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**Introduction to the**
**FHWA Bridge Welding Reference Manual**
December 3, 2019

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### Course Description

Introduction to the FHWA Bridge Welding Reference Manual
December 3, 2019

Welding revolutionized steel bridges in the late 1950s and early 1960s. The move from rivets to welding facilitated the use of long, slender, and curved steel members that give engineers extraordinary flexibility in developing solutions. Welding is a mature technology, but there are aspects of welding that are not well understood and can sometimes cause unnecessary concerns in design, fabrication, inspection, and field installation. To help address these issues, the FHWA published the Bridge Welding Reference Manual, which is available online for free from the FHWA. In this webinar, the lead author of the manual provides an overview of this new manual that will be of interest to all of those in the steel bridge industry.

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**Learning Objectives**

- Describe the history of steel bridge construction, including the period of transition from riveted to welded construction.
- Identify welding standards relevant to the construction of steel bridges.
- Explain how welding procedures are qualified differently for buildings and bridges. Explain the unique testing that takes place to ensure safe welds in bridge structures.
- Explain how to properly document fracture critical members for safety and economy.

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## Introduction to the FHWA Bridge Welding Reference Manual

Ronnie Medlock
Vice President of Technical Services
High Steel Structures, LLC
Lancaster, PA

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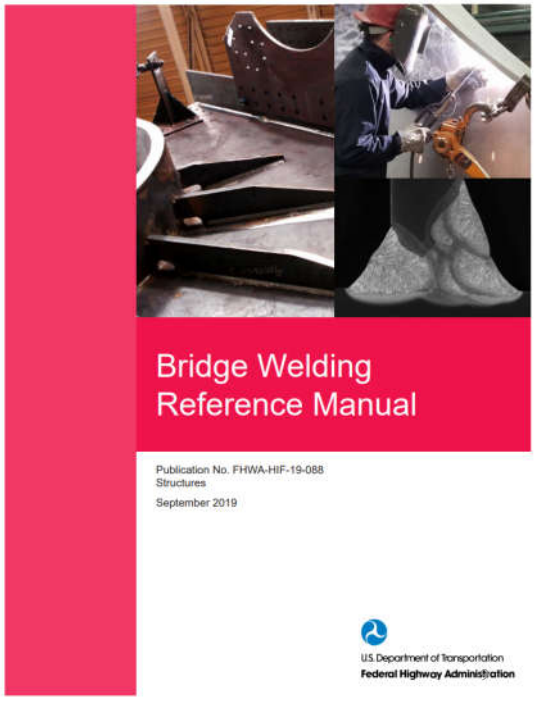
# FHWA Bridge Welding Reference Manual

Ronnie Medlock
VP Technical Services
High Steel Structures, LLC

To find the manual (download for free), search on,
"fhwa bridge welding",
or go to
fhwa.dot.gov/bridge/steel/pubs/hif19088.pdf




# Acknowledgments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  - Also Duncan Paterson, HDR
- Other content reviewers – Mary Grieco, MassDOT, Todd Niemann, Fickett, and Dayi Wang, FHWA


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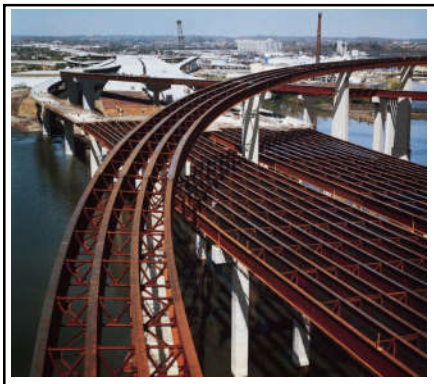
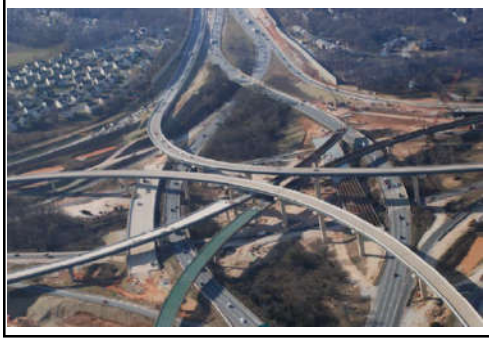
## Welding Revolution





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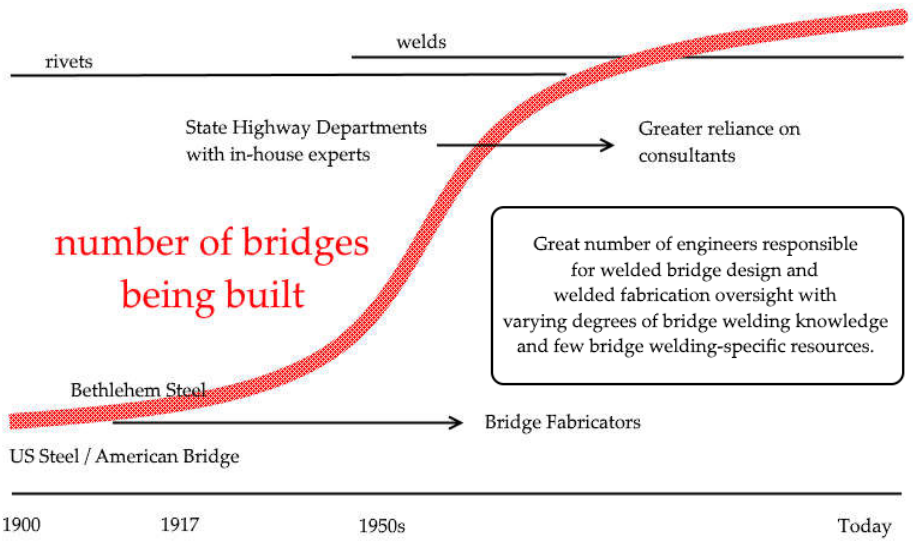
## Changing Times and the Need for Welding Resources

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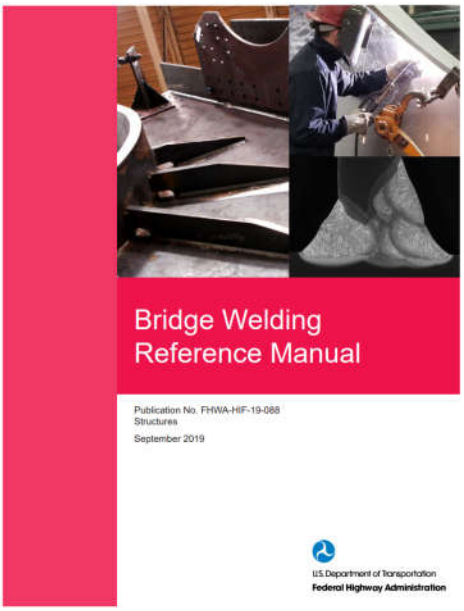
## Hence the Manual

- Welding knowledge for designers and materials engineers
- Compliments (and sometimes explains) the Bridge Welding Code (AWS D1.5)

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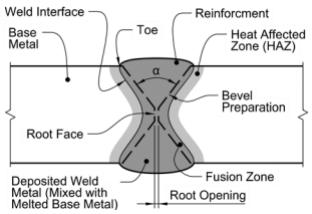
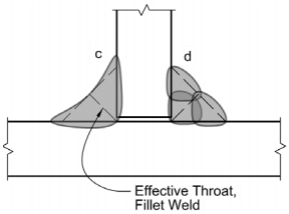
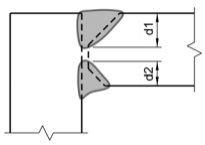
# Basic Anatomy




complete-joint-penetration weld (CJP)




fillet weld




partial-joint-penetration weld (PJP)

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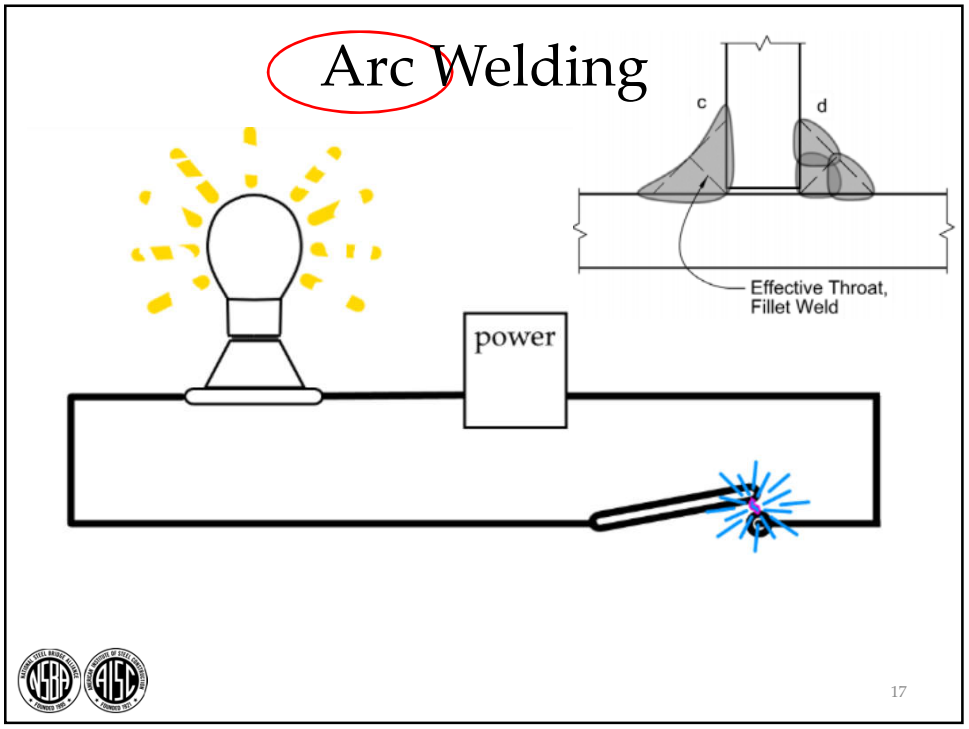
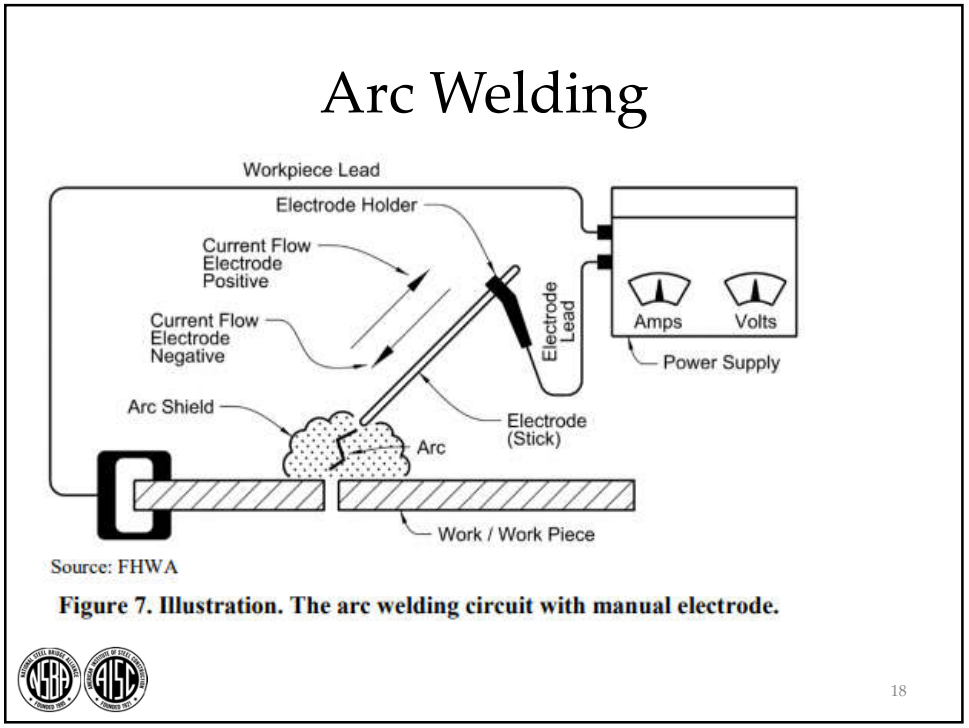
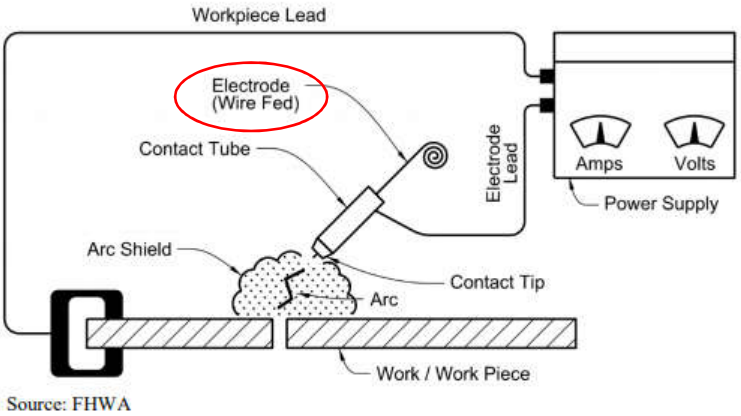


# Arc Welding




Source: FHWA

**Figure 8. Illustration. The arc welding circuit with wire electrode.**

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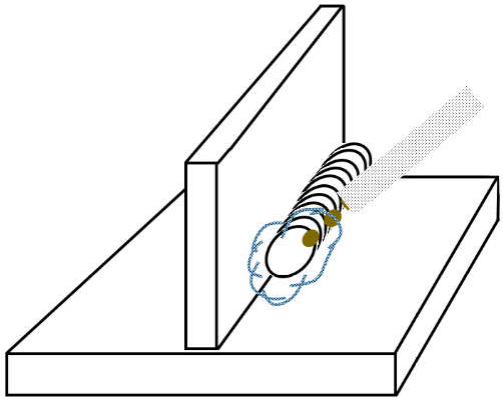
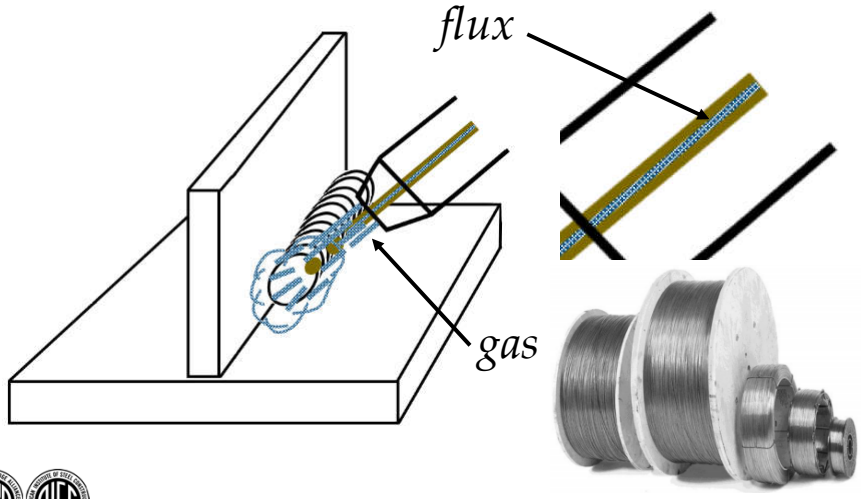
# SMAW / Stick

shielded metal arc welding



## FCAW- G

flux-cored arc welding, with gas shielding

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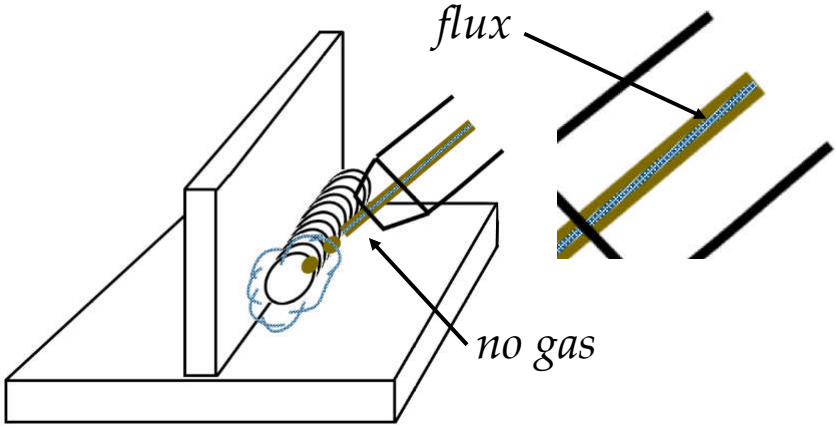
## FCAW-S

flux-cored arc welding, self-shielded

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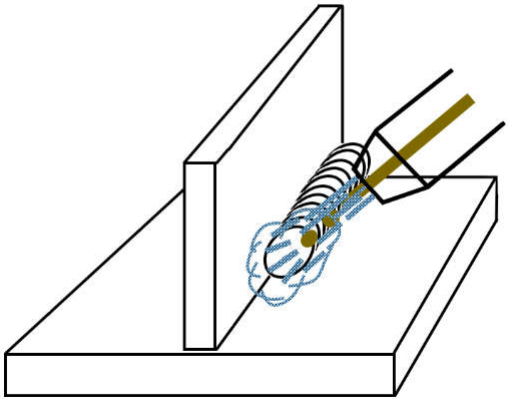
# GMAW
## gas metal-arc welding



- Transfer modes
  - Spray
  - Pulse-spray
  - Globular
  - Short-circuiting

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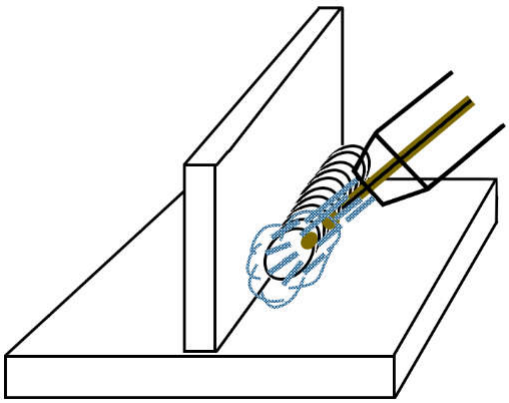
# GMAW, w/ metal core wire



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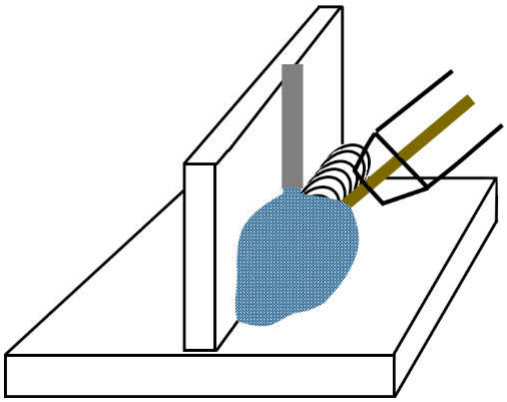
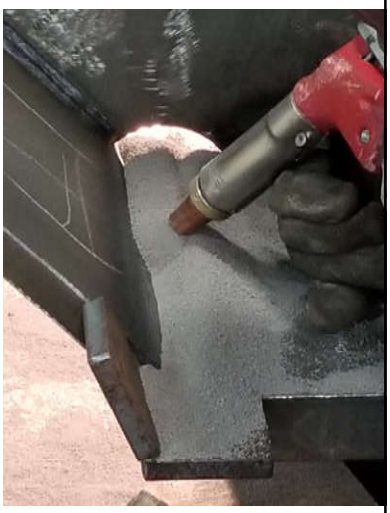
## SAW submerged arc welding





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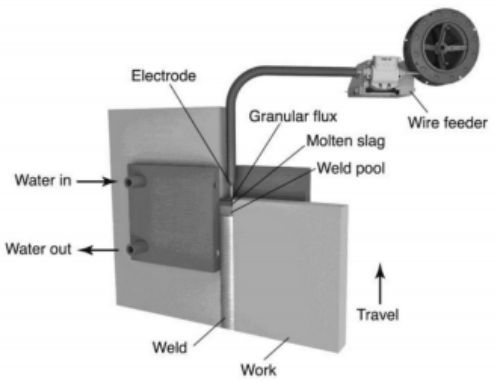
## Electroslag Welding




- Not arc welding: rather, resistance welding

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# Comparing Processes

- SMAW (stick)
  - Oldest process, highly versatile, low productivity
  - Out-of-position welding, small welds, repairs
  - Field welding
- FCAW / GMAW
  - Higher productivity than stick
  - Tack welds, small welds (including CJPs), robotic welding, also long mechanized long welds
  - When FCAW-S, field welding
- SAW
  - High productivity
  - Long mechanized welds, CJPs (flange and web butt splices), also small hand-held weld
- ESW
  - High productivity
  - CJPs only; only vertical; not FC or HPS

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# Weld Values

- Strength
- Ductility
- Weathering characteristics
- Toughness
  - Material properties (CVNs)
  - Geometry (fatigue details)
- Soundness
- Constructability
  - Ability to be made
  - Economy

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# Weld Values

- Strength
- Ductility
- Weathering characteristics
- Toughness
  - Material properties (CVNs)
  - Geometry (fatigue details)
- Soundness
- Constructability
  - Ability to be made
  - Economy

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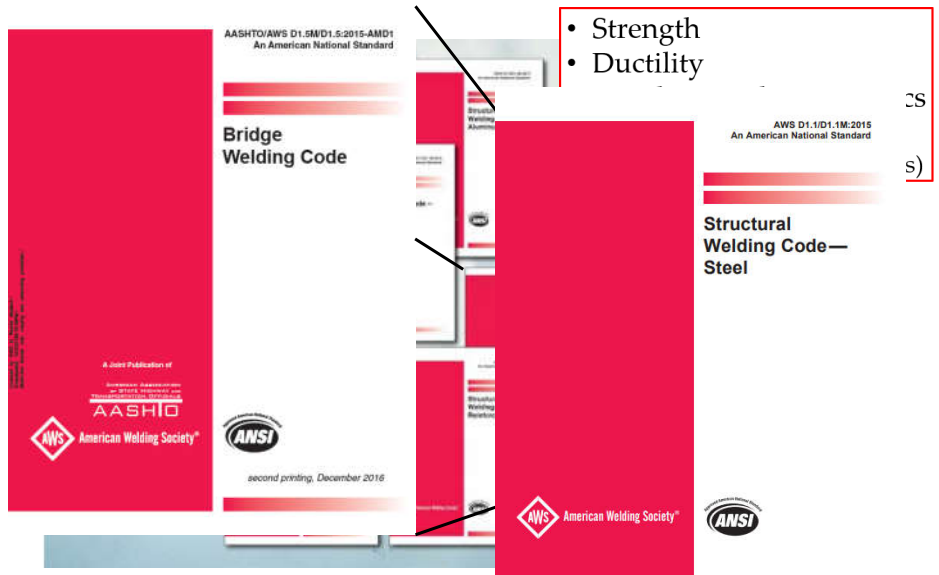


- Strength
- Ductility

- Get the proper weld metal p
  consumable to weld your material
  - The best way to do this is to simply specify the right Code
  - Make sure the Code you are using has the material you are using

# Base metal / weld metal combinations

**1.2.2 Approved Base Metals.** Unless otherwise specified, base metals to be welded under this code shall meet the requirements of the latest edition of AASHTO M 270M/M 270 (ASTM A709/A709M) for the grade of steel shown on the plans or described in the specifications. All Grade 345 (50) steel that is to be welded shall be Type 1, 2, or 3. Other steels may be approved by the Engineer. Thickness limitations shall not apply to bearing components.

**Table 4.1**
**Matching Filler Metals for WPSs[a, b, c, d]**

| Base Metal AASHTO [ASTM] Designation | Welding Processes and AWS Electrode Specification and Classifications | | | | | | |
|---|---|---|---|---|---|---|---|
| | SMAW[e] | SAW[e, f] | FCAW-G[g] | FCAW-S[g] | GMAW[g] | ESW-NG | EGW[g] |
| M 270M/M 270 (A709/A709M) Gr. 250 [36] | A5.1/A5.1M E6018 E7015 E7016 E7018 E7018-1 E7018M E7028 | A5.17/A5.17M F6A0-EXXX F6A0-ECX F7A0-EXXX F7A0-ECX | A5.20/A5.20M E7XT-1C, -1M E7XT-5C, -5M E7XT-9C, -9M E7XT-12C, -12M | A5.20/A5.20M E7XT-6, -8 | A5.18/A5.18M ER70S-2, -3, -6, -7 E70C-3C, E70C-3M E70C-6C, E70C-6M | See Annex I | A5.26/A5.26M EG60X-X EG62X-X EG70X-X EG72X-X |
| | A5.5/A5.5M E7015-X E7016-X E7018-X E7015, -16, -18-C1L, -C2L E7018-C3L E7018-W1 E8015-C1, C2, C3, C4 E8016, -18-C1, -C2 E8016, -18-C3, -C4 E8018-W2 | A5.23/A5.23M F7A0-EXXX-XX F7A0-ECXXX-XX F8A0-EXXX-XX F8A0-ECXXX-XX | A5.29/A5.29M E6XT1-NiC, -NiM E7XT1-XC, -XM E7XT5-XC, -XM E8XT1-XC, -XM E8XT1-NiXC, -NiXM E8XT1-W2C, -W2M E8XT5-XC, -XM E8XT5-NiXC, -NiXM | A5.29/A5.29M E6XT8-X E7XT4-X E7XT6-X E7XT7-X E7XT8-X E8XT8-X | A5.28/A5.28M ER70S-XXX ER80S-XXX ER80S-NiX E70C-XXX E80C-NiX E80C-W2 | | |
| M 270M/M 270 (A709/A709M) Gr. 345 [50] Type 1, 2, 3; Gr. 345S [50S]; Gr. 345W [50W] (up to 100 mm [4 in] thick); Gr. HPS 345W (HPS 50W)[h, i] | A5.1/A5.1M E7015 E7016 E7018 E7018-1 E7018M E7028 | A5.17/A5.17M F7A0-EXXX F7A0-ECX | A5.20/A5.20M E7XT-1C, -1M E7XT-5C, -5M E7XT-9C, -9M E7XT-12C, -12M | A5.20/A5.20M E7XT-6, -8 | A5.18/A5.18M ER70S-2, -3, -6, -7 E70C-3C, E70C-3M E70C-6C, E70C-6M | See Annex I | A5.26/A5.26M EG70X-X EG72X-X |
| | A5.5/A5.5M E7015-X E7016-X E7018-X E7015, -16-C1L, -C2L E7018-C1L, -C2L, -C3L E7018-W1 E8015-C1, C2, C3, C4 E8016, -18-C1, -C2 E8016, -18-C3, -C4 E8018-W2 | A5.23/A5.23M F7A0-EXXX-XX F7A0-ECXXX-XX F8A0-EXXX-XX F8A0-ECXXX-XX | A5.29/A5.29M E7XT1-XC, -XM E7XT5-XC, -XM E8XT1-XC, -XM E8XT1-NiXC, -NiXM E8XT1-W2C, -W2M E8XT5-XC, -XM E8XT5-NiXC, -NiXM | A5.29/A5.29M E7XT-X E7XT6-X E7XT7-X E7XT8-X E8XT8-X | A5.28/A5.28M ER70S-XXX ER80S-XXX ER80S-NiX E70C-XXX E80C-NiX E80C-W2 E80C-XXX | | |

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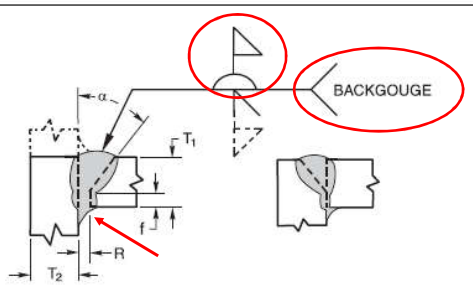
# Standard Joints for CJP and PJP Welds

Single-bevel-groove weld (4)
T-joint (T)
Corner joint (C)




| Welding Process | Joint Designation | Base Metal Thickness (U = unlimited) $T_1$ | Base Metal Thickness (U = unlimited) $T_2$ | Groove Preparation: Root Opening, Root Face, Groove Angle | Groove Preparation: Tolerances: As Detailed (see 2.12.1) | Groove Preparation: Tolerances: As Fit-Up (see 3.3.4) | Allowed Welding Positions | Gas Shielding for FCAW | Notes |
|---|---|---|---|---|---|---|---|---|---|
| SMAW | TC-U4b | U | U | R = 0 to 1/8<br>f = 0 to 1/8<br>α = 45° | +1/16, –0<br>+1/16, –0<br>+10°, –0° | +1/16, –1/8<br>Not limited<br>10°, –5° | All | — | a, c, k |
| GMAW FCAW | TC-U4b-GF | U | U | | | | All | Not required | c, k |
| SAW | TC-U4b-S | U | U | R = 0<br>f = 1/4 max.<br>α = 60° | ±0<br>+0, –1/8<br>+10°, –0° | +1/4, –0<br>±1/16<br>10°, –5° | F | — | c, k |

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## Welding Procedures and Qualification

- An approved welding procedure is required for all welding under the Bridge Welding Code
- Most procedures (exception: most stick procedures) require qualification testing
- Under the Code
  - Welding procedures are known as welding procedure specifications (WPSs)
  - Qualification tests are documented on procedure qualification records (PQRs)
- Short hand:

*Under the Bridge Welding Code, welding is done following WPSs that are backed up by PQRs*

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## Welding Procedures and Qualification

- An approved welding procedure is required for all welding under the Bridge Welding Code
- Most procedures (exception: most stick procedu
- Under t
  - Weldi specifi
  - Qualif qualifi
- Short ha

*Under the Bridge Welding Code, welding is done following WPSs that are backed up by PQRs*

*Fabrication cannot begin until welding procedures have been approved (and the fabricator gets them back)*

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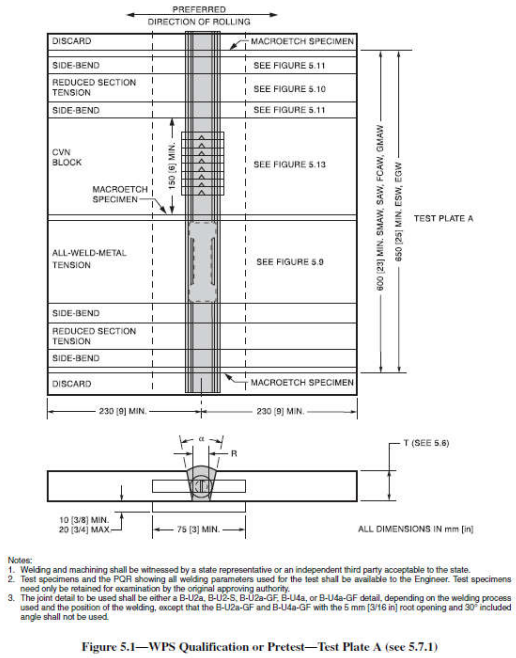


Notes:
1. Welding and machining shall be witnessed by a state representative or an independent third party acceptable to the state.
2. Test specimens and the PQR showing all welding parameters used for the test shall be available to the Engineer. Test specimens need only be retained for examination by the original approving authority.
3. The joint detail to be used shall be either a B-U2a, B-U2-S, B-U2a-GF, B-U4g, or B-U4a-GF detail, depending on the welding process used and the position of the welding, except that the B-U2a-GF and B-U4a-GF with the 5 mm [3/16 in] root opening and 30° included angle shall not be used.

**Figure 5.1—WPS Qualification or Pretest—Test Plate A (see 5.7.1)**

# Qualification Test (PQR)

- For CJPs, PJPs, and multi-pass fillets
- At representative settings, evaluates strength, ductility, toughness, and soundness of the base metal / consumable combination

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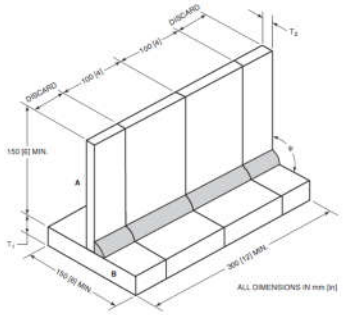
# Fillet Weld Soundness Test




- Required for fillet weld procedure qualification
- This is the only test required for single-pass fillet welds

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## WPS and PQR Approval Guide
*from the manual*

**APPENDIX A - GUIDE TO REVIEW AND APPROVAL OF WELDING PROCEDURE SPECIFICATIONS (WPSs) AND PROCEDURE QUALIFICATION RECORDS (PQRs) UNDER THE BRIDGE WELDING CODE (AASHTO/AWS D1.5)**

**Table of Contents – Review Sections**



**A.1. FILLET WELD SOUNDNESS TEST (FWST) REVIEW**

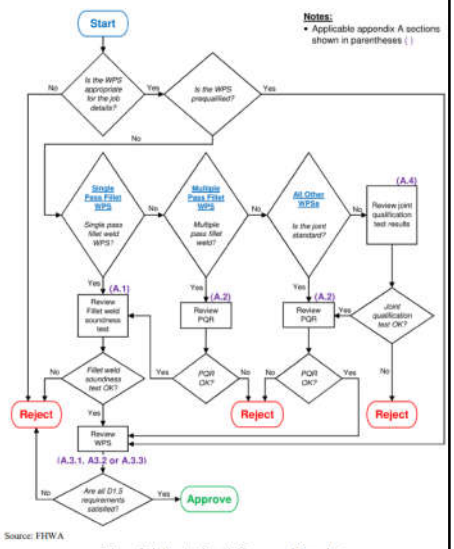
Steps for review and approval of fillet weld soundness test (FWST):

1. Check that the test plate thicknesses are correct for the fillet weld size being tested.
2. Check for proper preparation of the macroetch test specimens (clause 5.10.3(2) and 5.18.2).
3. Check specimen requirements. Macroetches must satisfy requirements of clause 5.19.3.
4. For multipass fillet welds, ensure that the parameters of the FWST are within the limitation of variables of the PQR. (This means essentially checking the FWST to the PQR as if it were a WPS. See the multipass fillet weld provisions of section A.3.2 below.)

**A.2. GROOVE WELD QUALIFICATION TEST REVIEW (PQR REVIEW)**

Fabricators may use Forms O-3 and O-4 (or O-8 for ESW) from the Bridge Welding Code or choose their own form, as long as the form presents the same information as required by the code. If the owner has a required form, check that the owner's form is used. Even if the owner has a required form, owners frequently grant an exception for reciprocity—i.e., if the PQR was previously approved by another owner.

There are a number of approaches for conducting the groove weld qualification test (section




Source: FHWA

**Figure 211. Illustration. WPS approval flow chart.**

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# Differences between D1.1 and D1.5

- Qualification
  - Under D1.1, most welding procedures are prequalified (no testing required)

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# Weld Values

- Strength
- Ductility
- Weathering characteristics
- Toughness
  - Material properties (CVNs)
  - Geometry (fatigue details)
- Soundness
- Constructability
  - Ability to be made
  - Economy

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# Discontinuities

Welding Technique Related
- Incomplete fusion, incomplete joint penetration
- Cracks – bead-shape induced, surface profile induced, crater cracks
  - AKA "hot cracks"; happen while cooling
- Other volumetric discontinuities – slag intrusions, undercut, overlap, craters
- Profile – concavity, convexity, size
- Spatter, arc strikes, porosity

Material Related
- Laminations, delaminations, lamellar tearing

Hydrogen Related
- Cracks –HAZ, transverse
  - AKA "cold cracks"; happen after solidification
- Porosity

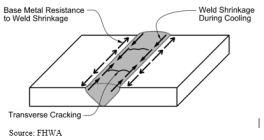


**Figure 64. Illustration. Transverse cracking.**

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# Hydrogen-Assisted Cracking

Cracking mechanism

- Hydrogen dissolves in the weld metal into free to diffuse hydrogen and non-free to diffuse hydrogen
- Weld metal cools; solubility of hydrogen reduces
- Weld solidifies; some diffusible hydrogen remains
  - Continues to diffuse
  - Accumulates in the microstructure lattice / hydrogen traps
- Residual stress from cooled weld metal pulls at **hydrogen** traps - cracks may grow under strain from residual **stress** depending on the amount of residual stress and the strength of the **microstructure**
- If cracks do form, still more hydrogen accumulates in the cracks, growing them

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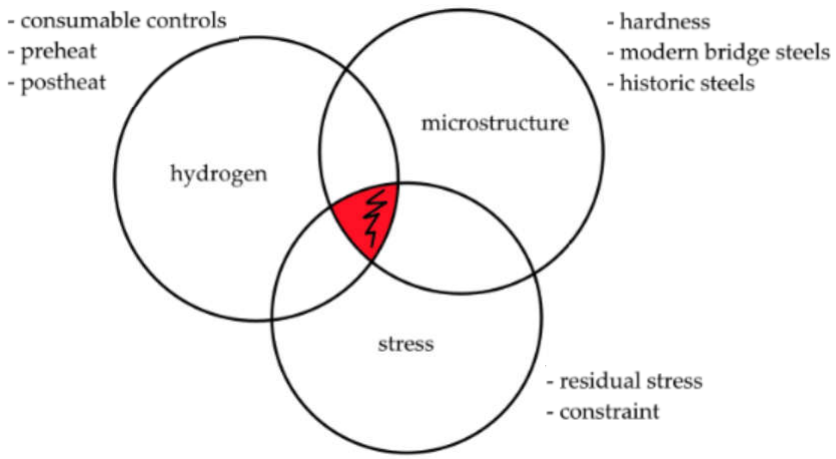
# Hydrogen-Assisted Cracking

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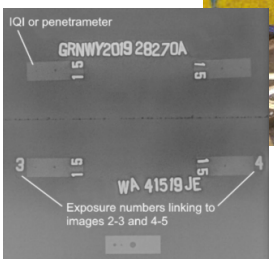
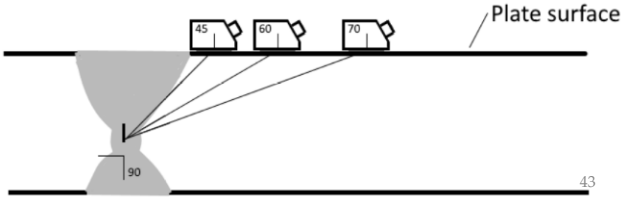
# Non-Destructive Evaluation




Radiographic Testing (RT)

Magnetic particle testing (MT)

Ultrasonic Testing (UT)

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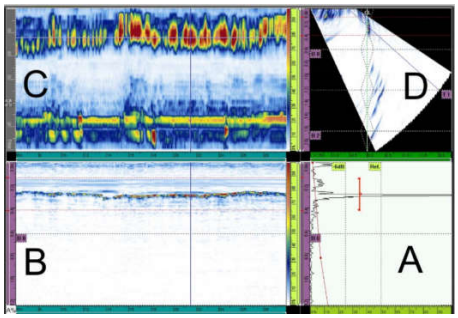
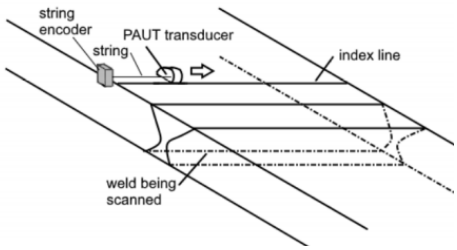
# Phased Array UT (PAUT)

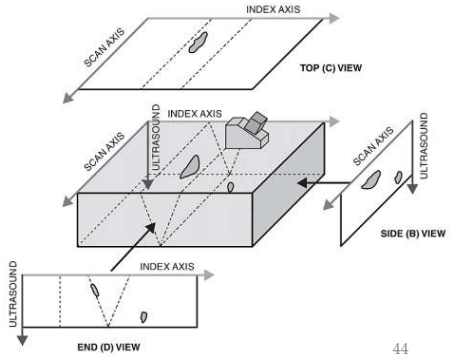




Source: FHWA

Figure 106. Illustration. Elevation of scanned weld.

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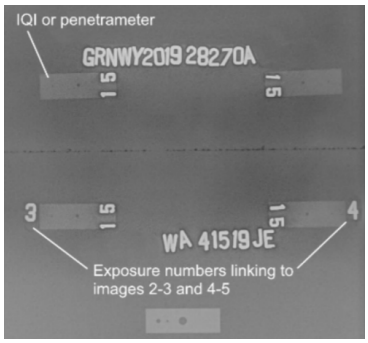
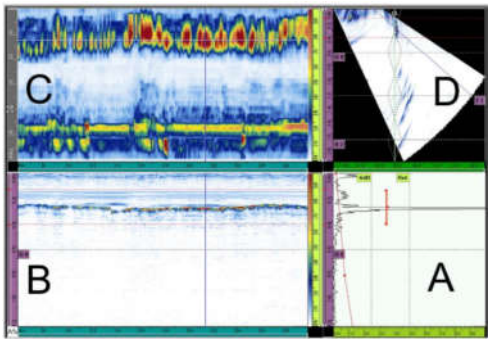
# PAUT v RT




- PAUT superiority
  - Better detection of planar discontinuities
  - Documented full volumetric view
    - RT: cannot tell depth of discontinuity
  - Joint flexibility (not just butt splices)
  - Improved productivity – result availability, equipment portability, safety (and standoff impact)

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# Differences between D1.1 and D1.5

- Qualification
  - Under D1.1, most welding procedures are prequalified
- Mandated NDE

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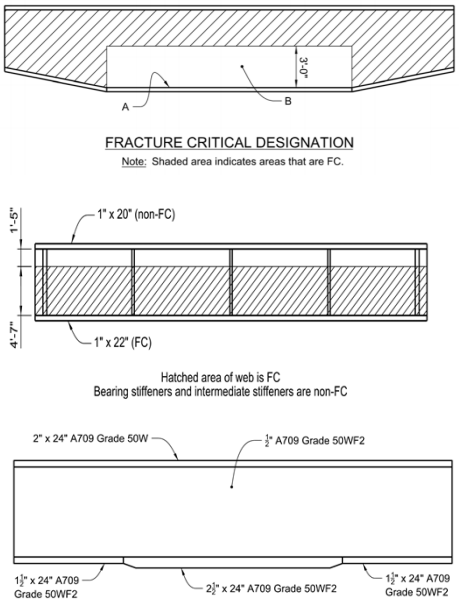
# Fracture Critical Welding

FC History
- •Point Pleasant Bridge
- •Catastrophic failures due to welds

Proper use / abuse of FC
- •Not pedestrian bridges (unless special circumstances)
- •Not compression members

FC material designations
- •Use grade and zone
  - ASTM A709 grade 50W, zone 2
  - ASMT A709 grade 50WF2
- •Do not designate by calling out
  - CVN requirements, i.e. "25 ft. lbs. at 40 degrees"
  - Service temperature, i.e, "Service temperature 0 to -30"

Detailing
- •Use sketches showing limits
- •Address attachments
- •Do not designate welds




# Differences between D1.1 and D1.5

- Qualification
  - Under D1.1, most welding procedures are prequalified
- Mandated NDE
- Special requirements for FC welding
  - Increased preheats
  - PQR expiry
  - Increased NDE

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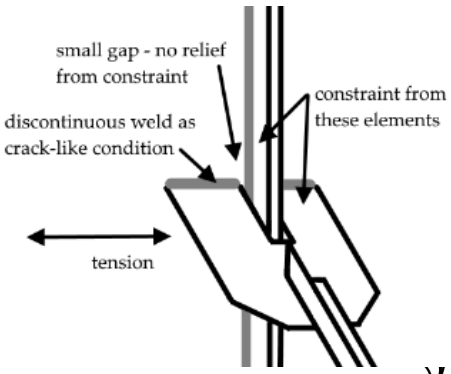
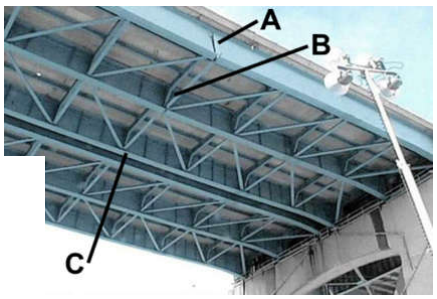
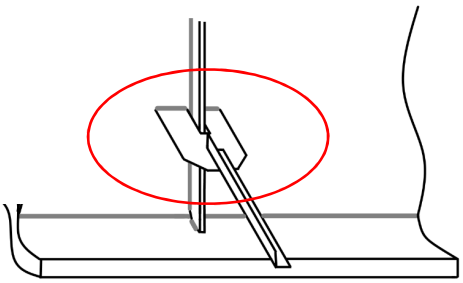
# Intersecting Welds

- Synergy with upcoming FHWA publication
- Original guidance based on Hoan bridge misconstrued



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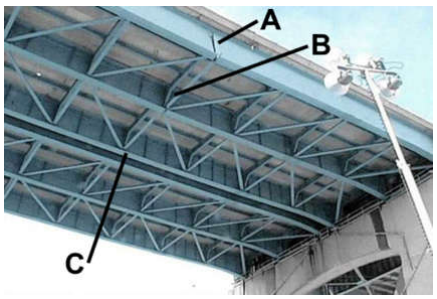
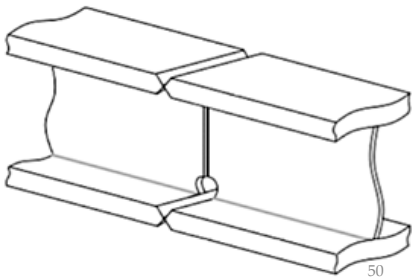
# Intersecting Welds

- Synergy with upcoming FHWA publication
- Original guidance based on Hoan bridge misconstrued
- Intersections in fabrication
- Component splicing – do avoid intersections at CJP corners
- As a general role, touching welds are not a problem



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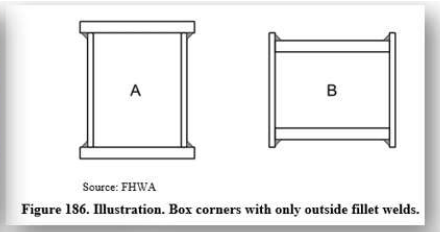
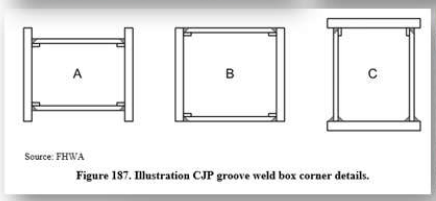
# Constructability – Box Details



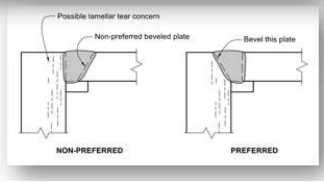

Source: FHWA

**Figure 186. Illustration. Box corners with only outside fillet welds.**




Source: FHWA

**Figure 187. Illustration CJP groove weld box corner details.**

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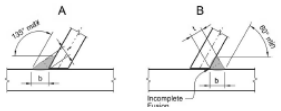
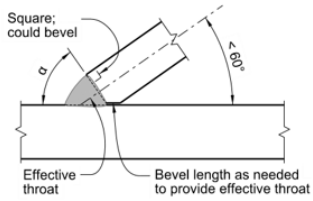
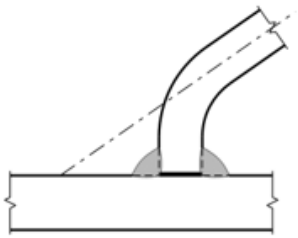
# Constructability – Skewed Joints

- Maximum fillet weld 60 degrees
- Then go to PJP or bent plate



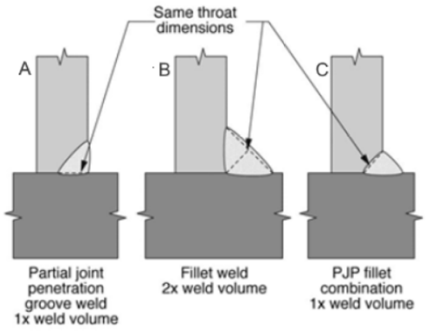



# Constructability

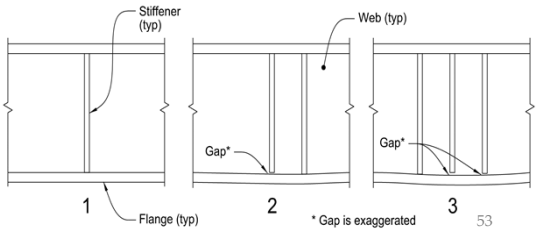
Weld types

- CJPs v PJPs v fillet welds
- Target single pass fillet welds
- Consider PJPs and PJP/fillet combinations




Bearing stiffeners

- Avoid multiples
- Use as connection plates
- Avoid CJPs – use finish to bear or finish-to-bear with fillet weld

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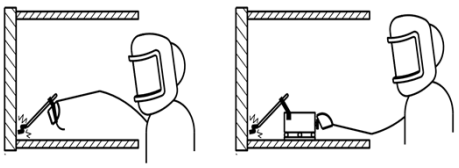
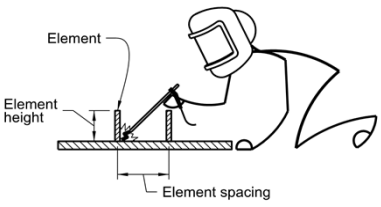
# Constructability - Access

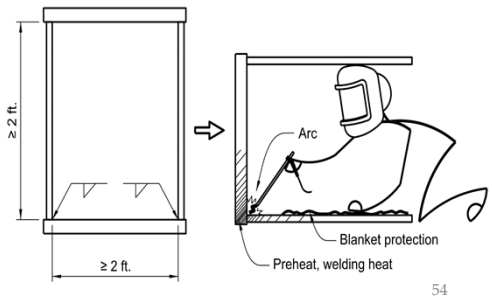
≤ 2′






Height + 3″

≥ 2′

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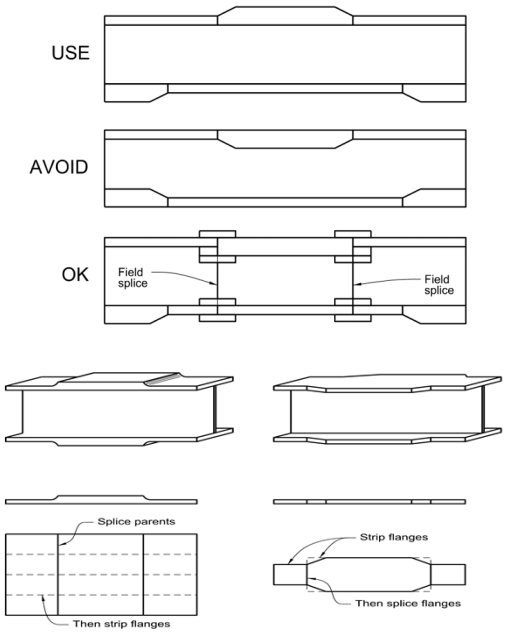


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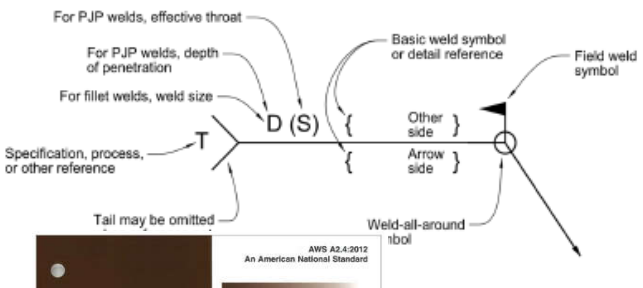
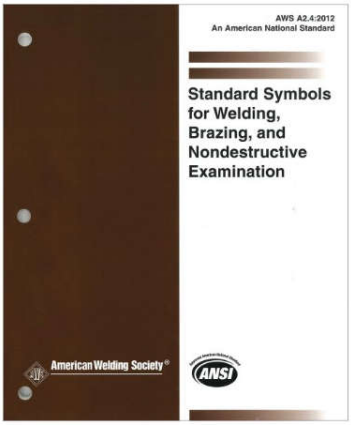
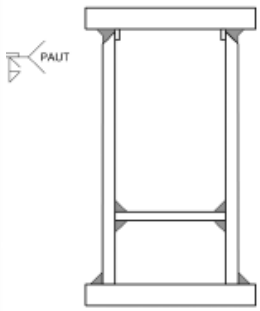
## Symbols

- Follow AWS A2.4
- Not crucial that symbol fully conforms with A2.4
  - Don't be afraid to use a sketch – just be sure the intent is clear

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# Other Topics

- Field Welding
  - New construction
  - Existing structures
- Other materials
  - Aluminum
  - Stainless Steel
- Reinforcing steel welding
- Welding coated members


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# Differences between D1.1 and D1.5

- Qualification
  - Under D1.1, most welding procedures are prequalified
- Mandated NDE
- Special requirements for FC welding
  - Increased preheats
  - PQR expiry
  - Increased NDE
- Far greater range of structural materials in D1.1
- Tubular material and joints

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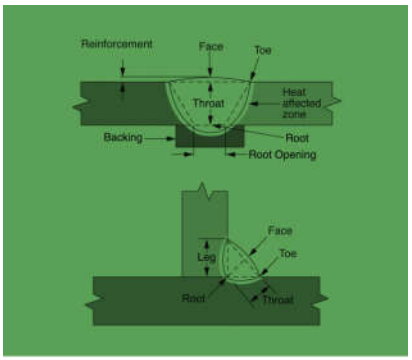
# Resources




Design Guide 21
Welded Connections—A Primer for Engineers
Second Edition

Smarter. Stronger. Steel.

**CHAPTER 12 - RESOURCES**

The documents listed in this chapter are useful references for engineers and others seeking information about welding and weld design.

**12.1. AASHTO DOCUMENTS**

***LRFD Bridge Design Specifications***
These specifications are required by the FHWA for the design, evaluation, and rehabilitation of highway bridges. Chapter 6 covers steel bridge design, including provisions for welded details (AASHTO, 2017a).

***LRFD Bridge Construction Specifications***
These specifications are not adopted directly by many states but are used as a reference for many state standard specifications. They represent a conservative consensus among all states. Chapter 11 addresses steel fabrication and erection, and refers to AASHTO/AWS D1.5 (AASHTO/AWS, 2015) for welding. As of this writing, AASHTO is in the process of creating a standalone steel fabrication specification that will supersede the steel bridge fabrication portions of chapter 11 (AASHTO, 2017). The *LRFD Bridge Construction Specifications* are discussed in section 1.4.3 of this manual.

***LRFD Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals***
These specifications address design, fabrication, and erection of highway signs, luminaires, and traffic supports (AASHTO, 2015).

***LRFD Guide Specifications for the Design of Pedestrian Bridges***
These guide specifications govern the design and construction of common pedestrian bridge types (AASHTO, 2009).

**12.2. AWS DOCUMENTS**

**12.2.1. AWS D1 Documents**

The AWS D1 documents are introduced in section 1.4.1. All include some weld-related design provisions, inspection and acceptance requirements, workmanship requirements and tolerances, and requirements for qualification of procedures and personnel.

**AASHTO/AWS D1.5, *Bridge Welding Code***
This code, which is the main focus of this manual, is specified by almost every bridge-owning agency in the United States and used in some other countries as well. It is a joint publication of AASHTO and AWS. The commentary is helpful for understanding the background and intention of many of the code's provisions. Many of its details are discussed throughout this manual. Designers should be particularly aware of the design provisions of clause 2 and the fabrication

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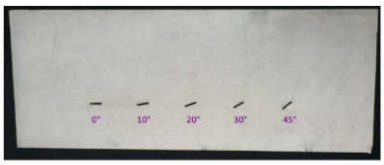
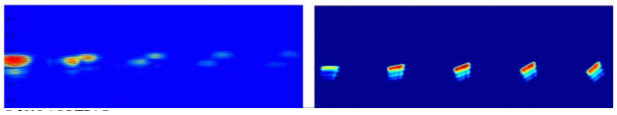
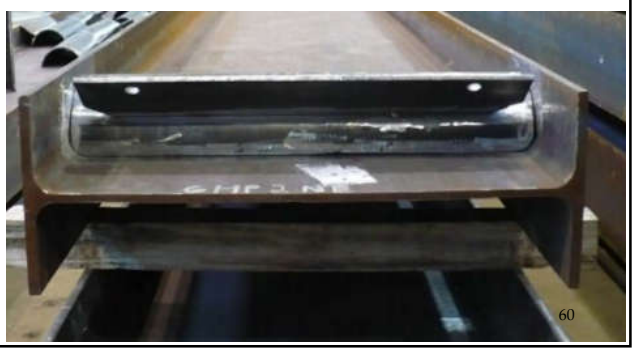
# Topics on the Horizon



- Full matrix capture, total focus method (FMC TFM) PAUT
- Pipe stiffener



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## Topics on the Horizon

- 50CR
- Tubular structures
- Welding coated surfaces
- Homopolar welding
- HLAW
- Multi-wire GMAW
- QST grades
- Castings

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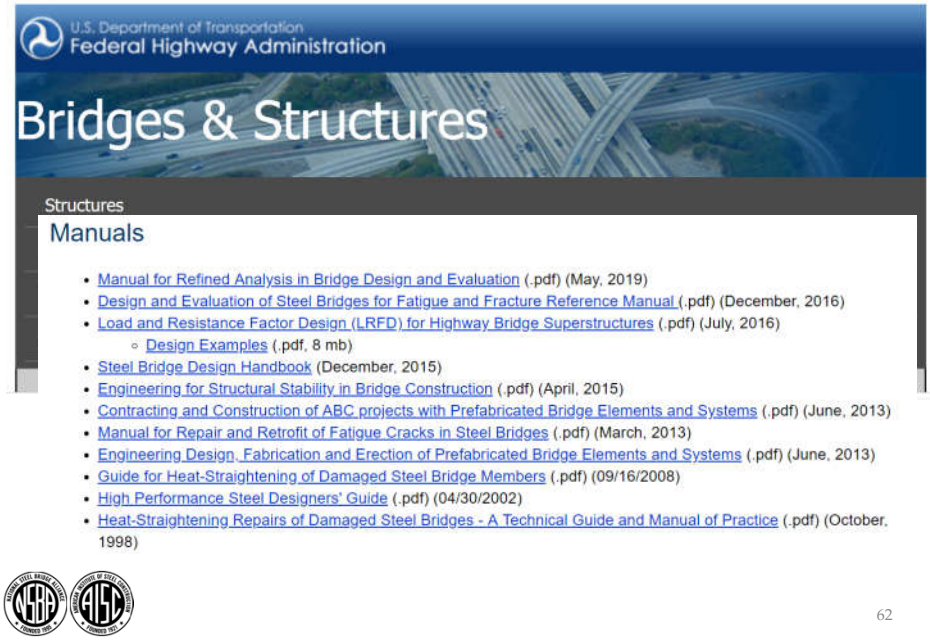
## Find the Manual Online

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# Summary

- The Manual
  - Is published and available for free
  - Is published as online .pdf only
  - Complements (and explains) D1.5
  - Emphasizes weld quality, knowledge, and constructability
- Remember
  - Consider specifying AWS D1.1 when AASHTO/AWS D1.5 is not appropriate
  - Expedite review, approval, and return of WPSs
  - Consider use of PAUT in lieu of RT
  - Clearly identify FC zones and attachments but do not call out FC welds
  - Do not be afraid of "touching welds"
  - Consider use of field welding to facilitate new construction as well as retrofits
  - Follow manual constructability recommendations and check with local fabricators for their preferences
- Feedback welcome

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**AISC** | Questions?

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## CEU / PDH Certificates

- You will receive an email on how to report attendance from: registration@aisc.org.
- Be on the lookout: Check your spam filter! Check your junk folder!
- Completely fill out online form. Don't forget to check the boxes next to each attendee's name!

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- Reporting site (URL will be provided in the forthcoming email).
- Username: Same as AISC website username.
- Password: Same as AISC website password.

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**AISC** | Thank you.

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