DESIGN OF SINGLE-SIDED FILLET WELDS UNDER TRANSVERSE LOAD

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ABSTRACT

In North American steel design specifications, a directional strength-enhancement factor is used to increase the predicted strength of fillet welds subjected to transverse loading (i.e., loading at 90° to the weld axis). Committees have expressed concerns about this factor being unsafe for single-sided fillet welds; however, due to a lack of testing, only cautionary statements have been made in most specifications to address this. An experimental program was hence developed to test 40 transversely loaded single-sided fillet welds in cruciform connections subjected to branch axial tension. The connections varied weld size, branch-plate thickness, and loading eccentricity, to investigate the effects of these parameters on fillet-weld strength. Results of this program are presented herein, and a first-order reliability method (FORM) analysis is performed. It is shown that current fillet-weld design provisions meet/exceed code-specified target safety indices (i.e., β = 4.0) provided that (i) the directional strength-enhancement factor is not used and (ii) stresses that result in opening of the weld root notch are avoided.

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INTRODUCTION

In North America, fillet welds connecting structural elements can be designed using a directional strength-increase factor ($1.00+0.50\sin^{1.5}\theta$) that permits engineers to take advantage of a 50% "strength increase" when load is applied perpendicular (i.e. at $\theta = 90°$) to the weld axis. This factor is included in CSA S16:19 Clause 13.13.2.2 (CSA 2019a), AISC 360-16 Section J2.4b (AISC 2016), and AWS D1.1:20 Clause 2.6.4.2 (AWS 2020).

The directional strength-increase (or "sinθ") factor is based on testing of lapped splice and cruciform connections with fillet welds on *both sides* of a plate loaded in tension, as shown in Figs. 1a,b (Butler & Kulak 1971; Kato & Morita 1974; Miazga & Kennedy 1989; Lesik & Kennedy 1990; Ng et al. 2004a,b; Deng et al. 2006; Kanvinde et al. 2009). Recently, however, CSA S16 and AISC 360 code committees have expressed concerns about the applicability of this sinθ factor to single-sided fillet welds (i.e. welds made on *one side* of a structural element) (Fig. 1c).

Unlike their two-sided counterparts (Figs. 1a,b), single-sided fillet welds are inherently subjected to eccentric loading and, thus, prone to local bending and rotation about the weld toe (see Fig. 1c). When this occurs, it can subject the weld to additional stress at its root and reduce its capacity (AWS 2020; CEN 2005). Until recently, only cautionary statements addressing this issue could be found in steel design specifications, e.g.:

- AISC 360-16 (AISC 2016): Commentary to Section J2b: "The use of single-sided fillet welds in joints subject to rotation around the toe of the weld is discouraged";
- CSA W59-18 (CSA 2018a) Clause 4.1.3.3.2: **"**Single fillet and single partial joint penetration groove welds shall not be subjected to bending about the longitudinal axis of the weld if it produces tension at the root of the weld"; and
- EN 1993-1-8 (CEN 2005) Clause 4.12: "local eccentricity should be taken into account where a tensile force transmitted perpendicular to the longitudinal axis of the weld produces a bending moment, resulting in a tension force at the root of the weld".

Experiments and numerical (finite element) analysis on single-sided fillet welds around the ends of hollow structural sections (HSS) have recently confirmed that bending about the weld axis can occur when the HSS (i.e. the connected element) is in tension (Packer et al. 2016; Tousignant & Packer 2017). It has also been shown that such welds, to rectangular HSS, do not develop the 50% strength increase at failure predicted by the sinθ factor (Tousignant & Packer 2017).

Based primarily on this evidence, the CSA S16 code committee opted to exclude/prohibit the sinθ factor in CSA S16:19 (CSA 2019a) for the design of all single-sided fillet welds to elements in tension. With a different interpretation of the results, the most recent public review version of AISC 360 excludes the sinθ factor for the design of fillet welds only to tension loaded rectangular HSS walls (AISC 2021; Tousignant & Packer 2019). While both these restrictions are rational, and in the interest of safety, major questions still exist about the “single-sided weld effect”, including: the effect of fillet-weld size, connected element thickness, and restraint against rotation at the weld root [which depends on the connected element shape (linear vs. curved), and the eccentricity direction (tension vs. compression at the weld root)] on weld strength.

This paper presents a study to: (1) determine the effects of key connection parameters on the strength of single-sided fillet welds; (2) compare the strength of such welds to those made on both sides of the same structural element (e.g. Figs 1a,b) and welds to HSS; (3) determine the inherent reliability (safety index) of current code equations for the design of single-sided fillet welds (with and without use of the sinθ factor); and (4) provide economical, yet safe, recommendations for their design in conjunction with CSA S16 and AISC 360 (i.e., recommendations calibrated to currently expected safety index levels).

BACKGROUND

Transverse Fillet Welds

Since the 1930s, extensive theoretical and experimental studies have been carried out to investigate the effect of loading angle (θ, in Fig. 2) on the strength and ductility of fillet welds.

Butler & Kulak (1971) tested 23 fillet-welded lap joints with a weld size of 6.4 mm and with $\theta = 0°$, 30°, 60°, and 90°, the results of which indicated that the so-called directional strength-increase factor (DSIF) [i.e., the ratio of the strength of transverse fillet welds ($\theta = 90°$) to longitudinal fillet welds ($\theta = 0°$)] equaled 1.44. A later study, by Kato & Morita (1974), using a theoretical model for fillet weld strength, found the DSIF to be 1.46. Kamtekar (1982, 1987) developed a simple formula that took both the weld geometry and ultimate strength of the weld metal into consideration to determine fillet weld strength for a given θ. The proposed formula was validated against experimental results reported by Butler & Kulak (1971), and the corresponding DSIF was found to be 1.41.

Miazga & Kennedy (1989) tested an additional 42 fillet-welded lap joints with a leg size of 5 or 9 mm. The specimens were tested with θ varying in 15° increments from 0° to 90°. Miazga & Kennedy's results showed that values of the DSIF for 5- and 9-mm transverse fillet welds were 1.36 and 1.63, respectively, indicating a "size effect". Based on a maximum shear stress failure criterion, Miazga & Kennedy (1989) proposed an analytical model to predict fillet weld strength as a function of θ. For transverse fillet welds, the implied DSIF was 1.5, which gave birth to the "modern" DSIF value assumed in North America for transverse fillet welds (i.e., 1.5). Miazga & Kennedy's (1989) model was extended by Lesik & Kennedy (1990) to produce the $\sin\theta$ factor; i.e.:

$$\mathrm{DSIF} = 1.00 + 0.50\sin^{1.5}\theta \tag{1}$$

Eq. (1) was developed for fillet welds in lap-splice connections welded on both sides, tested in tension, and made using the shielded metal arc welding (SMAW) process; however, Ng et al. (2002), and Li et al. (2007) later demonstrated its applicability to fillet welds in both lap-splice and cruciform connections (Fig. 1a,b) made using the flux-cored arc welding (FCAW) process. Kanvinde et al. (2009) evaluated the applicability of Eq. (1) to fillet welds in cruciform connections with large, transverse root notches, and found it to be suitable.

As a result, the fact that the strength (and ductility) of a fillet weld are affected by loading angle is widely recognized; i.e., in CSA (2019a), AISC (2016), CEN (2005), and AIJ (2012), engineers can generally take advantage of a "strength increase" when design loads are perpendicular (i.e. at $\theta = 90°$) to the weld axis. On the other hand, the strength and behaviour of single-sided welds (i.e., welds to only one side of a structural element) is much less established, and research done to-date has principally focussed on welds in HSS connections (which are invariably single-sided).

Single-Sided Fillet Welds

In the early 2000s, Chen et al. (2001) carried out an experimental program on the performance of single-sided fillet welds in "H-shape" steel members, testing two types of specimens: shear specimens (i.e., with $\theta = 0°$) (26 specimens), and tension specimens (i.e., with $\theta = 90°$) (20 specimens). Chen et al. (2001) found that the tension specimens exhibited reduced strength due to the eccentricity of the applied load with respect to the weld in the joint.

More than a decade later, Packer et al. (2016) reported the results of 33 tests on weld-critical HSS-to-rigid end-plate connections, with fillet weld throat dimensions (t_w) ranging from 3 mm to 11 mm. The aforementioned test database was then expanded, by Tousignant & Packer 2017, through the addition of 73 numerical (FE) results with t_w ranging from 0.45 to 1.41 times the branch (herein, "connected element") thickness (t_b). The studies by Packer et al. (2016) and Tousignant & Packer (2017) found that if the $\sin\theta$ factor [Eq. (1)] was used, the CSA S16 and AISC 360 fillet weld design provisions did not achieve the expected target safety (reliability) index of $\beta \geq 4.0$ at failure.

In the study by Tousignant & Packer (2017), the "single-sided weld effect" (i.e., the reduction in strength relative to two-sided welds) was shown to be more severe for fillet welds to square and rectangular HSS than fillet welds to round HSS, as well as for specimens with higher ratios of t_w/t_b. This was taken as an indication that the restraint provided to the weld(s) depends on both connected element shape (linear vs. curved) and thickness (t_b). Weld shrinkage and element boundary conditions are two additional factors that may contribute to the strength and behaviour of single-sided fillet weld joints.

In a later European study, Tuominen et al. (2018) examined the effect of applied bending moments (due to eccentricity) on the capacity of single-sided fillet welds in plate-to-box section connections. While the moment generated by the loading eccentricity in the connections studied was originally believed to decrease the stress at the weld root, Tuominen et al. (2018) found that, in some cases, tensile stresses on the root side of the weld due to bending plus tension created a critical/inhibiting combination of stresses. Tuominen et al. (2018) derived a "simplified" expression for the resistance of a single-sided fillet weld subjected to an eccentric load based on the provisions of EN 1993-1-8 (CEN 2005); however, in its given form, it cannot be used for design. Other practical examples of single-sided fillet welds (which have not yet been the topic of extensive research) include restrained lap joints and unstiffened seated connections (Figs. C-J2.3 and 10-7, respectively, of the AISC *Manual*) (AISC 2016).

North American Code Provisions

The following section discusses North American specification design provisions for fillet welds in joints made with matched electrodes.

CSA S16:19

In Clause 13.13.2.2 of CSA S16:19 (CSA 2019a), the factored resistance for the direct shear and tension- or compression-induced shear (V_r) of a fillet weld is taken as:

$$V_r = 0.67\phi_w A_w X_u \tag{2}$$

where ϕ_w = weld metal resistance factor (= 0.67); A_w = effective throat area of weld; and X_u = strength of matching electrode.

For cases other than single-sided fillet welds connected to an element in tension, the above resistance can be multiplied by the sinθ factor; i.e.:

$$(1.00 + 0.50\sin^{1.5}\theta) \tag{3}$$

For fillet weld groups concentrically loaded and consisting of welding segments in different orientations (i.e., multi-orientation fillet weld, or MOFW, joints), the strength of each weld segment is then multiplied by the reduction factor, M_w, given as: 1.0 for the weld segment with the largest θ; and 0.85 for the other weld segments.

As discussed in the Introduction, these CSA S16:19 (CSA 2019a) provisions incorporate revisions for single-sided fillet welds.

CSA S16-14

Prior to CSA S16:19, CSA S16-14 (CSA 2014) gave the factored resistance of fillet welds (V_r) as:

$$V_r = 0.67\phi_w A_w X_u (1.00 + 0.50\sin^{1.5}\theta) M_w \tag{4}$$

where, for single-orientation fillet weld (SOFW) joints, $M_w = 1.0$, and for MOFW joints, for each segment:

$$M_w = \frac{0.85 + \theta_1/600}{0.85 + \theta_2/600} \tag{5}$$

where θ_1 = orientation of the weld segment under consideration; and θ_2 = orientation of the weld segment in the joint that is closest to 90˚. Unlike in CSA S16:19 (CSA 2019a), CSA S16-14 (CSA 2014) made no distinctions for single-sided fillet welds.

AISC 360-16

In Section J of AISC 360, a similar approach to CSA S16:19 is taken for the design of fillet welds, i.e., the nominal weld strength (R_n) [and, hence, the factored resistance ($V_r = \phi R_n = 0.75R_n$, where ϕ = resistance factor)] is taken as:

$$R_n = F_{nw} A_w \tag{6}$$

where F_{nw} = nominal stress of the weld metal. In the above expression [Eq. (6)]:

$$F_{nw} = 0.60 F_{EXX} \tag{7}$$

where F_{EXX} = ultimate strength of weld metal (= X_u, in CSA S16).

For a linear weld group with a uniform leg size, loaded through the center of gravity (i.e., where all welds in the weld group are parallel and have the same deformation capacity), the provisions of Section J2.4(b) allow for use of the sinθ factor [Eq. (3)]. In that case:

$$F_{nw} = 0.60 F_{EXX} (1.0 + 0.50\sin^{1.5}\theta) \tag{8}$$

For MOFW joints, Eq. (6) is modified to:

$$R_n = 0.85R_{nl} + 1.5R_{nt} \tag{9}$$

where R_{nl} = total nominal strength of the longitudinal fillet welds; and R_{nt} = total nominal strength of the transverse fillet welds without the "sinθ" factor. This is akin to the approach now given in CSA S16:19 (via the M_w factor) to account for differences in deformation capacity between weld types.

European Code Provisions in EN 1993-1-8

Directional Method

In Europe, the EN 1993-1-8 Directional Method breaks up the resultant design force transmitted by a unit length of weld into components parallel and perpendicular to the longitudinal axis of the weld and normal and transverse to the plane of the weld throat. The following inequalities must then be met in order for the strength of the weld to be considered adequate:

$$\left[\sigma_{\perp}^2 + 3\left(\tau_{\perp}^2 + \tau_{\parallel}^2\right)\right]^{0.5} \le F_u / \left(\beta_w \gamma_{M2}\right) \tag{10a}$$

$$\text{and } \sigma_{\perp} \le 0.9F_u / \gamma_{M2} \tag{10b}$$

where $\sigma_{\perp}$ = normal stress perpendicular to the throat; $\tau_{\perp}$ = shear stress (in plane of throat) perpendicular to the longitudinal axis of the weld; $\tau_{\parallel}$ = shear stress (in plane of throat) parallel to the longitudinal axis of the weld; γ_{M2} = partial safety factor for the resistance of the weld (= 1.25); F_u = base metal ultimate strength (of the weaker part joined); and β_w = correlation factor for fillet welds. The three stress components used in the Directional Method ($\sigma_{\perp}$, $\tau_{\perp}$, and $\tau_{\parallel}$), as well as $\sigma_{\parallel}$, are shown in Fig. 3 for a fillet-welded connection with a local dihedral angle (i.e., angle between the base metal fusion faces) (Ψ) of 90˚.

It can be seen in Fig. 3 that the applied load (P), which causes stress on the weld throat, is assumed to act concentrically, at the centre of the weld, and at an incline angle, λ, from the horizontal weld leg, l_h. For general cases of Ψ of λ, Packer et al. (2016) showed that Eqs. (11a-c) can be used to calculate the stress components on a fillet weld at the assumed failure load, $P = V_r$:

$$\tau_{\parallel} = \frac{V_r \cos\theta}{t_w l_w} \tag{11a}$$

$$\sigma_{\perp} = \frac{V_r \sin\theta \cos\lambda}{t_w l_w} \tag{11b}$$

$$\tau_{\perp} = \frac{V_r \sin\theta \sin\lambda}{t_w l_w} \tag{11c}$$

When these equations [Eqs. (11a-c)] are substituted into Eq. (10a), the following expression can be derived for V_r according to EN 1993-1-8 (CEN 2005):

$$V_r = \frac{F_u}{\beta_w \gamma_{M2}} \frac{t_w l_w}{\left[\sin^2\theta \cos^2\lambda + 3\left(\sin^2\theta \sin^2\lambda + \cos^2\theta\right)\right]^{0.5}} \tag{12}$$

In the case of 90° unequal-legged fillet welds (i.e., $\Psi = 90°$ and $\lambda \neq 45°$), such as those used in this research, the weld throat thickness (t_w) in Eq. (12), and elsewhere, can be calculated from measured leg sizes; i.e.:

$$t_w = \frac{l_v l_h}{\sqrt{l_v^2 + l_h^2}} \tag{13}$$

where l_v = vertical weld leg (measured along the shear face); and l_h = horizontal weld leg (measured along the tension face), defined previously (Fig. 3).

The incline angle, λ, can also be determined from the leg sizes; i.e.:

$$\lambda = \tan^{-1}\left(\frac{l_h}{l_v}\right) \tag{14}$$

For $\Psi = 90°$ equal-legged fillet welds, a DSIF of 1.22 is inherent in the EN 1993-1-8 Directional Method (CEN 2005).

Simplified Method

The EN 1993-1-8 Simplified Method assumes that fillet weld strength is independent of the orientation of the weld throat plane with respect to the design force (i.e., independent of the angle θ). Welds are hence assumed to be loaded in pure shear (i.e., $\theta = 0°$), regardless of the actual loading angle, and can be proportioned according to the following expression:

$$V_r = \left(\frac{F_u}{\sqrt{3}\beta_w \gamma_{M2}} \right) t_w l_w \tag{15}$$

The Simplified Method is a conservative alternative to the Directional Method. Yet, even so, major questions exist regarding its applicability to single-sided fillet welds.

EXPERIMENTAL PROGRAM

Scope

An experimental program was hence developed at Dalhousie University to examine the parameters that affect the capacity of single-sided fillet welds subjected to transverse load. The purpose of this program was to: (i) determine the effect of eccentricity (magnitude/direction), weld size, and connected element thickness on weld strength, (ii) address (i.e. validate or modify) recent restrictions on the DSIF [i.e., ($1.00+0.50\sin^{1.5}\theta$)] in modern North American steel codes [i.e., AISC 360-16 (2016) and CSA S16:19 (2019a)], and (iii) provide recommendations for the design of single-sided fillet welds in both North America and Europe.

Specimen Description

A total of 40 weld-critical eccentrically tension loaded cruciform connection (ETLCC) test specimens was designed and fabricated with variations in fillet weld size [$1.8 \text{ mm} \leq t_w \leq 10.9 \text{ mm}$ (or $2.5 \text{ mm} \leq l_v$ or $l_h \leq 15.4 \text{ mm}$)], connected element (branch-plate) thickness ($6.4 \text{ mm} \leq t_b \leq 19.6 \text{ mm}$), and branch-plate offset (center-to-center distance of the branch plates) ($-31.6 \text{ mm} \leq S \leq 30.5 \text{ mm}$). The parameter ranges given in parentheses represent the measured (as opposed to nominal) properties.

As shown in Fig. 4, each specimen was comprised of two 305-mm long vertical steel branch-plates welded to a “rigid”, 19.1-mm thick horizontal plate with a nominal width of 75 mm (Figs. 4a,b), and the 40 specimens were saw cut (3 each) from a total of 14 fabricated connections. The top, vertical branch-plate in each specimen (Fig. 4b) was connected to the horizontal plate through a single-sided fillet weld that was designed to be “critical” (i.e., to fail). The bottom, vertical branch-plate was connected through two, larger fillet welds, one on each side, that were designed to remain intact during the testing.

All specimens were fabricated from plate material conforming to CSA G40.21 Grade 350W (CSA 2018b) and welded using a matching flux-cored (E491T) electrode wire from a single heat. The specimen geometric properties are summarized in Table 1, in which designations (Column 1) are based on the nominal dimensions t_b, t_w, and S (Fig. 4b) in that order [i.e., S6-S-30a denotes a specimen with: t_b = 6.4 mm, a “small” weld throat, and S = 30 mm. The character “a” at the end of the designation denotes that the offset S causes compression at the weld root. Offsets causing tension at the weld root are denoted by the character ‘b’.].

Material Properties

To determine the base metal material properties, tensile test coupons (TCs) were cut from the branch- and horizontal-plate material(s) and tested in accordance with ASTM A370 (ASTM 2020). The average measured yield strength (F_y, determined by the 0.2% strain offset method) and ultimate strength (F_u) of each plate are listed in Table 2. For the as-laid welds, all-weld-metal TCs were made at the time of fabrication and, later, tested in accordance with AWS D1.1 (AWS 2020). The average material properties of the weld metal (F_y and X_u), based on three coupon tests [(i), (ii), and (iii)], are summarized in Table 3. Additional parameters obtained from the TC tests (i.e., ε_y = yield strain; ε_f = rupture strain; and E = Young’s modulus) are also provided.

Geometric Properties

Post-testing geometric properties of the plates and as-laid welds were carefully measured by cross-sectioning, macro-etching and digitizing the broken weldments at five locations along their length (5 × 40

= 200 cross sections in total), polishing and macro-etching the cross-sections, and scaling off the digital weld profiles in AutoCAD. An example of the AutoCAD output, showing l_v and l_h based on the smallest triangle that could be inscribed into the weld, t_w based on the calculated throat dimension, CTD, as defined in the footnote 3 to Table 1, and λ calculated from l_v and l_h using Eq. (14), is shown in Fig. 5. In addition to CTD, the minimum throat dimension (MTD), defined in footnote 2 to Table 1, was determined. These dimensions, along with the externally measured weld length (l_w), are summarized in Table 1, where the CTD and MTD dimensions are in good agreement.

Testing Procedure and Instrumentaiton

The ETLCC specimens were tested in the Heavy Structures Laboratory, at Dalhousie University using a 2-MN Instron Universal Testing Machine. During testing, tension load on the branch-plate(s), and strain adjacent to the single-sided fillet weld (on both sides of branch-plate) were measured. A digital image correlation (DIC) technique was also used in conjunction with the strain gauges to verify/measure: (i) uniformity of loading (along the weld length), and (ii) any bending that occurred in the branch plate(s).

Strain gauges adjacent to the weld (3 per side) were evenly spaced, beginning 10-mm from the edges of the vertical plate (to avoid edge effects) and 15 mm from the toe of the test weld associated with l_v (see Fig. 3) to avoid detecting high-strain regions associated with the notch effect (Cassidy 1993). DIC paint was applied along one face of the specimen through the thickness of each plate (Fig. 6).

RESULTS

All 40 ETLCC specimens were tested to failure by weld rupture along a plane through the fillet weld throat. Strain gauges 1-6, adjacent to the weld (Figs. 6 and 7), showed that the welds were uniformly loaded along their length, and confirmed the direction(s) of the single-sided weld effect [i.e., the effect of bending due to +/- S on the weld root stress, as indicated by the symbols “a” and “b” in Table 1].Further analysis of the strain-gage data from the tests was attempted but did not yield a clear result for the magnitude of the moment transferred through the test weld(s) at rupture. This can be attributed to the complex interaction of primary and secondary bending effects near the welds.

For use in the following section, Fig. 8a,b compares the actual strengths (P_a) of the single-sided test welds with the predicted nominal strengths (R_n) according to CSA S16-14 (CSA 2014) and CSA S16:19 (CSA 2019a) [i.e., Eqs. (4) and (2), respectively, with $\phi = 1.0$]. Similarly, Fig. 9a,b compares P_a of the test welds with R_n per AISC 360-16 [i.e., Eq. (6)], both with and without the sinθ factor. Fig. 10a,b presents the results for the EN 1993-1-8 (CEN 2005) Directional and Simplified Methods using Eqs. (12) and (15), respectively, with $\beta_w = 0.9$ and $\gamma_{M2} = 1.0$. The actual strengths, predicted strengths, and load ratios (P_a/R_n) for the 40 test welds are summarized in Table 4.

It is important to note that predicted nominal strengths (R_n) values in Figs. 8-10 were calculated by using measured values of t_w (MTD) and l_w (Table 1), X_u (or F_{EXX}) = 561 MPa, and F_u of the weaker part joined (Table 2) for EN 1993-1-8. In Figs. 8-10, tests are grouped by nominal offset (S) to aid in the following discussion.

Effect of Weld Size

Fig. 11a compares the average weld stress at failure (P_a/A_w) of the single-sided welds to the weld throat size (t_w). Shown therein, as t_w increases, P_a/A_w generally decreases in ‘a’-series specimens (with compression due to bending at the root, causing closing of the so-called root notch) and increases in ‘b’-series specimens (with tension due to bending at the root, causing opening of the notch). Based on Fig. 11a, one could argue that this is attributed to the change in eccentricity (S+e) between the centroid of the single-sided fillet weld and the centroid of the double-sided weld (on the opposite side of the connection) associated with t_w. (This is confirmed in following sub-sections). For reference, R_n according to CSA S16:19 and AISC 360-16 without the sinθ factor are shown as horizontal lines in Fig. 11a-d. In Fig. 11a-d, and all subsequent comparisons, it is evident that the ‘b’-series specimens have significantly lower strength than the ‘a’-series specimens.

Effect of Plate Thickness

Fig. 11b shows a similar trend for P_a/A_w versus t_b to that described for P_a/A_w versus t_w; i.e., as t_b increases, P_a/A_w decreases in 'a'-series specimens and increases in 'b'-series specimens. Less rotation of the connection about the weld axis was also observed as t_b increased, regardless of weld size and offset. Fig. 12 shows two contour plots of y-axis strain (ε_{yy}) from DIC just prior to failure for specimens S6-L-30a, S6-L-30b, S20-S-30a & S20-S-30b. These plots were generated using DIC software. (Note that specimens S6-L-30a and S20-S-30a have the same nominal branch plate offset, *S*, but different values of t_b = 6.5 mm and 19.5 mm, respectively). It can be seen in Fig. 12 that, for the thicker specimens (S20-S-30a & S20-S-30b), ε_{yy} is greatly reduced in the branch plate adjacent to the weld, resulting in less rotation of the specimen about the weld toe. When observing the behaviour of the so-called "root notch": for the 'a'-series specimens, the root notch closes, and for the 'b'-series specimens, the root notch opens.

Effect of Eccentricity (Magnitude/Direction)

Total eccentricity magnitude/direction (S+e, where e = distance between the centre of the single-sided weld throat and the centre of the connected branch) was found to have the most significant effect on fillet weld strength. As shown in Fig. 11c, there is clear, negative correlation between P_a/A_w and S+e when S+e is between -15mm and 40mm. When S+e is less than -15mm, there is seemingly a positive correlation (and/or a marked increase in variance). Moreover, it is again clear that 'b'-series specimens, with tension due to bending at the root (causing opening of the notch) (i.e. 0b, 15b and 30b), show significantly lower strengths than 'a'-series specimens, with compression due to bending at the root (causing closing of the notch) (i.e. 15a and 30a). It is also worth noting that, as S+e decreases (causing further compression due to bending at the weld root), weld strength increases, but only up to a point (approx. when S+e = 15 mm). At that point, weld strength appears to remain relatively constant (see Fig. 11c). This may be due to the criticality of the stress combination or, simply, experimental scatter which is to be expected in tests on welds.

Effect of Weld Size-to-Branch Plate Thickness Ratio

Fig. 11d shows that the weld size-to-branch plate thickness ratio (t_w/t_b) bares some significance with respect to fillet weld strength (particularly for 0b connections), but it is less influential than total eccentricity $S+e$. This agrees with findings by Tousignant & Packer (2017), who related the strength of welds in HSS connections to the ratio t_w/t_b (see Single-Sided Fillet Welds). In those connections, the alignment condition was similar to that of the 0b connections in this study (i.e. $S = 0$).

The remainder of this paper aims to develop economical, yet safe, recommendations for the design of single-sided fillet welds in conjunction with current codes (i.e., CSA S16, AISC 360 and Eurocode) and, hence, using the existing/prescribed design models covered previously in this paper.

RELIABILITY ANALYSIS

While, historically, a so-called "separation factor" approach has been used to calibrate resistance factors (ϕ_w or ϕ) based on target reliability indices (β) (or vice-versa) independent of the load effects on an element (Lind 1971; Galambos & Ravindra 1978; Kennedy & Gad Aly 1980), it is an increasingly common practice to now consider both the resistance and load effects to calculate ϕ (CSA 2011). Taking this into consideration, an approximate first-order reliability method (FORM) analysis was performed to determine inherent β-values for existing fillet weld criteria.

Herein, the so-called Approximate Method in CSA S408-11 Annex B.2.5 is used, which stipulates Eq. (16) for calculating the necessary ϕ to achieve a target β (CSA 2011; 2019b):

$$\phi = \delta_R \frac{\sum \alpha_i S_{n,i}}{S_m} e^{\left(-\beta\sqrt{V_R^2+V_S^2}\right)} \tag{16}$$

where δ_R = bias coefficient for resistance; α_i = load factor (associated with load type i); $S_{n,i}$ = nominal load effect (for load type i); S_m = mean load effect; V_R = coefficient of variation (COV) for resistance [Eq. (22)]; and V_S = COV for load effects (load) [Eq. (19)].

For the basic combination of dead plus live load, Eq. (17) can be expanded and written in terms of a non-dimensional live-to-dead load (L/D) ratio (Schmidt & Bartlett 2002):

$$\phi = \delta_R \left(\frac{\alpha_D + \alpha_L \left({L}/{D} \right)}{\delta_D + \delta_L \left({L}/{D} \right)} \right) e^{\left(-\beta \sqrt{V_R^2 + V_S^2} \right)} \tag{17}$$

or, conversely, as:

$$\beta = \frac{1}{\sqrt{V_R^2 + V_S^2}} \ln \left[\frac{\delta_R}{\phi} \left(\frac{\alpha_D + \alpha_L \left({L}/{D} \right)}{\delta_D + \delta_L \left({L}/{D} \right)} \right) \right] \tag{18}$$

where α_D and α_L = load factor for dead and live load, respectively; δ_D and δ_L = bias coefficient for live and dead load, respectively; V_D and V_L = associated COVs. V_s in Eqs. (17) and (18) is well-approximated for normal and log-normal distributions of V_D and V_L by (Schmidt & Barlett 2002; CSA 2019b):

$$V_S = \frac{\sqrt{\left(\delta_D V_D \right)^2 + \left(\delta_L V_L \left(L/D \right) \right)^2}}{\delta_D + \delta_L \left(L/D \right)} \tag{19}$$

Resistance Model and Statistical Parameters

In this study, the bias coefficient, δ_R, and coefficient of variation, V_R, of the resistance are derived assuming the following resistance model, R:

$$R = (GMP)d \tag{20}$$

The quantity in parentheses represents the resistance model originally proposed by Galambos and Ravindra (1977), which considers geometric, G, material, M, and professional, P, factors. The factor d is a discretization factor, which is discussed further below.

If G, M, P and d are assumed to be independent quantities, then then distribution of R can be considered to be lognormal with bias coefficient:

$$\delta_R = \delta_G \delta_M \delta_P \delta_d \tag{21}$$

and COV:

$$V_R = \sqrt{V_G^2 + V_M^2 + V_P^2 + V_d^2} \tag{22}$$

where δ_G, δ_M, δ_P, and δ_d = bias coefficients of G, M, P and d, respectively; and V_G, V_M, V_P, and V_d = associated COVs. Herein, δ_G incorporates variability in the weld throat size; δ_M incorporates variability in electrode strength; δ_P incorporates the predictive accuracy of the design equation used to calculate R_n; and δ_d incorporates the effect of specifying discreet/commonly used weld sizes that are generally in excess of the minimum LSD/LRFD requirements.

Bias coefficients and COVs for dead and live load used in this work ($\delta_D = 1.05$, $\delta_L = 0.90$, $V_D = 0.10$, and $V_L = 0.27$) were extracted from MacPhedran & Grondin (2011), and the target β-value was taken as 4.0, for connection design, in accordance with Annex B.4 of CSA S16:19 (CSA 2019a) and Chapter B of the AISC 360-16 Commentary (AISC 2016). A summary of resistance factors for fillet welds (ϕ_w or ϕ) and load factors (α_D and α_L) for the two basic load combinations (live plus dead, and dead load only) and three specifications (CSA S16, AISC 360, and EN 1993-1-8) considered in this study are presented in Table 5. The parameters δ_M (= 1.12) and V_M (= 0.077) used in this study are based on 672 tests on weld metal tensile strength summarized by Lesik & Kennedy (1990).

The parameter δ_G (= 1.13) was derived by first considering common "measurement errors". Hence, the average actual weld throat sizes (t_w) (MTD, in Table 1) were divided by average measured values determined using a weld gauge prior to testing. The average of these values, 1.10, was then multiplied by the value of 1.03 reported by Calelle et al. (2009) to consider the effect of "fabrication errors" on the resulting weld geometry. The associated COV, V_G (= 0.16), was determined using the square root of the sum of squares of the COVs of the two basic geometric variables (which were 0.13 and 0.10, respectively).

A key finding from the current study is that the professional factor parameters (δ_P and V_p) depend on eccentricity magnitude and direction. Thus, bias coefficients and their associated COVs have been calculated for each offset (30a, 15a, 0, etc.), as shown in Table 6.

To determine δ_d, the shear resistance (V_r) of fillet welds for common weld throat and leg sizes from the CISC Handbook (CISC 2021) Tables 3-23, 3-24a and 3-24b, as well as common leg sizes from the AISC Manual Table 8-2 (AISC 2016) were considered. A list of factored shear (V_f) values with uniform increments, representing design scenarios, were arranged from 0 kN/mm to 10 kN/mm, and assigned the closest common weld size and corresponding strength (V_r) for design. The resulting ratios of V_r/V_f were then calculated, and averaged, to acquire δ_d (see Table 7), and V_d was then determined. Based on this analysis performed three ways (Table 7), values of $\delta_d = 1.09$ and $V_d = 0.062$, which represent the "worst case", were selected for the analysis.

Herein, β values are determined for single-sided fillet welds designed according to CSA S16-14/S16:19 and AISC 360-16 (with/without the sinθ factor) and EN 1993-1-8:2005 (Directional and Simplified Methods) for each branch plate offset (S), over the range of $0 \leq L/D \leq 3.0$. Plots of β vs. L/D for comparing the results to the target index ($\beta = 4.0$) are shown in Figs. 13 and 14.

Results

For CSA S16 (Fig. 13a,b), the target β (= 4.0) is only met for single-sided fillet weld joints with compression due to bending at the weld root (causing closing of the notch) (i.e., 30a, and 15a), and only when the sinθ factor is omitted. For these joints, β varies from 4.18 to $4.62 \geq 4.0$ (see Table 8). For joints with 0b offset, β varies from 4.33 to $4.69 \geq 4.0$, indicating that a small amount of tension due to the alignment of connected parts is not critical. On the other hand, for single-sided fillet welds with tension at the root (causing opening of the notch) (i.e., 15b & 30b), β varies from 1.36 to 2.56, which is well below the target β, indicating that tension at the weld must generally be avoided. Hence, for linear elements, the rule imposed in CSA S16:19 (CSA 2019a), i.e., to allow the sinθ factor for "cases other than single-sided fillet welds connected to elements in tension", as well as the requirement(s) of CSA W59-18 (CSA 2018a) Clause 4.1.3.3.2 (see Introduction), are appropriate.

For AISC 360-16 (Fig 13c,d), similar β values to CSA S16:19 are obtained when the sinθ factor is omitted, i.e., $\beta = 4.10$ to $4.65 \geq 4.0$ for joints with compression due to bending at the root (causing closing of the notch) (i.e., 30a and 15a), $\beta = 4.30$ to $4.68 \geq 4.0$ for joints with 0b offset, and $\beta = 1.26$ to 2.66 for joints with tension at the root (causing opening of the notch) (i.e., 15b & 30b).

For EN 1993-1-8:2005, the results in Fig. 14a,b and Table 8 support the use of the Simplified Method for the design of single-sided fillet welds in joints with compression (15a & 30a) or nominal tension (0b) at the weld root; however, for the Directional method, a maximum $\beta = 3.56 < 4.0$ is found for joints with compression at the root (causing closing of the notch), suggesting it should not be used without explicitly considering the effect of local eccentricity at the weld root, regardless of whether that eccentricity causes tension or compression.

It is clear from Figs. 13a-d and Table 8 that the sinθ factor should not be used to design any single-sided welds to flat elements in tension.

Comparison to Tests on Double-Sided Welds

To evaluate the behaviour of single-sided fillet welds in relation to double-sided fillet welds, Table 9 presents the results of the fillet-weld-critical lapped splice and cruciform connections tested by Ng & Driver (2002) and Miazga & Kennedy (1989). The databases compiled for tests by these authors is provided in Appendix F of Thomas (2021). By comparison of the δ_P and V_P values in Table 6 (for the ETLCCs) to those in Table 9, it is clear that that the former are 30-75% weaker (depending, primarily, on the stress condition at the root). It is therefore deemed critical to make a distinction between these two weld types in steel specifications. A typical correlation plot of P_a vs. R_n for the tests compared in this section is shown in Fig. 15 with R_n determined according to CSA S16-14 (i.e., with the sinθ factor).

Comparison to Tests on Single-Sided Fillet Welds in HSS Connections

Table 9 also compares the results of this study to results from single-sided fillet-weld-critical experimental tests/FE analyses in HSS connections [namely, RHS-to-rigid end plate connections tested by Oatway (2014) and Frater (1986) and CHS-to-rigid end plate connections tested/analyzed by Tousignant & Packer (2017)]. The database used is summarized in Appendix F of Thomas (2021).

It is clear from Table 9 that single-sided fillet welds in ETLCCs with 0b offsets share remarkable similar strengths to single-sided fillet welds in RHS-to-rigid end plate connections. This is likely because a similar condition at the root and similar boundary conditions were generated in the RHS-to-rigid-plate connections tested. As shown in Table 9, and Tousignant & Packer (2017), single-sided fillet welds to linear elements are weaker than such welds to curved elements (in CHS-to-rigid end plate connections). For that reason, the sinθ factor will be permitted by AISC 360 (2021) for the latter.

SUMMARY AND CONCLUSIONS

Based on the results of an experimental program consisting of 40 ETLCCs with single-sided welds, and comparison(s) of the results to experimental programs consisting of connections with double-sided fillet welds (lapped-spliced connections, cruciform connections) and single-sided fillet welds to HSS, the following can be concluded for single-sided fillets connecting linear elements in tension:

- Fillet weld eccentricity (magnitude and direction) has a significant effect on weld strength, i.e.:
    - eccentricity causing compression due to bending at the weld root (closing of the root notch) increases weld strength, while
    - eccentricity causing tension due to bending at the weld root (opening of the root notch) decreases weld strength.
- Fillet weld size and branch plate thickness (examined independently) have little effect on weld strength.
- DIC results demonstrate that bending will occur in branches/plates when single-sided fillet welds are subjected to transverse tension loading. Thinner branch plates will exhibit greater bending strains compared to thicker branch plates.
- For CSA S16:19 and AISC 360-16: when the sinθ factor is used, predictions of weld strength are unsafe for *all* single-sided fillet welds (with compression or tension due to bending at the weld root). When the sinθ factor is <u>not</u> used, predictions of strength are <u>safe</u> for single-sided fillet welds with compression due to bending at the weld root.
- For EN 1993-1-8:2005: when the Directional Method is used, predictions of weld strength are <u>marginally unsafe</u> for single-sided fillet welds with compression at the weld root. When the Simplified Method is used, predictions of strength are <u>safe</u> for single-sided fillet welds with compression at the weld root.

In general, the results of this study show that current North American fillet weld design provisions meet/exceed the target safety index (i.e. β = 4.0) specified by North American codes (e.g. CSA S16 and AISC 360) for linear (as opposed to curved elements) provided that: (i) the "sinθ" factor is not used and (ii) tension due to bending at the weld root is avoided. Moreover, single-sided fillet welded joints subjected to stresses that cause tension due to bending at the weld root are strongly discouraged.

DATA AVAILABILITY STATEMENT

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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NOTATION

The following symbols are used in this paper:

A_w = effective throat area of weld (= $t_w \times l_w$)

E = Young's modulus

e = distance between the centre of the single-sided weld throat and the centre of the connected branch

F_{EXX} = ultimate tensile strength of weld metal (in AISC 360)

F_{nw} = nominal strength of weld metal at failure (in AISC 360)

F_u = ultimate tensile strength for the base metal

F_y = yield strength

L/D = live-to-dead load ratio

l_h = weld leg (measured along the tension face)

l_v = weld leg (measured along the shear face)

l_w = total length of weld

M_w = strength reduction factor for multi-orientation fillet welds (in CSA S16)

P = applied load

P_a = actual strength for single-sided fillet weld (from ETLCC experimental tests)

R_n = nominal strength of fillet weld(s)

R_{nl} = nominal strength of longitudinal fillet welds

R_{nt} = nominal strength of transverse fillet welds

P_θ = ultimate strength of weld with loading angle θ

S = center-to-center distance of branch plates (for ETLCC specimens)

$S_{n,i}$ = nominal load effect (for load type i)

S_m = mean load effect

t_b = thickness of connected element

t_w = weld throat size

V_d = coefficient of variation for the discretization factor

V_D = coefficient of variation for the dead load effect

V_G = coefficient of variation for the geometry factor

V_L = coefficient of variation for the live load effect

V_M = coefficient of variation for the material factor

V_P = coefficient of variation for the professional factor

V_r = factored shear resistance

V_R = coefficient of variation for resistance

V_S = coefficient of variation for load effects

X_u = ultimate tensile strength of weld metal (in CSA S16)

α_i = load factor (for load type i)

β = reliability index

β_w = correlation factor for fillet welds (in EN 1993-1-8)

γ_{M2} = partial safety factor for the resistance of welds (in EN 1993-1-8)

δ_d = bias coefficient for the discretization factor

δ_D = bias coefficient for the dead load effect

δ_G = bias coefficient for the geometry factor

δ_L = bias coefficient for the live load effect

δ_M = bias coefficient for the material factor

δ_P = bias coefficient for the professional factor

δ_R = bias coefficient for the resistance

ε_f = rupture strain

ε_{yy} = y-axis strain (from DIC plots)

ε_y = yield strain

θ = angle between the axis of a weld segment and the line of action of the applied force (in degrees)

θ_1 = orientation of the weld segment under consideration (in degrees)

θ_2 = orientation of the weld segment in the joint that is closest to 90° (in degrees)

λ = angle of inclination of the weld throat plane

$\sigma_{\perp}$ = normal stress perpendicular to the weld throat

$\tau_{/\!/}$ = shear stress (in plane of throat) parallel to the longitudinal axis of the weld

$\tau_{\perp}$ = shear stress (in plane of throat) perpendicular to the longitudinal axis of the weld

ϕ = resistance factor

ϕ_w = resistance factor for weld metal (in CSA S16)

Ψ = local dihedral angle (angle between the base metal fusion faces)

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Table 1. Actual cross-sectional dimensions of ETLCC specimens and fillet welds

Specimen designation	Branch plate thickness, t_b (mm)	Offset, S (mm)	Shear leg [1], l_v (mm)	Tension leg [1], l_h (mm)	Weld throat (MTD) [2], t_w (mm)	Weld throat (CTD) [3], t_w (mm)	λ (°)	Weld length, l_w (mm)
S6-S-30a	6.40	-30.2	4.10	3.30	2.58	2.55	38.7	80.4
S6-S-15a	6.28	-12.4	3.95	4.15	3.20	2.84	46.1	74.7
S6-S-0	6.41	+1.1	4.43	4.03	3.17	2.98	42.3	75.0
S6-S-15b	6.41	+17.4	3.34	3.76	2.54	2.47	48.4	77.5
S6-S-30b	6.45	+30.5	3.18	3.12	2.42	2.22	44.5	75.4
S6-M-30a	6.39	-30.9	4.22	3.78	2.86	2.79	41.8	71.4
S6-M-15a	6.41	-13.1	5.63	4.17	3.43	3.35	36.4	76.0
S6-M-0	6.42	+0.9	5.54	3.84	3.52	3.14	34.9	76.2
S6-M-15b	6.42	+17.3	4.56	4.30	3.34	3.11	43.4	75.0
S6-M-30b	6.46	+30.3	3.30	3.46	2.46	2.35	47.4	77.9
S6-L-30a	6.52	-31.6	5.66	4.20	2.84	3.35	36.1	73.6
S6-L-15a	6.40	-12.9	6.10	4.54	3.86	3.61	36.7	73.5
S6-L-0	6.35	+1.1	6.10	4.68	4.04	3.69	37.5	73.8
S6-L-15b	6.43	+17.4	4.32	4.72	3.42	3.17	46.7	73.7
S6-L-30b	6.42	+30.0	4.14	4.66	3.24	3.08	48.4	72.4
S9-XS-0	9.63	+1.2	3.78	2.80	2.38	2.23	36.4	74.3
S9-S-0	9.57	+1.2	4.98	3.26	2.76	2.72	33.2	75.8
S9-M-0	9.64	+1.5	5.60	4.58	3.70	3.50	39.0	79.4
S9-L-0	9.62	+0.9	5.82	6.30	4.82	4.25	47.2	72.1
S9-XL-0	9.62	+1.1	8.16	6.78	5.68	5.20	39.8	75.2
S9-XXL-0	9.58	+1.6	8.36	7.44	6.00	5.52	41.8	74.9
S14-XS-0	15.93	-0.6	2.76	2.46	1.84	1.82	41.4	72.7
S14-S-0	15.90	-0.4	4.90	3.22	2.72	2.68	33.2	74.7
S14-M-0	15.88	-0.5	6.14	4.52	3.74	3.64	36.3	78.7
S14-L-0	15.90	+0.8	7.24	7.26	5.20	5.12	45.3	73.5
S14-XL-0	15.88	+0.6	10.18	8.82	6.70	6.66	41.0	76.5
S14-XXL-0	15.90	+1.5	12.16	11.08	8.42	8.17	42.4	71.5
S20-S-30a	19.50	-27.3	12.54	9.08	7.58	7.30	35.7	77.5
S20-S-15a	19.42	-13.5	11.60	9.28	7.58	7.21	38.3	74.5
S20-S-0	19.47	+2.8	9.76	8.76	6.86	6.41	42.0	77.5
S20-S-15b	19.56	+15.8	9.72	11.10	7.40	7.31	48.8	75.0
S20-S-30b	19.40	+30.1	10.76	12.08	8.22	8.02	48.3	72.8
S20-M-30a	19.53	-28.3	13.02	10.82	9.00	8.30	39.7	75.5
S20-M-15a	19.55	-13.3	12.54	11.50	9.22	8.46	42.6	76.5
S20-M-0	19.46	+3.5	13.16	11.90	9.74	8.81	42.1	74.5
S20-M-15b	19.42	+16.3	11.16	12.12	9.10	8.19	47.4	75.5
S20-L-30a	19.53	-27.9	12.94	11.04	9.12	8.39	40.4	74.5
S20-L-15a	19.41	-14.2	15.36	13.28	10.88	9.99	40.9	74.5
S20-L-0	19.41	+3.0	14.66	13.06	10.00	9.62	41.5	75.5
S20-L-15b	19.45	+16.2	14.30	13.32	10.52	9.74	43.0	74.5

[1] see l_v and l_h in Fig. 3.

[2] MTD = minimum throat dimension, taken as the shortest distance from the root to the face of the fillet weld from macro-etch examinations (see Geometric Properties)

[3] CTD = calculated throat dimension [using Eq. (13), with measured values of l_v and l_h (Columns 4 and 5)

Table 2. Average base metal tensile coupon test results

Nominal plate thickness	Yield strength	Ultimate strength	Yield strain	Rupture strain	Young's modulus
t_b (mm)	F_y (MPa)	F_u (MPa)	ε_y (mm/mm)	ε_f (mm/mm)	E (GPa)
6.4	486	519	0.00461	0.315	182.3
9.5	470	526	0.00428	0.318	210.6
15.9	387	531	0.00413	0.376	181.5
19.1	424	554	0.00435	0.371	172.1

Table 3. All-weld-metal tensile coupon test results

Coupon	Yield strength	Ultimate strength	Yield strain	Rupture strain	Young's modulus
	F_y (MPa)	X_u (MPa)	ε_y (mm/mm)	ε_f (mm/mm)	E (GPa)
(i)	502	558	0.00435	0.288	196.8
(ii)	497	554	0.00499	0.264	166.3
(iii)	514	571	0.00501	0.277	169.6
Average	504	561	0.00479	0.276	177.6

Table 4. Actual strengths, predicted strengths, and load ratios for the 40 test welds

		CSA S16:19				AISC 360-16				EN1993-1-8:2005			
		with *sinθ*		without *sinθ*		with *sinθ*		without *sinθ*		Directional		Simplified	
Specimen designation	P_a	R_n	P_a/R_n	R_n	P_a/R_n	R_n	P_a/R_n	R_n	P_a/R_n	R_n	P_a/R_n	R_n	P_a/R_n
	kN	kN		kN		kN		kN		kN		kN	
S6-S-30a	72.0	104.7	0.62	78.0	0.92	104.7	0.69	69.8	1.03	89.6	0.80	69.1	1.04
S6-S-15a	175.2	120.7	1.30	89.8	1.95	120.7	1.45	80.5	2.18	96.6	1.81	79.6	2.20
S6-S-0	110.5	119.9	0.82	89.3	1.24	119.9	0.92	79.9	1.38	99.2	1.11	79.1	1.40
S6-S-15b	47.4	99.4	0.43	74.0	0.64	99.4	0.48	66.3	0.72	78.0	0.61	65.5	0.72
S6-S-30b	35.1	92.1	0.34	68.6	0.51	92.1	0.38	61.4	0.57	74.7	0.47	60.8	0.58
S6-M-30a	109.9	103.1	0.95	76.8	1.43	103.1	1.07	68.7	1.60	85.7	1.28	68.0	1.62
S6-M-15a	138.4	131.7	0.94	98.1	1.41	131.7	1.05	87.8	1.58	115.2	1.20	86.9	1.59
S6-M-0	121.2	135.4	0.80	100.8	1.20	135.4	0.90	90.3	1.34	120.2	1.01	89.3	1.36
S6-M-15b	55.0	126.5	0.39	94.2	0.58	126.5	0.43	84.3	0.65	103.6	0.53	83.4	0.66
S6-M-30b	40.0	96.8	0.37	72.0	0.55	96.8	0.41	64.5	0.62	76.5	0.52	63.8	0.63
S6-L-30a	155.8	105.5	1.32	78.6	1.98	105.5	1.48	70.4	2.21	92.6	1.68	69.6	2.24
S6-L-15a	168.0	143.2	1.05	106.6	1.58	143.2	1.17	95.5	1.76	124.9	1.34	94.5	1.78
S6-L-0	122.3	150.5	0.73	112.1	1.09	150.5	0.81	100.4	1.22	130.2	0.94	99.3	1.23
S6-L-15b	55.1	127.3	0.39	94.7	0.58	127.3	0.43	84.8	0.65	101.3	0.54	83.9	0.66
S6-L-30b	43.0	118.4	0.32	88.2	0.49	118.4	0.36	79.0	0.54	92.9	0.46	78.1	0.55
S9-XS-0	95.9	89.3	0.96	66.5	1.44	89.3	1.07	59.5	1.61	79.2	1.21	59.7	1.61
S9-S-0	104.4	105.6	0.89	78.6	1.33	105.6	0.99	70.4	1.48	96.7	1.08	70.6	1.48
S9-M-0	133.7	148.3	0.81	110.4	1.21	148.3	0.90	98.9	1.35	128.2	1.04	99.1	1.35
S9-L-0	139.0	175.5	0.71	130.6	1.06	175.5	0.79	117.0	1.19	140.9	0.99	117.3	1.19
S9-XL-0	171.8	215.7	0.71	160.5	1.07	215.7	0.80	143.8	1.19	185.0	0.93	144.1	1.19
S9-XXL-0	171.3	226.9	0.68	168.9	1.01	226.9	0.75	151.3	1.13	191.2	0.90	151.6	1.13
S14-XS-0	56.8	67.5	0.75	50.3	1.13	67.5	0.84	45.0	1.26	57.7	0.99	45.6	1.25
S14-S-0	96.8	102.6	0.85	76.4	1.27	102.6	0.94	68.4	1.42	94.8	1.02	69.2	1.40
S14-M-0	143.6	148.6	0.87	110.6	1.30	148.6	0.97	99.1	1.45	133.2	1.08	100.3	1.43
S14-L-0	155.2	193.0	0.72	143.7	1.08	193.0	0.80	128.6	1.21	159.1	0.98	130.2	1.19
S14-XL-0	203.7	258.8	0.70	192.7	1.06	258.8	0.79	172.5	1.18	221.7	0.92	174.6	1.17
S14-XXL-0	208.3	304.0	0.61	226.3	0.92	304.0	0.69	202.6	1.03	257.0	0.81	205.1	1.02
S20-S-30a	349.6	296.6	1.06	220.8	1.58	296.6	1.18	197.7	1.77	278.8	1.25	208.8	1.67
S20-S-15a	267.1	285.1	0.84	212.3	1.26	285.1	0.94	190.1	1.41	261.4	1.02	200.7	1.33
S20-S-0	222.2	268.4	0.74	199.8	1.11	268.4	0.83	179.0	1.24	237.7	0.93	188.9	1.18
S20-S-15b	175.2	280.2	0.56	208.6	0.84	280.2	0.63	186.8	0.94	234.0	0.75	197.2	0.89
S20-S-30b	149.8	302.1	0.44	224.9	0.67	302.1	0.50	201.4	0.74	253.3	0.59	212.7	0.70
S20-M-30a	374.9	343.1	0.98	255.4	1.47	343.1	1.09	228.7	1.64	310.4	1.21	241.5	1.55
S20-M-15a	295.6	356.1	0.74	265.1	1.11	356.1	0.83	237.4	1.25	313.7	0.94	250.7	1.18
S20-M-0	258.7	366.4	0.63	272.7	0.95	366.4	0.71	244.2	1.06	324.0	0.80	257.9	1.00
S20-M-15b	194.8	346.9	0.50	258.2	0.75	346.9	0.56	231.3	0.84	292.9	0.66	244.2	0.80
S20-L-30a	435.7	293.6	1.33	218.6	1.99	293.6	1.48	195.8	2.23	263.8	1.65	206.7	2.11
S20-L-15a	337.4	353.2	0.86	263.0	1.28	353.2	0.96	235.5	1.43	316.0	1.07	248.6	1.36
S20-L-0	278.0	352.0	0.71	262.1	1.06	352.0	0.79	234.7	1.18	313.1	0.89	247.8	1.12
S20-L-15b	202.3	354.3	0.51	263.7	0.77	354.3	0.57	236.2	0.86	311.0	0.65	249.4	0.81

Table 5. Resistance factors and load factors

	CSA S16		AISC 360-16		EN 1993-1-8:2005
ϕ_w or ϕ	0.67		0.75		0.80 [1]
Load Combination	(1)	(2)	(1)	(2)	(1)
α_D	1.40	1.25	1.40	1.20	1.35
α_L	0	1.50	0	1.60	1.50

[1] $\phi = 1/\gamma_{M2} = 1/1.25 = 0.80$.

Table 6. Summary of δ_P and V_P values for CSA S16, AISC 360-16, and EN 1993-1-8:2005

			CSA S16		AISC 360-16		EN 1993-1-8:2005	
Offset, *S*			with sinθ	without sinθ	with sinθ	without sinθ	Directional	Simplified
30a	δ_P	=	1.043	1.564	1.164	1.746	1.314	1.706
	V_P	=	0.255	0.255	0.255	0.255	0.247	0.251
15a	δ_P	=	0.955	1.432	1.066	1.599	1.232	1.573
	V_P	=	0.208	0.208	0.208	0.208	0.259	0.237
0b	δ_P	=	0.761	1.141	0.849	1.274	0.979	1.260
	V_P	=	0.120	0.120	0.120	0.120	0.106	0.129
15b	δ_P	=	0.463	0.695	0.517	0.776	0.624	0.756
	V_P	=	0.155	0.155	0.155	0.155	0.131	0.122
30b	δ_P	=	0.370	0.555	0.413	0.620	0.511	0.615
	V_P	=	0.142	0.142	0.142	0.142	0.116	0.110

Table 7. Summary of δ_d and V_d for fillet weld throat and leg sizes from the CISC Handbook and AISC Manual *(one-column table)*

	CISC Handbook		AISC Manual
	Throat size, t_w	Leg size, l_v *or* l_h	Leg size, l_v *or* l_h
	Table 3-23	Table 3-24a-b	Table 8-2
δ_d	1.12	**1.09**	1.10
V_d	0.072	**0.062**	0.062

Table 8. Reliability index values by branch plate offset (*S*) using CSA S16, AISC 360-16 & EN 1993-1-8:2005

	CSA S16		AISC 360-16		EN 1993-1-8:2005	
Offset, *S*	with sinθ	without sinθ	with sinθ	without sinθ	Directional	Simplified
30a	2.95-3.24	4.18-4.41	2.88-3.33	4.10-4.46	3.30-3.56	4.06-4.30
15a	3.01-3.30	4.37-4.62	2.92-3.38	4.29-4.65	3.02-3.28	3.94-4.18
0b	2.73-3.06	4.33-4.69	2.62-3.14	4.30-4.68	3.28-3.60	4.08-4.44
15b	0.64-1.24	2.18-2.56	0.54-1.37	2.09-2.66	1.33-1.75	2.13-2.49
30b	-0.23-1.98	1.36-1.85	-0.33-0.66	1.26-1.98	0.55-1.11	1.32-1.75

Table 9. Summary of δ_P and V_P values for CSA S16, AISC 360-16, and EN 1993-1-8:2005 for single-sided fillet welds and double-sided welds for lapped-splice and cruciform connections

			CSA S16		AISC 360-16		EN 1993-1-8:2005	
			with $sin\theta$	without $sin\theta$	with $sin\theta$	without $sin\theta$	Directional	Simplified
Double-sided welds	δ_P	=	**1.493**	**2.240**	**1.668**	**2.502**	-	-
	V_P	=	0.237	0.237	0.237	0.237	-	-
RHS-to-rigid end plate welds	δ_P	=	**0.737**	**1.106**	**0.824**	**1.234**	**1.151**	**1.357** [1]
	V_P	=	0.135	0.135	0.135	0.136	0.132	0.090 [1]
CHS-to-rigid end plate welds	δ_P	=	**0.840**	**1.260**	**0.938**	**1.407**	**1.233**	**1.521**
	V_P	=	0.081	0.081	0.082	0.082	0.077	0.0591

[1] Based on tests from Tousignant and Packer (2017) only