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Recommendations for Developing Alternative Flaw Acceptance Criteria for Structural Steel Welds

Learn the benefits of employing an optional strategy to evaluate flaws when welding to AWS D1.1

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The challenge of separating steel welds with acceptable flaws and tolerances from those that are unacceptable (defects) is nearly as old as the challenge of welding itself. This challenge will continue to be with us long into the future. Setting limits that are too stringent can cause economic waste, and may even create unanticipated new technical risks when unnecessary modifications are made. Alternatively, setting limits that are too loose increases the risk of fracture.

Across the many industries that use welded joints, there are two different strategies for judging inspection results when addressing this challenge. The first strategy is to use a consensus-based, standardized, codified set of criteria, often referred to as workmanship criteria. In AWS D1.1/D1.1M:2020, *Structural Welding Code — Steel*, Clauses 7 and 8 exemplify this approach. The second strategy is to formulate project-specific acceptance criteria, usually through a combination of fracture mechanics, metallurgy, and performance-based inspection criteria. The strategy goes by many names, including alternate flaw acceptance criteria, engineering critical assessment (ECA), damage-tolerant design, fit-for-purpose assessment, fit-for-service assessment, and performance-based design.

The primary benefit of this approach is flexibility, backed up by technical rigor. Any combination of material properties, applied stresses, residual stresses, and flaw geometry that can be reasonably demonstrated to remain stable throughout the entire service life, or the minimum specified portion of the service life, can be considered acceptable. Subclause 1.5 allows for this approach, and subclause C-8.8 in the Commentary alludes to it. Because the method is free of explicit codified rules, new materials, joining methods, inspection technologies, and novel design applications can be readily addressed, as long as the fundamental technical data sets are available. For well-established materials, joining methods, inspection methods, and design applications, the key benefit is that tradeoffs between these can be explicitly accommodated.

Within the alternative flaw criteria strategy, there are two sub-options. One is based on simple hit/miss detection and the other on flaw sizing. The

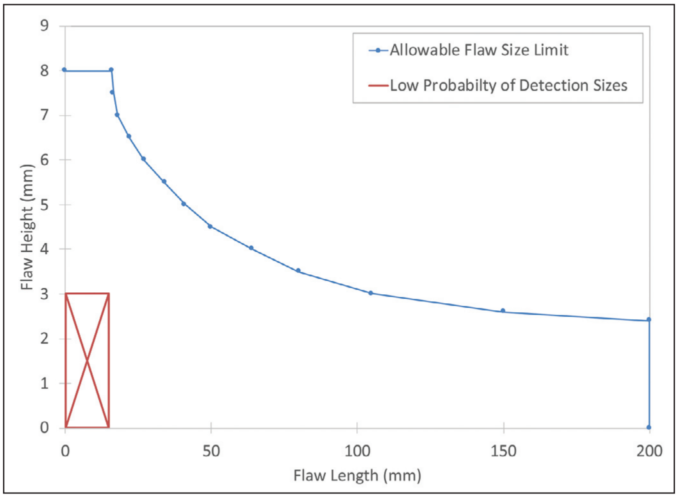

Fig. 1 — Example of flaw acceptance based on detection.

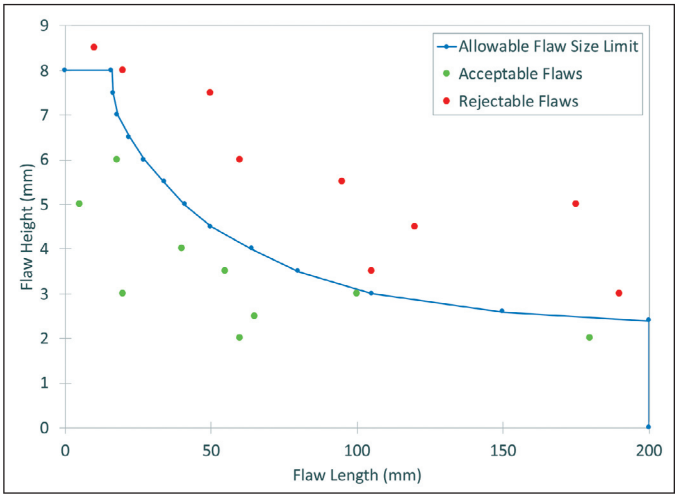

Fig. 2 — Example of flaw acceptance based on sizing.

flaw detection approach is based on choosing a combination of materials, applied stresses, residual stresses, and other considerations that lead to allowable flaw sizes that are larger than the specified inspection method can reliably detect. This is illustrated in Fig. 1. In this approach, a detected flaw is a rejected flaw. The flaw sizing approach is based on choosing a combination of the same factors to create a flaw-size limit curve. This is illustrated in Fig. 2. Here, the rejection of the flaw is based on the measured dimensions, usually flaw length, height, and position. Accompanying rules are usually provided for combing neighboring flaws into a single equivalent flaw.

The selection of codified workmanship vs. the ECA-based strategy varies greatly by industry, even for welded joints of similar construction. There is no simple answer as to why usage trends vary among industries. However, it is likely due to some combination of the respective industry's culture, economic incentives, and regulations.

Historically, for welds fabricated to AWS D1.1, the flaws have been evaluated using standardized workmanship requirements. Some owners, usually large corporations or government agencies, overlay their own internal standards onto the requirements of AWS D1.1. Depending on the application and region, regulators may also have additional requirements. The owner's engineer of record (EOR) may also modify the AWS D1.1 requirements based on the authority granted under subclause 1.5. When this is done, it is usually based on the EOR's qualitative evaluation and not a formal ECA approach. While no formal statistics exist on the choice of coded rules vs. an ECA approach for welded structural steel projects, it is safe to say that some version of the standardized approach is used more than 99% of the time.

For welded structural steel applications, the use of ECAs historically has been reserved for special applications, or as an option of last resort when the standard workmanship criteria could not be satisfied.

Workflow for Establishing Alternative Flaw Acceptance Criteria

The starting point is to form an interdisciplinary technical team. The team's expertise typically spans system design, metallurgy, welding, fracture mechanics, and inspection. A typical step-by-step approach is outlined ahead. For simplicity, in the descriptions we will assume each specialty is covered by one individual. Since the strategy is flexible, the steps can be conducted in a different order, and iteration between steps also is possible. While the workflow described below is focused on flaws in welded joints, a similar procedure can be followed to determine flaw tolerance in the base metal of castings, forgings, and rolled products.

Step 1: Establish Preliminary Design Drawings and Specifications

The lead design engineer, in consultation with others on the team, assembles a set of preliminary drawings, material specifications, and inspection criteria. The engineer also summarizes the design loads and the peak service conditions (e.g., minimum and maximum service temperatures, dynamic loading rates, and anticipated corrosion environment). Early consultation with the team is important because potential problems can be identified before significant effort is expended. For AWS D1.1 applications, the designed system is typically a structure, and the lead design engineer is most often a civil-structural engineer.

Step 2: Created Representative Test Welds

Representative test welds are fabricated for the purpose of creating material test specimens in Step 3. Creating welds that are reasonably representative and logistically feasible within the project constraints requires input from a metallurgist and welding engineer. Often the procedure qualification test plates form the basis for the material test program, but additional samples or sample preparation may be required. In some cases, additional effort is required to make the welds representative of the final in-service condition. For example, if the welds are to be cold bent during the fabrication process, then the test plates need to be strained a similar amount to capture any changes in the material properties.

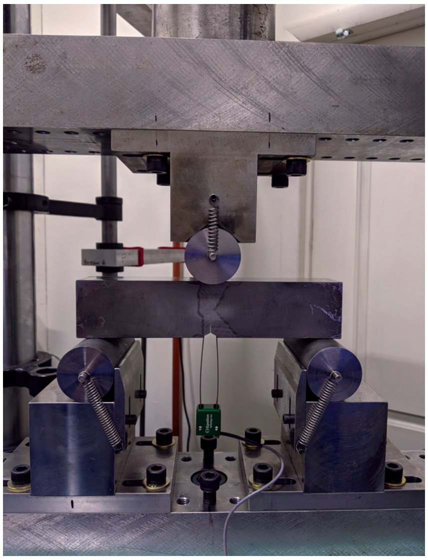

Fig. 3 — Weld metal fracture toughness test setup. (Courtesy of Product Evaluation Systems Inc.)

Step 3: Test Materials

The material test program typically involves tensile tests, fracture toughness tests, and microhardness traverses across the weld. The fracture toughness tests include the weld metal, weld interface, heat-affected zone, and base metal. Figure 3 illustrates a typical fracture toughness test setup, in which the precrack was placed in the weld metal. Charpy V-Notch (CVN) tests will sometimes be substituted for fracture toughness tests, often because CVN tests are quicker and cheaper. However, it is important to keep in mind that, at best, CVN results provide an indirect prediction of fracture toughness. As a result, the fracture mechanics specialist typically applies lower-bound empirical relationships to infer fracture toughness values from CVN results. The practical result of doing so is that the allowable flaw sizes are often artificially smaller than if they had been based on direct fracture toughness results, sometimes by a substantial amount.

Step 4: Conduct Fracture Mechanics Calculations to Determine Initial Flaw Sizes

Using the information from Steps 1 and 3, the fracture mechanics engineer calculates a set of flaw size curves, such as those shown in Figs. 1 or 2. Typically, the calculations are based on meth-

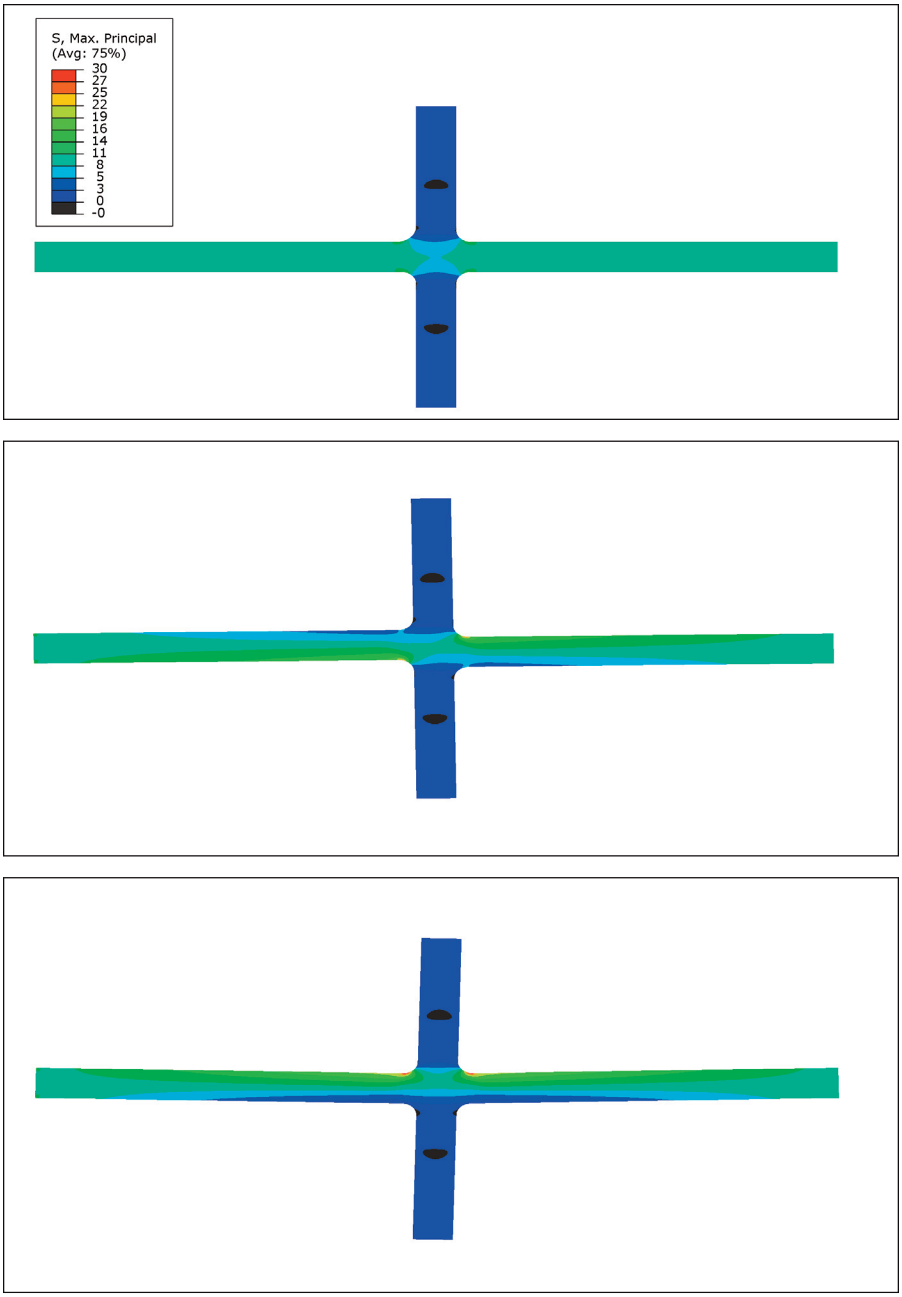

Fig. 4 — Elastic finite element maximum principal stress results for a nominal cruciform joint (top), eccentric parallel plates (middle), and angular misalignment (bottom).

ods and guidance from one or more of the major flaw assessment guidance documents. For welded carbon and low-alloy steel, the two most commonly used documents are BS7910:2019, *Guide to Assessing the Acceptability of Flaws in Metallic Structures*, and API 579-1/ASME FFS-1, *Fitness-for-Service*. The fracture mechanics specialist typically can select from relatively simple hand calculation techniques to advanced numerical simulations. Hand calculations are quicker and cheaper. However, they generally result in smaller allowable flaw sizes, due to the conservative simplifying assumptions built into the techniques. More advanced analysis generally allows for removing conservative assumptions. However, this benefit comes with larger budget and schedule requirements.

The fracture mechanics engineer may also provide guidance on the sensitivity of the preliminary solution to various inputs. During a new iteration, this can help decision-making for options such as postweld heat treatment (PWHT) vs. as-welded, as-welded profile vs. ground smooth surface, expanding or tightening fit-up tolerances, changing minimum and maximum material property limits, and modifying the nominal joint geometry. While sometimes not obvious, fit-up tolerances can have a substantial effect on local stresses in the region of the weld and thus the flaw tolerance. As an example, Fig. 4 illustrates a comparison of simple cruciform joints subject to a nominal tensile stress in the horizontal direction.

Step 5: Determine the Inspection Program

Selecting an inspection program in an ECA strategy requires consideration of the actual ability to detect the flaw sizes, positions, and orientations quantified in Step 4. The most rigorous option is to quantify probability of detection and sizing error through blind testing of the inspector, with the specified inspection technology being used on representative joints with known, representative weld flaws. For the reader who has no familiarity with these blind testing concepts, the book *Fundamentals of Structural Integrity* by A. F. Grandt Jr. is a recommended starting point. In the least rigorous approach, guidance from existing sources in combination with previous knowledge of the inspection team is used.

As a midpoint between the two extremes, a limited blind testing program is used to screen out inspectors or inspection technologies, but the number of specimens used is far less than what is included in a rigorous statistical study. Appendix T of BS7910 provides general guidance on flaw detection and sizing capabilities for various mainstream inspection techniques. This is a helpful reference to use during Step 1. However, readers are cautioned that there is no reasonable assurance that the detection and error numbers are accurate for their project's inspection program.

The inspection expert will review the preliminary flaw size curves from Step 4. If the flaw sizes are judged to be too small for reliable detection or reliable sizing, then either a revision will be suggested, or a decision to modify the inspection strategy will be made.

Step 6: Accept, Refine, or Abandon

After the preceding steps are comtpleted, a decision is made. The lead engineer can accept the proposed alternative flaw acceptance criteria, modify the approach, or go back to the drawing board. An additional benefit of this approach is that the flaw sizes can be recalculated during the fabrication and installation if an unforeseen issue arises.

Applications Where Developing Alternative Flaw Criteria May Not Be Practically Feasible

One of the most challenging applications for developing alternative flaw acceptance criteria is for designs where environmentally assisted cracking (EAC) is a credible concern. For these applications, typically the specific characteristics of the environment need to be estimated in advance, and the materials need to be tested under a simulated environment in the laboratory to determine representative crack growth rates and fracture toughness. In structural applications, concerns about EAC can often be greatly reduced by selecting materials that are known to not be susceptible in the given service environment.

A notable exception is hot-dip galvanizing (HDG). Any quantitative methodology for predicting crack extension under the combination of conditions that occur during HDG (e.g., transient hydrogen diffusion, transient thermal stresses, liquid metal-assisted cracking, and rate and temperature dependent material properties) will be fraught with uncertainty. To the authors' knowledge, no consensus methodology has been published for quantifying crack extension during the HDG process. In other words, if HDG is a project requirement, alternative flaw acceptance criteria should be applied with due caution, even healthy skepticism.

Product Management Considerations

Developing a new alternative flaw acceptance program calls for a level of cooperation among the technical disciplines that exceeds what is usually required for a standard codified approach. It is important to set expectations early in the project.

While there is no single method for estimating ECA cost, it will be in the range of $15,000 to hundreds of thousands of dollars for time and materials, excluding the cost to fabricate the test welds and conduct the inspection evaluation program. Relatively simply geometries, with relatively simple loading schemes, fabricated with well-established materials, and inspected using established methods will tend to be on the lower end of that range. The price tends to rise as complexity increases.

This raises the question of whether an alternative flaw criteria approach makes sense for one's next project. The short answer is that AWS D1.1, subclause 1.5 states that only the person meeting the definition of "engineer" for the project can officially answer that question. That being said, perhaps the discussion provided in this article can help. WJ

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