Welding WISDOM: Part Two

BY DUANE K. MILLER, P.E.

Following the right principles can lead to better welded connections and better projects.

IN THE AUGUST ISSUE OF *Modern Steel*, we posed the question: "What makes for a good welded connection?" and provided seven principles that can help create better, more efficient welds. Here are seven more.

Principle 8: A good welded connection has a clearly defined throat.

The strength of a weld depends on the throat dimension—and the length and the resistance provided by the deposited weld metal. Sometimes, the actual weld throat is not what it appears to be, and therefore the weld will not have the expected capacity. Engineers should be aware of this potential when designing and detailing welded connections. Two examples will be used to illustrate this principle, even though many more exist.

Consider the butt joints shown in Figure 1. In part A, the weld symbol calls for a CJP groove weld with a throat that extends through the thickness of the member (as illustrated in part B). However, as can be seen in part C, a non-prequalified square groove weld detail was selected. When welding on thick material, the weld will not penetrate through the thickness of the material, even when welded from both sides. Visually, the welds shown in parts B and C might look similar, and yet there is a significant difference in the actual weld throat dimensions and the resultant strength of the welded connection.

The tee joint with fillet welds, as shown in Figure 2 (opposite page), provides another example of weld throats that may be significantly less than they appear to be. In part A, the tee joint has good fit-up, and the weld throat dimension is as would be expected. In part B, a weld with the same leg size is provided, one that would appear identical to the one shown in part A. The actual throat, however, is essentially zero and consists of only a small ligament that is attached to the upper member of the tee joint.

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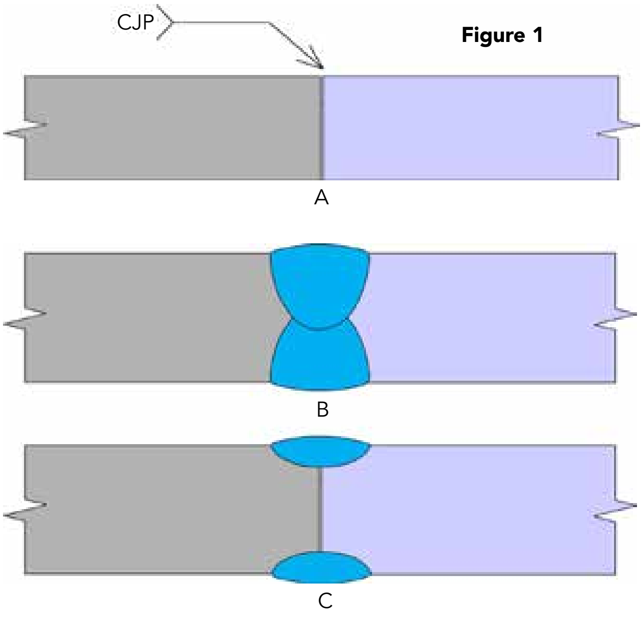


Figure 1

The designers of good welded connections anticipate these types of situations. In the case of the butt joints shown in Figure 1, AWS D1.1: *Structural Welding Code—Steel* recognizes this potential and accordingly does not prequalify the type of joint detail shown in Part C. As to the problem of fit-up shown in Figure 2, D1.1 has provisions to limit the fit-up gaps, as well as to compensate for excessive gaps.

Principle 9: A good welded connection recognizes material properties.

Steel is often treated as an isotropic material, and in many ways it is. It is certainly more isotropic than some other building materials. In general, steel has the best combination of properties in the direction of rolling. In terms of the yield and tensile strength, the transverse and through-thickness properties are typically at least 80% of those in the longitudinal direction. Remember that it is the longitudinal properties that are usually recorded on mill test reports. Fortunately, for most rolled members, the major forces imposed on the member are in line with the direction of rolling—i.e., aligned with the best properties of the steel.

This is not the case, however, with connections where members may intersect perpendicular to the rolling direction. And, in the case of welded connections, sometimes it is in the through-thickness direction that the greatest strains are applied, whether due to weld shrinkage or service loads.

While the strength properties in the three orthogonal directions are similar, the ductility may vary. One measure of ductility is reduction-in-area (R.A.), where higher values indicate better ductility. Differences in ductility in the transverse and through-thickness direction, as compared to the ductility in the longitudinal direction, should be considered when detailing welded connections.

The data in Figures 3 and 4 are based on the work of Barsom and Korvink ("Through-Thickness Properties of Structural Steels, Report No. SAC/BD-97/01, SAC Joint Venture, 1997). In general, the R.A. in the longitudinal direction was in the range of 60% to 80%. In Figure 3, the R.A. for the majority of the data in the transverse direction is in the 40% to 80% range. In the through-thickness direction, as seen in Figure 4, the R.A. ranges from 5% 80%, with many examples where the value is less than 20%. It is noteworthy, however, that in some cases, the ductility in the through-thickness direction is nearly the same as in the longitudinal direction.

Figure 2

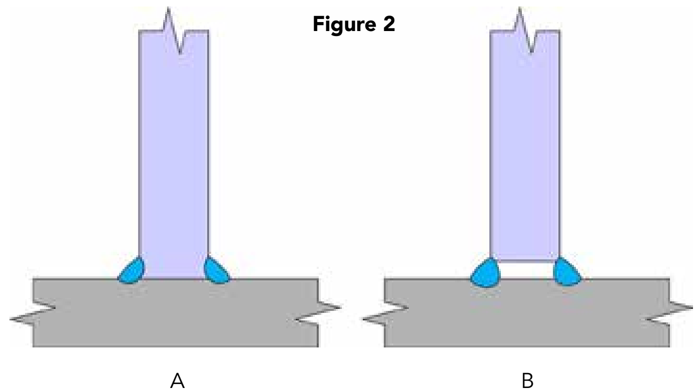


Figure 3
Adapted from Barsom and Korvink, *Through-Thickness Properties of Structural Steels*

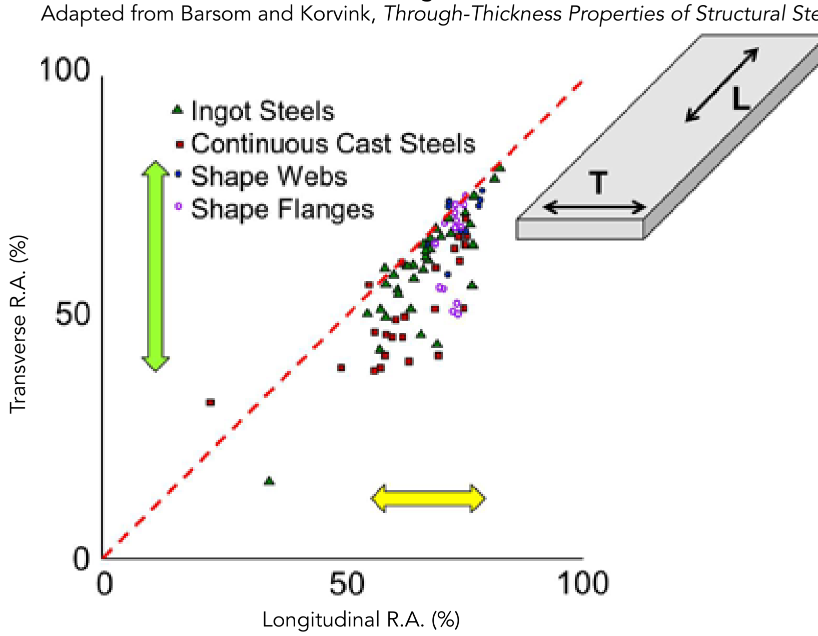
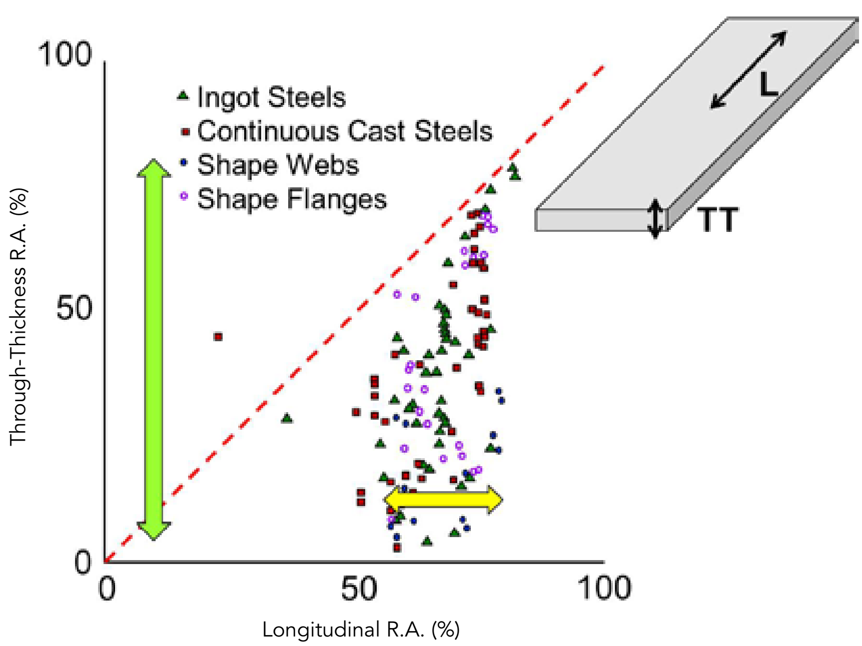


Figure 4
Adapted from Barsom and Korvink, *Through-Thickness Properties of Structural Steels*



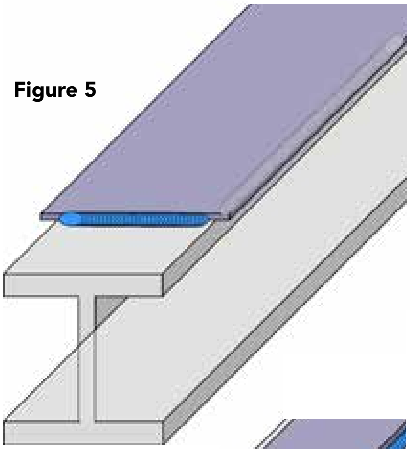


Figure 5

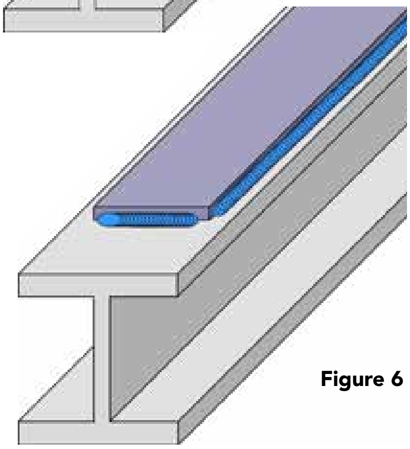


Figure 6

This variation in material property must be considered when connections are designed. The decrease in through-thickness ductility is one contributor to lamellar tearing. While steel with improved through-thickness ductility can be specified, better detailing and welding practices can also be employed to reduce the through thickness ductility demands.

Other material properties that must be considered include regions of potentially low notch toughness, such as the k-area, the "core" region of heavy rolled sections and the corners of cold-formed tubing. As was the case for ductility in rolled material, considerable variation in toughness is experienced in the three orthogonal directions.

Principle 10: A good welded connection is easy and economical to fabricate and erect.

Easy usually means economical, and complex usually means expensive. Further, issues of cost may be viewed by the engineer as the contractor's concern. However, there are many situations where easy and economical leads directly to quality and dependability.

Consider the two cover plate details shown in Figures 5 and 6. The longitudinal fillet welds associated with the wider cover plate would be made in the horizontal position (with the beam rotated 180° from the view shown in the figure). Next, the beam would need to be rotated to make the transverse weld. In the case of the narrower cover plate, all the welding could be made without the need to rotate the beam.

Principle 11: A good welded connection is easily inspected.

Hard-to-make welds are often hard to inspect. If the welder needs to duct tape an electrode holder to the end of a broom handle to gain access to the joint for welding, how will the inspector subsequently see the weld for inspection? In some cases, a welded detail may be easily inspected at one stage, but when other components are added, inspection may become difficult or impossible. A well-designed welded connection considers how inspection, both visual and nondestructive, will be performed.

An example from seismic design will illustrate this concept. The so-called "pre-Northridge" moment connection contained a number of deficiencies, one of which was the difficulty of reliable volumetric inspection with ultrasonic testing. Left-in-place backing made it difficult to distinguish between a weld with a quality root pass and a weld with a defect in the root. Further, the presence of the beam web precluded full length inspection of the bottom beam flange to column flange weld.

The inspection problem associated with the pre-Northridge moment connection was solved in AISC 358: *Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications* by requiring backing removal (which eliminated the naturally occurring planar discontinuity in the weld root and the corresponding UT challenges) and relying on back gouging to visually verify weld root quality.

Principle 12: A good welded connection recognizes commercial realities.

CAD files can produce drawings with perfectly dimensioned members, all shown accurately to scale. When the concepts shown on paper are translated into steel, commercial realities convert perfect dimensions into close approximations. Two examples of these commercial realities will be used as illustrations: the permitted variations in structural shapes and the permitted distortions caused by welding.

ASTM A6 controls the permitted variation in the dimensions of rolled structural members. While desirable, flanges are not always perpendicular to the web. The total out-of-square allowance (T' plus T) for W-sections over 12 in. deep is 5⁄16 in., as can be seen in Figure 7. The end of the beam that will frame into the column is ideally cut perpendicular to the beam's longitudinal axis for most construction. If the beam is perfectly prepared (i.e., cut square and to the proper length) with a properly prepared bevel for a groove weld, and if the column is delivered with the maximum permitted out-of-square variation, one end of the groove weld will have a root opening that is 5⁄32 in. too narrow while the other end will be 5⁄32 in. too wide. And all of this assumes the end of the beam has been properly prepared. If the beam is not cut to the proper length and the column is not perfectly plum, then more variation is added to the weld joint dimensions. Joints that are fit too tightly may have poor weld root quality; joints fit too loosely will require additional welding, which may result in increased distortion or higher residual stresses.

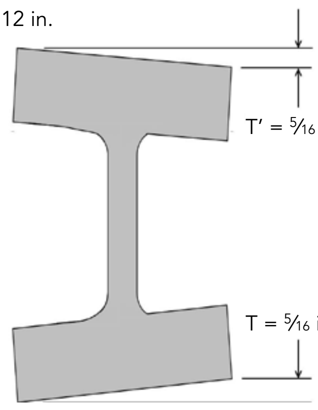
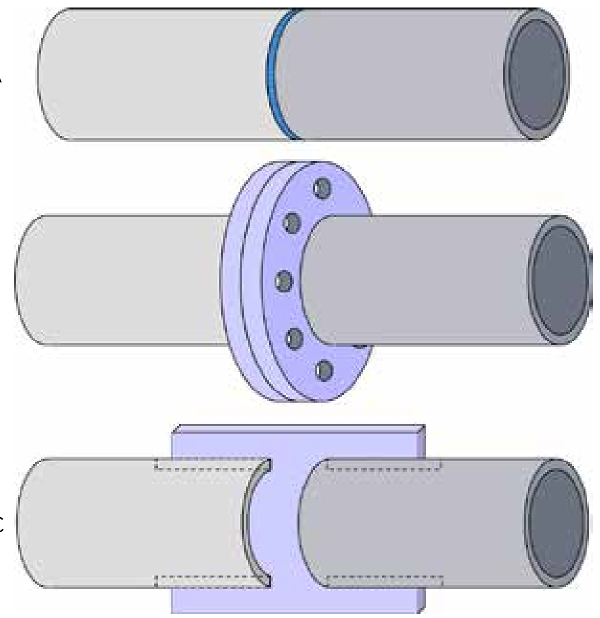


Figure 7

The distortion caused by welding is another commercial reality. AWS D1.1 imposes limits on some (but not all) distortions that may occur during welding. A notable exception is that D1.1 does not provide acceptance criteria for twist of box sections. For most structural applications, the D1.1 limits are reasonable and appropriate. However, for some projects such as AESS applications, the D1.1 limits may be excessive. When this is the case, the more stringent criteria must be specified in contract documents.

Figure 8



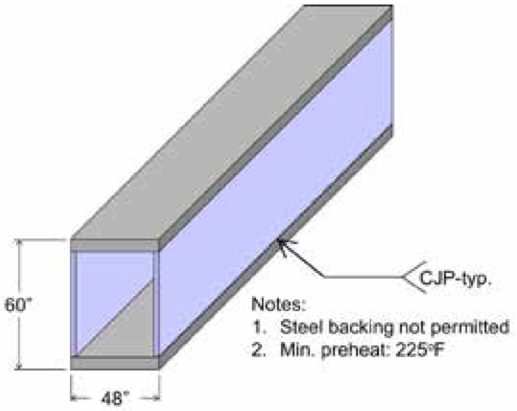
Principle 13: A good welded connection is aesthetically pleasing.

To begin this discussion, it must be first recognized that for the typical structural steel project, aesthetics are often immaterial. Certainly, this is the case when the steel is covered with fireproofing and buried behind drywall. However, AESS construction is becoming more popular, and the overall appearance of the structural members—and the structural connections—is increasingly important.

The ideal number of connections is usually zero, and aesthetically the ideal form of a connection is one that is "invisible" or "seamless." Figure 8 illustrates several options. Part A shows a directly welded butt splice; this is as close to "seamless" as possible (with the possible exception of grinding off the weld reinforcement). In part B, flanges have been welded to either end of the tube to facilitate a bolted connection. Whereas erection convenience must be recognized as an advantage of this option, the aesthetics obviously suffer. In part C, an intermediate "knife edge" detail has been selected. The straight, longitudinal welds are surely made more easily than the circumferential groove welds required by the directly welded splice of part A—but again, at a cost in terms of the aesthetics.

Issues of aesthetics are often viewed by pragmatic engineers as needless distractions that merely increase cost. However, it is ultimately the owner who decides whether the improved aesthetics are worth the extra cost or not. And when the owner

Figure 9



▲▼ Examples of welds in exposed steel assemblies.

decides that an aesthetically-pleasing structure is desirable, then the connections should be made aesthetically-pleasing as well. Directly welded connections—those that do not employ intermediate transitional elements—achieve this goal.

Principle 14: A good welded connection can be made safely.

A good welded connection can be fabricated in the shop and erected in the field in a safe manner. Consider the box section that is part of a bridge that is shown in Figure 9. In this case, the designer has called for CJP groove welds in the corners (a detail with dubious justification in most situations, but one that will remain unaddressed in this article). The drawings also note that steel backing must be removed. A final detail: The grade and thickness of the steel used for the bottom flange required a preheat of 225 °F.

For cyclically loaded longitudinal CJP groove welds, double-sided groove welds are assigned a fatigue category B whereas the same connection with single sided groove welds made into left-in-place steel backing is a category B' detail, with a slightly lower stress range capability. Presumably, it is for the improved fatigue behavior that backing removal requirement has been specified.

The contractor was left with three approaches, none of which were appealing: (a) use steel backing and then require backing removal and re-welding from the inside of the box; (b) eliminate the need for backing by using a double-sided joint, requiring welding from the inside of the box; or (c) use a non-prequalified un-backed CJP groove weld (open root), which would require WPS qualification and also necessitate a special welder qualification.

The options that required welding from the inside create safety concerns, including restricted access, ventilation issues and exposure of the welder to steel that was preheated to high temperatures. For the option that used steel backing that needed to be subsequently removed, using arc gouging for backing removal would probably be impossible to do safely under such conditions. While not presenting any unusual safety concerns, the open root joint would present practical challenges for such a large structural member.

Ideally, consideration of these types of concerns might lead to other weld details, such as a properly sized, single-sided PJP groove weld, or slight reconfiguration of the box section members to permit the use of properly sized, single-sided fillet welds. If no acceptable options other than CJPs exist, the overall member could be designed to be under the stress range limits of category B'. In most situations, neither category B nor category B' will control the design; it is likely that somewhere along the length of the box, there will be a transverse weld that would likely be a more restrictive category C detail. And the detail with the left-in-place backing, all welded from the outside, would provide a much safer situation for the welding personnel involved.

Go Forth and Weld

In two articles, we've summarized 14 principles of welded connection design, illustrating them with representative (although not exhaustive) examples. Using these 14 principles, perhaps in a check list-type manner, can help achieve dependable, economical welded connections that can be fabricated and erected in a safe manner. ■

*Part One of this article appeared in the August issue (**www.modernsteel.com**) and listed an additional seven welding principles. Both parts are based on the 2015 NASCC: The Steel Conference presentation N1 "Welded Connections: The Good, the Bad and the Ugly," available at **www.aisc.org/2015nascconline**. In addition, an updated version of the presentation will take place as a live webinar on December 3. See **www.aisc.org/weldingwebinar** for more information.*