Ultrasonic Testing of Structural Welds

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During the past five years Bethlehem Steel Corporation has developed and applied techniques for the ultrasonic testing of butt welds which provides an assurance of weld quality similar to that achieved with radiography. Although there are no revolutionary breakthroughs involved, a number of significant innovations permit a more repeatable weld test than has previously been achieved with ultrasonics. The Bureau of Public Roads has cooperated with Bethlehem Steel Corporation for several years in these developments. They have recently published a training text and have permitted the use of the method in a recent circular memorandum.

•THE ULTRASONIC testing of welds is a much discussed but little used inspection technique, which, in theory, offers significant advantages to both customer and fabricator. Bethlehem Steel Corporation has been using this inspection technique as a production tool for the last five years. Production work has provided the basis for a number of innovations in technique, equipment and inspection philosophy.

In general, this work has been limited to the inspection of full penetration butt welds in plate thicknesses from $^5/_{16}$ in. to 5 in.

Since the various innovations are interrelated in a complex manner, we shall arbitrarily discuss them in the order in the test in which they actually occur. Following this we will discuss auxiliary areas, namely calibration devices and defect location aids. For reference purposes the basic ultrasonic weld testing scheme is described in Figure 1.

Conventional pulse echo instrumentation is used. Pulse length controls are set at near maximum values. Transducers of 2.25-mc frequency either $^1/_2$ by 1 in. or $^1/_2$ in. square are generally used. Quartz has not been used as a transducer material. All of the common "ceramic" types are utilized.

A search unit wedge design of the type shown in Figure 1 was chosen for two reasons. First, this design permits extremely close approach to the weld bead reinforcement. Second, internal wedge reflections are minimized, permitting interpretation of near defects when testing at high sensitivity. Figure 2 compares internal reflection noise for various angle search unit designs with information on the relative closeness of approach to weld bead reinforcements.

All of the common couplants have been evaluated. Glycerine appears to be the best according to our production experience. Theoretical considerations reinforce this observation. The close acoustical match between lucite and glycerine minimizes spurious propagation caused by surface roughness. The overall efficiency of glycerine as a couplant minimizes transmission efficiency variations caused by surface roughness. It should be emphasized that surface roughness variations have a much greater effect on longitudinal beam testing than on shear wave testing for the same reasons of coupling efficiency. Therefore, angle beam tests of greater reliability can be conducted on rougher surfaces. These couplant effects are a result of transmission efficiencies (Table 1).

Having introduced the sound pulse into the plate adjacent to the weld, the next matter to be considered is the angle at which the sound is propagated through the plate and into

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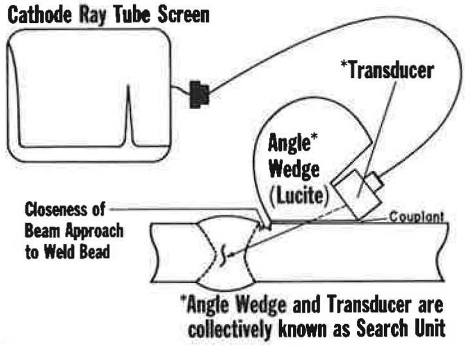

Figure 1. Basic ultrasonic weld testing scheme.

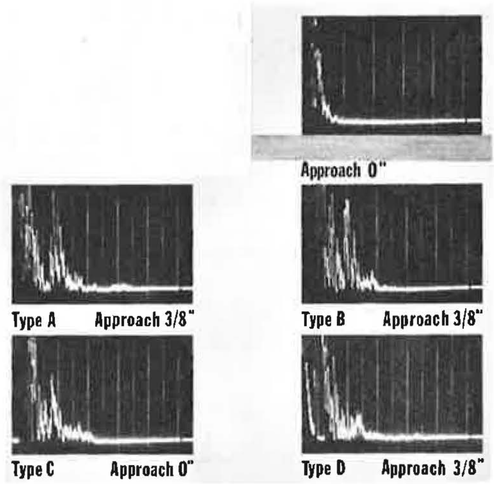

Figure 2. Wedge noise and weld bead approach.

the weld. It is believed that the flattest possible testing angle should be used. The basic reason for this choice is the fact that typical production defects tend to be perpendicular to the plate surface or are associated with weld preparation surfaces. The choice of flatter angles offers several other advantages. First, flatter angles result in more beam spread in the plate thickness. Second, flatter angles permit more of the weld volume to be inspected without resorting to bouncing the sound from the opposite plate surface. This is advantageous since bouncing causes definite errors in defect location (1).

The flattest angle we consider practical for weld inspection is 75 deg. Most tests are limited to 70 deg. Higher angles contain surface wave components which make interpretation difficult or impossible. The angles generally used for particular thicknesses are as follows:

Thickness (in.)	Angle (deg)
1/4 to 2	70
2 to 3	70 or 60
3 to 5	60 or 45
Over 5	45

Steeper angles are used in heavier material for two reasons. The long sound path needed for flatter angles introduces more attenuation into the test than can be easily compensated. Beam spread associated with flatter angles in heavy sections becomes a disadvantage, reducing defect detection reliability.

TABLE 1

	Transmissivity (single interface)	
	Lucite - glycerine	85.85%
	Lucite - water	63.05%
	Lucite - oil	53.87%
	Angle beam testing transmissivity	
(1)	Lucite glycerine steel	15.24%
(2)	Lucite water steel	7.10%
(3)	Lucite oil steel	4.91%
	Overall transmission variation with surface variation (a 2% variation from a 10% direct lucite steel coupling condition)	
(4)	Lucite glycerine steel (shear)	0.96%
(5)	Lucite water steel (shear)	3.65%
(6)	Lucite oil steel (shear)	5.39%
(7)	Quartz glycerine steel (longitudinal)	12.63%

The phenomenon of mode conversion is quite often discussed with regard to angle choice. Mode conversion is not related specifically to any testing angle but only to the angle of sound incidence upon a reflecting surface. The critical angle of incidence is 30 deg. Therefore, detection of vertical reflectors using a 60-deg angle is questionable. In practice, the only real precaution necessary when using 60 deg is the strict avoidance of plate edges or vertically drilled holes as calibration standards. Actually, 60 deg is a good testing angle because many weld preparations involve 30-deg surfaces, which, as a lack of fusion, are ideally de-

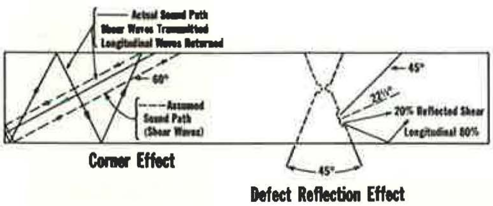

Figure 3. Mode conversion effects.

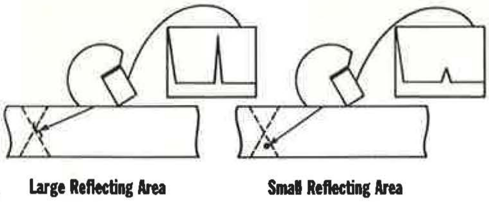

Figure 4. Signal amplitude is a measure of defect reflecting area.

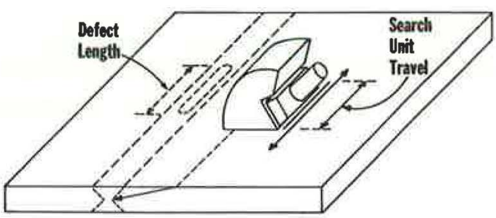

Figure 5. Search unit travel is a measure of defect length.

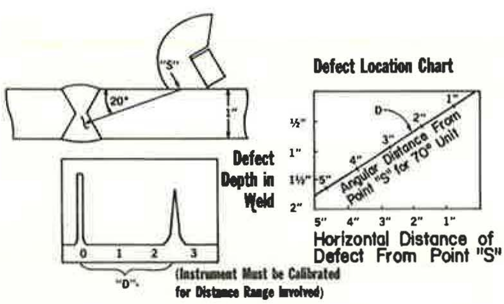

Figure 6. Defect location can be accurately done.

TABLE 2

Defect No.	Angle (deg)	Amplitude (db)	Plate Thickness (in.)	Defect Length (in.)
		(a) Defect Type Porosity		
53	70	7	⅜	3
	60	9		
56	70	7	2	½
	60	6		
	45	Not detected		
		(b) Defect Type Slag		
60	70	8	½	½
	60	10		
61	70	8	½	½
	60	10		
66	70	8	½	1
	60	11		
67	70	8	½	1¼
	60	7		
68	70	7	½	1
	60	8		
85	70	16	1¾	3
	45	10		
49	70	13	⅜	2
	60	15		
50	70	8	⅜	¼
	60	10		
51	70	12	⅜	¾
	60	14		
52	70	19	⅜	2
	60	17		
99	70	8	3	½
	60	13		
	45	Not detected		
100	70	11	3	½
	60	11		
	45	15		
101	70	13	3	½
	60	11		
	45	14		
103	70	8	3	½
	60	12		
	45	11		
105	70	13	3	1½
	60	18		
	45	8		
		(c) Defect Type Lack of Penetration		
54	70	31	1	5¼
	60	28		
58	70	19	2	12
	60	18		
	45	12		
		(d) Defect Type Cracking		
42	70	18	4½	1⅛
	45	26		
		(e) Defect Type Lack of Fusion		
57	70	19	2	1½
	60	24		
	45	18		
59	70	13	2	2
	60	15		
	45	15		
69	70	28	2	6
	60	16		
	45	26		
70	70	20	1½	4
	60	16		
	45	21		
102	70	21	3	2½
	60	20		
	45	21		
104	70	13	3	3½
	60	17		
	45	13		

tected with 60 deg. By the same token, 45 deg is a poor angle for the detection of lack of fusion for the same reasons. These effects are shown in Figure 3. Some data relating testing angle to defect detection reliability for actual defects are given in Table 2.

When the pulse has traveled to the defect, been reflected and returned through the transducer, it must be interpreted. There are six basic types of information which can

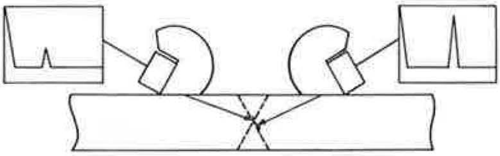

Figure 7. Testing from both sides of weld reveals defect orientation.

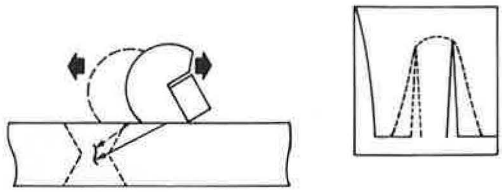

Figure 8. Travel to and from the weld reveals defect height.

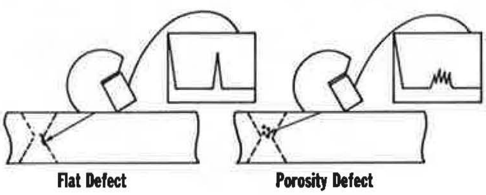

Figure 9. Pulse shape indicates nature of defect.

be extracted. Figures 4 through 9 depict these information types. We feel that the first three types of information are of primary importance in determining defect severity and pinpointing defect location for excavation. The other three types deal with parameters not easily quantified and should not be used as a basis for acceptance or rejection. However, these types of information are of great value to the welding engineer or supervisor who must intelligently correct defective welding conditions.

In order to establish a basis for amplitude rejection, it is necessary to develop data on a great many defects. It was found that conventional methods of test standardization and amplitude read out were not sufficiently accurate. Rather than attempt to judge the height of signals on the screen, an attenuator (or calibrated gain control) was used. The instrument is calibrated on an arbitrary nondirectional reference reflector such as the 1.5-mm hole in the IIW block. Defect amplitude is related to this reference by equating all signal heights to that of the reference using an attenuator. The difference (in db) is now amplitude information. CRT presentation, vertical linearity deviations, and visual error are largely eliminated.

Since CRT linearity limitations are eliminated, the clipping or reject control can now be used, not "to clean up the screen" but to decrease the vertical dynamic range presented on the CRT. This increases the accuracy of amplitude measurement using an attenuator still further.

Using this approach, a great many welding defects were measured, as shown in Figure 10. The attenuation within the material has been corrected by adding 2 db/in. after the first inch of sound travel to all readings. This value was obtained by making a great many readings on various steel thicknesses and reflector types. Figure 11 shows the

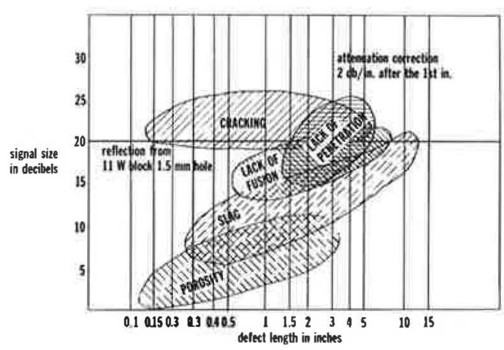

Figure 10. Weld tests at 70 deg: 120 defects—plate thickness $^5/_{16}$ in. to 5 in.

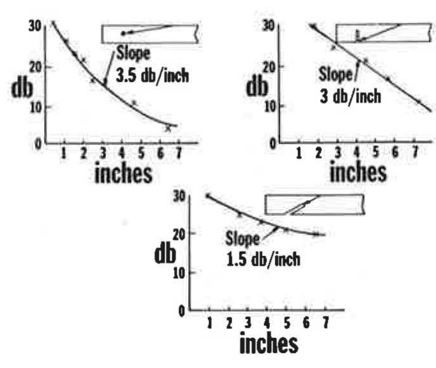

Figure 11. Results of some attenuation tests.

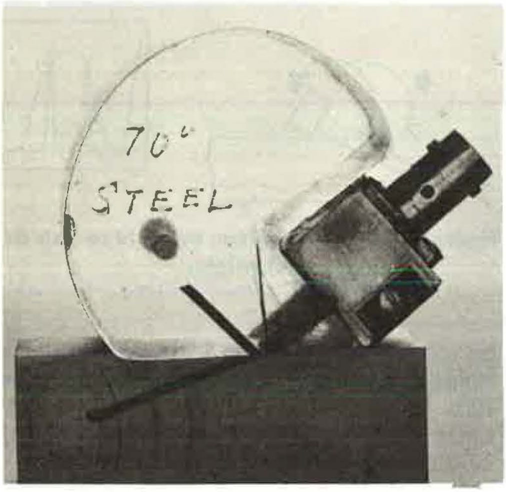

Figure 12. Sensitivity standard.

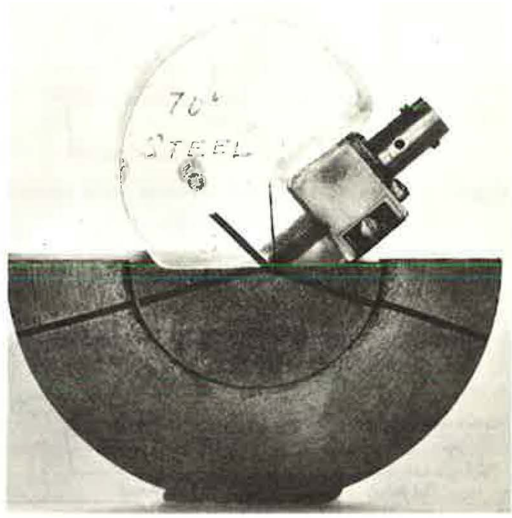

Figure 13. Distance calibration standard for angle beam testing.

results of some of these tests. Increased attenuation is noted close to the search unit for reflectors incorporating the cylindrical surfaces of drilled holes, as compared with flat-bottomed holes drilled at the testing angle. These geometrical effects apply only to cylindrical surfaces and care should be taken not to use such standards for attenuation measurements. In all cases, the attenuation is the slope of the curve.

As was previously stated, the IIW block 1.5-mm hole has been used as a sensitivity standard. Since different angles and resulting different path lengths introduce the geometrical effects, a simple standard, in which the distance to the reflector is 1 in. for 70 deg, 60 deg and 45 deg, has been developed (Fig. 12).

Defect length is measured conventionally based on the point at which a 5-db drop in signal is encountered.

Defect location in cross section is accomplished using conventional geometrical methods. IIW block distance calibration surfaces may be used. We have developed a simple calibration standard for distance which gives calibration pulses at even-inch increments. This standard is shown in Figure 13. We prefer to calibrate for actual sound path length. We feel that the weld inspector is thus made more aware of the geometrics with which he is working. Having thus calibrated, a chart such as Figure 14 can be used for defect location. To further simplify this procedure, we have developed a simple retractable tape (Fig. 15) for each angle

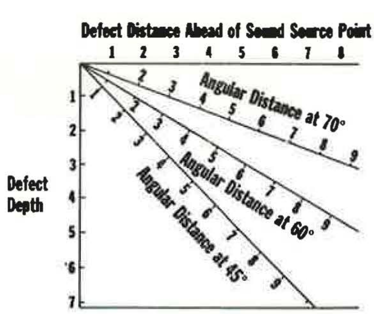

Figure 14. Defect location chart.

Figure 15. Retractable tape for defect location.

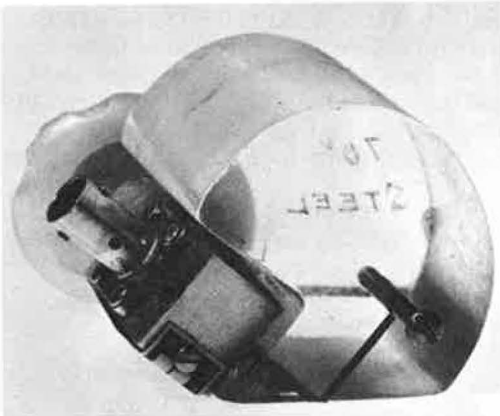

Figure 16. Internally calibrated search unit.

which becomes part of the search unit. The tape is pulled out to the equivalent path length. At this point the defect is directly under the tape end and the defect depth is read from a secondary scale opposite the observed path length dimension.

As mentioned earlier, it is necessary to correct for defect location errors when a bounce from the opposite plate surface is used. For angles greater than 45 deg, a small Δ value must be subtracted from the apparent horizontal dimension (sound emission point to defect). There is no correction at 45 deg. At 60 deg, the correction is about $\frac{1}{8}$ in.; at 70 deg, about $\frac{1}{4}$ in.

One of the pitfalls of ultrasonic weld testing is the fact that the test is not self-calibrating. There is no back reflection or other continual reminder of testing uniformity. Normal shop line voltages and battery-powered unit voltage variations near the end of battery life can cause gradual sensitivity changes which go unnoticed. We use constant voltage transformers and voltage drop alarms to protect us from these effects. In addition, we have developed an internally calibrated search unit (Fig. 16) which provides a continual simple check of amplitude and horizontal calibration stability. A hole is drilled in the wedge so that a small amount of sound reflected from the contact surface will be in turn reflected from the hole. This results in a small discrete signal on the screen which can be used to monitor testing uniformity. The reflector hole is threaded and a screw inserted. Moving the screw changes reflector characteristics slightly. The screw is used to compensate for slight wedge wear.

The nature of the data recorded in Figure 10 makes possible an ultrasonic weld inspection standard based on amplitude and length. Most present weld quality requirements can be interpreted in terms of amplitude and length using such information. The data clearly indicate the factors which lend to ultrasonic weld inspection reliability in detecting the more serious defect types. Radiography has forced on us the necessity of accurate defect identification since generally the most serious defects are most poorly detected. By its nature, ultrasonic testing reflects defect severity directly. Therefore defect identification becomes much less important:

Defect Type	Defect Severity	Radiographic Sensitivity	Ultrasonic Sensitivity
Crack	↑	↓	↑
Lack of fusion			
Lack of penetration			
Slag			
Porosity			

The most important part of the weld testing system is the inspector. Use of amplitude and length rejection criteria has removed from him the onus of defect decisions based purely on subjective observations. However, he must still have a detailed knowledge of ultrasonics and must be capable of working easily with complicated situations in three-dimensional geometry.

We give each of our weld inspectors a four- to five-week classroom course to this end. We have generally drawn on groups of radiographers qualified to 250-1500 or on experienced draftsmen for our personnel.

Our work in the area of ultrasonic weld testing over the past year has been in cooperation with the Bureau of Public Roads. We are developing a specification and a training manual for the inspection of bridge weldments. The publication and implementation of this work should expand the use of ultrasonics as a weld testing tool.

Generally, this work has been limited to full penetration butt welds in thicknesses from $^5/_{16}$ in. to 5 in. We have also applied it to full penetration T-welds in the same thickness range. It would be dangerous to attempt to apply the results of this work to other weld configurations or thicknesses. Partial penetration welds and backing strip welds can be thus inspected but spurious reflections caused by these configurations must be taken into account. We are extremely dubious as to the direct application of this information to fillet welds.

We hope that the result of our work will be greater use of ultrasonic weld testing. The use of amplitude and length rejection criteria will simplify interpretation. Eventually we may be able to treat particular areas in large welds more critically than others, depending upon the excellent defect location ability of ultrasonics to tell us whether or not defects are in more highly stressed weld areas.

REFERENCE

1. Niklas, L. In Materials Testing, Aug. 1965.