Why Did It Crack?

The Challenge of Determining the Root Cause of Cracking in Thick and Restrained Joints

By Elizabeth Mattfield, P.E.

While many clients seek to pinpoint a singular cause for cracking of welds, it can rarely be attributed to one single mistake. Most often, a crack is produced in a "perfect storm" of errors made during the design, procurement, and execution phases of fabrication. Individually, these oversights would be unlikely to cause weld failures but, combined, they can cause disastrous results to any welding operation, even in reputable shops.

Longitudinal crack at the weld toe.

A large steel fabrication shop was assembling and welding built-up columns for a new high-rise building in Manhattan. During fabrication of one column, the shop's quality control staff encountered visible cracking on the base metal of a welded joint. At the time of the discovery, welders were joining elements of 5½-foot-wide columns to be encased in concrete, which contained 3¼-inch-thick plates offset from the column's web that would serve as connecting elements for the steel framing once encased. These embedded plates were joined to the column via 3-foot-wide, 3¼-inch-thick stiffeners extending from the web of the column to create a plate surface in the outside face of the future encasement of the column. The 3¼-inch plates were joined at perpendicular angles to each other by welded double bevel tee joints with back-gouging.

To confirm the extent and origin of the crack, magnetic particle testing (MT) of the welded joint and surrounding base metal was conducted by the shop's quality control inspector. It revealed the crack shown in the photos, with yellow powder accumulating in the cracked metal to distinguish the extent of cracking. It is clear from the powder's location that this fracture had originated in the heat affected zone (HAZ) at the weld's termination and propagated as a transverse crack into the base metal. Ultrasonic testing revealed that the crack extended 1-inch-deep in the 3¼-inch-thick material.

This fabricator had diligently monitored welding parameters in accordance with a prequalified welding procedure specification (WPS). This WPS for Group II base metal required the use of a gas-shielded, semi-automatic flux cored arc welding (FCAW) process with 70 ksi wire. This is a process often favored by shops for both its productivity from a wire feeder as well as its penetration, attributed to its reverse polarity. The fabricator's quality manager was able to provide valuable information such as wire diameter, shielding gas, preheat and interpass temperature, and post weld treatment (PWHT) details.

In this case, a preheat temperature of 225°F had been achieved. This is acceptable by AWS standards for Category B base and filler metal combinations in AWS D1.1:2015 Table 3.3. The FCAW wire was classified as H8, with less than 8 mL/100g of diffusible hydrogen. The double-sided tee joint had even been welded by alternating sides, a practice recommended by AWS to control thermal stresses during welding.

This prompted an investigation of the base metal by the fabricator, who assumed that since everything was prequalified and executed with good practice, there must have been some flaw in the base material. The fabricator had gone so far as to hire laboratories to perform limited chemical analysis of the steel, yielding no reliable results to indicate why the cracking had occurred.

Upon first inspection of mill test certificates of the steel received, it was evident that, while the WPS was perfectly acceptable for the designed ASTM A572 Grade 50 steel, it did not account for the properties of the steel that was actually received and being welded. In fact, the steel far surpassed the minimum yield and tensile strength specified for ASTM A572 Grade 50 steel, with yield values in the 62-63 ksi range and tensile values in the 91-93 ksi range. From a welding perspective, this steel would fall into Group III base metal, becoming undermatched by the 70 ksi filler metal being used to weld it. Undermatching of filler metal is favored where acceptable, such as in this case, where the design only demanded 50 ksi base metal. However, the extremely high tensile strength also pushed the base-filler metal combination into Category C, a category which requires a *minimum preheat of 300 degrees F.*

After determination of preheat via a hydrogen control method (Annex H of AWS D1.1:2015), it was verified that, indeed, this base metal should have been preheated to a minimum temperature somewhere between 300° and 320°F.

One can argue that the fabricator was entirely within its right to use AWS D1.1:2015 Table 3.3 and that the material was indeed certified as a Group II metal. However, whether or not this material can be classified as a different grade by ASTM or AWS is not the point. Instead, the mill test certificate's information should have raised a flag that this material and and its required preheat needed special consideration beyond AWS's general Table 3.3. This is confirmed in the AWS code's commentary, which advocates against the use of Table 3.3 without careful consideration of factors as covered by Annex H used in the analysis. Simply stated, Table 3.3 is an available tool but it is up to the fabricator to determine if it satisfies the conditions required to make sound welds. In this case, elevated preheat beyond Table 3.3 would undoubtedly have been warranted. Annex H of AWS D1.1:2015 is an excellent tool for structural engineers tasked with reviewing mill certification reports since it aids in the determination of preheat using a combination of factors: chemistry, restraint level, and hydrogen control.

Despite its importance, insufficient preheat is rarely the sole cause of cracking. In this particular case, the weld was joining two very thick pieces of material, each 3¼-inch-thick. The volume of weld metal alone produces a joint of extremely high restraint, with stresses far exceeding the tensile strength of the steel during welding and cooling that occurred with each pass. The addition of stress relief holes at each end of the joint would provide a path for relief of heating and cooling stresses. Instead, the weld starts and stops abruptly at the ends of the tee joint, a perfect location for crack formation and subsequent propagation into the base metal.

Another noteworthy aspect of this operation was that the WPS did not have any provisions for post weld heat treatment (PWHT). AWS D1.1:2015 does not mandate the use of PWHT, but it does repeatedly emphasize that joints must be considered on an individual basis and, where needed, PWHT must be prescribed. In the case of steel over 2 inches in thickness, PWHT in the form of a controlled cooling rate would have been quite beneficial in relieving the stresses induced during welding.

Transverse base metal crack at the end of the weld.

Transverse crack at the end of the weld, propagated from weld into the base metal.

Besides the measures previously discussed, other steps can be taken by production crews to improve the execution of this joint and prevent cracking. For example, utilization of H8 consumables places this gas-shielded FCAW process in a low-hydrogen category, which is a good start. However, current, voltage, and gas moisture contamination are variables of low-hydrogen demand projects that can be monitored and controlled to avoid increasing the amount of diffusible hydrogen in the joint.

In conclusion, finding a singular cause for weld cracking can be a challenging task, particularly in a shop with proficient welders and established welding procedures that are rarely questioned. Fortunately, control of at least some of the most common contributing factors can often be enough to preclude weld cracking. In this case, the contractor's determination of appropriate preheat and interpass temperatures for thicknesses over 2 inches and providing stress relief holes in the joint would likely have been sufficient to prevent the welds from cracking.▪

Photos courtesy of Atlantic Engineering Laboratories (AEL).

Elizabeth Mattfield currently serves on SEAoNY's Board of Directors. She is also the vice chair of the AWS D1 Subcommittee on Reinforcing Steel, a member of AWS D1Q Fabrication and Inspection Task Groups, and a member of the AISC Code of Standard Practice Committee. (elizabeth.mattfield@gmail.com)

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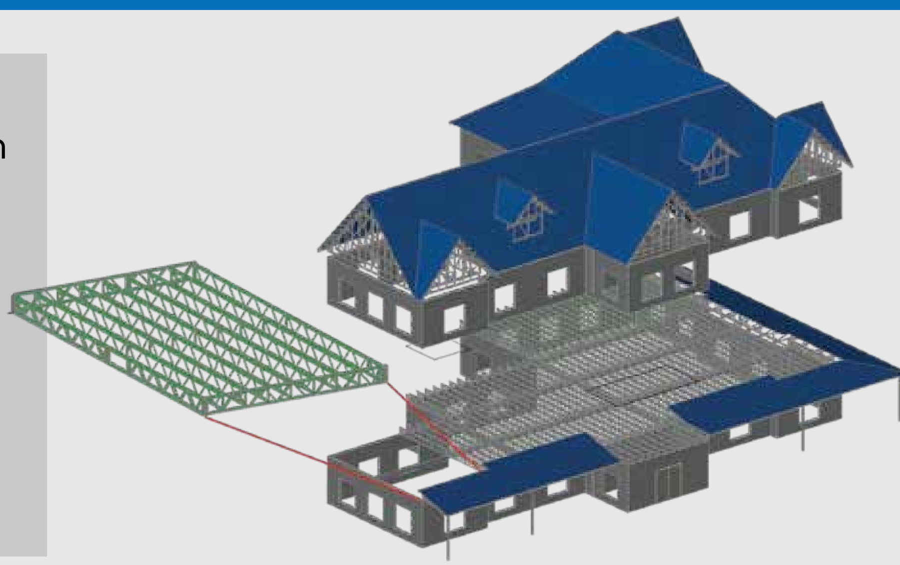

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