Ensuring Weld Quality in Structural Applications

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The James F. Lincoln Arc Welding Foundation

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Ensuring Weld Quality in Structural Applications, Part I of III

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The Roles of Engineers, Fabricators & Inspectors

This three-part series on ensuring weld quality in structural applications covers the following:

Part I reexamines the roles of the Engineer, the Fabricator, and the Inspector, as they relate to welded construction. The proper roles are defined, and misunderstandings corrected. First published in Welding Innovation, Vol. XIII, #2, 1996.

Part II emphasizes the importance of effective visual inspection and its vital role in achieving weld quality. First published in Welding Innovation, Vol. XIII, #3, 1996.

Part III discusses alternate acceptance criteria and explains the Engineer's responsibility for invoking such criteria. First published in Welding Innovation, Vol. XIV, #1, 1997.

Throughout the series, references have been updated to cite specific sections of the AWS D1.1-98 Structural Welding Code - Steel.

Introduction

In a mature industry such as welded steel construction, it is reasonable to believe that the role of the various individuals involved with a given project will be well understood and well defined. Unfortunately, experience indicates that there is a great deal of confusion in this area. Perhaps this is a reflection of misperceptions about the technology itself. Too many otherwise knowledgeable people still regard welding as a "black art," rather than a science that can be understood and controlled. The level of understanding among many Engineers regarding this important construction process is limited. Regardless of the reason, Engineers frequently do not perform their professional responsibilities as they relate to welding. Too often, they delegate this authority to Inspectors. Over-zealous Inspectors frequently overstep their role, making judgment calls that should be the purview of the Engineer. Furthermore, Fabricators do not always take full advantage of code-provided latitude for the resolution of many problems. In the end, Owners often pay too much for structures that have been plagued by delays, unnecessary repairs, and extraneous activities that add little or no value to the project.

Many problems result when the proper roles of the various individuals on the project are not understood. The most serious infractions occur when people accept responsibility for areas in which they have no authority or qualifications. This can result in disaster, but fortunately such cases are rare. More frequently, key individuals fail to carry out all of their appropriate responsibilities, causing costly delays.

With the design-build approach commonly used in Europe, communication is enhanced because one organization has financial responsibility for the entire project. In the U.S.A., however, the common practice that separates the design phase from the construction phase requires a clear understanding of the responsibilities of the various parties. The roles are defined in codes, specifications, and contract documents. The AWS *D1.1-98 Structural Welding Code - Steel*, defines such roles as they relate to welded construction. In addition to restating sections of the code itself, this paper will outline a philosophy that is conducive to increased cooperation and communication, and will foster the creation of higher quality products while minimizing fabrication costs.

Many problems result when the proper roles of the various individuals on the project are not understood.

Effective visual inspection requires that the Inspector be present when welding is being performed.

Various Roles Defined

At the heart of the issue is the proper definition of the roles and the responsibilities of various individuals involved in welded fabrication. The following are taken from the AISC Code of Standard Practice and/or the AWS *D1. 1-98 Structural Welding Code - Steel:*

Owner:
The owner of the proposed structure OR that individual's designated representatives, who may be the Architect, Engineer, General Contractor, Public Authority, or others.

Architect/Engineer:
The Owner's designated representative with the full responsibility for the design and integrity of the structure.

General Contractor:
The Owner's designated representative with the full responsibility for the construction of the structure.

Fabricator:
The party responsible for furnishing fabricated structural steel.

Erector:
The party responsible for the erection of the structural steel.

Verification Inspector:
The duly designated person who acts for, and on behalf of, the Owner or the Engineer in all inspection and quality matters within the scope of the contract documents. (In some codes, such as AASHTO/AWS *D1.5-96 Bridge Welding Code*, this Inspector is known as the Q.A. Inspector, that is, the Quality Assurance Inspector.)

Fabrication/Erection Inspector:
The duly designated person who acts for, and on behalf of, the Contractor in all inspection and quality matters within the scope of the contract documents. (In D1.5, this Inspector is known as the Q.C. Inspector, that is, the Quality Control Inspector.)

Inspector:
When the term Inspector is used without further qualification, it applies equally to both the Verification and Fabrication/Erection Inspector.

For the purposes of this paper, comments directed toward the Fabricator apply equally to the Erector. Since most or all of the welding will be performed by either the Fabricator or Erector, the General Contractor will not be considered in this discussion. The term Engineer will be used in lieu of Architect/Engineer.

Responsibilities

The Engineer has the ultimate and full responsibility for the integrity of the structure. It is the Engineer who must establish the required quality level for all welded fabrications. This may be done by invoking a standard such as the D1.1 Code. It is imperative that the Engineer understand the requirements, restrictions, and implications of the full code. The Engineer is responsible to ensure that the code provisions are adequate for the structure. Additional provisions may be required for unique structures, and these requirements must be invoked in contract documents. The Engineer is responsible for determining and specifying the level of quality required. The Engineer is also responsible to ensure that the specified level of quality is delivered by the Fabricator. The Engineer has a professional responsibility to the Owner to deliver the project in a timely fashion, and at an appropriate cost.

To assist in the quality issues, the Engineer may employ the services of a Verification Inspector. Under D1.1, this is left up to the Engineer's discretion. A Verification Inspector may be engaged either to duplicate the services of the Fabrication Inspector, or to supply spot checks. However, the Engineer may choose to rely solely upon the Fabrication Inspector to ensure the necessary quality is achieved. Many factors enter into this decision, including:

- the complexity of the structure;
- the degree of redundancy involved; and
- the relative level of confidence the Engineer has in the Fabricator.

The Fabricator is responsible for delivering a quality product to the Engineer. While the Engineer must be responsible to ensure the level of quality is achieved, it is ultimately the Fabricator's responsibility to produce a quality product. To this end, the Fabricator will employ Fabrication Inspectors (Q.C. Inspectors) to monitor the welding operations and inspect the final product. Under a shop qualification program, it is required that the inspection functions be kept organizationally separate from the manufacturing operations, in order to give the Q.C. Inspectors the necessary authority to carry out their responsibilities.

It is important to understand that since the Fabricator does all the welding, only the Fabricator can produce quality welds. Inspectors cannot "improve" the quality of the product that has been produced. The Inspector simply measures the level of quality achieved, and accepts those products that are within conformance.

Inspectors are responsible to ascertain that all fabrication and erection by welding is performed in accordance with the requirements of the contract documents. When contract documents invoke certain specifications or codes, the Inspector must ensure that all such requirements are met. It is important to note that the emphasis is placed on **acceptance** and **compliance** to the specification. A prevailing—but mistaken—impression of Inspectors is that their primary responsibility is to **reject** out-of-compliance work. This is more than an issue of semantics. The ability to reject a particular weldment is ultimately the Engineer's responsibility. The Inspector's responsibility is to accept materials that are in compliance.

The emphasis is placed on acceptance and compliance to the specification.

While this approach may seem new or revolutionary to some people, the author believes that it is the primary philosophy presented in codes. And, to eliminate any dispute or potential misrepresentation of code intentions, it is the author's opinion that this *should* be the philosophy of the code even when it is not, because it will result in optimum value to the Owner.

Misunderstandings Due To Choice of Words

The belief that the primary function of Inspectors is acceptance of products that are within established criteria is generally supported by the D1.1 Code, although deviation from this general philosophy is sometimes expressed in the code. In the author's opinion, this is more a reflection of poor wording on the part of the code writers than a representation of overall philosophy. The examples that conflict with the general trend will be cited, and proposed refinements presented.

The following references with appropriately highlighted portions support the contention presented above:

- Fabrication/erection ... inspection and tests shall be performed ... to ensure that materials and workmanship **meet the requirements** of the contract documents (6.1.2.1).
- The Inspector shall **ascertain** that all fabrication and erection by welding is performed **in accordance** with the requirements of the contract documents (6.1.5).
- The Inspector shall **make certain** that only materials **conforming** to the requirements of the code are used (6.2).
- The Inspector shall **verify** that all WPSs have been approved by the Engineer in conformance with 4.1.1 (6.3.1).
- The Inspector shall inspect the welding equipment to be used for the work to **make certain that it conforms** to the requirements of 5.11 (6.3.2).
- The Inspector shall **permit** welding to be performed only by welders ... who are qualified ... or shall **make certain** that each welder ... has previously demonstrated such qualification under other acceptable supervision and approved by the Engineer (6.4.1).
- The Inspector shall **make certain** that the sizes, length, and location of welds **conform** to the requirements of this code... (6.5.1).
- The Inspector shall examine the work to **make certain that it meets the requirements** of this code. Other acceptance criteria, different from those thus provided in the code, may be used **when approved by the Engineer** [Note: the Engineer has the authority to utilize alternate acceptance criteria] (6.5.5).
- Table 6.1 lists "Visual Inspection **Acceptance** Criteria."

The foregoing passages make it clear that the emphasis is on **accepting** products within compliance, and **making certain** that proper procedures are followed. It can be argued that when the Inspector refuses to accept a part, it is equivalent to rejecting the part. The code writers, however, have not chosen to use this language. Ultimately, all projects must be accepted. This is the role of the Inspector.

In two notable examples, the D1.1-98 Code deviates from this general principle. The provisions of Section 6.1.4.1 state that, "Inspectors responsible for acceptance or rejection of material and workmanship shall be qualified." This paragraph fits under the heading "Inspector Qualification Requirements." Clearly, the emphasis is not on the function of the Inspector, but rather on the Inspector's qualification. Had the code writers deleted the words "or rejection," the provision would have been consistent with the rest of the code. In the author's opinion, this wording is unfortunate, since it is not in the same spirit as the rest of the code. The second deviation from the overall philosophy of acceptance occurs in Section 6.6 "Obligations of the Contractor." The provisions of 6.6.2 require that "The contractor shall comply with all requests of the Inspector(s) to correct deficiencies in materials and workmanship as provided in the contract documents." Notice, however, that this provision is under the heading of the "Obligations of the Contractor."

Even though these two references deviate slightly from the general concept of acceptance, they do not contradict the overall philosophy. Moreover, because of their location, they do not present a strong case for an alternate approach.

A modification to these provisions of 6.1.4.1 that would delete the words "or rejection" would clarify the situation. Also, in Section 6.6.2, the following phrase would be a proposed improvement: "The Contractor shall comply with all requests of the **Engineer** to correct deficiencies in materials and workmanship as provided in the contract documents." This language would reaffirm the proper role of the Engineer. However, it is obvious that for minor nonconformances, the Engineer should not be consulted on a routine basis. Once again, this falls within the discretion of the Contractor. If the Inspector was being granted the full authority to direct all the activities of the Contractor, this would certainly have been included under a different heading.

It is interesting to note that the equivalent provision in the *D1.5-96 Bridge Welding Code* changes the word from the all-inclusive "Inspectors" used in D1.1 to "QA Inspectors". While the D1.1 provisions apply equally to both fabrication and verification inspection, the D1.5 words are exclusively applied to QA (verification) inspection. This wording is probably more correct, but since verification inspection is optional under D1.1, alternate words were selected.

Abuses and Errors

Abuses of, and deviations from, the philosophy outlined here are widespread. They can be perpetrated by Engineers, Inspectors or Fabricators. For instance, the Engineer may delegate engineering authority to the Inspector. The rationale for this type of decision appears to be fairly straightforward: the Engineer may not be familiar with the intricacies of the code and/or fabrication process, and therefore may empower the Inspector to make decisions on his/her behalf. On the surface, this appears to be a very logical approach, particularly when the Inspector is highly qualified, perhaps an Engineer by training. On the other hand, another Inspector may not have the background necessary to make these types of decisions. Moreover, rarely will the Inspector have the benefit of understanding the overall structural implications of various decisions. For example, a fillet weld has been sized based upon the minimum prequalified fillet weld sizes. This fact obviously should enter into the considerations regarding the acceptability of a slightly undersized fillet weld. In the absence of this design data, the Inspector does not have the necessary information to make the most responsible decision.

The descriptions assigned to various Inspectors by Fabricators generally fit into one of two categories: First, there are the Inspectors who are "reasonable," "practical," "someone we can work with," etc. The second category would cover those who are "a real stickler for details," "see everything as black or white," or "cut us no slack," etc.

The implication is that the first group of Inspectors utilize some "judgment call" when making their decision. They can negotiate, bargain, and give trade-offs. These are hardly the terms associated with the engineering profession. Fabricators may love this type of Inspector, but are the Engineer's obligations to the Owner fulfilled if such an Inspector compromises quality in a critical area?

The second type of Inspector sees everything as falling into one of two categories: acceptable or unacceptable. This individual knows every code provision and requires strict adherence to these requirements. On the surface, this may seem to be the optimum type of Inspector, from the Owner's point of view. However, two things must be considered: First, an Engineer's full dependence on this type of Inspector eliminates the Engineer's opportunities to utilize code-permitted engineering evaluations of situations that deviate from the code requirements. Secondly, this approach may unnecessarily increase costs, cause delays, and necessitate weld repairs that can actually impair the quality of the overall project. These implications will be developed and discussed in detail in Part III of this series, "Alternate Acceptance Criteria."

Inspectors are not immune from errors either. Some are all too eager to assume responsibility and authority beyond their role qualifications. Some Inspectors are fond of pointing out their "interpretation" of code provisions. Codes are meant to be followed, not interpreted. The term "interpretation" has a very specific meaning when applied to codes. An "interpretation," or more properly, an "official interpretation," is the decision rendered by the code-writing body that may, in the extreme, constitute a new code requirement. Only the code-writing body has the authority to issue an interpretation.

Inspectors should see that the code is followed, and report nonconformance to the Engineer. When the code requires that the "Engineer be notified" prior to some action, it is not the Inspector who should be notified. Inspectors are not in the business of deciding new acceptance criteria. That is the Engineer's responsibility. Inspectors should not be determining whether code provisions are adequate or overly restrictive. They are charged with following the established code provisions.

Many Inspectors feel they are the ultimate authority on the project. It is important to note that the Engineer has the authority to review the Inspector's credentials. Although the Fabrication Inspector is paid by the Fabricator, that Inspector's credentials and capabilities are subject to approval by the Engineer. The Engineer directly employs the Verification Inspector, who obviously is responsible to the Engineer.

Fabricators also make errors. Some companies will attempt to hide problems from the Inspector. More blatant abuses include offering bribes to Inspectors. Such activities are illegal, immoral, and unprofessional. The entire industry is hurt when a small minority thus abuses its responsibility. The Fabricator may also err by failing to utilize provisions within the code which permit deviation from standard acceptance criteria. Fabricators must know the entire code and understand what is mandatory, what is permitted, and what can be changed. Without reading the complete code, Fabricators will frequently apply one set of provisions in a universal fashion, believing it to be all-encompassing. Unnecessary increases in fabrication costs usually result. It is imperative that the whole code be understood in its entirety in order to meet the quality requirements at a reasonable cost.

Engineers are responsible for thoroughly understanding the code, the fabrication processes, and the proper roles of the Inspector and the Fabricator. If the Engineer of Record is not familiar with the intricacies of the welding processes or those of welding codes, it is imperative to consult a Welding Engineer, another professional, separate and distinct from the Inspector. The Inspector must understand how to enforce the application of the code, accept work that conforms to code requirements, and report to the Fabricator deviations from these requirements. The Inspector must know the whole code, and apply it to the situation, not "interpret" it.

Fabricators must know the entire code and understand what is mandatory, what is permitted, and what can be changed.

The Fabricator must know the entire code, accept the Inspector's report of deficient work, and either repair deficiencies or propose an alternative to the Engineer. With the report of nonconformance, the Engineer can apply engineering judgment to resolve the problem. This approach leaves the ultimate responsibility for the project with the Engineer of Record, where it must remain. The Inspector has not exercised engineering judgment, the Fabricator has gained all the latitude necessary, and ultimately, the result is a project of the required quality at a reasonable cost.

Case Study

To illustrate the "ideal" application, consider the following situation which (unfortunately) is true. Details have been changed slightly to protect both the innocent and the guilty!

Field erection of a steel frame building had progressed several stories when the Inspector reported to the Engineer that no preheat was being employed for the welding procedures. The Fabricator claimed he did not know preheat was required. The Inspector then announced that the building would have to be systematically disassembled and re-erected. The Engineer did not know what to think but was wise enough to consult a Welding Engineer for advice. The Engineer was obviously concerned about the integrity of the structure, but was also worried about the significant delays that would be incurred if the structure was disassembled. The tremendous cost could have resulted in bankruptcy of the Fabricator/Erector. On every front, the project was a mess.

Before a resolution of this project is presented, a review of the mistakes made is appropriate. The Fabricator/Erector had selected to use welding procedures (or more correctly welding procedure specifications, usually abbreviated WPSs) that could be prequalified under the provisions of D1.1. These WPSs are exempt from the mechanical testing requirements that apply to WPSs that are qualified by test. Prequalification of WPSs, however, does not eliminate the need for a **written** WPS. During the creation of the WPS, the Fabricator would have been forced to evaluate the requirements for preheat. However, the first error was that written WPSs were not employed (3.6).

The Inspector is responsible for the review of all WPSs. An important role of the Inspector is to make sure the WPSs are complete and followed. If the WPS was never written, it obviously could not have been approved. Therefore, erection welding should never have begun (6.3.1).

Furthermore, the Engineer has the responsibility to judge the suitability of the prequalified joints to the application. The specific joint detail is defined in the WPS, but, once again, in the absence of a written welding procedure, this obviously was not done (3.1).

The structure certainly should not have progressed to the height of several stories before the discovery of this oversight. The Inspector is responsible to ensure proper procedures are utilized (6.5).

While everyone bears some of the fault here, the Engineer did execute his responsibilities appropriately when the available alternatives were investigated. By consulting an expert in the field, he was able to obtain a professional, unbiased opinion regarding the implications and possible corrective actions. In this particular situation, a minimum prequalified preheat level would have been 150 degrees F. Construction had taken place during the summer when the ambient temperature was typically 70 degrees F.

Without question, the deviation in preheat requirements prohibited the Inspector from being able to accept these welds, regardless of the final quality. The Engineer did have the latitude, however, to employ alternate acceptance criteria. The consultant pointed out that the preheat levels were minimum requirements for prequalified procedures. The code itself indicates that under some conditions of restraint, base metal composition, and levels of weld metal hydrogen content, higher preheat levels would be required. Moreover, the code admits that in some situations, lower levels of preheat could be employed (3.5). WPSs that are qualified by test under the provisions of Section 4 of the code do not mandate the prequalified minimum preheat temperatures. Rather, an alternate preheat level could be selected if the procedures were qualified by test. Therefore, if a procedure qualification test duplicating the conditions actually used were employed, and if the mechanically tested specimens exhibited the ductility, strength, and soundness required by the code, a WPS could be qualified by a test that utilized a 70 degree F (or ambient) preheat level. This would be in complete compliance with the code, except that normally, the procedure would have been qualified before fabrication began.

In addition to requiring a procedure qualification test, the Engineer was advised to employ extra measures of nondestructive testing. The discontinuity of greatest concern is a weld crack. When adequate preheat levels are not maintained, cracking is the most obvious expected discontinuity. Therefore, the nondestructive testing method with the greatest ability to detect cracks was employed, that is, ultrasonic inspection, which also lends itself well to field inspection. Spot inspections were recommended. Locations were selected based upon work records reflecting which joints were likely to be welded on the coldest days and times during the project.

The welding procedure qualification test was successful. Ultrasonic inspection revealed no cracks on the joints examined, which constituted approximately 25% of the total. The project was able to proceed, although preheat was mandated for subsequent fabrication. In spite of the problems, the situation was resolved with a minimum amount of cost and delay because in this case, the Engineer exercised his responsibilities.

Conclusion

In many situations involving welding, Engineers simply do not have the background or experience necessary to perform all of the engineering responsibilities essential to the success of a given project. Therefore, it is incumbent upon the professional Engineer to admit the limits of his or her knowledge and consult an expert in the field. While both Inspectors and Fabricators have essential roles to play, the Engineer is responsible for the structural integrity of the project. Therefore, the Engineer must see to it that all other essential individuals fulfill their functions toward that end, no less and no more.

Ensuring Weld Quality in Structural Applications, Part II of III

Effective Visual Inspection

Introduction

Visual inspection is the most powerful tool that can be employed to ensure weld quality. The more technologically sophisticated nondestructive processes, such as ultrasonic or radiographic inspection, can only verify that the desired quality is present once welding is complete. Effective visual inspection examines each step of the welding process, well before the weld is completed. According to A. M. Gresnight of Delft University, the Netherlands, "Most serious failures in performance are due to gross error; e.g., wrong consumables or omission of preheat, and not minor non-compliances."

Everyone involved in a welding project can—and should—participate in in-process visual inspection, including the welders, Inspectors, foremen, etc. Minor discontinuities can be detected and corrected during the fabrication process, precluding the need for more expensive and complicated repair after the fabrication is complete. In order to be effective, visual inspection must take place prior to, during, and after welding. Obviously, visual inspection requires good eyesight and good lighting. Frequently, good lighting is scarce in a fabrication shop or even in certain parts of a construction site, so a simple flashlight can be a valuable aid to visual inspection.

"Steak Dinner" Analogy

To understand how visual inspection can be utilized to improve weld quality, consider the approach used in the restaurant industry. A perfectly good steak is delivered on a plate, accented by appropriate side dishes and garnish. The customer applies a visual inspection to satisfy his/her desire for a high-quality meal. Dirty dishes, burned edges on the meat, and inappropriate sizing of portions would detract from an image of quality. It is also important to note that the steak is complete; that is, a test portion of the steak has not been removed for examination in the kitchen. It is strange to even consider the notion that a wedge of meat might be removed for inspection or testing. The steak has not received either nondestructive or destructive testing. Rather, the process of creating the dinner has been carefully controlled by regular visual inspections at each step in the preparation.

Examining the process in total, the dinner starts with meat that has been graded by a suitable government agency. The kitchen facility has been approved by the Board of Health. The chef has appropriate training and credentials. The recipe has been taste-tested and time-proven. All the ingredients involved with the meal are suitably controlled, with the proper amount of each added at the proper time. The temperature of the broiler, and the amount of time the beef will be cooked, are both carefully controlled and regularly verified. The finished product is visually inspected by the chef, the waiter, and finally by the consumer. Without visual inspection, most people would be unable to detect a poorly prepared piece of meat before it is consumed. However, by the application of visual inspection throughout the process, the desired results are achieved.

The quality of a completed weld is predictable, providing the input variables are known.

Inspecting the Welding Process

The same approach can be used in welding because, like cooking, welding is a process. The fabrication shop is routinely inspected and approved by some outside agency such as the AISC Shop Certification Program. The steels employed are governed by agencies such as ASTM, and the Certificates of Conformance ensure product integrity. Welders are required to pass operator qualification tests to verify their ability. Like the chef, they are trained to carry out specific operations. In the welding industry, the welding procedure specification (WPS) is like a recipe. In the WPS, specific welding parameters are set forth, including preheat and interpass temperatures, wire feed speeds, voltage used, travel speeds, etc. Finally, the completed welds are required to be visually inspected. With the major exception of gas metal arc/short arc transfer, visually acceptable welds routinely exhibit the required quality for their application.

Over the years, welding has been described as both an art and a science. While it is both, there has been a disproportionate emphasis on the art of welding. Welding is a complex science involving the interaction of many disciplines. Nevertheless, the welding process is subject to certain physical and chemical laws that allow it to be controlled and the results predicted.

The quality of a completed weld is predictable, providing the input variables are known. Unfortunately, input variables (even critical input variables) are often misunderstood, ignored, or uncontrolled, resulting in welds of unpredictable quality. Variables may be overlooked for several reasons. During procedure qualification testing, for example, it is essential that critical welding parameters be evaluated and identified. During the qualification and testing of welders, the unique requirements of the specific application must be communicated to them. When all input variables are properly identified and controlled, welds of the required quality will be consistently achieved. Effective visual inspection can ensure that significant variables are controlled, resulting in welds of the required quality.

Discontinuities in welds do not occur by mere chance. They are the result of failing to identify and control for one or more critical variables. (Author's note: In our formal training, many of us have been taught the "scientific method," a system by which one variable is examined at a time. Experience demonstrates that variables rarely exist in isolation. First, in most applications, problems will be attributed to more than one variable. Secondly, the interaction of multiple variables is often overlooked. The more complex, but much more accurate methods associated with the "design of experiments" address these situations.) Even when critical variables are identified, they are frequently ignored or not properly communicated to the individuals involved.

While visual inspection is a powerful tool, its potency may be questioned because of past experience. For example, if a visual inspection is so powerful, why are weld discontinuities and defects routinely found by nondestructive testing methods?

One plausible explanation is that visual inspection is rarely properly performed. Welding is a process, and the process must be observed throughout its application. If an Inspector arrives on the job site after the welds are complete, it is impossible to properly apply visual inspection. Because the nondestructive testing methods evaluate completed welds, Inspectors are trained to focus on finished products. Attention must be refocused on visually inspecting the process, not merely the finished result.

Fillet weld sizes can be measured with gages. (Photo courtesy of G.A.L. Gage)

AWS B1.11 - Guide for Visual Inspection of Welds

To provide practical information about the requirements for conducting visual inspections, the American Welding Society has published a concise, 28-page document, AWS B1.11, entitled "Guide for Visual Inspection of Welds." Consistent with the philosophy already presented in this series of articles, AWS B1.11 emphasizes the importance of inspection prior to welding, during welding, and after welding. Practical suggestions, presented in a checklist format, are offered for each phase.

In Section 3.2 of B1.11, the following items are highlighted as part of inspection *prior* to welding:

1. Review drawings and specifications.
2. Check qualifications or procedures and personnel to be utilized.
3. Establish checkpoints.
4. Set up a plan for recording results.
5. Review materials to be utilized.
6. Check for base metal discontinuities.
7. Check fitup and alignment of welded joints.
8. Check preheat, if required.

When appropriate attention is paid to these issues, the quality of the yet-to-be-made weld can be expected to improve as a result of the pre-welding inspection. For example, when fitup and alignment of the joint are carefully inspected, consistent uniform fusion to the root of the weld and avoidance of excessive distortion and/or residual stresses can be achieved.

Item No.3 discusses checkpoints. This is particularly critical on large weldments or complex projects when subsequent fabrication activities may preclude further inspection of the fabrication process. Concurrent with this idea is the establishment of "hold points" where approval is required before further fabrication can be continued. This must be coordinated with the various contractors involved so that the overall project can proceed as expected. Establishment of "hold points," and communication with all parties involved, are critical to maintaining both quality and the job schedule.

In Section 3.3 of B1.11, items that should be inspected *during* welding are outlined. These include:

1. Quality of weld root bead.
2. Joint root preparation prior to welding the second side.
3. Preheat and interpass temperatures.
4. Sequence of welding passes.
5. Subsequent layer for apparent weld quality.
6. Cleaning between passes.
7. Conformance with the applicable procedure.

The root pass, often the most critical part of the weld, is often made under the most difficult conditions. Maintenance of the proper preheat and interpass temperatures is critical for the metallurgical integrity of both the weld metal and the heat affected zone. Inspection of intermediate weld layers, including removal of slag between layers, is absolutely essential for applications where only visual inspection will be applied. Conformance with the maximum layer thicknesses and bead widths as governed by the applicable welding code or WPS requirements can be visually verified at this point.

Visual inspection must take place well before the work is completed.

The requirements for post-weld inspection are covered in Section 3.4 of B1.11. Before the checklist is provided, the following statement is made: "Many people feel that visual inspection commences once the welding has been completed. However, if all of the previously discussed steps have been taken before and during welding, this final phase of visual inspection will be accomplished easily. It will simply provide a check to be sure that the steps taken have resulted in a satisfactory weld." This statement endorses the power of an effective visual inspection. The checklist of items to inspect after welding includes the following:

1. Final weld appearance.
2. Final weld size.
3. Weld length.
4. Dimensional accuracy.
5. Amount of distortion.
6. Post-weld heat treatment.

The importance of these issues is self-evident. The appearance of the weld is a strong indicator of the suitability of the actual welding procedure used, and the ability of the individual welder. More than merely a cosmetic issue, weld appearance provides some insight into how the weld was made.

Visual Inspection and the AWS D1.1 Code

Inspecting the work in process is not a new concept, but rather is part of the standard codes already. Take, for example, the *D1.1-98 Structural Welding Code - Steel*. In that code, visual inspection is mandated by 6.9, which states: "All welds shall be visually inspected...". In the chapter on Inspection, the following directions are given to the Inspector:

- The Inspector shall make certain that only materials conforming to the requirements of this code are used (6.2).
- The Inspector shall verify that all WPSs have been approved by the Engineer in conformance with 4.1.1 (6.3.1).
- The Inspector shall inspect all welding equipment to be used in the work to make certain that it conforms to the requirements of 5.11 (6.3.2).

Table 6.1
Visual Inspection Acceptance Criteria[1] (see 6.9)

Discontinuity Category and Inspection Criteria	Statistically Loaded Nontubular Connections	Cyclically Loaded Nontubular Connections	Tubular Connections (All Loads)
(1) Crack Prohibition The weld shall have no cracks.	X	X	X
(2) Weld/Base-Metal Fusion Thorough fusion shall exist between adjacent layers of weld metal and between weld metal and base metal.	X	X	X
(3) Crater Cross Section All craters shall be filled to the full cross section of the weld, except for the ends of intermittent fillet welds outside of their effective length.	X	X	X
(4) Weld Profiles Weld profiles shall be in conformance with 5.24.	X	X	X
(5) Time of Inspection Visual inspection of welds in all steels may begin immediately after the completed welds have cooled to ambient temperature. Acceptance criteria for ASTM A514 and A517 steels shall be based on visual inspection performed not less than 48 hours after completion of the weld.	X	X	X
(6) Underrun A fillet weld in any single continuous weld shall be permitted to underrun the nominal fillet size specified by 1/16 in. (1.6 mm) without correction, provided that the undersize portion of the weld does not exceed 10% of the length of the weld. On web-to-flange welds on girders, no underrun is permitted at the ends for a length equal to twice the width of the flange.	X	X	X
(7) Undercut (A) For material less than 1 in. (25.4 mm) thick, undercut shall not exceed 1/32 in. (1 mm), except that a maximum 1/16 in. (1.6 mm) is permitted for an accumulated length of 2 in. (50 mm) in any 12 in. (305 mm). For material equal to or greater than 1 in. thick, undercut shall not exceed 1/16 in. for any length of weld.	X		
(B) In primary members, undercut shall be no more than 0.01 in. (0.25 mm) deep when the weld is transverse to tensile stress under any design loading condition. Undercut shall be no more than 1/32 in. (1 mm) deep for all other cases.		X	X
(8) Porosity (A) Complete joint penetration groove welds in butt joints transverse to the direction of computed tensile stress shall have no visible piping porosity. For all other groove welds and for fillet welds, the sum of the visible piping porosity 1/32 in. (1 mm) or greater in diameter shall not exceed 3/8 in. (10 mm) in any linear inch of weld and shall not exceed 3/4 in. (19 mm) in any 12 in. (305 mm) length of weld.	X		
(B) The frequency of piping porosity in fillet welds shall not exceed one in each 4 in. (100 mm) of weld length and the maximum diameter shall not exceed 3/32 in. (2 mm). Exception: for fillet welds connecting stiffeners to web, the sum of the diameters of piping porosity shall not exceed 3/8 in. (10 mm) in any linear inch of weld and shall not exceed 3/4 in. (19 mm) in any 12 in. (305 mm) length of weld.		X	X
(C) Complete joint penetration groove welds in butt joints transverse to the direction of computed tensile stress shall have no piping porosity. For all other groove welds, the frequency of piping porosity shall not exceed one in 4 in. (100 mm) of length and the maximum diameter shall not exceed 3/32 in. (2 mm).		X	X

1. An "X" indicates applicability for the connection type; a shaded area indicates non-applicability.

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- The Inspector shall permit welding to be performed only by welders, welding operators, and tack welders who are qualified in accordance with the requirements of Section 4 (6.4.1).

- The Inspector shall make certain that only welding procedures are employed which meet the provisions of Section 3 or Section 4 (6.5.2).

- The Inspector shall make certain that electrodes are used only in the positions and with the type of welding current polarity for which they are classified (6.5.3).

- The Inspector shall, at suitable intervals, observe joint preparation, assembly practice, the welding techniques, and performance of each welder, welding operator, and tack welder to make certain the applicable requirements of this code are met (6.5.4).

These code requirements make it obvious that visual inspection must take place well before the work is completed. This may deviate from the approach used by many Inspectors, but it is the only approach that can actually prevent the formation of welding defects. For example, when the base materials being used are examined, the Inspector can prevent the use of the wrong type of material in a specific application. Careful examination of welding procedures will reveal the suitability of a specific procedure for a particular application. The welder's credentials will help determine the suitability of that individual for the specific application.

Inspecting the Completed Weld

Most of the emphasis to this point has been upon process inspection. The quality of a completed weld can also be visually determined in many situations. The single exception to this, as previously noted, is gas metal arc/ short arc transfer. With this process, a weld may have an excellent appearance and lack the essential fusion necessary for all forms of welding. In this case, extra emphasis on process inspection and nondestructive testing will be warranted. A good-looking weld is generally a good weld. A poor-appearing weld may or may not be a poor weld. However, the presence of visually discernible criteria that deviate from good appearance is generally an indication that one or more variables are not being properly addressed. For example, excessive spatter may not detract from the quality of the weld. However, it is a sign that the process is not being controlled sufficiently.

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In a meeting several years ago, a series of fatigue and brittle fractures that occurred on highway bridges was being examined. The organizer of the meeting was attempting to establish the need for more rigorous welded fabrication requirements. Hydrogen cracking, brittle fracture, fracture mechanics, and fatigue details were all discussed. Most revealing in the meeting, however, was a comment made by a very skilled technician, a welder, who had no formal engineering training. His comment was as follows: "I don't understand fracture mechanics, fatigue, or hydrogen embrittlement. However, from what I see in these photographs, none of these welds that failed would have met the visual acceptance criteria of the code." The silence in the room was deafening. The welder was correct. All of the technical issues that were being discussed had entered into these failures, but none of the welds should have ever been accepted based on simple visual inspection criteria.

The traditionally understood inspection responsibilities are summarized concisely in Table 6.1 of the D1.1-98 code, reproduced on the previous page.

Conclusion

Welding is a process. Only by properly controlling every element of the process can product quality be controlled. It is essential, however, that all the input variables be properly identified and controlled. During procedure qualification testing, critical variables can be identified. During welder qualification and training, important parameters must be appropriately stressed. Effective visual inspection can ensure that the variables are properly controlled and identified.

There are applications where additional nondestructive testing methods should be specified. However, in all situations, effective visual inspection must be employed to ensure weld quality. It is incumbent upon Engineers to properly direct Inspectors' attention to those issues that will contribute to higher quality products. When this is done, the quality of welding will improve, the cost will be reduced, and the Owner's best interests will be served.

Ensuring Weld Quality in Structural Applications, Part III of III

Alternate Acceptance Criteria

Introduction

Quality is tied to a given specification. The specification must be suitable to meet the needs of the ultimate Owner. For most welded construction, the AWS *D1.1-98 Structural Welding Code - Steel* provides adequate acceptance criteria for welded construction. Unusual structures, however, may demand additional requirements. D1.1 criteria may be overly restrictive for some lesser structures. For nonconformances to a standard specification, alternate acceptance criteria may be utilized in order to avoid unnecessary weld repairs. It is the Engineer's responsibility to evaluate the appropriateness of an alternate acceptance criterion before invoking it for a specific project.

Heavy sections may require especially rigorous alternate acceptance criteria.

Defining "Quality"

One of the currently popular definitions of a quality product is as follows: "A quality product is one that meets specification requirements." By this definition, quality is integrally linked to the applicable specification. As long as the product meets those requirements, it is deemed "quality." Unfortunately, if the specification is incorrect or inappropriate, conformance to those requirements may satisfy this definition but would not satisfy the wants and desires of the ultimate customer. Only when a proper specification is utilized, and when the product integrity meets or exceeds those specification requirements, will a true quality product have been produced that meets customer requirements. Therefore, a more appropriate definition of "quality" would include the concept of meeting customer expectations in addition to the standard specification requirements. This philosophy is summarized by A.M. Gresnight of Delft University, the Netherlands, as follows:

> "A good weld is any weld which does the job it is intended for during the service life of the structure."

In the structural field, the customer (Owner) has a representative (the Engineer) who develops the necessary specifications (contract documents and cited codes and standards) that enable the manufacturer (Fabricator) to deliver a quality product. In the case of fabricated steel, the commonly cited standard for quality is the AWS *D1.1-96 Structural Welding Code - Steel*.

D1.1 Quality Provisions

An understanding of the philosophy behind the D1.1 Code will help the Engineer to determine whether it will adequately address the needs of the Owner. Section 6.8, "Engineer's Approval for Alternate Acceptance Criteria," states: "The fundamental premise of the code is to provide general stipulations applicable to most situations." The emphasis is significant. It is important to consider the scope of the D1.1 Code, which covers structures that are static and dynamic: on- and off-shore applications that utilize plate, rolled shapes, and tubular members. The products covered range from simple single story metal-framed buildings to 100-story-plus skyscrapers and offshore drilling platforms. In some circumstances, these general stipulations may be overly restrictive, and in other situations, they may not adequately address the demands of the structure. Evaluating the suitability of the specification for the application is certainly the responsibility of the Engineer.

In the commentary to Section 6.8 of the code, the following can be found: “The criteria provided in section 5, Fabrication, are based upon knowledgeable judgment of what is achievable by a qualified welder. The criteria in Section 5 should not be considered as a boundary of suitability for service. Suitability for service analysis would lead to widely varying workmanship criteria unsuitable for a standard code. Furthermore, in some cases, the criteria would be more liberal than what is desirable and producible by a qualified welder. In general, the appropriate quality acceptance criteria and whether a deviation produces a harmful product should be the Engineer’s decision. When modifications are approved, evaluation of suitability for service using modern fracture mechanics techniques, a history of satisfactory service in similar structures, or experimental evidence is recognized as a suitable basis for alternate acceptance criteria for welds.” This commentary makes it clear that the code has utilized what is achievable as the acceptance criterion, not what is necessary for the particular application. This is a reasonable approach for a standard specification, and as is indicated in the commentary, precludes the need for widely varying fabrication standards which would be difficult to monitor in a typical fabrication facility. When the weld quality does not meet these standards, however, it is inappropriate to automatically assume that the weld will be unacceptable for service. This should, however, drive the Engineer to look to fitness-for-service type criteria for further evaluation.

A good weld is any weld which does the job it is intended for during the service life of the structure.

Few Engineers recognize that the D1.1 code permits the use of alternate acceptance criteria for welds. According to Section 6.8: “Acceptance criteria for production welds different from those specified in the code may be used for a particular application, provided they are suitably documented by the proposer and approved by the Engineer. These alternate acceptance criteria can be based upon evaluation of suitability for service using past experience, experimental evidence, or engineering analysis concerning material type, service load effects, and environmental factors.”

These provisions permit the Engineer to utilize alternate acceptance criteria. Since quality is integrally linked to the applicable specification, the acceptance criteria will have a major impact on the final product. The Engineer’s responsibility is to assess the suitability of a standard specification to a particular project, as well as to approve an alternate should the need arise.

Considering Alternate Acceptance Criteria

There are three areas in which alternate acceptance criteria should be considered: First, there are situations where standard acceptance criteria are inadequate to the demands of the structure. Secondly, standard acceptance criteria may be overly restrictive for a particular application. Finally, there are cases in which fabrication is routinely performed to a standard specification, with minor noncompliances that can be accepted through the use of an alternate acceptance criterion. All three are significant issues and will be addressed here.

Certain structures make unusual demands upon welds and weld quality. When new materials are employed, significant deviations from standard material thicknesses are utilized, new welding processes are employed, and/or when the design of the structure involves a significant departure from established practices, it is prudent for the Engineer to critically evaluate the suitability of standard specifications.

For example, the steel fabrication industry learned many lessons when “jumbo sections” were initially applied to tension applications in trusses. Standard materials (hot rolled, carbon and/or low alloy steel shapes) in unusual thicknesses (flanges exceeding 5” in thickness) were being used in new applications (direct tension connections). The common workmanship criteria set forth in the various codes and specifications, as well as normally acceptable workmanship criteria, proved to be inadequate in a number of structures. In hindsight, it would have been prudent to employ more rigorous alternate acceptance criteria for these types of structures. Since that time, provisions have been written to address these situations and have been presented in a variety of technical journals. Indeed, the standard specifications now include more rigorous requirements.

The second situation occurs when the standard acceptance criteria are more demanding than is justified for the particular application. An example in the structural field would be in the fabrication of steel joists. These components in steel buildings are usually covered by another specification that is more applicable to the particular product involved. Application of the same acceptance criteria as are applied to other fabricated steel structures and mandated by D1.1 would be overly restrictive, justifying alternate acceptance criteria. The Engineer should be careful when routinely suggesting that alternate acceptance criteria be employed which deviate from, or are less rigorous than, a national consensus standard such as D1.1. This practice would be recommended only for specific applications for components where well established, time-proven practices that have a history of adequacy have been used, and where deviation from these practices would constitute a major hardship. The D1.1 code, however, clearly gives the Engineer the authority to accept an alternate standard in these situations.

The most important use of alternate acceptance criteria, however, applies to the third situation, where standard acceptance criteria have been utilized for the fabrication practice and minor nonconformances have been uncovered. Alternate acceptance criteria can be utilized to accept these nonconformances and eliminate the need for unnecessary repairs. Obviously, the alternate acceptance criteria chosen must, as is true in the case of all engineering decisions, be applicable and appropriate for the application. Neither poor workmanship nor poor quality can be accepted. However, when the weld that does not conform to the standard specification is suitable for the specific situation, alternate acceptance criteria may be employed to eliminate the need for a repair. There are many reasons why this may be desirable for all (that is, the Owner, the Engineer, and the Fabricator). Unnecessary delays may be avoided. Costly repairs are avoided. Finally, and perhaps most importantly, an "acceptable" repaired weld may actually be inferior to the weld initially rejected as "unacceptable." Again, according to A.M. Gresnight:

> "Standards for weld discontinuities traditionally are based on good workmanship criteria. By extending the traditional standards with the second quality level, based on fitness for purpose, unnecessary and potentially harmful repairs can be avoided."

The 7 in (180 mm) flanges of these transfer girders require careful consideration of the NDT acceptance criteria.

Weld Discontinuities

Weld discontinuities fit into two broad categories: planar and volumetric. Planar discontinuities include cracks and lack of fusion. These are serious discontinuities that are unacceptable, and particularly critical in structures subject to fatigue. Volumetric discontinuities include items such as porosity, slag inclusion, and undercut. These are less significant, and when held within certain limits, are acceptable by most codes even under dynamic loading situations.

Volumetric discontinuities are readily discernible by nondestructive testing methods and, in many cases, by visual inspection. Planar discontinuities are harder to detect, and may even be overlooked by radiographic nondestructive testing. It has been shown that, during initial fabrication, most discontinuities are volumetric in nature. Under repair welding conditions, which are more demanding than original fabrication circumstances, planar discontinuities are more likely to develop. Notice the progression: readily detectable, less significant volumetric discontinuities observed in the original fabrication may be removed and replaced with welds that contain less detectable, but more significant, planar discontinuities. This is not to say or imply that welds cannot be effectively repaired. It does mean, however, that haphazard demands for weld repair may actually result in a product of decreased value to the Owner. It should also be noted that the deposition of additional weld metal is likely to increase distortion and residual stresses in the structure. When the nonconforming weld is adequate for the particular application, the responsible approach is to utilize an alternate acceptance criterion to eliminate the unnecessary repair.

Most Engineers are unsure of the suitability of alternate acceptance criteria. The search for appropriate documents that employ the "fitness for purpose" approach is generally a frustrating experience. Apart from finding information regarding the methods that may be employed for analysis, practical ideas as they relate to welds are all too scarce. Mr. Robert E. Shaw, Jr., P.E., of Steel Structures Technology Center, Inc., (40612 Village Oaks Drive, Novi, Michigan 48375-4462) has provided Engineers with a useful source of information regarding alternate acceptance criteria. Shaw has systematically evaluated specific discontinuities, the D1.1 Code requirements, and other standards that could be used as alternates. His summary is excellent and provides practical options to Engineers.

Undersized welds are a common problem. The situation is simple: the drawings call for a 5/16 in (8 mm) fillet weld and the welder deposits a 1/4 in (6 mm) fillet. At least two options are available: first, additional weld metal can be deposited over the surface to

Readily detectable, less significant volumetric discontinuities observed in the original fabrication may be removed and replaced with welds that contain less detectable, but more significant, planar discontinuities.

build it up to the required size; secondly, an alternate acceptance criterion could be employed that would allow these welds to be acceptable as deposited. It should be noted that the D1.1 Code would allow the welds to underrun the nominal fillet weld size by 1/16 in (1.6 mm) without correction provided that the undersized portion of the weld does not exceed 10% of the weld length (D1.1-98, Table 6.1, see Part II of this series). If the entire weld, however, is undersized, this provision would not be applicable. In many cases, the deposition of additional weld metal would be routine and would not constitute a major problem. However, the initial weld may have been produced with an automatic, submerged arc welding machine when the travel speed happened to be slightly too high, resulting in a slightly undersized weld. The weld may be beautiful and meet all criteria except for the size. To make the weld repair, a gang of manual or semiautomatic welders may be assigned to deposit the additional weld metal. The finished product may be visually inferior, and subject to all of the potential discontinuities of the starts and stops associated with manual and semiautomatic welding.

Has the product quality been enhanced by the repair? First, it must be determined if the undersized weld would have been acceptable. As is the case in many situations involving fabricated plate girders, the weld size may have been based upon the minimum prequalified fillet weld size prescribed in the D1.1 Code. The design basis was not strength, but this minimum size. A quality, 1/4 in (6 mm) fillet weld would have provided all the necessary strength in this particular situation. The reasoning behind the minimum fillet weld size in the code is based upon good workmanship practices and controlling the heat input to preclude weld cracking. However, in this example, it has been assumed that the initial weld is a quality weld, free of cracks, with acceptable weld contours, etc. If this is the situation, leaving the undersized weld in place, unrepaired, is a more responsible approach than demanding the weld repair. The initial weld is probably of higher quality than the repaired weld would be, will have less distortion, is less costly, and will eliminate unnecessary delays.

The decision to invoke alternate acceptance criteria must be made by the Engineer. In a separate article in this series, the roles of the Engineer, the Inspector, and the Fabricator are defined. The Inspector cannot make this decision and neither can the Fabricator. Only the Engineer with an understanding of the loading, design assumptions, and overall structural significance can make these types of decisions.

Conclusion

For most applications, the AWS *D1.1-98 Structural Welding Code - Steel* provides adequate acceptance criteria for welded construction. For welds that deviate from standard acceptance criteria, engineering judgment should be applied before repairs are mandated. If the weld will meet the structural requirements for the project without modification, the responsible approach of the Engineer is to utilize alternate acceptance criteria and accept these welds. Ultimately, a product of improved quality at reasonable cost will be the result of this approach.