U.S. Department of Transportation
Federal Highway Administration

Memorandum

Subject: **<u>ACTION</u>:** Recommendations to Account for Acoustic Dissimilarities in Steel Ultrasonic Weld Inspection.

Date: December 13, 2024

From: Joseph L. Hartmann, Ph.D., P.E.
Director, Office of Bridges and Structures

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In Reply Refer To:
HIBS-10

To: Division Administrators
Directors of Field Services
Federal Lands Highway Division Directors

The purpose of this memorandum is to recommend additional ultrasonic inspection procedures when using the AASHTO/AWS D1.5M/D1.5 *Bridge Welding Code*[1] to achieve credible ultrasonic weld inspection in accordance with incorporated design standards.

BACKGROUND

The AASHTO/AWS D1.5M/D1.5 *Bridge Welding Code* requires ultrasonic testing (UT) of certain types of complete joint penetration groove welds[2] as part of fabrication quality control and acceptance. The *Bridge Welding Code* further requires that the reference blocks used to calibrate UT equipment be "acoustically equivalent"[3] to the steel used in fabrication. Research published by the National Cooperative Highway Research Program (NCHRP)[4] found that the term "acoustically equivalent" was not defined, nor was the requirement regularly enforced, and observed two issues that could arise in the presence of acoustic dissimilarities between the test object (i.e. the welded steel member) and the reference block, and between the rolled direction and transverse-to-rolled direction in plates produced through certain rolling processes. The NCHRP research found:

1) Differences in shear wave velocity between the reference standard on which transducers were calibrated and the test object ultimately being inspected could have two concerning effects:
   - The real sound path in the test object will deviate from the angle indicated by the transducer wedge, which could lead to defect mislocation, and
   - At higher inspection angles (e.g., 70 degrees) the real sound path in the test object can approach the point of mode convergence, greatly reducing the amplitude of the shear wave or causing its disappearance altogether into a surface wave. This reduces the energy reflecting off defects, which can lead to incorrect defect evaluation thus rendering the inspection ineffective. Furthermore, the inspector has no indication this is happening and believes the weld is defect free.

[1] 23 CFR 625.4(d)(2)(iii), AASHTO/AWS D1.5M/D1.5 (2016) *Bridge Welding Code.*
[2] 23 CFR 625.4(d)(2)(iii), AASHTO/AWS D1.5M/D1.5 (2016) *Bridge Welding Code*, Clauses 6.7.1 and 12.16.2.
[3] 23 CFR 625.4(d)(2)(iii), AASHTO/AWS D1.5M/D1.5 (2016) *Bridge Welding Code,* Footnote 3 of Figure 6.5A.
[4] Connor, R.J., Schroeder, C.J., Crowley, B.M., Washer, G.A., and Fish, P.E. (2019). *Acceptance Criteria of Complete Joint Penetration Steel Bridge Welds Evaluated Using Enhanced Ultrasonic Methods*. National Cooperative Research Program Report 908. Transportation Research Board. Washington D.C.

2) Steel plates produced via the thermo-mechanical control process (TMCP)[5] had notable differences in shear wave velocity between the rolled direction and transverse-to-rolled directions of the steel, which is referred to as acoustic anisotropy. There are two concerns for UT in the presence of acoustic anisotropy:
   - Scan plans do not explicitly consider how much the shear wave velocity in the direction of inspection deviates from the reference block.
   - The *Bridge Welding Code* requires UT inspection to follow defined movements relative to the weld[6], which includes rotating the probe ±10 degrees from normal to the weld or 15 degrees off parallel to the weld[7]. In the presence of acoustic anisotropy, these variations in transducer angle relative to the direction of roll direct sound paths in different directions at different velocities, effectively splitting the sound beam. This results in sound loss which can lead to less reflection off internal discontinuities, and unconservative ratings of defects.

The results and conclusions of the NCHRP Report 908 were further validated by another study published in 2024[8] which used a different subset of steel specimens.

The American Welding Society (AWS) D1J Subcommittee on Bridge Welding, the body that develops changes to the *Bridge Welding Code* in cooperation with AASHTO, has yet to adopt code changes to address the concern of shear wave velocity differences between reference standards and test objects and their effects on inspection procedures. Additional research is needed to characterize the complex behavior of shear waves in acoustically anisotropic steels to ensure codified acceptance criteria account for this behavior. It is unclear the next time the code will be updated.

While NCHRP Report 908 found that these concerns are only applicable to a subset of steel grades and production methods, shear wave velocity is not an item reported (or at least not required) on mill test reports and a UT operator may not know that they are working with a test object that exhibits shear wave velocity differential or acoustic anisotropy. As a result, there is increased uncertainty in the validity of weld acceptance testing carried out on all bridge steels and a significant risk of bridges going into service with undetected weld flaws.

Recent closures of the Hernando De Soto Bridge in 2021, the Jennings Randolph Bridge in 2023, and Blue Mesa Bridge in 2024 highlight the importance of credible weld acceptance inspection to bridge safety. All of these bridges were closed to protect public safety during the repair of weld defects that were likely present when these bridges were fabricated (prior to the bridge welding standards currently in effect) and went undetected in subsequent arm's length nonredundant steel tension member inspections. The effects of shear wave velocity differential and acoustic anisotropy, and their effects on the credibility of modern weld acceptance inspection, is a similarly urgent bridge safety issue due to the likelihood that these effects can result in welds with unrepaired defects being put into service.

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[5] NCHRP research found the effect was most prominent in TMCP steels, but also in other non-TMCP steels. The research found the effect was not present in quenched and tempered (Q&T) processed steels.

[6] 23 CFR 625.4(d)(2)(iii), AASHTO/AWS D1.5M/D1.5 (2016) *Bridge Welding Code*, Movement A in Figure 6.7.

[7] 23 CFR 625.4(d)(2)(iii), AASHTO/AWS D1.5M/D1.5 (2016) *Bridge Welding Code*, Pattern E in Figure 6.7.

[8] Washer, G., Agbede, J., Yadav, K., Connor, R. and Turnbull, R. (2024) "Acoustic Wave Velocities in Bridge Steels and the Effects on Ultrasonic Testing." *Journal of Nondestructive Evaluation.* Vol. 43, Issue 115. https://doi.org/10.1007/s10921-024-01109-1.

RECOMMENDATION

Bridge owners should develop supplementary contract provisions to work within the authority of the *Bridge Welding Code* when performing ultrasonic inspections to ensure that proper calibrations are being performed, that procedures can properly account for acoustic dissimilarities between the reference standard and test object, and that acoustic anisotropy effects are properly considered in materials acceptance. Specifically, Clause 6.13.2[9] of the *Bridge Welding Code* allows for test procedure variations stating:

> "*Variations in test procedure, equipment, and acceptance standards not included in Part C of Clause 6 may be used upon agreement with the Engineer. Such variations include other thicknesses, weld geometries, transducer sizes, frequencies, couplant, coated surfaces, testing techniques, etc. Such approved variations shall be recorded in the contract records.*"

Appendix A provides suggested contract special provision language that includes supplemental procedures for determining the shear wave velocity in steels, calculating shear wave velocity and anisotropic ratios, and applying limitations on shear wave velocity and acoustic anisotropy ratios. The provisions in the Appendix are based on language developed by FHWA that was informed by ongoing work by the AWS D1J subcommittee, but is not intended to reflect approval or indicate any potential adoption by the AWS D1J subcommittee. The FHWA has individually briefed State DOTs represented on the AASHTO Steel and Metals Technical Committee on the purpose of this memorandum and Appendix A and used the feedback received during those briefings to inform its content.

Questions on the contents and recommendations in this memorandum can be directed to Derek Soden at (202) 493-0341 or e-mail at Derek.Soden@dot.gov, or to Justin Ocel at (202) 281-8213 or e-mail at Justin.Ocel@dot.gov.

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[9] 23 CFR 625.4(d)(2)(iii), AASHTO/AWS D1.5M/D1.5 (2016) *Bridge Welding Code*, Clause 6.13.2.

Appendix A

Recommended contract special provisions for use when performing work in accordance with the AASHTO/AWS D1.5M/D1.5 *Bridge Welding Code*[10,11]. FHWA makes no representation concerning the legal sufficiency of these special provisions. Bridge owners should consult with legal counsel to ensure compliance and consistency with applicable legal requirements.

Recommended Special Provision	Commentary on Recommended Special Provision
A. Shear Wave Velocity Checks. Three shear wave velocities shall be measured with a normal incident shear wave transducer (described in A.2) per the method in A.1. The three measurements are: 1. The reference standard in the direction of wave propagation, 2. The test object in the direction of wave propagation, and, 3. The test object transverse to the direction of wave propagation. From these three measurements, calculate the velocity ratio (A.1.1) and anisotropic ratio (A.1.2).	**Commentary A.** The velocity in the reference standard need only be checked once, though it could be checked at other representative temperatures that it will be used. All test object steels should be checked for shear wave velocity in the direction of and transverse to wave propagation, as opposed to just TMCP and control-rolled steels, because ASTM requirements for capturing processing methods on the mill certifications are not well defined. The two velocities in the test object may not need to be checked if velocities have been provided by a third party, such as the producing steel mill. If the mill provided the measurements, it would likely be provided in the direction of roll and transverse to roll. The Contractor would have to ensure which of those two measurements coincided with the direction of wave propagation in the test object, if they do not align, then the shear wave velocity will have to be measured.
A.1 Velocity Measurement. The steps for measuring velocity shall be as follows: (1) Using caliper or a micrometer, measure the actual thickness of the base metal. Use this actual thickness for the velocity calibration. (2) Using high-viscosity couplant, couple the normal incident shear wave probe to the same	**Commentary A.1.** Ultrasonic thickness gauges cannot be used to assess the sound path length. ASTM E1961 Annex A1 can be used to provide tolerances for the measurements. It specifies that physical plate thickness measurements should be measured to a

[10] 23 CFR 625.4(d)(2)(iii), AASHTO/AWS D1.5M/D1.5 (2016) *Bridge Welding Code.*

[11] Pursuant to 23 CFR 625.3(f)(2), the use of AASHTO/AWS D1.5M/D1.5 (2020) *Bridge Welding Code* is approved for use, although its use is not required (see memorandum dated April 11, 2022 at https://www.fhwa.dot.gov/bridge/structures/04112022.pdf). Clause, figure, and table references within the recommended special provisions cited from the *Bridge Welding Code* will change if using the 2020 edition.

location where the thickness measurement was taken. Manipulate the probe's direction of shear wave propagation to the direction of sound propagation in the test object. (3) Perform a velocity measurement using the time-of-flight between the first and third back-wall reflections to determine the velocity in the test direction.	tolerance of ±0.004 inches and that total time of flight should be measured to a tolerance of ±25 nanoseconds. ASTM E1961 relies on measuring time of one round trip reflection, whereas this clause is recommending measuring the time for two round trip reflections, thus the time measurement tolerance can be expanded. When using a normal incident shear wave transducer with high-viscosity couplant, the signal will take longer to normalize than with other liquid or gel couplants. Taking a time measurement too quickly will result in velocity errors. Measuring the time of flight between the first and third backwall reflections helps mitigate coupling and measurement error effects. Using the "Auto-cal" function on modern instrument is an acceptable means of performing this velocity measurement.
A.1.1 Shear Wave Velocity Ratio. Calculate the ratio between the shear wave velocity of the test object in the direction of sound travel and the shear wave velocity of the reference standard as a percentage using the following equation: $shear\ wave\ velocity\ ratio\ (\%) = \left\lvert \frac{v_2}{v_1} - 1 \right\rvert * 100$ v_1 = acoustic shear wave velocity in direction of sound propagation of reference standard v_2 = acoustic shear wave velocity in direction of sound propagation of test object	**Commentary A.1.1.** The shear wave velocity must be compared "in the direction of sound propagation" which is generally normal to the weld based on typical scanning patterns A, B, and C in *Bridge Welding Code* Figure 6.7, as these detect discontinuities that are likely of most consequence to the bridge function. While transverse scans (patterns D and E in *Bridge Welding Code* Figure 6.7) must also be performed, checking the shear wave velocity of the weld metal is not required, and because these scans are in-line with the weld, the error of beam angle from shear wave velocity differences is of lesser consequence. The shear wave velocity ratio should be rounded to the nearest 0.1 percent, in accordance with the rounding method of ASTM Practice E29 *Using Significant Digits in Test Data to Determine Conformance with Specifications*.
A.1.2 Anisotropic Ratio. Calculate the anisotropic ratio as a percentage using the following equation:	**Commentary A.1.2.** The anisotropic ratio should be rounded to the nearest 0.1 percent, in accordance with the rounding method of ASTM Practice E29

$$Anisotropic\ Ratio\ (\%) = \left\lvert \frac{v_2}{v_{transverse}} - 1 \right\rvert * 100$$ $v_{trtansverse}$ = acoustic shear wave velocity transverse to direction of sound propagation in test object	*Using Significant Digits in Test Data to Determine Conformance with Specifications.*
A.2 Normal Incidence Shear Wave Transducers (0-Degree Transverse). Use normal incidence shear wave transducers that are round contact transducers 13 mm [1/2 in] in diameter. The transducer frequency shall be 5 MHz. Use a high-viscosity shear wave couplant with these transducers. Prior to initial use or when undiscernible, mark the transducer to clearly indicate the direction of shear wave propagation using the procedure in A.2.1.	**Commentary A.2.** Normal incidence shear wave transducers are contact transducers that vibrate directly in the transverse mode and are able to introduce a shear wave directly into the tested material without relying on refraction and mode convergence of a longitudinal wave. Thus, these transducers are useful for measuring the shear wave velocity of a material. Transducers should be driven by a voltage recommended by the manufacturer. Applying too much high voltage for long periods of time can lead to re-poling, converting the transducer into longitudinal mode transducer. High-viscosity shear wave couplant is used to transfer the shear wave into the test piece because low and medium viscosity liquids, such as standard liquid or gel ultrasonic couplants, do not support shear stresses and will not transfer shear waves to the test piece. The couplant must be a non-Newtonian fluid meant for shear waves. Honey is a known suitable couplant. Any couplant which provides signal transmission (as evidenced by the fact that UT equipment shows a signal) is also considered suitable.
A.2.1 Direction of Shear Wave Propagation. Verify the normal incidence shear wave transducer's direction of shear wave polarization using the following steps: (1) Connect the normal incidence shear wave transducer to the "transmit" port of the UT instrument. (2) Connect a 60° or 45° shear wave angle beam search unit to the "receiving" port of the UT instrument.	**Commentary A.2.1.** The direction of shear wave polarization for normal incidence shear wave transducers is provided by the transducer manufacturer. However, it is possible for this to be incorrect, and therefore this verification is necessary.

(3) Configure the UT instrument for pitch-catch through the settings menu.

(4) Couple the normal incidence shear wave transducer to a defect free portion of base material using a high-viscosity couplant.

(5) Encircle the normal incidence shear wave transducer with the shear wave angle beam search unit directed at the normal incidence shear wave transducer until a signal is received. Where the signal peaks with the shear wave angle beam transducer is the direction of polarization of the normal incidence shear wave transducer.

(6) Mark the normal incidence shear wave transducer to clearly indicate the direction of shear wave propagation.

The frequency of this verification shall be at the discretion of the UT Level III.

B. UT Adjustments.

If the shear wave velocity ratio calculated in accordance with A.1.1 is greater than 1.0 percent, but less than or equal to 2.5 percent, restrict test angles specified by *Bridge Welding Code* Table 6.2 to no more than 60°.

Do not use reference standards for which the shear wave velocity ratio, calculated in accordance with A.1.1, exceeds 2.5 percent.

Where testing angles are limited to 60° in material less than or equal to 1-1/2 in., classify flaws using Tables 6.3 and 6.4 of *Bridge Welding Code* supplemented with the following columns.

Table B1
Supplemental UT Acceptance-Rejection Criteria—
Tensile Stress

Flaw Severity Class	Weld Thickness[a] (mm [in]) and Search Unit Angle	
	8 [5/16] through 20 [3/4]	>20 [3/4] through 38 [1-1/2]
	60°	60°
Class A	+13 and lower	+11 and lower
Class B	+14	+12
Class C	+15	+13
Class D	+16 and up	+14 and up

Commentary B.

The UT method in the *Bridge Welding Code* assumes that the shear wave velocity of the reference standard and the shear wave velocity of test object are appreciably the same, thus making the reference standard suitable for calibration. This is represented by the “acoustically equivalent” statement in Note 3 of *Bridge Welding Code* Figure 6.5A. However, research (NCHRP Report 908) discovered that some bridge steels have shear wave velocities that are appreciably different from the reference standard. This special provision represents a more defined definition of acoustically equivalency.

These limits were recommended by researchers in NCHRP Report 908. The 1.0 percent limit was established by ensuring the beam angle will not deviate more than the angle tolerance specified in Clause 6.15.7.3 for a 70° search angle. The 2.5 percent limit is roughly when the angle tolerance of 6.15.7.3 cannot be met with a 60° search angle, thus search angles are restricted to 60° (i.e. 70° search angles are prohibited) when the shear wave velocity ratio is between 1.0 percent and 2.5 percent inclusive.

If the 2.5 percent ratio limit is exceeded, the Contractor must find, or fabricate, a different

Table B2
Supplemental UT Acceptance-Rejection Criteria—Compressive Stress

Flaw Severity Class	Weld Thickness[a] (mm [in]) and Search Unit Angle	
	8 [5/16] through 20 [3/4]	>20 [3/4] through 38 [1-1/2]
	60°	60°
Class A	+8 and lower	+5 and lower
Class B	+9	+6
Class C	+10	+7
Class D	+11 and up	+8 and up

reference standard. Ideally, the different reference standard would have a shear wave velocity ratio less than 1.0 percent, though one with a ratio between 1.0 percent and 2.5 percent inclusive could be used with restricted angles.

This special provision also applies to approved use of phased array UT per Annex K, though angles are restricted between 40° and 60°. See NCHRP Report 908 Appendix G for mark-ups regarding how to address PAUT adjustments.

The *Bridge Welding Code* Tables 6.3 and 6.4 do not account for 60° test angles for thin material because of the Code's preference to use the 70° angle. However, due to the shear wave velocity issue, the 70° angle may have to be restricted and acceptance-rejection criteria is needed for 60° angles in thin material. The acceptance-rejection tables derive 60° criteria through a constant +3 dB adjustment from 70° values for 60°. The values shown in Tables B1 and B2 are meant to supplement *Bridge Welding Code* Tables 6.3 and 6.4, respectively, with the recommended additions.

C. Limit of Anisotropic Ratio.
Steel with an anisotropic ratio calculated in accordance with A.1.2 greater than 1.0 percent shall not be used in joints with CJP grove welds.

Commentary C.
Anisotropic ratios are limited to 1.0 percent to reduce any errors in defect ratings from beam splitting.

There is a possibility that plates on either side of the weld could fall into different percentage ranges. If this occurs, as a conservative approach, the highest percentage should be used to determine the required action.

To meet this special provision, the Contractor will have to order steel from the producing mill with a special shear wave velocity isotropy requirement or restrict steel in their inventory with an anisotropic ratio less than or equal to 1.0 percent for use in members fabricated with CJP welds. Owners will have to make a decision regarding how this

	restriction is extended. At a minimum, this restriction should be imposed upon members requiring fabrication to a fracture control plan, but it could be extended to all member types. The Engineer can also accept UT inspection procedures that have been proven to properly account for the beam splitting effects from acoustic anisotropy effects. NCHRP Report 908 recommended a +4 dB adjustment to the reference sensitivity to accommodate beam splitting effects.