



Guide for Strengthening and Repairing Existing Structures



American Welding Society



AWS D1.7/D1.7M:2010
An American National Standard

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American National Standards Institute
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Guide for Strengthening and Repairing Existing Structures

1st Edition

Prepared by the
American Welding Society (AWS) D1 Structural Welding Committee

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This guide provides information on strengthening and repairing existing structures. Included are sections on weldability, evaluation of existing welds, testing and sampling, heat straightening, and damage repair.



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Foreword

This foreword is not part of AWS D1.7/D1.7M:2010, *Guide for Strengthening and Repairing Existing Structures*, but is included for informational purposes only.

This guide has been developed to assist in the task of strengthening and repairing existing structures. The guide includes information to assist both Engineers and Contractors in order to provide general direction and guidance on weld repairs, weld strengthening, and other procedures to correct challenging issues faced while dealing with existing structures.

Informative Annexes. These annexes are not part of this guide but are provided to clarify the guide's recommendations by showing examples, providing information, or suggesting alternative good practices.

Errata. It is the Structural Welding Committee's Policy that all errata should be made available to users of the code. Therefore, any significant errata will be published in the Society News Section of the *Welding Journal* and posted on the AWS web site at: <http://www.aws.org/technical/d1/>.

Suggestions. Your comments for improving AWS D1.7/D1.7M:2010, *Guide for Strengthening and Repairing Existing Structures* are welcome. Submit comments to the Managing Director, Technical Services Division, American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126; telephone (305) 443-9353; fax (305) 443-5951; e-mail info@aws.org; or via the AWS web site <<http://www.aws.org>>.

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Guide for Strengthening and Repairing Existing Structures

1. General Provisions

1.1 Scope. This document contains basic information pertinent to the welded strengthening and repair of existing steel structures. The information contained in this guide is intended for both Engineers and Contractors with the purpose of providing direction and guidance to perform weld repairs, weld strengthening, and other weld procedures to correct problematic issues with existing structures. This guide contains background information that will be useful to the Engineer who is obligated under AWS D1.1/D1.1M:2008 Clause 8 to provide a comprehensive plan to address projects that involve strengthening and repairing of steel structures. The approach to the strengthening and repairing of these materials is to be developed using the information provided herein.

This guide is intended to apply to the strengthening and repair of existing structures made of the following materials:

- (1) Steel with a minimum specified yield strength of 100 ksi [690 MPa] or less
- (2) Cast iron
- (3) Wrought iron

Strengthening or repairing an existing structure includes modifications to meet new serviceability or load requirements as well as corrections made to repair conditions unsuitable for future use specified by the Engineer. The Engineer should prepare a contract for the work including, but not limited to, design, workmanship, inspection, acceptance criteria, and documentation. Except as modified in this clause, provisions of this guide should apply to the strengthening and repair of existing structures, including heat straightening of distorted members.

1.2 Limitations. This guide is intended to assist in the evaluation of existing structural elements and the development of appropriate procedures for repairing those elements. It does not provide exhaustive coverage of any specific topic.

This guide is intended to apply to the strengthening and repair of existing buildings and other structural systems. It is not intended to apply to:

- (1) Structures made of steels less than 1/8 in [3 mm] thick
- (2) Pressure vessels and pressure piping
- (3) Structures made of materials other than those listed under the scope
- (4) Seismic upgrades
- (5) New construction

Whereas this guide is not intended to apply the application outside the scope, the principles contained in this guide may be applied to other materials and applications. The Engineer is advised to use caution and engineering judgment for application outside the scope of this guide.

More importantly, it is critical to state here that this document does not provide detailed specific procedures and direction to correct any specific strengthening or repair operation regardless of how common or standard the procedure may be. Instead, information supplied herein as well as that material referenced in Annex A is intended to provide users with an overall approach to weld modifications as they pertain to: strengthening and repair; technical resources to develop

appropriate detailed specific strengthening and repair contract documents or procedures; summarized guidance on typical weldability of common metals; summarized guidance for testing the serviceability of the procedures and a summary of common procedures and approaches that are intended to be modified for the specific procedure.

1.3 Approval. All references to “approval” should be interpreted to mean approval by the Engineer.

1.4 Safety Precautions. Safety and health issues and concerns are beyond the scope of this standard and therefore are not fully addressed herein. However, in addition to the material supplied in subsequent chapters of this document, pertinent information can be found in the following standalone documents: ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*, and applicable federal, state, and local regulations. Other pertinent information can be found in the manufacturer’s safety literature on equipment and materials. These documents should be referred to and followed as required.

NOTE: This guide may involve hazardous materials, operations, and equipment. The document does not purport to address all of the safety problems associated with its use. It is the responsibility of the user to establish appropriate safety and health practices. The user should determine the applicability of any regulatory limitations prior to use.

1.5 Standard Units of Measure. This guide makes use of both U.S. Customary Units and the International System of Units (SI). The latter are shown within brackets ([]) or in appropriate columns in tables and figures. The measurements may not be exact equivalents; therefore, each system should be used independently of the other.

2. Normative References

The standards listed below contain provisions, which, through reference in this text, constitute mandatory provisions of this AWS guide. For undated references, the latest edition of the referenced standard shall apply. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply.

A list of informative documents referenced in this guide is included in Annex A. There are numerous documents that exist and are available that cover repairs to existing structures published by AISC, AASHTO, and AREMA. These and other documents will be referenced in Annex A and are all intended to provide a guide for successful strengthening and repair.

American Welding Society (AWS) standards¹:

- (1) ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*
- (2) AWS A3.0, *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*

3. Terms and Definitions

AWS A3.0, *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*, provides the basis for terms and definitions used herein. However, the following terms and definitions are included below to accommodate usage specific to this document.

Engineer. The “Engineer” is the duly designated individual who represents the Owner on all matters within the scope of the guide.

Contractor. The “Contractor” is any company, or that individual representing a company, responsible for the manufacture, preparation and/or installation of items, in conformance with the provisions of this guide.

Inspector. The “Inspector” shall be defined as the duly designated person who acts for, and in behalf of, the Contractor or the Engineer on all inspection and quality matters within the scope of the contract documents, any governing code, or as specified by the Engineer.

Owner. “Owner” is the organization (private or public), the individual or company that exercises legal ownership of the final product or structural assembly.

¹ ANSI Z49.1 and AWS standards are published by the American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

4. Weldability

4.1 Scope

This clause addresses the weldability of structural steels and older steels and irons used in steel construction; provides guidance on the welding of these metals, including selection of filler metals, welding techniques, and welding procedures; and offers other information useful to designers, welding engineers, and Contractors. It is expected that other D1 documents will be a major reference to support the material presented in this clause. Documents and guides found in Clause 2 Normative References and Annex A Informative References will also support examining the weldability of materials covered by this document.

4.2 Introduction

AWS A3.0:2001 defines weldability as:

The capacity of material to be welded under the imposed fabrication conditions into a specific, suitably designed structure and to perform satisfactorily in the intended service.

Strengthening and repair present numerous challenges to both Engineers and those performing the work. Often, one of the first tasks is to determine if the material is weldable using conventional welding procedures and techniques. If records of the original construction exist, they should be reviewed to determine base metal type and properties. Mechanical and/or compositional tests may be necessary to identify the material, determine its composition, and evaluate its weldability. Older structural steels and other materials (cast steel, iron, etc.) may require the use of welding procedures that are more demanding than those for new construction and newer materials. The access and positions available for performing the work may be less than optimal or desirable. Also, for the most part, structures that were constructed by welding regardless of age are suitable for weld repair now. Materials should always be identified to assure chemical compositions acceptable for the project needs.

Most steels are weldable but the composition, strength, and original method of manufacture can greatly affect the materials, procedures, and techniques necessary to accomplish the required operations. Metals are considered to have good weldability if, when used in properly designed and detailed connections, the following are achieved:

- (1) Welding can be accomplished with common, welding processes (SMAW, FCAW, GMAW except GMAW-S, and SAW).
- (2) The resulting joint has minimal risk of cracking due to poor fabrication or other quality problems.
- (3) The welded joint assembly can provide the required structural and mechanical properties in both the weld and adjacent base metal without the use of stress relief heat treatment, postweld heat treatment, or other special procedural controls.

AWS D1.1/D1.1M:2008 and AASHTO/AWS D1.5M/D1.5:2008 list specific weldable grades of steel used in structural applications, both prequalified and those that require qualification testing. Steels not listed in current or previous versions of AWS D1 documents warrant consideration to determine weldability. Structural steels produced to current ASTM specifications generally provide limits in composition, strength, thickness, production method, and other factors that affect weldability. Other ASTM steels, including unlisted hollow structural sections and unlisted sheet steels, do not contain all the limits necessary to ensure good weldability without special considerations.

A metal with poor weldability may be successfully welded with the use of appropriate joint design, filler metals and welding procedures, including preheat and possibly postheat. If these variables are not carefully selected and controlled, the weld, heat-affected zone (HAZ), and/or base metal may crack or contain other significant discontinuities; the mechanical properties of the weld and HAZ may fail to provide the necessary strength, ductility, or notch toughness to perform adequately in service.

The properties of steel are affected by the heating and subsequent cooling from the welding operation. Cooling the weld and HAZ too rapidly may result in a product low in ductility and notch toughness, leading to brittleness or cracking. Extremely slow cooling may lower yield and/or tensile strength. As welds cool, they create shrinkage stresses and strains that approach yield, so ductility and toughness are needed, particularly if stress concentrations from weld discontinuities, material defects, geometric transitions, and notches are present. Material composition, grain size, thickness effects, and other factors affect ductility and notch toughness. Overheating (in terms of both peak temperature and duration) may also be detrimental, particularly for Thermomechanically Controlled Processing (TMCP), Quenched and Self-Tempered (QST), Quenched and Tempered (Q&T), or micro-alloyed steels.

4.3 Structural Metals

4.3.1 Historic Steels. In the 1800s, wrought iron was the predominant structural metal used for the construction of buildings and bridges. Cast iron was also commonly used for compression members such as columns as well as connection material. The use of steel became more common near the end of this time period, with structural steel becoming available starting in the 1880s. Prior to about 1910, there was little standardization in the industry. Each steel manufacturer adhered to their own standards. This resulted in steel with a wide variety of chemical and mechanical properties, some with good weldability, some with poor weldability.

From approximately 1900 through 1939, a medium carbon steel designated ASTM A 9 was predominantly used for buildings. For bridges, ASTM A 7 was used. In 1939 these two standards were combined into ASTM A 7, and this steel continued in use until 1966. Riveting was the dominant method of connecting material, which limited the need for weldable material. ASTM A 7 and ASTM A 9 were generally accepted as weldable steel, but both had a wider range of carbon content and fewer limits on other alloys and undesirable elements than permitted by ASTM A 36, their eventual successor. ASTM A 373 steel, an interim steel specification before the adoption of ASTM A 36 in 1962, provided better assurance of good weldability than ASTM A 7. Electrodes in the E60 classes were routinely used for ASTM A 7 and ASTM A 9 steels, and E70 class electrodes came into use in the early 1960s.

The American Institute of Steel Construction Design Guide 15, *Rehabilitation and Retrofit Guide, a Reference for Historic Shapes and Specifications* is a helpful tool in investigating and identifying old steel sections, structural design properties, and applicable standards. By determining the member size, it may be possible to identify the manufacturer and the approximate time of production, which in turn may provide guidance regarding the weldability of the steel. It also provides the allowable design stresses permitted during various time periods, assisting one in determining the filler metal strength requirements for repairs.

4.3.2 Structural Steels. Several methods may be used to identify existing steels to determine chemistry and mechanical properties. These are presented in Clause 4.4. A metallurgical test report can be obtained from small sample chips or drillings that provide the chemical analysis of the steel. This, in turn, can be used to establish the weldability using the principles of carbon equivalency and also cite particular concerns for potential welding problems from high levels of particular elements.

When welding procedures are developed for older steels, it may be helpful and more economical to develop the procedures based upon actual composition, rather than the maximum compositional limits permitted for the particular steel grade being welded. When this approach is used, a sufficient number of tests should be conducted to determine the probable composition of members and connection materials that are not specifically tested.

4.3.3 Classification of Steels. Steels have been commonly categorized based upon the composition of the steel. First, using the carbon content; second, by the addition of designated alloys of given percentages; and third, by special methods of production. Common terms for steels that have been or are used for structural applications are:

- (1) Low carbon steels

- (2) Medium carbon steels
- (3) High strength, low alloy (HSLA) steels
- (4) Thermomechanically Controlled Process (TMCP) steels
- (5) Quenched and Tempered (Q&T) steels
- (6) Quenched and Self-Tempered (QST) steels

Other steels, such as stainless steels, may be used for limited structural applications. Their use is not addressed in this document. Recommended D1 documents that may be used to establish welding requirements include AWS D1.1/D1.1M, *Structural Welding Code—Steel*, AWS D1.2/D1.2M, *Structural Welding Code—Aluminum*, AWS D1.3/D1.3M, *Structural Welding Code—Sheet Steel*, AWS D1.4/D1.4M, *Structural Welding Code—Reinforcing Steel*, AASHTO/AWS D1.5M/D1.5, *Bridge Welding Code*, AWS D1.6/D1.6M, *Structural Welding Code—Stainless Steel*, AWS D1.8/D1.8M, *Structural Welding Code—Seismic Supplement*, and AWS D1.9, *Structural Welding Code—Titanium*.

4.3.3.1 Low Carbon Steels. Low carbon steels contain less than 0.30% carbon. These may be welded without significant difficulty provided the steel temperature is above 32°F [0°C], and if the material is relatively thin, 3/4 in [18 mm] or less. Lower steel temperatures and thicker sections warrant the use of preheat, low-hydrogen electrodes, or both. It should be noted, however, that preheat and interpass temperature maintenance needs to be considered regardless of thickness only that in some cases ambient air temperature may be sufficient. High levels of other elements such as sulfur, other alloys, and *tramp* elements can affect weldability and should be considered. Sulfur is particularly common in older steels.

4.3.3.2 Medium Carbon Steels. Medium carbon steels contain between 0.30% and 0.60% carbon. They were used where high strength and high notch toughness were desired. The higher carbon level increased the effectiveness of hardening and tempering. Some alloying elements may have been added to the composition to improve hardenability. The range in carbon content from 0.30% to 0.60% creates a wide range of mechanical properties and weldability. Steels at the lower portion of the range of carbon content, near 0.30%, have good weldability and may be welded using standard welding procedures and techniques. Steels at the upper portion of the range of carbon content, near 0.60%, may form very hard HAZs, as high as Rockwell C 63, and significant martensite, unless special welding procedures are used. With low ductility, the HAZ is susceptible to cracking upon cooling to ambient temperature. With low notch toughness, there is a greater risk of cracking in service if subjected to impact loads. Preheating the steel and/or the use of controlled cooling or postheating reduces the cooling rate of the weld and HAZ, thereby reducing the likelihood of martensite formation.

4.3.3.3 High Strength Low Alloy (HSLA) Steels. High strength, low alloy (HSLA) steels came into structural use with the adoption of ASTM A 242 and ASTM A 441 steels in 1963, and ASTM A 572 and ASTM A 588 steels in 1968. HSLA steel specifications offer a wider variety of mechanical properties than do carbon steel specifications. As steel producers developed specific steel compositions to meet these mechanical property requirements, designated grades and steel types were assigned with tight control compositions often specific to the producer. The producers required or limited carbon, manganese, and various alloying elements to specific levels or ranges, and in some cases specific combinations. Depending upon type, there could be considerable variation in the alloy and combinations of alloy for a given HSLA steel grade. For most HSLA structural steels, carbon content is relatively low when compared to carbon steels, typically between 0.10% and 0.25% and the total alloy content is less than 2%.

Because of the presence of additional alloys and higher levels of alloy, the weldability of HSLA steels is somewhat less than that of carbon steels with similar carbon levels. Although weldability generally decreases as the strength increases, the common structural HSLA steels are not considerably higher in strength than similar carbon steels used in construction.

4.3.3.4 Thermomechanically Controlled Processing (TMCP) Steels. The production of some HSLA as well as other steels uses thermomechanically controlled processing. Thermomechanically Controlled Processing Steels (TMPC) are steels which exhibit ultra fine grain structures resulting from controlled rolling and accelerated cooling to provide the desired mechanical properties. Weldability is similar to Q&T steels.

4.3.3.5 Quenched and Tempered (Q&T) Steels. Quenched and Tempered (Q&T) steels are produced by heating the steel to a specific minimum temperature. The steel is then quenched in water or oil to cool it below a maximum temperature, then tempered by reheating the steel to above a minimum tempering temperature and allowing the steel to cool

at a controlled rate. The tempering temperature is well below the initial heating temperature. The quenching operation adds strength to the steel, but decreases ductility and notch toughness. Through tempering, the quenched steel's toughness and ductility is restored to adequate levels. Steels of this type are sensitive to the heating and cooling rates associated with welding. Excessive heat can lead to loss of strength. When heat is applied too rapidly, it can also lead to brittleness, low ductility and toughness, with a high risk for weld or HAZ cracking. Therefore, prior to production welding, welding procedures should be tested using representative joints and steels to verify that adequate quality and mechanical properties will be achieved and maintained. In addition to welding, the mechanical properties of Q&T steels may similarly be adversely affected by improper heating during cambering or straightening operations.

4.3.3.6 Quenched and Self-Tempered (QST) Steels. Quenched and Self-Tempered (QST) steels have evolved from TMCP steel production. The QST process controls chemical composition and manufacturing processes, starting with ingot or bloom reheating with the use of in-line interrupted quenching and self-tempering. The steel is partially quenched during the hot-rolling operation and tempers itself using residual internal heat. QST steels have improved weldability when compared to traditional quench and tempered steels. ASTM A 913 steel, adopted in 1993, is the common structural QST steel, and is manufactured under patent. QST steels have lower alloy content and improved weldability when compared to traditional Q&T steels, but excessive heat can still lead to loss of strength.

4.3.4 Cast Steels. Steel castings for structural applications are typically produced to various commercial standards based on mechanical properties rather than composition. The weldability of steel castings is therefore unknown unless the composition is known. In general, the weldability of a steel casting can be determined using the same methodology for rolled structural steels of similar composition. The weldability of a steel casting of a given composition is similar to that of a rolled structural steel of the same composition and heat treatment, if any. Welding materials and procedures similar to those used for the rolled structural steel may be used.

4.3.5 Cast Iron. Compared to structural steels, structural cast irons typically have higher carbon and silicon content. Because cast iron is typically less ductile than steel, there is a higher risk of cracking from welding and higher risk of poor mechanical properties in the weld and HAZ. Because of the high levels of carbon and silicon, welds on cast iron require careful control of cooling rates to minimize cracking tendencies. When needed, sufficient ductility in the weld area may be achieved using special high-nickel electrodes.

4.3.6 Wrought Iron. When wrought iron is involved, mechanical means of making structural connections should be considered first. If mechanical connections are impractical, welding should be done with caution. Wrought iron generally contains layers of silica and slag inclusions that run along the direction of rolling; therefore, the material is very weak in the through-thickness direction. If welding is necessary, the connection and joint should be configured so that the wrought iron will not be subjected to through-thickness stresses from applied loads. Joint details should minimize through-thickness shrinkage stresses.

4.4 Weldability Based on Steel Composition

The composition of the steel is a key parameter when determining its weldability. Consideration of the presence and percentage of individual elements, as well as the combination of specific individual elements with other elements, and the total effect of all elements combined is often necessary.

Of all elements other than iron, carbon is the most important element that affects weldability. Other elements have less effect on weldability and their importance and effect, weighted in comparison to carbon, is conveyed through the use of a carbon equivalency calculation.

As the carbon equivalent value increases, weldability decreases. The hardness, and hence brittleness, of a HAZ upon weld cooling is indicated through carbon equivalency. Weldability is inversely related to hardenability, as weldability decreases hardenability increases and visa versa. Steel with high hardenability will have a higher risk of cracking when welded. Conversely, steel having low hardenability will have less risk of cracking when properly welded.

The steel's production method, if known, should be considered in evaluating the weldability of the steel and development of suitable welding procedure specifications. Older steels were likely ingot cast, making them more susceptible to segregation, laminations, and other internal discontinuities. Modern steels, starting in the 1980s, may have been continuous cast, reducing the frequency and size of these internal discontinuities. These modern steels have commonly been deoxidized, and this improvement in production is not readily apparent from chemical composition. Elements such as

silicon, aluminum, or titanium may have been added to accomplish such deoxidation, a process otherwise known as *killing*. Most chemical composition evaluations can detect a residual amount of the deoxidizing element(s) remaining in the steel. These elements should be considered.

Silicon content is the most common indication of whether the steel was rimmed, semi-killed, or fully-killed. Fully-killed steel is considered the best of the three and has improved weldability when compared to rimmed and semi-killed steels, which may cause porosity in the weld unless sufficient deoxidizers were used. If, however, the steel was deoxidized using a vacuum technique, no significant amounts of residual deoxidizers will be found. Determination of oxygen content in steel is complex and would rarely be warranted in determining weldability.

It is important to note, however, that lower carbon contents preclude neither the need for nor the use of preheat. There are numerous reasons why preheating may be required and the carbon content should be investigated as part of the overall welding process.

4.4.1 Carbon Equivalency. The weldability of steel is commonly estimated using its measured or estimated chemical composition. The carbon equivalency (CE) equation estimates hardenability by listing the elements that have the greatest affect on hardening. CE equations compare the relative hardenability of different steels based upon the hardening produced by the total amount of carbon and carbon equivalents in their composition. Carbon produces hardness more efficiently than any other element and is therefore used as the standard of comparison. The carbon equivalent (CE) is calculated using the percentage of select compositional elements. The most significant element adversely affecting weldability is carbon. The relative effects of other elements are considered by taking the percentage of those individual elements and dividing them by their relative importance, as compared to carbon. All alloys and other significant elements are then considered in the equation, stating it in terms of equivalency to steel that contains only iron and added carbon. Numerous and varied carbon equivalency equations have been devised. Some may be more appropriate than others for use with a given steel, but one should consider the values provided by all appropriate CE equations.

Steels with low CE values are typically considered to have good weldability. Carbon and other elements that increase hardenability increase the risk of HAZ cracking. For higher CE numbers, higher preheats than normal may be necessary to eliminate underbead or cold cracking. The HAZ is subjected to fast cooling rates because of the fast absorption of heat generated by the weld by the surrounding steel. In addition to HAZ cracking, welds may also develop cracks.

In addition to the alloys and other elements deliberately added to achieve a given composition and achieve certain mechanical or performance properties, elements detrimental to performance or mechanical properties may have been in the raw materials or scrap used to produce the steel. The presence of these elements should also be investigated.

4.4.1.1 Dearden–O’Neill Equation. The Dearden–O’Neill equation is an internationally used and accepted CE equation, and is applicable for steels with a carbon content greater than 0.12%.

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \quad (1)$$

where

C = Carbon content (%)

Mn = Manganese content (%)

Cr = Chromium content (%)

Mo = Molybdenum content (%)

V = Vanadium (%)

Ni = Nickel content (%)

Cu = Copper content (%)

Using this equation, a CE of 0.35% or lower is considered an indication of good weldability.

4.4.1.2 AWS D1 Codes’ Equation. The equation in AWS D1 codes is similar to the Dearden–O’Neill equation, but with additional consideration for silicon.

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} + \frac{Si}{6} \quad (2)$$

where

Si = Silicon (%)

Using this equation, a carbon equivalent of less than 0.48 is considered good weldability when following the prequalification limitations of AWS D1.1/D1.1M:2008, Clause 3 Prequalification of WPSs. A CE of 0.28 or lower indicates that preheat may not be necessary to avoid forming martensite in the HAZ, regardless of thickness.

4.4.1.3 Linnert Equation. Another CE equation was published in *Welding Metallurgy* by George E. Linnert.

$$CE = C + \frac{Mn}{6} + \frac{Ni}{20} + \frac{Cr}{10} + \frac{Cu}{40} - \frac{Mo}{50} - \frac{V}{10} \quad (3)$$

Mo and V can have positive or negative effects on CE, depending on whether they are present as carbides or in solution.

If the CE values determined by this equation are below 0.40, the steel is considered readily weldable. For values between 0.40 and 0.55, the use of preheat or low-hydrogen electrodes is suggested, although the use of low-hydrogen electrodes or processes is recommended when welding to virtually any structural steel. Values above 0.55 indicate an increased likelihood that cracks may develop unless special precautions are taken.

4.4.1.4 Ito–Bessyo Equation. For steels with carbon content between 0.07% and 0.22%, the Ito–Bessyo equation may be used. The Ito–Bessyo equation is also termed the composition-characterizing parameter, P_{cm} .

$$CE = C + 5B + \frac{V}{10} + \frac{Mo}{15} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Cr}{20} + \frac{Si}{30} + \frac{Ni}{60} \quad (4)$$

where

B = Boron content (%)

Using this equation, a CE value of 0.35% or lower is considered good weldability.

4.4.2 Effects of Carbon, Alloys, and Other Elements. Both carbon and alloying elements may have detrimental effects upon the weldability of steel. Higher carbon content increases hardenability from martensite formed during cooling. Higher alloy content provides a larger range of temperature over which weld metal solidification occurs. Both high carbon and high alloy content increases the hardenability of the steel and promotes HAZ cracking.

4.4.2.1 Carbon. Carbon (C) is the most commonly used and most economical element added in the making of steel to increase its strength. For various applications, carbon content as high as 2% may be used. However, high levels of carbon, generally considered to be above 0.30%, reduce weldability by increasing the hardenability of the steel with the formation of martensite when fast cooling of the HAZ occurs. Because steel and filler metal mix when welding, high levels of carbon in the steel may also lead to high levels of carbon in the completed weld; therefore, the weld itself may be hard. Higher preheats and higher heat input welding procedures may be needed when welding a steel with relatively high carbon contents. Modern structural steel specifications limit carbon content to a maximum of approximately 0.30%. Some steel specifications have considerably lower limits to maximum carbon content. Older steel specifications may not have had a specified limit on carbon content.

4.4.2.2 Manganese. Manganese (Mn) is an alloying element that increases strength and hardenability, but to a lesser extent than carbon. More than 1.0% manganese tends to reduce weldability. Manganese limits are typically 1.65% or lower.

Manganese also reduces the detrimental effects of sulfur by combining with it to form manganese sulfide (MnS); and therefore, steels usually contain at least 0.30% manganese. For good weldability, the ratio of manganese to sulfur should be at least 10:1. High levels of sulfur may cause numerous large MnS inclusions to be formed. These inclusions are flattened in the mill rolling operation, and the flat inclusions increase the risk of lamellar tearing from high through-thickness weld shrinkage strains.

Steel with a low ratio of manganese to sulfur may contain sulfur combined with iron in the form of iron sulfide (FeS) along the grain boundaries of the weld, which can cause hot cracking in the weld.

Manganese also assists in deoxidation of steel. Steel with low manganese content in combination with low carbon content may not have been properly deoxidized and may be difficult to weld.

Manganese content less than 0.30% may be prone to porosity and cracking in welds.

4.4.2.3 Nickel. Nickel (Ni) is an alloying element used to improve ductility and toughness, particularly at low temperature. Nickel also increases strength and hardenability. It has relatively little detrimental effect upon weldability other than its minor effect on hardenability. Where reported as an item in a structural steel specification, it is generally limited to a maximum value of 0.25% to 0.50%. However, nickel from 0.5% up to 5% may be added to some low-alloy steels. Nickel is often added in combination with chromium.

4.4.2.4 Sulfur. Sulfur (S) reduces ductility, particularly in the through-thickness direction, increasing the risk of lamellar tearing. It rarely causes problems for structural applications up to about 0.035%, when sufficient manganese is present. Typical structural steel specifications limit sulfur to 0.05%, at which point it tends to cause brittleness and reduce weldability.

To promote the formation of manganese sulfide (MnS), and thus good weldability, the ratio of manganese to sulfur should be at least 10:1.

Sulfur also reduces toughness and weldability because of nonmetallic sulfide inclusions. For those applications where cold forming capacity or impact toughness is important, limiting sulfur to less than 0.01% is desirable.

Unless mitigated by manganese, high sulfur levels will form iron sulfide (FeS) along the grain boundaries of the weld, increasing the risk of hot cracking in the weld.

Welds made on steels with high levels of sulfur may have increased amounts of porosity. Sulfur may also degrade the surface appearance in steels low in carbon and steels low in manganese.

Sulfur content of 0.10% to 0.30% may be deliberately used to improve machinability. Such steels are called sulfurized or free-machining steel. When cutting tools are used, the sulfide inclusions cause the material to form short chips instead of continuous, long shavings. Also, the sulfide inclusions act as a lubricant for the cutting tip to reduce galling or seizing between the tool and steel. Bessemer steels may have extremely high sulfur contents.

4.4.2.5 Vanadium. Vanadium (V) is another alloying element used for increasing strength and hardenability, but weldability may be reduced. When included as a reported item in a structural steel specification, vanadium is generally limited to a maximum value between 0.06% and 0.15%.

Vanadium may be used as a mild deoxidizing agent, and may be added to reduce austenite grain coarsening during heating.

4.4.2.6 Copper. Copper (Cu) is added to improve the corrosion resistance of steel and is essential in steels known as weathering steels. When weathering steel is specified to provide atmospheric corrosion resistance, a minimum copper content of 0.20% is required. Generally, copper up to 1.50% does not reduce weldability; however, copper content over 0.50% may affect mechanical properties in heat-treated steels. Most steels contain some copper, whether specified or not, but the level of copper need not be reported for most structural steels. In particular steels made from scrap steel that is recycled over and over may accumulate copper to a point that it will affect weldability.

4.4.2.7 Silicon. Silicon (Si) is a deoxidizer added during the production of steel to improve soundness, a process known as *killing*. Typically, about 0.20% silicon is present in rolled steel when it has been used for deoxidization. For some fully killed steels, additional silicon may be present as high as 1.0%.

In addition to its use as a deoxidizer, silicon increases both strength and hardness, but not as effectively as similar additions of manganese. Silicon dissolves in iron and tends to strengthen steel. Steel castings commonly have higher levels of silicon, usually between 0.35% and 1.0%. The use of silicon in filler metals as a deoxidizer is common, with weld metals typically containing approximately 0.50% silicon.

If carbon content is relatively high, silicon increases cracking tendencies. For best weldability, silicon content should not exceed 0.10%, but silicon content up to 0.30% is not considered as detrimental to weldability as sulfur or phosphorus. Higher levels of silicon in low-hydrogen welding practices have proven to be successful and should be employed.

4.4.2.8 Molybdenum. Molybdenum (Mo) is an alloying element that has a very strong tendency to form carbides and is very effective in increasing hardenability and strength. Whenever molybdenum is reported as a part of steel specification, it is generally limited to a maximum value between 0.07% and 0.10%.

This element is usually present in alloy steels in amounts well below 1.0%, as small additions of molybdenum anywhere between 0.25% to 0.50% are usually adequate to provide high hardenability.

When the steel is to be subjected to elevated service temperatures, molybdenum from 0.5% to 1.5% is often added to low-alloy steels to improve strength and creep resistance.

4.4.2.9 Chromium. In low-alloy steels chromium (Cr) is added in amounts up to 0.9% to increase oxidation resistance, hardenability, and elevated temperature strength. Chromium forms carbides, and in the low-alloy steels increased amounts tend to reduce weldability. In low-alloy steels where chromium levels up to 2% or 3% exist excessive hardening and subsequent cracking in the weld and HAZ is possible. Because of this, special welding procedures and techniques are warranted. When chromium amounts over 12%, the steel is considered stainless steel because of its oxidation resistance.

4.4.2.10 Phosphorous. Phosphorous (P) is an interstitial alloying element that increases strength. It reduces ductility and notch toughness since phosphorous tends to segregate in steel. Phosphorus-rich areas reject carbon into the surrounding metal. These areas contain abnormally small amounts of carbon, which are referred to as “ghost bands” in the microstructure. Such segregation effects are particularly noticeable in steels with higher carbon content.

Phosphorous is typically limited to 0.04% to minimize the risk of weld and HAZ cracking. Because phosphorus lowers the surface tension of molten weld metal, controlling the weld pool is more difficult.

Phosphorus may be added in amounts up to 0.01% to some low-alloy high-strength steels to improve their strength and corrosion resistance. In low-carbon steels, phosphorus may be added to improve both machinability, as is done with sulfur, and resistance to atmospheric corrosion.

Bessemer steels may have extremely high phosphorus contents.

4.4.2.11 Aluminum. Small amounts of aluminum (Al) may be added as a deoxidizer. It is also added to refine the grain structure in order to improve toughness.

4.4.2.12 Columbium. Small amounts of columbium (Cb) may be added as a deoxidizer and also to reduce the hardenability of steel. Columbium is synonymous with niobium (Nb).

4.4.2.13 Titanium. Small amounts of titanium (Ti) may be added as a deoxidizer and also to reduce the hardenability of steel. Titanium precipitates reduce the detrimental effect of nitrogen.

4.4.2.14 Tramp Elements. So-called *tramp* elements such as tin (Sn), lead (Pb), and zinc (Zn) may be present in scrap steel and metals melted for steel-making. Due to their low melting point, they cause hot cracking by solidifying last in the throat of the weld. Sulfur, phosphorous, and copper are also low-melting point elements but are not considered tramp elements. Low heat input welding procedures and buttering may be necessary to minimize dilution effects when the amount of tramp elements is significant.

4.4.3 Other Steel Factors

4.4.3.1 Grain Size. Grain size is a significant factor affecting the ductility and notch toughness. It is measured by removing material and sophisticated laboratory testing. Finer grain steels are more easily welded than those with coarse grain.

The grain size of the weld affects weldability. For a given electrode and diameter, a high heat input weld will cool more slowly and thus have a larger grain size than an identical weld made with a lower heat input. AWS D1.1/D1.1M:2008 limits maximum bead sizes and layer thicknesses for prequalified welding procedures, which helps ensure suitable properties. Smaller weld beads also have the added benefit of grain refinement from subsequent weld passes. Thin layers limit the extent of local brittle zones in the HAZ.

4.4.3.2 Thickness of Base Metal. In general, the thicker the material, the greater the required effort to provide acceptable weldability. For a given weld, thick materials extract heat and quench the weld pool more rapidly than thin materials. Therefore, thick materials may require more extensive amounts of preheating and maintenance of interpass temperatures. Postheating may also be used to reduce the quenching effect.

The notch toughness of thick steels is generally less than that of a thinner steel with an identical composition. The practice of fine-grain steelmaking is commonly used to improve notch toughness in thicker steels.

4.5 Welding Procedures and Techniques

4.5.1 Base Metal Preparation. Surfaces to be welded should be cleaned to avoid nonmetallic inclusions from oxides and porosity from coatings, oil, or grease. Prepared joints should be smooth and uniform to promote consistent penetration and fusion into the sidewalls of the joint. Correct fit-up of the joint is essential to prevent melt-through or lack of penetration at the joint root.

4.5.2 Filler Metal Selection. The selection of filler metal for welding carbon and low-alloy steels involves many factors such as welding process, steel composition, and required mechanical properties of the completed weldment. As the carbon and alloy content of the steel increases, selection becomes more critical. Cracking may be caused by hydrogen diffused in the weld or HAZ; therefore, low-hydrogen practices are recommended. As the carbon content of the steel being welded approaches 0.30%, the use of low-hydrogen practices becomes essential.

Most fusion welds utilize filler metal added during welding, usually a consumable wire or electrode, but additional metal or alloy may be supplied by a flux or slag. The base metal is melted by the heat of the welding process and mixed with the filler material, forming the resultant weld that is different in composition and properties than both the base and filler metal.

Because of dilution, the exact strength of the resultant weld will not be known; however, typically the yield strength and the tensile strength will be higher than the filler metal classification strengths. Because ductility generally decreases as strength increases, the weld metal strength may result in high shrinkage stresses in both the base metal and the weld metal. This may result in cracking in the base metal, HAZs, or the weld.

Most filler metals used for structural steel deposit weld metal containing fairly low levels of carbon, generally less than about 0.12%. Therefore the welds are not as prone to cracking from rapid cooling as is the HAZ, which typically contains higher levels of carbon. Weld cracking may be caused by a number of other sources, such as bead profile or width/depth ratio, diffusible hydrogen, and high residual stresses.

4.5.3 Joint Selection. The weld joint design and the welding procedure can have some effect on the weld metal composition. Measures that limit alloy pickup from the base metal will allow the weld metal to keep a low carbon content and also maintain a high degree of ductility. When access to both sides of the base metal is available, a weld joint and welding sequence that balances the residual stresses near the neutral axis of the member should be considered.

4.5.4 Welding Procedure Specification (WPS). Welding procedures that consider the need for slow cooling rates should be used. Factors such as heat input, preheat, weld bead size, joint restraint, hydrogen controls, and welding technique may need consideration.

In multiple-pass welding, it is good practice to deposit the final weld bead in such a fashion that it is surrounded on both sides by weld metal from previous passes. By so doing, the HAZs that resulted from the previous passes are tempered by the final pass.

As the thickness of the steel cross section increases, the cooling rate also increases. Thicker steels generate three-dimensional heat flow, whereas thinner steels are more uniform in heat and cool in only two directions at a slower rate. As cooling rates increase, HAZ hardness and strength increases and ductility decreases. Alloys such as nickel, chromium, and molybdenum may be added when making the steel to permit a reduction in carbon content and mitigate the adverse effects of fast cooling rates.

Preheat is commonly applied, and sometimes required, to slow the cooling rate and maintain better ductility. Maintaining such temperatures during welding, or interpass temperatures, is equally important. The use of higher preheat and interpass temperatures, and sometimes the application of postheat immediately upon completion of welding, may be needed to avoid HAZ cracking and provide adequate mechanical properties. Preheating the area surrounding the weld joints has the following potential benefits:

- (1) Reducing distortion;
- (2) Reducing the cooling rate, which in turn limits the hardness of the HAZ; and
- (3) Lowering residual stresses.

Modern steels in the low carbon classification can be welded by any welding process permitted by the applicable welding code. Preheat before welding is based on the governing welding code because all low carbon steels have fast critical

cooling speeds. The base metal does not cool rapidly enough to form martensite in the HAZs of the welds with the normal welding processes. Additional preheating may be used on extremely thick or rigid weldments to help reduce residual shrinkage stresses and control distortion. Also maintaining preheat, interpass, and even postheat, enables the diffusion of hydrogen out of the weld and HAZ, so as to avoid delayed cracking.

To prevent cracking when welding more hardenable steels, the cooling rate of both the weld and HAZ should be slow enough to allow transformation to be complete before it reaches the temperature at which martensite begins to form. The cooling rate can be slowed by preheating, postheating, using a high energy input WPS, or by a combination of these.

The methodology provided in AWS D1.1/D1.1M:2008, Annex I Guideline on Alternative Methods for Determining Preheat, is useful in determining preheat requirements based upon composition, restraint, and diffusible hydrogen controls.

The temperature at the joint should not fall below the preheat temperature during welding, otherwise known as the interpass temperature. Maintaining the interpass temperature is especially important in large or thick joints, as the weldment may lose heat faster than it is replaced by welding heat input. Ongoing or additional heating may be necessary. Occasionally, on small or confined sections or to prevent grain growth, it may be necessary to allow time between weld beads to prevent excess build-up of heat.

Postheating can further retard the cooling of the weld or temper any martensite that may have formed.

4.6 Weldability Testing

The term weldability is a qualitative term affected by the significant variables encountered in fabrication. Some of the variables are joint restraint, fit-up, surface condition, base metal composition and properties, and welding process parameters. Laboratory weldability tests can only provide an index to compare specific conditions together with different metals, procedures, and processes.

Within these limitations, weldability testing can provide valuable data on the suitability of proposed welding procedures for specific materials, situations, and service performance requirements. However, the results are only qualitative and laboratory testing, regardless of the extent, cannot quantitatively predict exact performance in an existing structure.

Numerous weldability tests have been devised, and can be classified as either simulated or actual welding.

4.6.1 Simulated Tests. In some cases it may be necessary to simulate the heat effect of welding on base metals and, thus, create a synthetic weldability test. Two general types of apparatus are available: (1) a unit that heats and cools a metal specimen over a small area according to a predetermined cycle, and (2) a unit that not only heats and cools the specimen, but also can apply a controlled tension load to the specimen at any time during the cycle.

While these tests provide very useful information with regard to the mechanical properties of various areas within a HAZ, during as well as after a welding cycle, they cannot account for residual and reaction stresses, contamination, and other conditions that may be imposed on production welds.

It should be noted that for typical structural applications these more advanced tests are not required.

4.6.2 Actual Welding Tests. An extensive variety of actual welding tests have been devised to investigate the weldability characteristics of base metals. In general, these tests serve two purposes. First, they may be used to evaluate the weldability of particular grades of steels. For this purpose, the specimen dimensions and welding conditions remain constant to make the base metal sample the only variable. Second, they may be used to establish compatible combinations of base metal, filler metal, and welding conditions that will produce acceptable results in the test. In effect, these tests fall into two groups: (1) fabrication tests to predict if a particular material and procedure can be used to produce a joint acceptably free of defects; and (2) service tests to measure the properties of the weldments.

4.6.2.1 Fabrication Weldability Tests. The tests in this category determine the susceptibility of the welded joint to cracking and can be grouped according to the type of cracking that they produce.

4.6.2.2 Hot-Cracking Tests. Hot cracks are formed at high temperatures and are often the result of solidification segregation and shrinkage strains. Several tests have been devised to study hot cracking many of which are described in AWS B4.0:2007, *Standard Methods for Mechanical Testing of Welds*.

One of the more common tests in use is the Vareststraint test, which utilizes external loading to impose plastic deformation in a plate while an autogenous weld bead is simultaneously made on the long axis of the plate. The severity of deformation is varied by changing the bend radius.

4.6.2.3 Delayed Cracking Tests. A large number of tests have been devised to investigate delayed cracking in steel weldments many of which are described in AWS B4.0:2007. All of the tests use large specimens relative to other laboratory investigations. The larger test specimens are required to simulate service conditions. Three restraint cracking tests include the Lehigh restraint, the controlled-thermal-severity, and the cruciform cracking.

(1) For the Lehigh restraint test, the normal size of the Lehigh specimen is 8 in by 12 in [200 mm by 300 mm]. To reduce the restraint, cut the slits along the long edge of the plate. To increase the restraint, reduce the weld groove length or increase the specimen size.

(2) The controlled-thermal-severity test consists of a plate bolted and anchor-welded to a second plate in a position to provide two fillet (lap) welds. The fillet located at the plate edges has two paths of heat flow (bithermal weld). The lap weld located near the middle of the bottom plate has three paths of heat flow (trithermal weld), which induces faster cooling. Further control of the cooling rate is attainable by varying the plate thicknesses, or by preheating.

(3) The cruciform cracking test comprises three plates with ground surfaces tack-welded at the ends to form a double T-joint. Four test fillet welds are deposited in succession, and then completely cooled between deposits. Cracking, detected by cross sectioning, is most likely to occur in the third bead. Careful fit-up of the plates is necessary to obtain reproducibility.

5. Evaluation of Existing Welds

5.1 Scope

In the course of inspecting and evaluating existing structures, welds that fail to meet existing weld quality criteria may be discovered. Welds may have been previously accepted for use, may not have been previously inspected, the weld quality criteria may have changed from previous standards, or welds may have damage resulting from poor design, overloading, or other unforeseen conditions. In addition, welds may have developed cracks from service. The purpose of this clause is to provide the Engineer an understanding of the possible causes of the weld's condition, as well as information for making a rational engineering judgment whether the existing weld should be repaired, replaced, or remain as is.

Note also that other D1 documents have applicability here. When specific references to AWS D1.1/D1.1M are made, appropriate clauses of other D1 documents may be considered as equally applicable.

5.1.1 Engineer's Authority. AWS D1.1/D1.1M:2008, *Structural Welding Code—Steel*, offers flexibility to the Engineer in the determination of weld quality requirements for a particular project. Clause 6.8 Engineer's Approval for Alternate Acceptance Criteria in AWS D1.1/D1.1M:2008 states:

The fundamental premise of the code is to provide general stipulations applicable to most situations. Acceptance criteria for production welds different from those described 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 considering material type, service load effects, and environmental factors.

5.1.2 Principles of Acceptance Criteria. AWS A3.0:2001 defines discontinuity as:

An interruption of the typical structure of a weldment, such as a lack of homogeneity in its mechanical, metallurgical, or physical characteristics. A discontinuity is not necessarily a defect.

Further, AWS A3.0:2001 defines a defect as:

A discontinuity or discontinuities that by nature or accumulated effect [for example total crack length] render a part or product unable to meet minimum applicable acceptance standards or specifications. This term designates rejectability.

Thus, a discontinuity is not necessarily a rejectable defect.

D1 codes have been written to apply to numerous situations, with applications that have included buildings, bridges, structures subjected to fatigue, offshore platforms, manufactured products, and a wide variety of other structures. Of these structures, buildings can often be considered the most forgiving of weld discontinuities. In buildings, fatigue is not normally a significant concern, since the ratio of recurring intermittent loads (live, wind, etc.) to dead load is low. In seismic applications using ductile connection details with appropriate weld consumables and base metals, it often takes several cycles of considerable plastic deformation before fracture would initiate at a weld discontinuity.

The Commentary to AWS D1.1/D1.1M:2008, Clause C-6.8 states:

The criteria provided in Clause 5, Fabrication, are based upon knowledgeable judgment of what is achievable by a qualified welder. The criteria in Clause 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.

The “fitness for purpose” or “suitability for service” concept has led to the development of several documents that provide suggested alternate acceptance criteria for structural welds. Consideration is made of several factors in developing such criteria:

- (1) The nature of the loading, whether static or cyclic. Also to be considered are nonstatic cyclic loads such as those found on bridges, crane rails, machinery supports, etc.;
- (2) The conservative analysis and design methods used for both structures and welds;
- (3) The loading criteria and factors of safety used in the design of structures;
- (4) Examine material and welding consumable mill certificates to determine if the actual materials used have higher strength levels than the specified minimum levels used in the original design;
- (5) The industry practice of rounding up to select a member size, part thickness, or weld size;
- (6) The true effect, as documented by research, of various forms of weld discontinuities upon the service performance of the weld and structure; and
- (7) NDT sensitivity to discontinuity detection.

The Engineer may permit an increase in theoretical strength, based upon the above factors. For example, the Engineer may consider welds acceptable that, for calculation purposes, are understrength, considering that actual strength and conservative practices will compensate adequately without significantly diminishing desired factors of safety. Many weld discontinuities, such as porosity, poor profile, undersize, underlength, incorrect location, overlap, lack of fusion, slag inclusions, undercut, and poor cleaning, may be evaluated for reasonable alternate acceptance criteria.

5.2 Strength Evaluation

The many conservative practices used in the design of welded joints provide engineering rationale to accept welds smaller than those specified. Other factors may also be considered as strength compensation for undersized welds.

A weld's strength and ductility vary depending upon the direction of the applied load relative to the axis of the weld. A longitudinally loaded weld, in which the load is applied in the same direction as the weld's axis, has the least strength but the greatest ductility. A fillet weld loaded transversely to its axis has a strength roughly 50% higher than a longitudinally loaded weld, but with reduced ductility.

For design purposes, the nominal classification tensile strength of the electrode, E70 as an example, has been multiplied by a strength reduction factor. The in-place weld metal will commonly have a strength about 10% higher than that used for design purposes. Convexity, reinforcement, and penetration also increase available strength for fillet and partial joint penetration (PJP) welds, but are not commonly considered in the calculated weld throat.

Under most circumstances, the original designer will have normally rounded up the weld size to the next nominal size. For example, a fillet weld size requirement of 0.20 in [5 mm] would have been rounded to 0.25 in [6 mm]. Should the weld run slightly below 0.25 in [6 mm], the weld will still carry the actual design load, even without consideration of overstrength factors. Often, fillet and PJP weld sizes are governed by code minimums based on heat input, so smaller welds may provide adequate strength as long as proper fusion was initially achieved.

The existing weld size may be irregular. Portions of the weld, larger than that specified or desired, may provide additional load-carrying capabilities to compensate for the undersized portions of weld.

Also the Engineer needs to address the larger picture of the joint and member when making the determination on remaining strength. Issues such as section loss, bolt hole deductions and other global properties should be evaluated.

5.2.1 Fillet Weld Size. For fillet welds, AWS D1.1/D1.1M:2008, Table 6.1(6) Undersized Welds, provides the following requirement: “The size of a fillet weld in any continuous weld may be less than the specified nominal size (L) without correction by the amounts (U).” These values are shown in Table 5.1.

In all cases, the undersized portion of the weld should not exceed 10% of the weld length. On web-to-flange welds on girders, underrun is prohibited at the ends for a length equal to twice the width of the flange due to the potential for high shear in that region.

Fillet welds may be undersized by the amounts noted in AWS D1.1/D1.1M:2008 Table 6.1 for up to 10% of their length (subject to certain restrictions), based on the expected higher than calculated strength and the fusion area not included in the nominal throat. AWS D1.1/D1.1M:2008, Table 5.8 Minimum Fillet Weld Sizes, establishes minimum fillet sizes based on the heat input required for fusion, so weld sizes below that criteria should be carefully examined for defects.

Engineering analysis, using the principle of equivalency, may be employed for other undersized situations. For example, using a 3/8 in [10 mm] fillet weld, the Engineer could also consider accepting a fillet weld with an underrun of 1/16 in [2 mm] for 20% of the weld length, or an underrun of 1/4 in [6 mm] for 5% of the weld length.

The existing code criteria allows for a reduction of strength below theoretical strength of roughly 3% to 4%. The Engineer may determine that additional reductions below theoretical strength are permissible to allow additional reduction in weld size, length, or both.

Caution should be taken when welds are both undersized and underlength. Cumulative effects should be considered.

5.2.2 Groove Weld Underfill. The strength of the weld may still be evaluated for adequacy if an existing groove weld has failed to achieve full throat because of underfill. For groove welds, AWS D1.1/D1.1M does not permit underfill, but its provisions for finishing butt joint welds could be applied. In this provision, the finishing should be such “so as to not reduce the thickness of the thinner base metal or weld metal by more than 1/32 in [1 mm] or 5% of the base metal thickness, whichever is smaller.” For 5/8 in [16 mm] and thicker plates, the 1/32 in [1 mm] governs. For thinner plates, 5% of the thickness governs.

Design rounding principles may apply for groove welds. For example, the required design thickness may be a 0.55 in [14 mm] thick plate, but would be “rounded up” to the next standard thickness, probably a 5/8 in [16 mm] thick plate. If the CJP groove weld is underfilled, the actual thickness of material required (0.55 in [14 mm]) could be used as the acceptance basis.

Should the weld be oversized, the higher capacity of the weld could be calculated when considering an underlength condition. For example, if a specified 1/4 in [6 mm] weld is actually oversized to 5/16 in [8 mm], the calculated weld strength per unit length is 25% higher than that specified, allowing a direct reduction in required weld length.

Undercut provisions are more liberal than the underfill provisions for building applications. If the primary concern is reduction of member thickness, the undercut permitted would be more than the underfill permitted.

For fatigue applications, very stringent undercut provisions apply when transverse to the direction of stress, and for new structures a 1/32 in [1 mm] undercut limit applies for all other cases. However, for existing structures the Engineer should consider the location of the undercut, the depth, the stress range at that particular location as well as additional repair methods such as peening, grinding etc.

5.2.3 Weld Length. Clause 5.13, Conformance with Design, in AWS D1.1/D1.1M:2008 states:

The sizes and lengths of welds shall be no less than those specified by design requirements and detail drawings, except as allowed in Table 6.1.

However, AWS D1.1/D1.1M:2008 Table 6.1 does not provide a specific underlength tolerance that is comparable to its undersize tolerance.

To avoid unnecessary repairs to existing structures, the Engineer may compare the loading conditions and strength required with the weld composition, length, and size. If an uninterrupted weld is not required for fatigue and the weld is sufficient to safely carry design loads, staying with the existing weld may be preferable to either adding short, intermittent repair welds or removing and replacing the entire weld.

Reduction in theoretical strength from underlength welds may also be compensated for by weld penetration, weld convexity, higher weld material strength, conservative load assumptions, and conservative design values. For example, if a reduction of 10% below the theoretical or specified weld length were permitted on this basis, a 3 in [75 mm] specified weld length could be acceptable as 2-3/4 in [70 mm] long; a 6 in [150 mm] weld could be 5-1/2 in [140 mm]; and a 12 in

[300 mm] weld could be 11 in [280 mm] with rounding. Additional root penetration may be evaluated with alternative UT methods.

Underlength allowances may also be considered when intermittent welds are used. One underlength segment of an intermittent weld may be offset by a nearby segment longer than that specified. However, 2.3.2.4 in D1.1/D1.1M:2008 requires intermittent weld segments to be at least 1-1/2 in [38 mm] long, ensuring a stable arc is established and sufficiently maintained between arc initiation and termination to avoid cumulative effects of residual stresses and start/stop discontinuities. Weld lengths below this minimum should be carefully examined for defects.

When considering underlength acceptance, caution should be taken when the weld is also undersized. In this case, a more careful evaluation by the Engineer is required to determine if the actual weld strength is adequate.

Often, weld length is not specified. The original design may have stipulated welds full length, but that may not be necessary or feasible. The Engineer may consider alternate weld termination limits.

5.2.4 Weld Profile. Weld profile considerations include fillet weld convexity, fillet weld concavity and groove weld reinforcement.

Excessive convexity of fillet welds and excessive reinforcement of groove welds increase local stress concentrations at the weld toe. These concentrations could be detrimental to joint performance if fatigue is a design consideration, or if a significant discontinuity or defect is present near the weld toe. Conventional buildings are seldom subject to high-cycle fatigue. In seismic applications with high stress and strain but relatively few cycles, low cycle fatigue is possible. If a significant discontinuity, such as a crack, occurs near the weld toe, the stress concentration caused by the weld geometry could enlarge that discontinuity to critical size with a few high stress cycles, leading to rapid propagation.

All welded joints are subject to residual stress and stress concentrations from weld shrinkage and the nature of stress flow, but the added effect of excess convexity is nominal for typical situations. The AWS workmanship criteria for weld convexity and groove weld reinforcement are found in AWS D1.1/D1.1M:2008 Figure 5.4, Acceptable and Unacceptable Weld Profiles. As a workmanship standard, the basis of these criteria is “what is achievable by a qualified Contractor.” It is not based upon limiting values for stress concentration, which would vary little within normal convexity range.

A weld with poor profile may indicate problems with the procedure, equipment settings, electrode selection, or technique used in making the weld. It is valid to further evaluate welds with poor profile for the possibility of other significant discontinuities or defects. However, poor profile alone does not necessarily mean that the weld cannot carry the load.

AWS D1.1/D1.1M:2008, limits convexity as shown in Table 5.2.

Per Figure 5.4 in D1.1/D1.1M:2008, groove weld reinforcement is limited to 1/8 in [3 mm] above the face of the base metal.

If considered detrimental to the performance of the welded joint, excessive fillet weld convexity or groove weld reinforcement should be repaired by removing the excess weld metal until the AWS D1 code criteria is met. However, this repair alone will minimally improve weld toe conditions and stress concentrations. It may be necessary to improve the base metal to weld metal transition by disc grinding, burr grinding, toe remelting (TIG dressing), toe peening, ultrasonic impact treatment (UIT), or other fatigue life improvement techniques. However, these will not alleviate concerns about fusion or other weld discontinuities.

Clause 5.24 Weld Profiles and Figure 5.4 in AWS D1.1/D1.1M:2008 do not establish specific limits on fillet weld concavity, provided the weld size requirements are met. Fillet weld strength is determined by its throat dimension, and a concave weld has reduced throat for a given leg size. Concave fillet welds provide a smoother transition and stress flow with minimal stress concentration at the toe of the fillet. However, weld solidification shrinkage stresses in the face of a significantly concave fillet may result in longitudinal centerline cracking detectable via visual inspection, MT, or PT methods.

5.2.5 Undercut. During welding, as the base metal melts and mixes with the filler metal, the resultant molten pool should refill the area of base metal that melted. Undercut is the failure to completely refill this area. Possible causes of undercut include gravity effects at the upper toe on horizontal welds, poor technique (improper electrode angle, travel speed too fast), or excessive welding current.

Per AWS D1.1/D1.1M:2008, Table 6.1 (7A) Undercut, for statically loaded structures, with

...material less than 1 in [25 mm] thick, undercut shall not exceed 1/32 in [1 mm], with the following exception: undercut shall not exceed 1/16 in [2 mm] for any accumulated length up to 2 in [50 mm] in any 12 in [300 mm]. For material equal to or greater than 1 in [25 mm] thick, undercut shall not exceed 1/16 in [2 mm] for any length of weld.

For fatigue applications, in AWS D1.1/D1.1M:2008 Table 6.1 (7B) limits undercut perpendicular to design tensile stresses in primary members to 0.01 in [0.25 mm] deep.

Undercut had been considered to create a notch effect, and is severely limited in some cases. However, typical undercut is generally rounded by the flow of material, therefore it does not have the same effect as a crack of the same depth. Undercut in statically loaded structures does not generally diminish structural performance, as the notch effect is minimal and the stress and service loads of the structure are not severe. An exception should be made for seismic applications where plastic straining should be tolerated.

A concern with undercut in statically loaded structures is the reduction in cross-sectional area, especially where undercut exists on both sides of a part, directly opposite one another. This is not fully addressed by ASTM A 6, but can be combined with analysis to determine if repair is warranted. Undercut on both sides of the plate, but not directly opposite one another, should be treated as undercut on one side only.

If the undercut is severe, transverse to tensile stress and/or subject to fatigue or high strain, repair of the undercut should be considered. This may require only light grinding to avoid the localized notch or a weld repair. If welding is needed, each pass should have sufficient heat input to ensure full fusion. A small, cosmetic pass may leave fusion defects much worse than the undercut.

5.2.6 Craters. A crater is a depression caused by shrinkage of the weld pool as it solidifies when the weld is terminated. The size of the crater is increased when poor technique is used when terminating the weld. The action of the arc creates a concave surface of weld pool and as the electrode travels, this is filled with molten weld metal. However, at a weld termination, technique is needed to fill the weld pool.

AWS D1.1/D1.1M:2008, Table 6.1 (3) Crater Cross Section, states: "All craters shall be filled to provide the specified weld size, except for the ends of intermittent fillet welds outside their effective length." Intermittent fillets are not permitted in tension areas subjected to fatigue.

Craters could be detrimental to the performance of a welded joint in three ways. First, the crater is a length of undersized weld with inadequate throat. The exception for intermittent fillet welds where the crater falls outside the effective weld length is because adequate weld is present to carry the load. It would be appropriate to extend this philosophy to permit craters in all welds, treating the crater as an undersized portion of the weld. AWS D1.1/D1.1M:2008 permits undersized welds, but those limits exclude most craters from consideration for acceptance. Craters could also be evaluated considering the actual length of full size weld and ignoring the weld length containing the crater.

Second, a crater could be detrimental to a joint through the sudden change in weld profile. A dramatic profile change leads to a stress concentration, reducing fatigue life for cyclically loaded structures. Under fatigue loading, a severe stress concentration could initiate a crack or localized deformation, but other points of transition such as the fillet toe may cause similar problems.

Third, a weld crater can be detrimental to a joint through crater cracking. The crater surface is highly concave, with considerable surface tension. Small fractures may initiate near the center of the crater, and under loading, these cracks may propagate into the weld or the base metal. The initial fractures usually have a star-shaped appearance, hence the nickname *star cracks*. Crater cracks occur immediately, rather than in service, but because they are typically very small, careful visual inspection is needed when craters remain.

Crater crack repairs should be carefully inspected since a weld bead placed to fill a crater may cause more problems, since small welds cool rapidly and leave high residual stress patterns and hard HAZs.

Grinding is another way to eliminate the crater.

5.2.7 Overlap. Overlap is a weld profile discontinuity that is more difficult to evaluate than fillet weld convexity or groove weld reinforcement.

Overlap, also commonly called rollover, is defined by AWS A3.0:2001 as: “The protrusion of weld metal beyond the weld toe or weld root.” It is commonly interpreted as a situation where the angle of intersection between the weld face and base metal is an acute angle. It is possible to have a fillet weld meet convexity limits but fail to meet the current AWS D1 overlap provisions.

Concern arises regarding the stress flow when a fillet weld exhibits overlap. In static structures, the stress riser effect may be minimal when the weld is longitudinally loaded and does not reduce static strength. In seismic applications and fatigue applications, especially if the weld is transverse to the direction of stress, the stress riser from overlap may reduce ductile behavior.

AWS D1.1/D1.1M:2008 Clause 5.24 states welds “shall be free from...overlaps...” except that overlap is permitted at the ends of intermittent fillet welds outside their effective length.

To evaluate overlap, the limits of fusion between weld nugget and base metal should be determined. Severe overlap can be indicative of poor procedure or workmanship that may have resulted in a lack of fusion. Good appearance indicates a higher probability of good fusion, but certainly is not a guarantee of good fusion. If a weld exhibiting overlap also has lack of fusion, removing the overlap would not improve the strength or performance of the weld.

Overlap impedes measuring the leg length of a fillet weld, so special measurement techniques should be employed when overlap is present in an existing structure.

A possible acceptance criterion for limited overlap in existing applications would be an occasional overlap not exceeding 1/8 in [3 mm] may remain, provided the weld size and fusion can be verified. If there is visible lack of fusion, or if fusion cannot be verified because of the overlap, acceptance should be based on the evaluation of incomplete fusion.

5.2.8 Incomplete Fusion. Incomplete fusion can be defined as a lack of coalescence between the weld and base metal or between adjoining weld passes. During welding, there should be melting of existing metal and mixing with deposited filler metal, the weld being the two combined. Incomplete fusion may occur in the welded joint between weld passes or at the weld to base metal interface.

Incomplete fusion may be caused by poor cleaning that leaves rust, grease, coatings, or similar foreign material. Slag from a previous pass, or slag that flowed and solidified in advance of the weld pool, can also cause incomplete fusion. Low heat input, too large an electrode for the current used, or the failure to follow the welding procedures may have caused fusion problems. Incorrectly positioning the electrode (an improper electrode angle or not centering on the joint), can reduce penetration into part of the joint. Poor joint design, especially inadequate access to the joint root and groove faces, can also lead to incomplete fusion.

AWS D1.1/D1.1M:2008 Table 6.1, addressing visual inspection in statically loaded structures, states: “Thorough fusion shall exist between adjacent layers of weld metal and between weld metal and base metal.” Because it is not defined, “thorough” is commonly interpreted as 100%.

To evaluate incomplete fusion below the surface, ultrasonic or radiographic techniques should be employed. For statically loaded nontubular structures, incomplete fusion in groove welds is evaluated using AWS D1.1/D1.1M:2008 Table 6.2 (UT) or Figure 6.1 (RT). For cyclically loaded nontubular structures evaluated by RT, incomplete fusion over 1/16 in [2 mm] is evaluated using AWS D1.1/D1.1M:2008 Figure 6.2 for tension areas and AWS D1.1/D1.1M:2008 Figure 6.3 for compression areas. Special UT techniques and criteria may be used to evaluate fillet welds.

The effect of incomplete fusion upon weld performance is only slightly more harmful than porosity and slag inclusions, provided ductile failure is still assured. Cold temperature, high stress-range fatigue applications, or the use of low-toughness materials would warrant further consideration. The orientation of the incomplete fusion plane relative to the direction of stress should be considered.

For fillet welds, lack of fusion of up to 10% of weld-base metal interface may have little effect upon the static strength of the weld. However, if in a fatigue application, the same 10% reduction could reduce fatigue life by 50%. Incomplete fusion at or near the surface of the weld would be most detrimental in fatigue or seismic loading.

For existing fillet welds in statically loaded structures, limited incomplete fusion may be acceptable. The incomplete fusion could be assumed to extend from the toe of the fillet inward to the root and evaluated similarly to underlength welds. This approach would be a conservative assumption, using a strength calculation assuming that the incomplete

fusion apparent at the surface extends entirely to the root. If adequate, sporadic incomplete fusion could be left unrepaired based upon the load-carrying capacity of the weld properly fused.

Incomplete fusion is usually a planar discontinuity, rather than a volumetric discontinuity. Therefore, engineering judgment should consider the direction of stress relative to the incomplete fusion plane. If a fillet weld is stressed in shear along its length, the above approach may be considered. However, if loads cause tension transverse to the incomplete fusion plane, such as in a T-joint, the condition should be more carefully evaluated. For such transverse loading, consideration should be made of the actual area lost due to incomplete fusion and the amount of strength actually required of the joint. Because of conservative practice, some margin is commonly available should an incomplete fusion exist. Even if the joint is loaded to its theoretical stress limit, research indicates that limited amounts of incomplete fusion would not reduce the ultimate strength.

Fracture mechanics may be applied to the evaluation process in circumstances involving fatigue and low material toughness. Considering the fatigue stress range, the number of cycles, and threshold stress intensity, fatigue cracks may be unlikely to propagate from small, isolated incomplete fusion locations.

5.2.9 Arc Strikes. Arc strikes are created when the energized electrode contacts the steel in a nonweld zone, creating a small surface weld. This may be an isolated point caused by careless manipulation or when a welder misses the weld starting point and then drags the electrode to the proper location.

The arc strike is essentially a very small weld, made without preheat and considerably smaller than the minimum weld size required by code to reduce the risk of cracking. The arc strike area cools very rapidly, potentially leaving a very small, hard surface, and HAZ, and cracking may occur. A surface crack is also more structurally significant than a crack below the surface.

In statically loaded structures, crack propagation requires a combination of high stress, sufficient crack size, and low toughness. Fatigue from cyclic loading and high plastic strains from seismic loading increase the likelihood of crack propagation from an arc strike. If a crack were to appear in the surface of the steel where an arc strike occurred, repair would be necessary.

Studies have confirmed that the hardness level of the HAZ is more significantly increased in older steels because of the higher carbon content. However, when in-service stress levels remain in the elastic region, and the loading is static, the HAZ properties should not affect performance.

AWS D1.1/D1.1M:2008, Clause 5.29 Arc Strikes, states:

Arc strikes outside the area of permanent welds should be avoided on any base metal. Cracks or blemishes caused by arc strikes shall be ground to a smooth contour and checked to ensure soundness.

For fatigue applications and areas subjected to high plastic strains, arc strikes should be ground sufficiently to remove the hard HAZ and leave a smooth surface. This is reflected in AASHTO/AWS D1.5M/D1.5:2008 for members in tension and in stress reversal, which also calls for magnetic particle testing and hardness testing of the region of the arc strike.

5.2.10 Surface Slag. Slag is a nonmetallic mixture of welding flux, impurities, and welding by-products that should rise to the surface of the molten weld pool during welding. Slag that failed to reach the surface is termed a slag inclusion. Some welding consumables produce a surface slag that is difficult to remove, particularly when the weld profile is irregular.

Manual chipping hammers are usually adequate to remove any adhering surface slag. In some cases, it may be necessary to use a pneumatic chipping hammer or needle gun when consumables, weld profile, or access make removal difficult. When slag chipping fails to remove remaining slag, a grinder may be used with care to avoid removing base metal and weld metal along with the surface slag.

AWS D1.1/D1.1M:2008, 5.30.1 In-Process Cleaning, requires:

...all slag shall be removed and the weld and the adjacent base metal shall be cleaned by brushing or other suitable means.

Additionally, AWS D1.1/D1.1M:2008 requires slag removal before subsequent weld passes are deposited.

Surface slag has no detrimental effect upon the structural load-carrying capability of the weld. However, there is a need to visually inspect the weld for quality and size, and this cannot be performed with the slag in place. Additionally, for

multipass welds, slag prevents uniform heating and electrical transfer for subsequent passes and may lead to slag inclusions or other discontinuities.

Acceptance criteria for surface slag could be based upon how large the slag can be before it covers up a discontinuity that would be significant. For a numerical value, underlength criteria could be applied.

In some cases, there are nonstructural reasons to require complete removal of all surface slag, such as coating systems where the surface slag would prohibit complete coverage and cohesion between steel and coating. If the coating is a non-critical element, such as an interior coating in a noncorrosive environment, the surface slag could still cause a coating failure, but the structural consequences would be minimal. Surface slag would also have minimal effect upon spray-on fireproofing adhesion.

5.2.11 Porosity. Weld porosity is a volumetric discontinuity formed by gases trapped by the solidifying weld metal. This condition occurs when the amount of gases present in the molten weld pool exceed the solubility limit of the molten metal, and the weld solidifies before the gas bubbles reach the surface. Some bubbles may just reach the surface, leaving partial open voids that are referred to as piping porosity, but may indicate the presence of other subsurface voids.

The welding process, the welding procedure, and base metal are factors that may affect the amount of porosity present. High sulfur content and nickel content in steels contribute to porosity. Porosity may also result from:

- (1) Steel surface contamination, grease, coatings, rust or moisture;
- (2) Gaps in the weld root area that allow entry of excess atmospheric gases;
- (3) Damp electrodes or flux;
- (4) Improper shielding gas or poor gas flow;
- (5) Too long an arc length;
- (6) Too low a welding current;
- (7) Too fast a travel speed;
- (8) Arc blow; and
- (9) Welding over tack welds to boil out existing gases.

Existing porosity can be classified into several categories:

- (1) Uniformly scattered
- (2) Clustered
- (3) Linear aligned
- (4) Elongated

Porosity may exist entirely below the surface or the gases may have left behind a trail as they escaped to the surface leaving a tubular appearance (i.e., piping porosity).

AWS D1.1/D1.1M:2008 Table 6.1 states: “[F]or fillet welds, the sum of 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 [20 mm] in any 12 in [300 mm] length of weld.”

For the typical groove weld, the same limits apply in AWS D1.1/D1.1M:2008 Table 6.1. However, as shown in AWS D1.1/D1.1M:2008 Table 6.1: “CJP groove welds in butt joints transverse to the direction of computed tensile stress shall have no visible piping porosity.” For statically loaded nontubular structures, subsurface porosity detected using ultrasonic testing would be evaluated with AWS D1.1/D1.1M:2008 Table 6.2, and if using radiographic inspection, with AWS D1.1/D1.1M:2008 Figure 6.1.

Studies of butt joints in fatigue indicate that porosity of even 20% does not reduce fatigue life in joints which have their reinforcement intact. Studies reveal that fatigue caused by the transition between weld and base metal precipitated failure first. When the reinforcement was removed from the butt joints, porosity degraded fatigue life, but porosity below 3%

did not have an effect. In fillet welded joints, stress concentrations at the toes of the weld and at the starts and stops of the weld caused fatigue failure before porosity had an effect.

For existing statically loaded structures, one format for acceptance criteria could be to use AWS D1 codes criteria, but only size and record piping porosity after the pore exceeds 1/16 in [2 mm] in diameter. Porosity would then be permitted in the range of 5% to 6%.

An additional evaluation criterion may be added that is not included in AWS D1.1/D1.1M:2008. If four or more pores over 1/16 in [2 mm] in diameter are aligned, and are separated by 1/16 in [2 mm] or less (measured edge to edge), then the porosity should be considered unacceptable. Porosity of this size, aligned with one another and located close together, may concentrate stress and precipitate a crack.

5.2.12 Cracks. A crack can be defined as a planar discontinuity characterized by sharp tips at the ends. These sharp tips make for easier propagation through the adjacent weld or base metal, as compared to rounded volumetric discontinuities such as porosity or slag inclusions. Even incomplete fusion boundaries are well-rounded compared to crack tips.

Typically, cracks are identified by their orientation and location. Longitudinal cracks are those parallel to the axis of the weld, either in the weld or in the HAZ. Transverse cracks are perpendicular to the weld axis. Cracks may appear at the face, in the throat, at the root, at the weld toe, or underbead in the HAZ.

Cracks are generally characterized as hot cracks or cold cracks. Hot cracks occur at elevated temperatures, when the steel and weld metal are still hot from the welding process with reduced yield strength and ductility, and the weld metal begins to shrink and solidify. Solidification cracks and HAZ cracks are the most common hot cracks. Reheat cracks due to residual and restraint stresses, reduced yield and ductility, and stress due to temperature gradients during the heating or cooling phases of postweld heat treatment are also considered hot cracks. Hot cracks spread between the grains of the material.

Many weld metal cracks and some HAZ cracks are cold cracks. Cold cracks occur after the solidification of the weld metal, although the temperatures involved may be somewhat elevated. Stress is involved in cold cracking, whether from applied loads, residual stress, or shrinkage stress via weld cooling. Dissolved hydrogen often plays a major role. Cold cracks spread both between grains and through grains.

One cause of solidification cracks is excessive, transverse shrinkage strains in welds because the parts are restrained from deforming to accommodate the weld shrinkage. Generally, these cracks occur when the depth-to-width ratio of the weld bead exceeds 2:1. High percentages of alloying elements (particularly carbon, sulfur, and phosphorus), gaps between connected parts, gross concavity, contaminated base metal surfaces, and weld metal dilution also contribute to solidification cracking.

HAZ cracking is typically associated with substantial diffusible hydrogen, high residual weld shrinkage stress, and a metallurgical structure susceptible to cracking. High hydrogen levels can result from electrode or flux moisture content; surface contaminants, such as water, oils, paints, rust or lubricants. Hydrogen cracking is further aggravated by large root openings or gaps, low heat input, and inadequate preheat. Thicker sections have higher restraint and faster cooling rates, leading to higher residual stresses. The HAZ is more prone to cracking when there is high carbon and alloy content in the base metal.

For weld repairs or postweld thermal stress relief, the crack-susceptible HAZ grain structure becomes coarser. The heat also strengthens individual grains, so deformation results in tension between the grains themselves, which can cause cracking at grain boundaries.

Crater cracks are another form of hot crack, created by an improper weld termination leaving a highly concave surface subject to high shrinkage stresses.

Crack propagation is caused by the failure of material in tension or shear to resist the stresses applied at the crack tip. The stresses at the crack tip are far greater than the nominal stress within the component due to the concentration where stresses flow around the crack.

AWS D1.1 Table 6.1 rejects any crack visible at the surface. AWS D1.1, Clause 6.12 RT, rejects all cracks detected radiographically. Under some conditions, discontinuities discovered through ultrasonic testing (UT) may include cracks that are accepted. If small and oriented such that the reflected signal strength is low, a Class B, C, or D discontinuity may be accepted under AWS D1.1/D1.1M:2008 Table 6.2. However, planar discontinuities, such as cracks, may give lower

indication ratings because of the angle of signal and defect orientation. Therefore, alternative UT techniques should be used. The alternative UT techniques are described in AWS D1.1, Annex S UT Examination of Welds by Alternative Techniques, and alternate acceptance-rejection criteria are given in Table S.1 Acceptance-Rejection Criteria.

When the cost or the detrimental effects associated with repairing an existing crack becomes substantial, or when the long-term risk to structural integrity from making the repair outweighs the potential benefit, then alternate acceptance or repair criteria should be considered. Discontinuity size, orientation, and location within the joint; applied and residual stress levels; material toughness and strength; and repair options should be considered in determining whether to eliminate a crack.

Surface cracks are generally more significant than internal cracks because of the stress concentrations and the unconfined edge. Cracks and other discontinuities below the surface have less effect upon the service performance of the joint. Cracks open to the surface may be more easily assessed and repaired. Buried cracks are more difficult to define (crack or crack-like, exact limits, etc.) and repair. In addition, their repairs lead to larger HAZs, more distortion, and higher residual stresses. The probability of initiating new cracks or propagating existing defects during repairs may be higher than during initial welding, if conditions are similar.

The acceptance of cracks or crack-like defects should be based on fracture mechanics. If the discontinuity is small enough, the stress level low enough, and material toughness high enough, the crack will not propagate. Even in fatigue situations, cracks may be determined to be acceptable. Linear Elastic Fracture Mechanics (LEFM) and elastic-plastic methods of fracture mechanics may be employed in establishing appropriate acceptance criteria. The Crack Tip Opening Displacement (CTOD) method and the J Contour Integral method are commonly used. Use of these testing methods is for critical joints and members and not for ordinary repair welds.

Table 5.1
Fillet Weld Sizes

L, Specified Nominal Weld Size, in [mm]	U, Allowable Decrease from L, in [mm]
$\leq 3/16$ [5]	$\leq 1/16$ [2]
$1/4$ [6]	$\leq 3/32$ [2.5]
$\geq 5/16$ [8]	$\leq 1/8$ [3]

Source: Reproduced from AWS D1.1/D1.1M:2008, *Structural Welding Code—Steel*, Table 6.1, Miami, American Welding Society.

Table 5.2
AWS D1.1, Figure 5.4 Convexity Limitations

Width of Weld Face or Individual Surface Bead, W	Max Convexity, C
$W \leq 5/16$ in [8 mm]	$1/16$ in [2 mm]
$W > 5/16$ in [8 mm] to $W < 1$ in [25 mm]	$1/8$ in [3 mm]
$W \geq 1$ in [25 mm]	$3/16$ in [5 mm]

Source: Reproduced from AWS D1.1/D1.1M:2008, *Structural Welding Code—Steel*, Figure 5.4, Miami, American Welding Society.

6. Testing and Sampling

6.1 General Considerations

The purpose of this clause is to provide various options for Nondestructive Testing (NDT) and for basic methodologies to be followed that will provide the information desired. The determination of what information is required and what methodology should be used as well as the levels of acceptability are to be determined by the Owner and Engineer. Also, it is important to note that the information provided assumes appropriately trained inspection staff are used for the actual inspection.

In selecting the sampling and NDT method to utilize, the Engineer should determine what flaw types are critical to the performance of the structure. Otherwise, an Inspector could spend significant time collecting data for little purpose. The Engineer identifies critical members and areas in them where flaws are likely to occur. Structural evaluation, especially for fatigue analysis, may depend on what is detectable by NDT. The initial flaw size used to calculate the fracture limit is assumed to be the largest one not detectable by the NDT method and settings selected. If test sensitivity is reduced (the minimum detectable size is increased), the estimated fatigue life will be reduced.

Selection of the NDT method and equipment establish detection capabilities and sensitivity. For example, fluorescent wet magnetic particle examination is more sensitive to fine surface cracks than dry magnetic particle examination, but the wet method's sensitivity to surface roughness may actually mask cracks. Radiography may detect weld quality flaws but is not sensitive to cracks perpendicular to its beam.

6.2 Sampling and Testing Plan

Prior to designing a sampling and testing plan for a particular structure, the Engineer should review existing drawings and the history of the structure. NDT methods and results from previous inspections should be reviewed when available. Surveys of similar structures should also be reviewed for potential common problems with material, structural details, and service conditions. A visit to the structure should be scheduled to consider access and evaluate structure components, including member damage and coating condition.

Testing and sampling should be planned to provide an adequate level of confidence. A statistical approach, such as ASTM E 141, *Standard Practice for Acceptance of Evidence Based on the Results of Probability Sampling*, should be utilized. An appropriate calibration standard should be developed. For ultrasonic inspection, calibration blocks duplicating specific structure component geometry with flat-bottomed holes, notches, or other known defects may be required. Such calibration standards should be documented and preserved so that inspection methods can be repeated in the future.

The goals of sampling and testing should be established. Typical goals include:

- (1) Flaw detection and categorization for fitness for purpose evaluations or repairs (size, shape, orientation, spacing, etc.);
- (2) Evaluating material properties and conditions for strengthening (weldability, yield and tensile strength, section loss, areas of distress due to overload or deterioration, etc.); and
- (3) Determination of existing stress levels.

For critical structures such as bridges, regular inspection intervals are mandated to minimize risk of structural failure and schedule necessary maintenance.

6.3 NDT Methods for Flaw Detection

6.3.1 Visual Testing. Visual testing (VT) can determine potential locations for other NDT methods. Typically, a preliminary visual survey of the structure is performed prior to finalizing an NDT inspection and testing plan. Logistical issues, such as access and test surface conditions, can be reviewed. The preliminary visit will also provide the Inspector with an overall sense of the condition of the structure, including damaged areas that require special attention.

Visual testing requires only simple equipment: a flashlight, weld gauges, an inspection mirror, and a wire brush. Binoculars and boroscopes may be required for areas that cannot be directly accessed. A digital camera should be used to provide a permanent record of structure conditions and provide files that can be electronically conveyed.

6.3.2 Magnetic Particle Testing. Magnetic particle testing (MT) is inexpensive and a sensitive method for locating small surface cracks in ferromagnetic materials. This method utilizes electrically induced or direct magnetism at the test surface. If the magnetic field is distorted by a change in material continuity, such as a crack, the disturbance creates magnetic flux leakage and iron particles applied to the surface are attracted to the site. Particles trapped in the leakage field will reveal the location, shape, and size of the crack. The image formed by the particles can be further enhanced by using contrasting colors, fluorescence, and liquid mediums.

Detection of discontinuities depends on several variables, such as the magnetizing method, type of current, magnetic field direction, field strength, and material properties of the test surfaces. Direct current can provide more evidence of shallow (1/8 in [3 mm] deep) subsurface discontinuities, but alternating current provides more particle mobility for finding flaws open to the surface. Typically, a handheld yoke electromagnet is used for inspecting existing structures. Other MT methods utilize prods to introduce electric current into the structure, producing magnetic fields. Usually, significant surface flaws in existing structures can be readily detected by electromagnetic yokes with alternating current.

As-welded surfaces can be examined by MT, but rough surface profiles may require grinding to condition the surface. MT with a yoke can be performed on tightly adhered paint no more than a few mils in thickness. Thick, cracked, chipped, and peeling paint can produce false crack-like indications and mask real flaws. Prods should have bare metal for electrical contact.

If a permanent record is required, MT indications can be recorded through photography or by application of clear plastic adhesive tape on the test surface. As the tape is lifted from the surface, the indication adheres to the tape. The tape may then be placed directly on the inspection report for future reference.

6.3.3 Dye Penetrant Testing. Dye penetrant testing (PT) is an inexpensive yet sensitive method for inspection of surface discontinuities. In this method, a visible or fluorescent dye is applied to the test surface and enters small openings, such as cracks, by capillary action. Excess dye is removed from the test surface, and a contrasting color developer is applied to act as a blotter and draws any residual dye from the openings to reveal evidence of flaws.

PT can require extensive surface preparation and time, which may be impractical on existing structures. Any surface roughness, poorly adhered paint, rust, or weld flaws such as overlap or slag will hold dye and can potentially mask real flaws. Weld surfaces may require grinding to provide smooth test surfaces to allow excess dye removal.

PT examination can be used on both magnetic and nonmagnetic materials. It is particularly useful on nonmagnetic materials such as aluminum, magnesium, and austenitic stainless steels where MT cannot be used. The process is simple and Inspectors find little difficulty in learning to apply it properly, but each location requires dwell time for dye to be pulled into discontinuities, especially in cold weather. The amount of dye extracted by the developer is an indication of the discontinuity size. Like MT, PT indications can be recorded by photography or absorbent tape transfer, if a permanent record is required.

6.3.4 Radiographic Testing. The Radiographic Testing (RT) method provides a volumetric examination of the component or weld. The RT image allows the characterization and measurement of discontinuities and provides permanent documentation.

RT utilizes gamma rays or x-rays to produce images on film or real time video. Changes in steel thickness and average density alter the rate of attenuation (loss of energy) for the radiation, producing inversely proportional levels of darkness in the film image (more or denser material equals lighter image). Voids, inclusions, or cracks parallel to the radiation lower average density. The film (or recording medium) and the radiation source are placed on opposing sides of the section to be tested.

The radiation hazard as well as government licensed radiation sources and operators associated with the RT method makes this an expensive and difficult process to perform, especially on existing, occupied structures. Another significant limitation of the RT method is that planar discontinuities should be favorably oriented with the radiation beam to be reliably detected. The RT method is often not sensitive to service flaws such as fatigue cracks and is commonly limited to steel thicknesses less than 3 in [75 mm] thick. And lastly, to place the film and source, access to both sides of the component is required. This may be a particular problem for tubular members and elements partially against concrete.

6.3.5 Ultrasonic Testing. The Ultrasonic Testing (UT) method can provide high sensitivity to locate small discontinuities. Usually, only one surface needs to be accessible. With some UT systems, a permanent record can be generated. Automated systems are available, which utilize multiple transducer arrays with mechanical scanners. These systems can produce 3D images of discontinuities, but are often not adaptable to existing structure geometry and access. Typically, manual UT systems are used for existing structures.

The UT method is widely used for welded structures to detect and characterize internal weld flaws and base metal cracking. Detection of laminations and determination of base metal thickness or thinning caused by corrosion are possible with this procedure. Information revealed includes flaw location, orientation, and size, which are all valuable for fracture mechanics analysis.

The pulse-echo method with A-scan data presentation is often employed. High frequency sound waves are introduced into the test material to detect surface and subsurface discontinuities. The sound waves travel through the material (with some attenuation loss) and are reflected by discontinuities (edges, cracks, inclusions, voids, etc.). The reflected sound beam is detected and analyzed to determine the presence, size, and location of discontinuities. The sound beam can be introduced at multiple surfaces and angles to improve discontinuity evaluation. The discontinuity should have some surface that is perpendicular to the sound beam to be detectable. As the area perpendicular to the beam increases, the reflected energy and accompanying signal also increase. Rounded voids and inclusions have little area perpendicular to beams from any direction, but cracks reflect almost all ultrasonic energy when the beam is perpendicular to the plane of the fracture.

The UT method has several disadvantages. One is the high degree of operator expertise required, especially for complex weldments. Also, components that are rough, irregular in shape, very small or thin, or nonhomogeneous require special techniques to evaluate. Irregular and rounded discontinuities can be difficult to characterize and size. Reference standards similar to examination conditions and component geometry with artificial flaws are needed to calibrate the UT equipment. AWS D1.1/D1.1M:2008 provides guidance for UT procedures and calibration standards that may be appropriate for the examination of existing structures. The Engineer should be consulted to determine applicable acceptance standards. Original UT standards used for fabrication of the structure, for example AWS D1.1/D1.1M:2008, Clause 6 Inspection, for buildings and AASHTO/AWS D1.5M/D1.5:2008, Clause 6 Inspection, for bridges, may not be appropriate for existing structures.

6.3.6 Electromagnetic Testing. The electromagnetic or “Eddy current” testing (ET) method induces small electrical currents in a material. Changes in current flow are detected by a nearby coil for interpretation, processing, and presentation. It can detect surface and shallow subsurface discontinuities. ET methods have also been used to measure grain size, hardness, thickness, heat treatment conditions, coating thickness, and categorize different materials.

Advantages of the ET method include portability of the equipment, high speed scanning capabilities, and potential optimization of procedures so coatings may remain on test surfaces. Rough surfaces can also be tested by ET without grinding. This method can be very sensitive to small surface flaws such as fatigue cracks.

One disadvantage is that test surfaces must be electrically conductive. Secondly, the depth of inspection is generally limited to 1/4 in [6 mm]. Another consideration is that many variables, which may be difficult to control or anticipate on existing structures, may adversely affect ET. Calibration samples, which need to match test material, may be difficult to obtain. It is possible to obtain information using ET without calibration samples by comparing test results from different surfaces on the same structure.

6.3.7 Acoustic Emission Testing. Acoustic Emission Testing (AE) is used to discover flaws as they grow microscopically within structures. The method utilizes acoustic sensors at several locations on the structure. As the structure is loaded, acoustic emanations (sounds from many spectrums) are monitored and compared with expected background noise. Discontinuities, such as cracks, provide identifiable acoustic emissions as the tip propagates, separating existing soundly joined metal molecules. The crack tip position can be located by triangulating sound arrival times to the differ-

ent sensor positions. The method can be expensive to assemble and difficult to implement on existing structures, which have many sources of acoustic emissions, including slippage at faying surfaces and metal-metal interplay between adjacent parts under loadings. As discovered during previous research, the sensors and data processing equipment for AE is sensitive and may not be suitable for extended exterior exposure or to industrial atmospheres (dust, stray electrical currents, paint, etc.).

6.4 NDT Methods for Material Identification

6.4.1 Material and Property Identification. Chemical analysis can be used to categorize unknown materials on the structure. The percentages of chemical elements can be used to determine carbon equivalency and thereby estimate the weldability of the metal. There are relatively inexpensive methods, such as wet analysis of drill shavings or portable spectrum analyzers, for use on existing structures.

6.4.2 Hardness Testing. Portable hardness testing can indicate possible material heat treatment and can provide an approximate tensile strength. Hardness testing can be used to determine uniformity between many members of a structure. If hardness testing indicates different base metal properties, further sampling may be performed by removing coupons from base metal groups for mechanical testing.

6.4.3 Mechanical Testing. Mechanical testing could be considered a nondestructive method if small samples can be removed from low stress areas for tensile and notch toughness testing without requiring member replacement or strengthening. Hardness and chemical testing can be performed on the samples to be compared with in situ tests.

6.5 NDT Methods for Flaw Sizing and Characterization

6.5.1 Ultrasonic Testing. Clause 6 Inspection in AWS D1.1/D1.1M:2008 and Clause 6 Inspection in AASHTO/AWS D1.5M/D1.5:2008 cover standard UT requirements. AWS D1.1/D1.1M:2008, Annex S UT Examination of Welds by Alternative Techniques, provides guidance for developing ultrasonic testing procedures for flaw sizing. Several techniques are available for sizing including tip diffraction, time of flight, and amplitude methods. Specialized training is required to successfully use these techniques. Fracture mechanics analysis requires comprehensive flaw dimensions and positions. Calibration standards and mockups with known flaws are required to qualify both procedures and ultrasonic technicians.

6.5.2 Radiography. Radiography can be used to measure flaw sizes and location. Flaw sizes will be projected on the film with dimensions longer than the actual flaw size. Depth can be estimated by changing source and film orientation.

6.5.3 Measurements. Physical measurements, including periodic monitoring to determine crack growth, can be used on surface cracks. Partially or completely fractured components can be removed from the structure to determine failure modes and crack growth rates.

6.6 NDT Methods to Determine Existing Stress Levels

There are several nondestructive methods available to determine existing stress levels including strain gauging, x-ray diffraction, residual stress measurements, harmonic techniques, and load deflection measurements.

6.7 NDT Methods to Determine Corrosion Effects

On many existing structures, corrosion of structural elements is an issue. If access allows, the simplest way to measure corrosion loss is by direct physical measurements using rulers, calipers, micrometers, etc. If only single side access is available, ultrasonic thickness gauging techniques can provide accurate measurements. Typically, a grid of coordinates is predetermined where thickness measurements will be taken. Verification may be done by small drilled holes or cores, depending on the situation.

6.8 NDT Personnel Certification

To perform visual inspections, each Inspector should be certified as appropriate for the type of work anticipated. An AWS Certified Welding Inspector (CWI) or CWB Level 2 Certified Welding Inspector may evaluate the surface quality of existing welds, while Inspectors qualified to American Society of Nondestructive Testing (ASNT) Level II or III for UT, RT, PT or other NDT methods may perform those tests. The Engineer provides overall direction to the Inspectors on which areas of existing structures are to be evaluated. These can be very different from new structures built to modern codes. The Inspectors act as the eyes of the Engineer, recording and documenting existing conditions for analysis as well as for planning future inspections.

Inspectors certified by their employer or through examination in accordance with American Society of Nondestructive Testing (ASNT) guidelines should provide documented evidence of current certification to the Engineer.

7. Heat Straightening

Clause 7 is intended to be used as a guide for correcting damaged or deformed members, or otherwise providing a means to correct defects without plastic deformation of the material at ambient temperature.

7.1 Evaluating Damaged Structural Steel

Before heat straightening operations begin, the base metal and weld metal in the area that will be straightened should be inspected for existing cracks or tears that might propagate during straightening operations. Cracks can be removed by grinding, repaired by welding, or the ends of cracks blunted by drilling arresting holes. Welded repairs should be inspected prior to straightening operations. After the repairs are completed, additional inspection should take place to ensure that no damage to adjacent components as a result of the repair has occurred.

7.2 Restraining Forces

Restraining forces, usually applied by jacks, should be set to restrain the steel during heating but allow free contraction during cooling. In addition, the restraining forces should be applied in a direction that tends to restore the member and should be limited so that the material is not overstressed during heating (see 7.3.4).

7.3 Heat Application

Heat patterns and external restraints should be based on Report FHWA-1F-99-004, *Heat Straightening Repairs of Damaged Steel Bridges—A Technical Guide and Manual of Practice*, unless an alternative technical guide is specified by the Engineer or proposed by the Contractor and accepted by the Engineer.

7.3.1 Temperature Limits. Maximum recommended temperature limits for heat application are as shown in Table 7.1.

Exceeding the maximum temperature may be a basis for rejection of the part, unless extensive metallographic analysis, hardness testing, or other NDT can justify acceptance. After applying the planned heat patterns for one sequence, the steel should be allowed to cool to below 250°F [120°C] so net effects can be measured before additional heat is applied. Adjustments in heating patterns and the number of cycles to suit actual field conditions are expected.

Additional steels may be heat straightened as well. Consult documents in Clause 2 Normative References and Annex A Informative References for appropriate temperatures or procedures to establish appropriate temperature for the steel in question.

7.3.2 Safety Catch Blocks. Prior to the initiation of the heating process, intermediate safety catch blocks should be placed at suitable intervals between supports to ensure deflections achieved do not exceed desired limits and buckling does not occur.

7.3.3 Procedures. Computations and a sketch describing the procedures of heating and loading should be prepared prior to the work. All tolerances for final results should be established as part of the procedure documents.

7.3.4 Restraint-Load Stresses. It is beneficial to minimize static tensile stress due to applied loads during heat straightening. Preloading a member to restrict undesired displacement during heating should not cause total stresses attributed to existing dead load plus applied loads exceeding $0.6F_y$ at ambient air temperature. Preloading reduces the number of heating cycles required to produce the desired displacement.

7.3.5 Heating Equipment. Standard equipment includes: oxygen and fuel gas, torches, hoses, single or multiple orifice tips, and temperature monitoring crayons or equipment.

7.3.5.1 Heating. Heat should be applied via single or multiple orifice tips. The size of the tip should be based on the thickness of the heated material and desired displacement. Cutting tips should only be used in special cases and the flame should be a neutral or reducing flame. An oxidizing flame is not permitted for use with cutting tips.

Common torch tips for various thicknesses are shown in Table 7.2.

7.3.5.2 Temperatures. Temperature sensitive crayons, pyrometers, or infrared noncontact thermometers may be used to verify temperatures during heating operations. Each product should be used within the limits of the manufacturer's recommendations. Heat measurements should be made between 5 seconds and 10 seconds after the heating flame has been removed from the steel.

7.3.5.3 Cooling. Cooling with dry compressed air or mist is allowed after the steel has cooled to 600°F [320°C]. Quenching with water or with a combination of water and air should not be allowed above 600°F [320°C].

7.3.5.4 Braces. During heating, if intermediate stiffeners are placed on only one side of a girder web, temporary intermediate braces (i.e., wood blocks or posts) should be placed on the opposite side to prevent rotation of the flange.

Table 7.1
Temperature Limits for Heat Application

Grade, Weathering, and Nonweathering	Maximum Temperature ($^{\circ}\text{F}$ [$^{\circ}\text{C}$])
36	1200 [650]
50, HPS 50, 50W	1200 [650]
HPS 70W	1200 [650]
70, Q & T	1100 [590]
100, Q & T	1100 [590]

Table 7.2
Torch Tip Guide

Steel Thickness		Orifice	
in	mm	Type	Size
<1/4	<6	Single	3
3/8	10	Single	4
1/2	13	Single	5
5/8	16	Single	7
3/4	20	Single	8
1	25	Single	8
1	25	Rosebud	3
2	50	Single	8
2	50	Rosebud	4
3	75	Rosebud	5
>4	>100	Rosebud	5

8. Strengthening and Damage Repair

8.1 Scope

This clause provides guidance for identifying causes of damage to steel members as well as structures, and presents techniques that may be used to repair or mitigate this damage. Possible causes of damage are poor fabrication techniques, failure under service, inadequate maintenance, and damage from an outside source. Many of these repair techniques can be adapted to repair deficiencies discovered during fabrication.

This clause will not assist the Engineer in determining whether particular damage to a member or structure will require repairs. If a weld does not meet the requirements of the applicable codes, the weld may still be judged sufficient for its intended purpose. Clause 5 Evaluation of Existing Welds assists the Engineer in making that determination.

8.2 Possible Causes of Damage

First, the Engineer determines the cause of damage. Damage assessment is necessary to properly formulate a repair plan and possibly avoid a recurrence. If the cause can be mitigated, future repairs may be avoided or further deterioration can be minimized. Some causes, like an impact from a large object, are obvious while, others require investigative techniques, such as the NDT techniques described in Clause 6 Testing and Sampling to determine the source of the problem. Some common causes are detailed in this clause, and damage may occur as an isolated event or in combination with other problems.

8.2.1 Fatigue. Fatigue cracks result from repeated stress fluctuations exceeding the critical level for structural details in a member. High tensile stress due to applied loads or restraint conditions in combination with a stress-concentrating geometric factor are usually involved. These geometric changes may be obvious, like the end of a welded cover plate, or subtle, such as subsurface fusion defects. Typical significant concentrators include cracks in the base or weld metal, weld toe undercut, weld terminations, intersecting welds, and welded attachments creating high restraint such as cruciform joints and triaxially restrained, welded plate intersects.

8.2.2 Impact. Cracked welds, buckling of secondary members, member misalignment, deformation, and torn steel members are examples of damage caused by impact. When possible, repairs are usually performed with the damaged steel member(s) in place.

A visual inspection and NDT can determine the extent of the damage.

8.2.3 Overload. Overload damage occurs when excessive loads are applied to a structure, and a single component or a combination of components are stressed beyond their capacity.

8.2.4 Additional Loads. There may be unforeseen loads introduced to portions of the structure in service. These can result from additions such as medians or the loss of other load carrying elements, such as a bearing failure. Unplanned bending or torsion can overload a member or connection designed for axial forces or simple bending. Triaxial loading and three-dimensional stresses on a common location act jointly on the weakest resistance. Abrupt failures can occur under these conditions.

8.2.5 Fire. Structural steel may be damaged from excessive heat during a fire or quench effects from rapid cooling by high pressure water. Structural steel subjected to fire should be investigated to determine if the original design requirements may be compromised due to a change in the steel properties. The heat during a fire may result in distortion, especially at midspan. Heat may also change the physical properties of the steel (yield, tensile, CVN toughness, ductility).

NDT and the removal of samples for chemical and mechanical testing may determine if the steel's properties have been altered, making it inadequate. Main member material should be examined for unacceptable deflections. Bolted connections should be checked to assure the connections have not loosened due to thermal expansion and contraction.

The AISC *Manual of Steel Construction*, offers guidance on evaluating components subjected to fire in the section titled "Effect of Heat on Structural Steel."

8.2.6 Cracked Welds and Base Metal. Cracks in originally sound material usually result from the types of damage listed in this subclause. However, cracks or crack-like defects may have been initially present in the structure, but were only detected after time and service loads made them more apparent.

For the most part, cracks in main, load carrying members need to be removed and rewelded, or the members need to be replaced. However, complete repair or replacement may not be practical, at which point repairs to add strength or establish an alternate load path are needed. In either case, repairs should reduce the stress at the crack below critical values for further propagation.

8.2.7 Weld Repairs. See AWS D1.1/D1.1M:2008, Clause 5.26 Repairs, or AASHTO/AWS D1.5M/D1.5:2008, Clause 3.7 Repairs and Clause 12.17 Repair Welding, as appropriate.

8.2.8 Shipping Damage. Precautions should be taken during loading and shipping to prevent damage. Damage caused by loading and shipping could include stresses caused by improper loading practices, excessive overhang, insufficient tie-downs or supports, missing stiffening beams or trusses, vehicular accident, or the instability of the member itself.

For large members, a principal consideration in shipping is the lateral stability of girders due to their large, unsupported length. Calculations should show the dead load plus impact stresses induced by the loading and transportation procedure. Support points should be taken into consideration. A sufficient number of tie-downs should be used to provide redundancy so that if any one tie-down fails, the member will remain stable.

8.2.9 Corrosion. Corrosion damage to welds is a common problem. It can be difficult to determine if this damage necessitates repair. The number and type of corrosion pits are good indicators. Due to fatigue considerations, shallow pits are usually less critical than deep ones. However, smaller diameter pits are more detrimental than larger ones. Pits that are close together, random, or linear are a concern. Deep pits that are tightly packed can lead to flaws similar to weld porosity. These pits act as multiple stress risers along a joint. Load stresses will concentrate at each pit and cracking possibilities are greatly increased. If not repaired as necessary, joint failure can occur. Cyclically-loaded members are more susceptible to corrosion failure than statically-loaded members.

8.3 Written Repair Procedures

Written repair procedures should be required and submitted to the Engineer for approval when any of the following conditions exist:

- (1) Base or weld metal defects which require welded repairs;
- (2) Deficient structural capacity requiring the replacement of existing material and/or the addition of new material;
- (3) Deterioration or damage of existing material requiring restoration by adding material or replacement;
- (4) Distortion in existing members caused by impact or overload, which will be corrected by heat, pressure, and/or adding material;
- (5) Requirements to redistribute design loads among existing members by strengthening, modifying members, or adding supplementary elements;
- (6) Members should be significantly modified to accommodate revised geometry or changes in structural function.

8.4 Methods of Repair

The Contractor should be permitted some latitude in determining the means and methods to employ based on the situation, the known accuracy of the plans, and the number of potential and viable alternates. For example, the options of repairing portions of an unacceptable weld, removing and replacing the entire weld, or replacing the weldment each have potential benefits and drawbacks. As long as the final product provides the required quality, durability and capacity, permitting alternate approaches may expedite work by allowing the Contractor to utilize available equipment and familiar techniques.

The acceptance criteria should be constant, regardless of production methods applied. These should be clearly defined in the contract and based on accepted industry practice. Repaired items, especially those with corrosion loss, cannot meet new condition requirements for material and coating, so specifications should have realistic expectations.

8.5 General Repair Considerations

Safety procedures for welding, cutting, brazing, and heating operations should be based on OSHA standards. The hazards associated with this type of work involve location, types of materials, and work practices. Safety measures include well-maintained and checked production equipment, ventilation, training, and personal protective equipment.

8.5.1 Safety Considerations. Refer to ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*, for safety considerations.

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Annex A (Informative)

Informative References

This annex is not part of AWS D1.7/D1.7M:2010, *Guide for Strengthening and Repairing Existing Structures*, but is included for informational purposes only.

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Annex B (Informative)

Guidelines for the Preparation of Technical Inquiries for the Structural Welding Committee

This annex is not part of AWS D1.7/D1.7M:2010, *Guide for Strengthening and Repairing Existing Structures*, but is included for informational purposes only.

B1. Introduction

The American Welding Society (AWS) Board of Directors has adopted a policy whereby all official interpretations of AWS standards are handled in a formal manner. Under this policy, all interpretations are made by the committee that is responsible for the standard. Official communication concerning an interpretation is directed through the AWS staff member who works with that committee. The policy requires that all requests for an interpretation be submitted in writing. Such requests will be handled as expeditiously as possible, but due to the complexity of the work and the procedures that must be followed, some interpretations may require considerable time.

B2. Procedure

All inquiries shall be directed to:

Managing Director
Technical Services Division
American Welding Society
550 N.W. LeJeune Road
Miami, FL 33126

All inquiries shall contain the name, address, and affiliation of the inquirer, and they shall provide enough information for the committee to understand the point of concern in the inquiry. When the point is not clearly defined, the inquiry will be returned for clarification. For efficient handling, all inquiries should be typewritten and in the format specified below.

B2.1 Scope. Each inquiry shall address one single provision of the code, unless the point of the inquiry involves two or more interrelated provisions. The provision(s) shall be identified in the scope of the inquiry along with the edition of the code that contains the provision(s) the inquirer is addressing.

B2.2 Purpose of the Inquiry. The purpose of the inquiry shall be stated in this portion of the inquiry. The purpose can be either to obtain an interpretation of a code's requirement, or to request the revision of a particular provision in the code.

B2.3 Content of the Inquiry. The inquiry should be concise, yet complete, to enable the committee to quickly and fully understand the point of the inquiry. Sketches should be used when appropriate and all paragraphs, figures, and tables (or the Annex), which bear on the inquiry shall be cited. If the point of the inquiry is to obtain a revision of the code, the inquiry must provide technical justification for that revision.

B2.4 Proposed Reply. The inquirer should, as a proposed reply, state an interpretation of the provision that is the point of the inquiry, or the wording for a proposed revision, if that is what inquirer seeks.

B3. Interpretation of Code Provisions

Interpretations of code provisions are made by the Structural Welding Committee. The secretary of the committee refers all inquiries to the chair of the particular subcommittee that has jurisdiction over the portion of the code addressed by the inquiry. The subcommittee reviews the inquiry and the proposed reply to determine what the response to the inquiry should be. Following the subcommittee's development of the response, the inquiry and the response are presented to the entire Structural Welding Committee for review and approval. Upon approval by the committee, the interpretation is an official interpretation of the Society, and the secretary transmits the response to the inquirer and to the *Welding Journal* for publication.

B4. Publication of Interpretations

All official interpretations shall appear in the *Welding Journal* and will be posted on the AWS web site.

B5. Telephone Inquiries

Telephone inquiries to AWS Headquarters concerning the *Structural Welding Code* should be limited to questions of a general nature or to matters directly related to the use of the code. The AWS Board of Directors' policy requires that all AWS staff members respond to a telephone request for an official interpretation of any AWS standard with the information that such an interpretation can be obtained only through a written request. Headquarters staff cannot provide consulting services. However, the staff can refer a caller to any of those consultants whose names are on file at AWS Headquarters.

B6. The Structural Welding Committee

The activities of the Structural Welding Committee regarding interpretations are limited strictly to the interpretation of code provisions or to consideration of revisions to existing provisions on the basis of new data or technology. Neither AWS staff nor the committees are in a position to offer interpretive or consulting services on: (1) specific engineering problems, or (2) code requirements applied to fabrications outside the scope of the code or points not specifically covered by the code. In such cases, the inquirer should seek assistance from a competent engineer experienced in the particular field of interest.

List of AWS Documents on Structural Welding

Designation	Title
D1.1/D1.1M	<i>Structural Welding Code—Steel</i>
D1.2/D1.2M	<i>Structural Welding Code—Aluminum</i>
D1.3/D1.3M	<i>Structural Welding Code—Sheet Steel</i>
D1.4/D1.4M	<i>Structural Welding Code—Reinforcing Steel</i>
D1.5M/D1.5	<i>Bridge Welding Code</i>
D1.6/D1.6M	<i>Structural Welding Code—Stainless Steel</i>
D1.7/D1.7M	<i>Guide for Strengthening and Repairing Existing Structures</i>
D1.8/D1.8M	<i>Structural Welding Code—Seismic Supplement</i>
D1.9/D1.9M	<i>Structural Welding Code—Titanium</i>

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