NONDESTRUCTIVE EVALUATION (NDE) METHODS FOR QUALITY ASSURANCE OF EPOXY INJECTION CRACK REPAIRS

by

Yajai Promboon, Ph.D., Larry D. Olson, P.E.
Olson Engineering, Inc.
and
John Lund, P.E.
Martin/Martin, Inc.

Abstract

A concrete bridge over Interstate 70 east of Denver, Colorado was impacted by a fork lift being transported by a truck moving at a speed of approximately 75 mph. The forklift impacted the east face of the prestressed concrete I-beam bridge girder, resulting in severe cracking and concrete spalling on both sides of the eastmost girder. Polymer-modified repair mortar was used to repair spalled areas and epoxy injection was used to repair the cracks. Various types of nondestructive tests including Impact Echo, Ultrasonic Pulse Velocity and Spectral Analysis of Surface Waves were performed after the repairs were completed to provide quality assurance of the epoxy injection filling of the cracks and concrete repairs. Although three nondestructive evaluation (NDE) methods were used in the investigation and all three provided useful information for the quality assurance process, this paper focuses on the primary nondestructive testing program consisting of a combination of Impact Echo and Ultrasonic Pulse Velocity tests. The combination of these two methods proved to be very effective in locating internal unfilled cracks. The results from both methods correlated well and taken together the NDE results better defined the extent of isolated, unfilled cracks.

Introduction

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 Fig. 1, although significant cracking was also seen on the west side of the girder as well. Epoxy injection and a concrete patching material 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 paper 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.

Fig. 1 - Damage on the Eastmost Concrete Girder before the Repairs

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 depth and partial depth spalled web areas were repaired by chipping out all loose or damaged concrete using light (15 pound) electric chipping hammers so that the repaired areas were approximately rectangular in shape. Edges of the repaired areas were cut perpendicular to the girder a minimum of ¾" deep. The repair area was pre-saturated with water and the surface allowed to air-dry to a saturated surface dry condition. Master Builders Emaco S77 structural repair mortar was installed using the form and pour method and cured for seven days. After the web repairs were complete, the bridge girder was pre-loaded and the bottom flange repairs were completed as detailed above. After the web and flange repairs were complete, approximately 800 lineal feet of cracks were injected with Master Builders Concresive 1380 Injection resin (Fig. 2 shows beam prior to epoxy injection, Fig. 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 repair mortar and at other critical times during the repair work.

Fig. 2 - The Damaged Girder Prior to Epoxy Injection Repairs


Fig. 3 - The Damaged Girder with Injection Ports in place

Nondestructive Quality Assurance Program

After the repairs were complete, a quality assurance program was developed using a combination of two nondestructive tests: Impact Echo (IE) and Ultrasonic Pulse Velocity (UPV). This part discusses general backgrounds of IE and UPV tests, nondestructive testing field investigation, and nondestructive testing results.

Impact Echo (IE)

Impact Echo is a stress wave method using 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 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 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 Fig. 4. The relationship between the resonant echo depth frequency peak (f), the compression wave velocity (V_P) and the echo depth (D) is expressed in the following equation:

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

where β 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)[1]. 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.

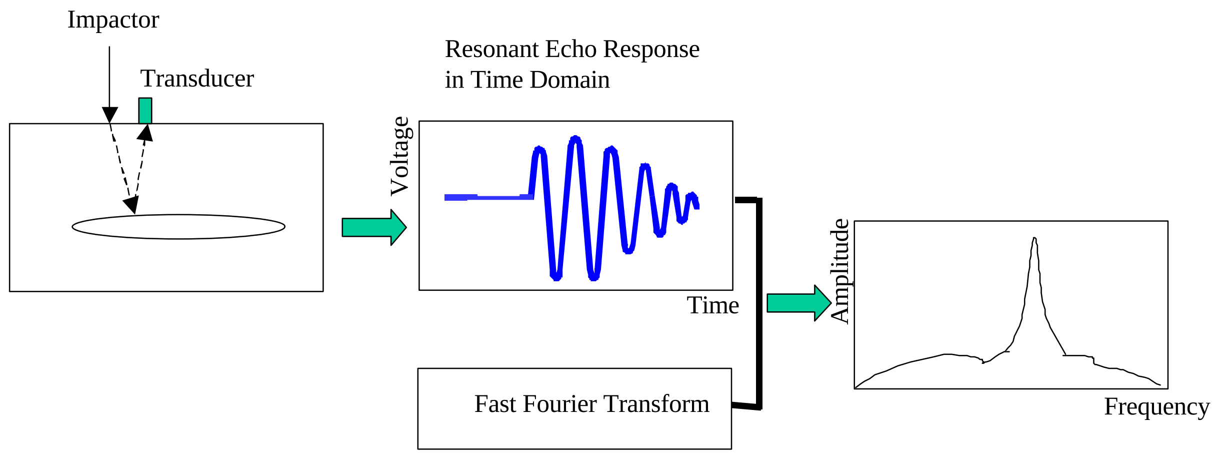


Fig. 4 - Diagram of Impact Echo Method

Ultrasonic Pulse Velocity (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 amplitudes indicate poorer concrete quality (or cracks). This method requires 2-sided access to the structure. Typically, two 54 kiloHertz UPV transducers used as a source and a receiver are greased-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 Fig. 5.

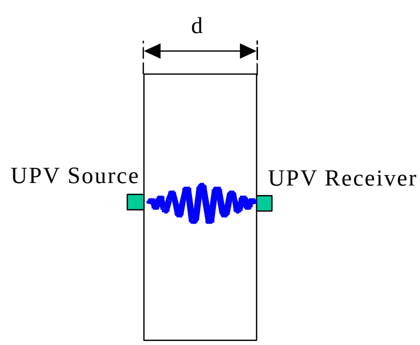


Fig. 5 - Typical UPV Test Setup

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

$$Vp = d/t \qquad (2)$$

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.

Impact Echo is best at characterizing unfilled cracks or voids parallel to the structure surface. Ultrasonic Pulse Velocity is suitable 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 Figs. 6a-c.

Fig. 6a - IE Test Setup

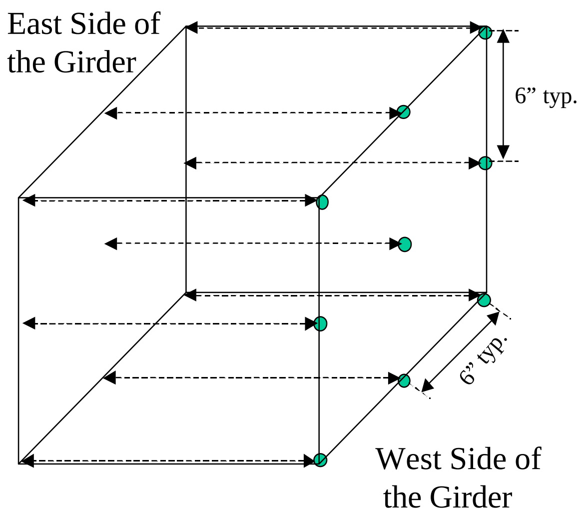
Fig. 6b - UPV Source on the East Side of the East Girder

Fig. 6c- UPV Receiver on the West Side of the East Girder

Fig. 6 - Nondestructive Test Setups for Impact Echo and Ultrasonic Pulse Velocity Tests

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 inch x 6 inch grid over a 1 ft by 1 ft area was set up at each station. A total of 16 stations were randomly selected for nondestructive evaluation (NDE) on the web of the repaired concrete I-beam girder, but all were located in areas which 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 Fig. 7a. 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 kiloHertz UPV transducers. The transducer that was used as a source was placed at the center of each test area on the east side of 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. Ultrasonic Pulse Velocity test locations and paths on the web at each station are shown in Fig. 7b. Note that Fig. 7 shows only the web portion of the

I-beam girder.



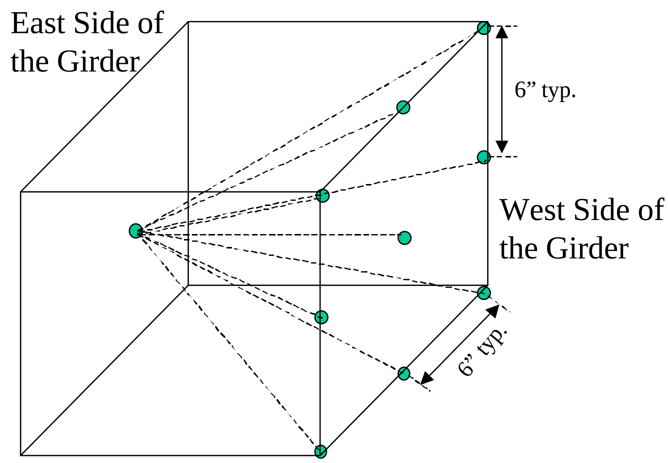


Fig. 7a - Impact Echo Test Paths

Fig. 7b - Ultrasonic Pulse Velocity Test Paths

Fig. 7 - Typical Nondestructive Test Locations and Paths at Each Station

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 Fig. 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 Fig. 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 Eq. 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 indicating a strong possibility of unfilled, internal concrete cracking at that point.

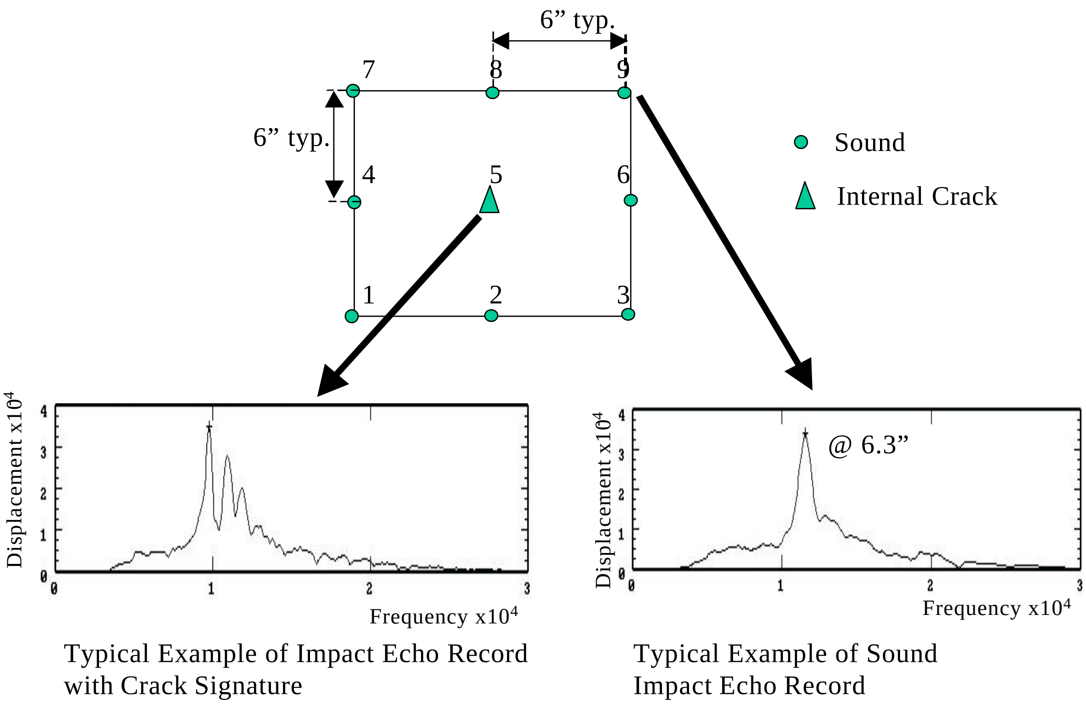


Fig. 8 - Example Impact Echo Results Showing Records of Sound Concrete and Cracked Concrete

Graphical UPV test results from Station O are presented in Fig 9. The UPV results were classified into 3 categories based on the UPV velocity results. The first category was when the UPV velocities were greater than 11,000 ft/sec. The second category was when the UPV velocities were between 10,000 and 11,000 ft/sec. The last category was when the UPV velocities were below 10,000 ft/sec. As discussed earlier, higher velocities normally indicate higher concrete quality. For Station O, the UPV velocity results indicated that the concrete qualities for Paths 5-1, 5-2, 5-3, 5-4 and 5-7 had higher concrete quality, the concrete qualities for Paths 5-5, 5-8 and 5-6 were lower quality, and those of Path 5-9 were in the lowest quality category.

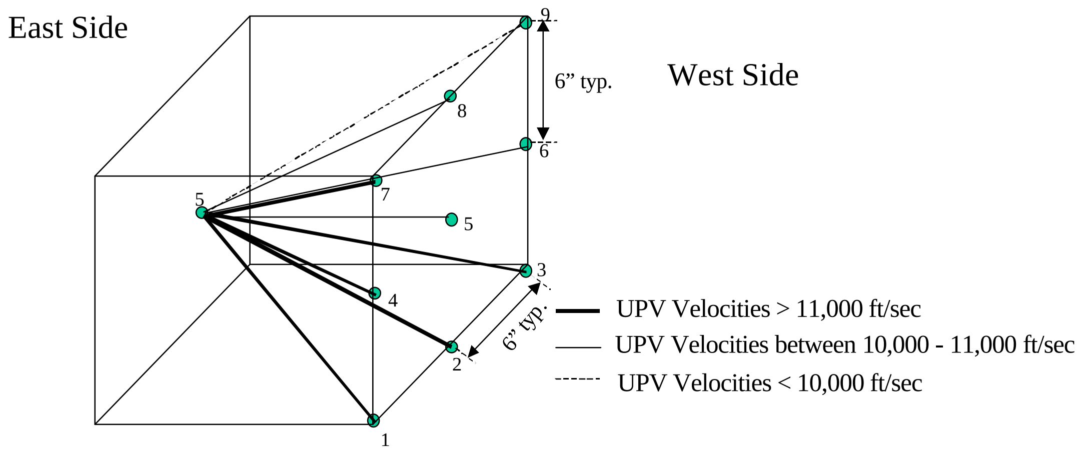


Fig. 9 - Example Ultrasonic Pulse Velocity Results from Station O

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 nondestructive evaluation (NDE) results showed that the unfilled cracks lie in angle across Paths 5-5, 5-6, and 5-9 with wider open area between Path 5-9 and 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.

Conclusion

Nondestructive testing is proving to be very useful in both initial concrete condition assessment and in the quality assurance process for concrete repairs. Internal cracks which cannot be seen visually can be detected by stress waves. The nondestructive testing program used for quality assurance of epoxy crack injection consisted of Impact Echo and Ultrasonic Pulse Velocity methods. Impact Echo requires only single sided access, which therefore reduced the field test investigation time and labor. Impact Echo was used to preliminarily detect internal cracks at each test point. Once a possible crack was defined, Ultrasonic Pulse Velocity tests with angular paths were performed to provide more information on the location and extent of the unfilled cracks. The combination of NDE methods provided the most effective and efficient testing program. The results from the NDE methods correlated well and increased the confidence in locating and 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. 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 repaired strength of the repairs. Semi-destructive tests such as the pull-off method (see ACI 228.2R-95) 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:

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2. ACI 228.2R-98, Nondestructive Test Methods for Evaluation of Concrete in Structures, ACI Manual of Concrete Practice, Latest Revision, American Concrete Institute, Detroit, MichiganACI Committee Report 228.2R-98, Nondestructive Test Methods for Evaluation of Concrete in Structures.

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Biography

1. Yajai Promboon, Ph.D. is a Project Engineer for Olson Engineering in Wheat Ridge, Colorado. She has conducted a wide range of NDE based engineering investigations of structures, slabs, deep foundations and geophysical studies since joining the firm in 2000. She obtained her Masters and Ph.D. in Structural Engineering from the University of Texas at Austin where she was heavily involved in research in nondestructive testing of steel, concrete and fiber reinforced plastic for 6 years.

2. Larry D. Olson, P.E. has been the President of Olson Engineering, Inc. and Olson Instruments, Inc. since their respective beginnings in 1985 and 1995. He has over 21 years of consulting engineering experience in geotechnical, materials, vibration, instrumentation and geophysical engineering with an emphasis on condition assessment and nondestructive evaluation of structures. He is a director of ICRI and the Chairman of ICRI's Evaluation Committee. He is also active in ACI Committees on Nondestructive Testing (228), Consolidation (309), and the Concrete Research Council. Mr. Olson is an internationally recognized expert in NDE and has been an instructor in the American Society of Civil Engineer course on " Structural Condition Assessment of Existing Structures" since 1997.

3. 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 the American Concrete Institute Committee 546, Repair of Concrete.