Welding Heavy Structural Steel—Successfully

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Attending to four key elements in the design and planning can head off potential problems.

STRUCTURAL STEEL is fabricated and erected successfully every day, using a variety of cost-effective and dependable arc welding processes. However, as steel plate becomes thicker, as shapes become heavier, and as assemblies become more restrained, the likelihood of problems in construction increase. Whereas distortion can be problematic when lightweight sections are welded, cracking and lamellar tearing are more likely to occur as members become heavier.

The use of heavy steel appears to be on the rise. Some of this increase is due to the movement to more blast-resistant design or seismic concerns. Column-free convention spaces and sports facilities with complex moving roofs require the use of heavier steel. Regardless of the reason, member sizes for these structures are larger, and connections are more complex. The inherent rigidity associated with such connections can pose fabrication and erection challenges.

Compounding the complexities of welding under such conditions is the reality that assemblies of highly restrained members typically serve critical functions. As redundancy decreases, for example, the remaining members usually are larger and thus more restrained, and simultaneously more critical in that fewer alternate load paths exist. Accordingly, it is essential that such connections be properly designed, detailed, fabricated, and inspected.

Background and History

Welding on thick, restrained steel is always a challenge, and successfully welding on "heavy sections" is no exception. AISC *Specification* A3.1c uses this term to describe rolled shapes with flange thicknesses exceeding 2 in., and built-up heavy shapes composed of components made from plate exceeding the same dimension. In the case of the rolled sections, these were formerly the Group 4 and 5 rolled shapes, typically called "jumbo sections." Originally contemplated for use as column sections, these shapes found use as tension members in trusses and other tensile members. Problems due to material properties, detailing practices, workmanship, and perhaps other issues, combined and resulted in some cracking during fabrication and erection (Doty, 1987; Fisher and Pense, 1987; Blodgett and Miller, 1993).

The typical cracking that had been experienced in the past was welding related, with the cracks occurring in the base metal, driven by the residual tensile stresses on the thermally cut surface as well as the shrinkage stresses caused by welding, not by service loads. Cracking often initiated from workmanship-related notches associated with weld access holes. Investigation into the problems revealed that near the web-to-flange interface, material existed with low Charpy-V Notch (CVN) toughness, even though at that time, the material was not required to meet minimum CVN toughness levels, nor was this region the typical ASTM CVN testing location. Small notches, combined with the high residual stress of welding and the low localized fracture toughness, enabled cracks to initiate in this region and propagate elsewhere.

AISC responded by codifying a variety of new provisions. To ensure that the base metal had adequate toughness to resist fabrication stresses, a minimum CVN toughness of 20 ft-lb at +70 °F was imposed. The CVN test specimen was required to be taken from a new location; not from the flange tip as is typically the case, but from a portion of the flange directly under the web—the location expected to have the lowest CVN values (AISC *Specification* A3.1c).

To control notches in the area, a maximum surface roughness value was imposed. When the radius portions of the access holes were to be thermally cut, a preheat of 150 °F before thermal cutting was mandated to decrease the possibility of cracking on the cut surface. As an alterna-

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tive to thermal cutting of the access holes, an alternative technique was promoted, namely drilling a hole to form the radius. Although not mandated in the AISC *Specification*, this practice had two beneficial effects. It eliminated the potential for harmful metallurgical structures developing due to thermal cutting, as well as reducing the residual stresses from cutting. All thermally cut surfaces were required to be ground to a bright finish, and inspected with magnetic particle or dye penetrant.

To help minimize the concentration of residual stresses from welding, the weld access holes were modified and increased in size, not simply for welding access, but to minimize the interaction of multi-directional residual stress fields created by the weld shrinkage.

Time and experience have shown that the provisions for welding on heavy shapes were appropriate and that when they are followed, such materials can be welded—successfully.

A fair question remains, however: if there are potential problems with welding, why not just bolt the sections together? The answer lies in economics. Various cost comparisons have been made that suggest welded connections may be up to 75% less expensive for comparable performance.

The AISC *Specification* Commentary C-J1.5 suggests a combination welded/bolted design might be a viable alternative to an all-welded connection for splices of rolled shapes with flanges that exceed 2 in. However, a quick review of the connection sketch in Figure C-J1.1 and the associated details shows that the figure is intended as an illustration only. A detailed connection employing bolts on one of both sides of a tension connection would be much more complicated and expensive.

Understanding the Basics

A review of some historical problems and the codified corrective measures highlight the factors involved, which can be summarized in the following four categories:

- High shrinkage strains
- High restraint
- Cracks and/or crack-like stress raisers
- Reduced material resistance to fracture

Shrinkage strains are created when localized portions of the base metal are heated and hot weld metal is deposited during welding operations. The hot, locally expanded metal must volumetrically shrink as it cools. If the whole weldment was all at the same temperature, it would globally expand and globally shrink. This, however, is not the case with structural steel weldments; only a small portion of the structure is heated.

The colder steel that surrounds the hot metal associated with a weld provides restraint. As the hot metal shrinks upon cooling, the surrounding steel resists the shrinkage. The combination of high shrinkage strains and high restraint lead to high residual stresses. It is essential to understand that both factors are involved. If metal didn't shrink when it cooled, there would be no residual stresses. Likewise, if the surrounding steel offered no resistance to shrinkage, there would be no residual stresses.

Traditionally, these stresses are viewed as "yield point" residual stresses. When triaxial shrinkage stresses are created, however, yielding of the material is restricted and even higher residual stresses result.

Restraint cannot be easily quantified, and thus terms like "heavily" and "highly" restrained can only be qualitatively described. Restraint is more likely to be identified by "feel" and experience. High restraint is typically associated with welds with all of the following conditions: weld throat dimensions of 2 in. or greater, weld lengths of 1½ ft or more, and where steel members intersect from all three orthogonal directions. A concentration of complete joint penetration (CJP) groove welds in a localized area increase concerns about welding under highly restrained conditions. Therefore, highly restrained members would include splices of heavy sections, welded splices on transfer girders, various splices on trusses, and others.

The third factor that contributes to cracking are *cracks and crack-like discontinuities*. Discontinuities in the base metal, notches and cracks on cut surfaces, and cracks in the deposited weld metal are all stress raisers that magnify the effects of residual stresses. When welding on highly restrained members, surfaces of materials should be smooth. Copes and weld-access holes, flame-cut and sheared edges, punched holes and other prepared surfaces that will be subject to the shrinkage stresses of welding should be carefully inspected before welding to ensure freedom from stress raisers. Grinding questionable areas is a simple way to eliminate potential crack initiation sites.

The final factor that contributes to fracture is *reduced material toughness*. Stated positively, higher material toughness resists fracture: therefore, using base metals and weld metals with defined notch toughness levels is helpful. However, specifying higher toughness in the absence of attention to other factors can be futile. The *Specification* Commentary A3.1c wisely notes:

"To minimize the potential for fracture, the notch toughness requirement of Section A3.1c must be used in conjunction with good design and fabrication procedures." One method of increasing toughness is to specify steels and filler metals with defined toughness levels. However, this is not the only way: preheat can improve the fracture toughness of the material during fabrication since at higher temperatures, steel is tougher. For some steels where the fracture toughness transition temperature is very near room temperature, using preheat may shift the material's behavior from lower shelf to upper shelf, providing significantly better resistance to fracture when at the elevated temperatures. Improved fracture toughness at elevated temperatures will assist in resisting welding-imposed residual stresses, but when the steel returns to room temperature, the fracture toughness will return to previous levels.

To maximize the resistance to cracking, all four elements need to be considered. Residual stresses and restraint should be reduced, the number and size of cracks minimized, and the resistance to fracture increased.

Practical and field-proven examples of how these objectives can be achieved are discussed in the full text of this paper, available online on the *Modern Steel Construction* website **www.modernsteel.com**. MSC