

CVEN 446

Structural Steel Design

Module 15

Design of Welds

April 20, 2015

Weldment Strength

The design strength of a welded joint or weldment is controlled by either the strength of the weld metal:

$$\phi F_w A_w$$

or the base material:

$$\phi F_{BM} A_{BM}$$

Both strengths are a function of the weld type and the orientation of the weld. AISC-14 Table J2.5 defines the resistance factor for the base metal and weld metal for various types welds and loading conditions.

Weld Design Strength

AISC-14 Table J2.5 defines the resistance factors and nominal strengths for the base metal and weld metal for various types welds and loading conditions.

The orientation of the applied stress with respect to the longitudinal weld axis determines whether the weld is subject to tension, compression, or shear.

TABLE J2.5 Available Strength of Welded Joints, ksi (MPa)						
Load Type and Direction Relative to Weld Axis	Pertinent Metal	ϕ and Ω	Nominal Stress (F_u or F_w) ksi (MPa)	Effective Area (A_{BW} or A_w) in. ² (mm ²)	Required Filler Metal Strength Level ^{(a)(b)}	
COMPLETE-JOINT-PENETRATION GROOVE WELDS						
Tension Normal to weld axis	Strength of the joint is controlled by the base metal				Matching filler metal shall be used. For T- and corner joints with backing left in place, notch tough filler metal is required. See Section J2.6.	
Compression Normal to weld axis	Strength of the joint is controlled by the base metal				Filler metal with a strength level equal to or one strength level less than matching filler metal is permitted.	
Tension or compression Parallel to weld axis	Tension or compression in parts joined parallel to a weld need not be considered in design of welds joining the parts.				Filler metal with a strength level equal to or less than matching filler metal is permitted.	
Shear	Strength of the joint is controlled by the base metal				Matching filler metal shall be used. ^(c)	
PARTIAL-JOINT-PENETRATION GROOVE WELDS INCLUDING FLARE V-GROOVE AND FLARE BEVEL GROOVE WELDS						
Tension Normal to weld axis	Base	$\phi = 0.75$ $\Omega = 2.00$	F_u	See J4	Filler metal with a strength level equal to or less than matching filler metal is permitted.	
	Weld	$\phi = 0.80$ $\Omega = 1.68$	$0.60F_{EXX}$	See J2.1a		
Compression Column to base plate and column splices designed per Section J1.4(1)	Compressive stress need not be considered in design of welds joining the parts.					
Compression Connections of members designed to bear other than columns as described in Section J1.4(2)	Base	$\phi = 0.90$ $\Omega = 1.67$	F_y	See J4		
	Weld	$\phi = 0.80$ $\Omega = 1.68$	$0.60F_{EXX}$	See J2.1a		
Compression Connections not finished-to-bear	Base	$\phi = 0.90$ $\Omega = 1.67$	F_y	See J4		
	Weld	$\phi = 0.80$ $\Omega = 1.68$	$0.90F_{EXX}$	See J2.1a		
Tension or compression Parallel to weld axis	Tension or compression in parts joined parallel to a weld need not be considered in design of welds joining the parts.					
Shear	Base	Governed by J4				
	Weld	$\phi = 0.75$ $\Omega = 2.00$	$0.60F_{EXX}$	See J2.1a		

Weld Design Strength

The continuation of Table J2.5 provides the design parameters for fillet welds as well as plug and slot welds.

Note that fillet welds are designed only for shear.

TABLE J2.5 (continued) Available Strength of Welded Joints, ksi (MPa)					
Load Type and Direction Relative to Weld Axis	Pertinent Metal	ϕ and Ω	Nominal Stress (F_{uBM} or F_{wBM}) ksi (MPa)	Effective Area (A_{BM} or A_{wE}) in. ² (mm ²)	Required Filler Metal Strength Level ^{(a)(b)}
FILLET WELDS INCLUDING FILLETS IN HOLES AND SLOTS AND SKEWED T-JOINTS					
Shear	Base	Governed by J4			Filler metal with a strength level equal to or less than matching filler metal is permitted.
	Weld	$\phi = 0.75$ $\Omega = 2.00$	$0.60F_{EXX}^{(c)}$	See J2.2a	
Tension or compression Parallel to weld axis	Tension or compression in parts joined parallel to a weld need not be considered in design of welds joining the parts.				
PLUG AND SLOT WELDS					
Shear Parallel to faying surface on the effective area	Base	Governed by J4			Filler metal with a strength level equal to or less than matching filler metal is permitted.
	Weld	$\phi = 0.75$ $\Omega = 2.00$	$0.60F_{EXX}$	See J2.3a	

^(a) For matching weld metal see AWS D1.1/D1.1M, Section 3.3.
^(b) Filler metal with a strength level one strength level greater than matching is permitted.
^(c) Filler metals with a strength level less than matching may be used for groove welds between the webs and flanges of built-up sections transferring shear loads, or in applications where high restraint is a concern. In these applications, the weld joint shall be detailed and the weld shall be designed using the thickness of the material as the effective throat, where $\phi = 0.60$, $\Omega = 1.68$ and $0.60F_{EXX}$ is the nominal strength.
^(d) Alternatively, the provisions of Section J2.4(a) are permitted provided the deformation compatibility of the various weld elements is considered. Sections J2.4(b) and (c) are special applications of Section J2.4(a) that provide for deformation compatibility.

Weld Strength

The weld area, whose definition differs for the different weld types is given as the effective throat times the weld length or:

$$A_w = t_e L_w$$

where

t_e = effective throat of the weld
= shortest distance from the root of the joint to the face of the weld

and

L_w = weld length

Matching Weld Metal

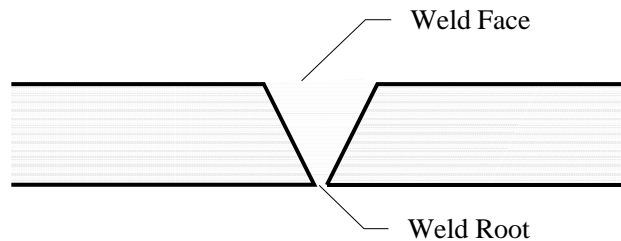
Matching weld metal means that the electrode strength (both yield and tensile strength) is similar to the strength of the base metal.

Base Metal		Matching Filler Metal
A36 $\leq \frac{3}{4}$ in. thick		60 & 70 ksi filler metal
A36 $> \frac{3}{4}$ in. A588* A1011	A572 (Gr. 50 & 55) A913 (Gr. 50) A992 A1018	SMAW: E7015, E7016, E7018, E7028 Other processes: 70 ksi filler metal
A913	(Gr. 60 & 65)	80 ksi filler metal
*For corrosion resistance and color similar to the base metal, see AWS D1.1/D1.1M, subclause 3.7.3. Notes: Filler metals shall meet the requirements of AWS A5.1, A5.5, A5.17, A5.18, A5.20, A5.23, A5.28 or A5.29. In joints with base metals of different strengths, use either a filler metal that matches the higher strength base metal or a filler metal that matches the lower strength and produces a low hydrogen deposit.		

Weld Terminology

Root - the innermost portion of the weld or the origin of the weld. The first pass of a multi-pass weld begins in the root of the weld.

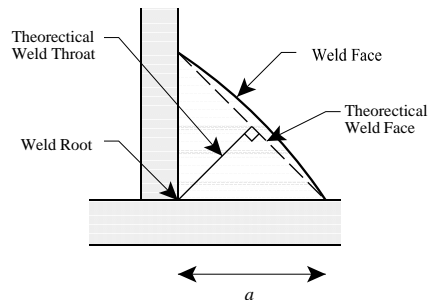
Face - is the outer most portion of the weld. The final passes of a multi-pass weld form the weld face.



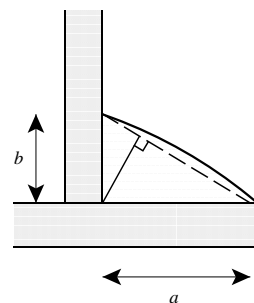
Complete Penetration Groove Weld

Fillet Weld Design Strength

The effective area is defined as the length of the weld times the effective thickness which is equal to the shortest distance between the root and weld face:



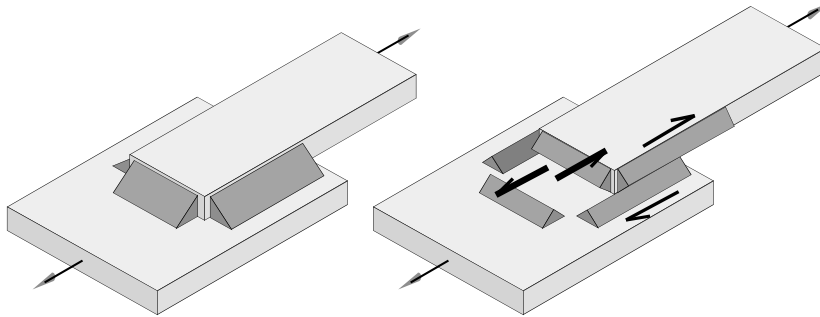
Equal Legs: $t_e = \frac{a}{\sqrt{2}} = 0.707a$



Unequal Legs: $t_e = \frac{ab}{\sqrt{a^2 + b^2}}$

Fillet Weld Design Strength

Failure of a fillet weld is assumed to always occur by shear on the throat. This failure occurs regardless of the orientation of the longitudinal axis of the weld with respect to the applied load.



Fillet Weld Design Strength

When the SAW process is used in conjunction with fillet welds, the AISC-LRFD specifications allow a slightly greater effective throat.

This is because the SAW welding process involves greater heat input resulting in a deeper penetration of the weld metal at the weld root. However, increased penetration only occurs during the first (or root) pass. Consequently, the effective throat is given as:

$$t_e = a \quad \text{for } a \leq 3/8"$$

and

$$t_e = 0.707 a + 0.11 \text{ for } a > 3/8"$$

Design of Fillet Welds

For design purposes, it is often convenient to express the design strength of a fillet weld per inch of length:

$$\phi k_w = \phi F_w t_e$$

For a given factored design load, the required weld length can then be determined by:

$$L_{req} = \frac{P_u}{\phi k_w} = \frac{P_u}{0.75(0.60) F_{EXX} 0.707 a}$$

where P_u is the factored design load.

Maximum Fillet Weld Size

In general, there is no absolute maximum fillet weld size. However, for large fillet welds (greater than 1/2"), a large amount of heat is put into the connection.

This can lead to distortion and weld cracking if precautions are not taken, such as preheating the base metal in the vicinity of the weld.

Preheat allows for more even cooling and a reduction in the formation of residual or restraint stresses.

Maximum Fillet Weld Size

Another consideration for the maximum weld size is the fact that only so much weld metal can be deposited during a single pass of the electrode.

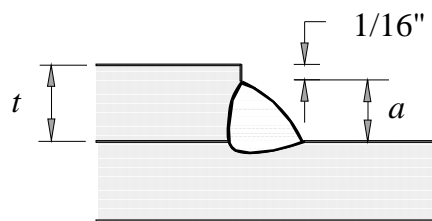
For manual welding (SMAW and SAW), the maximum size of a fillet weld that can be deposited during a single pass is 5/16".

A cost factor for welds is the number of passes that must be made to build up the required weld size, a . After each pass, the welding process must be stopped and the completed pass cleaned.

For automatic SAW, the maximum weld size is 3/8".

Maximum Fillet Weld Size

When welding along edges of connected parts, as is the case with fillet welded lap joints, the edge of the plate must not be consumed in the weld so that the correct weld size can be determined.



$$a_{max} = t \quad \text{for } t < 1/4"$$

$$a_{max} = t - 1/16" \quad \text{for } t \geq 1/4"$$

Minimum Fillet Weld Size

The minimum weld size is based on the quenching effect of thick plates on small welds.

If the weld metal cools too quickly due to the large flow of heat into the thick base plate, the weld may become brittle (low fracture toughness).

This weld size limitation is not based on strength considerations. Smaller weld size can be used with preheating.

Minimum Fillet Weld Size

Based on the thickness of the thicker part being joined, the minimum fillet weld size, a_{min} , is given in AISC-14 Table J2.4:

TABLE J2.4 Minimum Size of Fillet Welds	
Material Thickness of Thinner Part Joined, in. (mm)	Minimum Size of Fillet Weld, ^(a) in. (mm)
To 1/4 (6) inclusive	1/8 (3)
Over 1/4 (6) to 1/2 (13)	3/16 (5)
Over 1/2 (13) to 3/4 (19)	1/4 (6)
Over 3/4 (19)	5/16 (8)
^(a) Leg dimension of fillet welds. Single pass welds must be used. Note: See Section J2.2b for maximum size of fillet welds.	

Minimum Fillet Weld Length

A minimum fillet weld length is specified as:

$$L_{min} = 4a$$

This restriction is to ensure that the weld obtains the proper weld profile and throat. Fillet welds generally taper at their ends, reducing the effective thickness of the weld to zero.

Minimum Fillet Weld Length

When only longitudinal welds are used for the connection of plates and bars, their length may not be less than the distance between them.

Note the limitations for the reduction factor, U , for fillet welded connections

Design of C-J-P Groove Welds

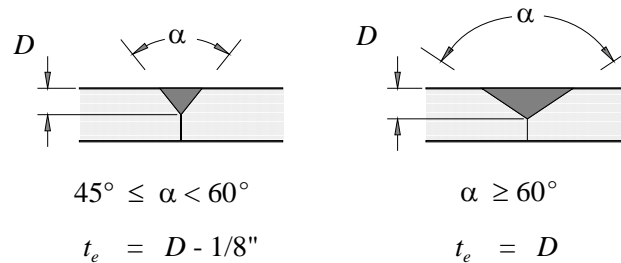
The design of complete-joint-penetration (C-J-P) groove welds is relatively simple since the effective area of the weld, A_w , is equal to the full cross sectional area of the base metal.

For C-J-P groove welds subject to tension (as in a butt splice), the strength of the weld metal need only match the strength of the base metal strength. The strength of the connection is controlled by gross section yielding of the base plate. No explicit design of the weld is required. If plates of different areas are joined, the design strength of the splice is controlled by the plate with the smaller cross sectional area.

Design of P-J-P Groove Welds

Similar to a C-J-P groove weld, the effective area of a partial-joint-penetration groove weld is equal to the effective throat times the length of the weld.

However, the effective throat of the partial penetration weld is less than either of the plate thicknesses being joined.



Design of P-J-P Groove Welds Subject to Tension

Partial-joint-penetration groove welds subject to tension normal to the effective area must be designed for both weld metal and base material strength. The weld metal strength is taken as

$$\phi F_w A_w = 0.80 (0.60) F_{EXX} A_w$$

and the base material strength as

$$\phi F_{BM} A_{BM} = 0.9 F_y A_w$$

which assumes only the area of the plate adjacent to the weld yields.

Design of P-J-P Groove Welds Subject to Compression

When a partial penetration groove weld is subject to compression normal to the effective weld area or either tension or compression parallel to the axis of the weld, only the strength of the base material needs to be checked:

$$\phi F_{BM} A_{BM} = 0.9 F_y A_w$$

Design of P-J-P Groove Welds Subject to Shear

For partial penetration groove welds subject to shear, both weld metal and base material strength must be checked as:

$$F_w A_w = 0.75 (0.60) F_{EXX} A_w$$

and

$$\phi R_n = 0.75 F_u A_{nv}$$

where A_{nv} is the net area subject to shear which is the effective area of the weld and

$$\phi R_n = 0.9 (0.60) F_y A_{gt}$$

where A_{gt} is the gross area of the plate subject to shear.

Weld Procedure Qualification

In order for fabricators to weld structural joints, they must qualify their welding procedures.

This involves welding up a C-J-P groove weld test plate and destructively testing it for strength and quality.

The parameters of the welding procedure include:

- Electrode strength and type
- Base metal strength
- Weld Process (SAW for example)
- Heat Input (current, travel speed, etc.)

Prequalified Welded Joints

The American Welding Society (AWS) Document D1.1 provides provisions for welded joints that are *prequalified*.

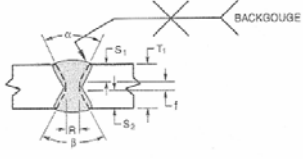
This means that the fabricator can use these joints with a prequalified procedure and not have to do any additional testing to insure weld joint strength and soundness.

Limits on joint geometries, such as root openings, angles, and clearance are given and are based on a long history of successful use and performance of these joints.

Use of prequalified joints still requires the application of sound engineering judgement.

Prequalified Welded Joints

AISC-14 provides a series of tables that replicates the AWS prequalified welded joints (pp. 8-36 to 8-64).

Table 8-2 (continued)						
Prequalified Welded Joints						
Complete-Joint-Penetration Groove Welds						
Double-V-groove weld (3) Butt joint (8) 				For B-U3c-S only		
				T ₁		S ₁
				Over	to	
				2	2 1/2	1 3/8
				2 1/2	3	1 3/4
				3	3 3/8	2 1/8
				3 3/8	4	2 3/8
				4	4 3/4	2 3/4
				4 1/2	5 1/2	3 1/4
				5 1/2	6 1/4	3 3/4
				For T ₁ > 6 1/4 or T ₁ ≤ 2 S ₁ = 1/2(T ₁ - 1/4)		
Welding Process	Joint Designation	Base Metal Thickness (U = unlimited)		Groove Preparation		Notes
		T ₁	T ₂	Root Opening Root Face Groove Angle	Tolerances As Detailed (see 3.13.1) As Fit-Up (see 3.13.1)	
SMAW	B-U3b	U	—	R = 0 to 1/8 f = 0 to 1/8 α = β = 60°	+1/16, -0 +1/16, -0 +10°, -0°	4, 5, 8, 10
GMAW FCAW	B-U3-GF	U	—	R = 0 f = 1/4 min α = β = 60°	+1/16, -0 +1/4, -0 +10°, -0°	1, 4, 8, 10
SAW	B-U3c-S	U	—	R = 0 f = 1/4 min α = β = 60°	+1/16, -0 +1/4, -0 +10°, -0°	4, 8, 10