Weld Effective Lengths for Round HSS Cross-Connections under Branch Axial Loading

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ABSTRACT

Recent experimental and numerical research performed on fillet-welded, round-to-round, HSS cross-connections is reviewed, along with prior research on round HSS-to-rigid plate connections. The data from these weld-critical tests are then interpreted to determine practical weld effective lengths for such connections, in conjunction with permitting the directional strength-increase factor for fillet welds to round HSS. Recommendations are made for AISC *Specification* Section K5, and a design example is given to illustrate the approach.

Keywords: hollow structural sections, welded joints, cross-connections, weld effective lengths, fillet welds, design procedures.

The AISC *Specification for Structural Steel Buildings* (AISC, 2016), hereafter referred to as the AISC *Specification*, gives weld effective lengths for plate-to-rectangular HSS welded joints and rectangular-to-rectangular HSS welded joints in Section K5. These are used to design welds between plate and HSS branches to rectangular HSS main members whenever the welds are to be "fit for purpose" and not necessarily able to develop the yield capacity of the branch. However, for round-to-round HSS connections, the AISC *Specification* is silent, and there are no weld effective length rules given for such connections. As a consequence of this uncertainty, there is a tendency for many designers to just specify complete-joint-penetration (CJP) groove welds for round-to-round HSS connections, which is an expensive and undesirable default practice.

It is known that the load distribution around the perimeter of a round HSS welded joint can be highly nonuniform (Marshall, 1992). To deal with potential weld "unzipping" caused by one part of a welded joint being much more highly loaded than another, AWS D1.1, clause 9.6.1.3(4), (AWS, 2015) implies that the weld effective length in axially loaded round-to-round HSS connections is equal to $1/1.5$ of the total weld length under factored loads. This simple rule is believed to be conservative, but the weld effective length is likely to vary with specific connection parameters, particularly the cross-sectional slenderness of the chord wall, D/t. This paper reviews research data with the objective of assessing—and improving on—this recommendation, while still satisfying the AISC target reliability index.

Because the design of welds in codes/specifications is based on simplification of a complex loading, any proposed effective length approach to the design of welds must be checked for its safety level in conjunction with the weld design rules of a particular specification. While AISC *Specification* Section K5 (AISC, 2016) explicitly prohibits the use of the "fillet weld directional strength-enhancement factor," $(1.0 + 0.50 \sin^{1.5} \theta)$, when designing "fit for purpose" welds for rectangular HSS, the AISC *Specification* is again silent about whether it is allowed when designing such welds for round HSS.

Laboratory testing and finite element analysis studies have been performed on fillet-welded joints to the ends of HSS members, where the HSS end is connected to a rigid plate and the HSS is subjected to axial tension (Packer et al., 2016; Tousignant and Packer, 2016; 2017a). In such situations, the entire weld length is effective due to the rigid base material. This research has shown that single-sided welds to a tension-loaded HSS wall element are partially unrestrained and are prone to local bending about the axis of the weld, as shown in Figure 1, leading to opening of the weld root. The restraint provided to the fillet weld depends on the connected element thickness and shape (linear versus curved), as well as the weld size and amount of penetration. It was found that the HSS welded joints in the aforementioned research did not achieve the expected target safety (reliability) index of $\beta^+ \geq 4.0$ at failure, as discussed in AISC *Specification* Commentary B3.1, if the fillet weld directional strength-enhancement factor was applied. In general, however, setting this factor of $(1.0 + 0.50 \sin^{1.5} \theta)$ to unity (i.e., taking θ as zero) when calculating the strength of fillet welds to tension-loaded HSS wall elements achieves $\beta^+ \geq 4.0$.

In the aforementioned studies, the single-sided weld effect was much more severe for square and rectangular HSS than

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Table 1. Proposed Changes to the Applicability of the sinθ Factor for Fillet Welds to HSS			
Case	**Loading Sense**	**2016 AISC *Specification***	**2022 AISC *Specification***
Fillet welds connecting round HSS branches to base plates, cap plates, or HSS chords	Tension	Permitted	Permitted
	Compression	Permitted	Permitted
	Pure bending	Permitted	Permitted
Fillet welds connecting square or rectangular HSS branches to base plates, cap plates, or HSS chords	Tension	Not permitted in truss-type connections, otherwise permitted (K5 Commentary)	Not permitted
	Compression		Permitted
	Pure bending		Not permitted*
Double-sided fillet welds connecting longitudinal or transverse branch plates to HSS chords	Tension	Permitted	Permitted
	Compression	Permitted	Permitted
	Pure bending	Permitted	Permitted

* AISC TC6 has recommended that the sinθ factor not be permitted when any face of the square or rectangular HSS branch is in tension (e.g., under pure bending). Provided that the entire branch remains under compression, the sinθ factor may be used for axial compression plus bending loading.

for round HSS, when viewed separately. Recent reliability analysis of round HSS-to-rigid plate experiments, combined with parametric finite element analyses thereof (Tousignant and Packer, 2019), has found that these connections generated a safety index of $\beta^+ = 3.7$. This is only marginally lower than the target value. AISC Committee on Specifications (COS) Task Committee 6 (TC6) on Connection Design has hence recommended that the fillet weld directional strength-enhancement factor for fillet welds to the ends of round HSS be permitted in the 2022 AISC *Specification*.

On the other hand, use of the directional strength-enhancement factor is not acceptable for fillet welds to the ends of square and rectangular HSS in which any face is in tension, when the design approach is to develop the yield strength of the connected HSS wall, nor when the design is a "fit-for-purpose" approach. The latter is covered in AISC *Specification* Section K5, and entails the use of weld effective lengths. The Section K5 provisions have been shown to generate suitable target safety (reliability) indices for welded joints to square and rectangular HSS with faces in tension, in conjunction with the weld effective lengths advocated and non-use of the "sinθ factor" (McFadden and Packer, 2014; Tousignant and Packer, 2015).

AISC TC6 has also recommended the use of the directional strength-enhancement factor for double-sided fillet welds to longitudinal or transverse plate branches, attached to all HSS, regardless of branch loading, and for single-sided welds between HSS branches and HSS chords where all of the branch remains in compression. Although not yet final for the 2022 AISC *Specification*, Table 1 provides a summary of the proposed changes to the applicability of the sinθ factor for fillet welds to HSS. For the purpose of this paper, it will be assumed that the fillet weld directional strength-enhancement factor is permitted for calculating the strength of welds to round HSS.

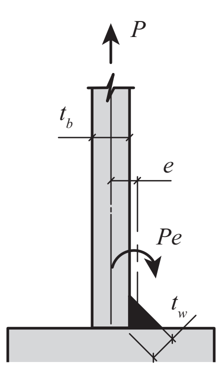


Fig. 1. Eccentric loading on a single-sided fillet weld, resulting in local bending.

EXPERIMENTS ON WELD-CRITICAL ROUND-TO-ROUND HSS CROSS-CONNECTIONS

A total of 12 laboratory tests have been performed on round-to-round HSS cross-connections, fabricated from large-size ASTM A500 (ASTM, 2018), dual-certified, Grade B/C HSS (Tousignant and Packer, 2017b). A professional fabricator was employed to deposit fillet welds all-around the branches using a semiautomatic, flux-cored arc welding process with a CO_2 shielding gas. The chord members were HSS10.75×0.500 and HSS16.00×0.500, with branches (at either 90° or 60°) selected to obtain branch-to-chord width ratios, β, ranging from 0.25 to 0.47. All test specimens had geometric configurations that permitted the use of fillet welding in accordance with AWS D1.1 (AWS, 2015). Welding procedure specifications were developed in conjunction with trial sectioning to achieve minimal, but adequate, root penetration; the welds were ground to an ideal triangular shape; and careful measurements were made of the geometric and mechanical properties of the welds. Specimens were well-instrumented and loaded to failure by applying a quasi-static axial tension force to the end of the branches, as shown in Figure 2. Failure in all cases occurred in a brittle manner by fracture along a plane through the weld. A typical rupture failure is shown in Figure 3 for a 90° connection.

Strain gauges around the branch members close to the welds (such as indicated by SG in Figure 3) confirmed the nonuniform strain, and thus the tensile load distribution, around the branch and hence in the neighboring weld. For the 90° connections, the tensile strain decreased as a function of distance away from the highly loaded saddle position (indicated in Figure 3). An example of this strain variation around the branch and weld is shown in Figure 4 for various load levels corresponding to 25%, 50%, 75%, and 100% of the weld fracture load, P_a. In Figure 4, the subtended angle, x, is the angle measured clockwise (CW) around the branch, with 0° and 180° corresponding to the two crown points and 90° corresponding to the saddle point (see Figure 3). The tensile (positive) strain is therefore smallest at the crown, with much of the weld remaining in compression (negative strain) for the entire tensile load range, and largest at the saddle points. This nonuniform loading is more pronounced for connections with higher β values.

The nonuniformity of stress observed in the experiments (Tousignant and Packer, 2017b) will be prevalent in all round-to-round HSS connections of similar geometries (T-, Y-, and X-type) with branch axial loading. This would also apply regardless of the weld type [fillet, partial joint penetration (PJP) groove weld, or CJP groove weld] used to join the branch(es) to the chord, assuming that the welds do not significantly change the footprint of the branch(es).

NUMERICAL MODELING OF WELD-CRITICAL ROUND-TO-ROUND HSS CROSS-CONNECTIONS

Nonlinear finite element (FE) models, incorporating a weld fracture criterion, have been validated against the results of the 12 laboratory tests (Tousignant and Packer, 2018). A parametric study was then performed, consisting of 256 FE weld-critical, round HSS cross-connections with varied width ratio β, chord slenderness D/t, branch angle θ, and branch-to-chord thickness ratio τ. All numerical models failed by weld fracture. It was found that the weld

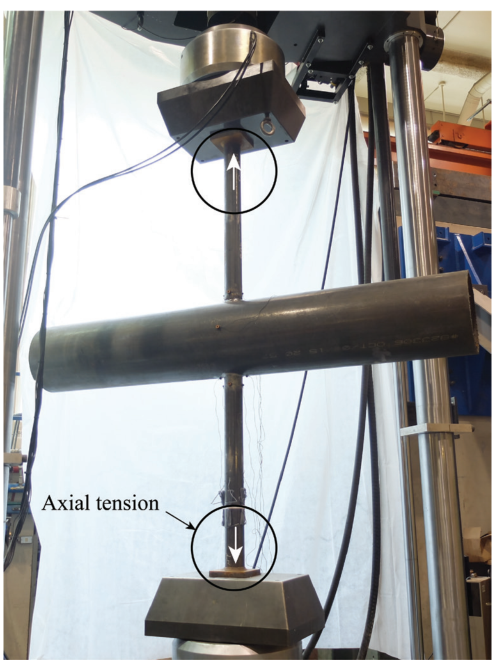


Fig. 2. Testing arrangement for round-to-round HSS cross-connections.

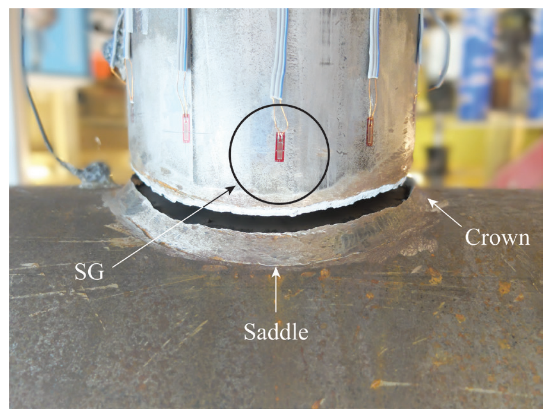


Fig. 3. Weld fracture in a 90° cross-connection.

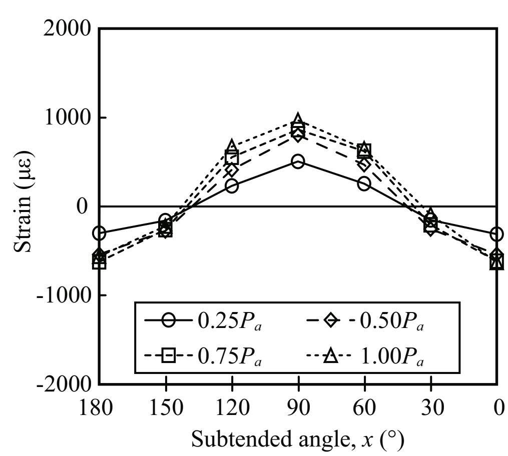


Fig. 4. Strain distribution around the weld, for a HSS5.00×0.500 branch to HSS10.75×0.500 chord.

effective length decreases as D/t increases, β increases, and τ increases. The weld effective length ranged from 0.58 to 1.0 times the total weld length within the parameter range studied (60° ≤ θ ≤ 90°; 10 ≤ D/t ≤ 50; 0.10 ≤ β ≤ 0.50; 0.20 ≤ τ ≤ 1.00), with the weld length becoming 100% effective for $\beta(D/t) \le 8$. Within the range studied, the branch inclination angle had only a very minor effect on the weld effective length.

DESIGN

In Section K5 of the AISC *Specification* (AISC, 2016), a detailed design method considering weld effective lengths for plate-to-rectangular and rectangular-to-rectangular HSS welded joints is given. According to this section, the nominal strength of welds, R_n or P_n, in connections subject to branch axial load is based on the limit state of shear rupture along the plane of the weld effective throat and calculated as follows:

$$R_n \text{ or } P_n = F_{nw} t_w l_e \quad \textit{Spec. Eq. K5-1} \quad (1)$$

where F_{nw} is the nominal stress of the weld metal calculated according to AISC *Specification* Chapter J, currently utilizing no increase in strength due to the directionality of load for fillet welds-to-rectangular HSS branches in tension or compression (i.e., omitting the sinθ factor) (AISC, 2016).

According to the load and resistance factor design (LRFD) method of the AISC *Specification* (AISC, 2016), resistance factors of ϕ = 0.75 and 0.80 for fillet and PJP groove welds, respectively, are applied to Equation 1 to determine available strength.

For round-to-round HSS welded joints, including cross-connections, Equation 1 would also apply. For such joints, based on the recent recommendation by AISC TC6, the sinθ factor is permitted; that is,

$$F_{nw} = 0.60 F_{EXX} \left(1.0 + 0.50 \sin^{1.5}\theta\right) \quad \textit{Spec. Eq. J2-5} \quad (2)$$

where θ is the angle between the line of action of the applied force and the weld longitudinal axis (in degrees) and F_{EXX} is the filler metal classification strength.

Application of the sinθ factor to fillet welds in round-to-round HSS welded joints is nontrivial. The angle of loading, θ, varies continuously around the joint (see Figure 5), and calculation of θ at any point along the weld axis, let alone the value of the sin θ factor for the entire joint, involves a complex procedure.

Calculation of the sinθ Factor for a Round-to-Round HSS Joint

To calculate the loading angle of a fillet weld, θ, at a point along the weld axis, and to determine the value of the sinθ factor for a round-to-round HSS joint, the following procedure can be used:

Step 1. Determine the coordinates of the branch/chord intersection at two points corresponding to x and $x + \Delta x$ at the root of the fillet weld. Calculate the vector $\overline{V}$ [see Figure 6(a)] to approximate the weld longitudinal axis between x and $x + \Delta x$. For the coordinate system shown in Figure 6(b):

$$\overline{V} = \left[\left(-l_{t,x+\Delta x} + l_{t,x}\right), \left(r_b \sin(x+\Delta x) - r_b \sin x\right), \left(-r_b \cos(x+\Delta x) + r_b \cos x\right)\right] \quad (3)$$

where r_b is the radius of the branch (= $D_b/2$), and:

$$l_{t,x} = \frac{r_b(1-\cos x)}{\tan\theta} + \frac{r - \sqrt{r^2 - (r_b \sin x)^2}}{\sin\theta} \quad (4)$$

where r is the radius of the chord (= $D/2$). The dimension $l_{t,x}$ is shown in Figure 6(b). For $l_{t,x+\Delta x}$, substitute $x + \Delta x$ for x in Equation 4.

Step 2. Calculate the magnitude of $\overline{V}$ to determine the length, l_i, of the pseudo-linear weld element i [see Figure 6(a)] between x and $x + \Delta x$; that is,

$$l_i = \left|\overline{V}\right| \quad (5)$$

The smaller the value of Δx, the closer l_i will be to the actual weld length between the two points [1 and 2, in Figure 6(a)] at the root of the fillet weld.

Step 3. Increment x by Δx and calculate l_i again. Do this for all values of x between 0° and 360° − Δx, then sum the results to determine the total weld length l_w; that is,

$$l_w = \sum l_i \quad (6)$$

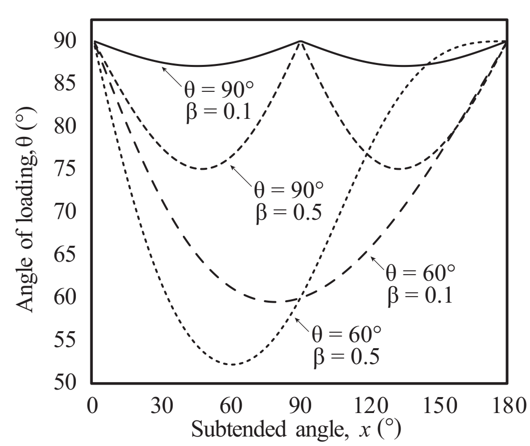


Fig. 5. Typical variations in loading angle of a fillet weld around a round-to-round HSS joint.

Step 4. Next, compute the vector that defines the direction of the applied force $\overline{P}$. For the coordinate system shown in Figure 6(b), one option is:

$$\overline{P} = [(1),(0),(0)] \tag{7}$$

Step 5. Calculate the angle of loading θ_i of each weld element i using the dot product; that is,

$$\theta_i = \cos^{-1}\left(\frac{\overline{V} \bullet \overline{P}}{|\overline{V}||\overline{P}|}\right) \tag{8}$$

In some cases, θ_i will be greater than 90°. It is recommended to calculate the acute angle of loading by subtracting the calculated angle from 180°. This has been done in Figure 5.

Step 6. Calculate the directional strength-enhancement factor for each weld element i by substituting θ_i for θ in the $(1.0 + 0.50 \sin^{1.5} \theta)$ term.

Step 7. Calculate the value of the $(1.0 + 0.50 \sin^{1.5} \theta)$ factor for the entire joint, K_{CHS}, by taking a weighted average of the $(1.0 + 0.50 \sin^{1.5} \theta_i)$ values for each weld element to account for variations in l_i; that is,

$$K_{CHS} = \frac{1}{l_w}\sum(1.0 + 0.50 \sin^{1.5} \theta_i)\, l_i \tag{9}$$

Equation 9 assumes that the weld effective throat, t_w, shown in Figure 1 is constant around the entire joint.

Sinθ Factor Design Aid

Using the procedure just outlined, with $\Delta x = 1°$, a design aid (given by Table 2) was developed to allow engineers to find the $(1.0 + 0.50 \sin^{1.5} \theta)$ factor for all-around fillet welds with a constant throat dimension in round-to-round HSS joints where fillet welds are potentially feasible. The value of $\Delta x = 1°$ used to develop the design values in Table 2 provides convergent values of the $(1.0 + 0.50 \sin^{1.5} \theta)$ factor within the range $0.1 \le \beta \le 0.5$ and $60° \le \theta \le 90°$. Table 2 is used by reading across and down for values of β and θ, respectively, for a given connection. For values of β and θ not shown, but within the range $0.1 \le \beta \le 0.5$ and $60° \le \theta \le 90°$, linear interpolation may be used.

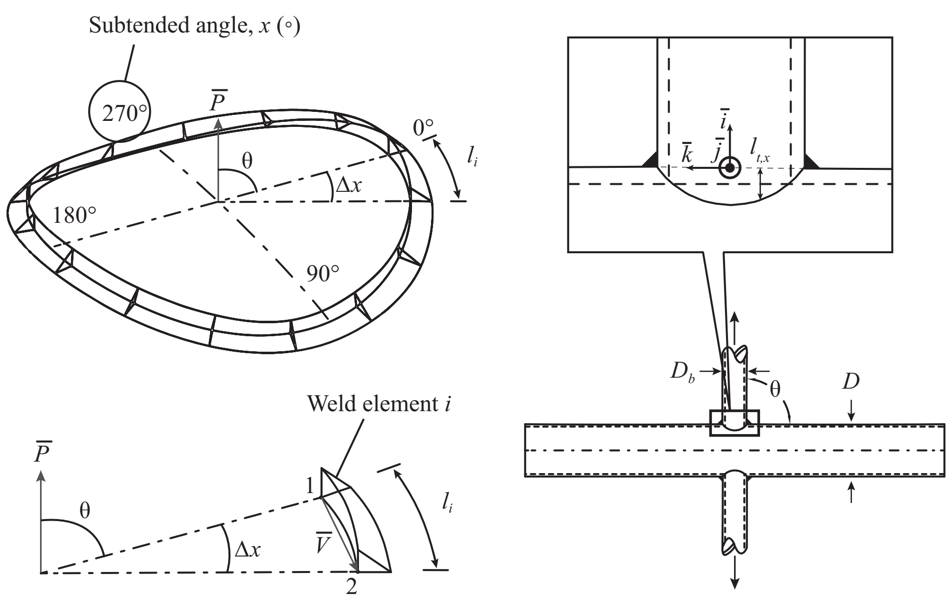
Total Weld Length

The total weld length, l_w, measured at the root of the fillet weld, can be determined from 3D solid models of intersecting cylinders. Alternatively, it was shown that the K_a approximation given by AWS D1.1, clause 9.5.4 (AWS, 2015), is remarkably good, and slightly conservative, within the range $0.1 \le \beta \le 0.5$ and $60° \le \theta \le 90°$ (Tousignant and Packer, 2017b); i.e.,

$$l_w = \pi D_b K_a \tag{10}$$

where D_b is the branch diameter, θ is the branch inclination angle, and K_a is the weld length factor, given by:

$$K_a = \frac{1 + 1/\sin\theta}{2} \tag{11}$$



(a) vectors and notation
(b) coordinate system and additional notation

Fig. 6. Calculation of the sinθ factor for a round-to-round HSS connection.

Table 2. Values of the $(1.0 + 0.50 \sin^{1.5} \theta)$ Factor (K_{CHS}) for an All-Around Fillet Weld in a Round-to-Round HSS Joint				
	Branch Inclination Angle, θ (°)			
Width Ratio, β	90°	80°	70°	60°
0.1	1.500	1.494	1.476	1.446
0.2	1.498	1.492	1.475	1.445
0.3	1.496	1.490	1.473	1.443
0.4	1.492	1.487	1.470	1.440
0.5	1.487	1.482	1.465	1.436
Note: The values of $(1.0 + 0.50 \sin^{1.5} \theta)$ assume a constant weld throat dimension, t_w.				

WELD EFFECTIVE LENGTHS FOR ROUND-TO-ROUND HSS CROSS-, T-, AND Y-JOINTS

Weld effective lengths are not necessary for round-to-round HSS joints (i.e., the total weld length can be used for l_e in Equation 2) when the sinθ factor is set to unity (i.e., θ taken as zero) in Equation 2 (Tousignant and Packer, 2019); however, a proposed approach for calculating weld effective lengths when the sinθ factor is used has not hitherto been addressed. Several options for the weld effective length, l_e, in round-to-round HSS cross-, T-, and Y-joints in the AISC *Specification* (AISC, 2016) are hence examined.

To evaluate the inherent safety level of each option, a reliability analysis, shown in Equation 12, is used to check that the target reliability index of $\beta^+ \geq 4.0$, as discussed in AISC *Specification* Commentary B3.1, is achieved (Ravindra and Galambos, 1978; Fisher et al., 1978); that is,

$$\phi = \phi_{\beta^+} \rho_R \exp\left(-\alpha \beta^+ V_R\right) \tag{12}$$

where α_R is the coefficient of separation, taken as 0.55 (Ravindra and Galambos, 1978); ρ_R is the bias coefficient for resistance; V_R is the associated coefficient of variation (COV) of ρ_R; and $\phi_{\beta+}$ is an adjustment factor that modifies ϕ when β^+ is not equal to the safety index used for the evaluation of the load factors, which is normally 3.0 (Fisher et al., 1978). An equation developed by Franchuk et al. (2002) was used to calculate this factor:

$$\phi_{\beta^+} = 0.0062\left(\beta^+\right)^2 - 0.131\beta^+ + 1.338 \tag{13}$$

The bias coefficient for resistance, ρ_R, and its associated COV, V_R, are:

$$\rho_R = \rho_M \rho_G \rho_P \tag{14}$$

$$V_R = \sqrt{V_M^2 + V_G^2 + V_P^2} \tag{15}$$

where ρ_M is the mean ratio of actual-to-nominal ultimate tensile strength for the weld metal, ρ_G is the mean ratio of actual-to-nominal values for the weld throat area, and ρ_P is the mean ratio of FE-to-predicted joint strength. V_M, V_G, and V_P are the associated COVs of ρ_M, ρ_G, and ρ_P, respectively.

In the current study, ρ_M and V_M account for actual filler metal strength being greater than the filler metal classification strength in most applications. The values of ρ_M and V_M shown in Table 3 were determined from 708 coupon tests on filler metal(s) by Lesik and Kennedy (1990), Callele et al. (2009), and others (as summarized in Tousignant and Packer, 2017b). The factors ρ_G and V_G account for the typical increase in weld throat area due to weld face convexity (i.e., via an increase in t_w). The values of ρ_G and V_G shown in Table 3 were justified by Callele et al. (2009) for similar fillet-welded connections. The factors ρ_P and V_P relate the FE rupture strength of the joint to the nominal weld strength predicted using one of the design model options discussed in detail in the following. The factor ρ_P was taken as the average over all of the 256 FE weld-critical, round HSS cross-connection tests of the FE fillet weld fracture load, P_a, divided by R_n, with R_n calculated using Equations 1 and 2 (i.e., including the sinθ factor) with actual values of t_w, l_w, and F_{EXX} (i.e., the values used in the FE models) as opposed to nominal values (Tousignant and Packer, 2018).

If the total weld length is assumed to be effective (i.e., $l_e = l_w$ in Equation 1), the mean FE-to-predicted strength ratio for the 256 fillet-welded joints, ρ_P, is 0.93 with a COV, V_p, of 0.19 (see Table 3). The correlation of the predicted capacity, R_n, to the FE fracture load, P_a, is shown in Figure 7. With $l_e = l_w$ and $\phi = 0.75$ (AISC, 2016), $\beta^+ = 2.8$, which is much less than the target reliability index of $\beta^+ \geq 4.0$. Thus, a weld effective length rule is necessary for round-to-round HSS cross-connections in the AISC *Specification* (AISC, 2016).

Option 1

In clause 9.6.1.3(4), AWS D1.1 (AWS, 2015) implies a weld effective length, l_e, in axially loaded round-to-round HSS connections equal to $1/1.5$ of the total weld length under factored loads; that is,

Table 3. Reliability Analysis Parameters and Results for the AISC *Specification*				
		Option 1	**Option 2**	**Option 3**
l_e	l_w	**Equation 16**	**Equation 17**	**Equation 17**
K_{CHS}	**Table 2**	**Table 2**	**Table 2**	**Equation 18**
ϕ	0.75	0.75	0.75	0.75
ρ_M V_M	1.12 0.12	1.12 0.12	1.12 0.12	1.12 0.12
ρ_G V_G	1.03 0.10	1.03 0.10	1.03 0.10	1.03 0.10
ρ_P V_P	0.93 0.19	1.40 0.19	1.07 0.06	1.08 0.06
ρ_R V_R	1.08 0.25	1.62 0.25	1.24 0.17	1.24 0.17
ϕ_{β^+}	1.02	0.87	0.90	0.89
β^+	**2.8**	**4.6**	**4.2**	**4.2**

$$l_e = \frac{1}{1.5} l_w \tag{16}$$

This rule has been derived from numerical work on round-to-round HSS T-connections (Caulkins, 1968) and is based on potential weld unzipping caused by one part of the weld being much more highly loaded than another (Marshall, 1992).

If the AWS D1.1, clause 9.6.1.3(4) (AWS, 2015), expression is used for l_e (i.e., $l_e = {}^1\!/_{1.5}\, l_w$) in Equation 1, the mean FE-to-predicted strength ratio for the 256 fillet-welded joints, ρ_P, is 1.40 with a COV of $V_p = 0.19$ (see Table 3). The correlation of predicted capacity, R_n, to the FE fracture load, P_a, is then as shown in Figure 8, providing a reliability index of $\beta^+ = 4.6 \geq 4.0$ when $\phi = 0.75$ is used (AISC, 2016).

This indicates that the AWS D1.1, clause 9.6.1.3(4) (AWS, 2015), expression for l_e shown in Equation 16 provides an acceptable level of safety; however, based on having ρ_P = 1.40, there is room to improve the l_e expression to increase the design efficiency (reduce the average ratio of P_a/R_n) of such joints. This is because Equation 16 was derived from the ratio of nominal-to-peak elastic strain in numerical tests (Calkins, 1968), and this has been shown to be conservative (Tousignant and Packer 2017b).

Option 2

Weld effective lengths in round-to-round HSS connections have also been shown to vary with D/t, β, and τ, though predominantly with D/t and β (Tousignant and Packer, 2018).

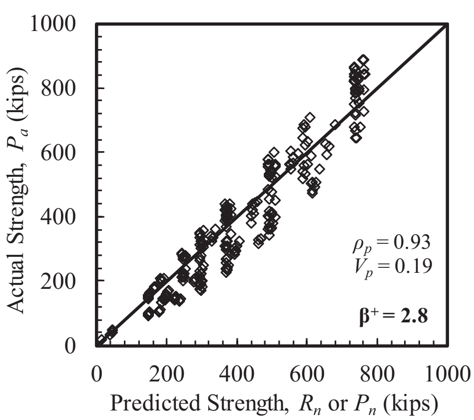


Fig. 7. Correlation of AISC Specification *provisions with FE results, assuming a weld effective length equal to the total weld length.*

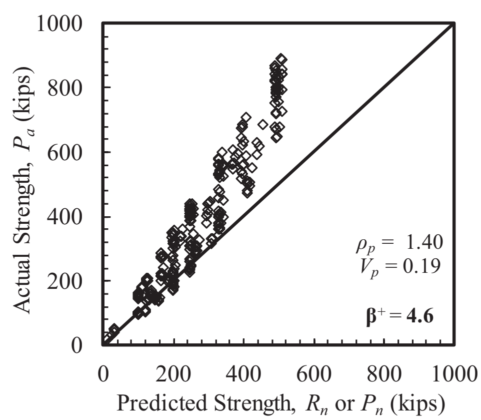


Fig. 8. Correlation of AISC Specification *provisions with FE results, assuming a weld effective length equal to ${}^1\!/_{1.5}$ of the total weld length (option 1).*

An accurate, yet simple, expression taking this into account is (Tousignant and Packer, 2018):

$$l_e = \frac{4}{\sqrt{2\beta(D/t)}} l_w \le l_w \tag{17}$$

If Equation 17 is used for l_e in Equation 1, the mean FE-to-predicted strength ratio for the 256 fillet-welded joints, ρ_P, is 1.07 with a COV of $V_p = 0.06$. The correlation of predicted capacity, R_n, to the FE fracture load, P_a, is then as shown in Figure 9.

Equation 17 provides $\beta^+ = 4.2 \ge 4.0$ when $\phi = 0.75$ is used (AISC, 2016), indicating that it also provides an acceptable level of safety. Notably, Equation 17 results in lower values of both ρ_P and V_p than the AWS D1.1, clause 9.6.1.3(4) (AWS, 2015), expression for l_e (Equation 16). It can therefore be concluded that Equation 17 results in greater efficiency of fillet welds in round-to-round HSS cross-, T-, and Y-connections than Equation 16 (i.e., it reduces the average ratio of P_a/R_n while still meeting the target reliability index). A side-by-side comparison of the reliability analysis parameters and results for these two options is given in Table 3.

Option 3

It may be argued that because the $(1.0 + 0.50 \sin^{1.5}\theta)$ factor already incorporates a simplification of a complex loading arrangement, a further simplification to option 2 is justified. Option 3 hence proposes that a designer take the loading angle [θ in the $(1.0 + 0.50 \sin^{1.5}\theta)$ factor] as equal to the branch inclination angle, to approximate the value of K_{CHS}; that is,

$$K_{CHS} = 1.0 + 0.5\sin^{1.5}\theta \tag{18}$$

where θ is the acute angle between the branch and chord (in degrees), as opposed to the angle between the line of action of the applied force and the weld longitudinal axis.

K_{CHS} will hence become a simple function of the branch inclination angle, θ, and can therefore be calculated without relying upon a design aid. This recommended approach ranges from being marginally unconservative (by less than 1%, for connections with high values of θ and high values of β) to marginally conservative (by about 3%, for connections with low values of θ and high values of β) within the range $0.1 \le \beta \le 0.5$ and $60° \le \theta \le 90°$.

If Equation 17 is used to calculate l_e in Equation 1, with K_{CHS} now approximated using Equation 18 (as opposed to using the values in Table 2), the mean FE-to-predicted strength ratio for the 256 fillet-welded joints, ρ_P, is 1.08 with a COV of $V_p = 0.06$, and the correlation of predicted capacity, R_n, to the FE fracture load, P_a, is as shown in Figure 10. Based on these results, which are summarized in Table 3, using Equation 18 to approximate K_{CHS} provides a similar (acceptable) level of safety to Option 2 [i.e., $\beta^+ = 4.2 \ge 4.0$ when $\phi = 0.75$ is used (AISC, 2016)].

CONCLUSIONS

Based on a review of recent experimental and numerical research performed on fillet-welded, round-to-round HSS cross-connections, in which FE results have been analyzed in conjunction with allowing the sinθ factor for fillet welds to the ends of round HSS in the AISC *Specification* (AISC, 2016), it has been found that:

- Application of the sinθ factor to fillet-welded round-to-round HSS joints is nontrivial, if the true angle of loading to the weld axis is considered as it varies around the joint.

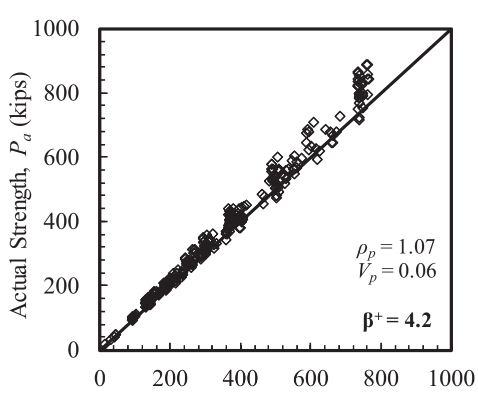


Fig. 9. Correlation of AISC Specification *provisions with FE results, assuming a weld effective length equal to Equation 17 (option 2).*

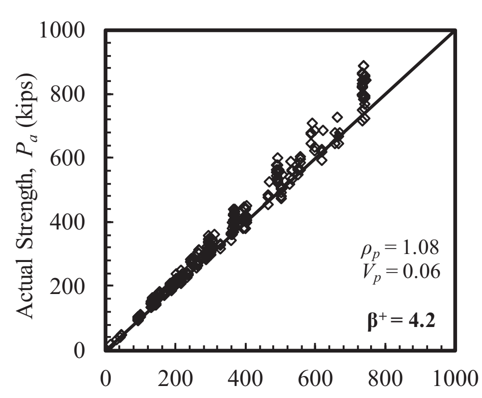


Fig. 10. Correlation of AISC Specification *provisions with FE results, assuming a weld effective length equal to Equation 17 and using Equation 18 to approximate* K_{CHS} *(option 3).*

A design aid as shown in Table 2 has been developed to simplify this procedure.

- Taking the total weld length as effective to design fillet welds in round-to-round HSS joints does not meet the target reliability index of $\beta^+ \geq 4.0$ (AISC *Specification* Commentary B3.1), when the sinθ factor is used to determine the available strength.
- The AWS D1.1, clause 9.6.1.3(4) (AWS, 2015), expression for the weld effective length in round-to-round HSS connections (i.e., $l_e = \frac{1}{1.5} l_w$) provides an acceptable level of safety ($\beta^+ = 4.6 \geq 4.0$) when the sinθ factor is used.
- Equation 17 for the weld effective length provides an acceptable level of safety ($\beta^+ = 4.2 \geq 4.0$) when the sinθ factor is used. This expression also provides lower values of actual-to-predicted nominal weld strength compared to the AWS D1.1, clause 9.6.1.3(4) (AWS, 2015) expression, allowing greater design efficiency to be achieved.
- Taking θ in the $(1.0 + 0.50 \sin^{1.5} \theta)$ factor as equal to the branch inclination angle (Equation 18), provides a similar (acceptable) level of safety ($\beta^+ = 4.2 \geq 4.0$) to the design aid (Table 2), when used in conjunction with Equation 17 to calculate the weld effective length.

RECOMMENDATION

It is recommended that the following design provisions be adopted for fillet welds in round-to-round HSS cross-, T-, and Y-connections:

$$R_n \text{ or } P_n = F_{nw} t_w l_e \tag{19}$$

where:

$$F_{nw} = 0.60 F_{EXX} K_{CHS} \tag{20}$$

where K_{CHS} is as shown in Table 2 for values of β and θ for a given joint, and

$$l_e = \frac{4}{\sqrt{2\beta(D/t)}} l_w \leq l_w \tag{21}$$

where l_w is determined from 3D solid models of intersecting cylinders or from the following simplified equation:

$$l_w = \pi D_b \frac{1 + 1/\sin\theta}{2} \tag{22}$$

The weld effective length given by Equation 21 is represented by two arcs of $l_e/2$ around the saddle regions, as illustrated in Figure 11.

Alternative Approach for Calculating K_{CHS}

As an alternative to using Table 2 to calculate K_{CHS} in Equation 20, it can instead be approximated with the following "modified sinθ factor":

$$K_{CHS} = 1.0 + 0.5 \sin^{1.5} \theta \tag{23}$$

where θ is the acute angle between the branch and chord (in degrees), rather than the angle between the line of action of the applied force and the weld longitudinal axis.

This recommendation is subject to the following limits of applicability:

Width ratio:	$0.1 \leq \beta \leq 0.5$
Branch angle:	$60° \leq \theta \leq 90°$
Chord wall slenderness:	$10 \leq D/t \leq 50$
Thickness ratio:	$0.20 \leq \tau \leq 1.00$
Weld throat:	t_w is constant around the joint

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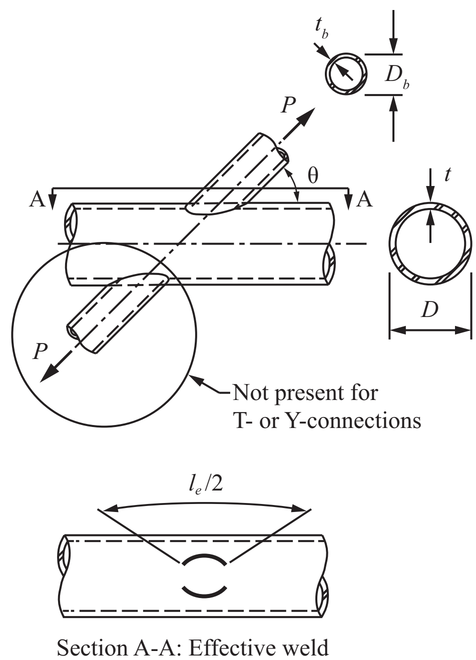

Fig. 11. Weld effective length for round-to-round HSS cross, T-, and Y-connections.

DESIGN EXAMPLE

Given:

A 60° cross-connection is formed between an HSS12.750×0.500 chord member and two HSS4.500×0.237 branch members in ASTM A500 Grade C material, as shown in Figure 12. The loads shown consist of 25% dead load and 75% live load. Determine a suitable fillet weld effective throat size around the branch members in this tubular connection, using matched electrodes with a specified ultimate strength of 70 ksi.

From the AISC *Manual* (AISC, 2017) Table 2-4, the material properties are as follows:

For all members
ASTM A500 Grade C
F_y, F_{yb} = 46 ksi
F_u, F_{ub} = 62 ksi

From the AISC *Manual* Table 1-13, the HSS geometric properties are as follows:

HSS12.750×0.500
D = 12.75 in.
t = 0.465 in.
A = 17.9 in.^{2}

HSS4.500×0.237
D_b = 4.50 in.
t_b = 0.220 in.
A_b = 2.96 in.^{2}

Solution:

Required strength (expressed as a force in the branch)

From ASCE/SEI 7 (ASCE, 2016) Chapter 2, the required strength is:

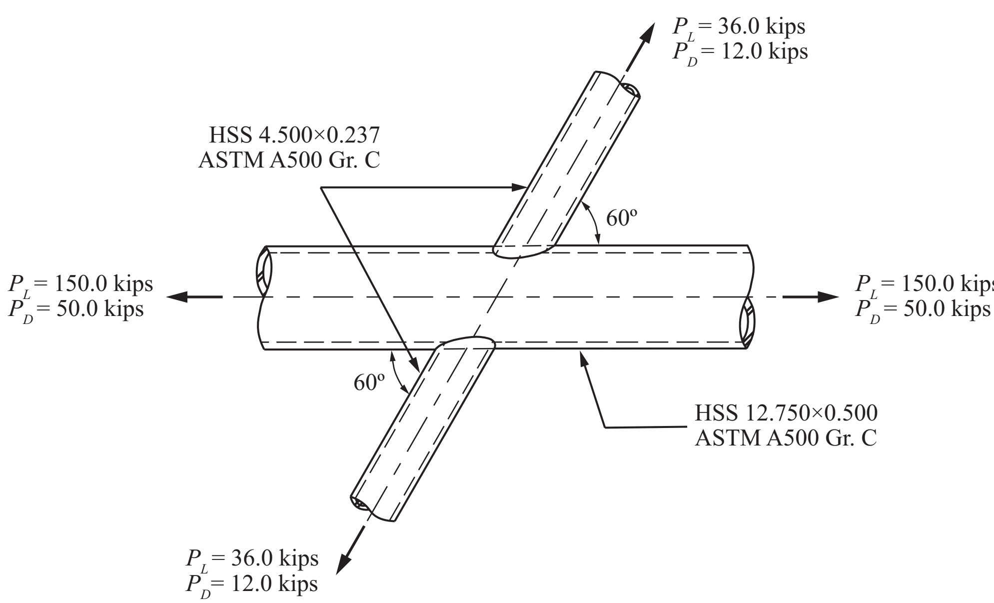

Fig. 12. Round-to-round HSS cross-connection subject to branch axial tension.

LRFD	ASD
$P_u = 1.2(12.0 \text{ kips}) + 1.6(36.0 \text{ kips})$ $= 72.0 \text{ kips}$	$P_a = 12.0 \text{ kips} + 36.0 \text{ kips}$ $= 48.0 \text{ kips}$

Note that this HSS connection satisfies the limits of applicability given by AISC *Specification* Table K3.1A (AISC, 2016); hence the connection strength can be determined from AISC *Specification* Table K3.1A for round HSS truss connections. Using AISC *Specification* Equations K3-1 and K3-3, the connection available axial strength (governed by the limit state of chord plastification) is P_n = 82.5 kips (LRFD) or P_n/Ω = 54.9 kips (ASD), which exceeds the required strengths and is therefore acceptable. It is worthwhile noting that the required strength of 72.0 kips (LRFD) is only 59% of the available branch axial yield strength = $\phi A_b F_{yb}$ = 122.5 kips.

Limits of applicability

A suitable fillet weld effective throat size around the branch members can be determined using Equations 19–21 only if the following limits of applicability are satisfied:

$0.1 \leq \beta = 0.353 \leq 0.5$ **o.k.**

$60° \leq \theta = 60° \leq 90°$ **o.k.**

$10 \leq D/t = 27.4 \leq 50$ **o.k.**

$0.20 \leq \tau = 0.473 \leq 1.00$ **o.k.**

t_w is constant around the joint **o.k.**

Because the limits of applicability are satisfied, Equations 19–21 can be used.

Required throat size

Determine the total weld length, l_w, using the approximation given by AWS D1.1, clause 9.5.4 (AWS, 2015):

$$\begin{aligned} l_w &= \pi D_b \frac{1 + 1/\sin\theta}{2} \\ &= \pi(4.500 \text{ in.}) \frac{1 + 1/\sin 60°}{2} \\ &= 15.2 \text{ in.} \end{aligned} \tag{22}$$

Calculate the weld effective length, l_e, using the previous results:

$$\begin{aligned} l_e &= \frac{4}{\sqrt{2\beta(D/t)}} l_w \leq l_w \\ &= \frac{4}{\sqrt{2(0.353)(27.4)}}(15.2 \text{ in.}) \leq 15.2 \text{ in.} \\ &= 13.8 \text{ in.} \leq 15.2 \text{ in.} \\ &= 13.8 \text{ in.} \end{aligned} \tag{21}$$

Account for the directional strength increase for fillet welds in round-to-round HSS connections using the factor K_{CHS}. For the connection considered, with β = 0.353 and θ = 60°, K_{CHS} can be found by linearly interpolating between β = 0.300 and β = 0.400 in Table 2 for θ = 60°.

For β = 0.300 and θ = 60°, K_{CHS} = 1.443, and for β = 0.400 and θ = 60°, K_{CHS} = 1.440. Hence, for β = 0.353 and θ = 60°:

$$\begin{aligned} K_{CHS} &= 1.440 + \frac{0.400 - 0.353}{0.400 - 0.300}(1.443 - 1.440) \\ &= 1.441 \end{aligned}$$

Alternatively, K_{CHS} can be approximated using Equation 23, as follows:

$$K_{CHS} = 1.0 + 0.5\sin^{1.5}\theta \tag{23}$$
$$= 1.0 + 0.50\sin^{1.5}(60°)$$
$$= 1.403$$

The remainder of the design example is completed using $K_{CHS} = 1.441$.

The nominal stress of the weld metal, F_{nw}, can now be determined using Equation 20:

$$F_{nw} = 0.60F_{EXX}K_{CHS} \tag{20}$$
$$= 0.60(70 \text{ ksi})(1.441)$$
$$= 60.5 \text{ ksi}$$

Applying the resistance factor of $\phi = 0.75$ to fillet welds designed using the LRFD method, or the safety factor of $\Omega = 2.00$ to fillet welds designed using the ASD method, an expression for the available weld strength, ϕP_n or P_n/Ω, can be written (AISC, 2016).

LRFD	ASD
$\phi P_n = 0.75F_{nw}t_w l_e$	$\dfrac{P_n}{\Omega} \geq \dfrac{F_{nw}t_w l_e}{2.00}$

Set the expression for the available weld strength equal to (or greater than) the required strength to determine the required weld throat size, t_w, to transmit the calculated forces.

LRFD	ASD
$0.75F_{nw}t_w l_e \geq P_u$ $t_w \geq \dfrac{P_u}{0.75F_{nw}l_e}$ $t_w \geq \dfrac{72.0 \text{ kips}}{0.75(60.5 \text{ ksi})(13.8 \text{ in.})}$ $t_w \geq 0.115 \text{ in.}$	$\dfrac{F_{nw}t_w l_e}{2.00} \geq P_a$ $t_w \geq \dfrac{2.00P_a}{F_{nw}l_e}$ $t_w \geq \dfrac{2.00(48.0 \text{ kips})}{(60.5 \text{ ksi})(13.8 \text{ in.})}$ $t_w \geq 0.115 \text{ in.}$

Rounding up to the nearest sixteenth of an inch, $t_w = 0.125$ in. would satisfy the strength requirements of this connection.

It should be noted that the limitations of AISC *Specification* Section J2.2b also apply, and the weld leg size, L, must not be less than the size given in AISC *Specification* Table J2.4. Therefore, for $t_b = 0.220$ in., corresponding to the material thickness of the thinner part joined, L must be greater than or equal to 0.125 in. Because L will never be less than t_w (= 0.125 in.) for a fillet weld, this requirement is satisfied.

Hence, $t_w = 0.125$ in., or ⅛ in., is a suitable fillet weld throat size.

SYMBOLS AND ACRONYMS

A Cross-sectional area of round HSS chord member, in.^{2}

A_b Cross-sectional area of round HSS branch member, in.^{2}

AISC American Institute of Steel Construction

AWS American Welding Society

COV Coefficient of variation

D Outside diameter of round HSS chord member, in.

D_b Outside diameter of round HSS branch member, in.

F_{EXX} Filler metal classification strength, ksi

F_{nw} Nominal stress of weld metal, ksi

F_u Specified minimum tensile strength of round HSS chord member, ksi

F_{ub} Specified minimum tensile strength of round HSS branch member, ksi

F_y Specified minimum yield stress of round HSS chord member, ksi

F_{yb} Specified minimum yield stress of round HSS branch member, ksi

K_a Weld length factor according to AWS D1.1 (AWS, 2015)

K_{CHS} Value of $(1.0 + 0.50 \sin^{1.5} \theta)$ for a round-to-round HSS joint

L Weld leg size, in.

LRFD Load and resistance factor design

P Axial force, kips

P_D Axial force due to dead load, kips

P_L Axial force due to live load, kips

P_a Actual weld fracture load, kips; required axial strength in tension or compression, using ASD load combinations, kips

P_n Nominal axial strength, kips

P_u Required axial strength in tension or compression, using LRFD load combinations, kips

$\overline{P}$ Vector defining the direction of the applied force

R_n Nominal strength, kips

V_G Coefficient of variation of ρ_G

V_M Coefficient of variation of ρM

V_P Coefficient of variation of ρP

V_R Coefficient of variation of ρR

$\overline{V}$ Vector approximation to the weld longitudinal axis between points at x and $x+\Delta x$

l_e Weld effective length, in.

$l_{t,x}$ "Template length" at x, parallel to branch, in.

$l_{t,x}+\Delta x$ "Template length" at $x + \Delta x$, parallel to branch, in.

l_i Length of weld element i, in.

l_w Total length of weld, in.

r Outside radius of round HSS chord member, in.

r_b Outside radius of round HSS branch member, in.

t Wall thickness of round HSS chord member, in.

t_b Wall thickness of round HSS branch member, in.

t_w Weld effective throat, in.

x Subtended angle around the branch, measured clockwise from the heel, degrees

α Coefficient of separation, taken as 0.55

β Width ratio; the ratio of branch diameter to chord diameter for round HSS

β^+ Reliability index

Ω Safety factor

ϕ Resistance factor

ϕ_{β^+} Adjustment factor for ϕ

τ Branch-to-chord thickness ratio

θ Acute angle between the branch and chord, degrees; angle between the line of action of the applied force and the weld longitudinal axis, degrees

θ_i Angle between the line of action of the applied force and the weld longitudinal axis for weld element i, degrees

ρ_G Mean ratio of actual-to-nominal values for the weld throat area

ρ_M Mean ratio of actual-to-nominal ultimate tensile strength for the weld metal

ρ_P Mean ratio of FE-to-predicted joint strength

ρ_R Bias coefficient for resistance

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