Design of Split-Tee Connections for Special Composite Moment Frames

ERICA C. FISCHER and AMIT H. VARMA

ABSTRACT

The beam-to-column connections of special composite moment frames (C-SMFs) serving as the primary seismic force resisting system (SFRS) of a building structure are required to meet the performance criteria specified in the 2010 AISC *Seismic Provisions*. Chapter K of the *Seismic Provisions* states that experimental results should be used to provide evidence that the specific beam-to-column connection satisfies the requirements for strength and story-drift angle. This paper focuses on the split-tee connection for C-SMFs with wide flange (WF) beams and rectangular concrete-filled tube (CFT) columns. The paper provides a general description of the split-tee connection identifying its key features and components. This is followed by discussion of expected behavior in the elastic and inelastic ranges of cyclic loading. This discussion is based on prior research and large-scale testing, and it focuses on the various limit states controlling the strength and deformation capacity of the connection. The paper includes the complete design procedure for split-tee connections along with a detailed design example. The information presented in this paper can be used to create a body of evidence to apply for prequalification of similar split-tee connections in C-SMFs.

Keywords: seismic design, special composite moment frames, moment connection, composite construction, prequalification.

INTRODUCTION

The AISC *Seismic Provisions* (AISC, 2010a) provide design requirements and performance criteria for beam-to-column connections in moment frames that serve as the primary seismic force resisting systems (SFRSs) for steel building structures. The AISC *Prequalified Connections* (AISC, 2010b), however, does not include examples of beam-to-column connections for composite moment frame construction. The engineer is required to (1) present experimental results for the desired beam-to-column connection configuration and (2) demonstrate that the connection meets the performance requirements set forth in the AISC *Seismic Provisions*. This paper provides an overview of previous research performed on split-tee connections for special composite moment frames (C-SMFs) and highlights potential failure modes of the connection. It also includes comprehensive guidance and a complete example for the design and detailing of split-tee connections in C-SMFs. The connection is detailed to achieve the strength and story-drift angle requirements of the AISC *Seismic Provisions*.

Erica C. Fischer, P.E., Ph.D. Candidate, Lyles School of Civil Engineering, Purdue University, West Lafayette, IN (corresponding author). Email: fischere@purdue.edu

Amit H. Varma, Ph.D., Professor, Lyles School of Civil Engineering, Purdue University, West Lafayette, IN. Email: ahvarma@purdue.edu

Paper No. 2013-29R

This paper, along with the results of the test results from Peng (2001), provides the tools required for structural engineers to create a body of evidence to apply for prequalification of similar split-tee connections in C-SMFs. The testing requirements outlined in Section K2 of the AISC *Seismic Provisions* are satisfied by the experimental program discussed here and in detail by Peng. This paper includes a comprehensive design procedure that satisfies the requirements of Section K1.5 of the AISC *Seismic Provisions*. It also outlines many of the necessary sections of the "Prequalification Record" required by Section K1.6 of the AISC *Seismic Provisions*, including the following:

- A general description of the prequalified connection.
- A description of expected behavior of the connection in the elastic and inelastic ranges.
- A definition of the region of connection that comprises the protected zone.
- A detailed description of the design procedure for the connection.
- A list of references of test reports, research reports and other publications that provide a basis for prequalification.

BACKGROUND

Composite construction originated in Chicago in the late 1800s and is currently being used around the world in a variety of applications. Examples of buildings with composite

construction for seismic resistance include the Two Union Square in Seattle, Washington, and the Jinyuan Building in Xiamen, Fujian, China. Composite construction optimizes the contributions of steel and concrete materials and provides members that are structurally efficient in terms of stiffness, strength and self-weight (Varma et al., 2002). In concrete-filled tube (CFT) columns, the concrete restrains the steel tube flanges from local buckling inward, and the steel tube confines the concrete infill (Lai, Varma and Zhang, 2014). The steel tube also acts as formwork for placing the concrete during construction. CFT columns and frames have been used in different building structures around the world; however, this paper focuses on their use as C-SMF construction for seismic design.

Section G3 of the AISC *Seismic Provisions* provides the design basis for C-SMFs. C-SMFs are expected to develop their seismic performance through inelastic deformations in the beams, column bases and limited yielding in the column panel zones. The beam-to-column connections are required to (1) satisfy the story-drift angle requirement of 0.04 rad, (2) develop at least 80% of the nominal plastic moment capacity of the beam at 0.04-rad drift and (3) develop the required shear strength of the connection. The required shear strength is based on the load combinations that include the amplified seismic load, E_{mh}, calculated using Equation 1 (AISC-341 Equation G3-3):

$$E_{mh} = 2\left[\frac{1.1M_{p,exp}}{L_h}\right] \quad (1)$$

where, $M_{p,exp}$ is the expected plastic moment capacity of the beam and L_h is the distance between the plastic hinge locations in the beam.

The AISC *Seismic Provisions* require the beam-to-column connections in composite moment frames to engage both the steel and concrete portions of the column and thus transfer forces effectively during a seismic event. This can be achieved through direct bearing from internal bearing mechanisms, shear connections, shear friction or a combination of these means (Peng, 2001).

AISC SEISMIC PROVISIONS

Section G3.6b of the 2010 AISC *Seismic Provisions* requires the beam-to-column connections of C-SMFs to satisfy the following:

1. The connection shall be capable of accommodating a story-drift angle of at least 0.04 rad.
2. The measured flexural resistance of the connection, determined at the column face, shall equal at least $0.8M_p$ of the connected beam at a story-drift angle of 0.04 rad, where M_p is nominal plastic moment capacity of the beam.

Typical beam-to-column connections used in C-SMFs can be categorized as beam uninterrupted or beam interrupted connections. Beam uninterrupted connections consist of beams that are continuous through the composite column; beam flange welded joints are not used, and the connection is not susceptible to premature fracture. Beam uninterrupted connections were tested by Schneider and Alostaz (1998) and others, and they demonstrated good ductility when subjected to cyclic loading. Beam interrupted connections consist of beams that are interrupted at the composite column faces and connected to them using welded or bolted connections.

There are no prequalified beam-to-column connections for C-SMFs. As a result, beam-to-column connections in C-SMFs must satisfy requirements 1 and 2 listed earlier in accordance with Chapter K of the AISC *Seismic Provisions*. Chapter K provides guidelines for using experimental results from large-scale beam-to-column connection tests to satisfy both the requirements. For beam uninterrupted connections, the AISC *Seismic Provisions* require testing results in accordance with Section K2 but also permit other substantiating data in the literature (e.g., Kanno and Deierlein, 1997). For beam interrupted connections, the AISC *Seismic Provisions* require testing results to be submitted in accordance with Section K2. Minimums of two tests are required with the same or very similar beam and column sizes as those designed for in the building structure.

SPLIT-TEE CONNECTION

AISC *Seismic Provisions* require fully restrained (FR) connections to be used in C-SMF systems. FR connections have the capacity to deform elastically as the structure deflects and story drift increases. This deformation redistributes the moment from the beam to the column as a plastic hinge forms in the C-SMF beams. The split-tee connection is an example of an FR connection with interrupted beams. A schematic of the split-tee connection is shown in Figure 1.

As shown in Figure 1, the (interrupted) wide-flange (WF) beams—the C-SMF beams—are connected to the composite CFT columns with split-tee moment connections. These connections utilize pretensioned through bolts to attach the split-tee flanges to the column. These bolts pass through holes cast into the concrete infill and are pretensioned to the CFT columns. Figure 1a shows a bolted split-tee connection where the split-tees are also bolted to the beam flanges. Figure 1b shows a bolted-welded split-tee connection where the split-tees are welded to the beam flanges. As shown, the connection length may be longer for the all-bolted split-tee connection. Shear studs are used within the CFT column to engage the concrete infill. Figures 1a and 1b show the pretensioned through bolts and shear studs.

The split-tee connection is designed so that seismic loading causes plastic hinges in the WF steel beams outside of

the connection region. The plastic hinge zones extend from the face of the column to one-half the beam depth beyond the plastic hinge point and are considered protected zones. The expected plastic moment, $M_{p,exp}$, in the beam hinges is resolved into effective forces, $M_{p,exp}/d$, in the beam flanges. These forces are transferred to the stems of the split-tees using bolts in Figure 1a and welds in Figure 1b. The shear force associated with the plastic mechanism in the frame and the gravity loads is transferred to the column through the split-tee stems as well. The split-tee is pretensioned to the CFT column, and the pretensioning is designed to resist the beam flange force without decompression and to transfer the shear force through friction between the column faces and the split-tee flanges. The panel-zone shear in the CFT column is resisted primarily by the webs of the steel tube and the compression strut in the concrete infill. Figure 2 illustrates this force transfer mechanism for the split-tee connection.

The experimental data presented in detail by Peng (2001) and summarized by Ricles, Peng and Lu (2004) shows that beam-column subassemblies with split-tee connections exhibit ductile behavior under cyclic loading. Relative rotation between the wide-flange beams and CFT column is calculated as the sum of (1) beam rotation, (2) column rotation, (3) panel-zone shear deformation and (4) connection deformation. For the all-bolted split-tee connection shown in Figure 1a, the relative rotation is larger due to slip between the split-tee and WF beam flange and the flexibility of the split-tee itself. The relative rotation of split-tee connections can be reduced by welding the split-tee to the WF beam flange, which eliminates the slip between them. This detail, shown in Figure 1b, will also eliminate pinching in cyclic (hysteresis) response, which was observed in the all-bolted split-tee connections. As discussed in Ricles, Peng and Lu, this pinching was primarily due to the elongation of bolt holes during large story drifts.

As shown in Figure 1a, through bolts and shear studs are used in split-tee connections to engage both the steel and concrete portions of CFT columns in C-SMFs. This allows for a concrete compression strut to form in the panel zone of the CFT column with minimal yielding of the steel tube. This was observed in the tests performed by Peng (2001).

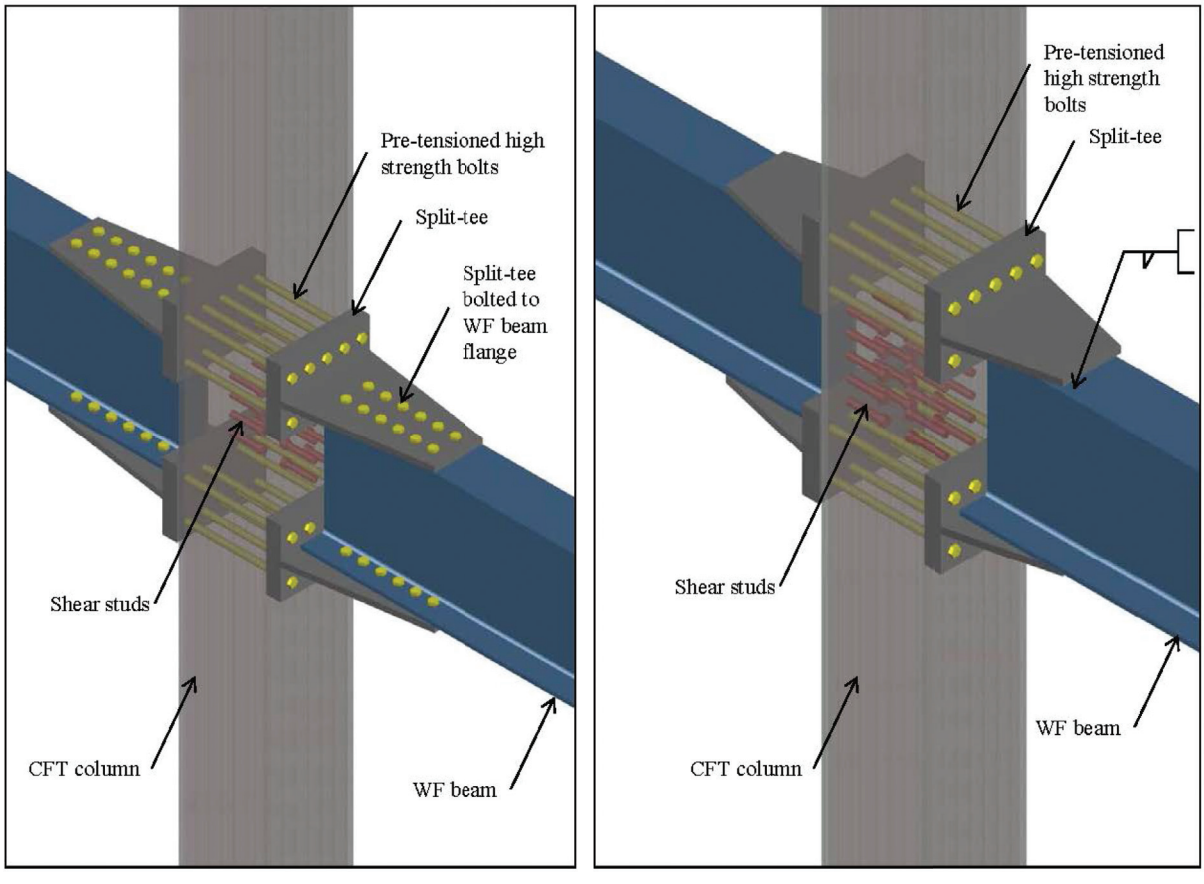


Fig. 1. Split-tee connection schematic of WF beam to CFT column (columns shown as transparent): (a) bolted split-tee connection; (b) welded split-tee connection.

EXPERIMENTAL DATA

The tests performed by Peng (2001) included a number of configurations for WF beam-to-rectangular CFT column connections. These also included the all-bolted and bolted-welded split-tee connections in Figure 1. The square CFT columns were 12-ft long, 16-in. × 16-in. steel tube columns with 8-ksi concrete infill. The W24×62 beams were 10 ft long. The specimens were designed as weak-beam, weak-panel zone or weak-connection specimens. Gravity loading (axial compression) was applied to the column first. It was followed by cyclic lateral loading in accordance with ATC-24 (Applied Technology Council [ATC], 1992) provisions; consisting of six elastic loading cycles, followed by inelastic displacement (or drift) cycles with increasing amplitude. Lateral bracing prevented out-of-plane movement of the connection region during the experiments.

Table 1 shows the connection types tested by Peng (2001) along with the ratio of the measured flexural resistance at the connection, M_{max}, to the measured plastic flexural capacity of the connected beam calculated using measured material properties, $M_{p,meas}$. Specimens 1, 2, 3, 3R, 4, 5, 6 and 7 were weak-beam tests that formed plastic hinges in the beams outside of the connection regions. The maximum flexural resistance, M_{max}, at the connections for the weak-beam specimens ranged from 1.18 $M_{p,meas}$ for specimen 2 to 1.56 $M_{p,meas}$ for specimen 7.

Specimens 4 through 7 used split-tee moment connections. Specimen 4 had pinched hysteresis loops due to the slip between the split-tee and the WF beam top flange. Specimens 5, 6 and 7 used a welded washer detail to prevent this behavior. Specimen 5 was an all-bolted split-tee connection without a shear tab. It did not have bolt-hole elongation during cyclic testing and, therefore, no pinching of the hysteresis loops. Specimens 6 and 7, which were bolted-welded split-tee beam-to-column connections also showed the formation of plastic hinges in the beams. These plastic hinges included inelastic local buckling of the beam web and flanges with

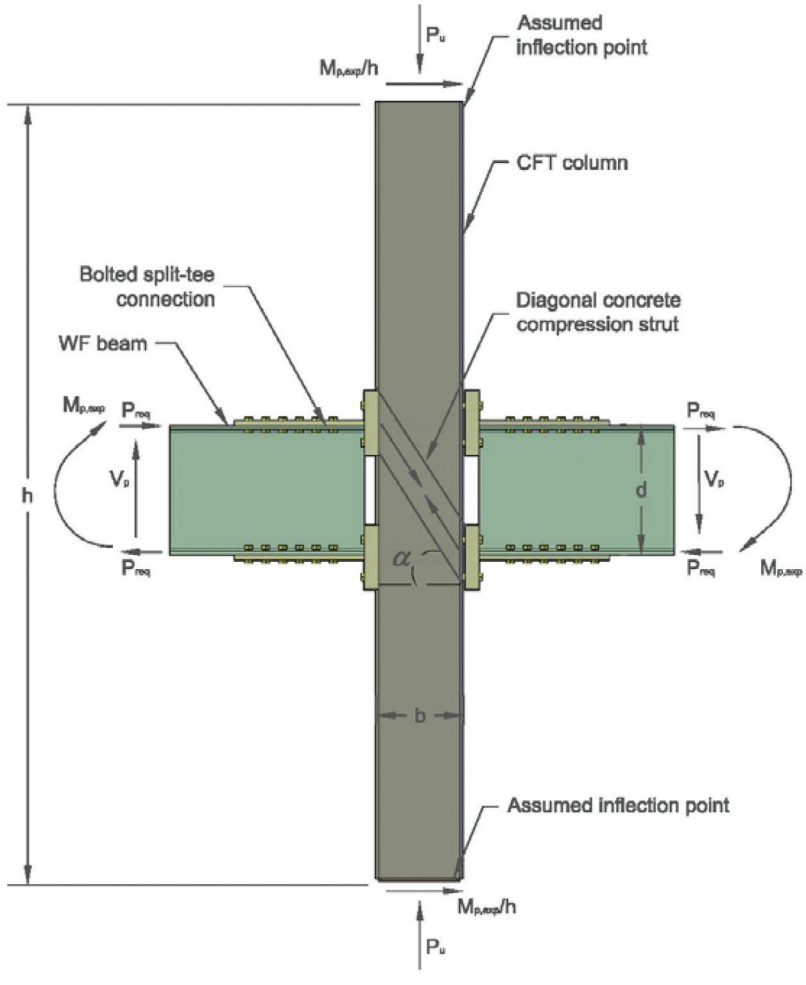


Fig. 2.Force transfer mechanism in split-tee connection along with panel zone in CFT.

Table 1. Test Matrix for Rectangular WF Beam-to-CFT Column Connection Experiments (Peng, 2001; Ricles et al., 2004)		
Specimen Number	Connection Detail	$\frac{M_{max}}{M_{p,meas}}$
1	Interior diaphragms (four-sided weld)	1.25
1R	Retrofitted interior diaphragms (four-sided weld), weak beam	1.08
1R2	Interior diaphragms with tapered plates (four-sided weld), weak-panel zone	1.03
2	Interior diaphragms (three-sided weld), weak beam	1.18
2R	Interior diaphragms with tapered plates (three-sided weld), weak-panel zone	0.89
3	Extended tee, weak beam	1.21
3R	Extended tee with tapered plates, weak beam	1.23
4	Bolted split-tee connection with shear tab, weak beam	1.34
5	Bolted split-tee connection without shear tab, weak beam	1.29
6	Welded split-tee connection without shear tab, weak beam	1.44
7	Welded split-tee connection with shear tab, weak beam	1.56

increasing inelastic deformations (story drifts). Flange local buckling eventually extended into the split-tee stem, with increasing story drifts. At story-drift angle of 0.05 rad, two cracks were observed in the specimen: (1) a crack in the beam top flange at approximately 1.5 in. from the edge of the split-tee stem and (2) a crack in the beam bottom flange approximately 2 in. from the edge of the split-tee stem. Specimens 4 through 7 all showed local yielding at the base of the split-tee stem during inelastic deformation cycles.

There was limited panel-zone shear yielding observed in the split-tee connection specimens (specimens 4 through 7). Because the through bolts connecting the split-tee to the CFT column were pretensioned, limited prying action of the split-tees was observed during the test.

Figure 3 shows the story-drift angles corresponding to the maximum load as well as 0.8 M_p (post-peak) for all the tested specimens. As shown, except for specimens 1, 1R and 2R, all other specimens met the AISC *Seismic Provisions* requirements for composite intermediate moment frames (C-IMFs) by having story-drift angles exceeding 0.02 rad at 0.8 M_p. Additionally, specimens 4, 5, 6 and 7 met the AISC *Seismic Provisions* requirements for C-SMFs by having story-drift angles exceeding 0.04 rad at 0.8 M_p. The full-scale tests demonstrated that split-tee moment connections could develop the expected plastic moment capacity, $M_{p,exp}$, of the beams, and accommodate story-drift angles exceeding 0.04 rad while maintaining (post-peak) flexural resistance at 0.8 M_p.

SPLIT-TEE CONNECTION DESIGN EXAMPLE

Section G3 of the AISC *Seismic Provisions* states that the basis of design for C-SMFs is that the frame will provide significant inelastic deformation capacity through flexural yielding of the C-SMF beams and limited yielding of the column panel zone. Flexural yielding of the column bases is permitted. The split-tee design example presented in this section assumes that plastic hinges form in the WF beams outside of the protected connection zone. The failure modes of split-tee connections are listed here in order, from most ductile to least ductile:

1. Plastic hinge formation in beam.
2. Stem yielding of split-tee.
3. Flange yielding of split-tee due to prying action.
4. Panel-zone failure of column.
5. Bolt fracture in split-tee due to prying action of split-tee flange.

The following example presents the design procedure for split-tee connections bolted to the CFT columns and welded to WF beams. The split-tee connection is designed and detailed to resist the expected shear force due to the expected plastic moment capacity of the beam and the gravity loads. The connection is also designed and detailed so that the governing failure modes occur in the just-listed order 1 through 5 from most ductile (desirable) to least ductile. Figures 4 through 12 provide a step-by-step approach for designing this connection. In this example, the beams are W24×76 ASTM A992 wide-flanged sections that are 30 ft in length (F_y = 50 ksi, F_u = 65 ksi, R_y = 1.1), and the CFT column is HSS16×16×0.75 made from ASTM A500 Grade B steel (F_y = 46 ksi, F_u = 65 ksi) and filled with normal-weight, 7-ksi concrete (f'_c = 7 ksi). The gravity loads considered on the beam are 0.84 kip/ft distributed dead load

Table 2. Beam and Column Section Properties for C-SMF	
Width of column, B	16 in.
Depth of column, h	16 in.
Thickness of web of column, t_w	0.75 in.
Depth of beam, d	23.9 in.
Width of beam flange, b_f	8.99 in.
Thickness of beam web, t_w	0.44 in.
Thickness of beam flange, t_f	0.68 in.
Beam plastic section modulus, Z_x	200 in.^{3}

and 0.60 kip/ft distributed live load. The dimensions of the beam and column sections taken from the 14th edition AISC *Steel Construction Manual* are shown in Table 2.

Figure 4 shows the final dimensions and details for the split-tee connection. Figure 5 shows the general procedure for design and detailing split-tee connections. This procedure addresses the primary failure modes (1 through 5 mentioned earlier) and references Figures 5 through 12, which specifically address each of these failure modes and provide procedures for detailing split-tee connections. The following steps provide an overview of split-tee connection design and a description of each of the Figures 6 through 12.

Step 1: Calculate the flexural and shear demands for the connection at the face of the column. Figure 6 provides the procedure for calculating these demands using the expected plastic flexural capacity, $M_{p,exp}$, of the beams and the gravity loads on the structure. Calculate the flange forces in the split-tee connection. Figure 6 shows how to calculate the flange forces from the flexural demand.

Step 2: Determine the number of pretensioned through bolts required to resist the flange forces in the connection. The bolts are sized to resist the shear demand calculated in step 1 and the flange forces calculated in step 1.

Step 3: Establish the layout of pretensioned through bolts in the split-tee flanges to satisfy force-equilibrium equations. The force-equilibrium equations are based upon the geometry of the split-tee as shown in Figure 7.

Step 4: Design the thickness of the split-tee stem. Consider failure modes of stem fracture and stem yielding.

Step 5: Determine the minimum flange width based on the bolt layout determined in step 3.

Step 6: Design the thickness of the split-tee flange so that stem yielding of the split-tee occurs prior to bolt fracture due to prying forces. The maximum thickness of the split-tee flange is determine to prevent bolt fracture due to prying forces prior to yielding of the split-tee flanges. The minimum thickness of the split-tee flange is determined so that split-tee stem yielding occurs prior to bolt fracture. (See Figure 8.)

Step 7: Detail the final dimensions of the connection based upon the minimum and maximum split-tee flange and stem thicknesses calculated in steps 4, 5 and 6.

Step 8: Calculate the actual flange forces in the connection based upon the final geometry of the connection detailed in step 7.

Step 9: Calculate prying forces in the flanges of the split-tee using the final dimensions of the connection. Yielding of the split-tee flanges due to prying should occur prior to bolt fracture as a potential failure mechanism. Figure 9 shows the procedure for checking the final dimensions of the split-tee connection for this.

Step 10: Figure 10 shows the steps for checking the detailed geometry for stem fracture, stem yield, balanced failure (split-tee stem yielding before flange yielding) and shear.

Step 11: Figure 11 shows the procedure for sizing the weld between the split-tees and the WF beam flanges based on the thicknesses of the connecting material and the flange forces calculated in step 8.

Step 12: Figure 12 shows the calculations for the panel-zone shear strength of the CFT column. The shear strength of the panel zone should be greater than the flange forces calculated in step 8. This is consistent with the initial assumption that plastic hinge formation occurs in the WF beams of the C-SMF.

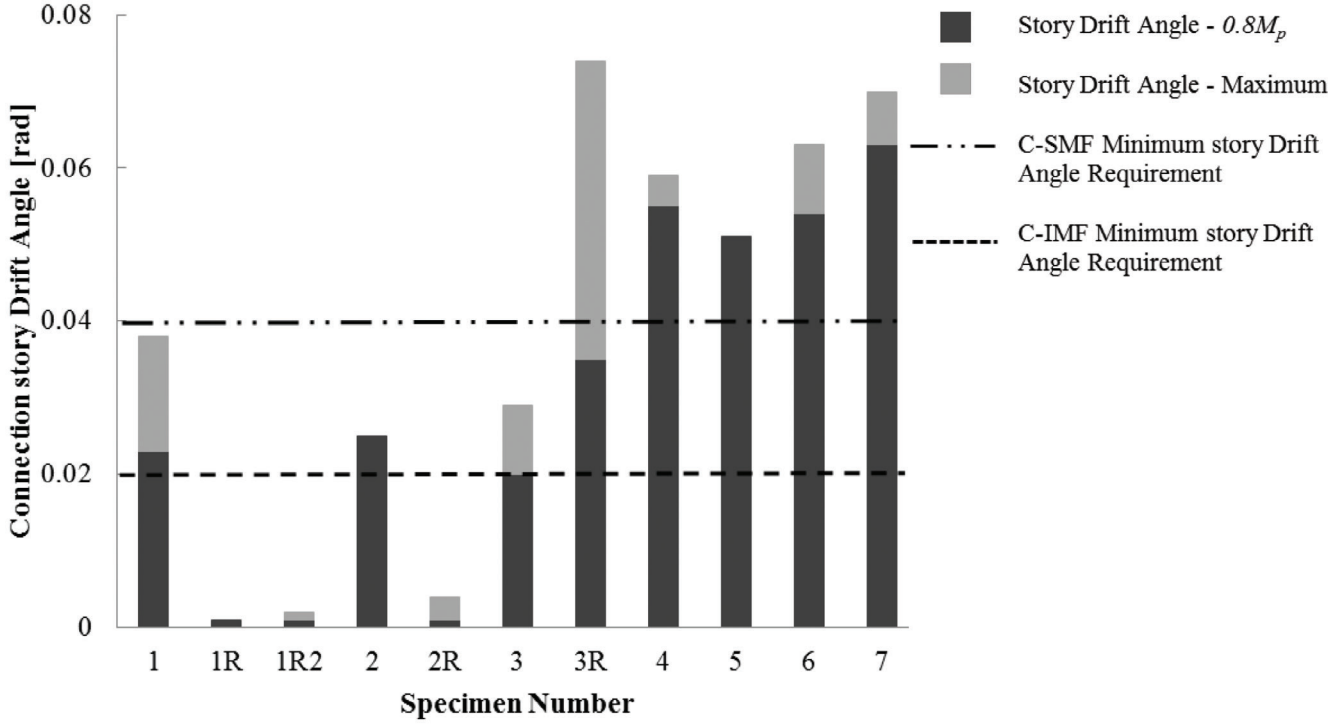


Fig. 3. Summary of story-drift angle for connections tested (Peng, 2001).

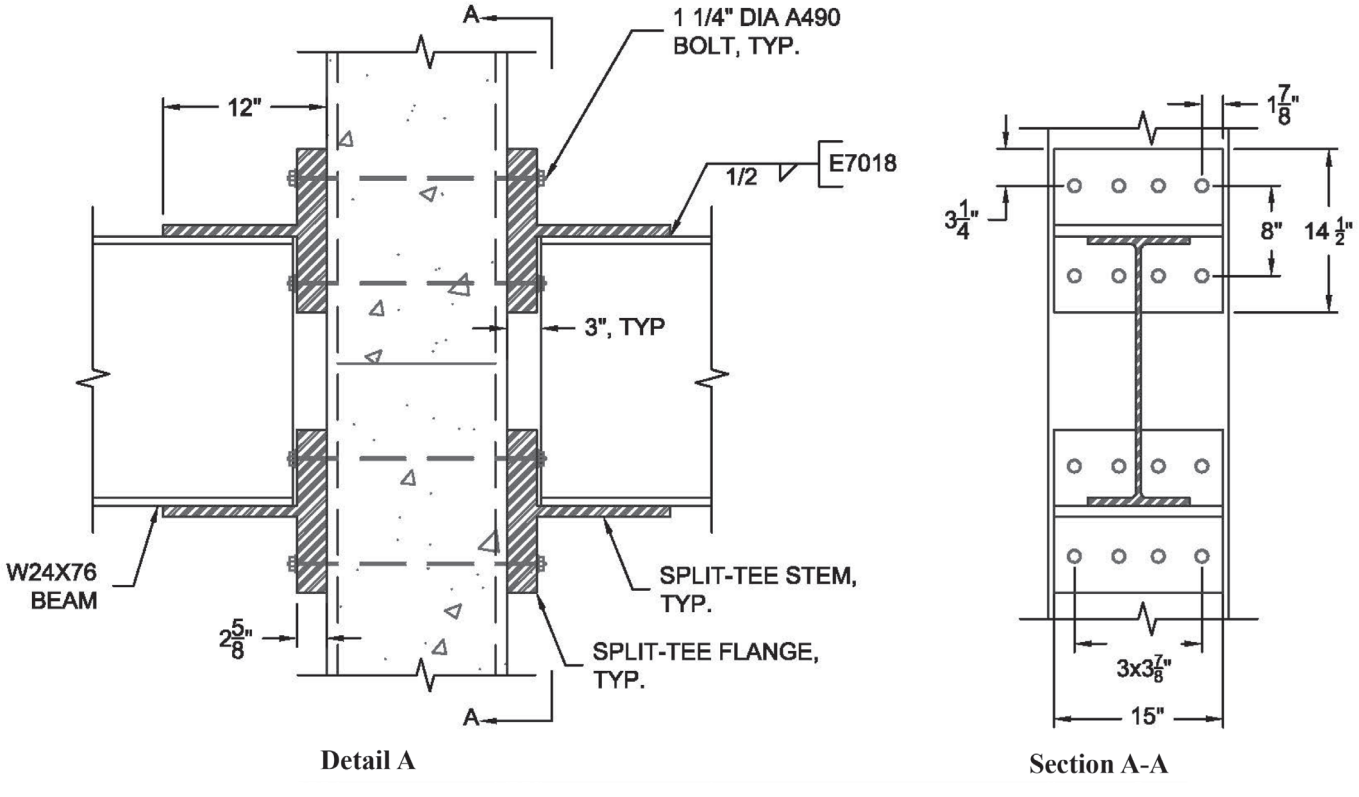


Fig. 4. Split-tee connection detail.

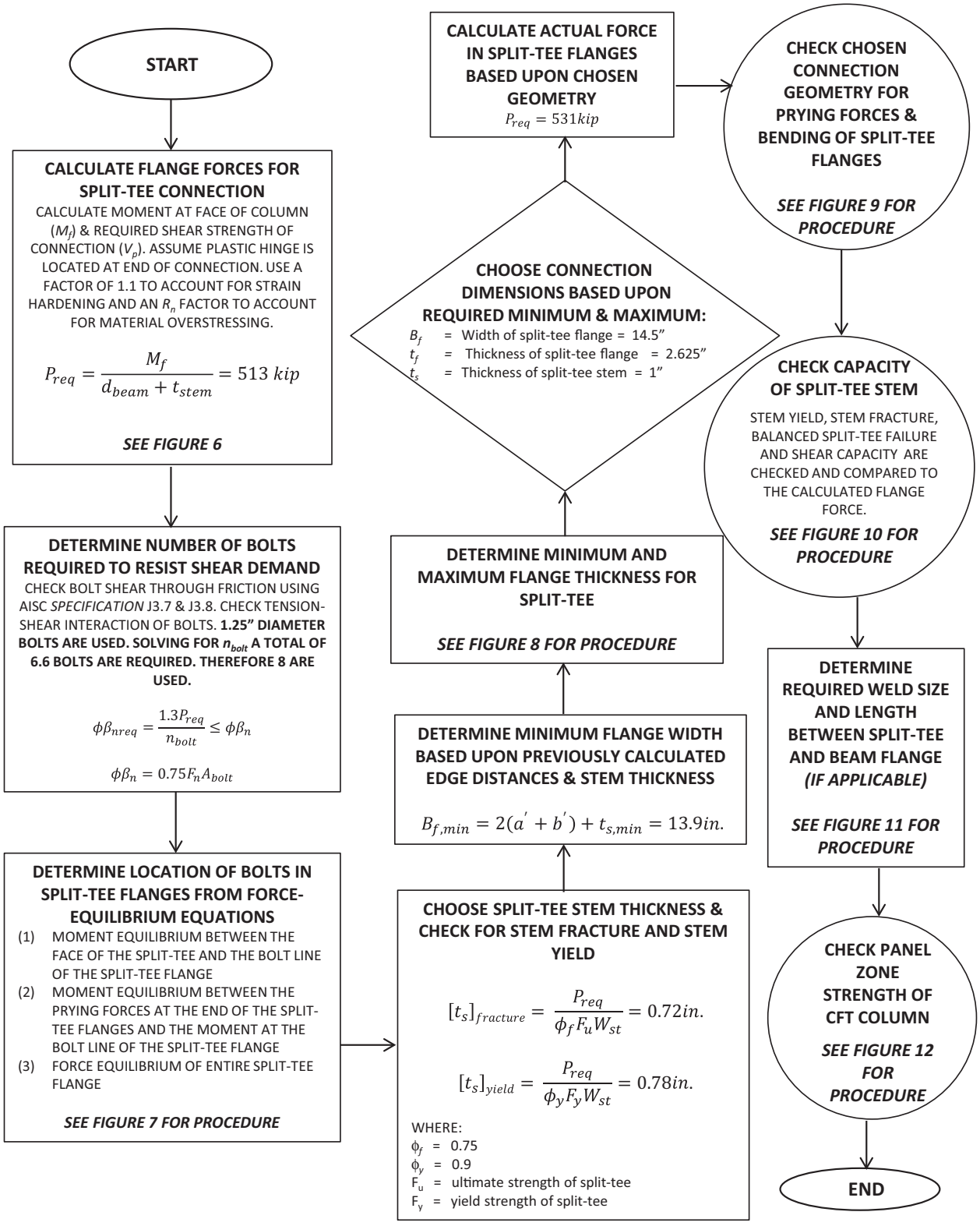


Fig. 5. Main flow chart for split-tee connection design.

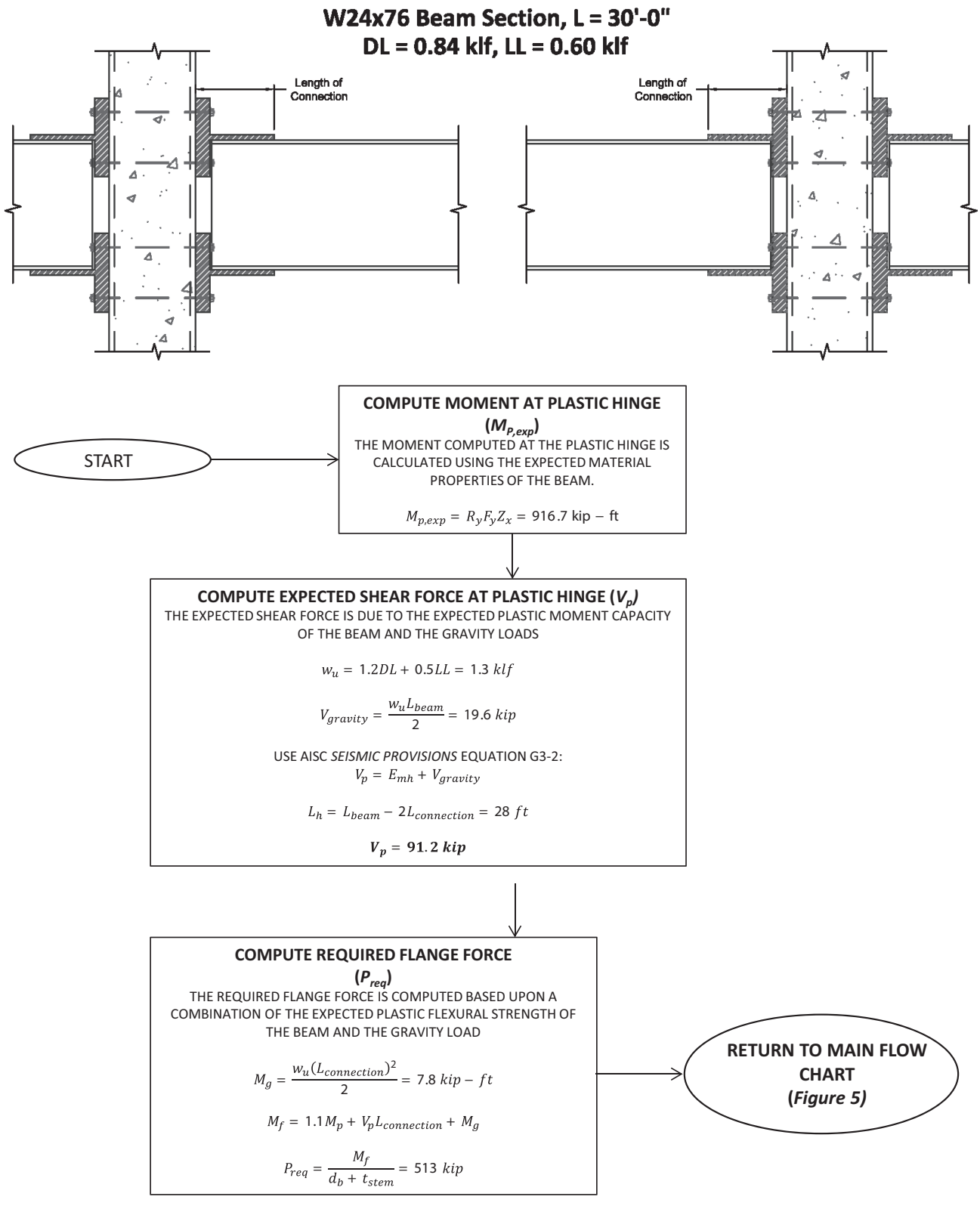
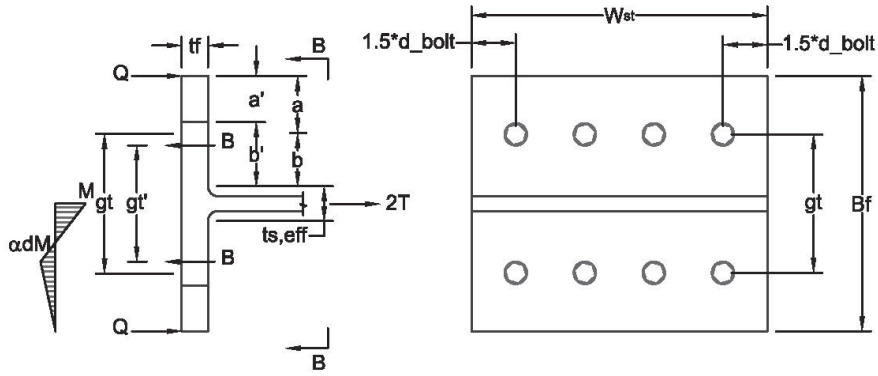


Fig. 6. Calculate moment at the face of the column and required shear strength of the connection.



(a) SPLIT-TEE GEOMETRY & FORCES

SECTION B-B
(b) SPLIT-TEE GEOMETRY

START

CHOOSE LENGTH OF SPLIT-TEE BASED UPON NUMBER OF BOLTS REQUIRED FOR CONNECTION (W_{st})

$W_{st} = 15in.$

SOLVE FOR TRIBUTARY WIDTH OF SPLIT-TEE TO ONE PAIR OF BOLTS IN TENSION (*p*)

$$p = \frac{2W_{st}}{n_{bolt}} = 3.75in.$$

SOLVE FOR RATIO OF THE NET SECTION OF THE FLANGE AT THE BOLT LINE TO THE GROSS SECTION AT THE FACE OF THE BEAM (δ)

$$\delta = 1 - \frac{d_{hole}}{p} = 0.633$$

WHERE d_{hole} IS THE DIAMETER OF THE BOLT HOLE:

$$d_{hole} = d_{bolt} + \frac{1}{8}inch = 1.375in.$$

SOLVE FOR TENSION FORCE IN EACH BOLT PRODUCED BY FLANGE FORCES

$$T_{req} = \frac{P_{req}}{n_{bolt}} = 66.2kip$$

SOLVE FOR a′

FOR A DUCTILE FLANGE THE TENSION BOLTS WILL BE LOCATED NEAR THE EDGE OF THE FLANGE. IF MINIMUM EDGE DISTANCE IS $1.5d_{bolt}$ TO ENSURE DUCTILITY USE THE FOLLOWING:

$$a' = 2d_{bolt} = 2.5in.$$

SET UP FORCE-EQUILIBRIUM EQUATIONS TO DETERMINE REQUIRED SPLIT-TEE DIMENSIONS

1) MOMENT EQUILIBRIUM BETWEEN THE FACE OF THE SPLIT-TEE STEM AND THE BOLT LINE OF THE SPLIT-TEE FLANGE

$$M(1 + \delta\alpha) = Tb'$$

2) MOMENT EQUILIBRIUM BETWEEN THE PRYING FORCE AT THE END OF THE SPLIT-TEE FLANGES AND THE MOMENT AT THE BOLT LINE OF THE SPLIT-TEE FLANGE

$$Qa' = \delta\alpha M$$

3) FORCE EQUILIBRIUM OF THE ENTIRE SPLIT-TEE FLANGE RESULTS IN

$$\beta = T + Q = \phi\beta_n = 0.75F_nA_{bolt}$$

SOLVE FOR REQUIRED b′ USING FORCE-EQUILIBRIUM EQUATIONS

BY COMBINING EQUATIONS (1) AND (3) FROM THE PREVIOUS STEP AND REARRANGING FOR b′:

$$b' = \left[\frac{\phi\beta_n - T_{req}}{T_{req}}\right]\left[\frac{1 + \delta}{\delta}\right]a' = 3.68in.$$

RETURN TO MAIN FLOW CHART (*Figure 5*)

Fig. 7. Force equilibrium equations for location of bolts.

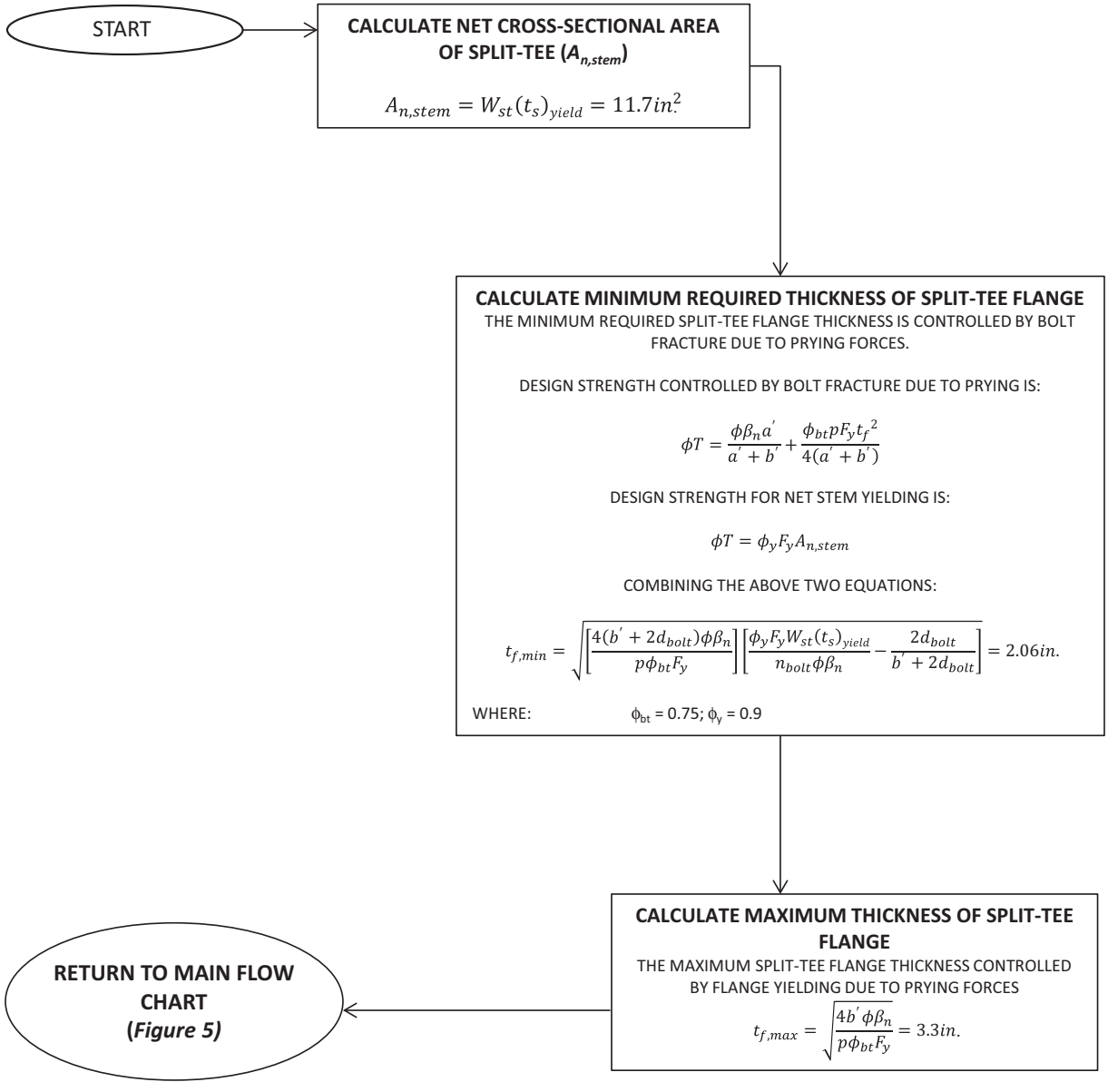
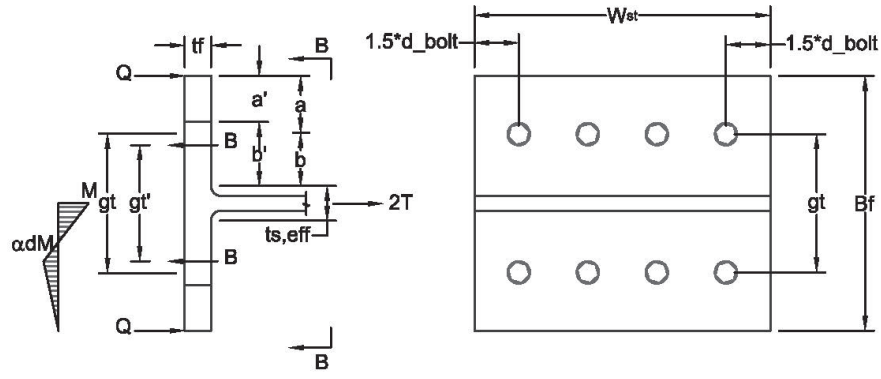


Fig. 8. Check minimum and maximum flange thickness for split-tee.



(a) SPLIT-TEE GEOMETRY & FORCES **SECTION B-B (b) SPLIT-TEE GEOMETRY**

START

CALCULATE EFFECTIVE THICKNESS OF SPLIT-TEE STEM, $t_{s,eff}$

$$t_{s,eff} = k_1 + \frac{t_s}{2} = 0.5in.$$

WHERE:
k_1 = fillet dimension from AISC *Specification*
= 0 for built up sections

CALCULATE g_t FROM MINIMUM REQUIRED EDGE DISTANCE DIMENSIONS

TO ENSURE DUCTILITY IN THE FAILURE OF THE CONNECTION, THE EDGE DISTANCE *a* AND *b* MUST SATISFY THE FOLLOWING:

$$a = \frac{B_f - g_t}{2} \leq 1.25b$$

$$b = \frac{g_t - t_{s,eff}}{2}$$

FROM THESE ABOVE RESTRICTIONS THE MINIMUM OF THE DIMENSION g_t CAN BE CALCULATED:

$$g_{t,min} = \frac{B_f + 1.25t_{s,eff}}{2.25} = 6.72in.$$

CHOOSE A g_t DIMENSION CONSISTENT WITH THE CONNECTION

g_t = 8 in.

CALCULATE REMAINDER OF PRYING DIMENSIONS:

$$a = \frac{B_f - g_t}{2} = 3.25in. \leq 1.25b$$

$$b = \frac{g_t - t_{s,eff}}{2} = 3.75in.$$

$$a' = a + \frac{d_{bolt}}{2} = 3.875in.$$

$$b' = b + \frac{d_{bolt}}{2} = 3.125in.$$

CALCULATE FLANGE CAPACITY USING MODIFIED KULAK ET AL MODEL (Swanson & Leon, 2000) (Kulak, Fisher, & Struik, 1987)

THE MODIFIED KULAK ET AL. MODEL SHOWS THAT THE SPLIT-TEE FLANGE CAPACITY SHALL BE THE MINIMUM OF THE FOLLOWING THREE FAILURE MODES MULTIPLIED BY THE NUMBER OF THROUGH BOLTS. THIS SHOULD BE COMPARED WITH THE FLANGE FORCES CALCULATED.

1) PLASTIC FLANGE MECHANISM

$$\phi T_1 = \frac{\phi_{bt}\left(2a' - \frac{d_{bolt}}{4}\right)pF_y t_f}{4a'b' - d_{bolt}(a' + b')} = 182kip$$

2) BOLT FRACTURE DUE TO PRYING ON SPLIT-TEE FLANGE

$$\phi T_2 = \frac{\phi\beta_n a'}{a' + b'} + \frac{\phi_{bt} pF_y {t_f}^2}{4(a' + b')} = 92kip$$

3) BOLT FRACTURE WITHOUT EFFECTS OF PRYING

$$\phi T_3 = \phi\beta_n = 104kip$$

CHECK FLANGE CAPACITY

$$\phi R_{n,flange} = n_{bolt}\phi T_n \geq P_{req}$$

$$\phi R_{n,flange} = 736kip \geq 513kip$$

RETURN TO MAIN FLOW CHART (*Figure 5*)

Fig. 9. Check prying forces and flange bending on split-tee.

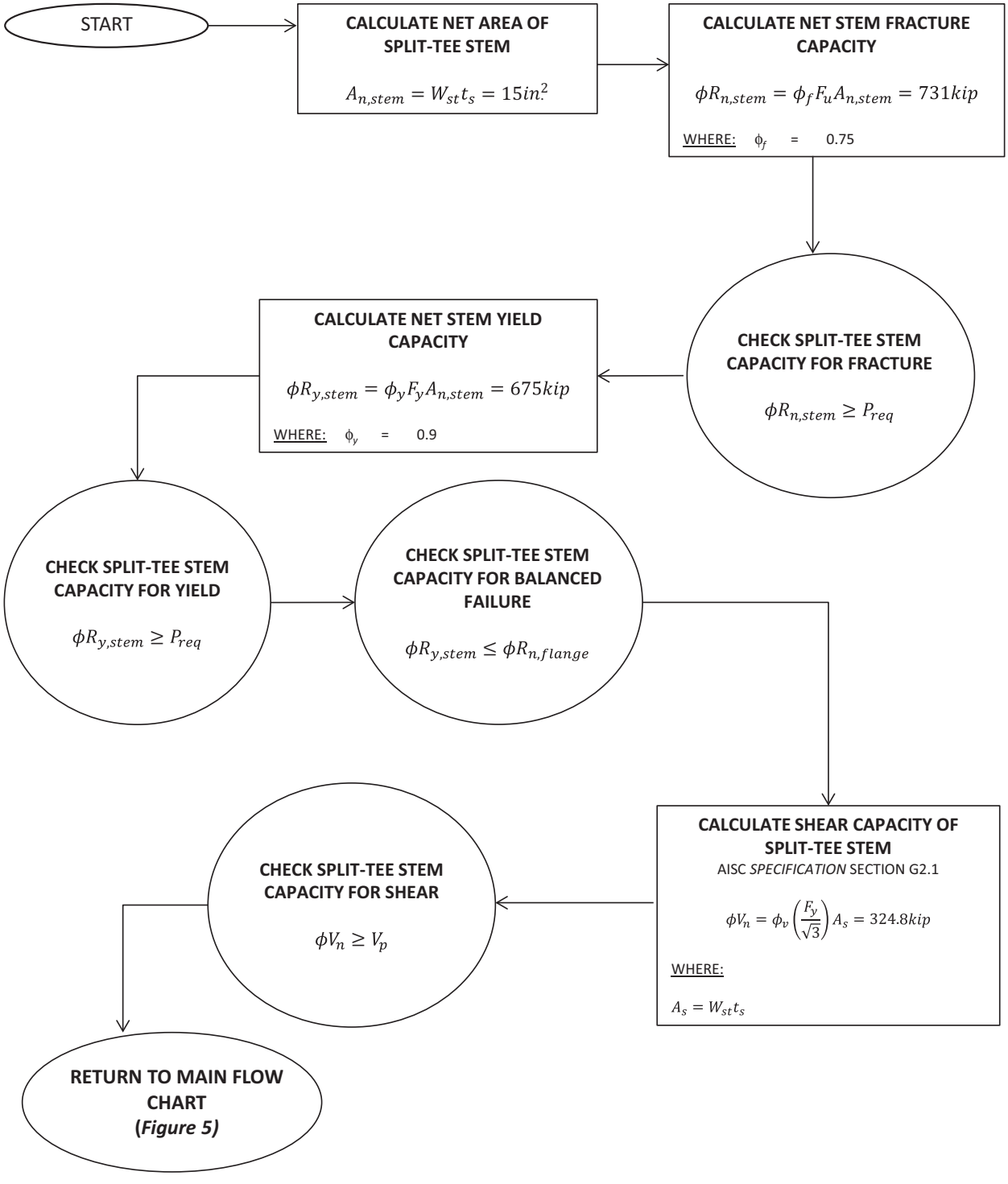


Fig. 10. Split-tee stem capacity check.

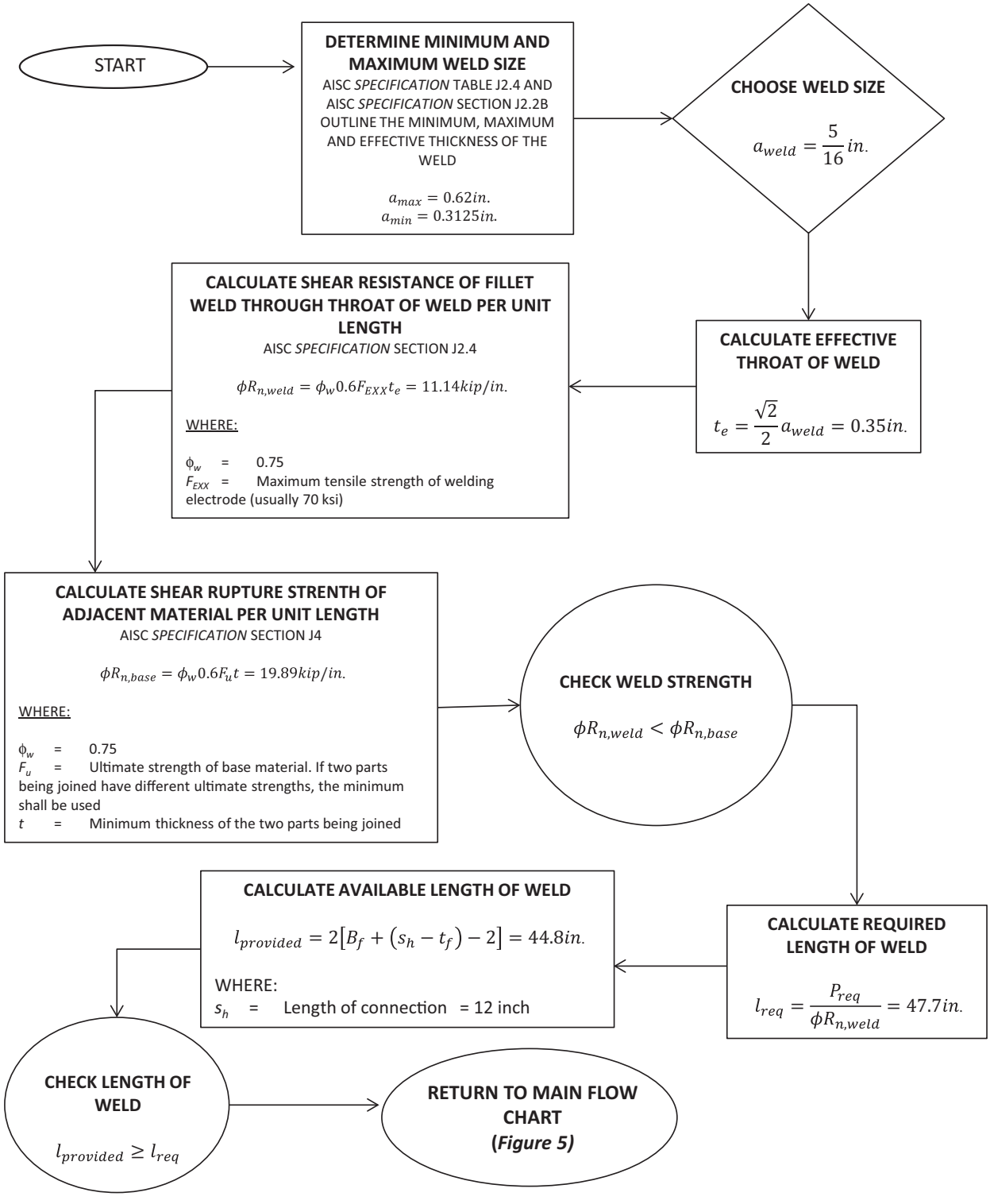


Fig. 11. Fillet weld at split-tee stem and beam flange.

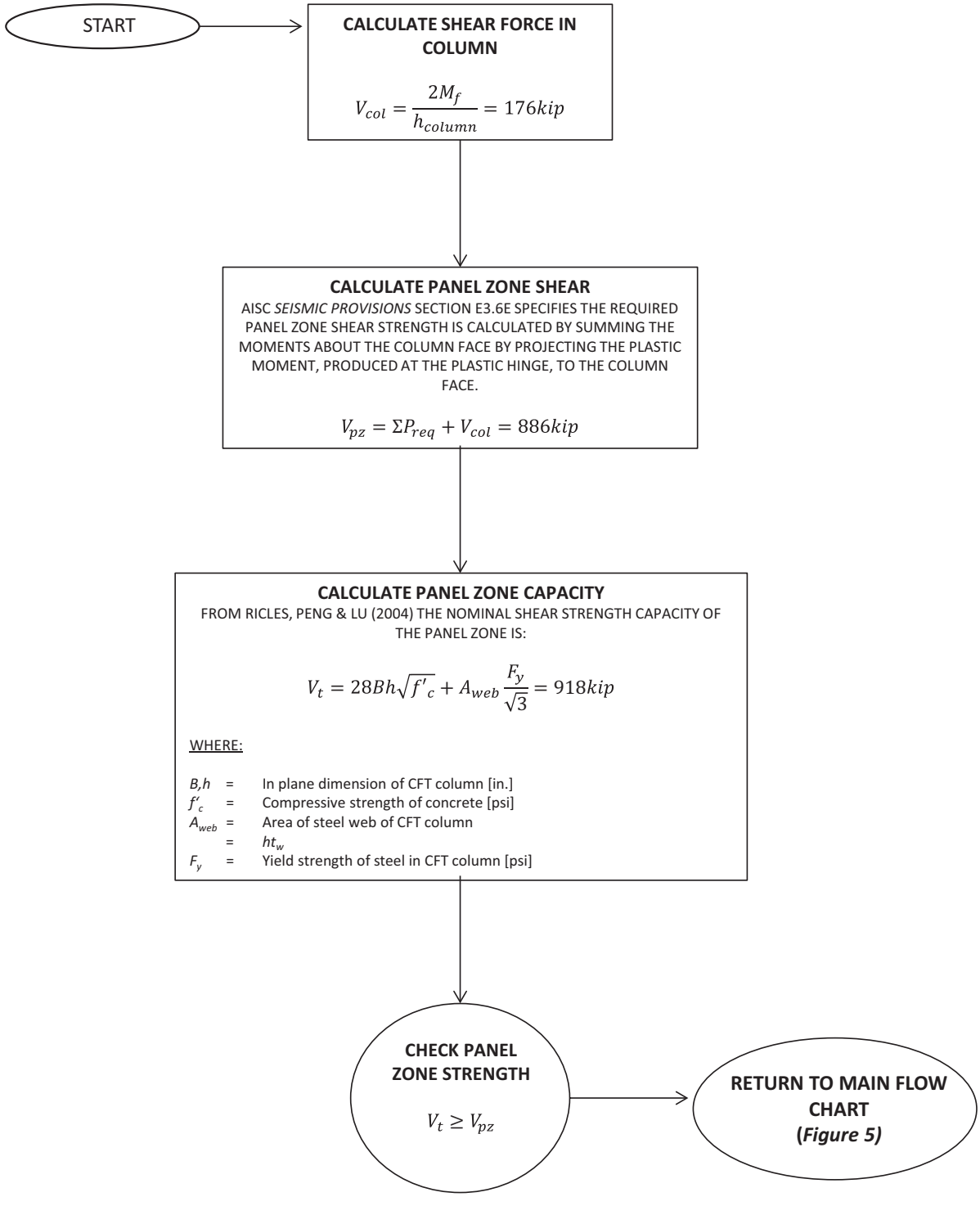


Fig. 12. Check panel zone of CFT column.

SUMMARY AND CONCLUSIONS

The experimental program conducted by Peng (2001) showed that split-tee connections satisfy the requirements of the AISC *Seismic Provisions* (AISC, 2010a) for beam-to-column moment connections in C-SMFs. The all-bolted split-tee connection had pinching in the cyclic (hysteresis) response due to elongation of the bolt holes and slipping between the stems of the split-tee and the WF beam flanges. The bolted-welded split-tee connection resolved this (pinching) issue by welding the split-tee stem to the WF beam flanges.

The AISC *Prequalified Connections* (AISC, 2010b) does not include examples of beam-to-column connections for C-SMF construction. The engineer is required to create a "Prequalified Record" for the designed beam-to-column connection. This paper along with the test results from Peng (2001) provides many of the necessary sections for the "Prequalified Record" outlined in Section K1.6 of the AISC *Seismic Provisions*, including the following:

- A general description of the prequalified connection.
- A description of expected behavior of the connection in the elastic and inelastic ranges.
- A definition of connection region that comprises the protected zone.
- A detailed description of the design procedure for the connection.
- A list of references of test reports, research reports and other publications that provide basis for prequalification.

This paper presented a comprehensive design procedure and associated design example for bolted-welded split-tee connections in C-SMFs. The design procedure accounts for the potential failure modes of the connection and organizes them in hierarchal order from most ductile (desirable) to least ductile, namely: (1) plastic hinge formation in beam, (2) stem yielding of the split-tee, (3) flange yielding of split-tee due to prying action, (4) panel-zone failure of column and (5) bolt fracture due to prying action of split-tee. Both the design procedure and the design example establish plastic hinge formation in the WF beams outside of the connection region as the controlling limit state for the split-tee moment connection. The comprehensive design procedure and example are illustrated using flowcharts in Figures 5 through 12.

SYMBOLS

Beam and Column Dimensional Notation

B	Width of column (in.)
F_u	Ultimate stress of steel (ksi)
F_y	Yield stress of steel (ksi)
R_y	Material correction factor
b_f	Width of beam web (in.)
d	Depth of beam (in.)
f'_c	Compressive stress of concrete (ksi)
h	Depth of column (in.)
t_f	Thickness of beam flange (in.)
t_w	Thickness of column or beam web (in.)

Split-tee Notation

B_f	Width of split-tee flange (in.)
$L_{connection}$	Length of the connection (in.)
W_{st}	Depth of split-tee (in.)
Z_x	Plastic section modulus (in.^{3})
t_f	Thickness of split-tee flanges (in.)
t_s	Thickness of split-tee stem (in.)
t_{stem}	Assumed thickness of split-tee stem (in.)

Capacity Notation

$[t_s]_{fracture}$	Minimum required stem thickness for fracture limit state (in.)
$[t_s]_{yield}$	Minimum required stem thickness for yield limit state (in.)
A_{bolt}	Area of bolt
$A_{n,stem}$	Net area of stem (in.^{2})
$B_{f,min}$	Minimum flange width (in.)
F_n	Nominal stress of bolt (ksi)
M_f	Moment at face of column (k-ft)
M_p	Plastic flexural strength using nominal material properties (k-ft)
$M_{p,exp}$	Plastic flexural strength using expected material properties (k-ft)
$M_{p,meas}$	Plastic flexural strength using measured material properties (k-ft)

P_{req}	Required flange forces for double split-tee connection design (kip)
V_{col}	Shear force in column (kip)
V_{pz}	Shear force in panel zone (kip)
V_t	Column panel-zone capacity (kip)
α_{max}	Maximum required weld size (in.)
α_{min}	Minimum required weld size (in.)
α_{weld}	Actual weld size (in.)
$l_{provided}$	Provided length of weld (in.)
l_{req}	Required length of weld (in.)
n_{bolt}	Number of bolts
t_e	Effective throat of weld (in.)
$\phi R_{n,base}$	Shear rupture strength of adjacent material per unit length (kip/in.)
$\phi R_{n,flange}$	Flange capacity of split-tee (kip)
$\phi R_{n,stem}$	Net stem fracture capacity (kip)
$\phi R_{n,weld}$	Fillet weld shear resistance through throat of weld per unit length (kip/in.)
$\phi R_{y,stem}$	Net stem yield capacity (kip)
ϕV_n	Shear capacity of split-tee stem (kip)
$\phi\beta_n$	Capacity of bolt (kip)
$\phi\beta_{nreq}$	Required capacity of bolt (kip)

REFERENCES

American Institute of Steel Construction, Inc. (2010a), *Seismic Provisions for Structural Steel Buildings,* ANSI/AISC 341-10, Chicago, IL.

American Institute of Steel Construction, Inc. (2010b), *Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications,* ANSI/AISC 358-10, Chicago, IL.

American Institute of Steel Construction, Inc. (2010c), *Specification for Structural Steel Buildings,* ANSI/AISC 360-10, Chicago, IL.

American Institute of Steel Construction, Inc. (2011), *Steel Construction Manual,* 14th Ed., Chicago, IL.

Applied Technology Council (1992). "Guidelines for Seismic Testing of Components of Steel Structures," Redwood City, CA.

Kanno, R. and Deierlein, G.G. (1997), "Seismic Behavior of Composite (RCS) Beam-Column Joint Subassemblies," *Composite Construction III,* ASCE, Reston, VA.

Kulak G., Fisher, J. and Struik, J. (1987), *Guide to Design Criteria for Bolted and Riveted Joints*, Indianapolis: John Wiley & Sons, Inc.

Lai, Z., Varma, A.H. and Zhang, K. (2014), "Noncompact or Slender Rectangular CFT Members: Experimental Database, Analysis and Design," *Journal of Constructional Steel Research*, Vol. 101, pp. 455–468.

Peng, S.W. (2001), "Seismic Resistant Connection for Concrete-Filled Tube Column-to-WF Beam Moment Resisting Frames," Ph.D. Dissertation. Bethlehem, PA: Lehigh University.

Ricles, J.M., Peng, S.W. and Lu, L.W. (2004), "Seismic Behavior of Composite Concrete Filled Steel Tube Column-Wide Flange Beam Moment Connections," *Journal of Structural Engineering*, Vol. 130, pp. 223–232.

Schneider, S.P. and Alostaz, Y.M. (1998), "Experimental Behavior of Connections to Concrete-filled Steel Tubes." *Journal of Constructional Steel Research*, Vol. 45, No. 3, pp. 321–352.

Swanson J.A. and Leon, R.L. (2000), "Bolted Steel Connections: Tests on T-Stub Components," *Journal of Structural Engineering,* Vol. 126, pp. 50–56.

Varma, A.H., Ricles, J.M., Sause, R. and Lu, L.W. (2002), "Seismic Behavior and Modeling of High Strength Composite Filled Steel Tube Beam-Columns," *Journal of Constructional Steel Research*, Vol. 58, No. 5–8, pp. 725–758.