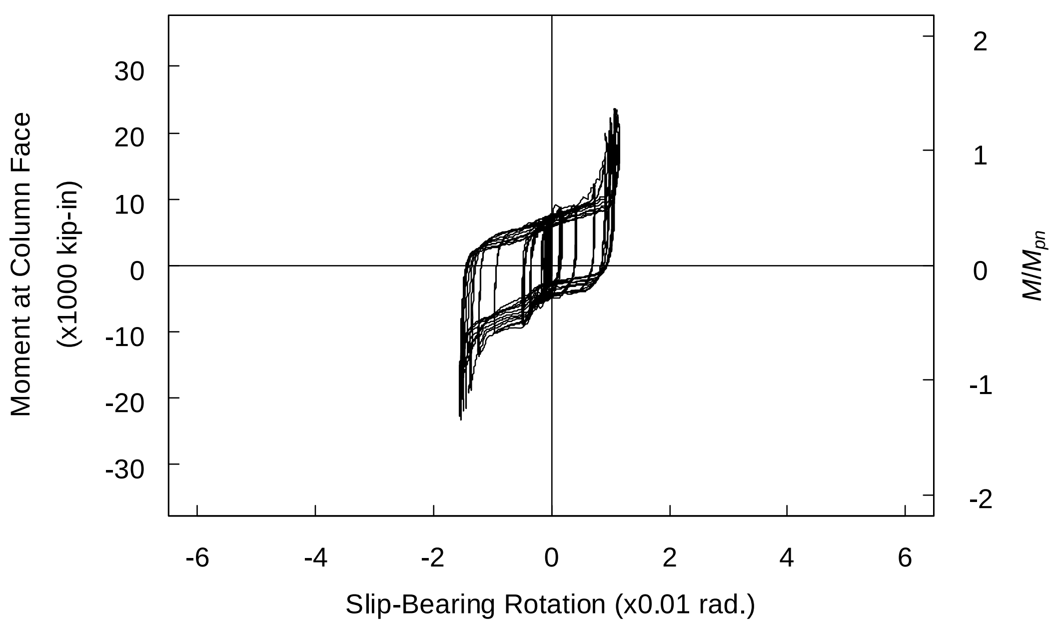


Figure 3.12 Specimen BFP-1: Beam Moment versus Slip-Bearing Rotation

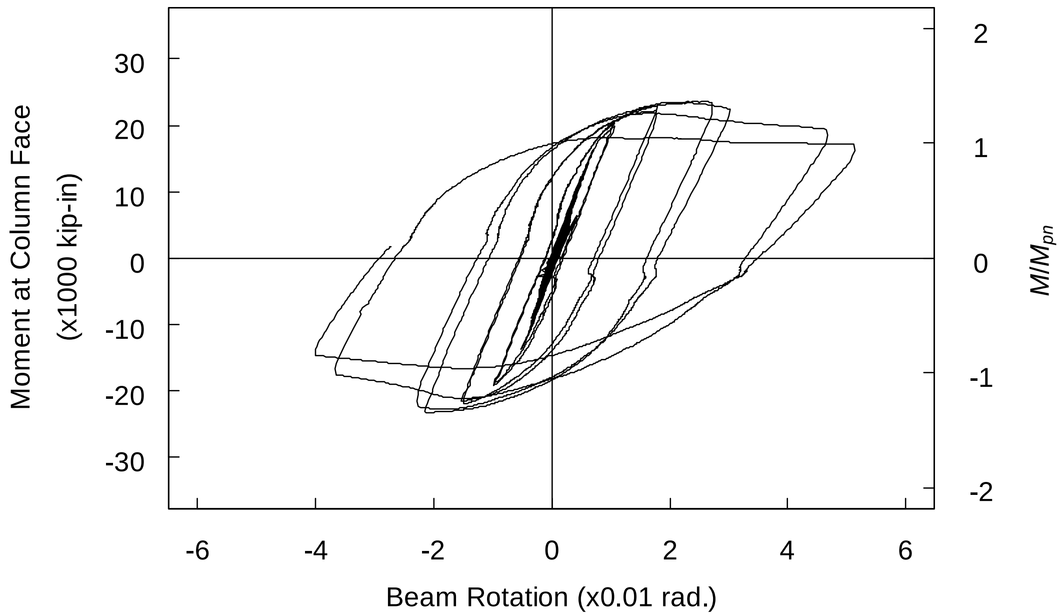


Figure 3.13 Specimen BFP-1: Beam Moment versus Beam Rotation

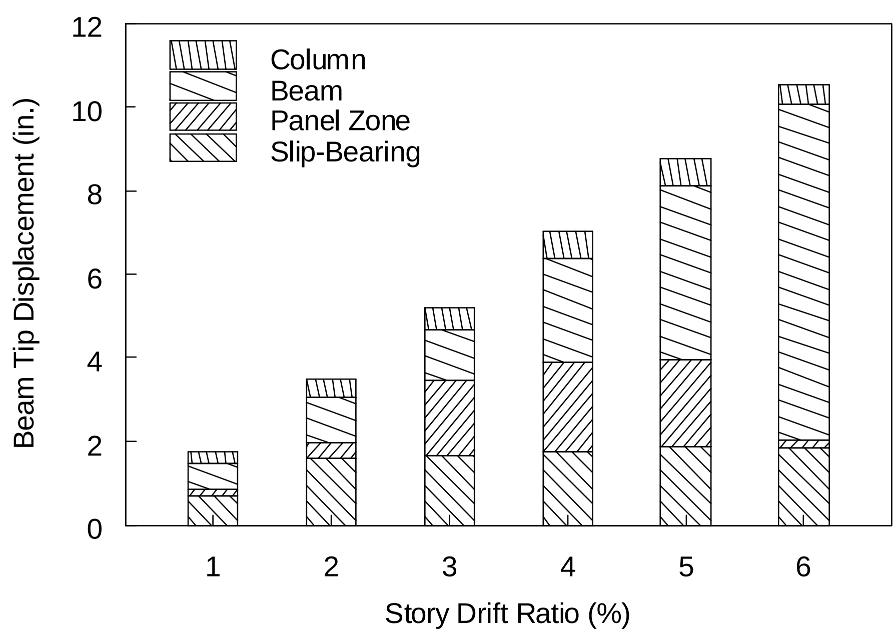
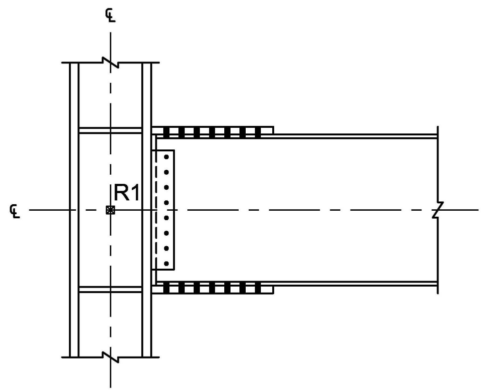
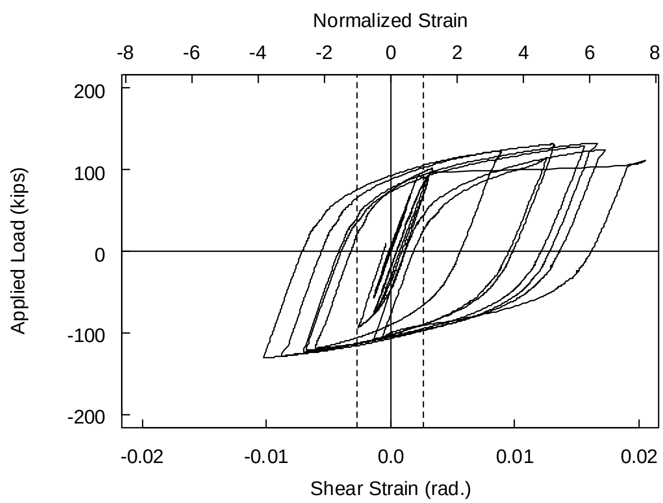


Figure 3.14 Specimen BFP-1: Components of Beam Tip Displacement

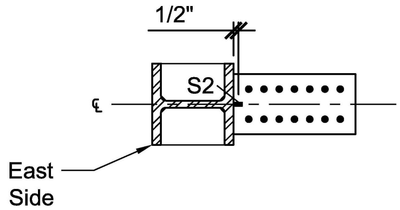


(a) Strain Rosette Location

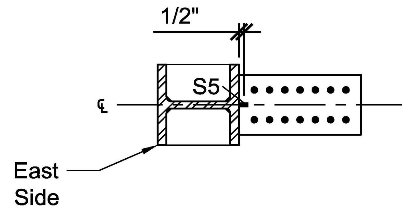


(b) Strain Rosette R1

Figure 3.15 Specimen BFP-1: Shear Strain in Panel Zone

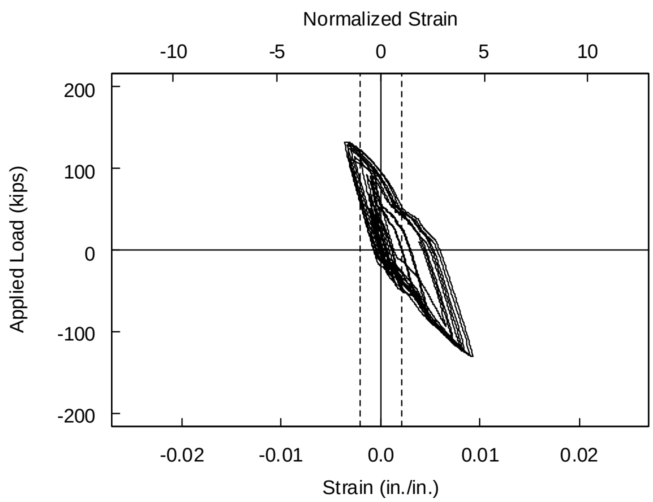


Top Flange Plate

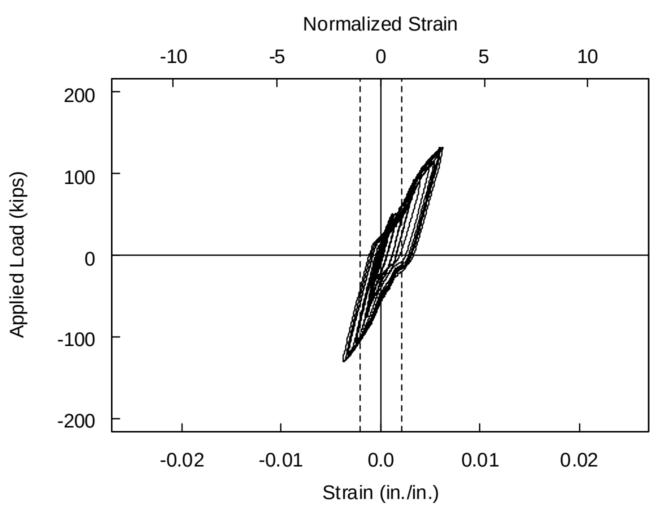


Bottom Flange Plate

(a) Strain Gage Locations

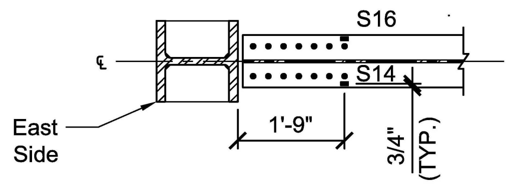


(b) Strain Gage S2



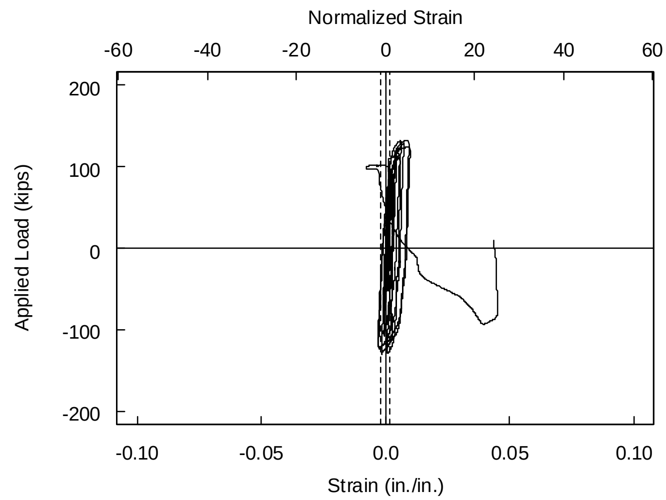
(c) Strain Gage S5

Figure 3.16 Specimen BFP-1: Strains in Flange Plate near Electroslag Weld

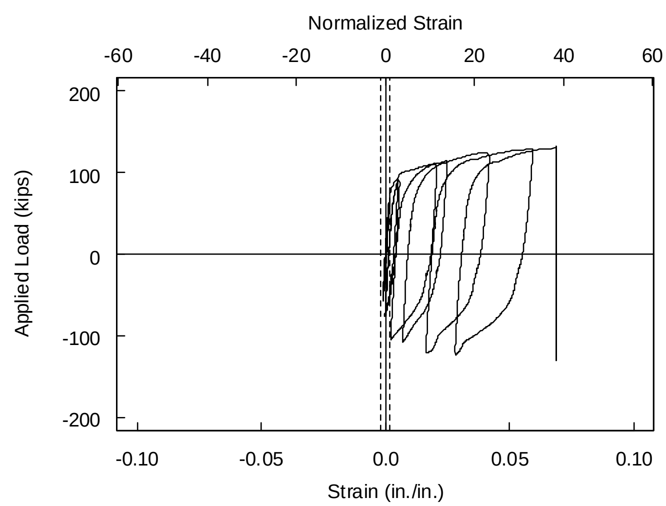


Beam Bottom Flange

(a) Strain Gage Locations

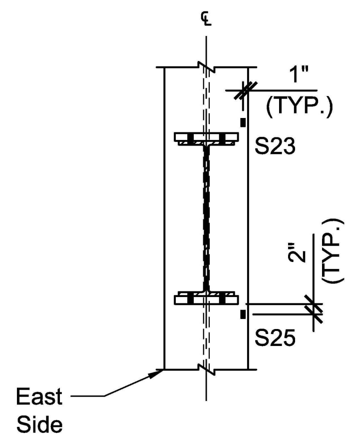


(b) Strain Gage S14

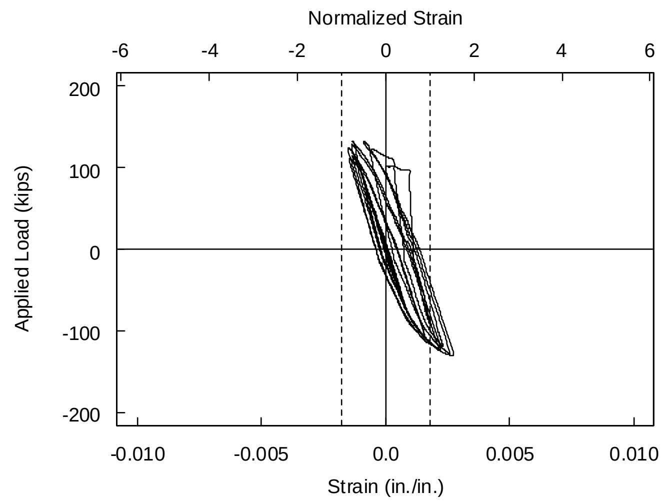


(c) Strain Gage S16

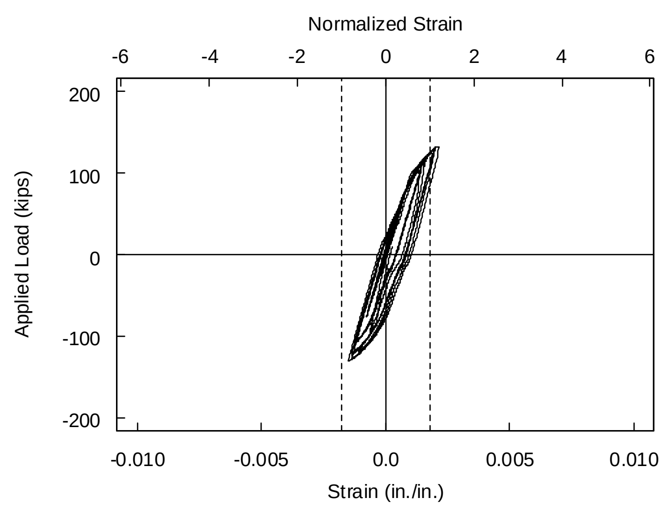
Figure 3.17 Specimen BFP-1: Beam Flange Strains at Net Section



(a) Strain Gage Locations

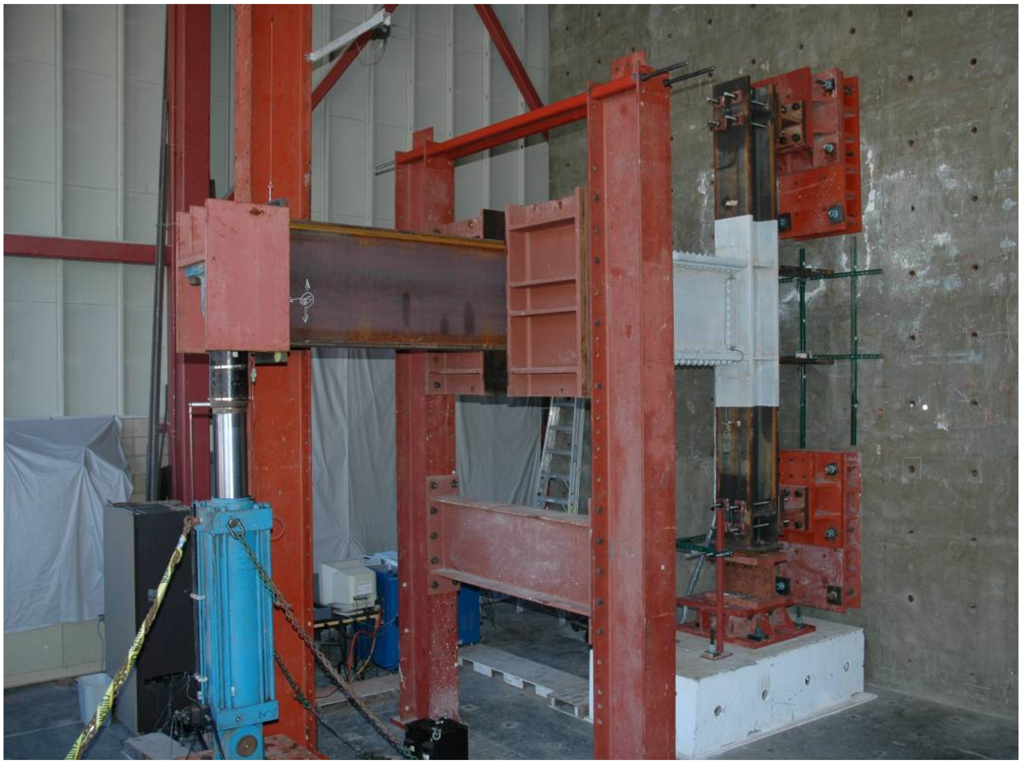


(b) Strain Gage S23



(c) Strain Gage S25

Figure 3.18 Specimen BFP-1: Strains in Column Flange



(a) Overall View

(b) Close-up of Connection Region

Figure 3.19 Specimen BFP-2: Before Testing

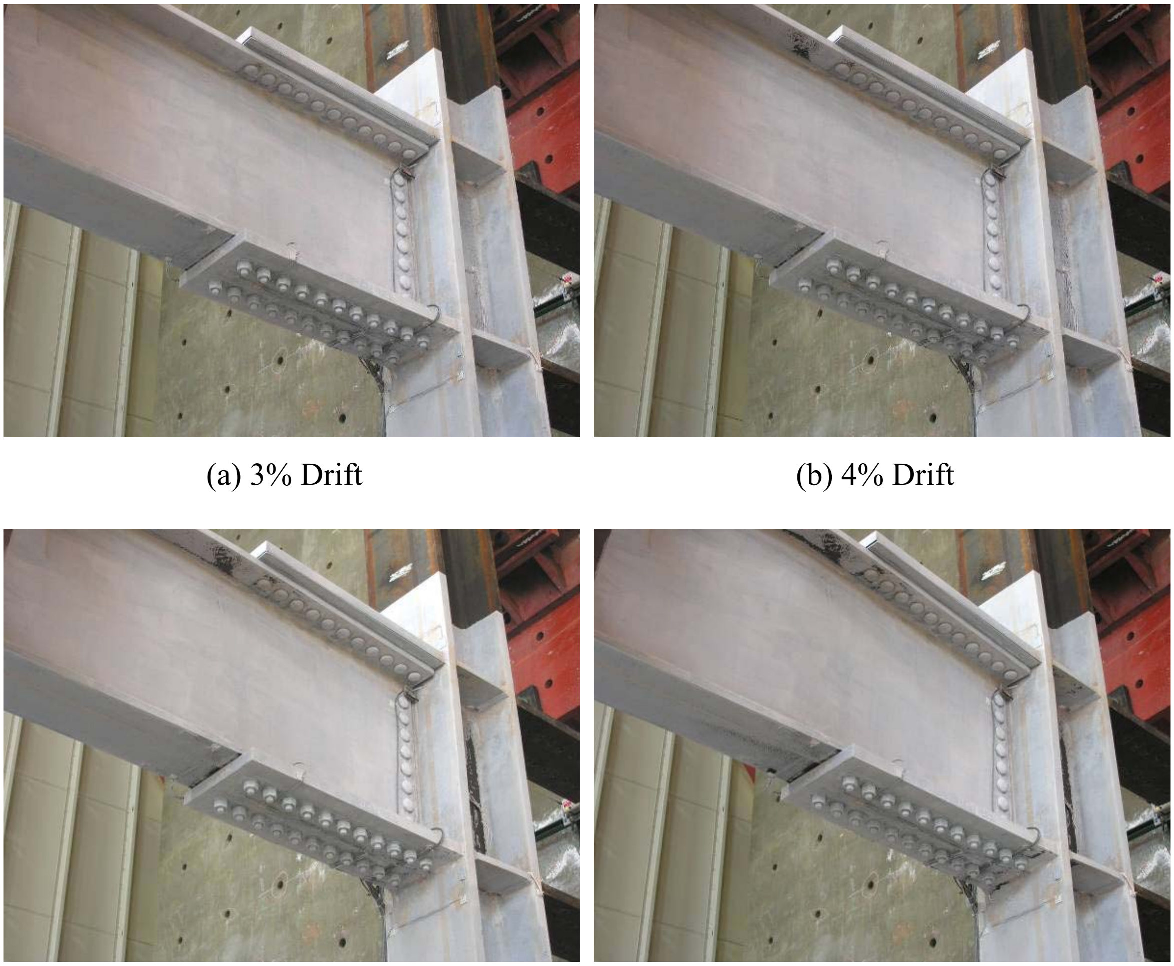
Positive Drift Negative Drift

(a) 4% Drift

(b) 5% Drift

(c) 6% Drift

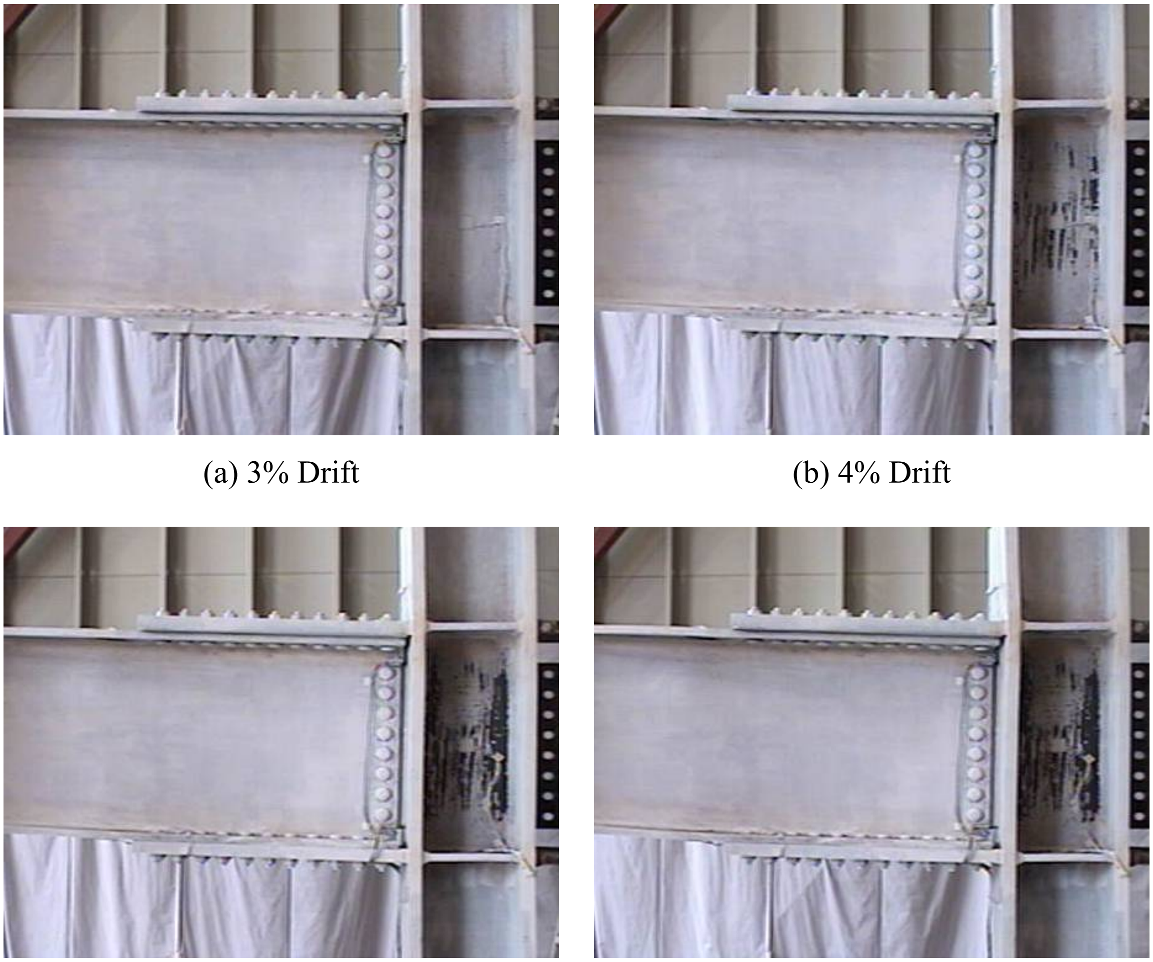
Figure 3.20 Specimen BFP-2: Overall Deformed Configuration



(a) 3% Drift (b) 4% Drift

(c) 5% Drift (d) 6% Drift

Figure 3.21 Specimen BFP-2: Yielding Pattern and Beam Local Buckling



(a) 3% Drift (b) 4% Drift

(c) 5% Drift (d) 6% Drift

Figure 3.22 Specimen BFP-2: Panel Zone Yielding Pattern

(a) +5% Drift

(b) -5% Drift

(c) +6% Drift

Figure 3.23 Specimen BFP-2: Beam Lateral-Torsional Buckling

(a) +5% Drift (b) +6% Drift

Figure 3.24 Specimen BFP-2: Actuator Skewed to East Side

Figure 3.25 Specimen BFP-2: Beam Flange Bolt Hole Ovalization and Necking at Outermost Bolt Row (after Testing)

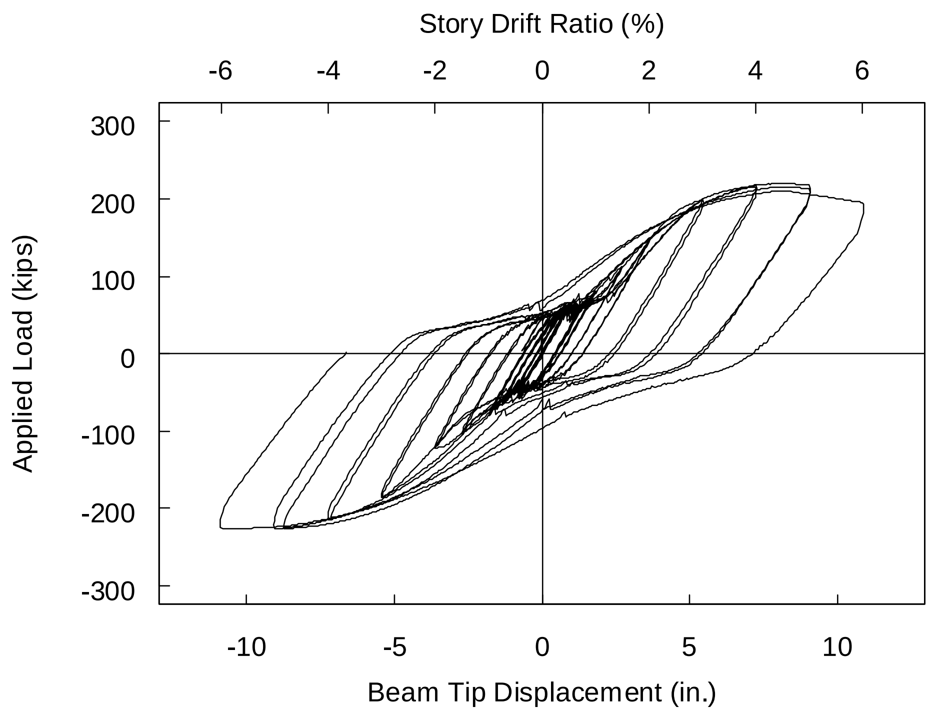


Figure 3.26 Specimen BFP-2: Load versus Beam Tip Displacement

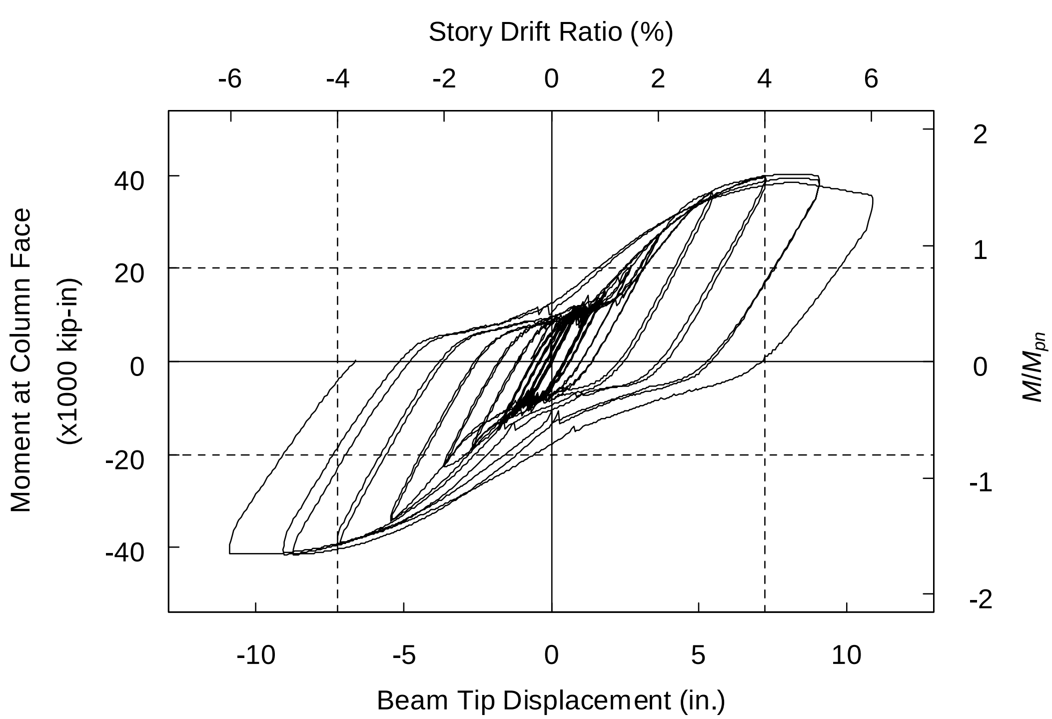


Figure 3.27 Specimen BFP-2: Beam Moment versus Beam Tip Displacement

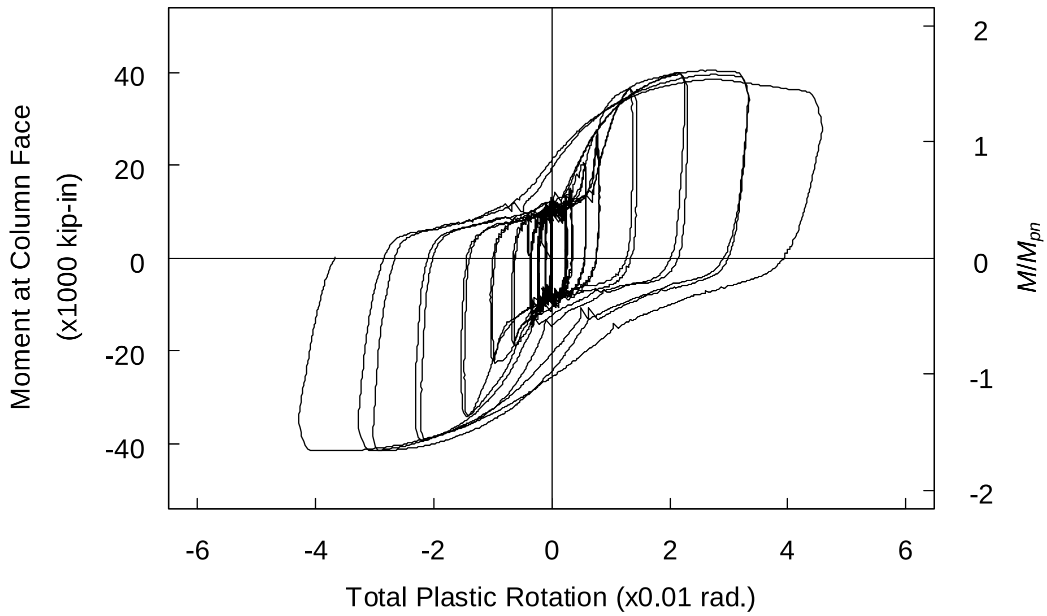


Figure 3.28 Specimen BFP-2: Beam Moment versus Total Plastic Rotation

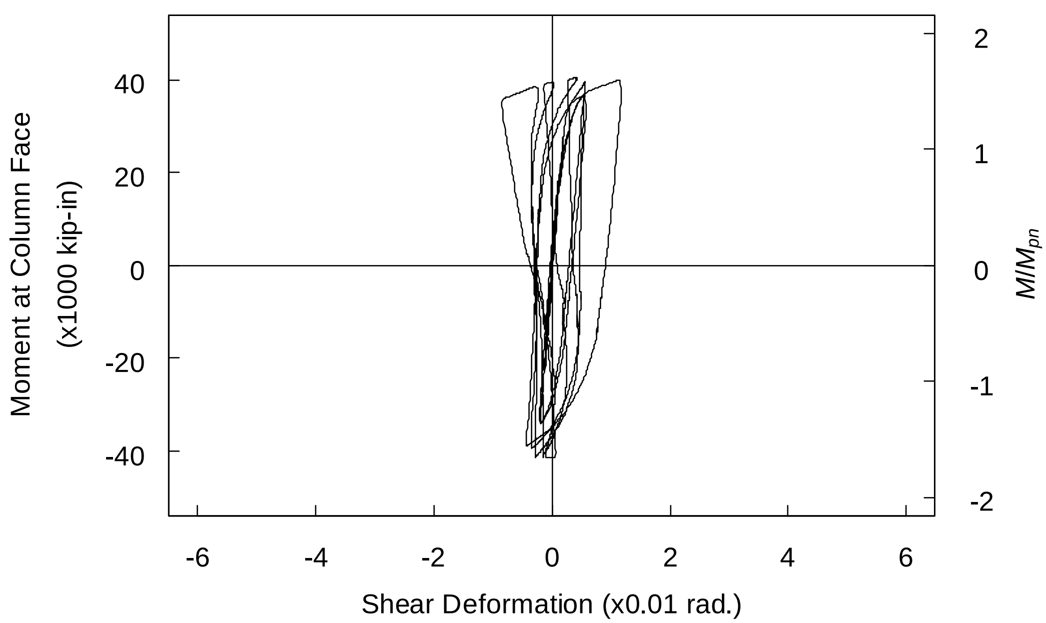


Figure 3.29 Specimen BFP-2: Beam Moment versus Panel Zone Deformation

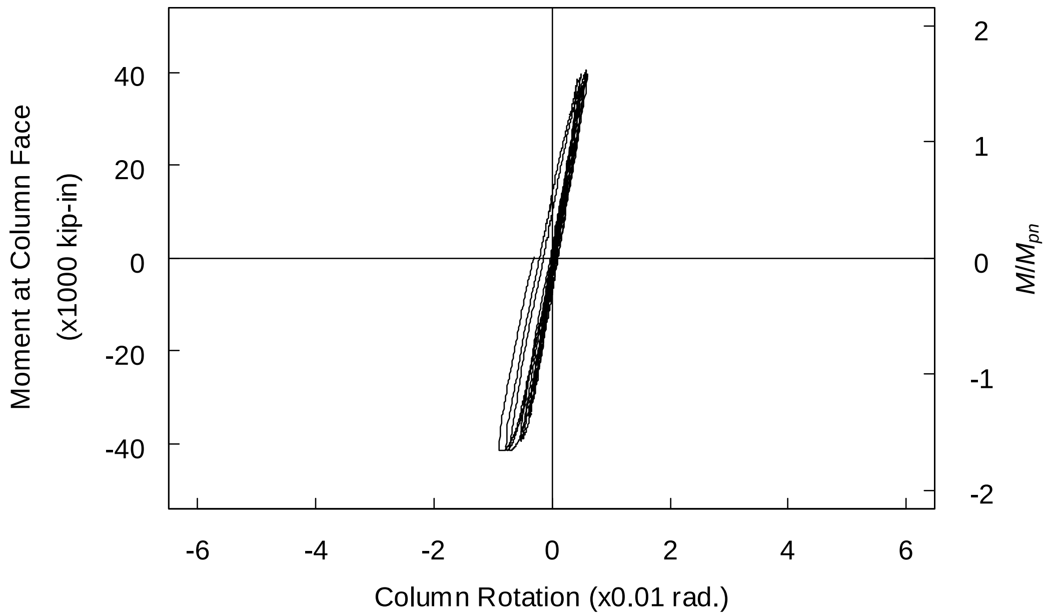


Figure 3.30 Specimen BFP-2: Beam Moment versus Column Total Rotation

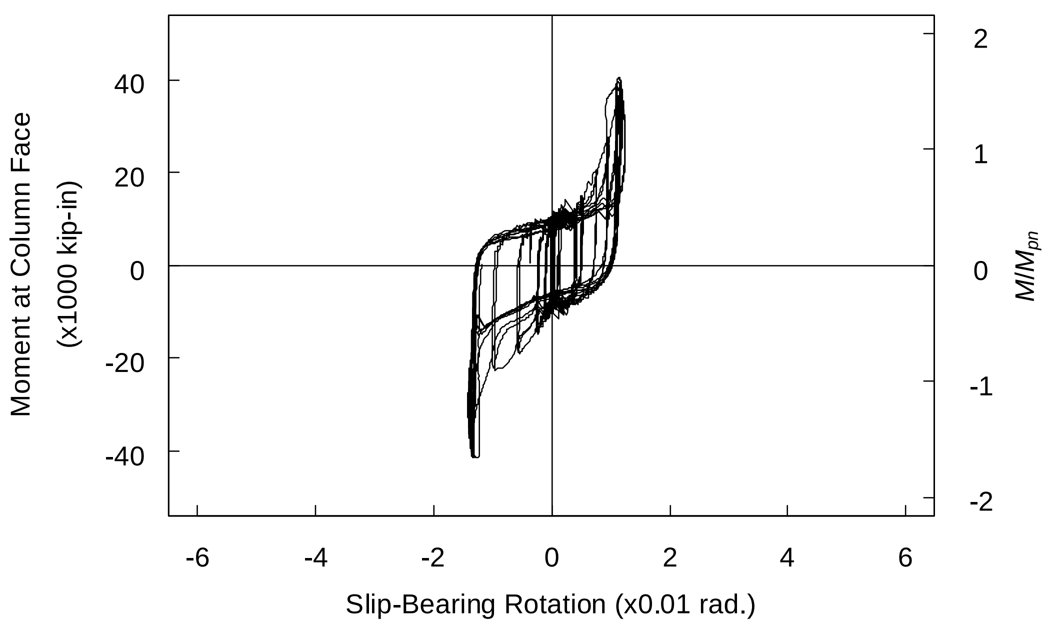


Figure 3.31 Specimen BFP-2: Beam Moment versus Slip-Bearing Rotation

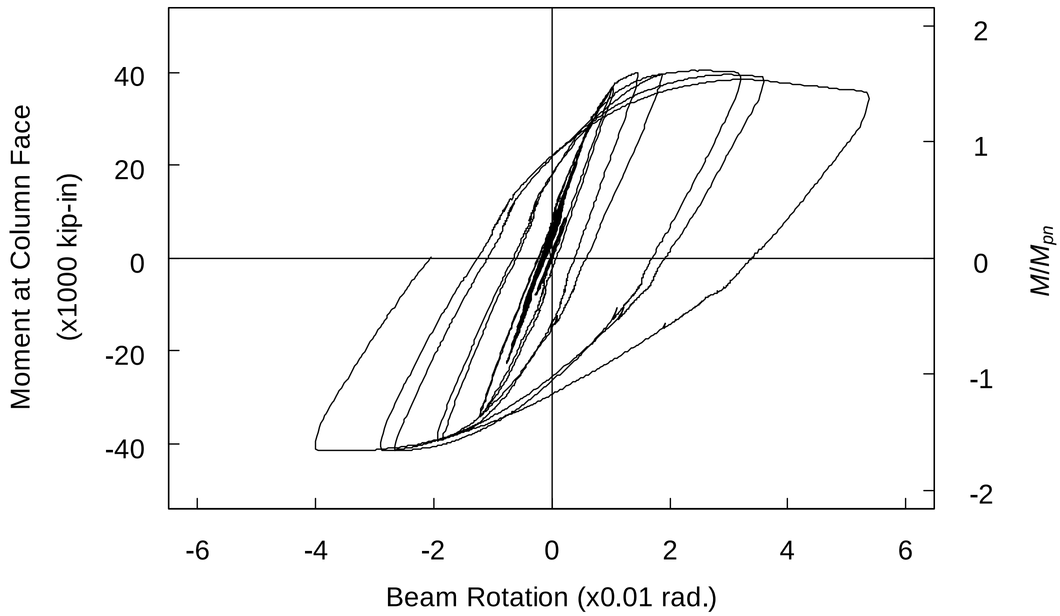


Figure 3.32 Specimen BFP-2: Beam Moment versus Beam Rotation

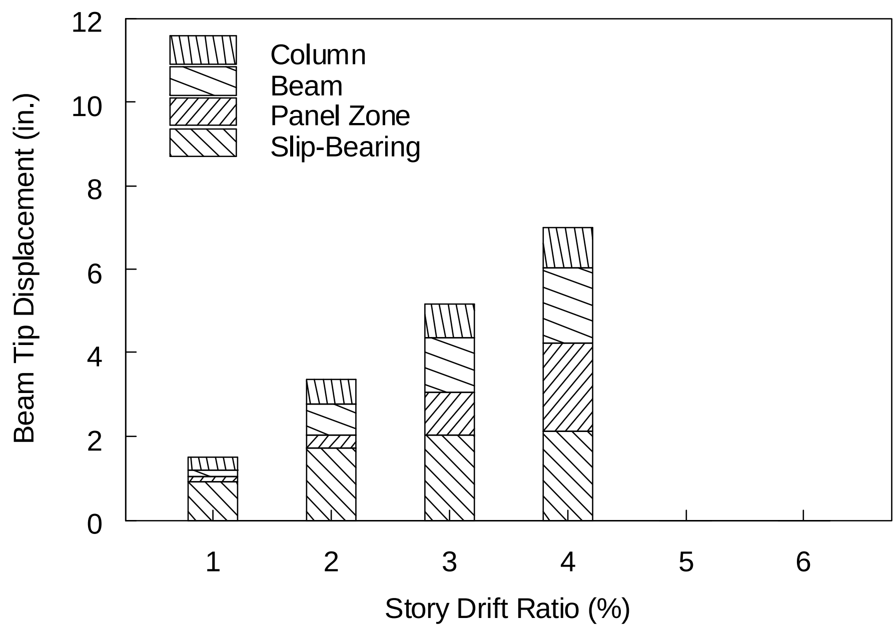
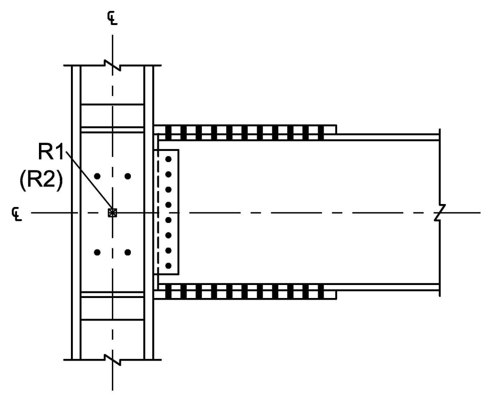
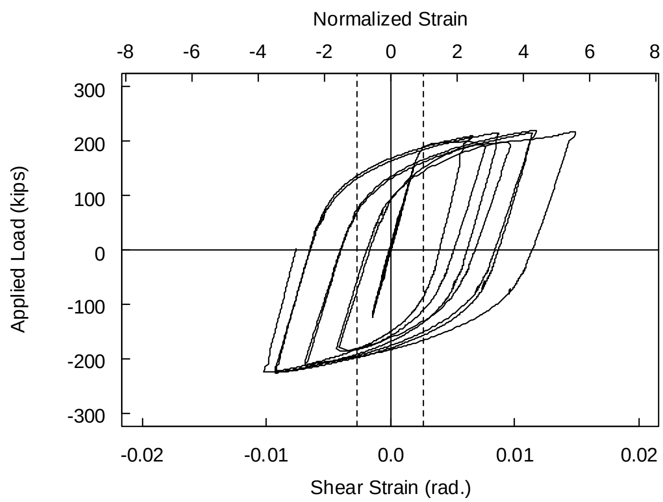


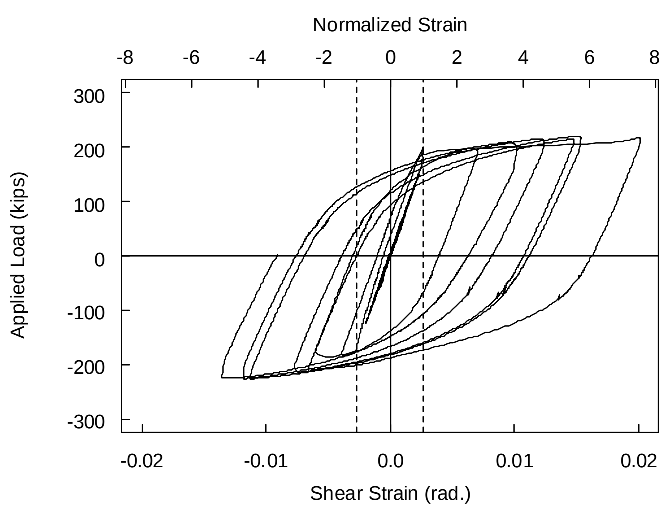
Figure 3.33 Specimen BFP-2: Components of Beam Tip Displacement



(a) Strain Rosette Location

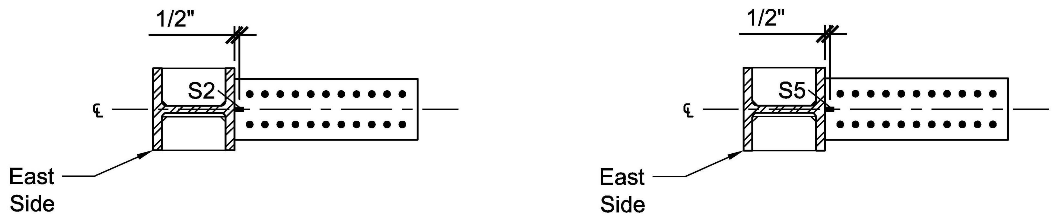


(b) Strain Rosette R1 (on Doubler Plate)



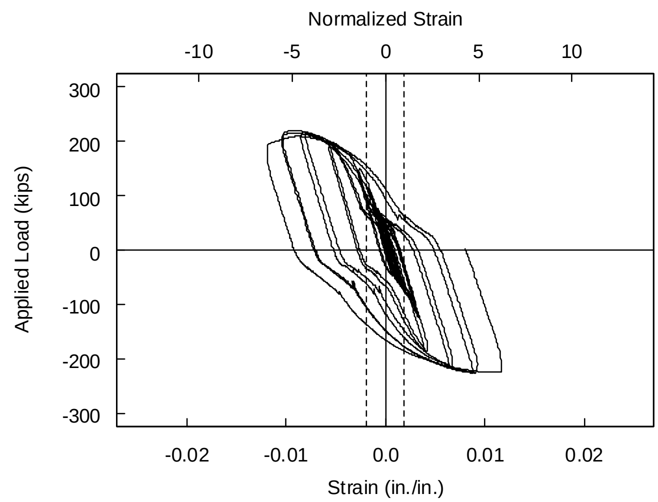
(c) Strain Rosette R2 (on Column Web)

Figure 3.34 Specimen BFP-2: Shear Strain in Panel Zone

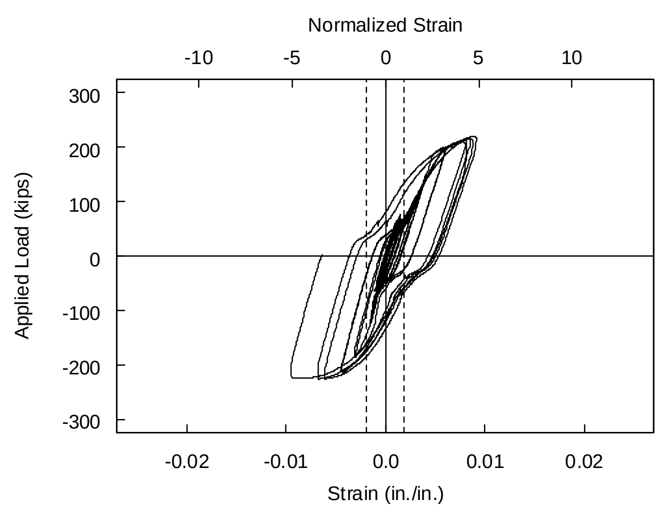


Top Flange Plate　　Bottom Flange Plate

(a) Strain Gage Locations

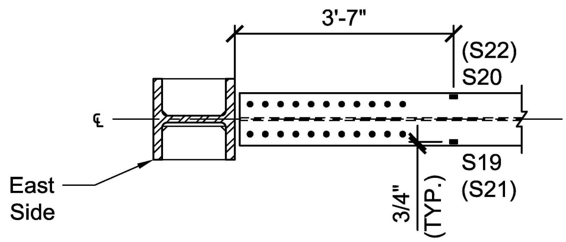


(b) Strain Gage S2



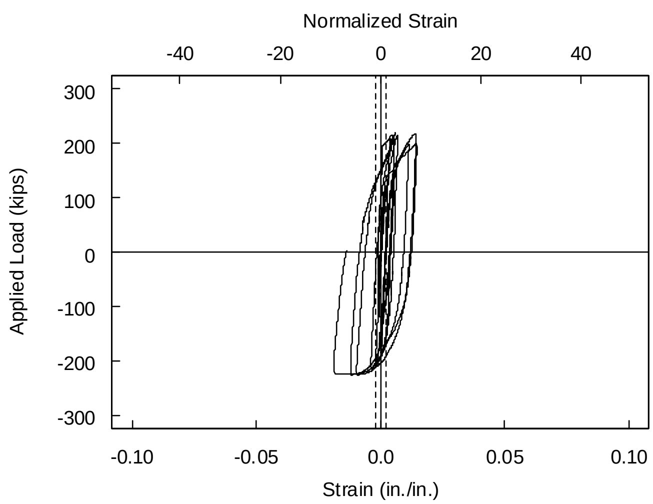
(c) Strain Gage S5

Figure 3.35 Specimen BFP-2: Strains in Flange Plate near Electroslag Weld

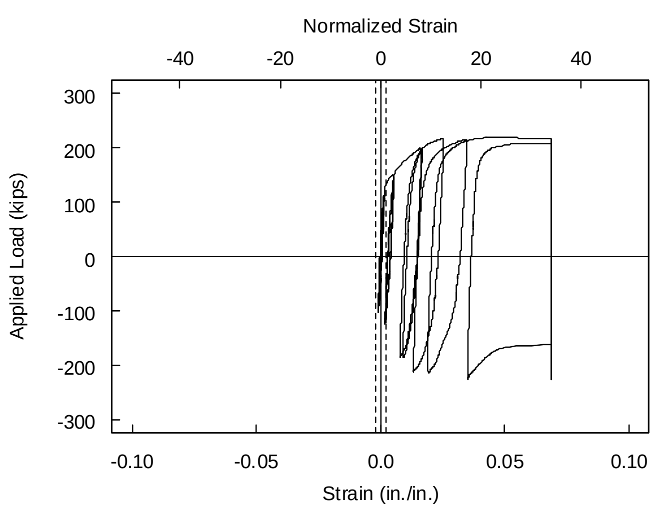


Bottom Beam Flange

(a) Strain Gage Locations

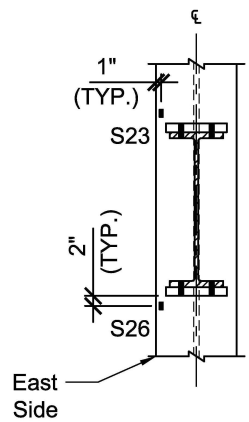


(b) Strain Gage S16

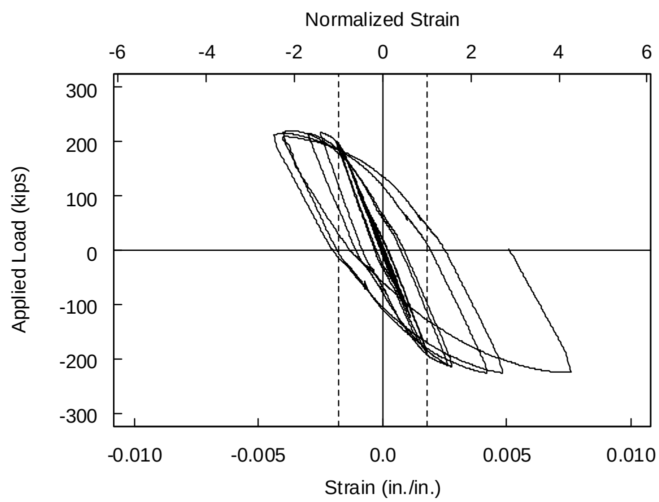


(c) Strain Gage S18

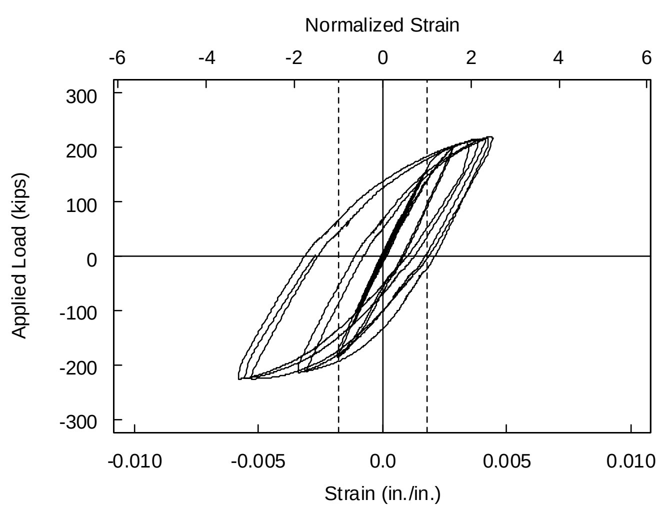
Figure 3.36 Specimen BFP-2: Beam Flange Strains at Net Section



(a) Strain Gage Locations



(b) Strain Gage S23



(c) Strain Gage S26

Figure 3.37 Specimen BFP-2: Strains in Column Flange

(a) Overall View

(b) Close-up of Connection Region

Figure 3.38 Specimen BFP-3: Before Testing

Positive Drift Negative Drift

(a) 4% Drift

(b) 5% Drift

(c) 6% Drift

Figure 3.39 Specimen BFP-3: Overall Deformed Configuration

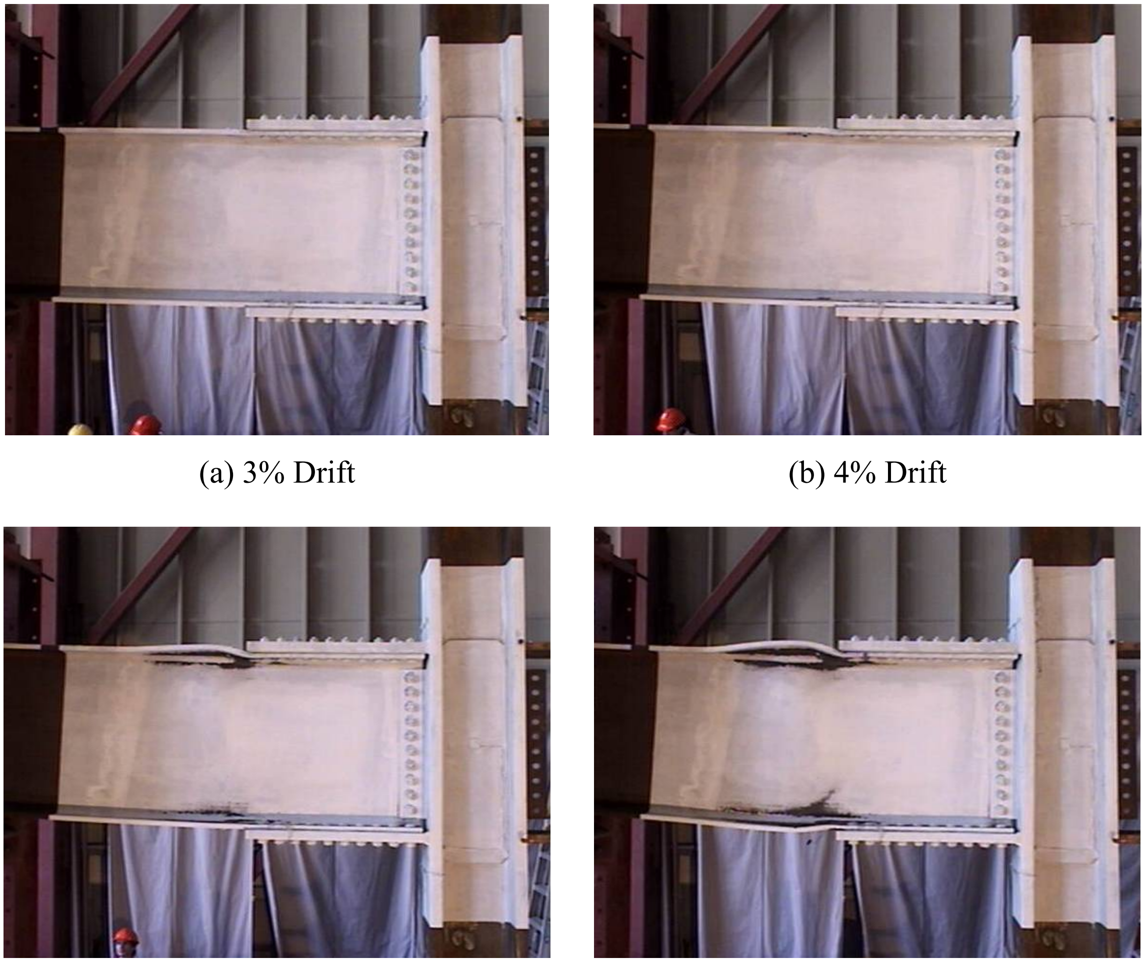
(a) 3% Drift

(b) 4% Drift

(c) 5% Drift

(d) 6% Drift

Figure 3.40 Specimen BFP-3: Yielding Pattern and Beam Local Buckling



(a) 3% Drift (b) 4% Drift

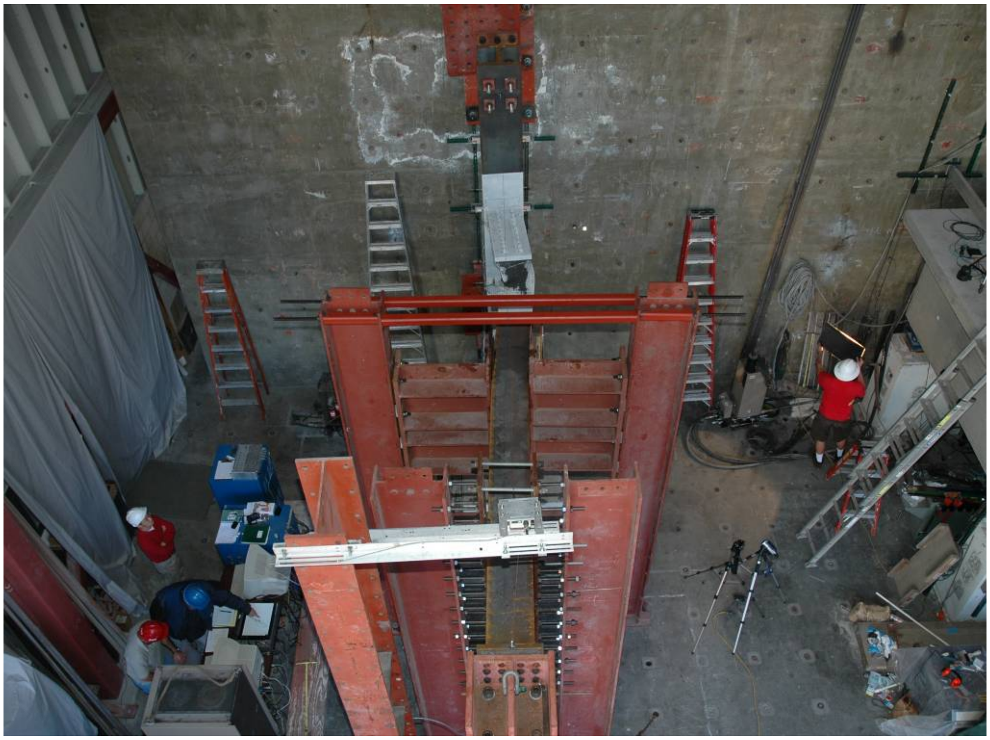
(c) 5% Drift (d) 6% Drift

Figure 3.41 Specimen BFP-3: Panel Zone Yielding Pattern

(a) Web Local Buckling

(b) Flange Local Buckling

Figure 3.42 Specimen BFP-3: Local Buckling at +5% Drift



(a) Overall View

(b) Close-up of Connection

Figure 3.43 Specimen BFP-3: Lateral-Torsional Buckling at +6% Drift

(a) Overall

(b) West Side Top Detail

(c) East Side Top Detail

Figure 3.44 Specimen BFP-3: Yielding in Column

(a) Fracture Location

(b) Close-up

Figure 3.45 Specimen BFP-3: Beam Bottom Flange Net Section Fracture on 1st Cycle at +7% Drift

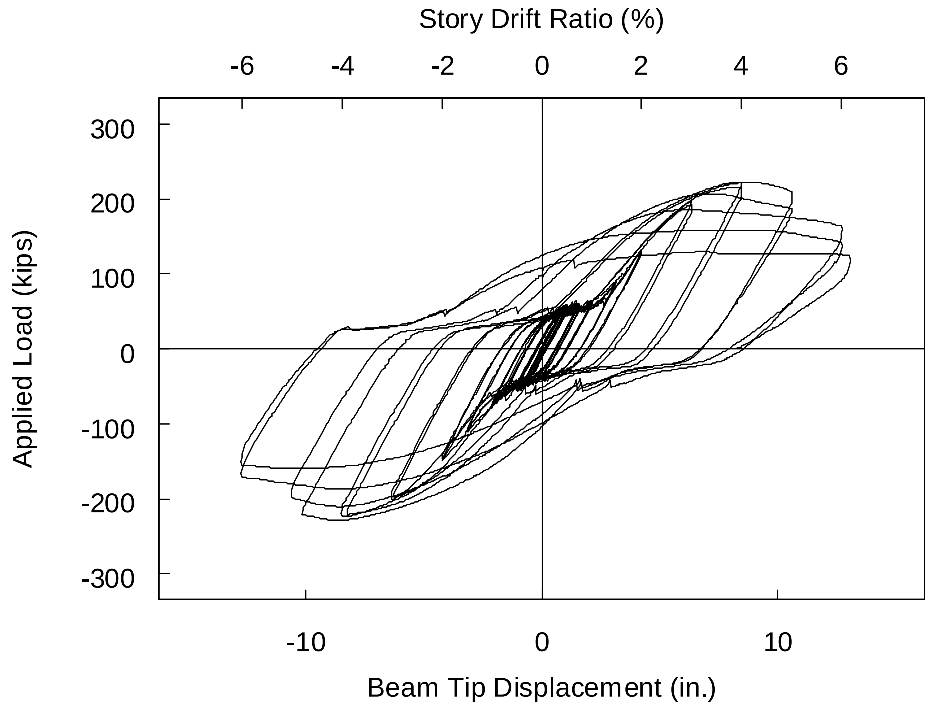


Figure 3.46 Specimen BFP-3: Load versus Beam Tip Displacement

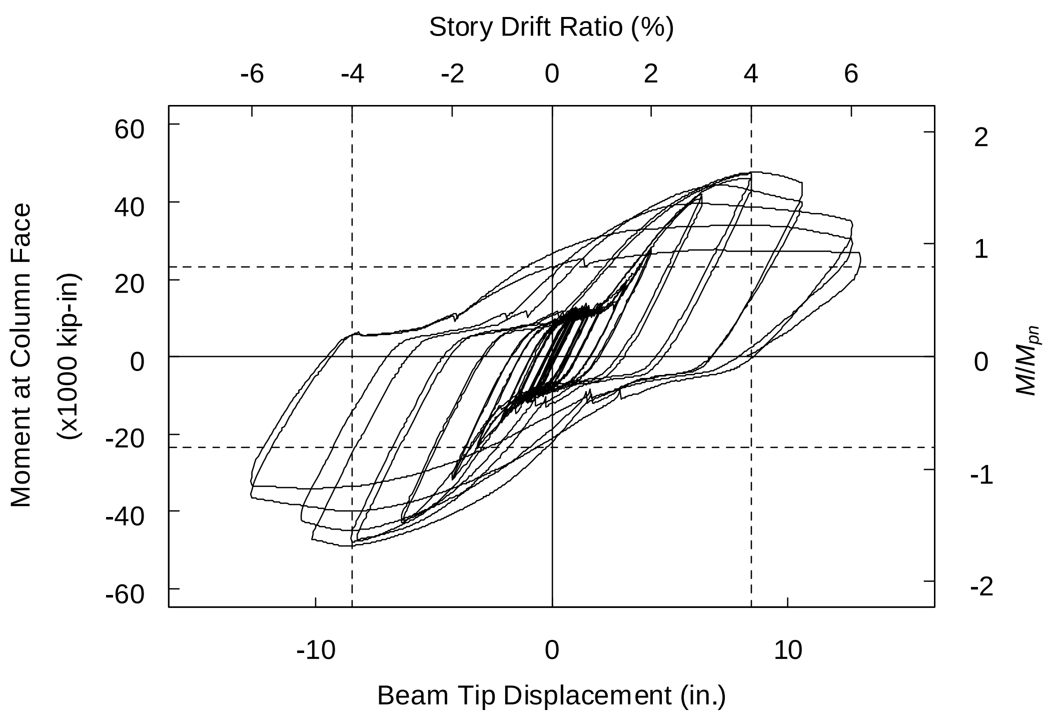


Figure 3.47 Specimen BFP-3: Beam Moment versus Beam Tip Displacement

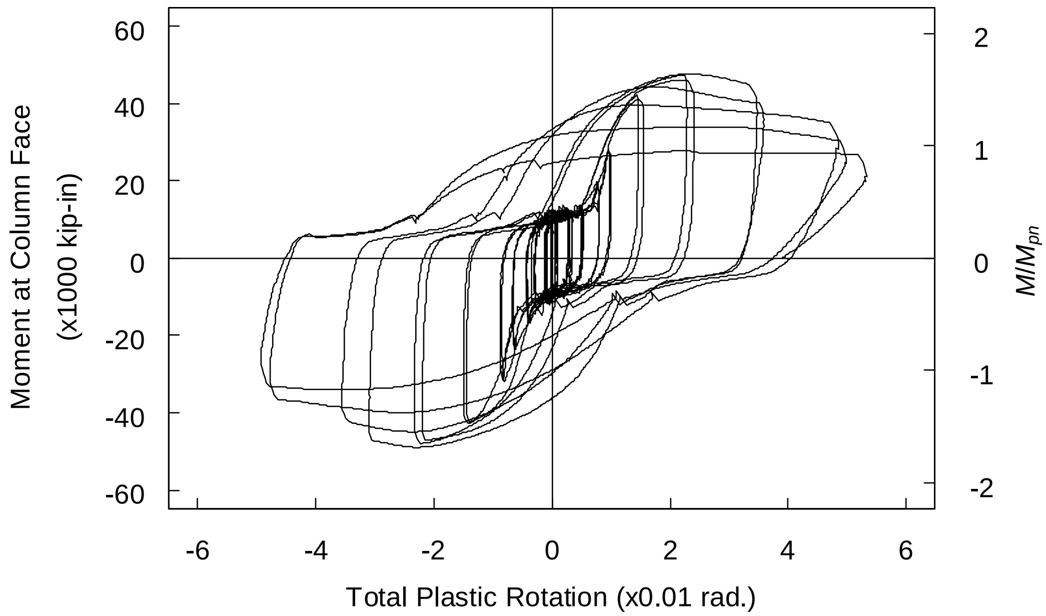


Figure 3.48 Specimen BFP-3: Beam Moment versus Total Plastic Rotation

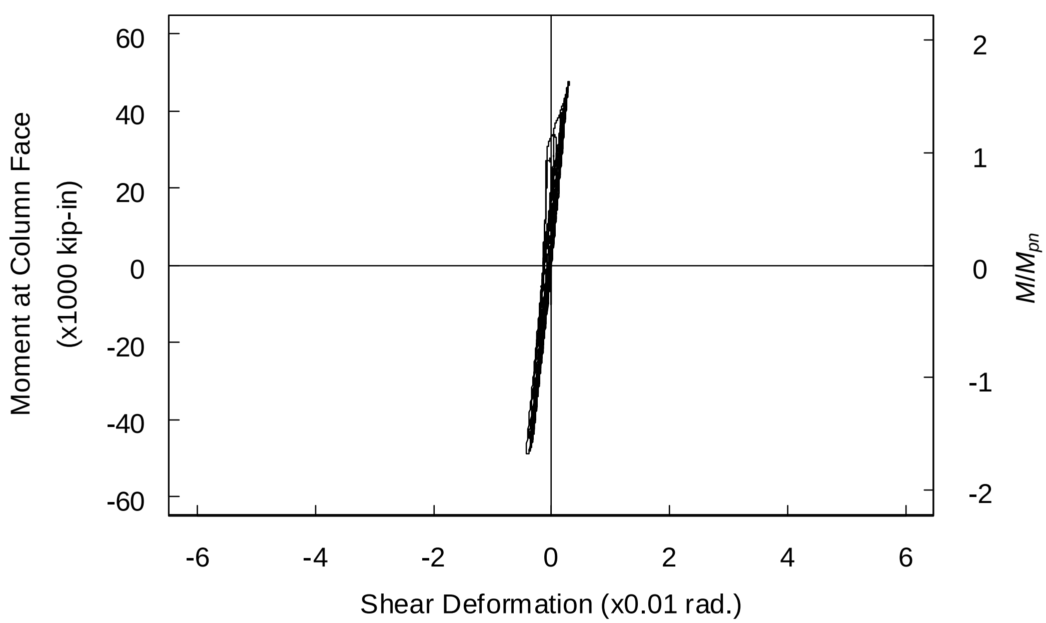


Figure 3.49 Specimen BFP-3: Beam Moment versus Panel Zone Deformation

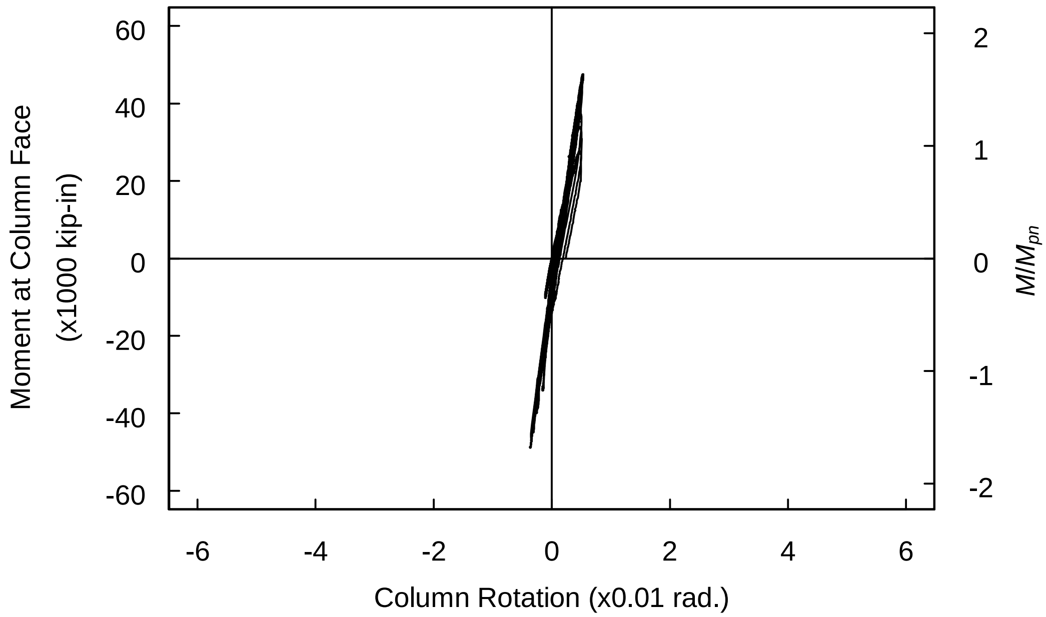


Figure 3.50 Specimen BFP-3: Beam Moment versus Column Total Rotation

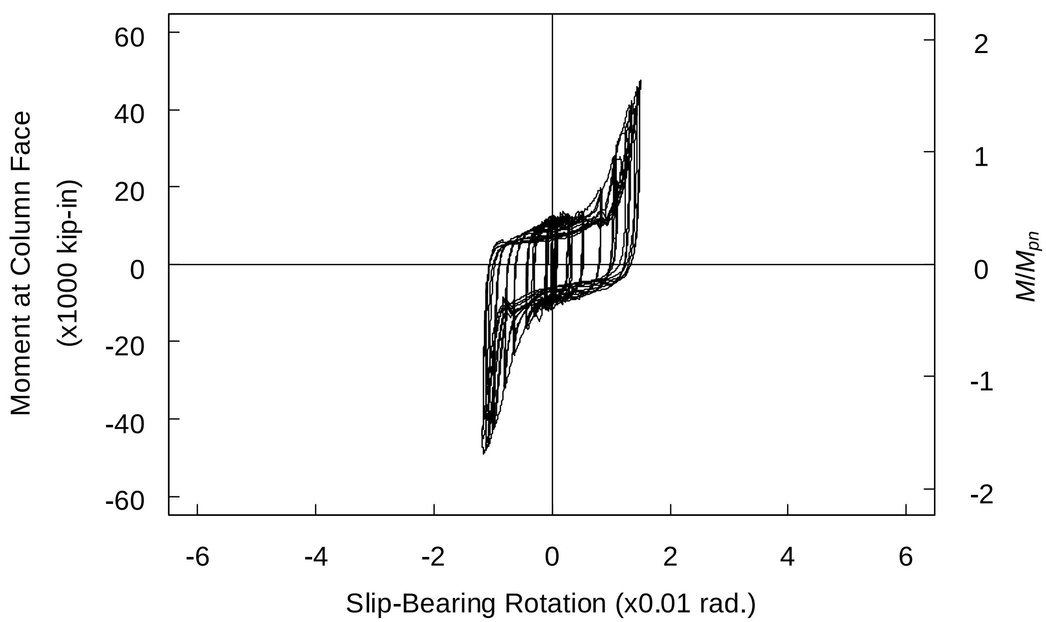


Figure 3.51 Specimen BFP-3: Beam Moment versus Slip-Bearing Rotation

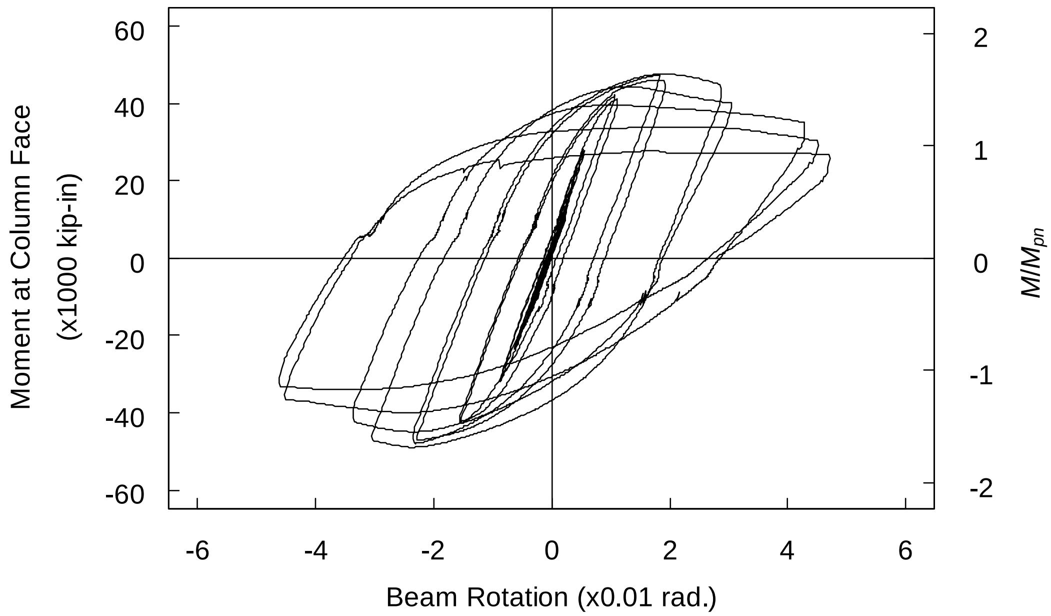


Figure 3.52 Specimen BFP-3: Beam Moment versus Beam Rotation

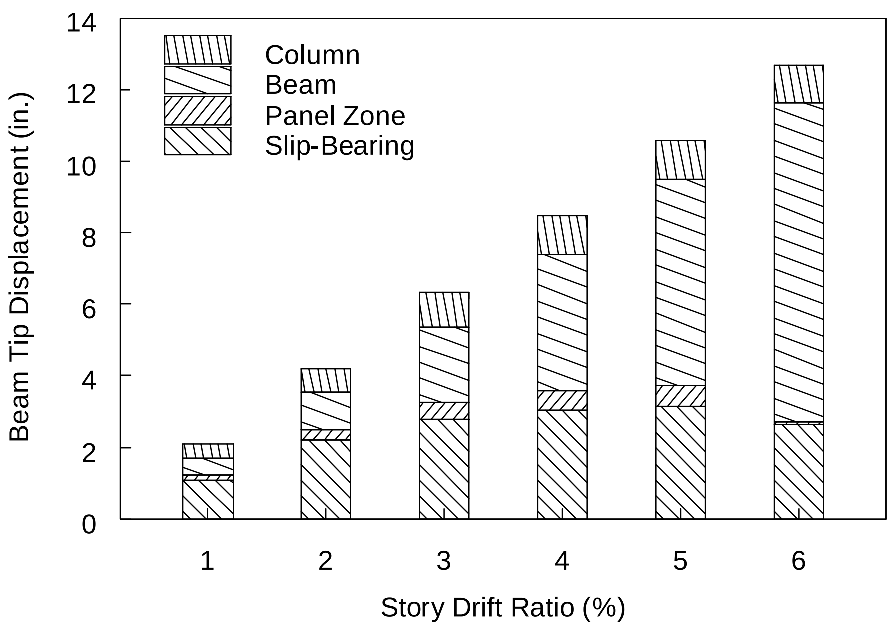
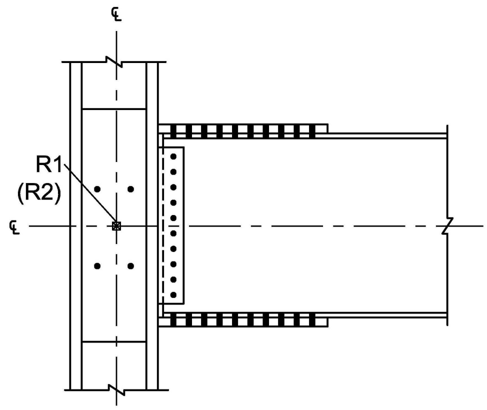
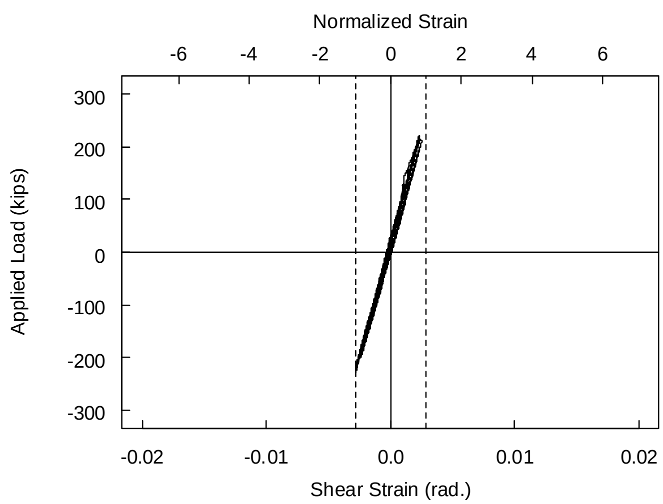


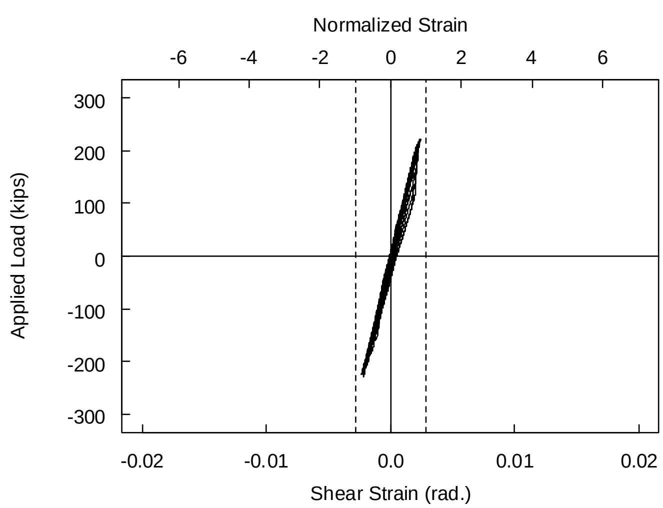
Figure 3.53 Specimen BFP-3: Components of Beam Tip Displacement



(a) Strain Rosette Location

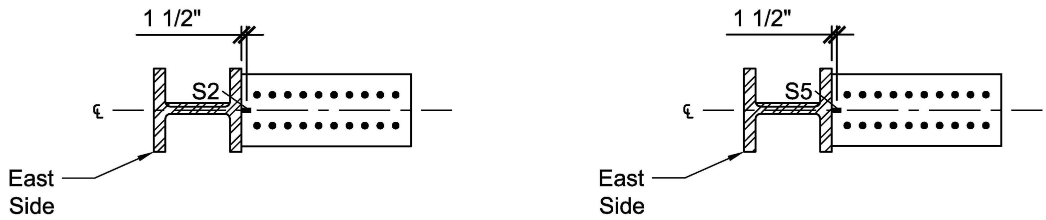


(b) Strain Rosette R1 (on Column Web)



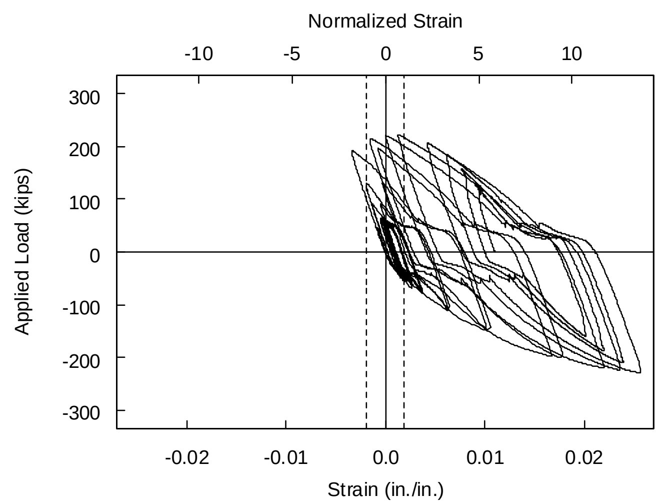
(c) Strain Rosette R2 (on Doubler Plate)

Figure 3.54 Specimen BFP-3: Shear Strain in Panel Zone

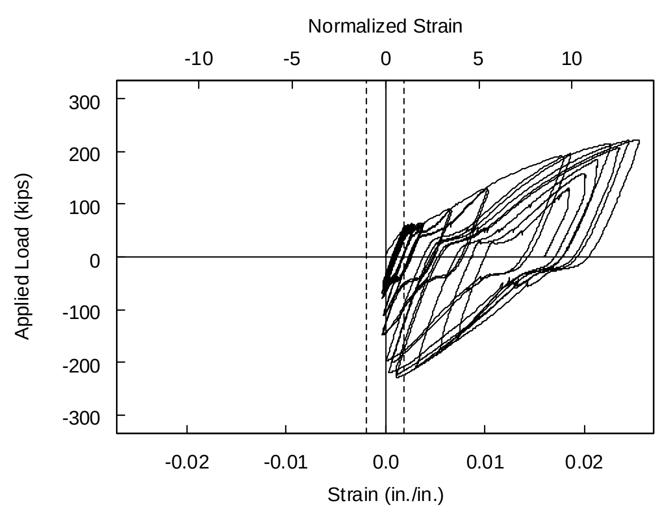


Top Flange Plate Bottom Flange Plate

(a) Strain Gage Locations

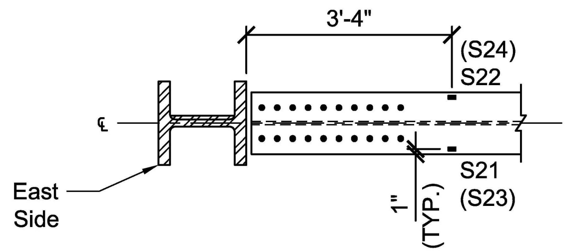


(b) Strain Gage S2



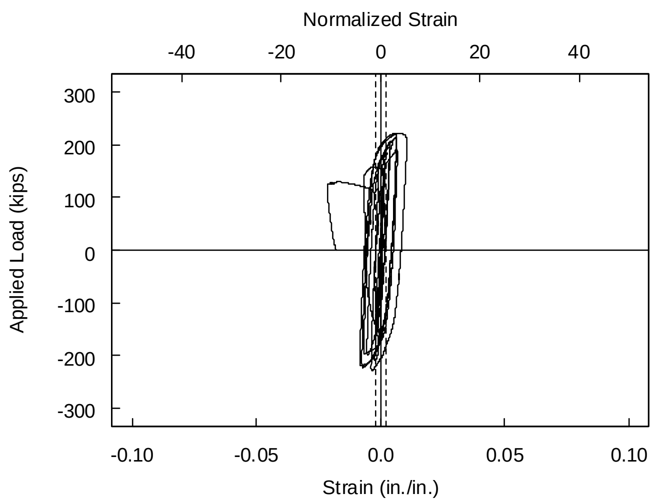
(c) Strain Gage S5

Figure 3.55 Specimen BFP-3: Strains in Flange Plate near Flux-cored Arc Weld

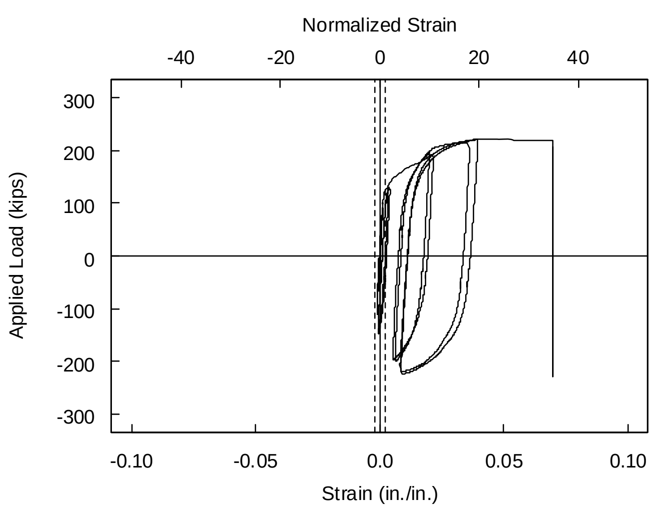


Bottom Beam Flange

(a) Strain Gage Locations

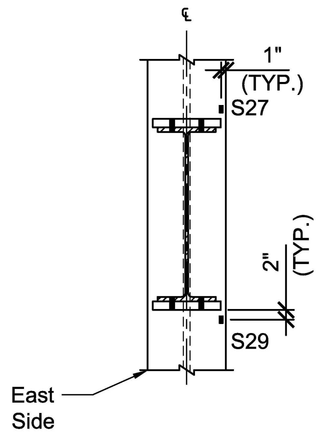


(b) Strain Gage S17

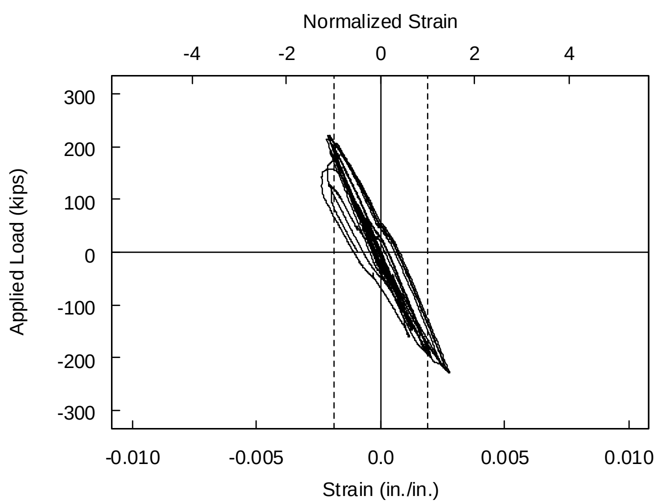


(c) Strain Gage S19

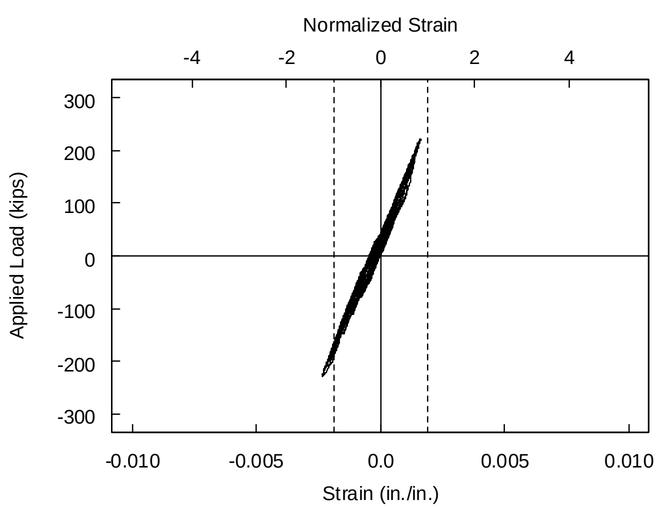
Figure 3.56 Specimen BFP-3: Strains in Beam Flange



(a) Strain Gage Locations



(b) Strain Gage S27



(c) Strain Gage S29

Figure 3.57 Specimen BFP-3: Strains in Column Flange

4. COMPARISON OF EXPERIMENTAL RESULTS

4.1 Global Response

A plot of the moment (at column face) versus beam tip displacement relationship is shown in Figure 4.1 for the three specimens. To meet the Acceptance Criteria of the AISC *Seismic Provisions*, specimens shall satisfy the following requirements: (1) the connection must be capable of sustaining an interstory drift angle of at least 0.04 radians, and (2) the required flexural strength of the connections, determined at the column face, must equal at least 80% of the nominal plastic moment (M_{pn}) of the connected beam at an interstory drift angle of 0.04 radians. The vertical dashed lines shown in Figure 4.1 are at 4% drift and the horizontal dashed lines are at 80% of the nominal plastic moment. Specimens exceeded the requirements of the AISC Acceptance Criteria and achieved an interstory drift angle of at least 0.06 radian. The pinching observed in the hysteresis loops is mainly attributed to the slip-bearing behavior of the bolted connection. After some amount of initial slippage, hardening behavior can be observed due to bearing between the bolt, flange plate, and beam flange.

4.2 Displacement Components

Figure 4.2 shows the relative contribution of the column, beam, panel zone, and slip-bearing deformation to the overall beam tip displacement at different drift levels. [For Specimen BFP-2, components at 5% and 6% drift are not shown in Figure 4.2(b) because column twisting affected the measurements.] Shear deformation in the panel zone and slippage between the flange plate and beam flange made significant contributions to the total beam tip displacement of Specimens BFP-1 and BFP-2. Deformation in the panel zone of Specimen BFP-3 was limited because of the strong panel zone (demand-capacity ratio of 0.73). But slippage and bearing between the flange plate and beam flange made a significant contribution to the total beam tip displacement. The BFP connection differs from welded moment connections in that the additional component of bolt slip-bearing contributes to overall inelastic deformation of the connection. Slip-bearing deformation contributed a significant amount to the total deformation (approximately 30% of the total deformation at an interstory drift angle of 0.04 radians).

4.3 Beam Overstrength

The overstrength factor, α, resulting from cyclic strain hardening, for each specimen as computed from Eq. 4.1 is shown in Figure 4.3.

$$\alpha = \frac{M_u}{M_{pa}} \qquad (4.1)$$

Ultimate moment, M_u, was calculated from test data at the assumed plastic hinge location [i.e., at the center of the outermost (furthest from the column face) row of bolts] and M_{pa} was the plastic moment of the beam based on measured flange yield strength. Specimen overstrength values were similar to the value of 1.15 [$=(F_y+F_u)/2F_y$] given by AISC *Prequalified Connections* (AISC 2005a).

4.4 Lateral-Torsional Buckling and Column Twisting

Beam flange and web local buckling initiated at 4% drift, and lateral-torsional buckling (LTB) of the beam together with twisting of the column was observed at 5% drift for all specimens. Figure 4.4(b) shows one column flange strain gage, near the flange tip, plotted versus the gage near the opposite flange tip [see Figure 4.4(a)] for Specimen BFP-2. Deviation from the one-to-one (dashed) line provides an indication of column twisting (i.e., warping stress). Similar evidence of column twisting was observed for the other specimens. The specimens did not include a concrete structural slab, which would have provided lateral bracing to the beam top flange and torsional restraint to the column. Column twisting has been observed in testing of RBS moment connection specimens with deep columns and without a concrete structural slab (Chi and Uang, 2002), but not in testing with W14 columns. Additional deep column moment connection testing has indicated that the presence of a concrete structural slab mitigates column twisting issues associated with deep columns (Zhang and Ricles, 2006). However, the column twisting observed in this testing is a phenomenon that has not been previously observed in testing of moment connections with W14 columns with or without a concrete structural slab.

Potential contributing factors to the observed column twisting include: (1) the geometry of the flange plate connection, which pushes the plastic hinge location further away from the column face, and (2) the oversized holes in the flange plates allowing transverse movement of the beam. The gap between oversized bolt holes and the bolt shank allows for transverse movement of the beam; the second-order effect resulting from such eccentricity in the beam compression flange, although small initially, promotes LTB of the beam. With the plastic hinge located further away from the column face than for typical (e.g., RBS) welded moment connections, the effect of out-of-plane forces is magnified (Chi and Uang, 2002).

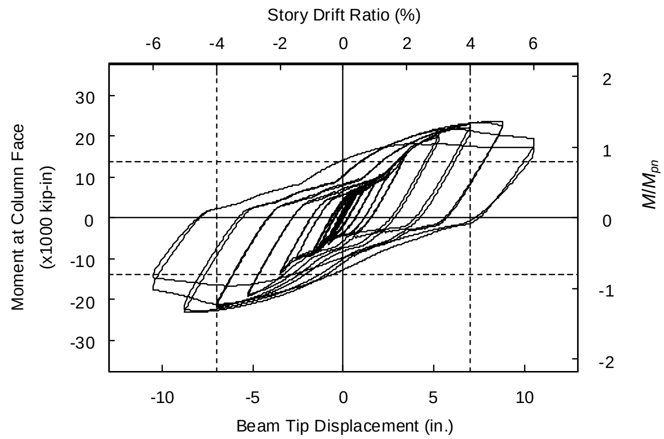
4.5 Bolt Slip-Bearing Deformation

It is expected based on the design of the bolted connection that slip will occur. However, slip occurred at approximately one-half the expected slip capacity considering the total resistance of all bolts in the connection. Bolt slip, which produced very loud noises, occurred during early cycles (at 0.375% or 0.5% drift) and on all subsequent cycles. As shown in Figure 4.2, deformation from slip-bearing made a significant contribution to the total deformation. For all specimens at 4% drift slip-bearing deformation contributed approximately 30% of the total deformation. The level of slip-bearing deformation was observed to be consistent for different loading amplitudes (i.e., 2, 3, 4% drift).

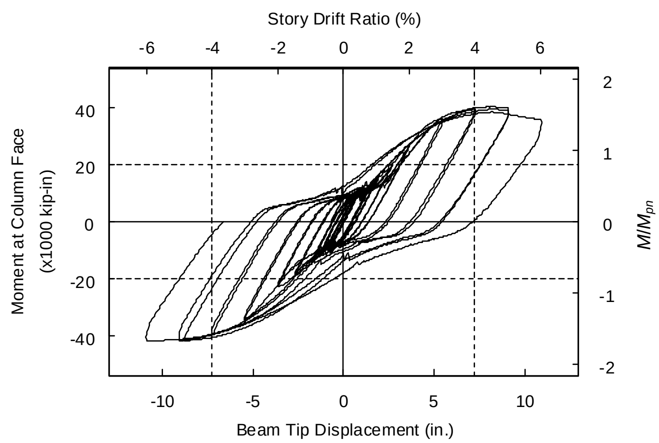
The contribution of slip-bearing deformation to the total deformation is dependent on the oversize of the bolt holes in the flange plate and beam flange. During testing bolt slip was observed to occur on early cycles and significantly contributed to the overall beam tip displacement on these cycles. As a result, beam flange yielding for the BFP specimens was not observed to occur until 2% drift, whereas for a typical welded moment connection, flange yielding would be expected at about 1% drift. Also, the observed level of beam flange and web local buckling was less severe than observed in previous testing of welded moment connections (Uang et al., 2000). Bolt slippage and bearing deformation in the BFP connection accommodated deformation that would have induced both local and lateral-torsional buckling in a welded connection.

4.6 Net Section Fracture

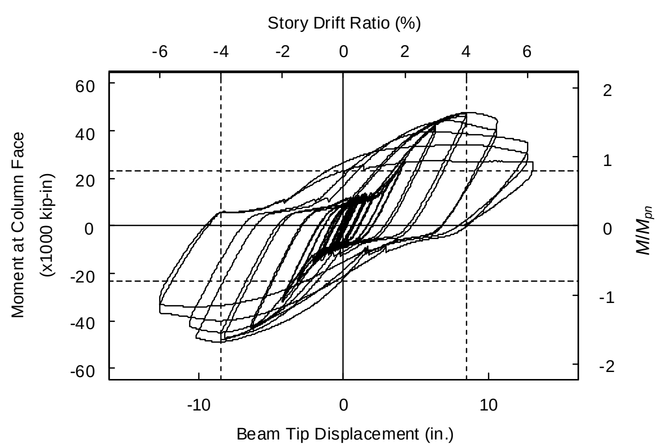
Specimens BFP-1 and BFP-3 eventually failed by net section fracture of the beam flange at the outermost row of bolts. Testing of Specimen BFP-2 was stopped before fracture, but necking at the outermost row of bolts was observed and it is likely that fracture on the net section would have occurred if testing was continued. Strain demand on the net section was exacerbated by LTB of the beam. Figure 4.5 shows strain profiles across the Specimen BFP-3 beam bottom flange for different drift levels. The skew of the strain profiles at higher drift levels resulted from beam LTB. Maintaining an adequate edge distance is, therefore, important for the design of BFP connections.



(a) Specimen BFP-1

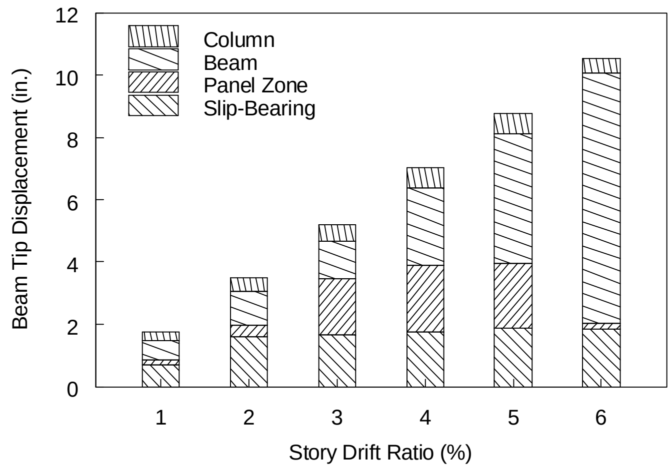


(b) Specimen BFP-2

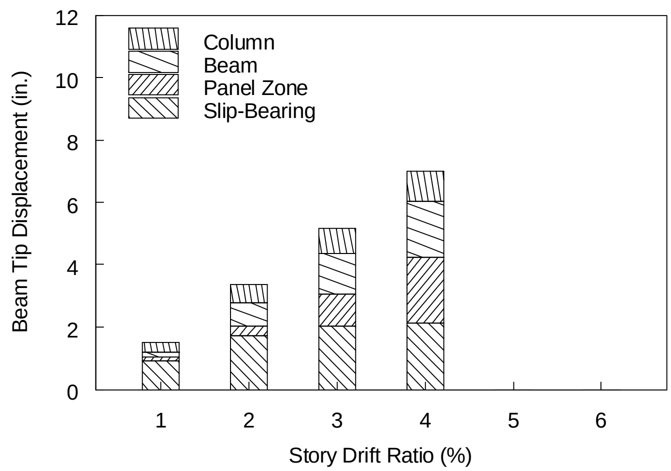


(c) Specimen BFP-3

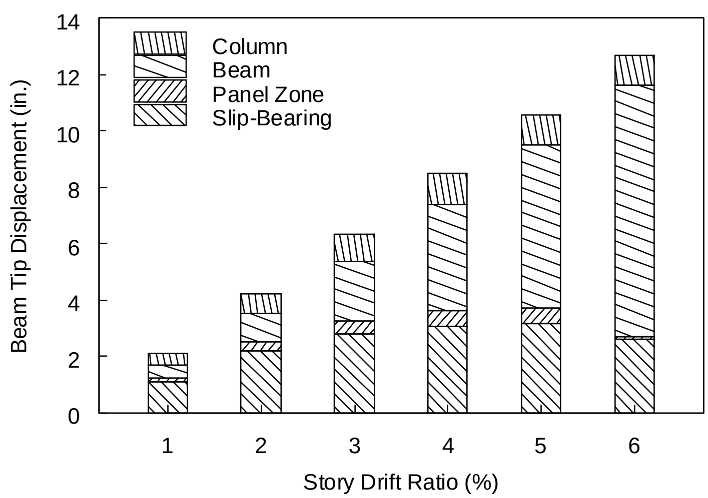
Figure 4.1 Moment versus Beam Tip Displacement Relationships



(a) Specimen BFP-1



(b) Specimen BFP-2



(c) Specimen BFP-3

Figure 4.2 Components of Beam Tip Displacement

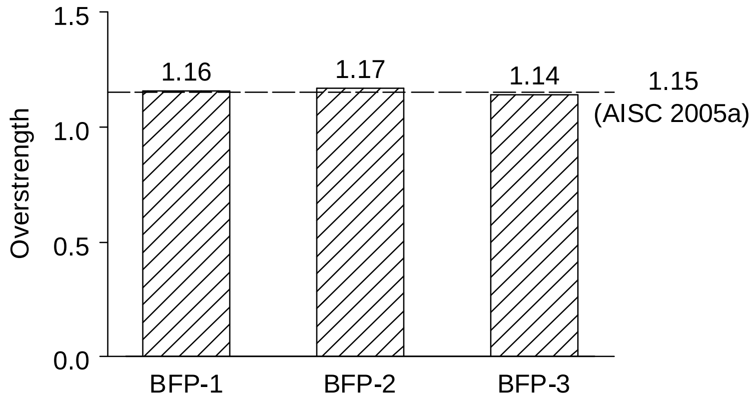
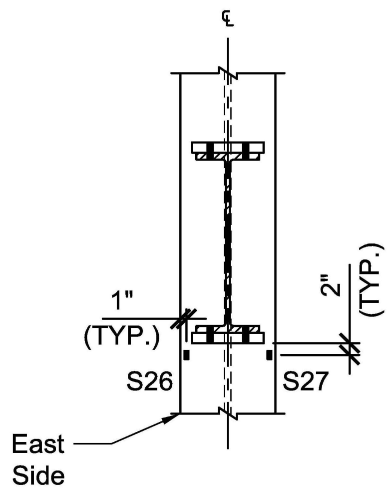
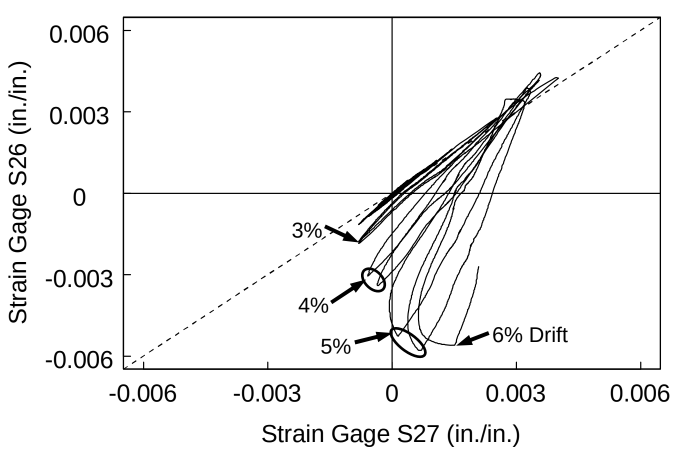


Figure 4.3 Beam Cyclic Overstrength Ratio

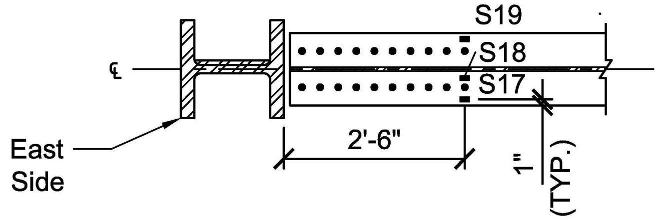


(a) Strain Gage Locations

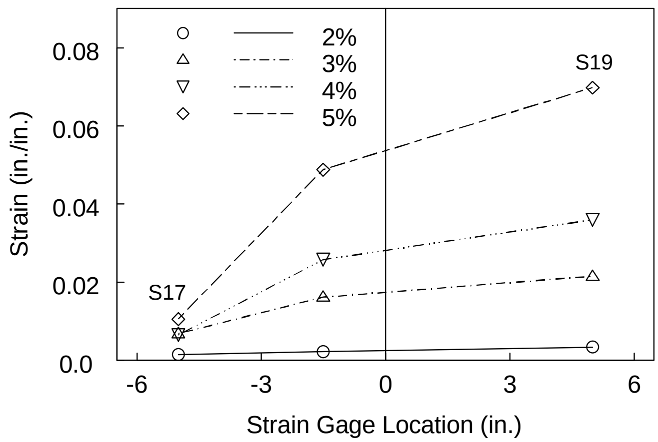


(b) Comparison of Strain Gages S26 and S27

Figure 4.4 Specimen BFP-2: Column Flange Strains



(a) Strain Gage Locations



(b) Strain Profile (S17, S18, S19)

Figure 4.5 Specimen BFP-3: Strain Profiles across Beam Bottom Flange Width

5. SUMMARY AND CONCLUSIONS

5.1 Summary

Three full-scale, one-sided, bolted flange plate steel moment-frame connection specimens consisting of W14 columns and W30 to W36 beams were subjected to increasing amplitude cyclic testing to support prequalification of the bolted flange plate connection for special moment resisting frames. Specimens were designed in accordance with the design procedure developed by the BFP Committee of AISC's Connection Prequalification Review Panel.

5.2 Conclusions

All three specimens performed well and met the Acceptance Criteria of the AISC *Seismic Provisions*. Specimens achieved an interstory drift angle of 0.06 radians before failure. All three specimens experienced necking in the beam flange at the outermost row of bolts. Specimens BFP-1 and BFP-3 eventually failed by beam flange net section fracture. The tensile demand on the net section where fracture occurred was further increased by LTB of the beam.

On large drift cycles (0.05 and 0.06 radians) column twisting was observed in addition to beam LTB. The specimens did not include a concrete structural slab, which would limit LTB and column twisting. However, column twisting has not previously been observed in testing of moment connection specimens with W14 columns without a concrete structural slab.

Bolt-slip occurred early during testing of all three specimens. The BFP connection differs from welded moment connections in that the additional component of bolt slip-bearing contributes to overall inelastic deformation of the connection. Slip-bearing deformation contributed a significant amount to the total deformation (approximately 30% of the total deformation at an interstory drift angle of 0.04 radians).

REFERENCES

(1) American Institute of Steel Construction (AISC). (2005a), *Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications*, ANSI/AISC 358-05, Chicago, IL.

(2) American Institute of Steel Construction (AISC). (2005b), *Seismic Provisions for Structural Steel Buildings,* ANSI/AISC 341-05, Chicago, IL.

(3) American Institute of Steel Construction (AISC). (2005c), *Specification for Structural Steel Buildings,* ANSI/AISC 360-05, Chicago, IL.

(4) American Welding Society (AWS). (2005), *Structural Welding Code–Seismic Supplement*, AWS D1.8, Miami, FL.

(5) Chi, B., and Uang, C.-M. (2002), "Cyclic Response and Design Recommendations of Reduced Beam Section Moment Connections with Deep Columns," *Journal of Structural Engineering*, ASCE, Vol. 128, No. 4, pp. 464-473.

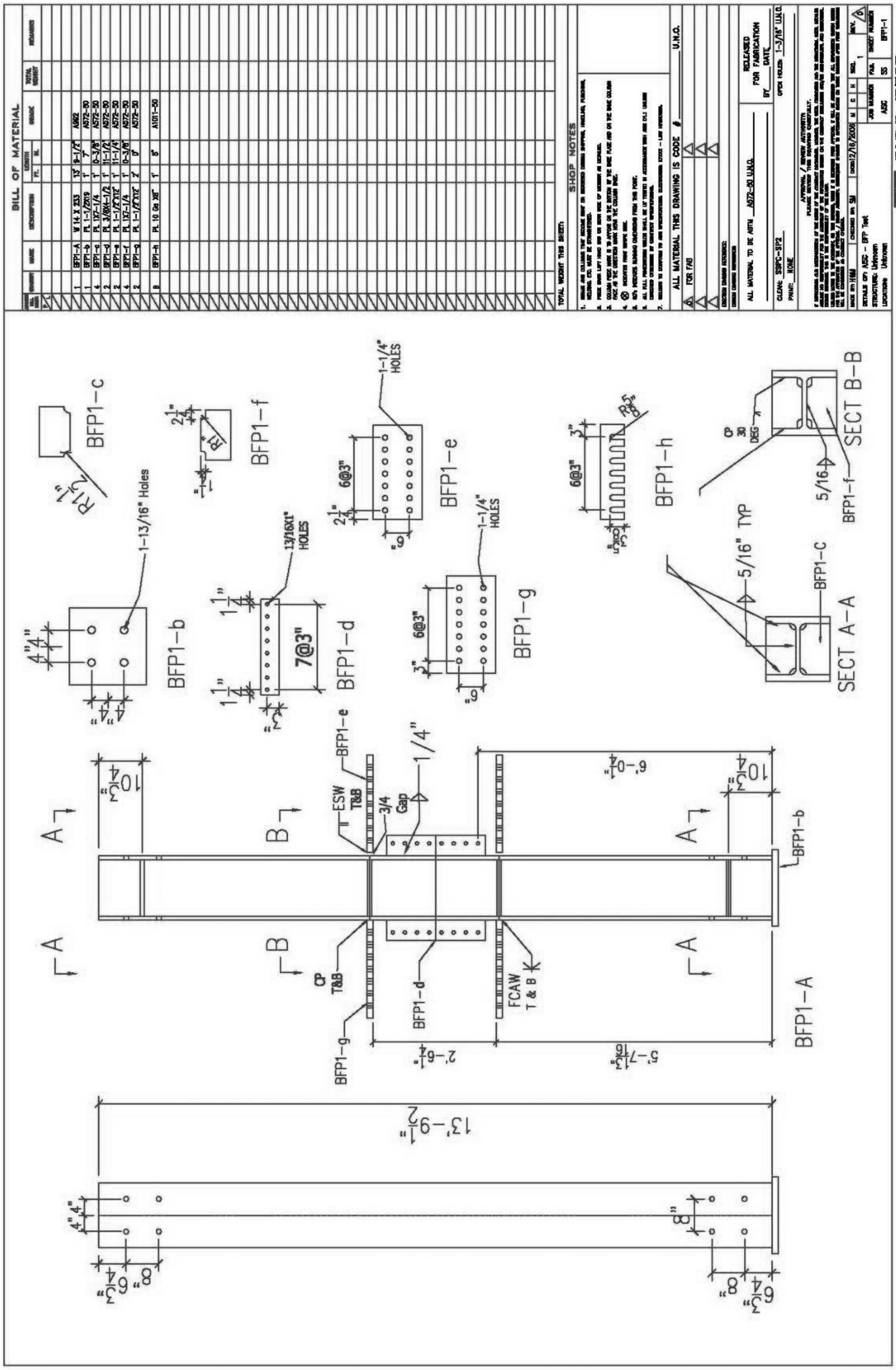
(6) Schneider, S., and Teeraparbwong, I. (2000), *Bolted Flange Plate Connections*, *Report No. SAC/BD-00/05*, SAC Joint Venture, Sacramento, CA.

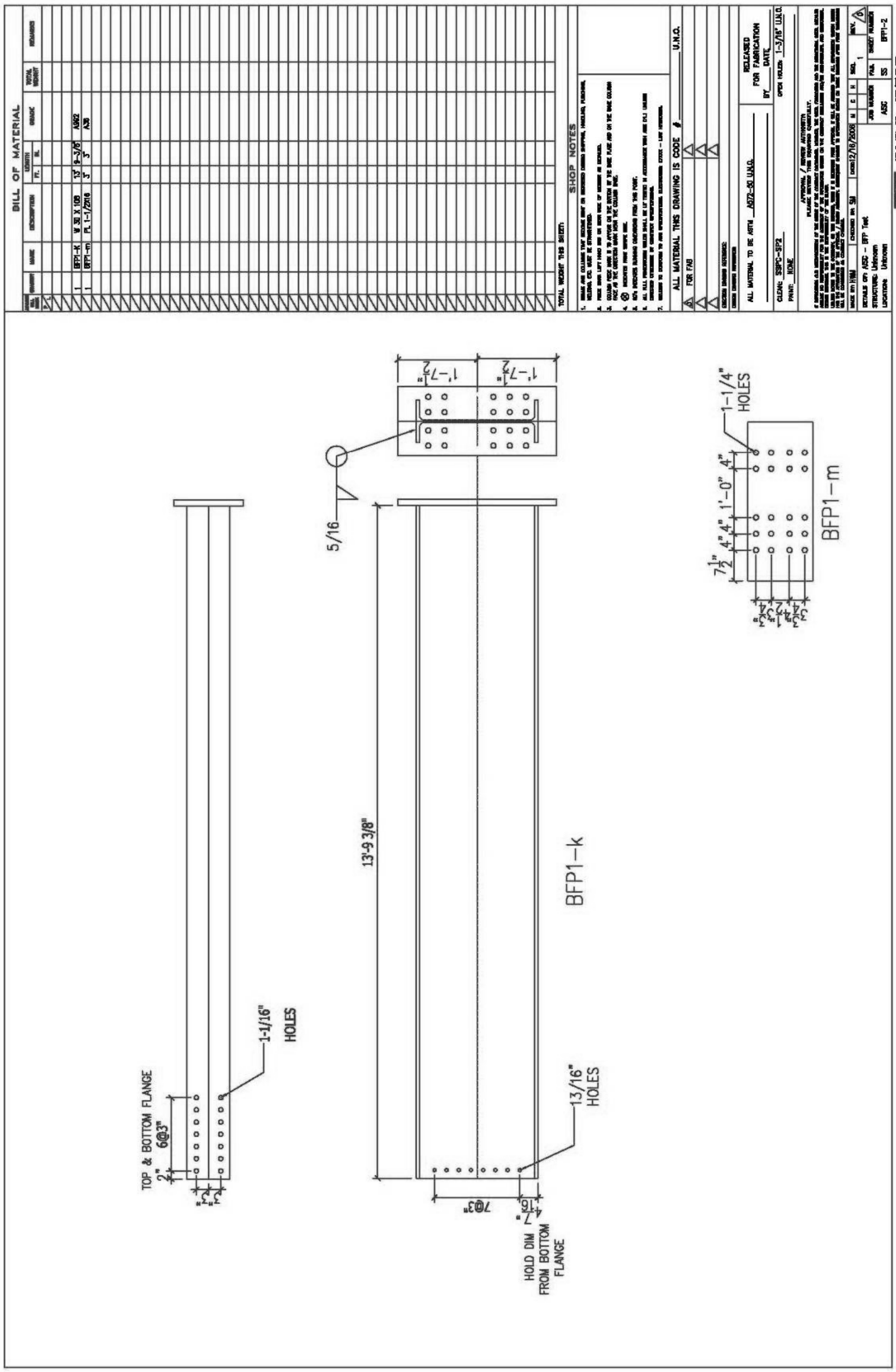
(7) Uang, C.M., and Bondad, D. (1996), *Static Cyclic Testing of Pre-Northridge and Haunch Repaired Steel Moment Connections, Report No. SSRP-96/02*, Division of Structural Engineering, University of California, San Diego, La Jolla, CA.

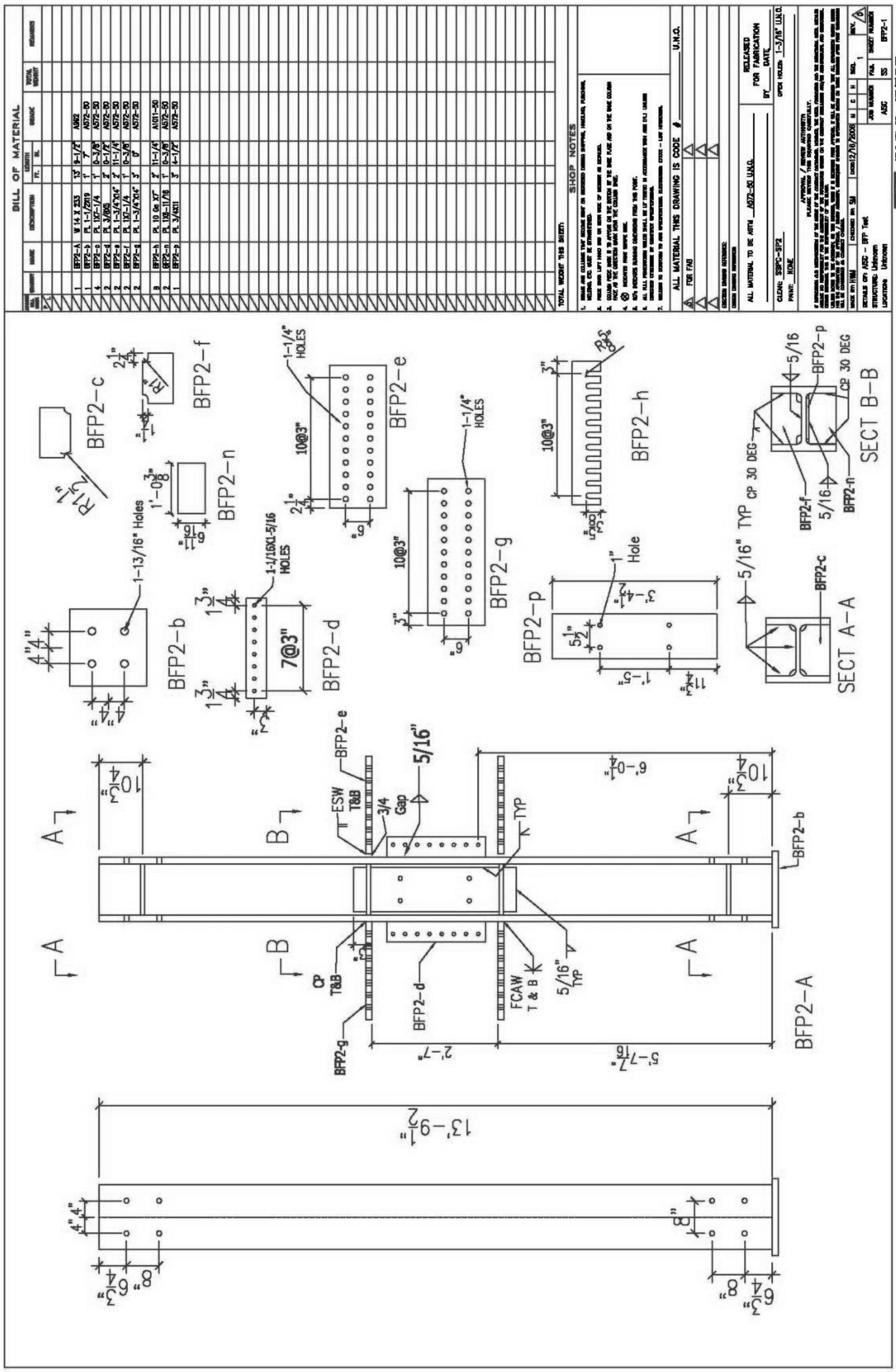
(8) Uang, C.M., Yu, Q.S., Noel, S., and Gross, J. (2000), "Cyclic Testing of Steel Moment Connection Rehabilitated with RBS or Welded Haunch," Journal of Structural Engineering, ASCE, Vol. 126, No. 1, pp. 57-68.

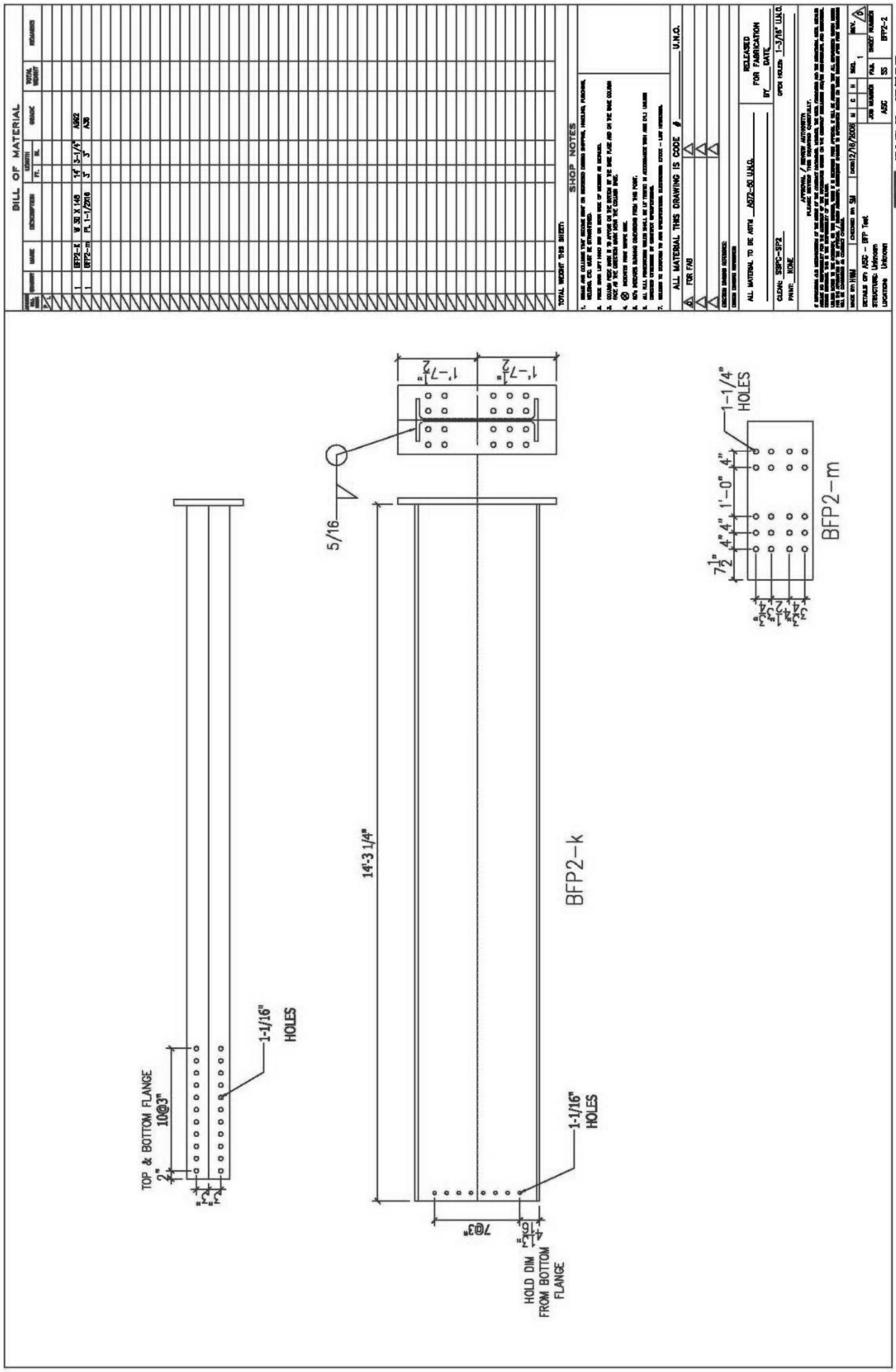
(9) Zhang, X., and Ricles, J. (2006), "Experimental Evaluation of Reduced Beam Section Connections to Deep Columns," *Journal of Structural Engineering*, ASCE, Vol. 132, No. 3, pp. 346-357.

APPENDIX A: Shop Drawings

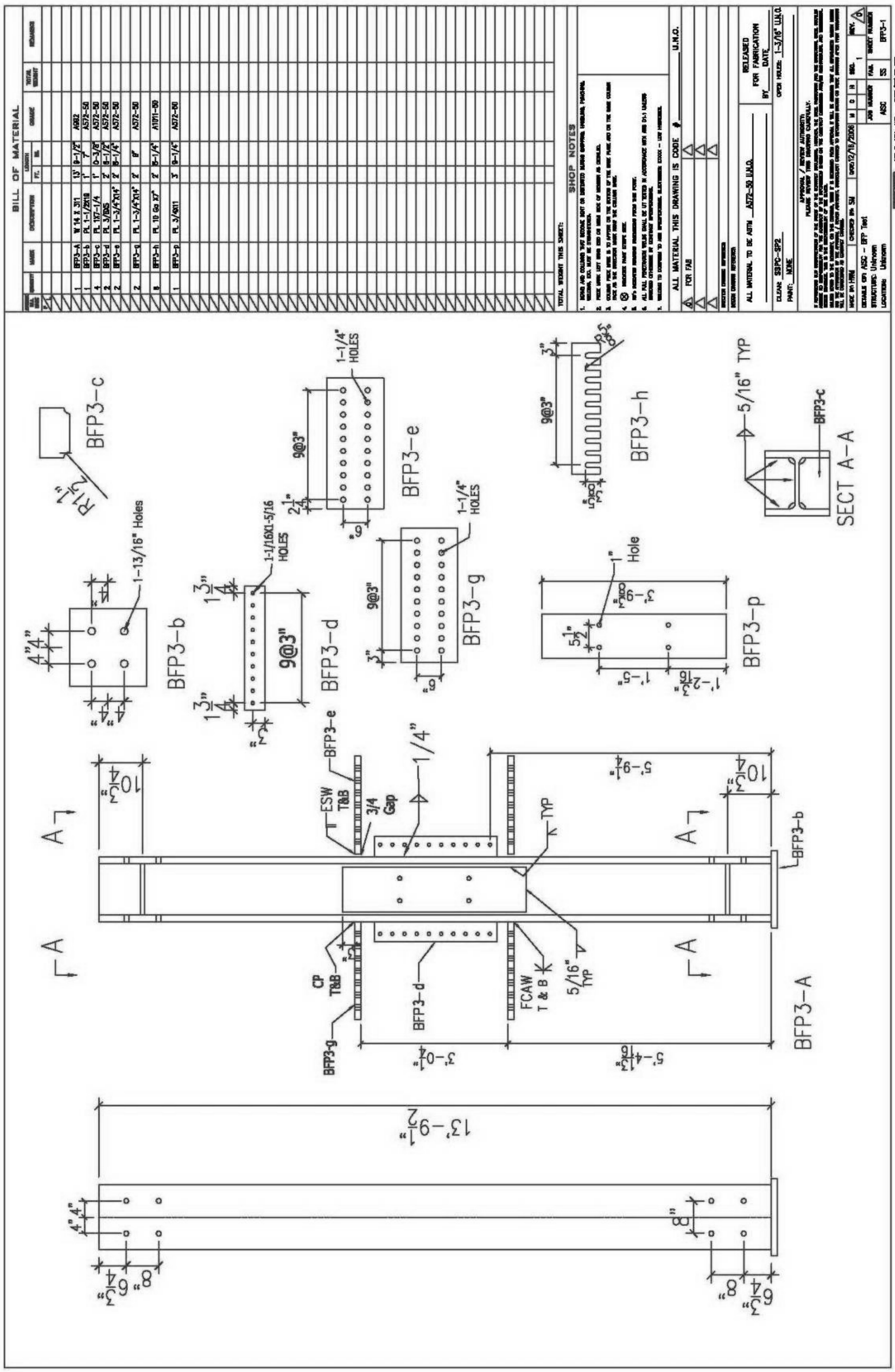

BILL OF MATERIAL
SHOP NOTES
ALL MATERIAL THIS DRAWING IS CODE
BFP1-A
BFP1-b
BFP1-c
BFP1-d
BFP1-e
BFP1-f
BFP1-g
BFP1-h
SECT A-A
SECT B-B
13'-9 1/2"
5/16" TYP
1-13/16" Holes
13/16X1" HOLES
1-1/4" HOLES
7@3"
6@3"
FCAW T & B
ESW T&B
CP T&B

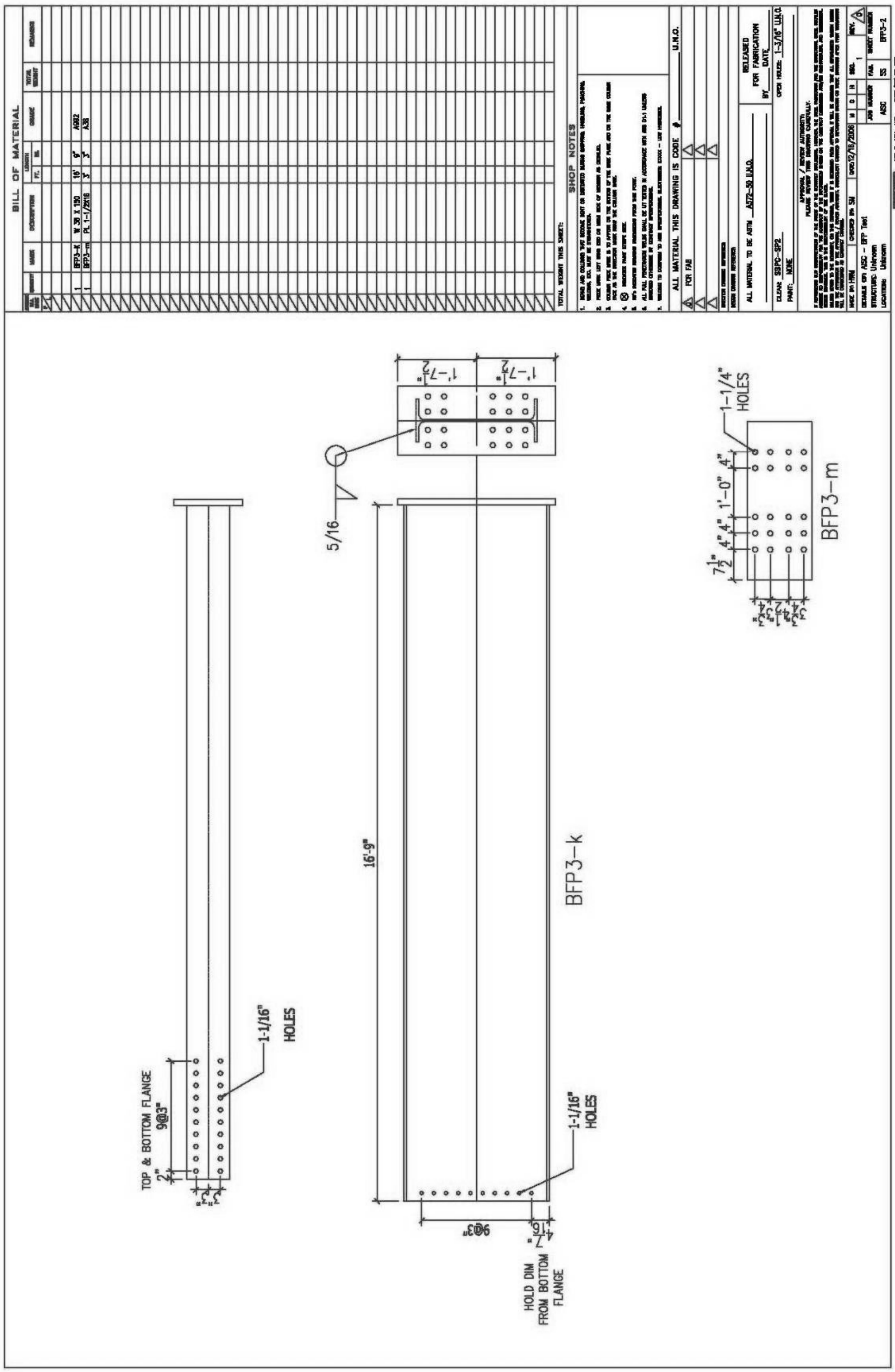

BILL OF MATERIAL
SHOP NOTES
ALL MATERIAL THIS DRAWING IS CODE
RELEASED FOR FABRICATION
TOP & BOTTOM FLANGE
6@3"
1-1/16" HOLES
13'-9 3/8"
13/16" HOLES
7@3"
HOLD DIM FROM BOTTOM FLANGE
5/16
BFP1-k
1-1/4" HOLES
1'-0"
BFP1-m


BFP2-A
BFP2-b
BFP2-c
BFP2-d
BFP2-e
BFP2-f
BFP2-g
BFP2-h
BFP2-n
BFP2-p
SECT A-A
SECT B-B
BILL OF MATERIAL
SHOP NOTES



BILL OF MATERIAL
SHOP NOTES
ALL MATERIAL THIS DRAWING IS CODE
RELEASED FOR FABRICATION
TOP & BOTTOM FLANGE
10@3"
1-1/16" HOLES
14'-3 1/4"
BFP2-k
5/16
7@3"
HOLD DIM FROM BOTTOM FLANGE
1-1/4" HOLES
BFP2-m


BILL OF MATERIAL
SHOP NOTES
BFP3-A
BFP3-b
BFP3-c
BFP3-d
BFP3-e
BFP3-g
BFP3-h
BFP3-p
SECT A-A
9@3"
1-13/16" Holes
1-1/4" HOLES
5/16" TYP
13'-9 1/2"



BILL OF MATERIAL
BFP3-k W 36 X 150 16' 9" A992
BFP3-m PL 1-1/2X18 3' 3" A36
TOTAL WEIGHT THIS SHEET:
SHOP NOTES
ALL MATERIAL THIS DRAWING IS CODE # U.N.O.
FOR FAB
ALL MATERIAL TO BE ASTM A572-50 U.N.O.
CLEAN: SSPC-SP2
PAINT: NONE
RELEASED FOR FABRICATION
BY DATE
OPEN HOLES: 1-3/16" U.N.O.
APPROVAL / REVIEW AUTHORITY:
PLEASE REVIEW THIS DRAWING CAREFULLY.
DETAILS OF: AISC - BFP Test
STRUCTURE: Unknown
LOCATION: Unknown
BFP3-2
SCHUFF STEEL COMPANY
TOP & BOTTOM FLANGE
9@3"
2"
1-1/16" HOLES
16'-9"
5/16
1'-7"
1'-7"
BFP3-k
1-1/16" HOLES
9@3"
HOLD DIM FROM BOTTOM FLANGE
1-1/4" HOLES
7½"
4"
4"
1'-0"
4"
BFP3-m

APPENDIX B: Welding Procedure Specifications and Procedure Qualification Records

SCHUFF STEEL CO.

Welding Procedure Specification

WPS No. **W 215 (NGI-ESW)** Revision **0** Date **11/5/2001** By **BRIAN ROBERTS**

Authorized By **JIM MURRAY** Date **11/5/2001** Prequalified ☐

Welding Process(es) **ESW** Type: Manual ☐ Machine ☐ Semi-Auto ☐ Auto ☒

Supporting PQR(s) **88647**

JOINT

Type **T-JOINT**

Backing Yes ☒ No ☐ Single Weld ☒ Double Weld ☐

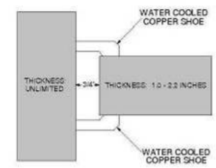
Backing Material **WATER COOLED COPPER**

Root Opening **3/4"** Root Face Dimension **MAT'L THK.**

Groove Angle **0°** Radius (J-U) **NA**

Back Gouge Yes ☐ No ☒

Method **NA**



BASE METALS

Material Spec. **ASTM A6** to **ASTM A 6**

Type or Grade **SEE MEMO (1)** to **SEE MEMO (1)**

Thickness: Groove (IN.) **1.0** - **2.2**

Fillet ( ) -

Diameter (Pipe,) -

POSITION

Position of Groove **VERTICAL** Fillet

Vertical Progression: ☒ Up ☐ Down

ELECTRICAL CHARACTERISTICS

Transfer Mode (GMAW):

Short-Circuiting ☐ Globular ☐ Spray ☐

Current: AC ☐ DCEP ☒ DCEN ☐ Pulsed ☐

Other **NA**

Tungsten Electrode (GTAW):

Size **NA** Type **NA**

FILLER METALS

AWS Specification **A5.25-97** **ARCMATIC**

AWS Classification **VMC 105** **VERTASLAG**

SHIELDING

Flux **FES72** Gas **NA**

Composition **NA**

Electrode-Flux (Class) **FES72-EWTG** Flow Rate **NA**

Gas Cup Size **NA**

PREHEAT

Preheat Temp., Min. **NONE**

Thickness Up to 3/4" Temperature **NA**

Over 3/4" to 1-1/2" **NA**

Over 1-1/2" to 2-1/2" **NA**

Over 2-1/2" **NA**

Interpass Temp., Min. **NONE** Max. **NONE**

TECHNIQUE

Stringer or Weave Bead **NA**

Multi-pass or Single Pass (per side) **NA**

Number of Electrodes **2**

Electrode Spacing: Longitudinal **NA**

Lateral **5/8"**

Angle **0°**

Contact Tube to Work Distance **NA**

Peening **NA**

Interpass Cleaning **NA**

POSTWELD HEAT TREATMENT PWHT Required ☐

Temp. **NA** Time **NA**

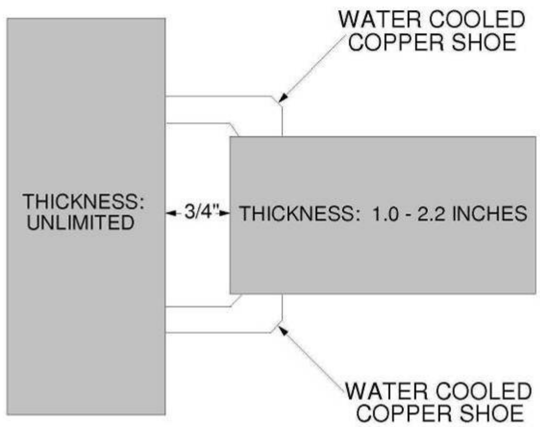
WELDING PROCEDURE

Layer/Pass	Process	Filler Metal Class	Diameter	Cur. Type	Amps or WFS	Volts	Travel Speed	Other Notes
1	ESW	EWTG/VMC 105	3/32"	DCEP	785/165ipm	38	1-1/2 ipm	TS = Rate of Rise
								Oscillation Required
								See Memo (2)

SCHUFF STEEL CO.

Welding Procedure Specification

W 215 (NGI-ESW)



MEMO

(1) BASE METALS: A 572 GRADE 50 TO A 572 GRADE 50
A 572 GRADE 50 TO A 992
A 572 GRADE 50 TO A 913 GRADE 50

(2) GUIDE TUBE OSCILLATION:
DWELL TIME: .8 SECONDS
SPEED: 25 IPM
TRAVERSE LENGTH: PLATE THICKNESS - 1.18 INCHES (GUIDE TUBE TO SHOE DISTANCE: .215 IN.)

GUIDE TUBE: 1 IN. WIDE, TWO 3/32" WIRES (PART NO. 0233-2503)

FLUX ADDED BY HAND.

ALLOWABLE RANGE VARIANCES:*
VOLTS: ± 10%
AMPERAGE: ± 20%
WIRE FEED SPEED: ± 40%
TRAVEL SPEED: ± 20%
ROOT OPENING: ± 1/4 INCH

OSCILLATION SPEED: ± 10 IPM
OSCILLATION DWELL TIME: ± 2 SECONDS
OSCILLATION TRAVERSE LENGTH: ± 1/8 INCH

*REFERENCE AWS D1.1: 2000, TABLE 4.6 - PQR ESSENTIAL VARIABLES REQUIRING WPS REQUALIFICATION FOR ELECTROSLAG OR ELECTROGAS WELDING.

SCHUFF STEEL CO.

Procedure Qualification Record

88647

PQR No. **88647** Revision **0** Date **6/14/2001** By **JIM MURRAY**

Authorized By **JIM MURRAY** Date **6/14/2001** Type Manual ☐ Machine ☐

Welding Process(es) **ESW** Reference WPS No. **W 215, W 216** Semi-Auto ☐ Auto ☒

JOINT

Type **BUTT**

Backing Yes ☒ No ☐ Single Weld ☒ Double Weld ☐

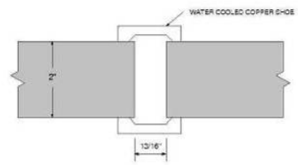
Backing Material **WATER COOLED COPPER**

Root Opening **13/16"** Root Face Dimension **MAT'L THK.**

Groove Angle **0°** Radius (J-U) **NA**

Back Gouging Yes ☐ No ☒

Method **NA**



BASE METALS

Material Spec. **A572** to **A572**

Type or Grade **50** to **50**

Thickness: Groove (IN.) **2** Fillet ( )

Diameter (Pipe,)

FILLER METALS

AWS Specification **A5.25-92** **ARCMATIC**

AWS Classification **VMC 105 (EWTG)** **VERTASLAG**

SHIELDING

Flux **FES72** Gas **NA**

Composition **NA**

Electrode-Flux (Class) **FES72-EWTG** Flow Rate **NA**

Gas Cup Size **NA**

PREHEAT

Preheat Temp., Min. **NONE**

Interpass Temp., Min. **NONE** Max. **NONE**

POSTWELD HEAT TREATMENT

Required ☐

Temp. **NA**

Time **NA**

POSITION

Position of Groove **VERTICAL** Fillet

Vertical Progression: Up ☒ Down ☐

ELECTRICAL CHARACTERISTICS

Transfer Mode (GMAW):

Short-Circuiting ☐ Globular ☐ Spray ☐

Current: AC ☐ DCEP ☒ DCEN ☐ Pulsed ☐

Other **NA**

Tungsten Electrode (GTAW):

Size **NA** Type **NA**

TECHNIQUE

Stringer or Weave Bead **NA**

Multi-pass or Single Pass (per side) **NA**

Number of Electrodes **2**

Electrode Spacing: Longitudinal **NA**

Lateral **5/8"** Angle **0°**

Contact Tube to Work Distance **NA**

Peening **NO**

Interpass Cleaning **NA**

WELDING PROCEDURE

Layer/Pass	Process	Filler Metal Class	Diameter	Cur. Type	Amps or WFS	Volts	Travel Speed	Other Notes
1	ESW	EWTG	3/32"	DCEP	785/165ipm	38	1 1/2 ipm	TS = Rate of Rise

SCHUFF STEEL CO.

Procedure Qualification Record

88647

TEST RESULTS

TENSILE TEST

Specimen no.	Width	Thickness	Area	Ultimate tensile load, lb	Ultimate unit stress, psi	Character of failure and location
T1A	.755	.901	0.68025	60,000	88.2 KSI	B.M. / DUCTILE
T1B	.756	1.011	0.76432	68,400	89.5 KSI	B.M. / DUCTILE
T2A	.755	.990	0.74745	65.200	87.2 KSI	B.M. / DUCTILE
T2B	.756	.932	0.70459	61,700	87.6 KSI	B.M. / DUCTILE

GUIDED BEND TEST

Specimen no.	Type of bend	Result	Remark
1	SIDE	PASS	
2	SIDE	PASS	
3	SIDE	PASS	
4	SIDE	PASS	

VISUAL INSPECTION

Appearance ACCEPT
Undercut ACCEPT
Piping porosity ACCEPT
Convexity ACCEPT
Test date 5/23/2001
Witnessed by NA

Other Test
CVN IMPACTS @ -20°F; 0°F; +70°F
CVN: @ -20°F;
#1=30, #2=42, #3=35; AVG=36 ft/lb
CVN: @ 0°F;
#1=32, #2=63, #3=47; AVG=47 ft/lb
CVN: @ +70°F;
#1=92, #2=92, #3=93; AVG=92 ft/lb

Radiographic-ultrasonic examination

RT report no: 45524 Result ACCEPT
UT report no: ______ Result ______

FILLET WELD TEST RESULTS

Minimum size multiple pass Macroetch
1. ______ 3. ______
2. ______

Maximum size single pass Macroetch
1. ______ 3. ______
2. ______

All-weld-metal tension test
Tensile strength, psi 90.9 KSI
Yield point/strength, psi 67.2 KSI
Elongation in 2 in.,% 23.3
Laboratory test no. 45524B

Welder's name SERGIO BARRERA Clock no. 95011 Stamp no. SB
Test conducted by CANSPEC GROUP INC. Laboratory
Test number 45524 Per RON JACOBS

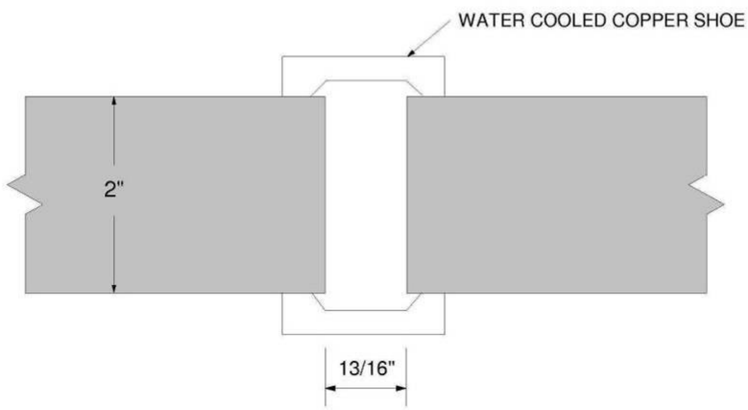
We, the undersigned, certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of section 4 of ANSI/AWS D1.1, 2000) Structural Welding Code-Steel.

Manufacturer SCHUFF STEEL CO. By JIM MURRAY Date 6/14/2001
Title N.D.E. TECH.

SCHUFF STEEL CO.

Procedure Qualification Record

88647



MEMO

GUIDE TUBE OSCILATION:
DWELL: .8 SECONDS
SPEED: 25.0
WIDTH: TOTAL WIDTH = .6" (.91" EACH WAY FROM CENTER)

GUIDE TUBE: WIDTH: 1"; 2 WIRE TUBE: PART # 0233-2503

NO GUIDE TUBE COATING

FLUX ADDED BY HAND

AGED AT 200° F TO 220° F FOR 48 ± 2 HOURS IN ACCORDANCE WITH AWS D1.1 - 2000, SECTION 4.2.2.

SCHUFF STEEL COMPANY

PREQUALIFIED FCAW WELDING PROCEDURE SPECIFICATION (WPS)
LINCOLN O.S. 70 (E70T-1 / E70T-9) REV. 0

FILLER METAL	SHIELDING	TECHNIQUE
FILLER METAL: **LINCOLN O.S. 70**	GAS: CO-2	STRINGER OR WEAVE BEAD: STRINGER
AWS CLASSIFICATION: E70T-1 / E70T-9	COMPOSITION: 100%	SINGLE PASS OR MULTI-PASS: BOTH
AWS SPECIFICATION: A5.20	FLOW RATE: 40 – 50 CFH	NUMBER OF ELECTRODES: 1
TYPE: SEMI-AUTO	GAS CUP SIZE: 1/2"	ELECTRODE SPACING: N/A
POSITION(S): F, H		CONTACT TUBE TO WORK DISTANCE: 1-1/8" (± 1/4")

PREHEAT / INTERPASS TEMP. (EXCLUDING GRADE 65)		PREHEAT / INTERPASS TEMPERATURE – GRADE 65	
THICKNESS	TEMPERATURE (MIN.)	THICKNESS	TEMPERATURE (MIN.)
UP TO 3/4"	32° F	UP TO 3/4"	50° F
OVER 3/4" TO 1-1/2"	50° F	OVER 3/4" TO 1-1/2"	150° F
OVER 1-1/2" TO 2-1/2"	150° F	OVER 1-1/2" TO 2-1/2"	225° F
OVER 2-1/2"	225° F	OVER 2-1/2"	300° F
MAXIMUM INTERPASS TEMP. :	550° F	MAXIMUM INTERPASS TEMP. :	550° F

NOTE: THE MINIMUM PREHEAT OR INTERPASS TEMPERATURE APPLIED TO A JOINT COMPOSED OF BASE METALS WITH DIFFERENT MINIMUM PREHEATS SHALL BE THE HIGHEST OF THESE MINIMUM PREHEATS.

WELDING PROCEDURE

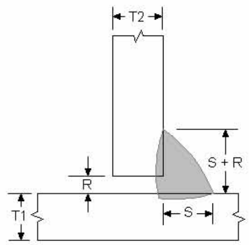
PASS OR WELD LAYER(S)	PROCESS	FILLER METAL CLASS	FILLER METAL DIAM.	CURRENT TYPE & POLARITY	CURRENT AMPS OR WIRE FEED SPEED	VOLTS	TRAVEL SPEED (IPM)	NOTES
ALL	FCAW	E70T1	3/32"	DCEP	455/200 ipm	30	18	MATERIALS ≥ 3/8"
		E70T9			410 - 500	28 -32	13 - 23	RANGES
HEAT INPUT: 32.7 – 73.8 kJ/in.								
ALL	FCAW	E70T1	3/32"	DCEP	350/125 ipm	25.5	11	MATERIALS < 3/8"
		E70T9			315 - 385	24 - 27	8 - 14	RANGES
HEAT INPUT: 32.4 – 77.9 kJ/in.								

BASE METALS		ATTACHED PREQUALIFIEID JOINT DETAILS AND TOLERANCES			
BASE MATERIAL 1 TO BASE MATERIAL 2		FILLET	PJP	CJP	
BASE MATERIAL 1 (TYPE/GRADE)	BASE MATERIAL 2 (TYPE/GRADE)	☒ FILLET	☐ BC-P2-GF	☐ B-L1a-GF	☒ TC-U4b-GF
☒ A 36	☒ A 36		☐ B-P3-GF	☐ B-L1b-GF	☐ B-U5-GF
☒ A 53	☒ A 53		☒ BTC-P4-GF	☐ TC-L1-GF	☐ TC-U5-GF
☒ A 500 A, B, C	☒ A 500 A, B, C		☐ BTC-P5-GF	☐ B-U2a-GF	☐ B-U6-GF
☒ A 572-50	☒ A 572-50		☐ BC-P6-GF	☐ C-U2a-GF	☐ C-U6-GF
☐ A 913-50	☐ A 913-50		☐ B-P7-GF	☐ B-U2-GF	☐ B-U7-GF
☐ A 913-65	☐ A 913-65		☐ TC-P8-GF	☐ C-U2-GF	☐ B-U8-GF
☒ A 992	☒ A 992		☐ BC-P8-GF	☐ B-U3-GF	☐ TC-U8a-GF
☐ OTHER: ____________	☐ OTHER: ____________		☐ BTC-P9-GF	☒ B-U4a-GF	☐ B-U9-GF
			☒ BTC-P10-GF	☒ TC-U4a-GF	☐ TC-U9a-GF
				☒ B-U4b-GF	

BACKING MATERIAL (IF APPLICABLE): ☒ STEEL ☐ OTHER: ______________________	
BACKGOUGE METHOD (IF APPLICABLE): ☒ AIR CARBON ARC ☐ OTHER: ______________________	
INTERPASS CLEANING: CHIP OR BRUSH	PEENING: NONE

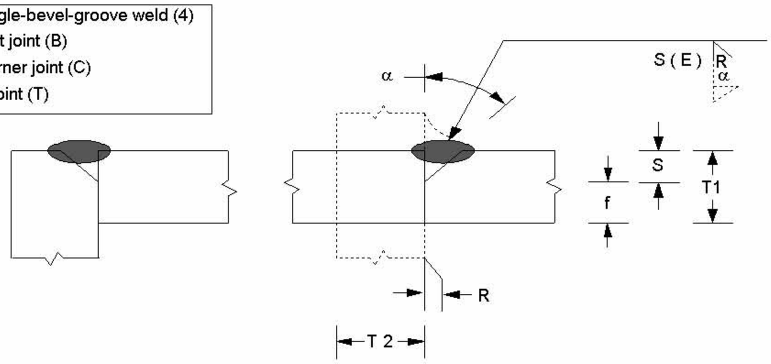
BY: BRIAN ROBERTS	DATE: 1-24-2007	AUTHORIZED BY: KEITH LANDWEHR	DATE: 1-24-2007

Fillet Weld
T-joint (T)

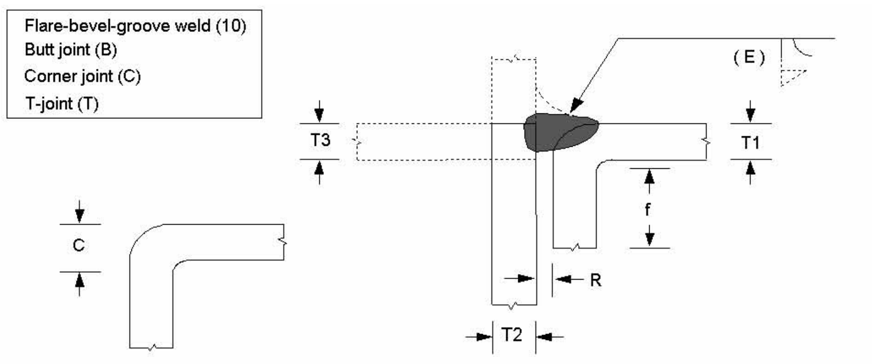


Welding Process	Joint Designation	Base Metal Thickness (U=unlimited) T1	Base Metal Thickness (U=unlimited) T 2	Joint Preparation Root Opening	Tolerances As Detailed	Tolerances As Fit Up	Weld Size	Permitted Welding Positions	Gas Shielding	Notes
FCAW (E70T-1) (E70T-9)	FILLET	U	U	R = 0	R = 0	-0, +3/16	S	F, H	Required	

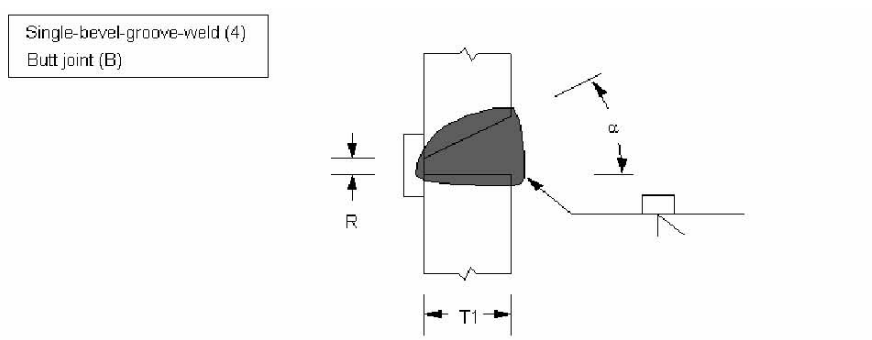
Single-bevel-groove weld (4)
Butt joint (B)
Corner joint (C)
T-joint (T)



Welding Process	Joint Designation	Base Metal Thickness (U=unlimited) T1	Base Metal Thickness (U=unlimited) T2	Groove Preparation Root Opening Root Face Groove Angle	Tolerances As Detailed (see 3.12.3)	Tolerances As Fit Up (see 3.12.3)	Permitted Welding Positions	Weld Size (E)	Notes
FCAW (E70T-1) (E70T-9)	BTC-P4-GF	1/4 min	U	R = 0 f =1/8 min α = 45°	+1/16, -0 unlimited +10° , -0°	+1/8, -1/16 ±1/16 +10° , -5°	F,H	S	B E, J N, V

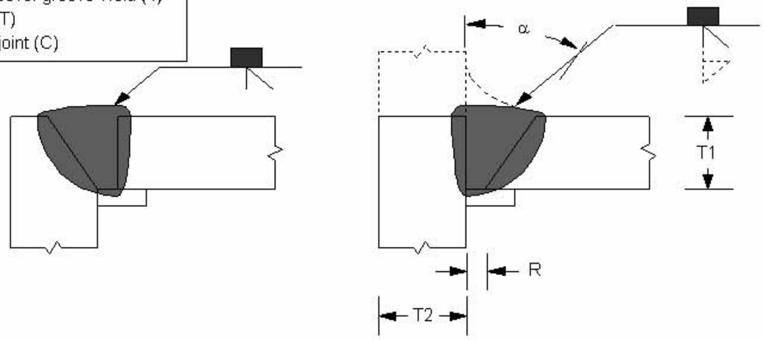


Welding Process	Joint Designation	Base Metal Thickness (U=unlimited) T1	T2	T3	Groove Preparation: Root Opening Root Face Bend Radius	Tolerances: As Detailed (see 3.12.3	As Fit Up (see 3.12.3)	Permitted Welding Positions	Weld Size (E)	Notes
FCAW (E70T-1) (E70T-9)	BTC-P10-GF	3/16 min	U	T1 min	R = 0 f =3/16 min C =3T1 / 2 min	+1/16, -0 +U, -0 -0, +Not - Limited	+1/8, -1/16 +U, -1/16 -0, +Not - Limited	F, H	5/8 T1	J N, Z



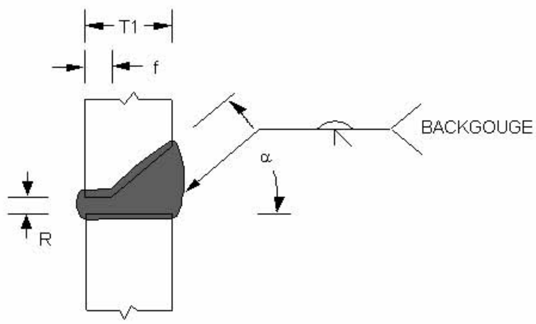
Welding Process	Joint Designation	Base Metal Thickness (U=unlimited) T1	T 2	Groove Preparation: Root Opening	Groove Angle	Tolerances: As Detailed (see 3.13.1)	As Fit Up (see 3.13.1)	Permitted Welding Positions	Gas Shielding	Notes
FCAW (E70T-1) (E70T-9)	B-U4a-GF	U	-	R = 3/16	α = 30°	R = +1/16, -0 α = +10°, -0°	+1/4, -1/16 +10°, -5°	F, H	Required	Br N
				R = 1/4	α = 45°					
				R = 3/8	α = 30°			F		

Single-bevel-groove-weld (4)
T-joint (T)
Corner joint (C)



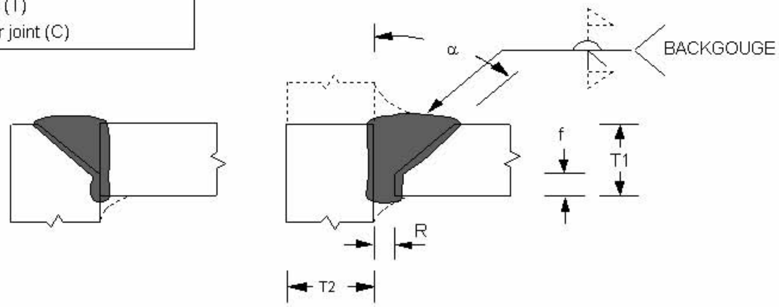
Welding Process	Joint Designation	Base Metal Thickness (U=unlimited) T1	Base Metal Thickness (U=unlimited) T 2	Groove Preparation: Root Opening	Groove Preparation: Groove Angle	Tolerances: As Detailed (see 3.13.1)	Tolerances: As Fit Up (see 3.13.1)	Permitted Welding Positions	Gas Shielding	Notes
FCAW (E70T-1) (E70T-9)	TC-U4a-GF	U	U	R = 3/16	α = 30°	R = +1/16, -0 α = +10°, -0°	+1/4, -1/16 +10°, -5°	F, H	Required	J N V
				R = 1/4	α = 45°					
				R = 3/8	α = 30°			F		

Single-bevel-groove weld (4)
Butt joint (B)



Welding Process	Joint Designation	Base Metal Thickness (U=unlimited) T1	Base Metal Thickness (U=unlimited) T2	Groove Preparation: Root Opening Root Face Groove Angle	Tolerances: As Detailed (see 3.13.1)	Tolerances: As Fit Up (see 3.13.1)	Permitted Welding Positions	Gas Shielding	Notes
FCAW (E70T-1) (E70T-9)	B-U4b-GF	U	-	R = 0 to 1/8 f = 0 to 1/8 α = 45°	+1/16, -0 +1/16, -0 +10°, -0°	+1/16, -1/8 Not limited +10°, -5°	F, H	Required	Br C N

Single-bevel-groove weld (4)
T-joint (T)
Corner joint (C)



Welding Process	Joint Designation	Base Metal Thickness (U=unlimited)		Groove Preparation			Permitted Welding Positions	Gas Shielding	Notes
				Root Opening Root Face Groove Angle	Tolerances				
		T1	T2		As Detailed (see 3.13.1)	As Fit Up (see 3.13.1)			
FCAW (E70T-1) (E70T-9)	TC-U4b-GF	U	U	R = 0 to 1/8 f = 0 to 1/8 α = 45°	+1/16, -0 +1/16, -0 +10°, -0°	+1/16, -1/8 Not limited +10°, -5°	F, H	Required	C J N V

Notes:
B: Joint is welded from one side only.
Br: Cyclic load application limits these joints to the horizontal welding position.
C: Backgouge root to sound metal before welding second side.
E: Minimum weld size (E) as shown in Table 3.4. S as specified on drawings.
J: If fillet welds are used in statically loaded structures to reinforce groove welds in corner and T-joints, these shall be equal to 1/4 T_1, but need not exceed 3/8 in. (10 mm). Groove welds in corner and T-joints of cyclically loaded structures shall be reinforced with fillet welds equal to 1/4 T_1, but need not exceed 3/8 in. (10 mm).
M: Double-groove welds may have grooves of unequal depth, but the depth of the shallower groove shall be no less than one-fourth of the thickness of the thinner part joined.
Mp: Double-groove welds may have grooves of unequal depth, provided these conform to the limitations of Note E. Also the weld size (E) applies individually to each groove.
N: The orientation of the two members in the joints may vary from 135° to 180° for butt joints, or 45° to 135° for corner joints, or 45° to 90° for T-joints.
V: For corner joints, the outside groove preparation may be in either or both members, provided the basic groove configuration is not changed and adequate edge distance is maintained to support the welding operations without excessive edge melting.
Z: Weld size (E) is based on joints welded flush.

Prequalified WPS Requirements:
- Maximum Root Pass Thickness: Flat – 3/8", horizontal – 5/16".
- Maximum Fill Pass Thickness: 1/4"
- Maximum single-pass fillet weld: flat – 1/2", horizontal –3/8".
- Split layers when the layer width w > 5/8"

Allowable Range Variances:
- Volts: ± 7 %
- Amps: ± 10 %
- Wire Feed Speed: ± 10 %
- Travel Speed: ± 25%

OUTERSHIELD 70 AWS A5.20-95: E70T-1 & E70T-9

This low hydrogen wire is designed for single and multiple pass, semi-automatic and automatic welding in the flat and horizontal positions. It penetrates through rust, mill scale and light oil. Its spray type transfer, low spatter and easy to remove slag, contribute to its high operator appeal. Outershield 70 can be used on both mild and many low alloy steels.

ADVANTAGE LINCOLN

- For mild steel and many low alloy steels.
- Especially recommended for applications requiring deep penetration.
- Excellent bead wetting, low spatter, and fast follow characteristics.
- Exceptional mechanical properties and x-ray quality.
- Good resistance to porosity due to heavy scale or rust contamination.
- CSA approved.
- Manufactured under a quality system certified to ISO 9002 requirements.

TYPICAL APPLICATIONS

- Bridge, ship, barge or offshore drilling rig construction.
- General fabrication.
- Machinery fabrication.
- Structural fabricating.

WELDING POSITIONS

CONFORMANCE

AWS A5.20-95: E70T-1 & E70T-9
ASME SFA-5.20: E70T-1
ABS: 2SA-2YSAH15
DNV: IIYMSH15
Lloyd's: 2S-2YSH15

SHIELDING GAS

100% CO_2
Flow Rate: 40-50 CFM

DIFFUSIBLE HYDROGEN

Shielding Gas	Typical Results (ml/100g weld deposit)
100% CO_2	7-14

DIAMETERS / PACKAGING

Diameter Inches (mm)	25 Lb. (11kg) Readi-Reel®	50 Lb. (23kg) Coil	300 Lb. (136 kg) Speed Feed® Reel	600 Lb. (272 kg) Speed Feed Reel	600 Lb. (272 kg) Speed Feed Drum	900 Lb. (408 kg) Speed Feed Reel
1/16 (1.6)	EDS12783	ED012782		ED014588		
5/64 (2.0)		ED012785				
3/32 (2.4)		ED012784	ED015022	ED014120	ED014119	EDS14622
1/8 (3.2)		ED014324				

MECHANICAL PROPERTIES (1) - As Welded per AWS A5.20

	Yield Strength psi (MPa)	Tensile Strength psi (MPa)	Elongation (%)	Charpy V-Notch ft-lbs (Joules) @ 0°F (-18°C)	Charpy V-Notch ft-lbs (Joules) @ -20°F (-29°C)
Required					
AWS E70T-1	58,000 (400)	70,000 (483)	22	20 (27) min.	—
AWS E70T-9	min.	min.	min.	—	20 (27) min.
Test Results					
100% CO_2 As Welded	83,500 (576)	92,100 (635)	27	28 (39)	23 (31)
100% CO_2 Stress Relieved for 1 hour at 1150°F (621°C)	76,400 (527)	80,500 (555)	27	20 (27)	18 (24)

(1) Typical all weld metal.

6

TYPICAL OPERATING PROCEDURES

Wire Polarity Electrical Stickout Wire Weight	Wire Feed Speed in/min (m/min)	Arc Voltage (volts)	Approx. Current (amps)	Melt-Off Rate lbs/hr (kg/hr)	Deposition Rate lbs/hr (kg/hr)	Efficiency (%)
1/16" DC+ 3/4" (19mm) 0.707 lbs/1000"	125 (3.2)	23-25	170	5.3 (2.4)	4.6 (2.1)	87
	200 (5.1)	25-27	235	8.5 (3.8)	7.4 (3.4)	87
	250 (6.4)	25-28	275	10.6 (4.8)	9.2 (4.2)	87
	300 (7.6)	27-29	310	12.7 (5.8)	11.1 (5.0)	87
	375 (9.5)	29-31	365	15.9 (7.2)	14.0 (6.4)	88
5/64" DC+ 1" (25mm) 1.123 lbs/1000"	125 (3.2)	23-26	250	8.4 (3.8)	7.0 (3.2)	83
	175 (4.4)	26-28	350	11.8 (5.4)	10.0 (4.5)	85
	225 (5.7)	27-29	375	15.2 (6.9)	13.0 (5.9)	86
	250 (6.4)	29-31	400	16.9 (7.7)	14.4 (6.5)	86
	300 (7.6)	30-32	450	20.2 (9.2)	17.4 (7.9)	86
	325 (8.3)	31-33	470	21.9 (9.9)	18.8 (8.5)	86
3/32" DC+ 1-1/8" (29mm) 1.554 lbs/1000"	125 (3.2)	24-27	335	11.7 (5.3)	9.8 (4.4)	84
	200 (5.1)	28-31	455	18.6 (8.5)	16.0 (7.3)	86
	250 (6.4)	30-32	530	23.3 (10.6)	20.2 (9.2)	87
	300 (7.6)	31-34	590	28.0 (12.7)	24.3 (11.0)	87
	325 (8.3)	33-35	615	30.3 (13.7)	26.4 (12.0)	87
1/8" DC+ 1-1/8" (29mm) 2.680 lbs/1000"	75 (1.9)	26-28	375	12.1 (5.5)	9.5 (4.3)	79
	100 (2.5)	27-29	460	16.1 (7.3)	13.2 (6.0)	82
	125 (3.2)	28-30	535	20.1 (9.1)	17.0 (7.7)	85
	150 (3.8)	29-31	595	24.1 (10.9)	20.8 (9.4)	86
	175 (4.4)	30-32	640	28.1 (12.7)	24.6 (11.2)	87

DEPOSIT COMPOSITION (1)

	%C	%Mn	%P	%S	%Si
Requirements AWS E70T-1	.18 max.	1.75 max.	.03 max.	.03 max.	.90 max.
Test Results 100% CO_2	.084	1.41	.009	.011	.73

(1) Typical all weld metal.

LINCOLN ELECTRIC

The Lincoln Electric Company
22801 St. Clair Avenue
Cleveland, Ohio 44117-1199

CERTIFICATE OF CONFORMANCE
(APPLIES ONLY TO U.S. PRODUCTS)

LINCOLN® ELECTRIC

Product: Outershield® 70 [1 Year]
Classification: E70T-1-H16, E70T-9-H16
Specification: AWS A5.20-95, ASME SFA-5.20
Test Completed: February 23, 2006

This is to certify that the product named above and supplied on the referenced order number is of the same classification, manufacturing process, and material requirements as the material which was used for the test that was concluded on the date shown, the results of which are shown below. All tests required by the specifications shown for classification were performed at that time and the material tested met all requirements. It was manufactured and supplied according to the Quality System Program of the Lincoln Electric Company, Cleveland, Ohio, U.S.A., which meets the requirements of ISO9001, NCA3800, ANSI/AWS A5.01, JIS Z9902, and other specification and Military requirements, as applicable. The Quality System Program has been approved by ASME, ABS, and VdTUV.

Operating Settings

Electrode Size		3/32 inch
Polarity		DC+
Shielding Gas		100% CO_2
Voltage, V		29
Wire Feed Speed, cm/min (in/min)		**508** (200)
Current, amps		460
Contact Tip to Work Distance, mm (in.)		**25** (1)
Passes/Layers		9/5
Preheat Temp, °C (°F)	(60 min.)	**20** (68)
Interpass Temp, °C (°F)	(275-325)	**165** (325)

Mechanical properties of the weld deposits (in the as-welded condition)

	AWS/ASME Requirements	
Tensile Strength, MPa (ksi)	(70 min.)	**620** (90)
Yield Strength, MPa (ksi)	(58 min.)	**540** (79)
Elongation, %	22 min.	25
Average Hardness Rockwell B	Not Required	92
Charpy V-notch Impact Properties		33 (25)
Joules @ -29 °C (ft-lbs @ -20 °F)	(20 min.)	**31,32,37** (23,24,27)
		38 (28)
Joules @ -18 °C (ft-lbs @ 0 °F)	(20 min.)	**38,38,39** (28,28,29)

Chemical analysis (weight %)

C	0.18 max.	0.06
Mn	1.75 max.	1.56
Si	0.90 max.	0.73
S	0.03 max.	0.01
P	0.03 max.	0.01
Diffusible Hydrogen (mL/100g) per AWS A4.3	16.0 max.	15.4
Absolute Humidity (grains moisture/lb dry air)		24

The strength and elongation properties were obtained from .505" tensile specimen artificially aged at 220 ° F (104 ° C) for 48 hours, as permitted by AWS A5.20-95. A naturally aged tensile specimen may take months to achieve the specified properties. See AWS A5.20-95, paragraph A8.3. The time required for the natural aging of weld deposits is dependent upon ambient conditions, weldment geometry, the metallurgical structure of the weld deposit and other factors.

The diffusible hydrogen result for the 1/16 is 4.1 mL/100g with absolute humidity of 24 grains of moisture per lb. of dry air.
Radiographic Test: Met requirements. Fillet Weld Test: (positions as required): Met requirements.
Test assembly constructed of A36. The electrode diameter required to be tested is 3/32", smaller sizes will also meet these requirements.
Results below the detection limits of the instrument or lower than the precision required by specification are reported as zero.
Strength values in SI units are reported to the nearest 10 MPa converted from actual data. Preheat and interpass temperature values in SI units are reported to the nearest 5 degrees.

Phillip J. Woodring, Certification Supervisor — Feb 24, 2006 — Date

David A. Fink, Manager, Compliance Engineering, Consumable R&D Department — 25 Feb 2006 — Date

Cert. No. 13100

Page 1 of 1

SCHUFF STEEL CO.

Welding Procedure Specification

F 254

WPS No. **F 254** Revision **2** Date **7/24/2003** By **JIM MURRAY**

Authorized By **JIM MURRAY** Date **7/16/2002** Prequalified ☐

Welding Process(es) **FCAW** Type: Manual ☐ Machine ☐ Semi-Auto ☒ Auto ☐

Supporting PQR(s) **88667**

JOINT

Type **DOUBLER PLATE WELD "J" Groove**

Backing Yes ☒ No ☐ Single Weld ☒ Double Weld ☐

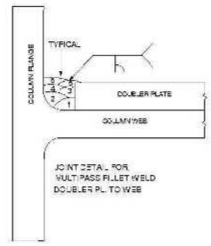
Backing Material **MAIN MEMBER**

Root Opening **NA** Root Face Dimension **NA**

Groove Angle **NA** Radius (J-U) **5/8"**

Back Gouge Yes ☐ No ☒

Method **NA**



BASE METALS

Material Spec. **SEE NOTES** to **SEE NOTES**

Type or Grade to

Thickness: Groove (in) **1/8** - **3/4**

Fillet ( ) **NA** - **NA**

Diameter (Pipe,) **NA** - **NA**

FILLER METALS

AWS Specification **A5.20**

AWS Classification **E70T-9** **LINC. O.S. 70**

SHIELDING

Flux **NA** Gas **CO-2**

Composition **100%**

Electrode-Flux (Class) **NA** Flow Rate **45 CFH**

Gas Cup Size **1/2"**

PREHEAT

Preheat Temp., Min. **NONE******

Thickness	Temperature
Up to 3/4"	**NONE******
Over 3/4" to 1-1/2"	**50°**
Over 1-1/2" to 2-1/2"	**150°**
Over 2-1/2"	**225°**

Interpass Temp., Min. **NONE****** Max. **NONE**

POSITION

Position of Groove **Flat** Fillet

Vertical Progression: ☐ Up ☐ Down

ELECTRICAL CHARACTERISTICS

Transfer Mode (GMAW):

Short-Circuiting ☐ Globular ☐ Spray ☐

Current: AC ☐ DCEP ☒ DCEN ☐ Pulsed ☐

Other **NA**

Tungsten Electrode (GTAW):

Size **NA** Type **NA**

TECHNIQUE

Stringer or Weave Bead **Stringer***

Multi-pass or Single Pass (per side) **Either***

Number of Electrodes **1**

Electrode Spacing: Longitudinal **NA**

Lateral **NA**

Angle **NA**

Contact Tube to Work Distance **1 1/8"**

Peening **NONE**

Interpass Cleaning **HAND/AIR TOOL**

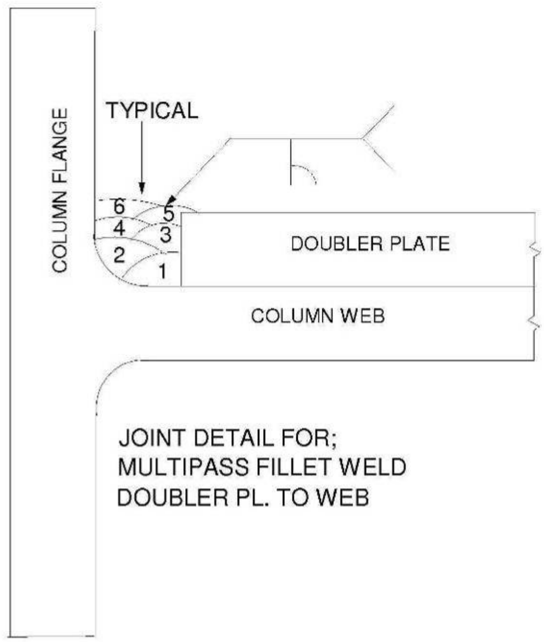
POSTWELD HEAT TREATMENT

PWHT Required ☐

Temp. Time

WELDING PROCEDURE

Layer/Pass	Process	Filler Metal Class	Diameter	Cur. Type	Amps or WFS	Volts	Travel Speed	Other Notes
ALL	FCAW	E70 T9	3/32	DCEP	500/180ipm	28	18	NOTE**



MEMO

NOTES:
*AWS D1.1; TABLE 3.7:
IN FLAT, HORIZONTAL SPLIT LAYERS WHEN THELAYER WIDTH >5/8". MAX BEAD THK=1/4"
MAXIMUM ROOT PASS THICKNESS: FLAT= 3/8", HORIZONTAL= 5/16"

**AWS D1.1; TABLE 4.5:
ALLOWABLE RANGE VARIANCES:
VOLTS: ± 7%
AMPS: ± 10%
WIRE FEED SPEED: ± 10%
TRAVEL SPEED: ± 25%

APPLICABLE MATERIAL FOR THIS PROCEDURE:
A36; A572 GR-50; A992; A913 GR-50; A500 GR-B; A53, GR-B.

****AWS D1.1 TABLE 3.2 NOTE 1:
1. When the base metal temperature is below 32°F (0°C), the base metal shall be preheated to at least 70°F (21°C) and this minimum temperature maintained during welding.

SCHUFF STEEL CO.

Procedure Qualification Record

88667

PQR No. **88667** Revision **3** Date **12/7/2004** By **JIM MURRAY**

Authorized By **JIM MURRAY** Date **10/6/2001** Type Manual ☐ Machine ☐

Welding Process(es) **FCAW** Reference WPS No. **F 254,F 265** Semi-Auto ☒ Auto ☐

JOINT

Type **"J" GROOVE**

Backing Yes ☒ No ☐ Single Weld ☒ Double Weld ☐

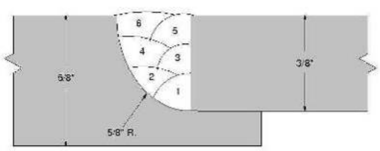
Backing Material **STEEL**

Root Opening **0** Root Face Dimension **3/8**

Groove Angle **0** Radius (J-U) **5/8"**

Back Gouging Yes ☐ No ☒

Method **NA**



BASE METALS

Material Spec. **A572** to **A572**

Type or Grade **50** to **50**

Thickness: Groove (in)**3/8** Fillet ( )

Diameter (Pipe,)

FILLER METALS

AWS Specification **A5.20**

AWS Classification **E70T9** **LINC. OS-70**

SHIELDING

Flux **NA** Gas **CO-2**

Composition **100%**

Electrode-Flux (Class) **NA** Flow Rate **45 CFH**

Gas Cup Size **1/2"**

PREHEAT

Preheat Temp., Min. **AMBIENT**

Interpass Temp., Min. **AMBIENT** Max. **NONE**

POSTWELD HEAT TREATMENT Required ☐

Temp. **NA**

Time **NA**

POSITION

Position of Groove **Flat** Fillet

Vertical Progression: Up ☐ Down ☐

ELECTRICAL CHARACTERISTICS

Transfer Mode (GMAW):

Short-Circuiting ☐ Globular ☐ Spray ☐

Current: AC ☐ DCEP ☒ DCEN ☐ Pulsed ☐

Other

Tungsten Electrode (GTAW):

Size Type

TECHNIQUE

Stringer or Weave Bead **Stringer**

Multi-pass or Single Pass (per side) **Multiple**

Number of Electrodes **1**

Electrode Spacing: Longitudinal **NA**

Lateral **NA** Angle **NA**

Contact Tube to Work Distance **1 1/8"**

Peening **NONE**

Interpass Cleaning **HAND TOOL**

WELDING PROCEDURE

Layer/Pass	Process	Filler Metal Class	Diameter	Cur. Type	Amps or WFS	Volts	Travel Speed	Other Notes
ALL	FCAW	E70T-9	3/32	DCEP	500 AMPS	28	18	

SCHUFF STEEL CO.

Procedure Qualification Record

88667

TEST RESULTS

TENSILE TEST

Specimen no.	Width	Thickness	Area	Ultimate tensile load, lb	Ultimate unit stress, psi	Character of failure and location
A	.754	.335	0.25259	20,440	81.0 KSI	B.M.; BRITTLE
B	.756	.328	0.24797	20,570	83.0 KSI	B.M.; BRITTLE

GUIDED BEND TEST

Specimen no.	Type of bend	Result	Remark
A	FACE	PASS	
B	FACE	PASS	
A	ROOT	PASS	
B	ROOT	PASS	

VISUAL INSPECTION

Appearance **ACCEPT**
Undercut **ACCEPT**
Piping porosity **ACCEPT**
Convexity **ACCEPT**
Test date **9/20/2001**
Witnessed by **NA**
Other Test

Radiographic-ultrasonic examination

RT report no: **88667** Result **PASS**
UT report no: ________ Result ________

FILLET WELD TEST RESULTS

Minimum size multiple pass
Macroetch
1. ________ 3. ________
2. ________

Maximum size single pass
Macroetch
1. ________ 3. ________
2. ________

All-weld-metal tension test
Tensile strength, psi ________
Yield point/strength, psi ________
Elongation in 2 in.,% ________
Laboratory test no. ________

Welder's name **ALFONSO OLGUIN** Clock no. ________ Stamp no. **AO**
Test conducted by **CANSPEC GROUP INC.** Laboratory
Test number **207-01-09-046050** Per **ROBERT STEWART PE**

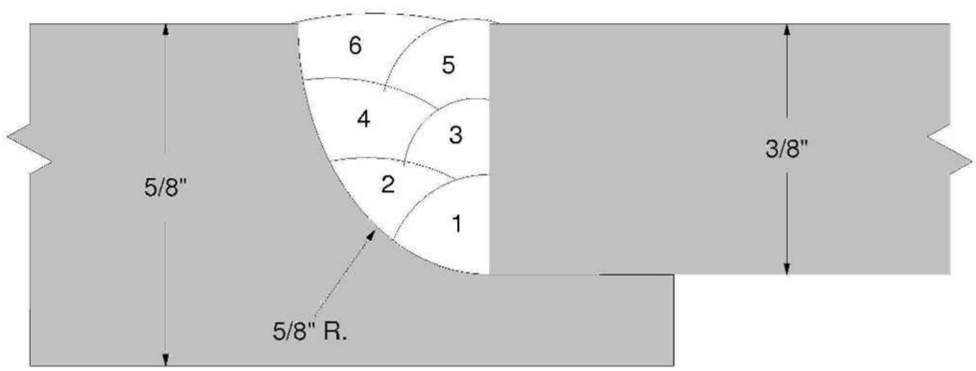
We, the undersigned, certify that the statements in this record are correct and that the test welds were prepared, welded, and tested in accordance with the requirements of section 4 of ANSI/AWS D1.1, **2000**) Structural Welding Code-Steel.

Manufacturer **SCHUFF STEEL CO.** By **JIM MURRAY** Date **10/6/2001**
Title **N.D.E. TECH.**

SCHUFF STEEL CO.

Procedure Qualification Record

88667



MEMO