Crack Detection at Cover Plate Ends and Welded Splices Using Ultrasound Technology

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Many steel bridges constructed before 1970 are now of concern because they contain welded fabrication details that are highly susceptible to the formation of fatigue cracks. It is imperative that nondestructive evaluation methodology be available to examine such bridges, especially those with more than 25 years of service history and high volumes of truck traffic. Within Ohio a large number of bridges were fabricated with welded splices and cover plates located over the piers of continuous-beam bridges. Commonly accepted analytical models indicate that the average fatigue life has already been exceeded in some situations. Unfortunately, unaided visual inspection allows no opportunity for early crack detection because the critical top flange surface is embedded in the concrete deck. Research conducted on behalf of the Ohio Department of Transportation has demonstrated that ultrasonic testing procedures may be used to determine whether cracks have been initiated within a top flange surface that is embedded in concrete. Three Interstate highway bridges experiencing high volumes of truck traffic and containing AASHTO Category E′ cover plate details were examined during 1989. Application of the ultrasound technology is described and the results of this field investigation are presented.

Existing steel bridges designed with welded connection details and constructed before 1970 are a source of concern for their owners because frequently they must be considered highly susceptible to the formation of fatigue cracks when viewed in the light of current fatigue design standards and specifications. Figure 1 shows a field-welded detail used extensively in Ohio that consists of welded cover plates plus full-penetration, vertical-seam welds located over the piers of continuous-beam bridges. Commonly accepted analytical models indicate that the average fatigue life has already been exceeded in some situations. Unfortunately, unaided visual inspection allows no opportunity for early crack detection because the critical top flange surface is embedded in a concrete deck.

On the one hand, it is essential that any necessary corrective measures be undertaken to maintain an adequate level of safety. On the other, it would be inappropriate to embark on an extensive rehabilitation program based solely on the predictions of analytical models, which may indicate that the fatigue life of a particular detail has reached, or is nearing, exhaustion. Considering the wide statistical scatter in many of the key fatigue-life parameters and the influence of the volume of truck traffic, it could be many years (if ever) before sufficient damage has accumulated to cause distress, such as a fatigue crack, to actually occur. Nondestructive evaluation strategies may be employed to assist bridge owners in making difficult economic decisions consistent with requirements for safety.

The welded connection shown in Figure 1 was a standard splice detail in Ohio's expressway construction from the late 1950s to the mid-1960s, some of which detail was eventually incorporated into the Interstate system. Frequently, the stress range at the end of the top flange cover plate, calculated using the standard HS-20 design vehicle, is much higher than that allowed by the AASHTO specifications (*1*). Considering that the majority of cover plate terminations within this study are AASHTO Category E′ details and that one-way traffic volumes exceed 4,000 trucks per day, it is quite difficult to find any acceptable location within a tension zone for terminating the cover plates.

Confronted with a calculated stress range greater than that allowed, one may select from alternative, probability-based methods for computing the remaining life at the ends of these cover plates. Procedures recently proposed by Moses et al. (*2*) allow for considerable latitude in selecting the distribution factor, the weight of the fatigue-evaluation truck, the truck traffic volume, the degree of composite action, and other factors. Moses et al. indicate that computed "estimates of remaining life provide a useful indication of fatigue safety and facilitate reasonable cost-effective decisions regarding repair, rehabilitation, or replacement." Thus, because fatigue lives are probabilistic rather than deterministic, calculated values primarily provide a basis for priority ranking and planning. For maximum effectiveness, however, such calculations should be complemented with physical evidence gathered during an on-site examination before extensive rehabilitation or costly repairs are initiated.

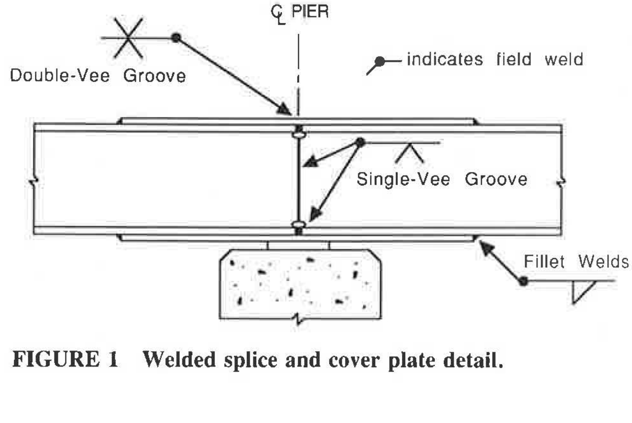

FIGURE 1 Welded splice and cover plate detail.

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The primary objective of the research reported here was to demonstrate that ultrasound technology may be effectively used to detect any cracks that may have initiated at the ends of welded cover plates or within butt-welded flange splices embedded in a concrete deck. A brief validation was conducted in the laboratory followed by an on-site examination of 20 cover-plated and weld-spliced beams selected from three different bridges (six, counting the structure for each traffic direction separately).

A brief description of the characteristics of ultrasound waves and their role in crack detection is provided below, followed by discussion of the work that was conducted in the laboratory and at the three bridges. Specific findings regarding the application of ultrasound technology to nondestructive bridge evaluation are reported.

ULTRASOUND

Sound is the mechanical vibration of particles in a medium, and it travels as an elastic wave. Particles of the medium do not travel with the wave but only react to its energy (*3*) and vibrate about a fixed point. Thus, it is the energy of the wave that moves through the material. For many applications, ultrasound waves are generated by crystalline materials, which exhibit a piezoelectric effect in which the application of an alternating voltage through the thickness of a "crystal" causes it to expand and contract. Thus, a sound wave may be created and transmitted from one medium into another by direct contact with the crystal or through an intervening medium. It is noteworthy, especially in applications of nondestructive testing, that the reverse phenomenon also occurs. An ultrasonic wave incident on a crystal (hereafter referred to as a transducer) causes it to vibrate, producing an alternating current across the faces of the transducer (*4*). Defects (cracks, inclusions, etc.) cause sound waves to be reflected back to a transducer, and the resulting voltage serves notice that a defect is present.

The normal audible frequency range of sound is approximately 20 Hz to 20 kHz. In contrast, the ultrasonic frequency (beyond the range of the human ear) employed during this study was 2.25 MHz. Utilizing a lead zirconate titanate (PZT) crystal, the propagation velocity employed was approximately 9,500 ft/sec.

Basic Application

The most basic application of ultrasonics in flaw detection involves transmitting a sound wave with a zero-degree angle of incidence (measured from the normal to the surface) into a medium, such as the plate shown in Figure 2. In the study described here, ultrasound was transmitted as a series of extremely short pulses, and a single transducer functioned as both transmitter and receiver. The transducer detected reflected signals between transmissions.

Voltage traces are viewed on a cathode-ray oscilloscope. The screen shown in Figure 2(a) corresponds to an ultrasound scan conducted away from the interior defect. Only the initial voltage burst and echo from the bottom surface of the plate appear. When the transducer occupies a position above the defect, an additional voltage "spike" appears corresponding to reflection of sound from the defect, as shown in Figure 2(b).

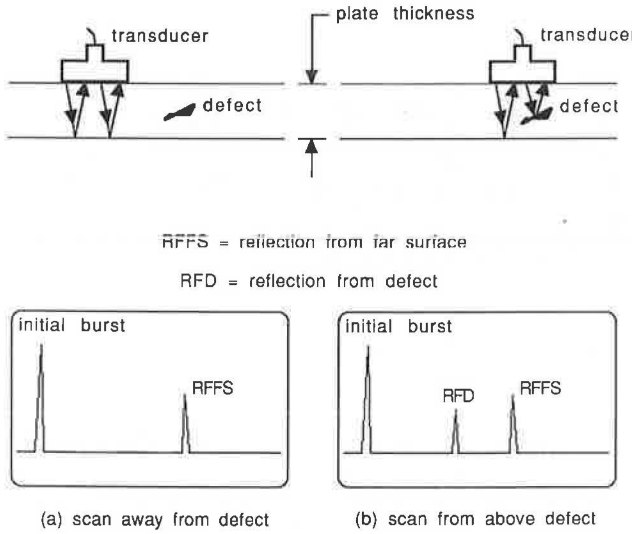

FIGURE 2 Typical oscilloscope traces for ultrasound scans.

Because air greatly impedes sound transmission, a thin film of liquid couplant, or gel, must be brushed onto the surface of an element before ultrasonic examination. This ensures intimate contact with the surface of the transducer and provides for efficient sound transmission into the test part. Preferably, the gel may be applied to smooth, bare metal. Paint removal is briefly discussed later in the section entitled "Field Study."

Most often, applications of ultrasonics are more complex than those shown in Figure 2. Sound frequently is transmitted with a nonzero angle of incidence, and it may be necessary to interpret multiple reflections. Orientation of the defect with respect to the direction of sound travel is one primary consideration for requiring sound to be transmitted along an oblique path. Detailed consideration of types of sound waves and reasons for employing them is beyond the scope of this paper; nevertheless, a brief discussion is provided in the next section. A thorough discussion is available, however, in the literature (*3–6*).

Oblique Sound Path

The strongest indication of cracks and line-type flaws is obtained when the sound is directed at right angles to the defect. That optimum orientation is not possible, however, for a fatigue crack located at the toe of a cover plate weld (Figure 3). The crack is nearly vertical and the sound must be transmitted toward the crack at an oblique angle, as shown. The sound is shown as being directed from the bottom surface of the top flange because it is typical construction practice to embed the top flange within the concrete deck, with only the bottom surface exposed.

The angle at which an ultrasonic wave is refracted and travels through an object is controlled by the angle of incidence (Figure 4). Furthermore, the sound may travel as either a longitudinal wave or a shear wave, or both, and possibly

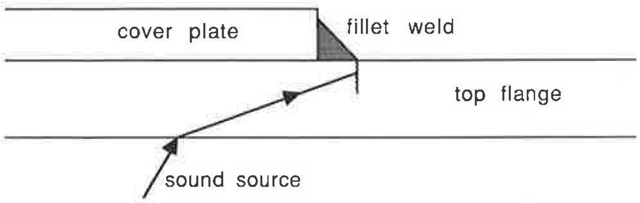

FIGURE 3 Sound path at oblique angle to fatigue crack in beam flange.

even as a surface wave, also depending on the angle of incidence.

Longitudinal waves differ from shear waves with respect to the direction of particle excitation. For the former, particle motion (recalling that this is about a fixed position, not travelling with the wave) is parallel to the direction of the sound path, and for the latter, particle motion is perpendicular to the sound path. Surface waves (a shear wave with refraction angle of 90 degrees) travel along the surface at a shallow depth. A complete discussion may be found elsewhere (*5*).

A range of incident angles above a certain critical angle exists such that only one type of wave, the shear wave, is transmitted into the object being inspected. For such angles, the longitudinal wave is totally reflected from the surface. Transmitting only one type of wave is crucial because the presence of two types of waves would give confusing results (*4*). Sound wave refraction, a function of the angle of incidence and velocities in the respective mediums of transmission, is governed by Snell's law. A standard physics text (*7*) or the literature previously cited may be consulted for detailed treatment.

Determining Defect Position with Shear Waves

For shear waves transmitted into plates containing no defects, only one spike, the initial voltage burst, appears on the oscilloscope screen. Nothing is directed back to the transducer because the sound wave is totally reflected at the plate surfaces (metal-air interfaces) (*4*), as shown in Figure 5(a). For a plate containing a crack, a second spike appears because sound is directed back toward the transducer from irregular features (very small, intermittent concave surfaces) along the

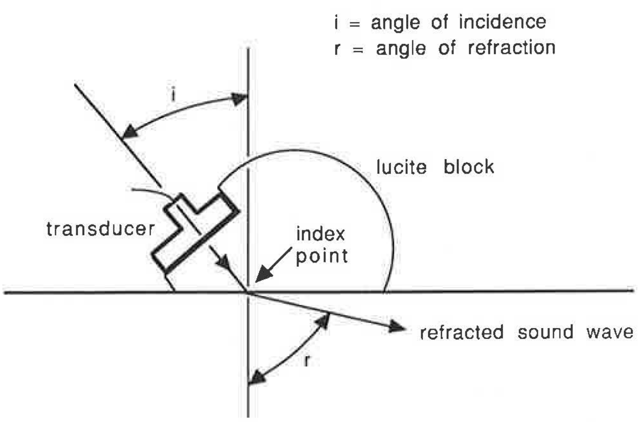

FIGURE 4 Sound wave geometry.

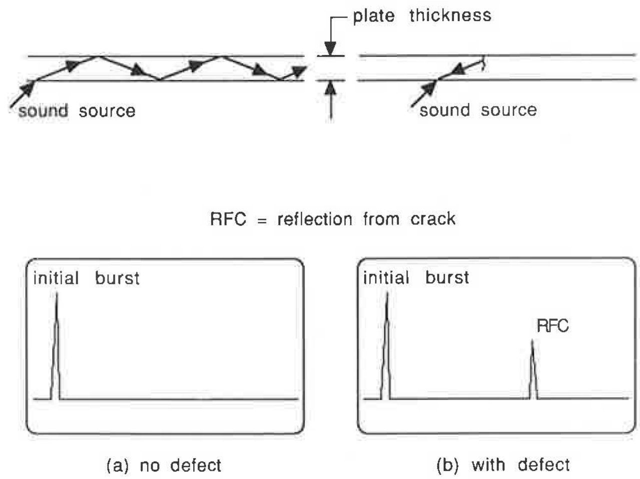

FIGURE 5 Oscilloscope activity with shear waves.

side face of the crack. This is shown in Figure 5(b) (although the minute concave surfaces do not appear because of the scale of the figure).

Reflections may also occur from sources other than a crack, including irregular surface features of the weld, the heel of the weld, an undercut, or the corner of the cover plate. Procedures for interpreting sound wave reflections and identifying the source of the reflections are discussed in the subsection devoted to examining cover plate ends in the "Field Study" section of this paper.

The horizontal distance between spikes in Figure 5(b) corresponds to the elapsed time between the initial sound transmission and subsequent reception. The time may be easily converted to the horizontal distance between the index point of the transducer and the location of the defect because the angle of the sound path and velocity of the shear wave in steel are known. In fact, by utilizing a calibration block containing precision-machined "defects" at accurately known depths and adjusting the sweep settings on the oscilloscope, one may directly read actual distance on the horizontal axis of the screen.

One may determine crack depth as well as crack location. The change in transducer position from the time the crack is first detected until the last indication may be noted. Then when the transducer translation and the refraction angle are known (*6*), the crack height may be computed.

LABORATORY EXAMINATION

A laboratory validation of nondestructive evaluation with ultrasound was performed before the field work was conducted at existing bridges. Two test plates (with dimensions comparable with the components in the bridges) with welded cover plates were subjected to cyclic loading in a servohydraulic material test system until a crack was initiated at one weld toe. The welds at the ends of the cover plates were subjected to ultrasonic examination, and dye penetrant examination was also performed. Subsequently, one of the plates was cast into a surrounding mass of concrete, simulating embedment of a top flange within a concrete deck, and reevaluated with ultrasonic examination. Once again the cracks

were detected in a reliable manner. Several aspects of this work are described below.

The test specimens, fabricated from ASTM A36 steel, consisted of a cover plate 18 in. long welded all around to a base plate 36 in. long with a ½-in. fillet weld deposited using the submerged arc process. The cross section of the base plate was 8 in. by ⅞ in. and that of the cover plate was 6.5 in. by ¾ in. The specimen configuration is shown in Figure 6.

The plates were subjected to repeated cycles of three-point bending rather than axial load as an expeditious way of initiating a crack at the toe of a weld, that is, within the base metal along the transverse weld at an end of the cover plate. The plate was inspected periodically under bright light and with a magnifying glass to determine the presence of a crack.

The plates were examined with ultrasound by moving the transducer on the surface of the larger plate on the side without the cover plate. The locations of crack indications were recorded and a confirming evaluation was performed with dye penetrant. The results were consistent with one another.

The dye penetrant indicated the presence of a crack (manifested as a red stain against a white developer background) in the same zones that were indicated by the ultrasound. The depth of the cracks indicated by the ultrasonic inspection varied depending on location; the depth was found to be in the range of ⅛ in. to 5/16 in.

A limited magnetic particle inspection was also conducted, but very quickly discontinued. The concentration of iron filings characteristic of a crack was occurring in weld toe zones that had provided no indication of cracks by either ultrasonics or dye penetrant examination. Perhaps a dissimilarity between base metal and weld metal might have caused such a "false indication," but it was not within the scope of the investigation to pursue the matter further.

A general guideline in ultrasound technology is that an ultrasonic beam being transmitted in metal is reflected by an internal defect (void or nonmetallic inclusion) if the size of the defect is greater than one wavelength. Thus, cracks within plate surfaces covered with concrete (or cracks containing concrete debris) may be readily detected from the opposite surface if the defects are at least as large as the 1.25-mm wavelength employed in this study.

To demonstrate that cracks could be detected within components embedded in concrete, one cracked plate was cast in a central position within a block of concrete 2 ft wide by 3.3 ft long by 8 in. deep (Figure 7). After being cured, the block was turned over to provide access to the plate. The ultrasound transducer was moved over the exposed plate surface and indications of cracks were obtained that essentially matched the results from the previous examination of the plate that had been conducted without the covering of concrete.

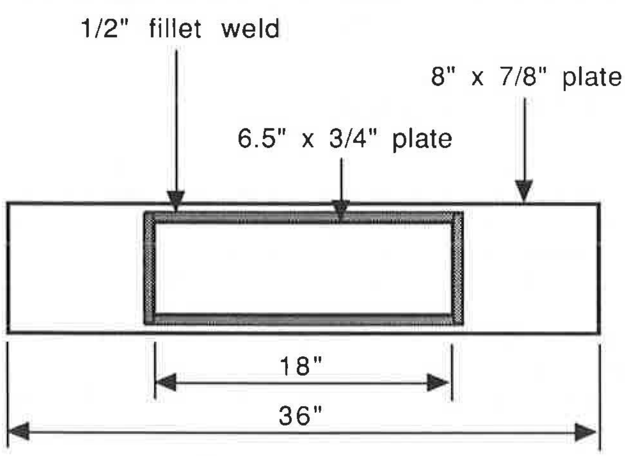

FIGURE 6 Welded cover plate test specimen.

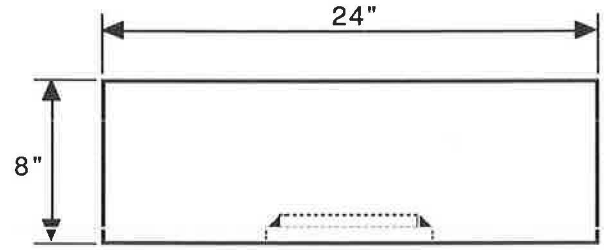

FIGURE 7 Cover plate specimen cast within concrete.

FIELD STUDY

Three urban Interstate highway bridges that have been in service for approximately 25 years were examined with ultrasound. Each structure is a continuous-beam bridge with W33 or W36 wide flange sections that incorporate the welded-splice and cover plate detail shown in Figure 1. Two bridges have three spans, and one has four spans, and the beam spacing is approximately 7.75 ft. All three bridges are of noncomposite construction and are located within 3.5 mi of one another on the same segment of Interstate highway. All flange thicknesses exceed 0.8 in. except for the exterior spans in one bridge, which have a thickness of 0.7 in. Therefore, the most severe AASHTO fatigue classification, Category E′, applies in most instances for the cover plate ends. The full penetration flange splices are nominally Category B, but only when weld soundness is established by nondestructive inspection.

Further discussion regarding fatigue performance characteristics of the bridges is provided below, followed by a summary of the findings from the ultrasound examination. No fatigue cracks were detected at the ends of the cover plates. Some weld-root flaws and crack-type indications were detected within the full penetration butt welds connecting the top flanges. It was necessary to properly interpret certain "false indications," however, to conclude that cracks were not present at the ends of the cover plates. The observations gathered in the field will be described in detail.

It is possible that fatigue cracks could already have been initiated at a cover plate end and not have been detected by visual inspection because the top flange (tension surface) is embedded in the concrete deck. A combination of a high volume of truck traffic (more than 4,000 trucks per day in each direction) and a calculated stress range that exceeds 10 ksi in some situations [AASHTO specifications allow 2.6 ksi for Category E′ (*1*)] provided the justification for a careful field examination. Even according to recently proposed, reliability-based fatigue evaluation (*2*) and design (*8*) procedures that more properly account for actual service conditions (compared with the current design specification), the mean fatigue life has already been exceeded for one of the bridges. (The

FIGURE 8 Beam lines with deck removed.

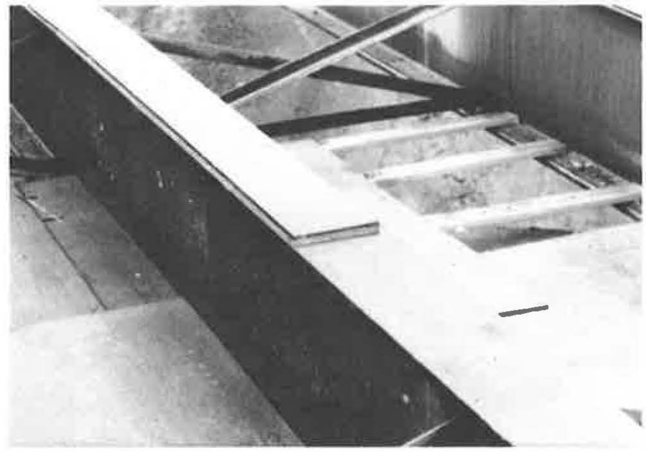

FIGURE 9 Termination of top flange cover plate.

fatigue life analysis of these bridges will be reported in a subsequent paper.)

These bridges presented a special opportunity, because their concrete decks were being removed as part of a routine construction contract. The field work was conducted at that time so that access would be available to both the top and bottom surfaces of the top flange. None of the field work was conducted while the deck was still in place.

Four beam lines within one of the bridges, exposed after deck removal, are shown in Figure 8, which also shows the angle-type cross bracing frames between the girders. The termination of a typical top flange cover plate is shown in Figure 9. Falsework was installed between bottom flanges of the girders to protect the roadway below during deck removal. It also provided convenient access to the cover plates for ultrasound examination.

Calibration and Preparation

The first operations conducted at each bridge site were to calibrate the ultrasound transducer and to remove the paint from the surfaces over which the transducer would be moved. Setting up the instrumentation and calibrating the transducer required less than 30 min at each site. The time required for paint removal was approximately 15 min at each cover plate end.

Calibration involves the simple operation of moving the transducer over a calibration block containing narrow slits located at a precisely specified depth. Because the distance to the slit, the angle of the sound path, and the sound velocity are known, sweep settings may be adjusted on the oscilloscope of the accompanying instrumentation so that actual distances are shown instead of time.

Paint should be removed from the surface over which the transducer is moved for a distance of approximately 5 in. on each side of the transverse weld toe. Separate techniques with small power tools, wire wheels, and disks covered with coarse aluminum oxide grit were employed for the removal. The last method provided the best results. Paint removal is not necessary for obtaining a trace on the oscilloscope screen, but it greatly enhances the quality of the signal. Figure 10 shows the transducer positioned on the bottom surface of a cover-plated flange, and Figure 11 shows actual usage of the instrumentation.

Examination of Cover Plate Ends

Even though no cracks were detected at the ends of the cover plates, indications (spikes) did appear on the oscilloscope screen during the examination. It was discovered that certain undulations in the surface of the weld (sometimes referred to as "rollovers"), shown schematically in Figure 12 and in a

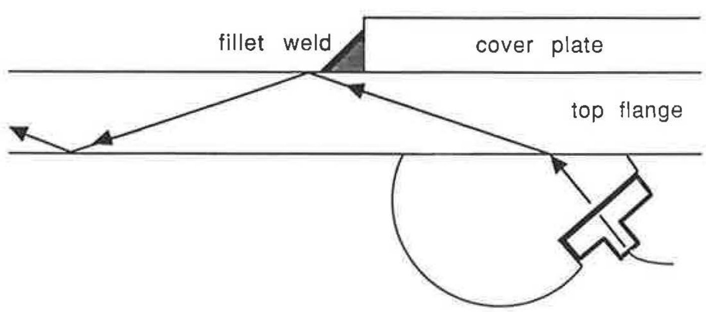

FIGURE 10 Inspection at end of welded cover plate: scan of cover plate end.

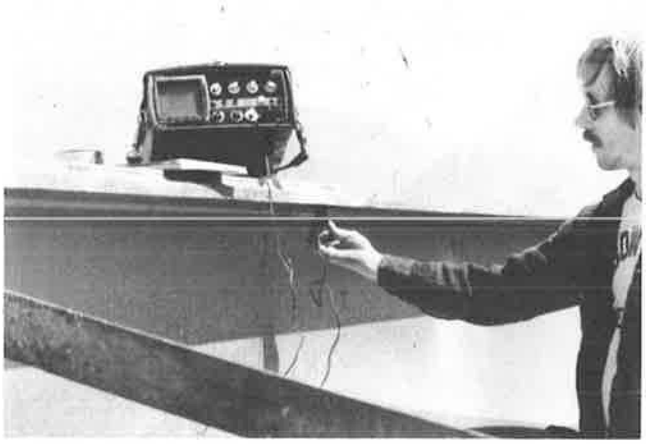

FIGURE 11 Inspection at end of welded cover plate: ultrasound instrumentation.

FIGURE 13 Irregularity in weld surface at end of cover plate.

photograph in Figure 13, provide false indications. The sound incident to the concave surface in Figure 12 is focused by the corner-like trap back toward the transducer, and an indication appears on the screen.

Undercutting is another potential source of false indications. This type of defect is associated with the unintentional introduction of a groove (left unfilled by weld metal) into the base material adjacent to the toe of a weld. Such a disruption in the flange surface may also focus sound back toward the transducer.

The indication caused by a rollover does not differ from that caused by a real crack, such as the one shown in Figure 14. The corner created by the intersection of the crack and surface of the top flange focuses the sound back toward the transducer in a manner similar to the rollover. It is possible, however, to distinguish between a real crack and a false indication by conducting the ultrasound scan from both sides of the weld. The crack shown in Figure 14, representative of a fatigue crack at the end of a cover plate, causes an indication to appear for scans conducted from both the left and right sides of the weld. When a scan is conducted from the right side of the weld in Figure 12, there is no indication because the sound is no longer incident on a trapping surface feature.

Two other methods were used to reject the indications caused by the rollovers. First, after several indications (not known to be false at the time), the end of the cover plate was subjected to dye penetrant examination. There was no evidence of a crack. Second, a procedure referred to as "damping" was used to distinguish between alternative locations as the source of a crack. Damping involves applying a small amount of the liquid couplant to one's finger and tapping on the surface near the toe of the weld. (When the finger is in contact with the surface, a portion of any incident sound is refracted into the finger.) The transducer was translated until a spike appeared on the screen and was then held stationary. Tapping on the weld at the rollover caused the spike on the screen to jump. Tapping on the base metal of the top flange at a slight distance from the weld toe did not cause the spike to jump.

One must usually rely on scanning from both sides of the weld, however, as a basis to reject the false indications, because the top surface is not visible in most situations. With the deck in place, it is not possible to tap on the weld or to conduct a dye penetrant examination.

Considering a typical situation, in which the top surface of the beam is not visible, the first important step before an ultrasonic examination would be to establish the position of the toe, or end, of the weld. The design drawings would indicate the distance from the flange butt-weld splice to the end of the cover plate. Next, the precise position of the end weld may be established by directing a longitudinal wave into the flange at an incident angle of zero degrees. The beginning of the weld can be accurately established (within approximately 1/64 in.) by watching for a change in signal on the screen. Therefore, any indication detected with a shear wave transducer that is not located right at the weld toe must be something other than an end-of-plate fatigue crack.

In a few situations, a false indication came from the top corner of the cover plate from sound that was directed toward the weld with the transducer on the left side of the weld (as

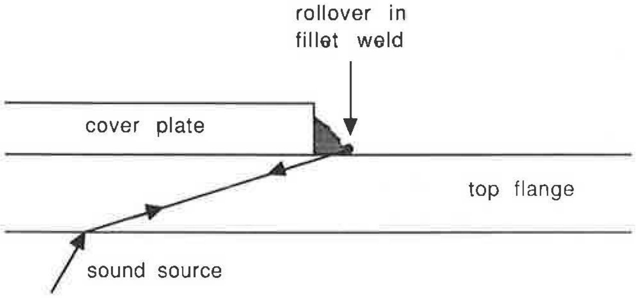

FIGURE 12 Sound reflection from irregularity in weld surface: rollover in fillet weld.

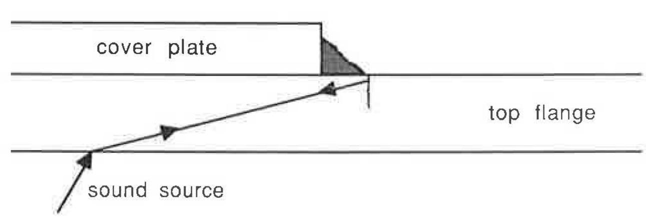

FIGURE 14 Sound reflection from fatigue crack at weld toe.

in Figure 12). Damping the sound by tapping the surface at the corner and watching the spike jump revealed that the source of the indication was not at the end of the weld. However, the same conclusion could have been reached without access to the surface by noting the distance from the transducer to the source of the indication and by noting further that the location of the source did not coincide with the toe of the weld.

Examination at Flange Splices

Indications of voids and defects within the full penetration butt welds joining the top flanges were detected at several locations by ultrasonic examination. In the majority of cases the defects were restricted to the center-depth regions of the flange, which pointed toward incomplete fusion, lack of penetration, or a similar fabrication flaw as the source of the indications. Very little depth ($\leq 1/8$ in.) makes it possible that these defects have been present since fabrication of the welded splices 25 years ago and that an active crack front is not present.

At three locations, however, indications were detected that revealed a through-thickness dimension extending from the center of the flange to near its top surface. It becomes difficult to assess the full extent of the flaw as it nears the surface because of interference from the metal-air interface at the top of flange and irregularities in the flange surface. In one instance, there was evidence from the ultrasound that a defect had travelled to within $1/64$ in. of the surface of the top flange. The evidence indicated the type of crack shown in Figure 15. There was no way to confirm this finding by visual methods, because the cover plate and side fillet welds obscured the top flange surface from view.

Radiographic (x-ray) examination was conducted on the three butt welds with the largest flaw depth in an attempt to confirm the findings from the ultrasonic examination. The radiographic film did not show any evidence of cracks. It is not proper to state, however, that a crack was not present, because when viewed from above, the crack could be "lost" in the background. That is, any crack propagating vertically from a lack-of-fusion defect would likely be obscured in the film within the dark region that characterizes the defect zone.

To ensure safety and preserve the overall integrity of the negative moment connection, a bolted flange splice was installed at the location where ultrasonic examination revealed that the defect had nearly reached the surface. Other locations with flaws of significant depth will be closely monitored.

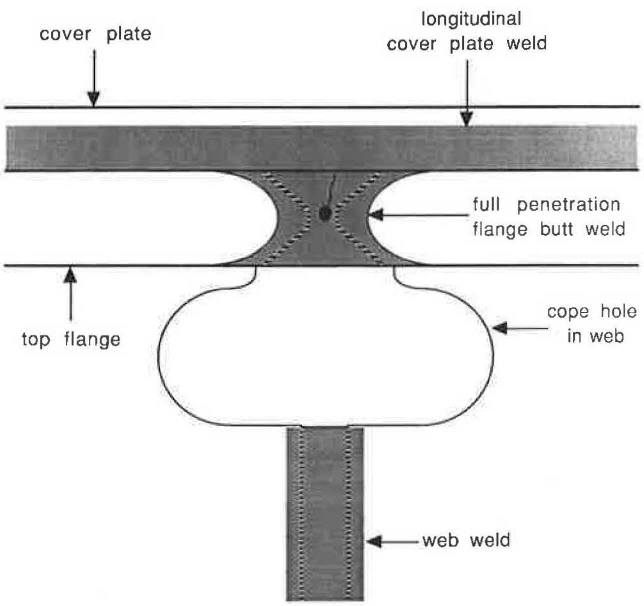

FIGURE 15 Crack propagation from flaw within root of flange splice butt weld.

CONCLUSIONS

Ultrasound may be effectively employed as a nondestructive evaluation tool for crack detection in existing bridges. Embedment of the cracked surface of an element in concrete does not alter the ability of the ultrasound testing to detect a crack, as long as a scanning surface is exposed. Before an agency initiates an ultrasonic inspection program, a test specimen composed of a welded cover plate and a base plate should be fabricated to provide guidance. By incorporating welds with smooth surfaces, welds with rollovers, and cracks at some locations in the weld toes, the test specimen simulates conditions that may be encountered in the field. This provides control and helps in interpreting the field results.

ACKNOWLEDGMENTS

This project was funded by the Ohio Department of Transportation (DOT) and the Federal Highway Administration. Vikram Dalal and Florian Euteneuer were liaison representatives for the Ohio DOT. Ultrasonic testing and the other nondestructive tests described in this paper were conducted by Glitsch Field Services/NDE, North Canton, Ohio.

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Publication of this paper sponsored by Committee on Steel Bridges.