Fillet welding of skewed reinforcing steel to steel plate

Erin D. Pratt

- Steel reinforcing bars are often fillet welded to structural steel plates for connections in precast concrete construction; however, design guidance is lacking for the design of the fillet welds when the reinforcing steel is welded at an angle (skew) to the structural plate.

- This paper discusses the experimental testing and theoretical analysis of the connection strength for reinforcing bars welded at various angles to a steel plate.

- The results of the testing and analysis were used to make recommendations for updates to the American Welding Society's *Structural Welding Code—Reinforcing Steel* that would provide specific guidance for the design of fillet welds connecting reinforcing bars to structural plates at a skew.

Precast concrete construction commonly uses reinforcing steel anchored to structural steel plates or structural shapes by fillet welding around the circumference of the reinforcing steel bar (**Fig. 1**). The design of these welds is governed by the American Welding Society's *Structural Welding Code—Reinforcing Steel* (AWS D1.4-18).[1]

Notably, AWS D1.4-18 is silent on the design of fillet-welded reinforcing steel if the reinforcing steel is detailed at a skew to the plate (**Fig. 2**). This paper studies the effect on the overall strength of the connection when the reinforcing steel is placed at a skew to the structural plate or shape.

Research significance

When reinforcing steel is welded at a skew to a plate, several overlapping factors affect the final connection strength. First, the overall length of the weld increases as the skew increases. Where the weld was a perfect circle in plan view at a perpendicular alignment, the weld becomes an increasingly elongated ellipse as the reinforcing steel is skewed. This effect is expected to increase the connection strength.

Next, there is a nonlinear eccentricity effect. Compared with the weld on the obtuse side, the weld on the acute side of the reinforcing steel has a greater effective throat (the minimum distance from the joint root to the face of the fillet weld [see AWS D1.4-18[1] section 4.2.3.2]). The greater effective throat creates more rigidity on the acute side, thus causing eccen-

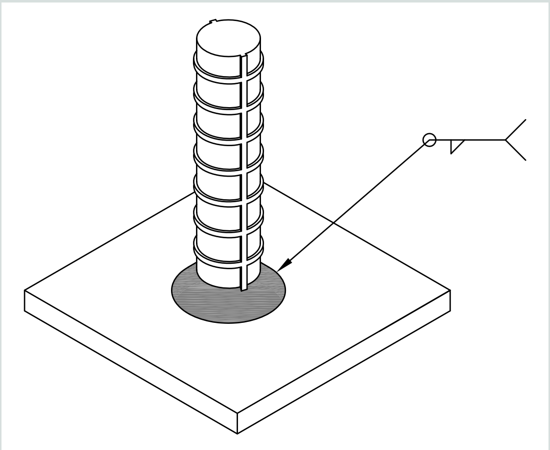


Figure 1. Typical reinforcing bar–to–steel plate fillet weld detail.

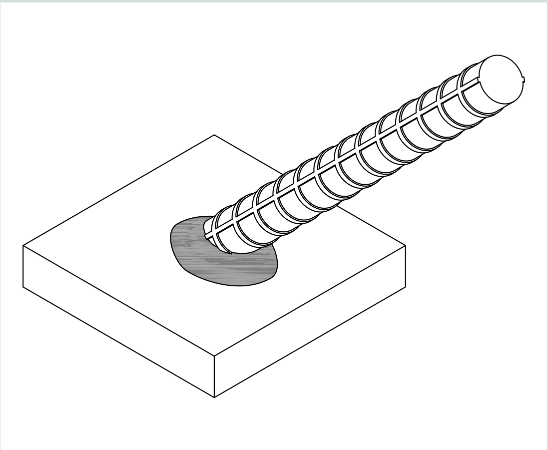


Figure 2. Skewed reinforcing bar–to–steel plate fillet weld detail.

tricity in the connection. This effect will decrease the connection strength.

Finally, there is what is called the "Z-loss factor" in AWS D1.1-20, *Structural Welding Code—Steel*.[2] Z-loss is a dimension of effective throat lost due to uncertainty of sound weld metal in the root pass of the narrow angle based on the welding process used. This factor accounts for a lack of penetration when the skew angle becomes too acute. This effect also tends to weaken the connection.

The provisions of AWS D1.1-20[2] are written for plates joining at a skewed angle (**Fig. 3**). The weld on the acute side has a much larger effective throat than the weld on the obtuse side, but the throat width is constant throughout the length of the weld on each side. For the case of welding reinforcing steel at a skew to a plate, the effective throat width is also larger at the acute angle side than at the obtuse angle side; however, in this configuration, the effective throat is constantly changing as the weld wraps around the bar. Given these fundamental differences between the skewed plate condition of AWS D1.1-20 and skewed reinforcing steel, a new study was needed to quantify the overall strength of the welded connection.

Experimental program

In this experimental program, physical testing was performed to quantify the effect of the skew angle on joint strength. To this end, eight samples were prepared for each of the configurations shown in **Fig. 4** (32 samples total).

Samples

Each sample consisted of a no. 8 (25M) reinforcing bar, approximately 24 in. (610 mm) long. Each reinforcing bar was cut into two equal lengths and then beveled at the designated angle to fit flush with the splicing plate. The splicing plates were approximately 4 × 4 in. (100 × 100 mm) and ½ in. (13 mm) thick. As illustrated in Fig. 4, the reinforcing bars were carefully lined up so no accidental eccentricity would be introduced into the joint during tensile testing. To facilitate accurate and consistent weld configurations, the ¼ in. (6.4 mm) weld size was scribed onto the reinforcing bar, as well as on the splice plate, in the shape of the design ellipse (Fig. 4). The size of the design ¼ in. weld followed the detailing prescribed by AWS D1.1-20[2] Fig. 3.4, Prequalified skewed T-joint details (nontubular), where the vertical leg is measured at ¼ in. perpendicular to the splice plate, and the horizontal leg is measured at ¼ in. parallel to the outside face of the reinforcing bar (**Fig. 5**).

Materials

Standard test methods determined that the structural steel properties of the reinforcing steel used for this study conformed to both the ASTM A615/A615M[3] and ASTM A706/

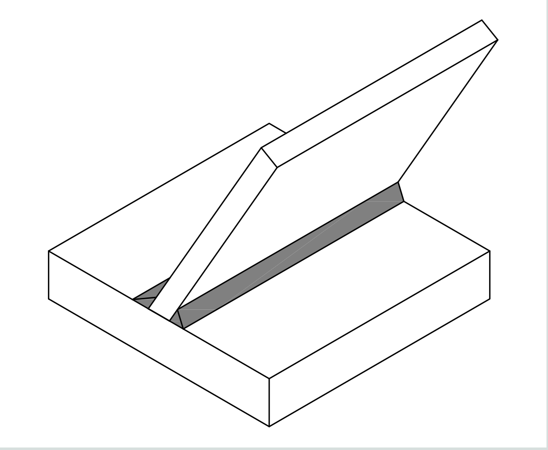


Figure 3. Skewed plate–to–plate fillet weld detail as defined by the American Welding Society's *Structural Welding Code—Steel* (AWS D1.1-20).

A706M[4] specifications for Grade 60 (414 MPa) reinforcing steel. The structural properties of significance to this study were the yield strength of 68.5 ksi (472 MPa), the tensile strength of 99.0 ksi (683 MPa), and the carbon equivalence of 0.52%.

The splice plates conformed to ASTM A516 Grade 70 (483 MPa).[5] This material had a yield strength of 51.3 ksi (354 MPa), a tensile strength of 75.5 ksi (521 MPa), and a carbon equivalence of 0.40%.

A gas-shielded flux-cored arc welding (FCAW-G) process was used with E71T-1C electrode and 100% carbon dioxide shielding gas. All materials were preheated to 70°F (21°C), and a 350°F (177°C) maximum interpass temperature was maintained.

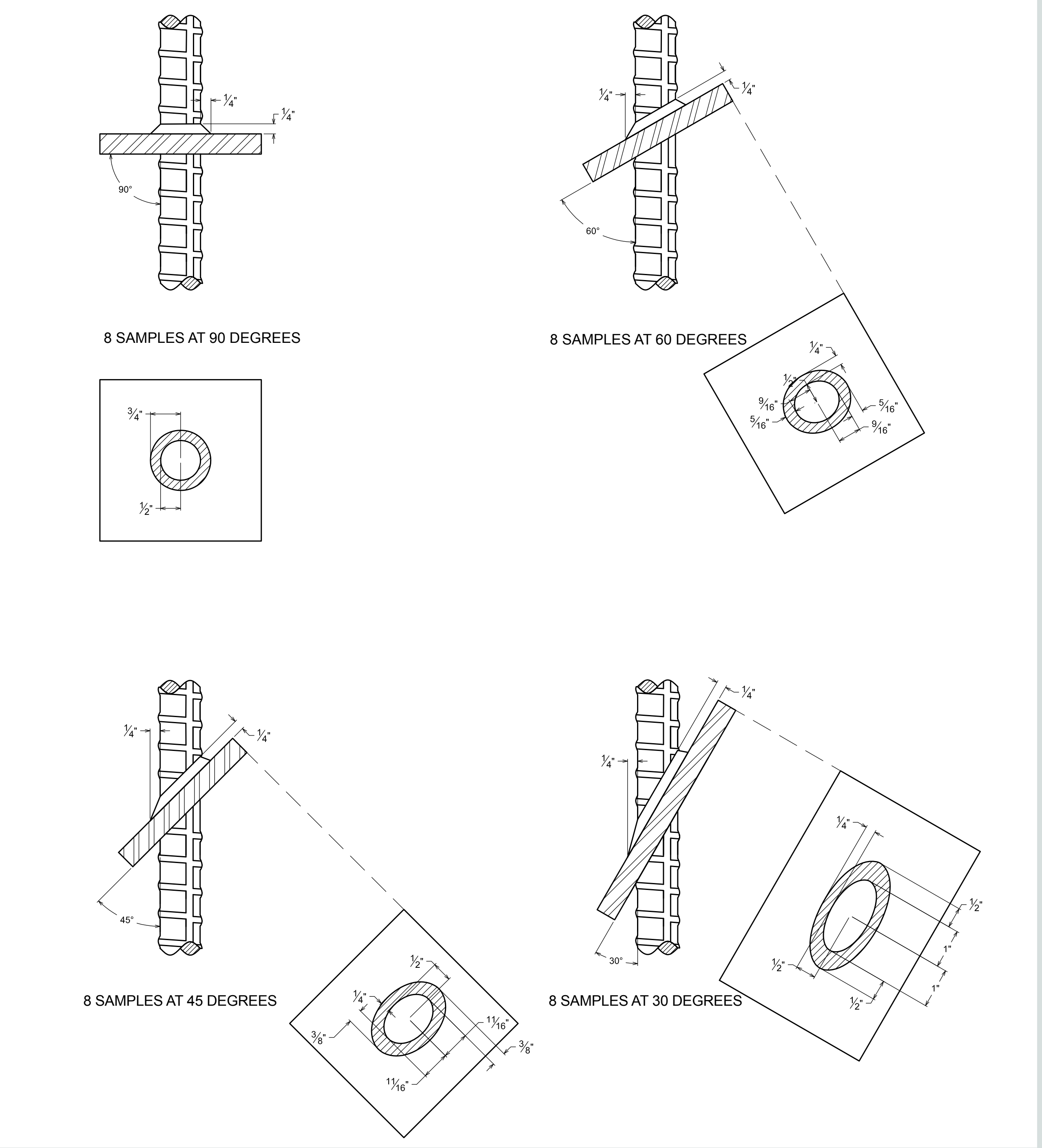


Figure 4. Test sample configurations. Note: 1" = 1 in. = 25.4 mm.

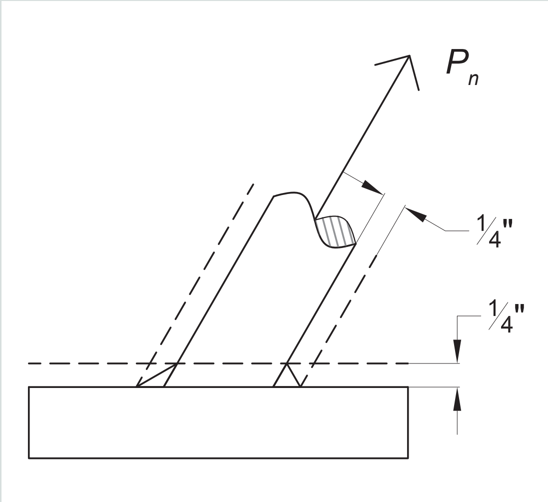


Figure 5. Configuration of weld leg size for skewed reinforcement. Note: P_n = nominal capacity of weld group applied at eccentricity *e*. 1" = 1 in. = 25.4 mm.

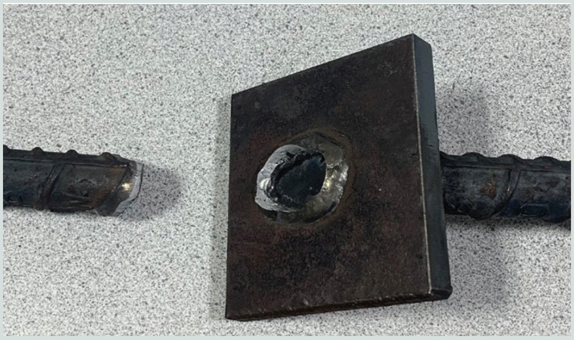


Figure 6. Test sample showing fracture surface. Reproduced by permission from Michael Kerr.

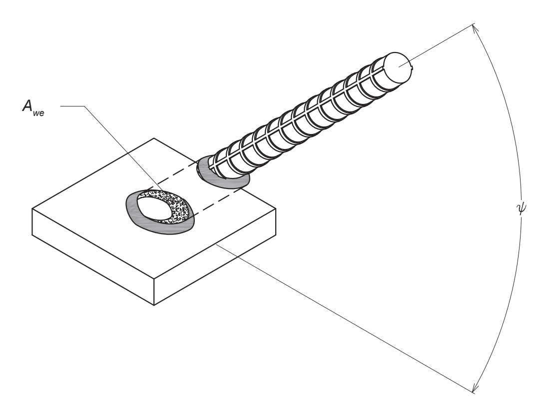


Figure 7. Definition of the fracture surface A_{we} and the angle from plate to reinforcing bar Ψ.

Test results

All 32 welded assemblies were tested in tension to failure, with one sample lost due to equipment malfunction. All 32 samples failed by fracture of the weld material (**Fig. 6**).

Table 1 presents the test results. **Figure 7** illustrates the definition of the reinforcing bar–to–splice plate angle Ψ. **Figure 8** plots the average of each eight-sample series, along with the standard error. Figure 8 shows that there was a clear decrease in capacity from 90 degrees (perpendicular to the splice plate) to 60 degrees, but fracture strength increased at angles less than 60 degrees.

Table 1. Summary of failure loads

Sample	Reinforcing bar-to-splice plate angle Ψ, 30 degrees	Reinforcing bar-to-splice plate angle Ψ, 45 degrees	Reinforcing bar-to-splice plate angle Ψ, 60 degrees	Reinforcing bar-to-splice plate angle Ψ, 90 degrees
	Failure load, kip			
1	60.1	47.6	45.9	49.3
2	61.5	52.4	45.8	50.7
3	58.5	54.1	46.4	51.2
4	60.1	53.2	43.5	49.6
5	58.2	51.3	44.2	51.4
6	62.8	54.7	45.5	48.9
7	59.1	53.7	40.1	51.9
8	57.9	54.2	n.d.	45.6
Average	59.8	52.7	44.5	49.8

Note: See Fig. 7 for definition of angle Ψ. n.d. = no data. 1 kip = 4.448 kN.

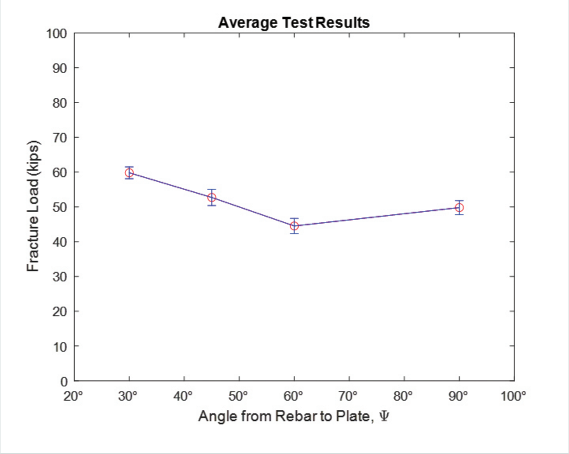


Figure 8. Average test results of 31 tensile-tested samples grouped in four configurations, with error bars. Note: 1 kip = 4.448 kN.

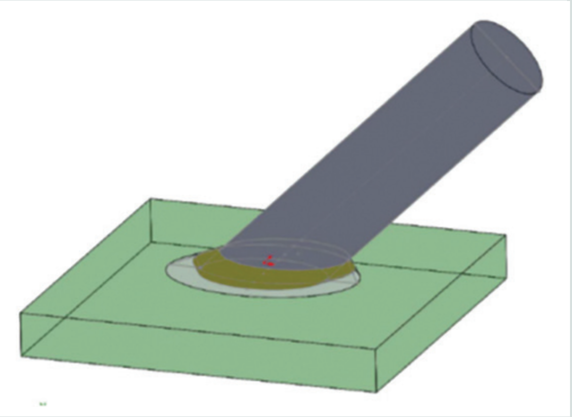


Figure 9. Three-dimensional solid computer model with shaded area representing the theoretical weld fracture surface.

Theoretical analysis

From Fig. 4 and observation of the fractured test samples, it is clear that as the angle of skew becomes more acute, the length of weld resisting the total load increases. Figure 4 also shows that at a skew angle of 90 degrees, the weld traces a perfect circle; however, as the skew angle decreases, the weld follows an elliptical shape. Therefore, as the skew angle becomes more acute, there is more effective weld area A_{we} to resist loading. Fig. 7 illustrates the theoretical fracture plane A_{we}.

From these findings, it was hypothesized that the capacity of the skewed reinforcing bar fillet weld has two contributing but opposing factors: the effective weld area grows larger with decreasing skew angle, but at the same time, the effective shear stress is reduced with decreasing skew angle, most likely due to imposed eccentricity to the weld as a group.

The first step to test this hypothesis was to quantify the effective weld area as a function of the skew angle. To this end, a three-dimensional (3D) solid computer model (**Fig. 9**) was created that offered the capability to create a surface feature through the plane of anticipated fracture. The model was configured with parametric dimensioning so that the skew angle could be varied to determine the effective weld area with different skew angles.

To verify the validity of the 3D model, another mathematical computer model (**Fig. 10**) was created using equations for an elliptic cone and skew planes. From this model, the surface area was also derived, and compared with the solid model.

The calculated effective weld areas from each model were found to be nearly identical, and together these areas were used to validate the final design procedure. A plot of the effective weld area compared with the skew angle revealed a smooth, polynomial pattern (**Fig. 11**).

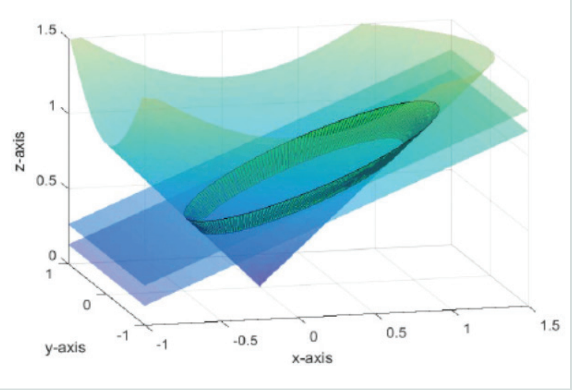


Figure 10. Mathematical computer model with green shaded area representing the theoretical weld fracture surface.

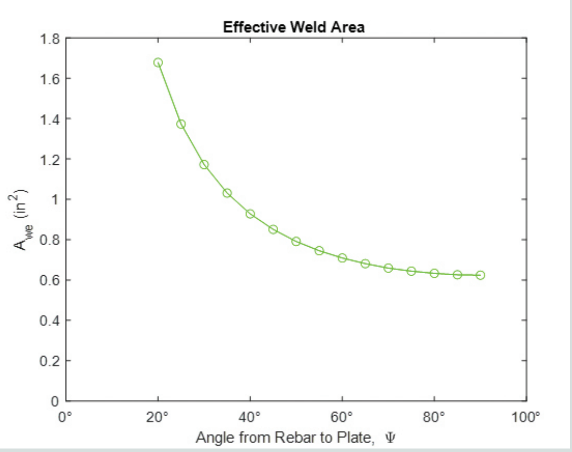


Figure 11. Effective weld fracture surface area A_{we} as a function of the reinforcing steel skew angle Ψ for no. 8 bar with ¼ in. weld. Note: no. 8 = 25M; 1 in. = 25.4 mm; 1 in.^{2} = 645 mm^2.

With the anticipated fracture surface area defined, the effective stress on the weld surface at fracture, defined as the average test failure load divided by the calculated shear area, could be evaluated. From the results in **Table 2**, it is clear the effective stress at fracture is reduced as the skew angle decreases.

For the analysis of the skewed weld configuration, the instantaneous center of rotation method, as presented in AWS D1.1-20[2] section 4.6.4.3, was adapted. The following modifications were made:

$F_{vi} = 0.30F_{EXX}(1.0 + 0.50\ \sin1.5\theta)F(\rho)$ was revised as $F_{vi} = 0.60F_{EXX}(1.0 + 0.50\ \sin1.5\theta)F(\rho)$ to bring the equation to a strength-based level instead of an allowable stress–based level, and $\Delta_m = 0.209(\theta + 6)^{-0.32}t_i$ was revised as $\Delta_m = 0.209(\theta + 2)^{-0.32}t_i$ to correct a typographical error, where F_{vi} is allowable unit stress of ith segment, F_{EXX} is electrode strength classification, θ is angle between the direction of force and the axis of the weld element, $F(\rho)$ is $[\rho(1.9 - 0.9\rho)]0.3$, ρ is ratio of ith element deformation to deformation in element at maximum stress, Δ_i is deformation of element i, Δ_m is deformation of element at maximum strength, and t_i is effective throat of fillet weld in segment i.

The instantaneous center of rotation method depends on dividing the weld group into small segments and then calculating the resistance of each weld segment R_i:

$$R_i = L_i t_i 0.60F_{EXX}(1.0+0.50\sin^{1.5}\theta)\left[\frac{\Delta_i}{\Delta_m}\left(1.9-0.9\frac{\Delta_i}{\Delta_m}\right)\right]^{0.3}$$

where

R_i = nominal strength of weld segment i

L_i = length of segment i

Δ_i = deformation of element i $= r_i \dfrac{\Delta_u}{r_{crit}}$

Δ_m = deformation of element at maximum strength $= 0.209(\theta + 2)^{-0.32}t_i$

r_i = distance from instantaneous center of rotation to ith weld element

Δ_u = deformation of element when fracture is imminent, usually in the element farthest from instantaneous center of rotation $= 1.087(\theta + 6)^{-0.65}t_i \le 0.17t_i$

r_{crit} = distance from instantaneous center of rotation to weld element having minimum ratio $\dfrac{\Delta_u}{r_i}$

Table 2. Average effective stress at failure of test samples

Skew angle Ψ, degrees	Average test load, kip	Calculated shear area, in.^{2}	Apparent shear stress, ksi
30	59.8	1.174	50.9
45	52.7	0.851	61.9
60	44.5	0.709	62.7
90	49.8	0.625	79.7

Note: 1 in.^{2} = 645 mm^2, 1 kip = 4.448 kN, 1 ksi = 6.895 MPa.

Figure 12 illustrates the assumed geometry of the instantaneous center of rotation on an arbitrary weld group located entirely in a two-dimensional plane. The method involves iterating the position of the instantaneous center until all the forces and moments are in equilibrium with the applied loading. Typically, when using this method, the length of each segment is a chosen constant and the thickness or leg size of each segment is also constant. For the skewed fillet weld in this study, both the segment length and segment effective throat were variable for each segment as the weld wrapped around the reinforcing bar. As a first step in modeling the test specimens (¼ in. [6.4 mm] weld on a no. 8 [25M] reinforcing bar), the geometry with a skewed reinforcing bar was established following the provisions of AWS D1.1-20[2] Fig. 3.4 (Fig. 5).

Using this configuration as the basis of design, a three-dimensional model was created, where the weld was divided at

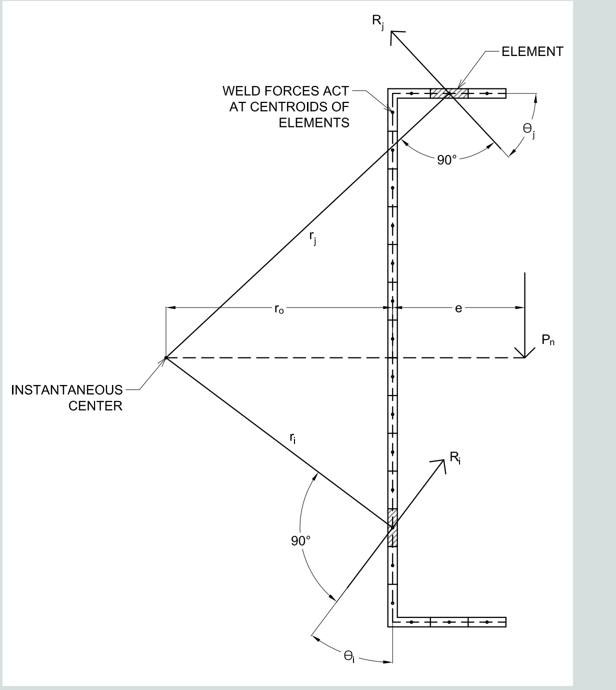


Figure 12. Illustration of the instantaneous center of rotation method in a two-dimensional plane. Note: e = eccentricity of applied load; P_n = nominal capacity of weld group applied at eccentricity e; r_i = distance from instantaneous center of rotation to ith weld element; R_i = nominal strength of weld segment i; r_o = dimension locating instantaneous center of rotation from weld group, iterated for convergence; θ_i = angle between the direction of force and the axis of the weld element of weld segment i.

every 5 degrees to create 36 segments on each side of the reinforcing steel bar (**Fig. 13**). By choosing an appropriate plane of symmetry, only one side needed to be analyzed.

Equations for ellipses in polar coordinates were used in a spreadsheet to automate analysis of the geometry of the segment length, the segment effective throat, and the distance of the segment to the instantaneous center of rotation. Notably, the effective area of each segment was assumed to be the segment length multiplied by the segment effective throat. For Ψ of 90 degrees, this assumption led to nearly zero error. However, as Ψ was reduced, the error in the effective area increased until the error was almost 10% at Ψ of 30 degrees. To correct this error, the area of triangles established at the start and stop coordinates of each segment were used to find the effective area; this method reduced the error to less than 0.2% at Ψ equal to 30 degrees.

To locate the instantaneous center of rotation at which all the forces and moments are in equilibrium with the applied loading, the location of the center of rotation was iterated in two dimensions, X and Y. With two independent variables to iterate, a two-variable optimization algorithm was used to find the solution. Each angle of study was iterated until the moments about the center of the reinforcing bar summed to zero, the forces in the X direction equaled the cosine of Ψ times the total design force P_n, and the forces in the Y direction equaled the sine of Ψ times P_n.

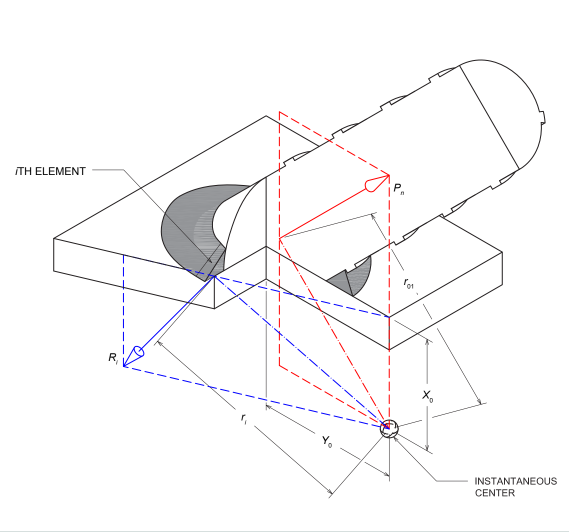


Figure 13. Illustration of the instantaneous center of rotation method in three dimensions with skewed reinforcing steel. Note: P_n = nominal capacity of weld group applied at eccentricity e; r_i = distance from instantaneous center of rotation to ith weld element; R_i = nominal strength of weld segment i; r_o = dimension locating instantaneous center of rotation from weld group, iterated for convergence; X_o = dimension locating instantaneous center of rotation in the vertical direction, iterated for convergence; Y_o = dimension locating instantaneous center of rotation in the horizontal direction, iterated for convergence.

An online appendix, which can be found at www.pci.org/2023Jan-Appx2, presents an example of the summation for Ψ equal to 45 degrees. In this spreadsheet, the values of r_{o1} and r_{o2} are iterated until the summation of the R_{ix} column equals $\cos(\Psi)P_n$ (26.155 kip [116.3 kN]), summation of the R_{iy} column equals $\sin(\Psi)P_n$ (also 26.155 kip for this example), and the summation of the $R_{ix}Y + R_{iy}X$ column equals zero. The value for P_n is the calculated capacity for the weld connection.

Results

With the analysis procedure automated, each angle of Ψ was calculated from 90 to 20 degrees. The results are shown in **Fig. 14**. The capacity at Ψ equal to 90 degrees (R_n = 39.291 kip) was very close to what we would expect based on AWS D1.1-20[2] section 4.6.4.2:

$$R_n = A_{we}0.60F_{EXX}(1.0 + 0.50\sin^{1.5}\theta)$$

where

R_n = nominal resistance of the weld

In the case of a ¼ in. (6.4 mm) weld on a no. 8 (25M) reinforcing bar, the analysis result was as follows:

$$R_n = \pi(1.125\text{ in.})(0.7071)(0.25\text{ in.})0.60(70\text{ ksi})(1.0 + 0.5\sin^{1.5}(90\text{ degrees}) = 39.361\text{ kip} \approx 39.291\text{ kip}$$

From the physical testing, the actual rupture strength at Ψ of 90 degrees was 49.8 kip (221.5 kN) on average. This greater experimental strength can be explained by the actual shear strength of the filler metal as compared with a nominal strength of $0.60(1.5)F_{EXX}$. To make a meaningful comparison, the tested values normalized to the strength found at Ψ

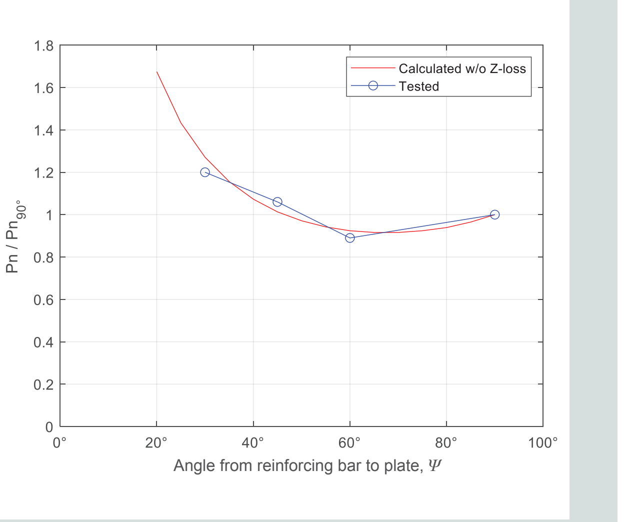


Figure 14. Normalized test results compared with theoretical analysis without consideration for Z-loss. Note: P_n = nominal capacity of weld group applied at eccentricity e.

equal to 90 degrees can be compared with the normalized calculated capacities. Figure 14 indicates good correlation between the calculated capacity and the tested capacity. In particular, the dip in capacity between Ψ of 50 degrees and Ψ of 90 degrees was captured by both the theoretical analysis and the physical testing. The trend also clearly shows an increase in capacity as Ψ was reduced below about 45 degrees, as the perimeter length of weld grew exponentially with the decrease in skew angle. However, Fig. 14 also shows an overprediction of strength at Ψ equal to 30 degrees. This overprediction might be explained by the fact that the design procedure did not acknowledge Z-loss (lack of penetration at the root of the fillet weld at the most acute angle). Inspection of the broken test samples at Ψ of 30 degrees showed that there was indeed a lack of penetration of about ⅛ in. (3.2 mm), and this lack of penetration extended for a zone of about 15 to 20 degrees from either side of the centerline at the point of the most severe angle between the reinforcing steel and the base material.

The design procedure was subsequently modified to include the Z-loss. AWS D1.1-20 Table 4.2 provides various Z-loss values depending on angle of acuteness, weld position, and weld process. Because this study was performed with the FCAW-G process in the horizontal position, the Z-loss was taken as ¼ in. (6.4 mm) for any segment with the dihedral angle from reinforcing bar to anchor plate Ψ_i less than 45 degrees. **Figure 15** shows the calculated capacity of the connection corrected for Z-loss.

Correction factors

Additional analysis was performed to determine correction factors for the weld strength of skewed reinforcing bars fillet welded to a plate for various skew angles, reinforcement sizes, and welding processes. Using the instantaneous center of rotation method described earlier, reinforcement sizes no. 4 (13M) to no.11 (36M) were analyzed at each 5 degrees of skew from 90 to 30 degrees, with fillet welds at a minimum size needed to develop 125% of the reinforcement bar's yield strength. The Z-loss was based on self-shielded flux-cored arc welding (FCAW-S) as noted previously, with Z-loss equal to ⅛ in. (3.2 mm) for Ψ_i angles less than 45 degrees. This process generated 104 data points, each of which was normalized to the 90 degrees datum for each set. **Figure 16** shows the resulting scatter graph.

The final correction value χ was found for each angle of Ψ by using a fourth-degree polynomial regression that was found to fit the data best. Similarly, the design values of χ were found for the FCAW-G, gas metal arc welding (GMAW), and shielded metal arc welding (SMAW) welding processes, with the only analytical variance being the Z-loss factors. For FCAW-G and GMAW processes, the Z-loss is defined as ¼ in. (6.4 mm) for Ψ_i angles between 45 and 30 degrees (**Fig. 17**). For SMAW, the Z-loss is defined as ⅛ in (3.2 mm) for Ψ_i angles between 60 and 45 degrees, and ¼ in (6.4 mm) for Ψ_i angles between 45 and 30 degrees (**Fig. 18**).

Table 3 presents the final correction value χ for each welding process.

Recommendations

AWS D1.4-18[1] lacks provisions for skewed reinforcing steel fillet welded to a structural plate or shape. The following revisions are proposed:

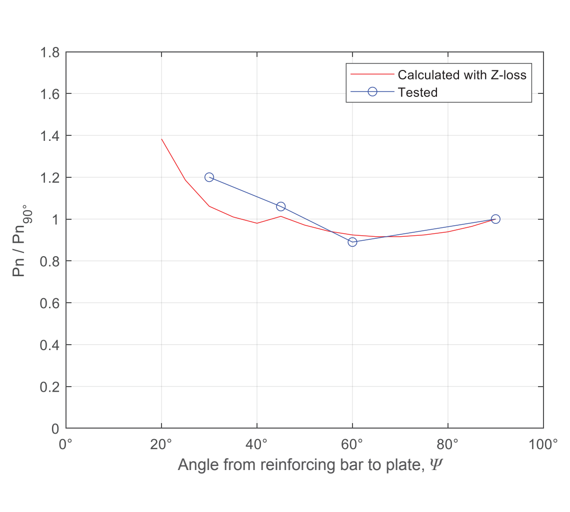


Figure 15. Normalized test results compared with theoretical analysis with consideration for Z-loss. Note: P_n = nominal capacity of weld group applied at eccentricity e.

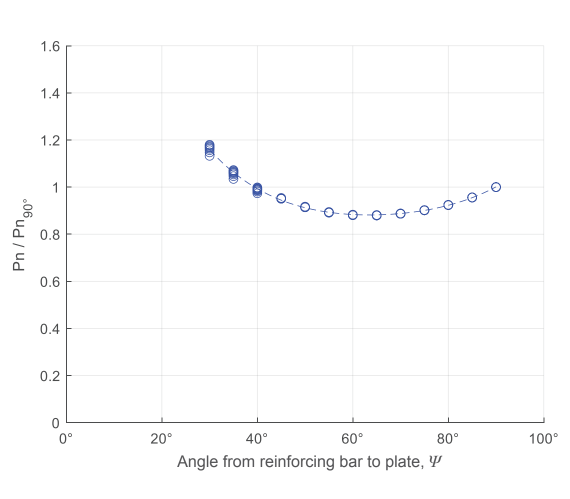


Figure 16. Normalized theoretical values for reinforcement sizes no. 4 to no. 11 at various values of reinforcing steel skew angle Ψ. Note: Dotted line represents the best-fit polynomial regression. This figure is specific to the Z-loss values for self-shielded flux-cored arc welding (FCAW-S). P_n = nominal capacity of weld group applied at eccentricity e. No. 4 = 13M; no. 11 = 36M.

Table 3. Calculated χ factors for various reinforcement skew angles Ψ and weld processes

Skew angle Ψ, degrees	χ factor		
	FCAW-S	FCAW-G, GMAW	SMAW
30	1.16	1.11	1.09
35	1.06	1.03	1.01
40	0.99	0.98	0.95
45	0.94	0.94	0.92
50	0.91	0.91	0.90
55	0.89	0.89	0.89
60	0.88	0.89	0.88
65	0.88	0.88	0.88
70	0.89	0.89	0.89
75	0.90	0.90	0.90
80	0.92	0.92	0.92
85	0.95	0.95	0.95
90	1.00	1.00	1.00

Note: FCAW-G = gas-shielded flux-cored arc welding; FCAW-S = self-shielded flux-cored arc welding; GMAW = gas metal arc welding; SMAW = shielded metal arc welding; χ = skew correction factor.

4.2.3 Fillet Welds. The effective weld area A_{we} shall be the effective weld length multiplied by the effective throat. *For skewed T-joints, the effective area A_{we} shall be the effective weld length multiplied by the effective throat multiplied by the χ factor based on the angle Ψ (see Figure 4.8).*

4.2.3.1 Effective Weld Length. The effective weld length of a curved fillet weld shall be measured along the centerline of the effective throat. *For skewed T-joints (see Figure 4.8), the effective weld length shall be based on a Ψ value of 90 degrees.*

AWS D1.4-18 also lacks provisions for an increase of capacity due to the angle of loading to weld axis comparable to the provisions in AWS D1.1-20[2] sections 4.6.4.2 and 4.6.4.3. The following revision to AWS D1.4-18 Table 4.1, Fillet Welds—External and Internal, is proposed. Revise $0.60F_{EXX}$ as $0.60(1.5)F_{EXX}$.

Given the observed penetration issues at $\Psi \leq 30$ degrees, and in alignment with AWS D1.1-20 section 4.4.3.4, which limits the dihedral angle to at least 30 degrees, an AWS D1.4 minimum Ψ angle restriction of 30 degrees is recommended. The following addition of a new section is proposed:

4.5.5.1 Required Detail. Where reinforcing bars are skewed to base material, see *Figure 4.8. The angle Ψ shall not be less than 30 degrees.*

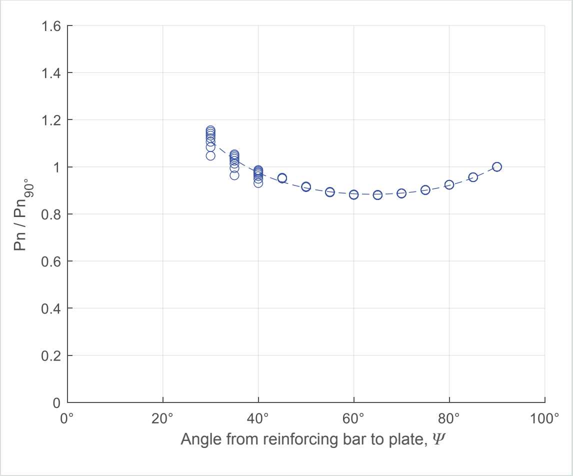


Figure 17. Normalized theoretical values for reinforcement sizes no. 4 to no. 11 at various values of reinforcing steel skew angle Ψ. Note: This figure is specific to the Z-loss values for gas-shielded flux-cored arc welding (FCAW-G) and gas metal arc welding (GMAW). P_n = nominal capacity of weld group applied at eccentricity e. No. 4 = 13M; no. 11 = 36M.

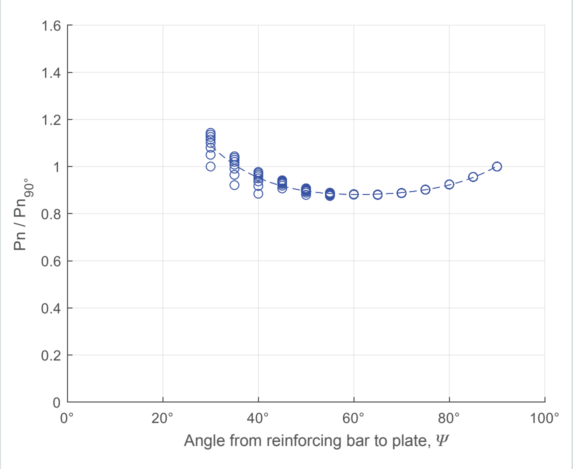


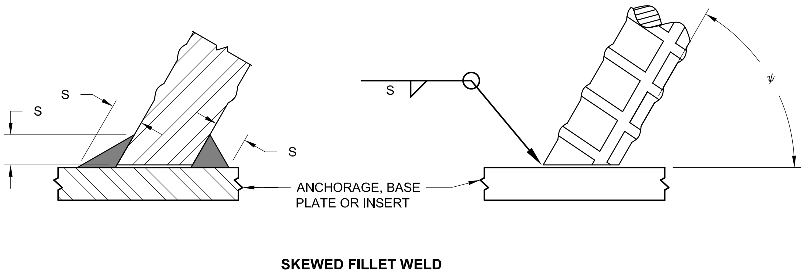
Figure 18. Normalized theoretical values for reinforcement sizes no. 4 to no. 11 at various values of reinforcing steel skew angle Ψ. Note: This figure is specific to the Z-loss values for shielded metal arc welding (SMAW). P_n = nominal capacity of weld group applied at eccentricity e. No. 4 = 13M; no. 11 = 36M.

Figure 19 presents a proposed Fig. 4.8 for AWS D1.4.

Design example

Analyze a no. 8 (25M) reinforcing bar with 9⁄16 in. (14.3 mm) fillet weld to develop 125% of the reinforcing bar's yield strength.

Assume A706 Grade 60 (414 MPa) reinforcing steel, E70 filler material, FCAW-S process, and the angle from plate to reinforcing steel Ψ equal to 60 degrees.



Angle ψ	SMAW χ	FCAW-G GMAW χ	FCAW-S χ
90°	1.00	1.00	1.00
85°	0.95	0.95	0.95
80°	0.92	0.92	0.92
75°	0.90	0.90	0.90
70°	0.89	0.89	0.89
65°	0.88	0.88	0.88
60°	0.88	0.89	0.89
55°	0.89	0.89	0.89
50°	0.90	0.91	0.91
45°	0.92	0.94	0.94
40°	0.95	0.98	0.99
35°	1.01	1.03	1.06
30°	1.09	1.11	1.16

Figure 19. Proposed Fig. 4.8 to be added to the American Welding Society's *Structural Welding Code—Reinforcing Bars* (AWS D1.4). Note: FCAW-G = gas-shielded flux-cored arc welding; FCAW-S = self-shielded flux-cored arc welding; GMAW = gas metal arc welding; SMAW = shielded metal arc welding; *s* = nominal size of fillet weld; χ = skew correction factor .

R_u = demand = (0.79 in.^{2})(60 ksi)(125%) = 59.3 kip

From AWS D1.4 Table 4.1 (with proposed revision) and AWS D1.4-18 section 4.1:

$$\phi R_n = \phi A_{we}(0.60)(1.5)F_{EXX}$$

where

ϕ = capacity reduction factor for shear strength of weld

From AWS D1.4 sections 4.2.3 and 4.2.3.1 and Table 4.8 (with proposed revisions) for $\Psi = 60$ degrees,

$$A_{we} = (l_w)(t_{eff})\chi = \left[\pi\left(d_b + \frac{a}{2}\right)\right]\left(\frac{a}{\sqrt{2}}\right)\chi$$

$$= \left[\pi\left(1\text{ in.} + \frac{\frac{9}{16}\text{ in.}}{2}\right)\right]\left(\frac{\frac{9}{16}\text{ in.}}{\sqrt{2}}\right)0.89 = 1.42\text{ in.}^2$$

where

l_w = length of weld

t_{eff} = effective throat of weld

χ = skew correction value

d_b = diameter of reinforcing steel

a = size of fillet weld

From AWS D1.4 Table 4.1, Fillet Welds—External and Internal, $\phi = 0.75$. Therefore, the allowable capacity is as follows:

$$\phi R_n = 0.75(1.42\text{ in.}^2)(0.60)(1.5)(70\text{ ksi}) = 67.1\text{ kip}$$

67.1 kip > 59.3 kip, so the connection is adequate.

Acknowledgments

Michael Kerr with CB&I Storage Solutions provided the physical testing samples and testing services that made this study possible.

References

1. AWS (American Welding Society) D1.4 Structural Weld-

ing Committee. 2018. *Structural Welding Code—Reinforcing Steel*. AWS D1.4-18. Miami, FL: AWS.

2. AWS D1.1 Structural Welding Committee. 2020. *Structural Welding Code—Steel*. AWS D1.1-20. Miami, FL: AWS.

3. ASTM Subcommittee A01.05. 2018. *Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement*. ASTM A615/A615M-18. West Conshohocken, PA: ASTM International.

4. ASTM Subcommittee A01.05. 2016. *Specification for Low-Alloy Steel Deformed and Plain Bars for Concrete Reinforcement*. ASTM A706/A706M-16. West Conshohocken, PA: ASTM International.

5. ASTM Subcommittee A01.11. 2015. *Standard Specification for Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service*. ASTM A516/A516M-10(2015). West Conshohocken, PA: ASTM International.

Notation

a = size of fillet weld

A_{we} = effective weld area

d_b = diameter of reinforcing steel

e = eccentricity of applied load

F_{EXX} = electrode classification number, electrode strength classification

F_{vi} = allowable unit stress of *i*th segment

$F_{(\rho)}$ = $[\rho(1.9 - 0.9\rho)]^{0.3}$

l_w = length of weld

L_i = effective length of segment *i*

P_n = nominal capacity of weld group applied at eccentricity e

r_{crit} = distance from instantaneous center of rotation to weld element having minimum ratio $\frac{\Delta_u}{r_i}$

r_i = distance from instantaneous center of rotation to *i*th weld element

r_o = dimension locating instantaneous center of rotation from weld group, iterated for convergence

R_i = nominal strength of weld segment *i*

R_n = nominal resistance of weld

R_u = ultimate (factored) demand of connection

s = nominal size of fillet weld

t_{eff} = effective throat of weld

t_i = effective throat of fillet weld in segment *i*

X_o = dimension locating instantaneous center of rotation in the vertical direction, iterated for convergence

Y_o = dimension locating instantaneous center of rotation in the horizontal direction, iterated for convergence

Δ_i = deformation of element *i*

Δ_m = deformation of element at maximum strength

Δ_u = deformation of element when fracture is imminent, usually in the element farthest from instantaneous center of rotation

θ = angle between the direction of force and the axis of the weld element

θ_i = angle between the direction of force and the axis of the weld element of weld segment *i*

ρ = ratio of *i*th element deformation to deformation in element at maximum stress

ϕ = capacity reduction factor for shear strength of weld (taken as 0.75)

χ = skew correction value

Ψ = minimum angle measured from structural plate or shape to inside face of reinforcement bar

Ψ_i = dihedral angle from reinforcing bar to anchor plate at the *i*th segment

About the Author

Erin Pratt, PE, SE, is a structural engineering manager at Clark Pacific, based in the Los Angeles, Calif., area. Pratt is a committee member for the development of the AWS D1.4, *Structural Welding Code—Reinforcing Bars*.

Abstract

Connecting or anchoring reinforcing steel to structural steel plate or shapes using fillet welds is a common detail in precast concrete construction. However, there is currently no guidance on the effects of skewing the reinforcing bar with respect to the plate. This paper reports findings from a study of the effects of a skewed reinforcing bar on both the effective weld area and the overall connection strength. Thirty-two samples of reinforcing bars welded to steel plates at various skew angles were fabricated and tested in tension to failure. These results were compared with an analysis based on the instantaneous center of rotation method presented in the American Welding Society's *Structural Welding Code—Steel* (AWS D1.1-20). Recommendations are presented to revise the *Structural Welding Code—Reinforcing Bars* (AWS D1.4) to account for the effect of skewed reinforcing bars welded to structural steel plate or shapes.

Keywords

Effective area, fillet weld, instantaneous center of rotation, skewed reinforcement.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process. The Precast/Prestressed Concrete Institute is not responsible for statements made by authors of papers in *PCI Journal*. No payment is offered.

Publishing details

This paper appears in *PCI Journal* (ISSN 0887-9672) V. 68, No. 1, January–February 2023, and can be found at https://doi.org/10.15554/pcij68.1-04. *PCI Journal* is published bimonthly by the Precast/Prestressed Concrete Institute, 8770 W. Bryn Mawr Ave., Suite 1150, Chicago, IL 60631.

Reader comments

Please address any reader comments to *PCI Journal* editor-in-chief Tom Klemens at tklemens@pci.org or Precast/Prestressed Concrete Institute, c/o *PCI Journal*, 8770 W. Bryn Mawr Ave., Suite 1150, Chicago, IL 60631.