

# Nondestructive Evaluation (NDE) Methods for Quality Assurance of Epoxy Injection Crack Repairs

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**A** concrete bridge over westbound Interstate 70 just outside Denver, Colorado, was recently impacted by a forklift carried by a truck moving at a speed of approximately 75 mph. The impact resulted in cracking and concrete spalling on both sides of the easternmost prestressed concrete I-beam bridge girder. The damage was most severe on the east side of the girder where the impact occurred, as shown in Figure 1, although significant cracking and spalling were also seen on the west side of the girder. Epoxy injection and polymer-modified repair mortar were used to repair the cracks in the damaged girder.

After the repairs were complete, a nondestructive testing program was developed to help assure the quality of the repairs by checking for areas of unfilled cracks. The nondestructive testing program used in this investigation consisted of impact echo (IE), ultrasonic pulse velocity (UPV), and spectral analysis of surface waves (SASW). Since a combination of IE and UPV tests was found to be most effective in characterizing unfilled cracks in this repaired concrete bridge girder, this article focuses on the combination of these two methods. The SASW tests were used in a more limited role in this investigation, primarily in areas with unfilled vertical cracks, to increase the confidence level in

the quality assurance program. The nondestructive tests used for this quality assurance cannot determine the bond strength of the epoxy material used in the repairs, but can identify areas of unfilled cracks. Repair procedures, brief backgrounds of the IE and UPV test methods, the nondestructive field investigation, and the results are presented herein.

## Repair Procedure

The impact on the bottom flange of the bridge girder caused the girder to rotate inward, toward the center of the bridge. The rotation was resisted by the concrete diaphragm attached to the web of the girder, causing a large amount of spalling and cracking to occur in the region of the diaphragm. The full- and partial-depth spalled web areas were repaired by chipping out all loose or damaged concrete using light (15 lb) electric chipping hammers, so that the repaired areas were approximately rectangular in shape. The edges of the repaired areas were cut perpendicular to the girder, a minimum of  $\frac{3}{4}$  inch deep. The repair area was presaturated with water and the surface allowed to air-dry to a saturated surface-dry condition. A polymer-modified structural repair mortar was installed using the form-and-pour method and cured for 7 days. After the web repairs were complete, the bridge girder was preloaded and the bottom flange repairs were completed as detailed above. After the web and flange repairs were complete, approximately 800 linear feet of cracks were injected with epoxy (Figure 2 shows beam prior to epoxy injection; Figure 3 shows injection ports in place). As part of the overall quality control process, inspections were performed by the structural engineer prior to placement of the repair mortar and at other critical times during the repair work.



Fig. 1: Damage on the eastmost concrete girder before the repairs

## Nondestructive Quality Assurance Program

After the repairs were complete, a quality assurance program was developed using a combination

of two nondestructive tests: IE and UPV. This part discusses general backgrounds of IE and UPV tests, nondestructive testing field investigation, and non-destructive testing results.

## IE

IE is a stress wave method that uses a small steel impactor to generate an impact on the face of a member and a nearby receiver to pick up echoes of the impact. The IE test requires only one-side access to the structure. The resonant echoes from the impact of the displacement responses in time domain are recorded by a displacement transducer mounted in contact with the test surface and next to the impact location. Resonant echoes from member thicknesses and/or flaws are not readily apparent in the time domain, but are more easily identified in the frequency domain. To accomplish this, the linear frequency spectra of the displacement response is calculated by performing a Fast Fourier Transform (FFT) analysis on the received signals to determine the resonant echo peak(s).

A simplified diagram of the method is shown in Figure 4. The relationship among the resonant echo depth frequency peak ( $f$ ), the compression wave velocity ( $V_p$ ), and the echo depth ( $D$ ) is expressed in the following equation:

$$D = bV_p/(2*f) \quad (1)$$

where  $b$  is a factor ranging from 0.75 for a round column to 0.96 for a slab/wall shape (such as an I-beam web).<sup>1</sup> Typical applications of IE are concrete thickness measurement, concrete quality evaluation, and internal flaw detection. The IE method is most sensitive to cracks that are parallel to the test surface.

## UPV Method

The UPV method involves measuring compression wave velocity and amplitude in concrete by measuring the direct travel times and amplitude of compression waves. In general, low velocities and



Fig. 2: The damaged girder prior to epoxy injection repairs



Fig. 3: The damaged girder with injection ports in place

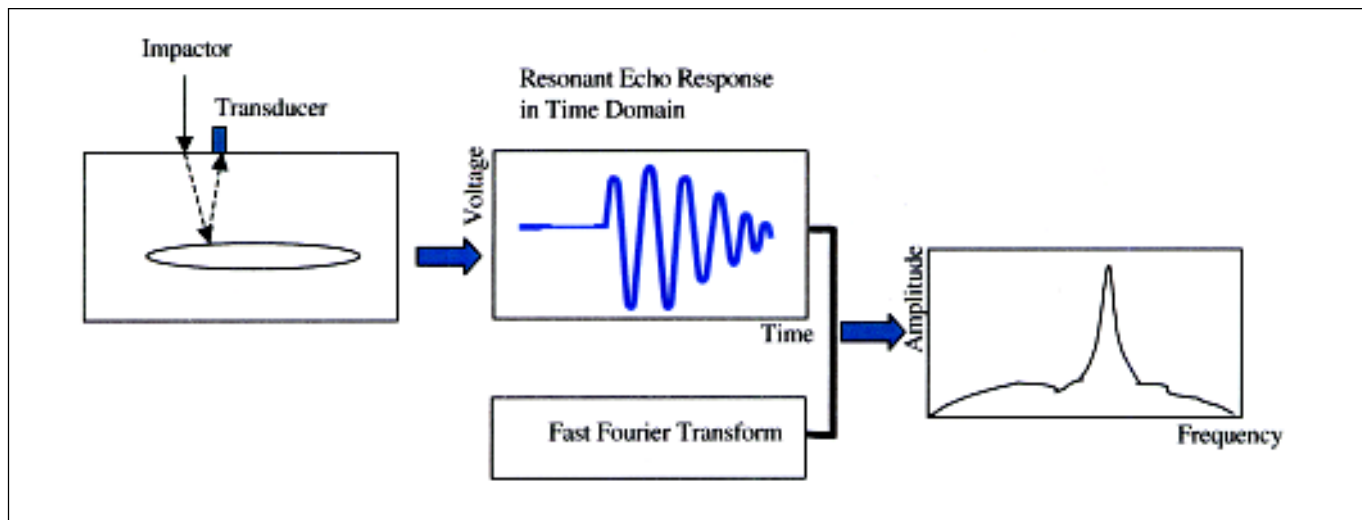


Fig. 4: Diagram of IE method

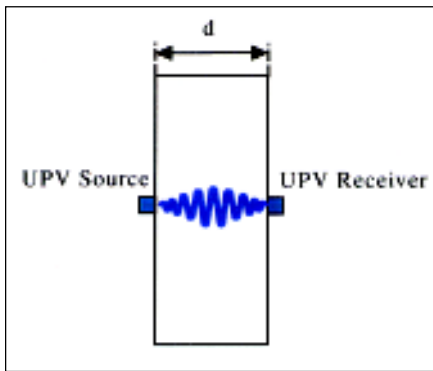


Fig. 5: Typical UPV test setup

amplitudes indicate poorer concrete quality (or cracks). This method requires two-sided access to the structure. Typically, two 54-kHz UPV transducers used as source and receiver are grease-coupled to the concrete and placed at two locations on a structure with a known distance between them. A schematic of the UPV method is presented in Figure 5.

The ultrasonic pulse (compression wave) velocity is calculated by dividing the path distance ( $d$ ) by the wave travel time ( $t$ ) as follows:

$$V_p = d/t \quad (2)$$

## Nondestructive Testing Field Investigation

Internal unfilled cracks cannot normally be detected visually; therefore, a nondestructive testing

program was developed to locate areas of unfilled cracks for quality assurance of the epoxy injection crack repairs of the damaged concrete bridge girder. The nondestructive testing program presented herein consists of two different methods: IE and UPV.

IE is best at characterizing unfilled cracks or voids parallel to the structure surface. UPV is suitable for detecting unfilled cracks or voids in other directions. IE and UPV are less sensitive to cracks that are perpendicular to the test paths. However, with angular UPV test paths, the UPV method can be used to detect perpendicular cracks. A combination of the two nondestructive testing methods was found to be suitable in detecting unfilled internal cracks. The field test setup of the two tests are shown in Figures 6(a) through (c).

The damaged section on the concrete girder was approximately 70 ft long. The cracks and spalls were most severe on the web and bottom flange of the east side of the damaged concrete girder. The nondestructive tests were performed on a "spot-check" basis. A test grid consisting of a 6 x 6-inch grid over a 1 x 1-ft area was set up at each station. A total of 16 stations was randomly selected for NDE on the web of the repaired concrete I-beam girder, but all were located in areas that had filled cracks. The IE tests were performed on the west side of the girder, at every grid point, at every station. The IE test locations and test paths are shown in Figure 7(a). If the IE tests detected possible unfilled internal cracks, UPV tests were used in the area to confirm and further identify the existence and extent of the unfilled cracks. The UPV tests were performed with two grease-coupled, 54-kHz UPV transducers. The transducer that was used as a source was placed at the center of each test area on the east side of



(a) IE test setup



(b) UPV source on the east side of the east girder



(c) UPV receiver on the west side of the east girder

Fig. 6: Nondestructive test setups for IE and ultrasonic pulse velocity tests

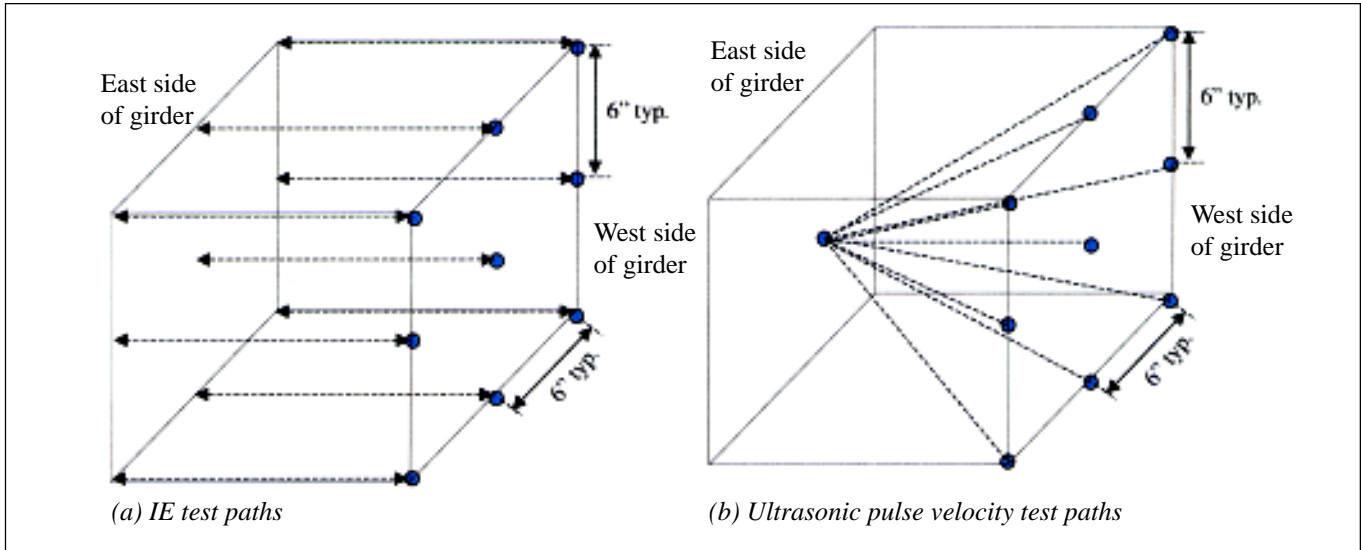


Fig. 7: Typical nondestructive test locations and paths at each station

the girder, while the receiver transducer was placed at each grid point on the west side. A total of 9 UPV test paths were performed at each station for a total of 144 test paths on the girder. The UPV test locations and paths on the web at each station are shown in Figure 7(b). Note that Figure 7 shows only the web portion of the I-beam girder.

**NDE Example Results**

This section presents example IE and UPV results from one test station (Station O) on the repaired bridge girder. The graphical IE frequency results from Station O on the web area are shown in Figure 8. The IE data from Location 5 shows a signature of internal cracking (unfilled), as can be seen by multiple echo peaks in the frequency domain. A typical IE record indicating sound concrete at Location 9 is also included in Figure 8. Data from the rest of the tested points on Station O were similar to data from Location 9, indicating sound concrete with no internal cracks. The typical sound concrete record from Location 9 shows a resonant echo peak from the back wall of the web at a frequency corresponding to a depth of 6.3 inches (using Equation 1), which is close to the design thickness of 6.0 inches. The IE record with a crack

signature shows multiple peaks resonating from different depths, which indicates a strong possibility of unfilled, internal concrete cracking at that point.

Graphical UPV test results from Station O are presented in Figure 9. The UPV results were classified into three categories based on the UPV velocity results. The first category contained UPV velocities greater than 11,000 ft/sec; the second category contained UPV velocities between 10,000 and 11,000 ft/sec; and the last category contained UPV velocities below 10,000 ft/sec. As discussed previously, higher velocities normally indicate higher concrete quality. For Station O,

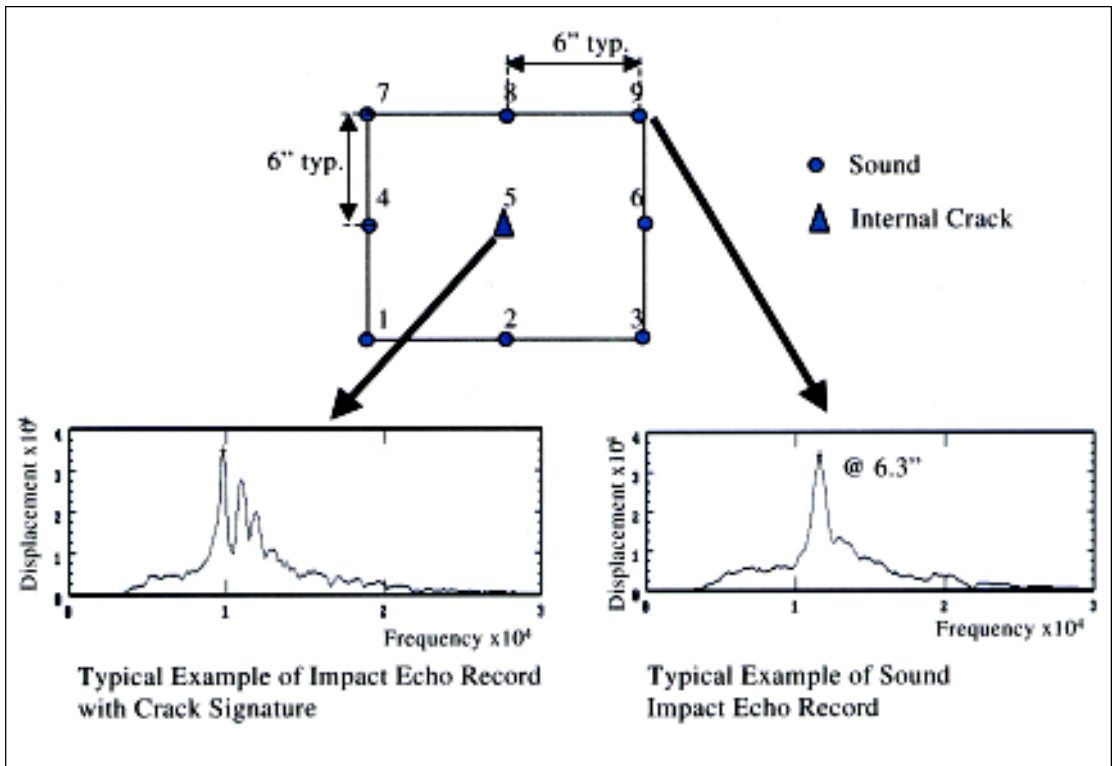


Fig. 8: Example IE results showing records of sound and cracked concrete

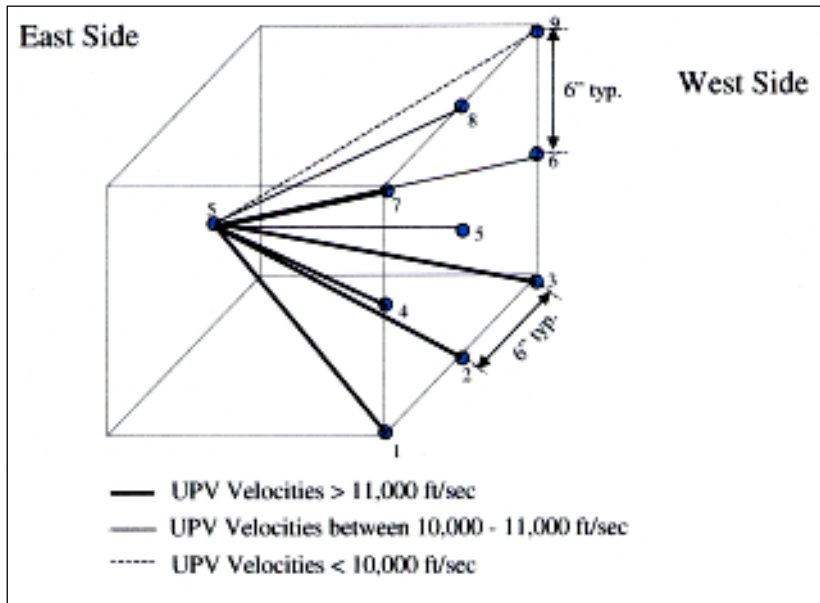


Fig. 9: Example ultrasonic pulse velocity results from Station O

the UPV velocity results indicated that the concrete qualities for Paths 5-1, 5-2, 5-3, 5-4, and 5-7 were higher; the concrete qualities for Paths 5-5, 5-8, and 5-6 were lower; and those for Path 5-9 were in the lowest-quality category.

Based on the UPV results, an area of unfilled cracks was located on the south corner of Station O. From the IE tests, the results from Location 9 were sound with no internal cracks. Taken together, the NDE results showed that the unfilled cracks lie in an angle across Paths 5-5, 5-6, and 5-9, with a wider open area between Path 5-9 and a tighter crack tip between Path 5-5. The unfilled cracks did not appear to spread to the south end (Location 9) of Station O, since the IE results from Location 9 were sound.

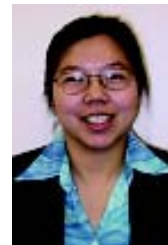
## A Useful Assessment Tool

Nondestructive testing is proving to be very useful in both the initial concrete condition assessment and the quality assurance process for concrete repairs. Internal cracks that cannot be seen visually can be detected by stress waves. The combination of NDE methods in this quality-assurance program provided the most effective and efficient testing program. The results from the NDE methods correlated well and increased confidence in estimating the location and extent of isolated, unfilled cracks. With a combination of NDE approaches, the confidence level in rating concrete conditions can be increased significantly. The NDE methods discussed herein are detailed further in ACI 228.2R-98.<sup>2</sup> Note that the nondestructive tests used in this quality-assurance program are capable of locating unfilled cracks, voids, and other flaws in concrete, but do not provide data on the strength of the completed repairs. Semidestructive tests such as the pull-off method (see ACI 228.1R-95)<sup>3</sup> or destructive core drilling and laboratory tests should be used to determine the strength of epoxy injection and the bond strength of patching repairs

(pull-off method). Stress wave velocity measurements can be used to predict undamaged concrete strength when correlations are made with cylinders or cores per ACI 228.1R-95.

## References

1. Sansalone, M. J., and Streett, W. B., *Impact-Echo Non-destructive Evaluation of Concrete and Masonry*, Bullbrier Press, 1997, Ithaca, N.Y.
2. ACI Committee 228, "Nondestructive Test Methods for Evaluation of Concrete in Structures (ACI 228.2R-98)," American Concrete Institute, Farmington Hills, Mich., 1998, 62 pp.
3. ACI Committee 228, "In-Place Methods to Estimate Concrete Strength (ACI 228.1R-95)," American Concrete Institute, Farmington Hills, Mich., 1995, 41 pp.



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**John Lund, P.E.**, has over 17 years of experience in the structural assessment, evaluation, and repair of buildings, including historic preservation and expert witness services. Mr. Lund is a principal at Martin/Martin, Inc., in their Wheat Ridge, Colorado, office, where he leads a team of investigative engineers. He is also a member of ACI Committee 546, Repair of Concrete.