By Richard L. Holdren

What Is This Thing Called Convexity?

An approach is suggested that would provide inspectors with a method to better assess and determine the acceptability of convexity

Convexity is defined in AWS A3.0:2010, *Standard Welding Terms and Definitions*, as "the maximum distance from the face of a convex fillet weld perpendicular to a line joining the weld toes." Figure 1, which is adapted from Fig. 25B of A3.0:2010, illustrates this dimension. Red arrows have been added to show this dimension at the location where a measurement would be made. It also illustrates the inherent difficulty visual welding inspectors face in the assessment of convexity, i.e., the dimension is referenced from a hidden (or imaginary) line. This would be akin to a requirement to measure the size of a bolt by measuring its radius. While convexity is easy to observe and measure in cross section, the visual welding inspector is severely challenged in terms of assessing this condition and determining its acceptability according to common industry standards when only the weld face is accessible.

In simpler terms, convexity is a condition found only in a fillet weld with a convex profile. An analogous dimension in a groove weld would be weld reinforcement height. Most codes provide visual weld acceptance criteria for convexity in terms of a simple linear dimension; however, as noted above, this dimension is measured from a hidden line. Therein lies the challenge for the visual welding inspector.

Many codes provide acceptance criteria for this discontinuity, with AWS D1.1, *Structural Welding Code — Steel*, being the one most prominent in the United States. The other structural welding codes published by the American Welding Society deal with convexity in approximately the same manner as D1.1. Table 1 provides a sampling of fillet weld convexity requirements from various industry standards.

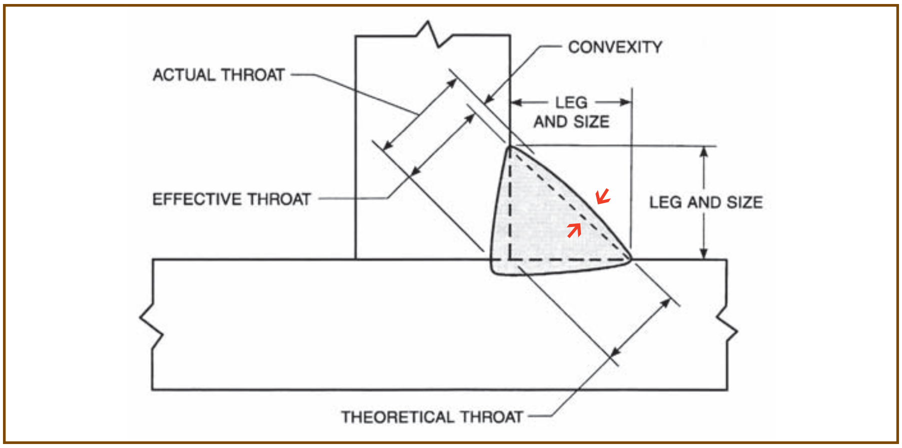

Fig. 1 — Convex fillet weld.

While there certainly is no consensus among the various standards for the permissible amount of convexity, virtually all of them specify a maximum dimension for the geometric condition. That dimension, however, is virtually immeasurable, as indicated previously. So, the welding inspector is at a severe disadvantage when asked to evaluate this discontinuity during the course of visual examination. Specification of quality requirements in such a fashion is considered irresponsible. There needs to be a better means of evaluating this discontinuity, but before an alternate approach is proposed, it's important to better understand what impact convexity has from a structural, or performance, standpoint.

At first glance, convexity appears to be a benefit, since it represents an increase in the fillet weld cross section, or throat. Convexity represents the difference between the effective and actual throat of a convex fillet weld. In a correctly designed structure, fillet welds are intended to only transmit loads in shear, where the shear stress is transmitted through the weld throat. Consequently, the greater the amount of convexity, the greater the shear plane cross section, and therefore, the greater the load-carrying capacity of the fillet weld.

The issue, however, relates to the direction in which the loads are applied. If the loads are applied parallel to the weld axis, the increase in weld cross section due to convexity is indeed a benefit. Should the fillet weld lie transverse to the applied stress, however, convexity represents a geometric discontinuity due to the stress concentrations created at the weld toes. This geometric discontinuity is even more critical when the primary

Table 1 — Convexity Requirements from Various Welding Standards

Standard	Category	Requirement
AWS D1.1:2006	Statically and cyclically loaded structures (5.24.3)	•For face width (W) ≤ 5/16 in. ⇒ 1/16 in. maximum convexity (C) •For 5/16 in. < W < 1 in. ⇒ 1/8 in. maximum convexity (C) •For W ≥ 1 in. ⇒ 3/16 in. maximum convexity (C)
AWS D1.1:90	Statically and cyclically loaded structures	•For measured leg size (L) ≤ 5/16 in. ⇒ 1/16 in. maximum convexity (C) •For 5/16 in. < L < 1 in. ⇒ 1/8 in. maximum convexity (C) •For L ≥ 1 in. ⇒ 3/16 in. maximum convexity (C)
AWS D1.1:85	Statically and cyclically loaded structures	Maximum convexity (C) = 0.07 × face width (W) + 0.06 in.
AWS D1.2:2003	Statically and cyclically loaded structures (5.14.2)	Maximum convexity (C) = 0.07 × face width (W) + 0.06 in.
	Tubular structures – Class 1 (5.14.4, Table 5.5)	Maximum convexity (C) = 0.15 × largest specified leg size (S) + 0.06 in.
	Tubular structures – Class 2 (5.14.4, Table 5.6)	Maximum convexity (C) = 20% of theoretical throat
AWS D1.3:98	Fillet weld face (6.1.1.4)	Faces of fillet welds shall be flat or slightly convex.
AWS D1.5:2002	Quality of Welds – Visual Inspection (6.26.1.4)	Maximum convexity (C) = 0.07 × face width (W) + 0.06 in.
AWS D14.1:2005	Welding Profiles (10.7.1)	Maximum convexity (C) = 0.1 × actual fillet weld size (S) + 0.03 in.
AWS D14.3:2005	Quality of Welds – Fillet Welds (9.5.5.1)	Maximum convexity (C) = 0.1 × actual leg size + 0.06 in.
AWS D14.4:2005	Joint Class I through VI	•For face width (W) ≤ 5/16 in. ⇒ 1/16 in. maximum convexity (C) •For 5/16 in. < W < 1 in. ⇒ 1/8 in. maximum convexity (C) •For W ≥ 1 in. ⇒ 3/16 in. maximum convexity (C)
AWS D14.6:2005	Weld Surface Conditions (7.4.1)	Maximum convexity (C) = 0.1 × actual (or longer) leg size + 1/32 in.
AWS D15.1:2001	Weld Profiles – Fillet Welds (13.4.1)	General Note: Maximum convexity (C) = 0.07 × face width (W) + 0.06 in. •For face width (W) ≤ 5/16 in. ⇒ 1/16 in. maximum convexity (C) •For 5/16 in. < W < 1 in. ⇒ 1/8 in. maximum convexity (C) •For W ≥ 1 in. ⇒ 3/16 in. maximum convexity (C)
AWS D17.1:2001	Figure 6.1 – Acceptable and Unacceptable Weld Profiles	•For face width (W) ≤ 5/16 in. ⇒ 1/16 in. maximum convexity (C) •For 5/16 in. < W < 1 in. ⇒ 1/8 in. maximum convexity (C) •For W ≥ 1 in. ⇒ 3/16 in. maximum convexity (C)
MIL-STD-1688A	Shape of fillet weld face (7.4.4)	•–1/16 in. to + 3/16 in. from line drawn toe to toe •Reentrant angles > 90 deg
MIL-STD-1689A	Shape of fillet weld face (8.2.3)	Fillet and fillet reinforced welds shall be essentially flat (–1/16 in. to + 3/16 in. of a line drawn toe to toe).
MIL-STD-2035	Shape of the weld face (4.2.1)	Welds shall be free of sharp irregularities between weld beads and shall blend smoothly and gradually with the base metal at the weld edges without exceeding the undercut (4.2.16) or reentrant angle (4.2.19) limits of this specification. 4.2.19 Reentrant angle. The angle formed between the base plate and the toe of the weld and the angle formed between adjacent beads of a weld must be 90 deg or greater.
ISO 5817(a)	No. 1.12, Incorrect weld toe – groove welds	α = toe reentrant angle
	Quality Level D	α ≥ 90 deg
	Quality Level C	α ≥ 110 deg
	Quality Level B	α ≥ 150 deg
ISO 5817(a)	No. 1.12, Incorrect weld toe – fillet welds	α = toe reentrant angle
	Quality Level D	α ≥ 90 deg
	Quality Level C	α ≥ 100 deg
	Quality Level B	α ≥ 110 deg

(a) *Welding — Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) — Quality levels for imperfections* stresses are transverse to the weld axis, and the structure is loaded in a cyclic (fatigue) manner.

So, the critical issue is the resulting reentrant angle at the weld toes, which defines the degree of stress concentration. Consequently, if the goal is to judge convexity in terms of its effect on the structural performance of a fillet weld, a better approach would be to limit the reentrant angle at the weld toes rather than the amount of convexity present. Not only does this more directly address how a weld performs in service, reentrant angle is a geometric condition that could be more easily measured by the welding inspector. In fact, go/no-go gauges could be developed to aid in a more efficient and effective measurement of the condition. Figure 2 shows various combinations of convexity and reentrant angles in fillet welds.

The illustrations shown in Fig. 2 are drawn approximately to scale to show how much convexity might be present and the weld still be considered acceptable in terms of the current requirements in AWS D1.1 and several other codes. The ¼-in. weld size has an actual face of just over 5⁄16 in., so the maximum permissible convexity is ⅛ in. In both cases, the amount of convexity is acceptable, but the reentrant angles at the weld toes are less than 90 deg so these welds would be considered unacceptable due to overlap.

Another issue with the bracketed approach to defining permissible convexity, i.e., a given amount of convexity for a range of face widths, is the fact that the same amount of convexity produces dramatically different reentrant angles. In the current D1.1 system, theoretical face widths from 5⁄16 to 1 in. relate to fillet weld sizes from ¼ to 11⁄16 in. Figure 3 shows the same amount of convexity (⅛ in.) as in Fig. 2A, but in this case, the fillet weld size is 11⁄16 in.

It is obvious here that, not only is the convexity acceptable, the weld is free from overlap. Comparing Figs. 2A and 3 shows that assignment of a specific amount of convexity for a range of fillet weld sizes can result in dramatically different stress concentrations at the weld toes.

While the intent of this article is to point out the deficiencies in most of the currently employed systems for limiting convexity in fillet welds, both from a geometric and inspection standpoint, it is realized that requesting such a dramatic change in the approach will not result in any immediate changes in the standards. Before providing what I believe to be a viable solution, I'd like to present a description of a technique that can be employed, with available gauges, to measure the amount of convexity present in a fillet weld. It must be pointed out that such an approach is theoretical, and measurements are based on nominal fillet weld sizes. It does, however, provide the inspector with a better approach than just "eyeballing" the weld profile and making a judgment. Since AWS D1.1 is generally considered to be the dominant standard for structural welding, the example below is based on the current AWS D1.1 requirements for convexity.

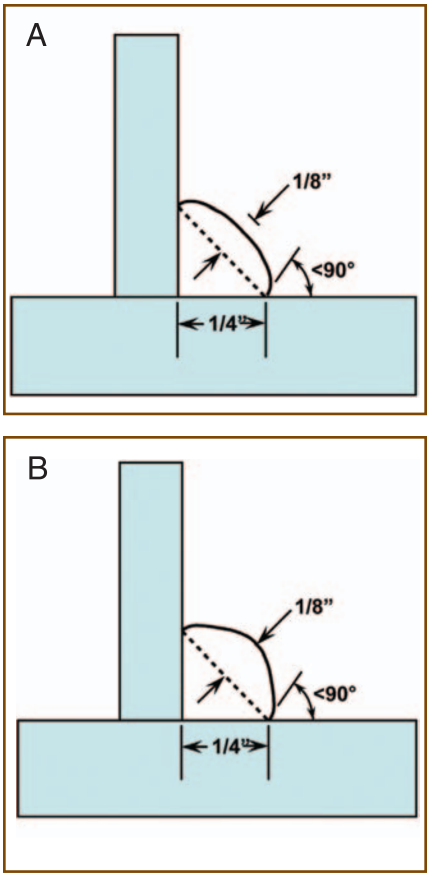

Fig. 2 — ¼-in. fillet welds with acceptable convexity per AWS D1.1.

Method for Measuring Fillet Weld Convexity

AWS D1.1 Limits. The limitations on convexity are shown in Table 2 (from Fig. 5.24 of AWS D1.1:2006). The permissible amount of convexity is based upon the fillet weld face width, or width of individual weld bead, either of which is difficult to measure. Once the face width is determined, the permissible convexity is then per Table 2.

Measurement Technique

This technique utilizes trigonometry to determine the theoretical dimensions and then uses a fillet weld gauge normally employed for measurement of concave fillet weld profiles to make the actual measurement. This example is for a specified ¼-in. (6-mm) fillet weld. Refer to Fig. 4 for the nomenclature used in the calculations.

Calculations. Per the geometric properties of a triangle:

$T_1 = 0.707 \times 0.25$ in.
$T_1 = 0.18$ in.

$T_2 = T_1 + 0.13$ in.
$T_2 = 0.31$ in.

$L_2 = T_2/0.707$
$L_2 = 0.31/0.707$
$L_2 = 0.44$ in. (7⁄16 in.)

A 7⁄16-in. concave fillet weld gauge

Table 2 — Determining Permissible Convexity

Face width or width of individual weld bead, W	Maximum permissible convexity
W ≤ 5⁄16 in. (8 mm)	1⁄16 in. (2 mm)
5⁄16 in. < W < 1 in. (25 mm)	⅛ in. (3 mm)
W ≥ 1 in.	3⁄16 in. (5 mm)

Table 3 — Dimensional Limits for a Range of Fillet Weld Sizes

Fillet weld size, in.	Theoretical face width, in.	Permissible convexity, in.	Concave fillet weld gauge or fillet weld throat gauge to be used to measure convexity
3⁄16	0.27	1⁄16	0.28 (~9⁄32)
¼	0.35	⅛	0.43 (~7⁄16)
5⁄16	0.44	⅛	0.49 (~½)
⅜	0.53	⅛	0.55 (~9⁄16)
7⁄16	0.62	⅛	0.61 (~⅝)
½	0.71	⅛	0.68 (~11⁄16)
⅝	0.88	⅛	0.80 (~13⁄16)
¾	1.1	3⁄16	1.02 (~1)
⅞	1.2	3⁄16	1.14 (1 9⁄64)
1	1.4	3⁄16	1.27 (~1¼)

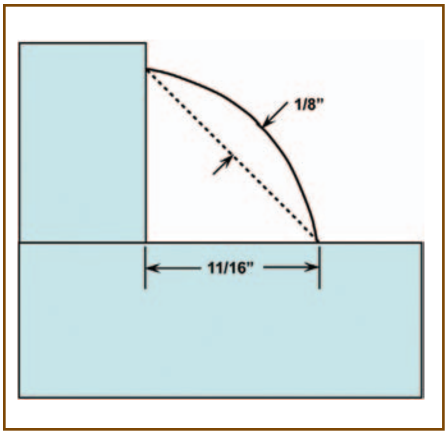

Fig. 3 — Acceptable convexity in a 11⁄16-in. fillet weld per AWS D1.1.

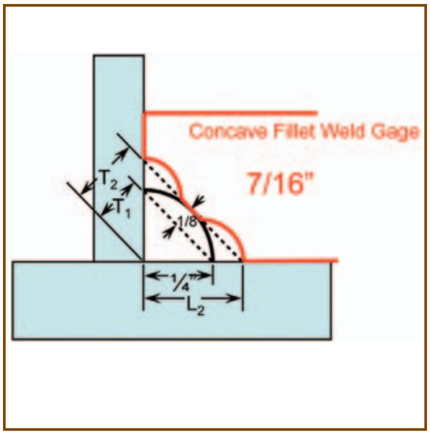

Fig. 4 — Use of a concave fillet weld gauge to approximate the amount of permissible convexity.

can be used to approximate the amount of convexity permissible for a ¼-in. fillet weld (as shown in Fig. 4).

Table 3 summarizes the dimensional limits for a range of fillet weld sizes and what concave fillet weld (or fillet weld throat) gauges can be used to measure convexity.

The Proposed Solution

Having laid this foundation, the important aspect of this exercise is to provide some viable solution to allow the designer to stipulate the necessary fillet weld profile for a given weld based on the expected loading conditions and to provide the inspector with a means of judging the result in a more effective and accurate manner.

I believe the solution is the approach put forth in ISO 5817, *Welding — Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) — Quality levels for imperfections*. With various classes available to the designer, convexity requirements for different loading conditions can be specified quite easily. This can be done on a weld-by-weld basis, so those welds subject to more critical loading conditions can be specified as Class B, for example. Other welds whose loading conditions deem them less critical can be assigned Class C or D status. This differentiation could be included in the tail of the welding symbol so the designer could very easily dictate the specific weld requirements to both production and inspection personnel.

AWS D1.1 has used this type of approach for limits on undercut; however, the requirement falls short because there is no stipulation that the designer designate which welds are transverse to the applied stress and which ones are parallel. It should be designated in the tail of the symbol so the inspector has all the information necessary to perform his/her job effectively.

Proposed Solution

1. Rather than controlling fillet weld profile by specifying a dimension for convexity, specify limits for the reentrant angle at the weld toe.

2. Provide different limits for different loading conditions so the toe angle can be specified according to the expected service conditions.

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