Evaluating Historic Concrete Bridges

By Kevin A. Michols, Allen G. Davis, and Carlton A. Olson

Recent years have seen a growing demand for evaluation of reinforced concrete bridges built during the first 40 years of the 20th century. Just as public interest in preserving historic buildings has increased, so has the appreciation of older bridge structures. Many older bridges have been designated as historic structures, a move that requires rehabilitation rather than replacement as the bridges age and deteriorate. Preserving such structures requires a thorough knowledge of existing conditions, structural integrity, and material durabilities.

But acquiring such thorough knowledge can be a challenge. For many older bridges, only limited information is available on existing concrete strength and steel reinforcing details. The quality of concrete materials, including strength and degree of consolidation, can vary greatly in older structures because of the limitations in construction techniques that were common years ago. Because air-entrained concrete was not widely used until the early 1950s, many structures of the period have suffered freeze-thaw damage, not all of which is readily detectable by visual inspections. Service and maintenance records are often sparse or unavailable, particularly those from the early years of the structure's existence. A further challenge is that many bridges are required to have an increased load rating after rehabilitation. All these unknown and variable conditions necessitate a comprehensive evaluation before designing the rehabilitation, in order to avoid expensive surprises and unforeseen problems during reconstruction.

Evaluation Approach

The authors have evaluated a number of historic reinforced concrete bridges in different regions of the United States over the past few years. The bridges include open spandrel arches, closed spandrel (filled) arches, and beam and slab structures that were constructed between 1907 and 1938. Typical structural evaluations include a review of historical information, field investigation, laboratory testing, structural calculations, and report preparation. The focus here is on the field investigation phase and, in particular, on the use of advanced nondestructive testing (NDT) as an efficient and economical tool to investigate a structure's condition.

Field investigations typically include a visual review of the structure, followed by the selection of areas needing more detailed investigation, including NDT and core sample removal. Impulse radar and magnetic cover meters can be used to evaluate steel reinforcement in bridge components. Impulse Response (IR), Impact-Echo (I-E) and Ultrasonic Pulse Velocity (UPV) testing can help characterize such items as concrete quality, degree of deterioration, and member thickness. These NDT methods are fully described in ACI Committee Report 228.2R-98 *"Nondestructive Test Methods for Evaluation of Concrete in Structures,"* but many engineers and contractors have limited experience with them. The authors have extended the use of the Impulse Response test to bridge evaluation as a way to qualitatively assess the structure's general condition and rapidly identify localized zones of poor quality concrete.

Recent Stress Wave NDT Methods

The IR test method is a stress wave test used extensively to evaluate machined metallic components in the aircraft industry. Its application to concrete structures in civil engineering is less well known, and the method has received far less publicity than the recently developed Impact-Echo test (Sansalone & Streett, 1997). However, its range of applications for concrete structural elements has increased in recent years to include assessment of:

- Voiding beneath concrete highway, spillway and floor slabs (Davis & Hertlein, 1987)
- Delamination of concrete around steel reinforcement in slabs, walls and large structures such as dams, chimney stacks and silos (Davis & Hertlein, 1995)
- Poorly consolidated concrete (honeycombing) and cracking in concrete elements (Davis & Hertlein, 1995)
- Debonding of concrete and asphalt overlays to concrete substrates (Davis et al., 1996)

The IR test uses a low-strain impact to send a stress wave through the tested element. The impactor is usually a 1-kg sledgehammer with a built-in load cell in the hammerhead. Response to the input stress is normally measured using a velocity transducer (geophone). Both the hammer and the geophone are linked to a portable field computer for data acquisition and storage. Time records

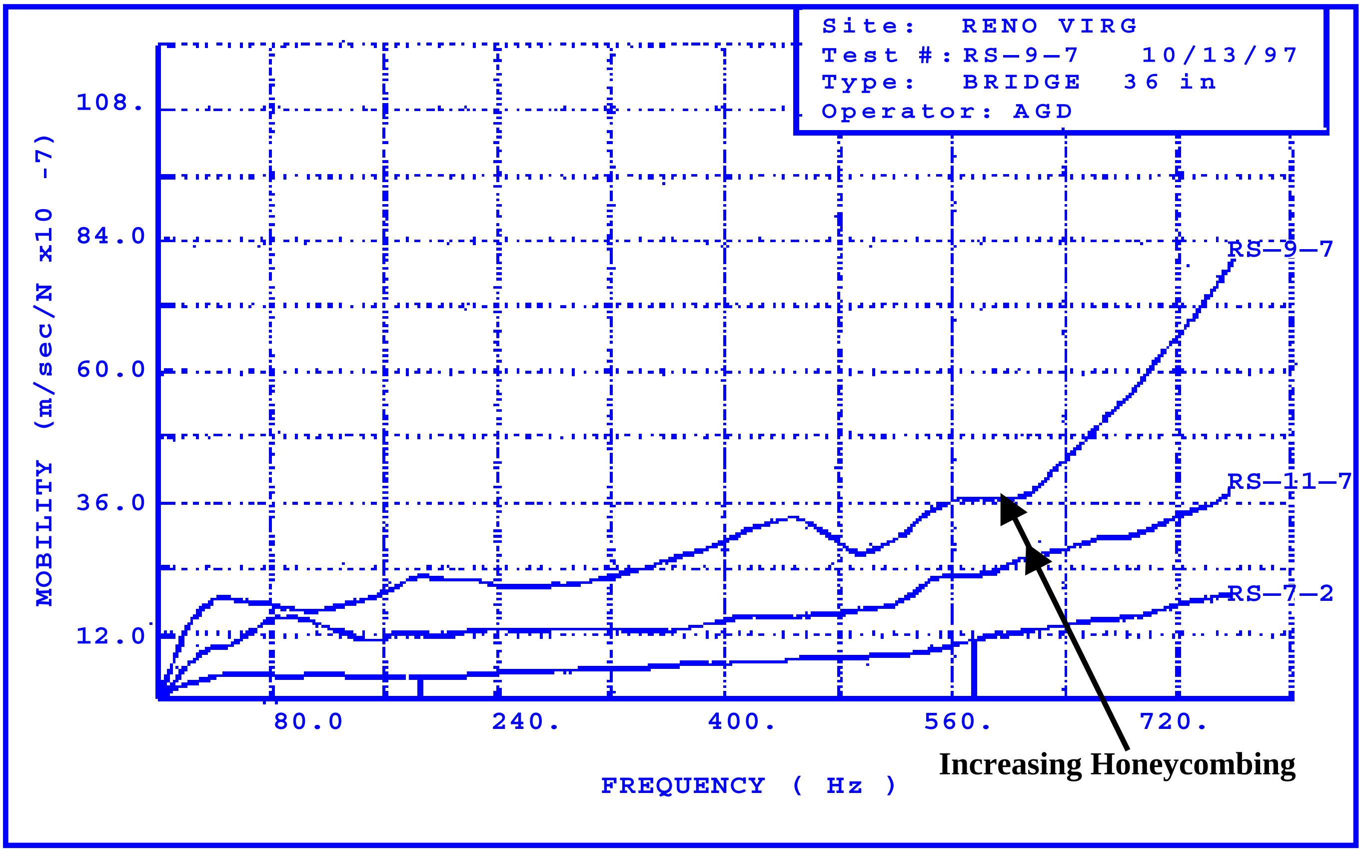

Fig. 1: Examples of IR test responses

for the hammer force and the geophone velocity response are processed in the field computer. The resulting velocity spectrum is divided by the force spectrum to obtain a transfer function, referred to as the *Mobility* of the element under test. Three typical mobility response spectra from one of the bridge arches described in this paper are shown in Figure 1. The test graph of *Mobility* plotted against *Frequency* over 0.1-1 kHz contains information on the condition and the integrity of the concrete in the tested elements, obtained from the following measured parameters:

- *Dynamic Stiffness:* The slope of the portion of the *Mobility* plot below 0.1 kHz defines the dynamic stiffness of the structural element at the test point. Dynamic stiffness is a function of concrete quality, element thickness, and element support condition.
- *Mobility and Damping:* The mean mobility value over the 0.1-1 kHz range is directly related to the density and the thickness of a plate element. A reduction in plate thickness corresponds to an increase in mean mobility. Also, any cracking or honeycombing in the concrete will reduce the damping and hence the stability of the mobility plots over the tested frequency range.
- *Peak/Mean Mobility Ratio:* When debonding or delamination is present within a structural element, or when there is loss of support beneath a concrete slab on grade, in addition to the increase in mean mobility between 0.1 and 1 kHz, the dynamic stiffness decreases greatly. The ratio of the peak below 0.1 kHz to mean mobility indicates the presence of these problems.

In summary, the IR test measures the actual dynamic response of a structure to an impact, and the response will vary depending on concrete quality, presence of defects, element thickness, and element support.

Like the Impulse Response test, the Impact-Echo (I-E) test uses stress waves to detect flaws within concrete structures. However, the I-E test evaluates a much smaller area than the IR test and should be considered as a localized point test versus an area test. The frequency range used is considerably higher in the I-E test, since much shorter wavelengths are required to detect smaller anomalies. The I-E test is capable of detecting flaws in concrete elements, including the depth of the flaw from the test surface. In addition to localized flaw detection, the I-E test can be used to determine the thickness of an element. The authors routinely use a combination of both IR and I-E tests, typically with IR testing first performed on a larger grid to evaluate overall condition, and then I-E tests performed at point locations to further characterize anomalous areas.

Case History 1

The two-span soil-filled spandrel wall arch bridge was built in 1907, and each arch is approximately

18 m (60 feet) wide by 25 m (80 feet) in length. The very limited information that was available suggested that the arches are approximately 1.15 m (45 inches) thick at the springing line, decreasing to 0.6 m (24 inches) thick at the crown, and that they are filled with soil to form the subgrade for the asphalt paving deck. Reinforcement-corrosion-induced spalling was evident on the underside, particularly along construction joints and at the water line. The structural engineer wanted to assess the overall concrete quality, identify deteriorated areas, and determine the arch thickness.

Impulse Response testing was used to locate and map changes in concrete quality, such as the degree of concrete consolidation and the occurrence of delamination around steel reinforcement. A test grid 1.5 x 1.5 m (5 x 5 feet) was set up for the underside of each arch, with access by a bridge inspection snooper truck (Figure 2). Individual IR test results were plotted on the field computer on a grid representing the underside of each arch. After onsite interpretation of the IR tests, Impact-Echo tests were performed at selected locations to measure the thickness of the concrete arch, and to confirm the location and extent of delaminations and cracks. Results from both NDT methods were used to select core locations for correlation of NDT test results.

Sound concrete in structural arches yields constant values of Impulse Response average mobility, indirectly proportional to the concrete thickness. Figure 1 shows three test responses from this bridge with an increasing degree of poor concrete consolidation in the body of the concrete, not visible on the surface. Figure 3 shows an average mobility area plot for the arch undersides and highlights areas with higher mobility values, mainly to the west of the arch crown. These areas of high mobility represent zones of poorly consolidated concrete, a fact that was later confirmed by coring. In addition, there was excellent correlation between arch thickness measured by Impact-Echo and measurements of through-thickness cores.

Fig. 2: Snooper vehicle access

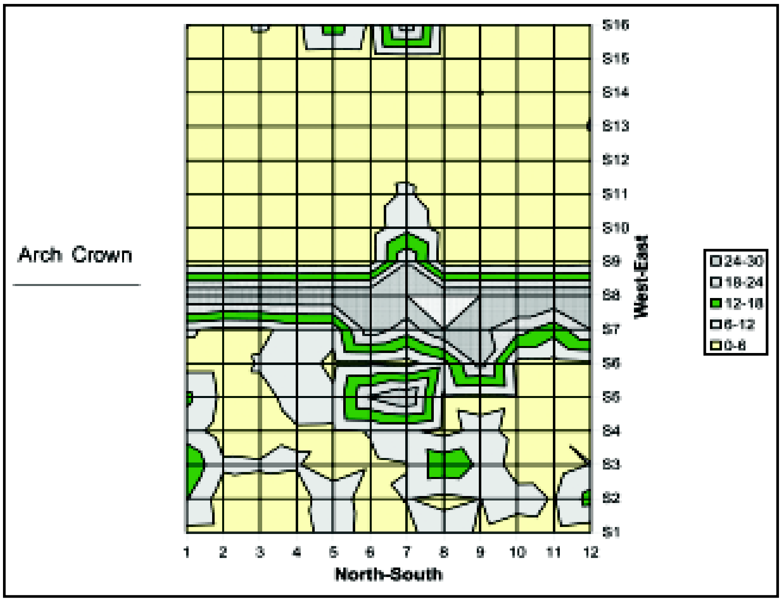

Fig. 3: South arch - average mobility x 1e-7 m/s/N

Fig. 4: Case History 2 bridge

Case History 2

This bridge (Figure 4) is a six-span, cast-in-place reinforced concrete spandrel arch bridge designed by Daniel B. Luten and constructed in 1927-1928. Bridge spans range from 27 to 30 m (90 to 100 feet). Arches measure 3.6 m (12 feet) wide and 0.5 m (20 inches) thick. Spandrel walls support transverse beams that cantilever out approximately 2 m (6 feet) beyond walls and are spaced approximately 2 m (6 feet) apart. Outer portions of the roadway are supported by reinforced concrete decks that span between the cantilevered beams. The center portion of the roadway is supported on fill between the spandrel

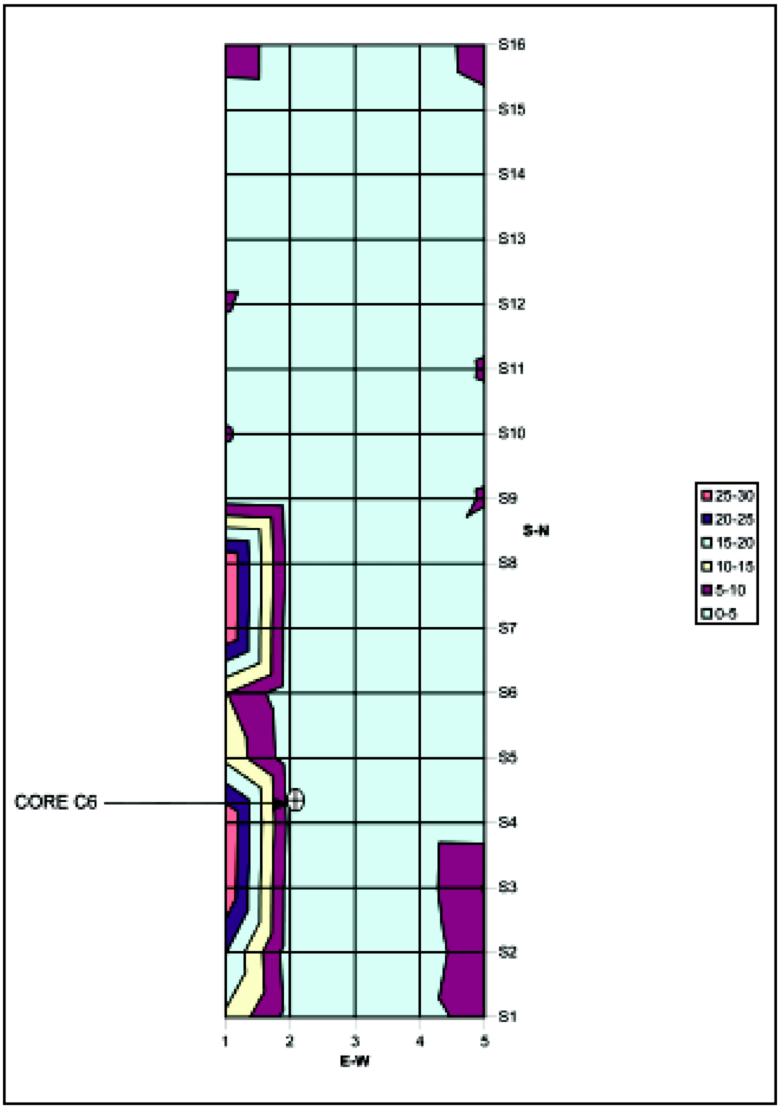

Fig. 5: IR testing revealed areas of high mobility and mobility slope along arch edges, identifying extent of freeze-thaw damage

walls. A combination of visual review, nondestructive testing, and removal of core samples was performed to characterize bridge concrete conditions.

IR testing was performed on the arch rings to delineate areas of concrete freeze-thaw damage and delamination distress. Access for IR testing was achieved using a snooper truck equipped with a work platform. Test results revealed that the center portions of the arches were typically in good condition; however, areas of high mobility and mobility slope were identified along some of the arch edges (Figure 5). Concrete cores removed from the edge portions of the arches confirmed these conditions, which included severe freeze-thaw cracking and some locally delaminated areas.

IR testing also was performed on the spandrel walls. Although the walls appeared to be in generally good condition, IR testing revealed one area of high mobility and mobility slope. Concrete core samples removed from this location revealed freeze-thaw cracking through the full spandrel wall thickness.

Case History 3

This open spandrel single-arch bridge, which was completed in 1929, appeared on the surface to be in very bad condition (Figure 6). The bridge consisted of two short approaches and one 39 m (127 foot) span with a bridge width of 5.5 m (18 feet). However, IR testing along both spandrel arch beams revealed that the interiors of the beams were in relatively sound condition, with good concrete consolidation and little cracking. Most of the damage had occurred because water draining through the deck beam expansion joints flowed down the arches, resulting in freeze-thaw activity in the cover concrete, followed by limited corrosion of reinforcing steel.

Occasionally, the IR tests revealed zones with high average mobility and mobility slope. Core drilling at these locations revealed poorly consolidated concrete, as shown in Figure 7, even though the concrete appeared sound on the surface. Overall, the arches were judged to be in relatively good condition, despite the localized distress. The positive conclusion about the concrete quality in the body of the arches could not have been reached based on visual and invasive testing alone.

Conclusion

The case histories given here illustrate advantages of incorporating nondestructive test techniques in a historic concrete bridge evaluation program. In particular, Impulse Response and Impact-Echo tests give rapid coverage of relatively large concrete volumes, even where access is difficult. Test data are easily stored for future analysis and reference, and test results are repeatable for subsequent follow-up evaluation. Identification of anomalous areas for more detailed, invasive investigation is made at the site, thereby reducing site time and remobilization costs. Cracking, delamination, poor consolidation and freeze-thaw damage can be determined by the nondestructive tests, even when they are not visible at the structure surface.

References

1. Davis A. G. and Hertlein, B. H., "Nondestructive Testing of Concrete Pavement Slabs and Floors with the Transient Dynamic Response Method," *Proceedings of the International Conference on Structural Faults and Repair*, London, July 1987, Vol. 2, pp. 429-433.

2. Davis, A. G. and Hertlein, B. H., "Nondestructive Testing of Concrete Chimneys and Other Structures," *Nondestructive Evaluation of Aging Structures and Dams,* eds. S. Nazarian and L. Olson, Proc. SPIE 2457, Oakland, Calif., June 1995, pp. 129-236.

3. Davis, A. G., Hertlein, B. H., Lim, M. K., and Michols, K. “Impact-Echo and Impulse Response Stress Wave Methods: Advantages and Limitations for the Evaluation of Highway Pavement Concrete Overlays,” *Nondestructive Evaluation of Bridges and Highways,* ed., S.B. Chase, Proc SPIE 2946, Scottsdale, Ariz., Dec. 1996, pp. 88-96.

4. Sansalone, M., and Streett, W. B., “Impact-Echo: Nondestructive Evaluation of Concrete and Masonry,” Bullbrier Press, Ithaca, NY, 339 pp.

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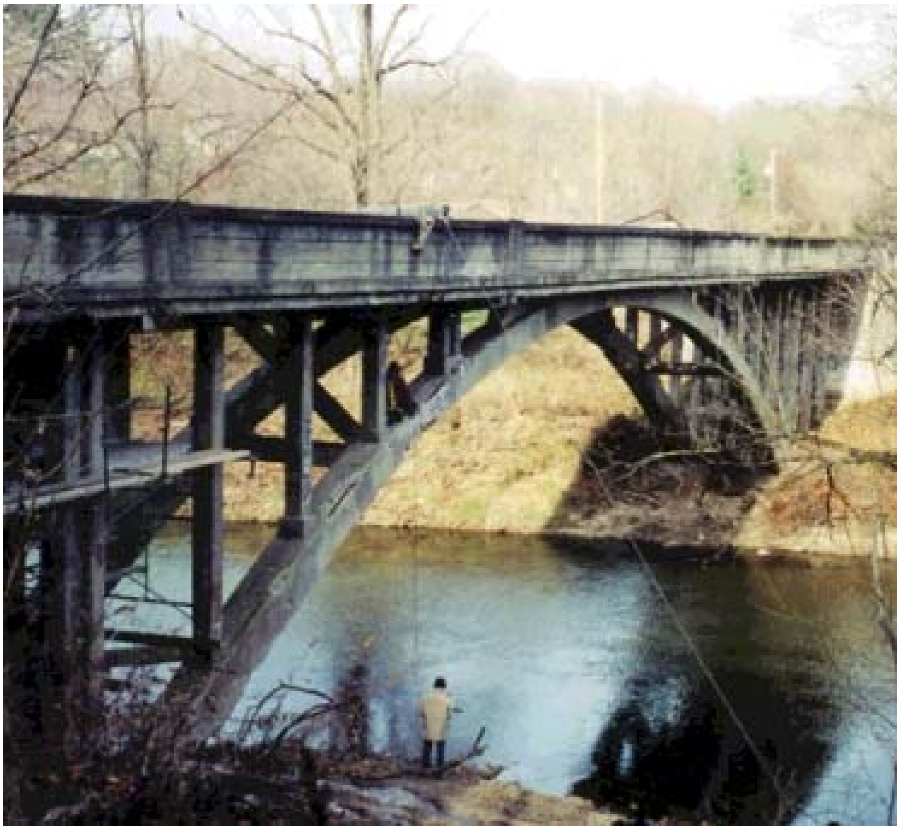

Fig. 6: Case History 3 bridge

Fig. 7: Poor consolidation detected by IR testing, even though concrete surface was sound