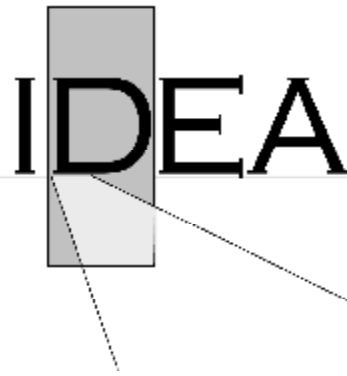


**Innovations Deserving
Exploratory Analysis Programs**



Highway IDEA Program

**INVESTIGATION OF A FULL-LANE ACOUSTIC
SCANNING METHOD FOR BRIDGE DECK
NONDESTRUCTIVE EVALUATION**

Final Report for Highway IDEA Project 134

Prepared by:
John S. Popovics, University of Illinois at Urbana-Champaign

November 2010

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

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November, 2010

TABLE OF CONTENTS

ACKNOWLEDGMENTS	iii
EXECUTIVE SUMMARY	1
BODY OF REPORT	3
INTRODUCTION AND PROBLEM STATEMENT.....	3
IDEA PRODUCT	4
CONCEPT AND INNOVATION	4
INVESTIGATION	5
Literature Review	5
Laboratory Testing Samples	7
Numerical Simulations	7
Development of Source and Sensor Configurations.....	9
Development of Scanning Prototypes	11
Development of Data Acquisition, Manipulation and Presentation Methods	12
Field Verification of Methods.....	15
PLANS FOR PROTOTYPE IMPROVEMENT AND IMPLEMENTATION.....	19
CONCLUSIONS.....	21
INVESTIGATOR PROFILE	22
JOHN S. POPOVICS.....	22
ALEXANDER GIBSON	22
CITED REFERENCES.....	23

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EXECUTIVE SUMMARY

We have developed technology for rapid, contactless, accurate nondestructive evaluation (NDE) of large areas of bare concrete bridge deck structures for corrosion-induced delamination defects. Such damage in bridge decks results in significant costs to infrastructure management agencies. By developing a fully contactless acoustic impact-echo scanning system that incorporates advanced analysis technology, unparalleled bridge deck inspection capability to scan large sections of bridge deck in a timely and efficient manner is enabled. A testing prototype scanning system with an array of sensors has been designed, assembled and tested. The prototype makes use of a moving platform on a wheeled test frame that is designed to be towed behind a survey vehicle, as illustrated in Figure 1. At present, the prototype operates at a human walking pace. The system is designed to provide testing coverage of an entire lane of bridge deck in a single pass. With a modest amount of technical refinement, this technology has potential to bring significant impact to transportation practice; timely and accurate NDE and assessment yield significant benefit for practice through longer-lasting, more cost-effective systems that can better serve the users and reduce congestion and transportation costs while at the same time recouping the yearly high costs associated with bridge deck maintenance.

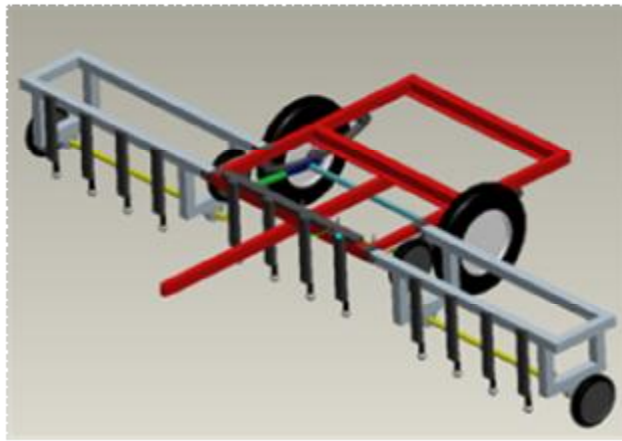


FIGURE 1. Concept of towed bridge deck scanning prototype; testing wings deployed for full-width lane scan.

The fundamental technologies that comprise the testing prototype (wave sources, air-coupled sensors, etc.) were evaluated through experimental tests carried out on concrete slab specimens that contained delamination defects. A range of impact sources were investigated, varying from hardened steel spheres to conventional hand-held hammers. A suitable impact source for detecting delaminations with acoustic sensors should have relatively high force amplitude, relatively low frequency content, and minimal production of ancillary acoustic noise. All of these features are provided by hardened steel spheres (ball bearings) connected to a wire. However, these impactors proved to be difficult to incorporate into the moving testing prototype. Small hand-held hammers were much easier to incorporate into the prototype and worked sufficiently when the vibration of the handle is damped and muted. Several commercially-available air-coupled sensors were investigated for the purpose of detecting seismic signals in concrete, and all of them were able to detect impact-echo and seismic responses from concrete in a fully contactless manner. Of these, conventional vocal microphones provide the lowest sensitivity and frequency bandwidth, but are still capable of detecting impact-echo and seismic data without any external bias or noise shielding in normal, reasonable ambient noise environments. Furthermore the conventional vocal microphones are very rugged, and allow close placement to the surface; in light of the benefits, these sensors were selected for implementation in the area scan testing prototype.

The dynamic finite element method (FEM) was used to compute the seismic response (modal vibration frequencies and shapes) of concrete slabs containing delamination defects subject to a point impact event. Dynamic finite element method (FEM) simulations are helpful when interpreting the complicated dynamic behavior of delamination defects. Our FEM model provided reliable results, which were confirmed by comparison to analytical and experimental data. The FEM results demonstrate that several sets of resonance harmonics are set up when a delamination defect resonates, with each set having a unique frequency and modal shape. Although the frequencies of vibration depend on the relative areal size and depth of the delamination, most resonance frequencies of interest that are related to delamination vibration are below 5 kHz. Thus in our analysis we only considered frequencies up to 5 kHz.

Two different styles of testing prototype were developed: a line scan prototype and an area scan prototype. Our study revealed that the area scan prototype that employs impact-echo analysis was more effective for rapid scanning of bridge decks. The design concept of the area scan prototype is shown in Figure 1. The current version of the area prototype holds twelve unshielded vocal microphones on the testing wings, maintaining regular spacing in between sensors at one foot. The testing axle contains twelve sets of un-instrumented hammer pairs (with insulated handles), which are aligned nearby each microphone. The handle of each hammer is mounted using a two-bar linkage which allows the rotating axle to regularly drive impact event as the trailer moves forward at a human walking pace. The microphones are connected to a 16-channel signal digitizer, which in turn is connected to a laptop computer that acquires, processes and stores the data. Precise location of the testing prototype during a test is obtained by a magnetic wheel sensors and a GPS locator system. The system has a self-contained power supply, which powers all testing components.

Since the hammers are not instrumented in the current design, the signal acquisition must be triggered by the sensor itself. We developed a signal triggering scheme that accounts for this situation and utilizes information from all impact events that are detected by a single sensor. The data collection scheme involves continuous data collection runs for all sensors, which is parsed and processed later. A time/location stamp provided by the wheel sensor and GPS guide the data parsing effort. The collected and processed impact-echo data are presented in a visual format that enables engineers to accurately assess the state of the bridge deck in terms of quantity and severity of near-surface delamination defects. We developed a 3-D, semi-transparent plot presentation format, which we call a “cloud” plot, where all of the spectral data up to a given high end cut-off frequency (usually 4 or 5 kHz) across the area of measurement are presented. High spectral amplitude, which corresponds to measured resonance behavior, are represented by “warm” colors and higher opaque indices. Once the data set is collected, it takes several minutes to manipulate the data and create the image. The impact-echo data collected above a square delamination defect are shown in cloud plot format in Figure 2. The areal extent of the delamination is accurately identified as the rectangular region beneath the clouds. Furthermore, we can identify two layers of clouds, which represent the known fundamental and harmonic modes of vibration for this particular defect. We stress that the frequency of vibration need not be known in advance with the cloud plot configuration; all of the data are collected and presented revealing the full spectrum of vibration.

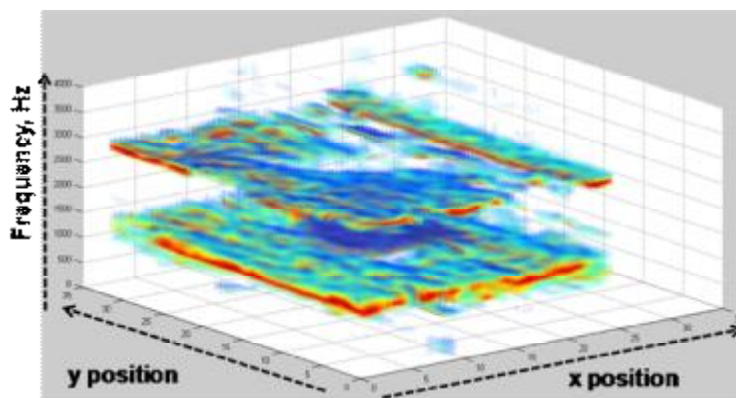


FIGURE 2. “Cloud plot” presentation mode for impact-echo data collected using contactless scanning configuration. The data are presented across a range of frequencies (0 to 4000 Hz).

The basic operation of the area testing prototype was confirmed. However, when the prototype was deployed at our outdoor field test site, the constructed cloud images contained high levels of acoustic noise, which obscured the resonance indications above the defects. Deeper investigation of this problem revealed that the acoustic noise stems from the impactor hammer heads dragging on the rough surface of the test pavement in the moments immediately after impact. However, the utility of the overall approach was verified by collection of impact-echo data at each test location while the prototype is stationary, which restricts the hammer drag after impact. The cloud plot presentations of the impact-echo data collected while the prototype was stationary contain much less acoustic noise, and the indications set up by the local resonances are clearly seen. The image indications provide excellent location characterization of the defects, illustrating the accuracy and reliability of the method once the acoustic noise problem is resolved. The current area scan prototype shows much promise. However problems associated with the rolling impactor configuration, especially high acoustic noise content from rough pavement surfaces, suggests the need for a modest re-design of the rolling impactor configuration. We aim to incorporate improvement to the testing prototype and then deploy it to actual in-service bridges under realistic testing environments and damage conditions found in the field. These efforts should be further extended in future research. Once the acoustic noise in the signal has been improved, the proposed prototype technology and approach offers excellent and reliable identification of delamination defects within concrete.

BODY OF REPORT

INTRODUCTION AND PROBLEM STATEMENT

The United States is served by some of the best transportation infrastructure in the world, however many of the current structures are reaching the end of their service lives. Of the nearly early 600,000 bridges in the United States, 27% were rated as structurally deficient or functionally obsolete in 2003, and many of these are located in the congested northeast and California coast sections of the United States as illustrated in Figure 3. This situation represents a serious problem because all deteriorated infrastructure systems cannot simply be replaced at once, and transportation facilities should not be unduly taken out of service for extended periods of time. Furthermore the cost required to fully renew the American infrastructure is high, with some estimates exceeding \$2.2 trillion over five years (1). So it is clear that “intelligent” renewal, maximizing the return from taxpayers’ dollars used for maintenance and rehabilitation, is necessary. A significant portion of the transportation infrastructure deterioration and maintenance requirements stem from corrosion-based damage in reinforced concrete structures. The cost of corrosion damage to highway bridges in the United States alone has been estimated at \$6 to \$10 billion per year (2). In particular, reinforced concrete bridge decks are problematic; during the life of a typical bridge, the deck is replaced once and repaired frequently because of corrosion-induced delamination (3). A delamination is a planar defect oriented parallel to the surface of the bridge deck that most commonly occurs at the depth of the reinforcing steel in the deck. Currently, the most popular nondestructive method used to detect dangerous delaminations is sounding by chain drag or hammer tap. This process, though somewhat effective, is highly subjective and insensitive to small, irregular or deep delaminations. Furthermore the method requires decreased accessibility of bridges that are under test. These deficiencies have led to a need to create a faster, more efficient way to detect bridge deck delaminations.



FIGURE 3. Location of structurally deficient bridges in the US highway system (4).

Current bridge safety regulations stipulate that bridge decks must be replaced once a critical number of defects are present. The principal problem with corrosion-induced deterioration in concrete decks is that its severity and extent are difficult to assess. The mechanisms of deterioration occur below the surface, and their onset and early manifestations are not readily seen in visual inspections and sounding. More advanced non-destructive evaluation (NDE) methods, such as impact-echo, can accurately detect and locate the internal defects when applied and interpreted properly. However these methods are time consuming to carry out, require the closure of the deck to traffic during testing and in some cases need an expert’s interpretation. Thus the potential of these effective methods is presently under-utilized, and agencies are reluctant to apply them in the field. Instead, agencies are forced to program, prioritize, and budget limited resources for the repair and replacement of many structures whose conditions are virtually unknown. This situation has led to cost overruns and over-repairs, and works against intelligent renewal efforts.

Intelligent renewal of service life is enabled if rapid, accurate and reliable non-destructive scanning technologies (such as that developed here) are applied to assess transportation infrastructure components (e.g. bridge decks) with minimal disruption to structure service. When applied properly, timely and accurate NDE and assessment yield significant benefit for practice though longer-lasting, more cost-effective systems that can better serve the users and

reduce congestion and transportation costs while at the same time recouping the yearly high costs associated with bridge deck maintenance.

IDEA PRODUCT

We have developed technology for rapid, contactless, accurate nondestructive evaluation (NDE) of large areas of bare concrete bridge deck structures for delamination defects. By developing a fully contactless acoustic impact-echo scanning system and incorporating other advanced analysis technology, unparalleled bridge deck inspection capability is enabled, so it is expected that large sections of the deck will be able to be scanned in a timely and efficient manner. A testing prototype scanning system with an array of sensors has been designed, assembled and tested. The system is comprised of a moving platform on a wheeled test frame that is designed to be towed behind a survey vehicle. The system is designed to provide testing coverage of an entire lane of bridge deck in a single pass. The collected data are presented in a visual format that enables engineers to accurately assess the state of the bridge deck in terms of quantity and severity of near-surface delamination defects. The product of this effort has significant potential impact to transportation practice; timely and accurate NDE and assessment yield significant benefit for practice through longer-lasting, more cost-effective systems that can better serve the users and reduce congestion and transportation costs while at the same time recouping the yearly high costs associated with bridge deck maintenance.

CONCEPT AND INNOVATION

In this work we have proposed technology that can provide rapid (in motion) and accurate non-destructive evaluation of large areas of bare concrete bridge deck structures; the concept and principle of the technology are presented in Figure 4. By developing a fully contactless acoustic impact-echo scanning system and incorporating other advanced analysis technology, significantly enhanced bridge deck inspection capability will be provided to infrastructure management agencies. The testing prototype consists of an array of sensors in a wheeled frame configured to be towed behind a survey vehicle. This scanning test prototype enables inspection across the full width of a bridge deck lane in a single inspection pass under continuous motion. The data analysis and imaging procedure employed is based on local air-coupled (contactless) impact-echo measurements; impact-echo has been shown to be the optimal method to characterize delamination defects in bridge deck structures. In the impact-echo method resonance vibration frequencies of a structure, which are set up by an applied impact event, are related to the presences and (in some cases) depth of the defect; see conceptual illustration in Figure 5. With this combination, this effort provides an unparalleled fusion of an accurate and reliable NDT method (impact-echo) with effective scanning and data presentation configuration, not offered by existing inspection technology. Successful application of this innovative technology will have significant beneficial impact to the transportation infrastructure management community.

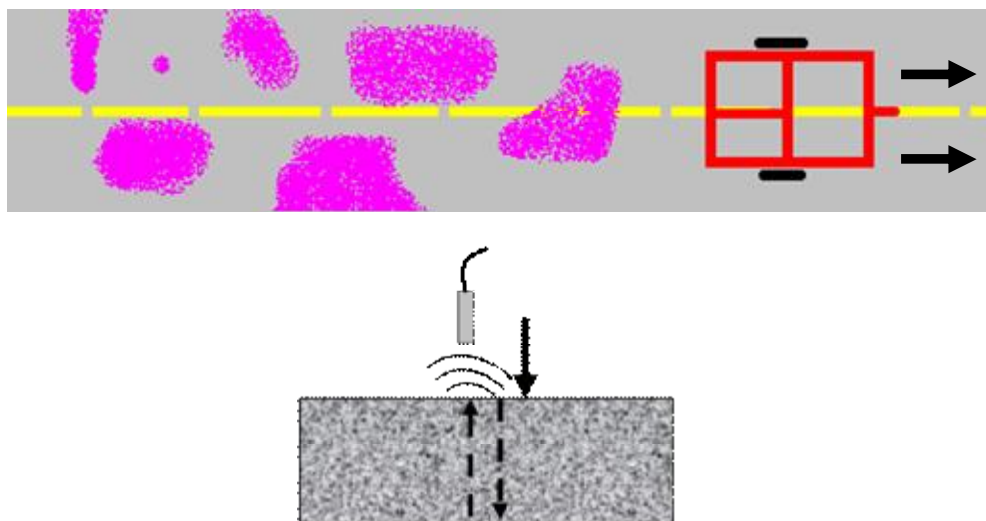


FIGURE 4. Illustration of full-lane bridge deck impact-echo scanning concept: proposed application from a towed platform (top) and illustration of contactless impact-echo sensing (bottom).

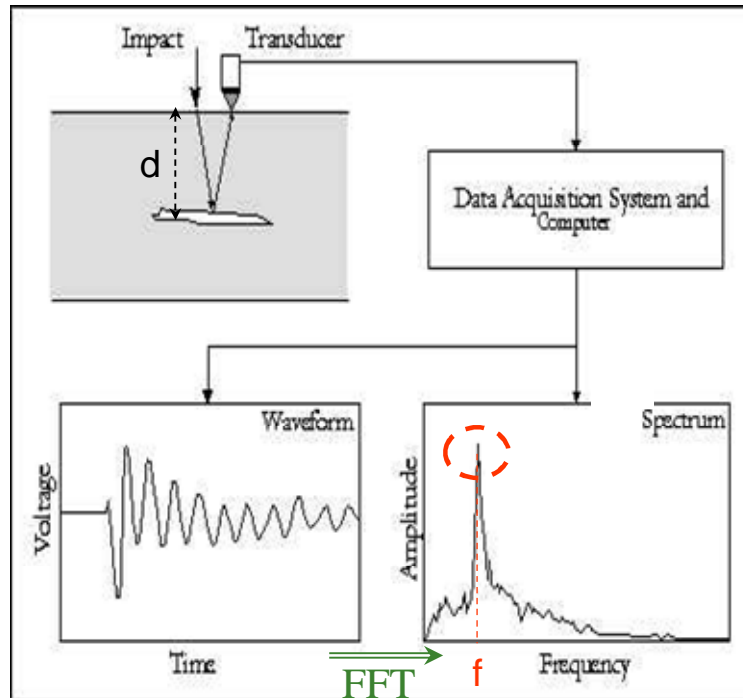


FIGURE 5. Illustration of impact-echo method applied for delamination defect detection.

INVESTIGATION

After a brief literature review, the investigation plan, all results, and the IDEA product are described in this section. The obtained results are evaluated in terms of development and practical implementation of the IDEA product.

Literature Review

When an embedded steel bar mat in concrete corrodes in the presence of oxygen, the expansive iron oxides produced at the surface of the bars generate significant stresses in the concrete, which can lead to concrete cracking. With continued corrosion the cracks tend to coalesce into a large crack plane, parallel to the deck surface and at the depth of the affected reinforcement layer. This defect is called a “delamination,” and it can extend to several meters in length although the width (crack thickness) of the delamination remains quite small; see Figure 6. Often, bridge maintenance efforts focus on monitoring the initiation and development of these delamination defects. Several non-destructive test methods are applied to detect and characterize delaminations, including visual surveys, manual sounding (chain drag, hammer tap) automated sounding (e.g. the “Delamdetect” tool), impact-echo (5), surface wave methods (6), infrared thermography and short pulse radar - also known as ground penetrating radar or GPR. The most commonly applied method is manual sounding, despite problems with operator desensitization and fatigue (7).



FIGURE 6. Illustration of typical bridge deck delamination (8). Note large horizontal extent of the crack compared to depth (~5 cm) and width (~1mm).

All current deck inspection techniques exhibit limitations. Automated sounding methods, such as Delamdetect, are considerably less accurate than manual sounding methods, showing a high false negative indication rate (9). Mechanical wave methods, such as impact-echo, are labor intensive, and surface wave methods cannot reliably detect delaminations in concrete. (10). GPR is often insensitive to the presence of air-filled delaminations. Most methods, for example sounding, mechanical wave and infrared thermography, do not work well to detect delaminations in asphalt-covered bridge decks. (11)

Impact-echo is a proven NDT method, used for the past 25 years for the evaluation of in-situ concrete members such as slabs, pavements and girders (5). Although it is labor intensive to deploy, it offers the most sensitivity to the presence of internal delamination defects. The method is based on frequency analysis of vibrational resonance modes, excited by tapping the structure with a light-weight tuned steel impactor, as illustrated in Figure 5. It should be noted that upper and lower bounds of thickness resolution exist for any given testing configuration, the principal limiting factor being the harmonic properties of the impactor source and the linear range to the receivers. Traditionally, resonance frequency has been associated with the return time of successive P-wave reflections between two adjacent surfaces. More recently, the impact-echo frequency has been identified as the S_1 Lamb wave frequency under resonance conditions, i.e. zero group velocity (12). In either case, the measured thickness frequency (F_t) is defined in terms of material properties and section geometry:

$$F_t = \frac{b \cdot C_p}{2t} \quad (1)$$

where C_p is P-wave velocity, t is section thickness, and β ranges between values of 0.945 to 0.958 for normal concrete material properties. Impact-echo is normally limited to the measurement of a single thickness layer, and results are affected by internal flaws that manifest a reduction in cross-sectional stiffness, such as corrosion-induced cracking and voids. Mechanical discontinuities presented by complete delaminations or poorly bonded cold-joints will result in measurement of the debonded section thickness only. Shallow delaminations and unbounded thin sections give rise to the excitation of a distinct low-frequency flexural resonance mode that is audible to the human ear, and the basis for the acoustic sounding method. The frequencies of such flexural modes of vibration cannot be estimated using Equation 1.

Shokouhi studied the application of the impact-echo method to detect delamination in concrete bridge decks. She found that impact-echo generally is an effective method, although the detectability of delamination defects depends on the relative areal size and depth of the defects, and the position of the impact-echo sensor with respect to the delamination. For optimal detectability, the sensor should be located above the delamination, and the areal size (e.g. diameter) of the defect should be greater than its average depth. She concludes that the impact-echo method can be

improved by deploying multiple sensors, preferably using a contactless air-coupled configuration, together with advanced signal processing methods and visualization techniques in order to present the data in an effective manner (13).

Laboratory Testing Samples

A reinforced concrete test slab was manufactured in order to evaluate the developed technology. This slab simulates a typical bridge deck in the state of Illinois, with a total thickness of eight inches and steel cover depth of approximately two inches. The slab contains different types of pre-placed defects. Corrosion-induced delamination defects are simulated by placing a double layer of thin polymer sheets on top of the steel bar mesh; see Figure 7 for details about the test slab. Although this a relatively large slab, it is too small to enable moving application of the area scan prototype. So this slab served as a well controlled sample to prove to principle of the various developed technologies before being deployed in the testing prototype. Tests were carried out on this slab over large and shallow near-surface delamination defects numbers 6 and 8, since these are expected to produce measureable resonances with predictable vibration frequencies, and also because they serve as reasonable simulations of actual delamination defects.

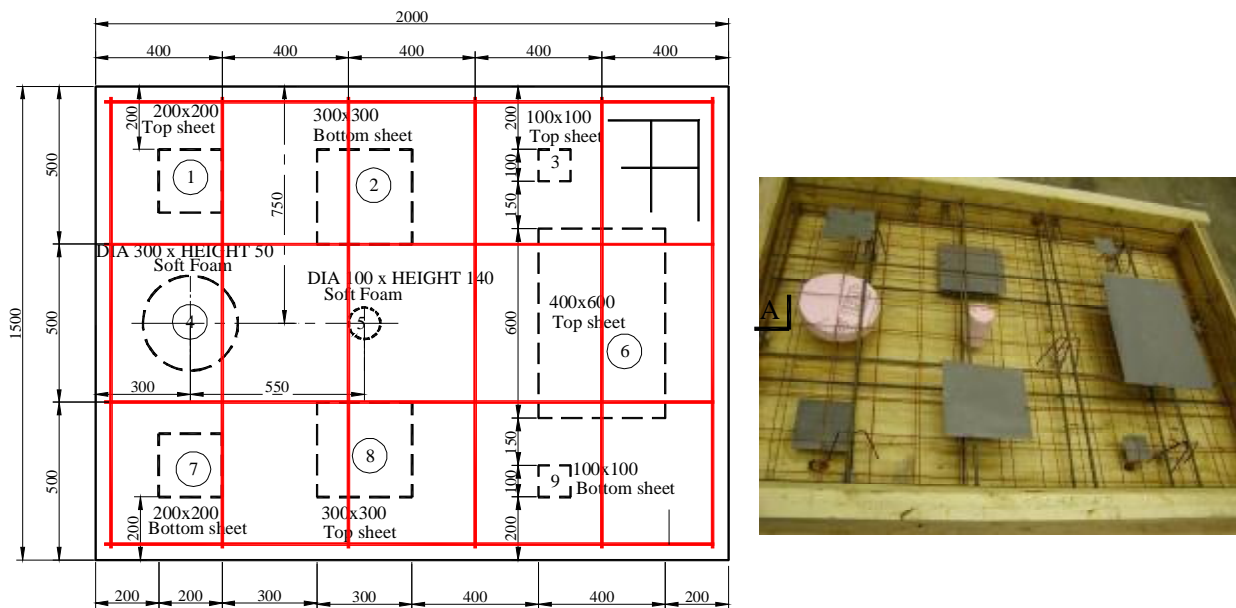


FIGURE 7. Reinforced concrete slab containing internal defects: defect layout plan (left) and photo of slab before casting (right). All dimensions in mm. Verification tests carried out over near-surface delaminations #6 and #8.

Numerical Simulations

The dynamic finite element method (FEM) was used to compute the seismic response (i.e. surface motion) of concrete slabs subject to a point impact event; this serves to simulate the impact-echo method. Both solid slabs and those containing delamination defects were simulated. The purpose of this effort is to gain insight into the dynamic behavior of such structures. ABAQUS software was used to execute the computations. A full 3-D model was constructed, where the delamination defect was simulated by a section of section elements; see Figure 8. A 20mm element was used with a computation time step of 1 μ s. The impact event was simulated by a 60μ s \sin^3 half cycle of 1N peak amplitude force. The computed dynamic responses from the solid slab provided reasonable results, matching expected impact response results obtained by an analytical model. Thus the FEM model was deemed to be sufficient for our simulations. Impact-echo results from the test slab were simulated by computing the Fourier transform (magnitude spectrum) of the dynamic time responses. The results confirmed the expected characteristic low frequency impact echo response when measured over the delamination defect; this response comes from the excitation of the flexural mode of vibration for the material above the delamination. For a delamination with an area of 2400 cm² at a depth of 50mm (delamination defect #6 in

Figure 7), this frequency (fundamental mode) is approximately 1500 Hz. However, we noted consistently higher resonances at approximately 2400 Hz and 3000Hz. An Eigen-mode analysis of the delaminated region showed that these are the higher harmonics of flexural vibration, at 2400 Hz and 3000 Hz respectively for this particular defect. The characteristic mode shapes of the three modes are shown in Figure 9. The obtained results were compared to classical analytical solutions for thin element vibration, and found to compare well, providing confidence in the results.

The developed FEM computation procedure was applied to simulate dynamic response of other laboratory and field specimens, including impact-echo and other seismic methods.

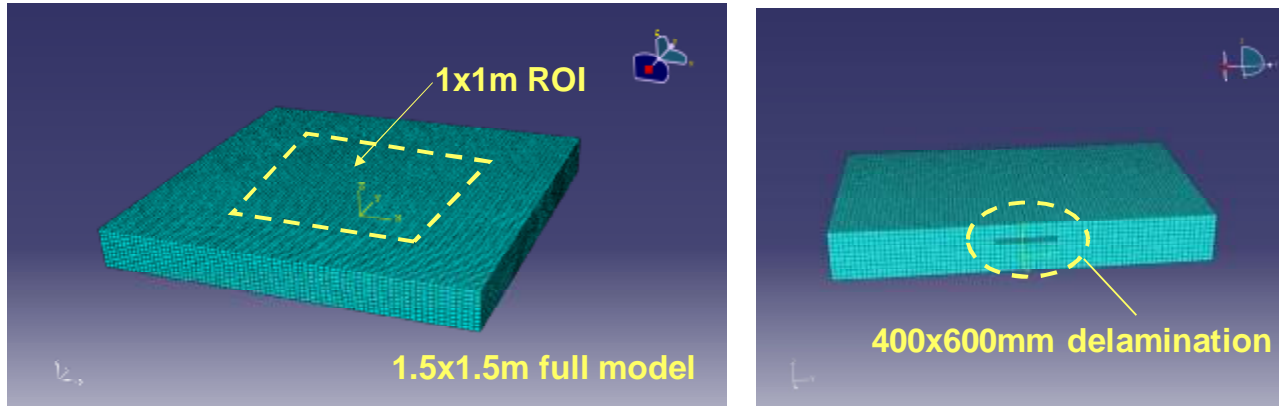


FIGURE 8. Finite element simulation model (FEM) using 20mm element size and 1ms time step: full model (left) and cross-section within region of interest (ROI) showing delamination defect (right). This model simulates defect #6 in the laboratory slab specimen shown in Figure 7

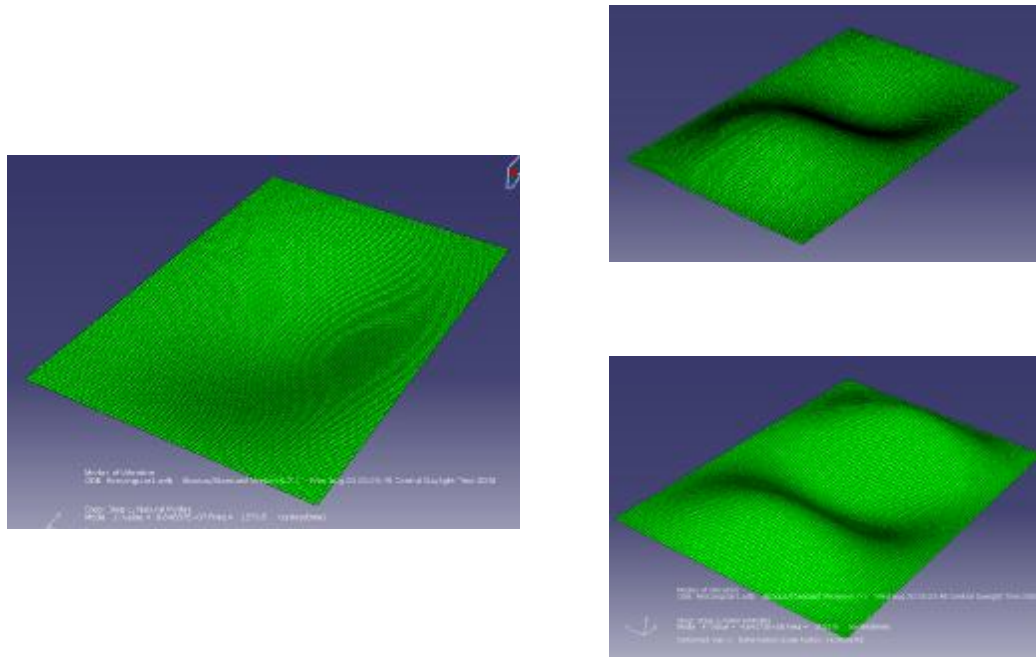


FIGURE 9. Results from FEM simulation for vibration above delaminated area #6 in the test slab shown in Figure 7. Expected mode shapes for fundamental bending at 1500 Hz (left), 1st anti-symmetric harmonic at 2400 Hz (top right) and 1st symmetric harmonic at 3000 Hz (bottom right) are shown.

Development of Source and Sensor Configurations

In the proposed approach, a point impact source of waves (vibration) was employed since they are extremely efficient generators of wave energy in a solid material. However, impact sources vary in applied force amplitude and frequency content. A range of impact sources were investigated, varying from hardened steel spheres to conventional hand-held hammers. One important characteristic of an impact source for the particular circumstances related to this effort is the generation of ancillary acoustic noise, which may obscure the acoustic signal of interest, i.e. the impact-echo or seismic response from the pavement. A suitable impact source for detecting delaminations with acoustic sensors should have relatively high force amplitude, relatively low frequency content, and minimal production of ancillary acoustic noise. All of these features are provided by hardened steel spheres (ball bearings) connected to a wire, shown in Figure 10. However, these impactors proved to be difficult to incorporate into the moving testing prototype. Small hand-held hammers were much easier to incorporate into the prototype and were also investigated. However, the hammer generates much unwanted acoustic noise, and it worked sufficiently only when the vibration of the handle is muted; the muting is achieved by wrapping the handle with insulating foam. The developed impact source is also shown in Figure 10.



FIGURE 10. Impact-echo wave sources employed in the research effort: hardened steel impactor set (left), and 2 oz. ball-peen hammers with varying levels of acoustic damping on the handle (right).

Several commercially-available air-coupled sensors were investigated for the purpose of detecting seismic signals in concrete: broad-frequency high sensitivity industrial sensor, highly focused high-sensitivity “shotgun” microphones, and conventional vocal microphones. A collection of some of the different sensors that were evaluated is shown in Figure 11. Although the different sensors have distinct performance characteristics, all of them were able to detect impact-echo and seismic responses generated by an impact event, from concrete, in a fully contactless manner. A comparison of impact-echo data collected by conventional contact transducer and an air-coupled sensor is shown in Figure 12. Although the signal level from the air-coupled sensor is lower, the spectrum contains the same data as that from the contact sensors: the flexural mode at 2.7 kHz is clearly indicated. In fact, the air coupled sensors contains additional useful information (high frequency stretch mode of vibration at 33 kHz). The broad frequency industrial sensor does provide the highest sensitivity and broadest frequency response – up to 60 kHz – of the various sensors. However, this sensor must be physically shielded from other external ambient noise during operation; this was achieved by forming a foam acoustic shield around the sensor (see Figure 11). Also, this sensor requires continuous external bias (power) to operate. These are significant limitations to incorporation in a testing prototype, although it was incorporated into one prototype design. The shotgun microphone provides good sensitivity without the need for external noise shielding. However the design of the shotgun microphone prohibits close placement of the sensor to the concrete surface, which may be a significant drawback with regard to practical implementation within a scanning prototype device. The shotgun microphone also requires continuous external bias for sensing. These also are significant limitations for incorporation in a prototype. The conventional vocal microphone provides the lowest sensitivity and frequency bandwidth. However, this sensor is still capable of detecting impact-echo and seismic data without any external bias or noise shielding, it is very rugged, and allows close placement of the sensor to the surface. The Shure SM-58 vocal microphone, shown in Figure 11, was selected for implementation in one of the testing prototypes.



FIGURE 11. Contact-less (air-coupled) sensors employed in the research effort: focused shotgun microphone (left), conventional vocal microphone (center) and pre-polarized high sensitivity and bandwidth sensor with acoustic shield (right).

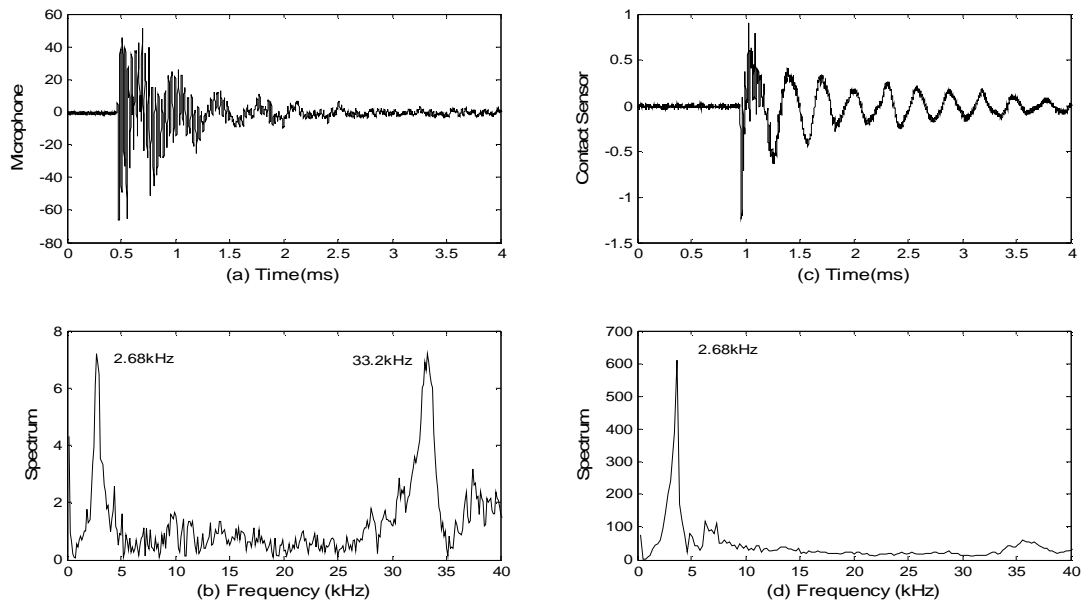


FIGURE 12. Impact-echo results obtained over a delaminated concrete slab using air-coupled (left set) and conventional contact (right set) transducers. Time domain signals are shown on the top and associated frequency spectra on the bottom.

Development of Scanning Prototypes

Two different styles of prototypes were developed: a line scan prototype and an area scan prototype. The developed line scan prototype contains a broadband high-sensitivity directional microphone for recording frequencies up to 100 kHz. Traditional impact-echo sources (small steel impactors) have been incorporated, which are activated at fixed spatial increments by the rotation of the scanner's wheels. The mechanism includes a trigger signal which is provided to the data acquisition system on impact, eliminating the risk of false triggering on background noise. The initial prototype consists of single rolling sensor and impactor units, following a modular design so as to be easily replicated and incorporated into an array on a testing frame.

The design concept of the area scan prototype is shown in Figure 13. This prototype is towed behind a vehicle, and allows for full lane width coverage (12 feet) in a single testing pass when the testing wings are deployed. The testing wings can be secured vertically for street legal transport to the testing site. The current version of the area prototype holds twelve unshielded Shure SM58 microphones on the testing wings, maintaining regular spacing in between sensors at one foot. The prototype features an additional testing axle that can be lowered from a secure position for testing. The testing axle contains twelve sets of un-instrumented hammer pairs (with insulated handles), which are aligned nearby each microphone. The handle of each hammer is mounted using a two-bar linkage which allows the rotating axle to regularly drive impact event as the trailer moves forward. This configuration can be moved no faster than a human walking pace. Impact events are separated by approximately 1 foot intervals (with respect to the movement direction) as the trailer rolls forward. Detail of the testing axle, mounted impact hammers and suspension are shown in Figure 14. The microphones are connected to a 16-channel signal digitizer, which in turn is connected to a laptop computer that acquires, processes and stores the data. Since the hammers are not instrumented in the current design, the signal acquisition must be triggered by the sensor itself; this requires precise control of the sensor position and trigger threshold parameters in order to collect meaningful data. Precise location is obtained by a magnetic wheel sensors and a GPS locator system. The system has a self-contained power supply, which powers all testing components. With this testing configuration, it is possible to optimize the sensing configuration to collect useful data, even in an unregulated outdoor environment.

The basic operation of the testing prototype was confirmed through tests on a long stretch of concrete floor. We were able to continuously collect (while moving) usable impact-echo data in a normal, uncontrolled ambient noise environment. When the triggering is assigned to a single sensor, the collected data from that particular sensor are clean, consistent and useable for impact-echo analysis. Thus fundamental testing concerns about ambient noise, and consistent signal triggering were addressed. However the neighboring sensors also collect data generated by the impactor near the first sensor. Thus we developed an alternative signal triggering scheme that accounts for this situation and utilized information owing to all impact events that are detected by a single sensor. The data collection scheme involves continuous data collection runs for all sensors, which is parsed and processed later; this signal processing effort takes several minutes when carried out on a standard pc computer. A time/location stamp provided by the wheel sensor and GPS guide the data parsing effort.

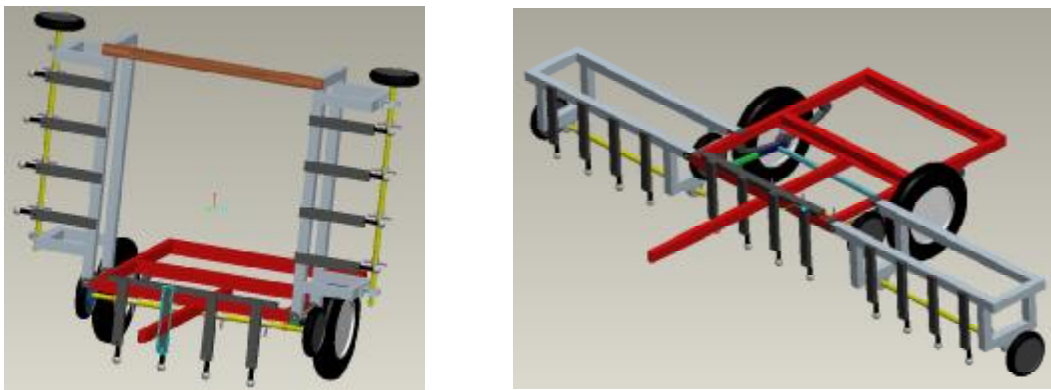


FIGURE 13. Concept of towed bridge deck scanning prototype: testing wings stowed for transport (left), and testing wings deployed for full-width lane scan (right).



FIGURE 14. Detail of developed bridge deck scanning prototype: axle-driven impactor system (left), and testing hardware including self-contained power supply, 16-channel DAQ and computer, and GPR locator system (right).

Development of Data Acquisition, Manipulation and Presentation Methods

Self-contained data acquisition and analysis software have been developed using a MATLAB[®] platform. The software provides data acquisition and data analysis capabilities for impact-echo and other seismic methods, including digital data acquisition, Lamb wave dispersion analysis, and 3-D imaging to interpret the data. Digital signal processing capabilities such as filtering, windowing, zero padding are provided. All data shown in this report are collected and processed with the developed software packages.

When an impact event is applied to the surface of a solid, P-waves, S-waves and surface waves are generated. Multiply-reflected P- and S-waves set up resonances within the structure, such as the impact echo thickness mode and flexural modes above a delamination defect. The seismic response (characterization of surface-guided waves) can also be used to characterize the structure, for example by implementing the MASW protocol, Lamb wave dispersion analysis, or other seismic analysis methods. The various types of seismic tests can be conceptually represented in normalized frequency time space, as represented in Figure 15. Theoretical modal arrivals are calculated based on group velocity dispersion at a given offset. The superimposed blue curve shows time and frequency domain FEM response for matching geometry, with higher order modes present depending on the frequency content of the source. As illustrated in Figure 15, seismic phenomenon is characterized in the early portion of the time signal where, in terms of a Lamb wave analysis, the behavior is dominated by s_1 mode resonance and a_0 and s_0 mode propagation. On the other hand the impact-echo phenomenon is characterized by the latter complete part of the time signal, where the dominant propagating mode is the Rayleigh surface wave (asymptotic a_0 and s_0) and s_1 resonance. All of these methods can be carried out using microphones as sensors. However, our experimental tests demonstrate that resonance type behavior is easier to measure, with higher signal-to-noise ratio, than seismic behavior using air-coupled sensors. For this reason, we focused on implementation of the impact-echo method, which is a resonance method, in the testing prototype.

Since impact-echo represents a local characterization about the tested surface point, the relative positions of impact event, sensed point and location of delamination are important. We carried out a test series to investigate this issue. Figure 16 shows air-coupled impact-echo data collected and analyzed with the developed software. The plots show the effects of relative source-sensor position, with respect to defect (delamination) position, on the obtained impact-echo results. The high sensitivity industrial microphone (shielded) is used to sense the response over delamination #8 in the concrete slab specimen. Similar results were obtained using the conventional vocal microphone. In the tests, the air coupled sensor was positioned above the center of the delamination defect, and a series of impact events were applied at locations both above and outside of the same delamination defect. In another test series, the site of the impact point was fixed at the center of the defect, and the sensed point was moved away until it was beyond the extent of the defect. The results indicate that the expected “flexural” mode of vibration (approx. 5 kHz) is excited and dominates the spectral response when both the impactor or sensor are located above the delamination area. The more interesting and unexpected result was that this same mode dominated the spectrum even when the impact site was well outside of the delamination area, as long as the sensor was above the defect. This is seen in Figure 16 for impact case “E”: the 5 kHz resonance still dominates even though the impact source is away. Conversely, the full thickness (defect-free) vibration mode dominated the spectrum when the sensor was located outside of the extent of the defect, regardless of the location of the impact event.

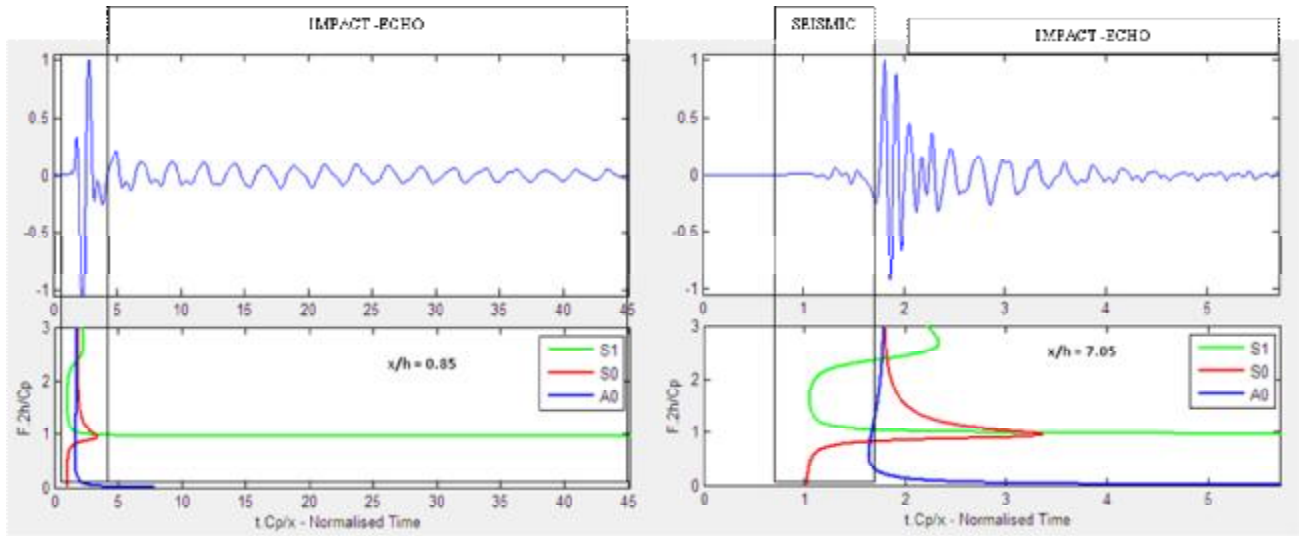


FIGURE 15. Numerical illustration of effects of source-receiver spacing on analysis approach of results, expressed in terms of time domain response (top set) and normalized group velocity curves (bottom set). Close spacing (left set) promotes measurement of impact-echo resonances. Far spacing (right set) enables measurement of seismic responses in addition to resonances.

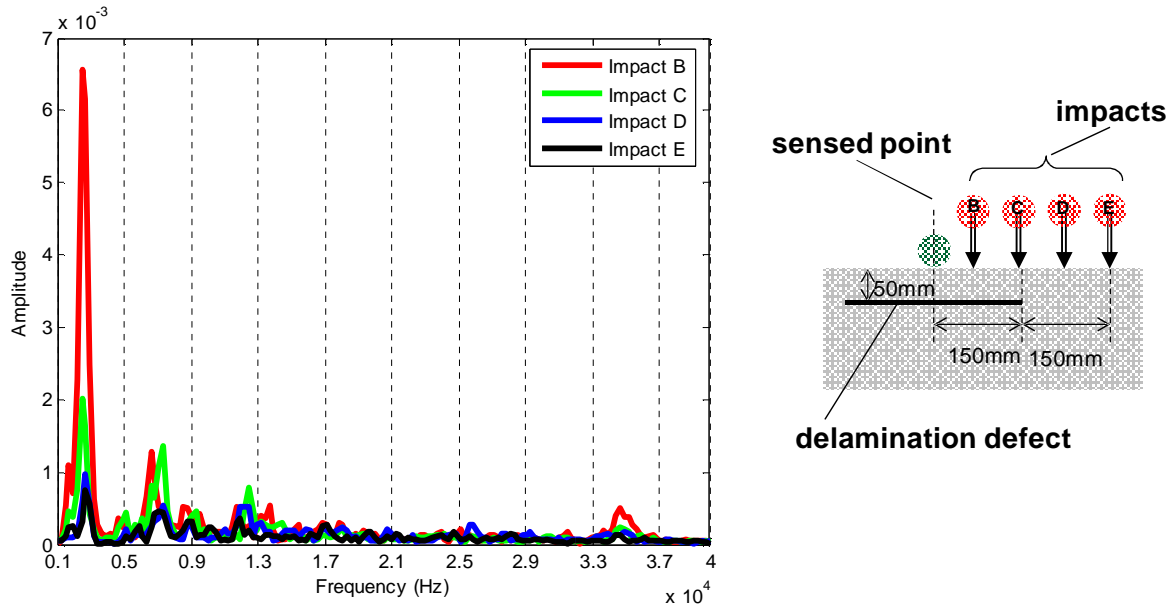


FIGURE 16. Experimental study of effects of relative defect – test configuration position collected above delamination #8 shown in Figure 7: obtained impact-echo spectral results (left), and positioning of impactor and sensor with respect to defect (right). Sensor is fixed above center of defect and impact position is moved. Fundamental bending mode expected at 5 kHz.

The preliminary tests confirm that the impact-echo frequency measured by an air-coupled sensor represents the impact-echo resonance of that sensed location, regardless of where the impact event is applied as long as sufficient mechanical energy is supplied. This finding is significant, as it enables us to construct “maps” of vibration resonance activity at the surface based on individual, local impact-echo measurements that reflect the defect character within the slab. However, there are several different ways to construct these maps and present the data. For example, the data can be presented in line-scan or area-scan formats, and furthermore several different types of area scan formats are possible. Considering the options, we investigated the best data presentation format for the impact-echo data. At the outset, we determined that area scan presentation is more appropriate for rapid and effective interpretation of data from large areas of bridge decks. We collected a set of impact-echo data over a defect (delamination #6) in the laboratory test slab, where air coupled impact echo data were collected at 2.5 cm spacing in a grid around the area above the defect. Two types of area scan images, which are constructed from this data, are presented in Figure 17. In the images, “warm” colors indicate high signal amplitude, and the actual boundaries of the defect are indicated with red dashed lines. In this format, the data at a pre-determined frequency “slice” are presented. Based on our FEM Eigen mode computations, we expect the fundamental flexural mode for this defect to occur at 1500 Hz. Clear indications of high amplitude in the frequency spectra are seen at that frequency when the sensor is located above the defect, and the expected mode shape is captured. Presentations at other (higher) frequencies reveal that the proper frequencies and mode shapes of the higher resonances match those predicted by our FEM computations, which are shown in Figure 9. Clearly we can excite and identify the correct vibration mode for the defect, and we conclude that the proposed air-coupled impact echo testing configuration is sensitive enough to capture meaningful data from defects. In these area scans, the signal amplitude at a specific frequency is plotted across the tested area; again, warm colors indicate high signal amplitude. The plot frequency was selected to match that of the fundamental and first harmonics of the flexural vibration of the defect. Clearly, the extent of delaminated area is indicated by high amplitude at these various frequencies. This sort of data presentation offers an effective manner to indicate the location and extent of delamination in an image. However this data presentation format contains a significant drawback: the frequency of the plot must be determined a priori. The frequency of flexural vibration of a delamination defect depends on the areal extent, shape and depth of a delamination. In an actual bridge deck structure, these defect characteristics cannot be known in advance, although we would expect all meaningful frequency indications to be less than 5 kHz. A more feasible approach would be to plot all of the data – across all frequencies of interest and area – at once, thus eliminating the problem of not knowing the frequency of interest in advance.

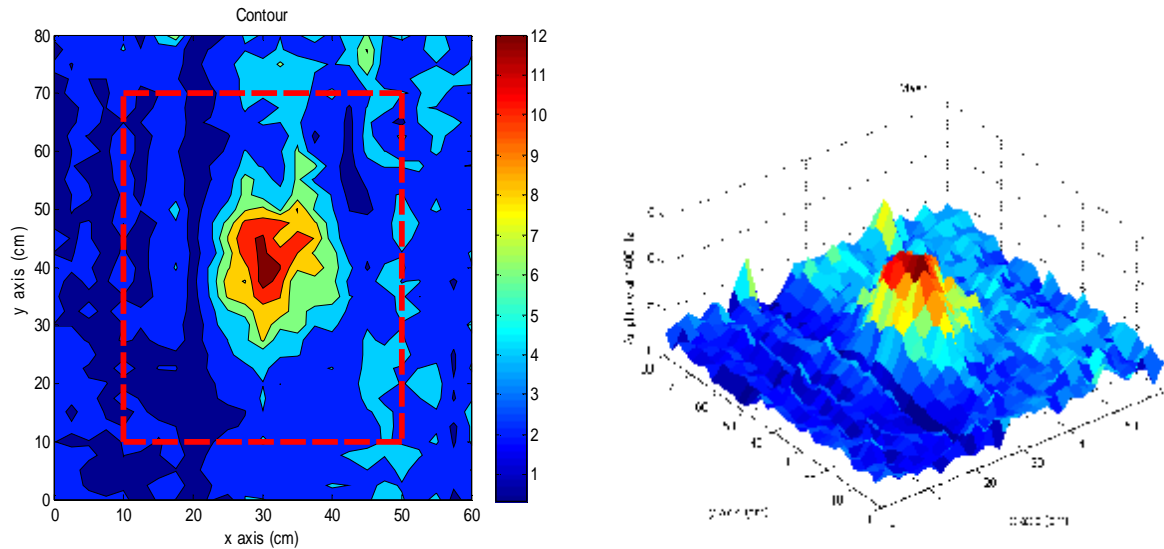


FIGURE 17. Data presentation modes for impact-echo data collected above delamination #6 shown in Figure 7. The data are presented a given frequency (1500 Hz): area contour plot format where delamination indicated by red dashed line (left), and area 3-D mesh plot format (right). Fundamental bending mode expected at 1500 Hz.

In order to present all of the data effectively in an area scan format, we developed a 3-D, semi-transparent plotting format, which we call a “cloud” plot. In a cloud plot, we present all of the spectral data up to a given high end cut-off frequency (usually 4 or 5 kHz) across the area of measurement. High spectral amplitude, which corresponds to measured resonance behavior, are represented by “warm” colors and higher opaque indices. In other words, low signal amplitude portions of the signal become transparent, and we can see through these insignificant portions of the signal to reveal the resonances in the plot. The impact-echo data shown in Figure 17 are reconfigured as a cloud plot in Figure 18. In this plot, the spatial dimensions (x and y position) are represented as sensed position point, where each point is separated by 2.5 cm. The areal extent of the delamination is accurately identified as the rectangular region beneath the clouds. Furthermore, we can identify two layers of clouds, which represent the known fundamental and first harmonic modes of vibration for this particular defect. This behavior serves as confirmation that we are indeed measuring flexural resonance behavior of a delamination defect. We stress that the frequency of vibration need not be known in advance with the cloud plot configuration; all of the data are collected and presented revealing the full spectrum of vibration. An addition strong feature of the cloud plot software that we developed is the ability to “grab” and rotate the plot in order to change the perspective of the viewer. For example, a 3-D isometric plot, such as that shown in Figure 18, can be rotated to show an x-y plot (perspective from top) or an x-frequency plot (perspective from side).

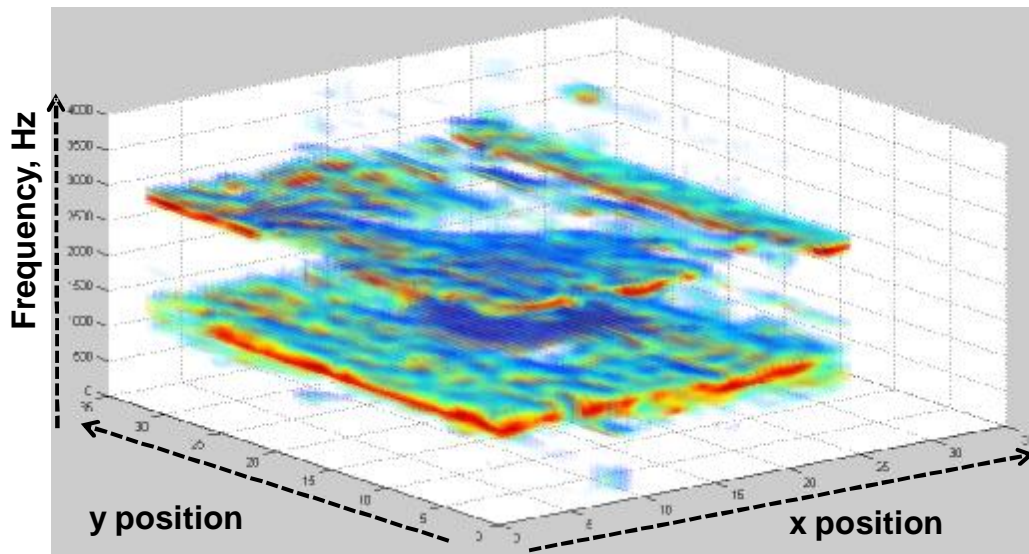


FIGURE 18. “Cloud plot” presentation mode for impact-echo data collected above delamination #6 shown in Figure 7. The data are presented across a range of frequencies (0 to 4000 Hz). Fundamental bending mode expected at 1500 Hz and 1st symmetric mode at 3000 Hz. Sensed position points (x and y position) separated by 2.5cm.

Field Verification of Methods

The utility of air-coupled impact-echo and plot imaging was verified through small-scale experimental tests carried out in a laboratory setting. In a parallel effort, a towed testing prototype was designed, constructed and the basic operation was verified. To confirm the field performance of the testing prototype equipment and analysis scheme, a full-scale concrete slab delamination sample was constructed and experimental test series was carried out on it. The test slab was cast at the ATREL test facility of the University of Illinois, shown in Figures 19 and 20. Six sites of delamination were cast with areal sizes ranging from 0.25m² to 1m² at two different depths: 25 mm and 50 mm. Five of the defects are flat and parallel to the top surface of the slab, and the remaining one is flat but slants at an angle with respect to the top surface. The delaminations vary in size to represent the realistic range of delamination defects in terms of absolute area and depth to size ratio. The delamination defects were simulated by a double-layer of poly-ethylene sheeting cut to appropriate size and were attached to a precast base layer of concrete. Then another layer of concrete was cast over top. An FEM Eigen mode computation was carried out in order to determine the expected frequencies of the values orders of

flexural modes for each defect. The results of those computations for defects numbers 4, 5 and 6 (50 mm depth) are shown in Table 1. Note that the frequencies of the first three flexural modes for all delaminations are expected to occur below 4 kHz.

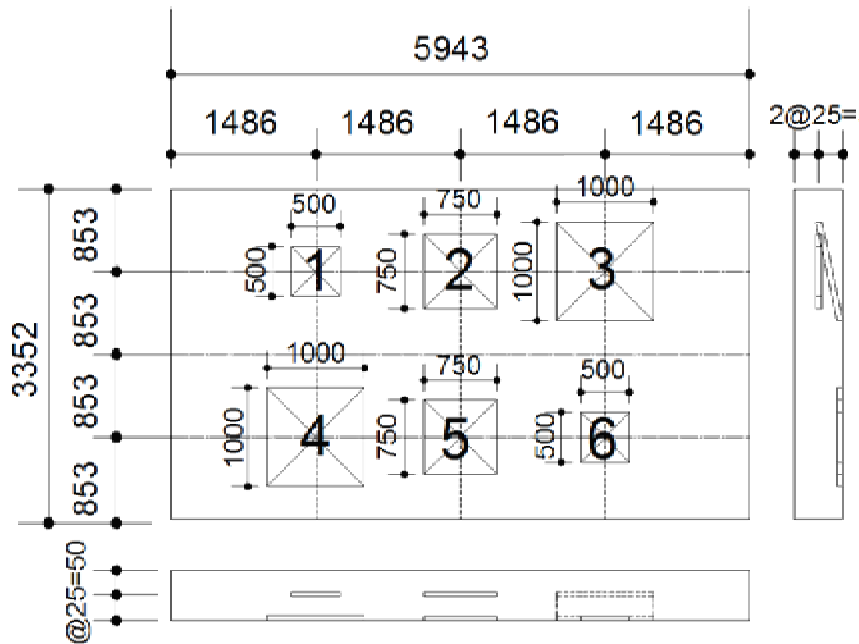


FIGURE 19. Plan for full-scale concrete slab delamination test specimen, constructed and cast in July 2009. Six delaminations are identified by number. All units in mm.



FIGURE 20. Construction of full-scale concrete slab delamination test specimen, constructed and cast in July 2009; placement of six artificial delaminations before final cast (left) and after final casting (right).

TABLE 1. Vibration mode frequencies predicted using FEM simulation, for delamination defects 4, 5 and 6 shown in Figures 19 and 20. The depth of these delaminations is 50 mm. All frequencies in units of Hz.

Mode	Delam 4	Delam 5	Delam 6
1st (sym)	316	553	1187
2nd(anti-sym)	634	1093	2280
3rd(sym)	1115	1895	3829

The testing prototype was verified at the field test site. Data from all delaminations (1 through 6) are presented here. The prototype was configured with the axle-driven damped hammers, vocal microphones and computer hardware as shown in Figure 14. The data were collected continuously for all sensors and were subsequently parsed and processed. The time/location stamp was provided by the wheel sensor - GPS system. The prototype was towed across the test slab in the axial direction so that delamination numbers 4 ,5 and 6 were scanned in one pass, and delaminations 1,2 and 3 in a second pass. The prototype did operate well and data were collected and processed. However, the constructed cloud images contained high levels of acoustic noise, which obscured the resonance indications above the defects. An example of a noisy cloud image is shown in Figure 21, where no useful information about defects is seen. Deeper investigation of this problem revealed that the acoustic noise stems from the impactor hammer heads dragging on the rough surface of the test pavement in the moments immediately after impact. We had not noticed this problem before because verifying tests in the laboratory were carried out on smooth finished concrete surfaces, which are not realistic representations of actual bridge decks. Therefore this operational problem must be solved before the prototype can be realistically applied to a bridge deck. However, the utility of the overall approach can still be verified if we temporarily eliminate the noise from dragging. This was achieved by collection the data at each test location while the prototype is stationary, and thus the hammers will not drag after impact. In order to do this, we moved the prototype to a test position and then manually activated each hammer so that data were collected from each of the sensors. Although not practical for field use, this procedure enabled us to evaluate the overall utility and sensitivity of the approach, thus providing guidance on how to improve the prototype for eventual field application. The cloud plot presentations of the impact-echo data collected while the prototype was stationary are shown in Figures 22, 23 and 24: Figure 22 shows the 3-D isometric perspective, Figure 23 the x-frequency perspective, and Figure 24 the x-y perspective. Clearly, these figures contain much less acoustic noise, and the indications set up by the local resonances are clearly seen. Since the frequency of the image indications (i.e. “cloud” layers) agree with those predicted by the FEM analysis, as shown in Figure 23, it is certain that they are set up by the flexural resonances of the defects. The image indications provide excellent location characterization of the defects, as shown in Figure 24: the edges of the cloud layers coincide very well with the actual boundaries of the defects shown with red dashed lines. Very few indications are seen outside of the defect boundaries, illustrating the accuracy and reliability of the method once the acoustic noise problem is resolved.

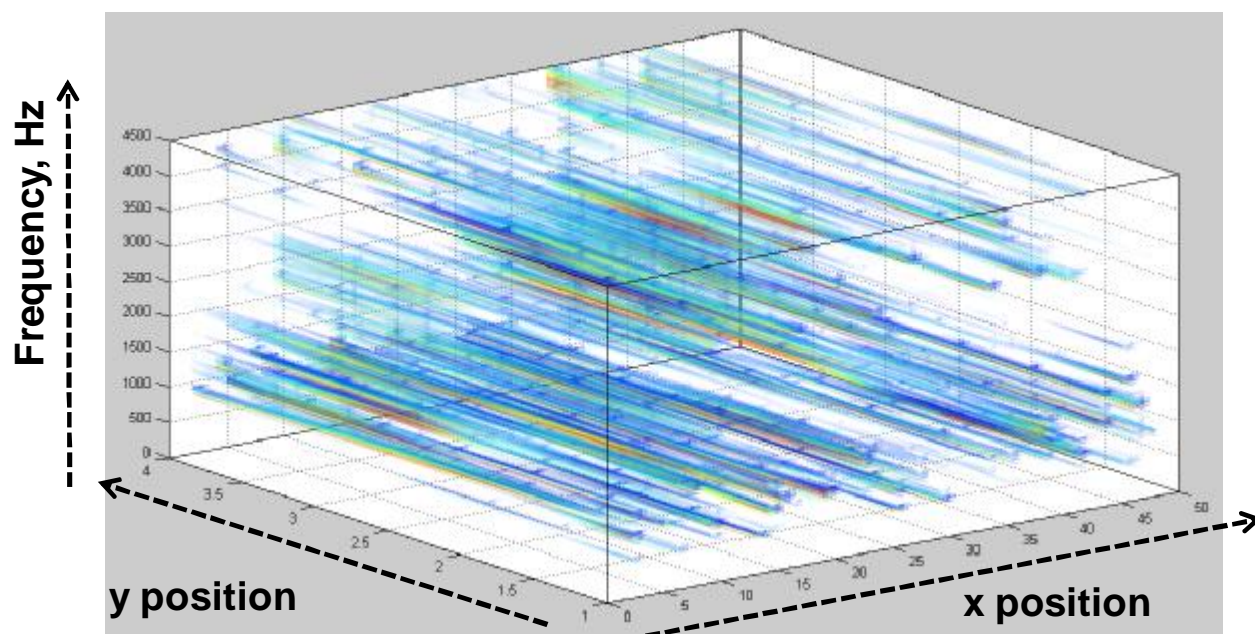


FIGURE 21. 3-D cloud plot image of scan data from the *moving* testing prototype collected along parallel test lines across defects 1 through 6 shown in Figures 19 and 20. Sensed position points separated by 20cm in x direction and 28cm in y direction.

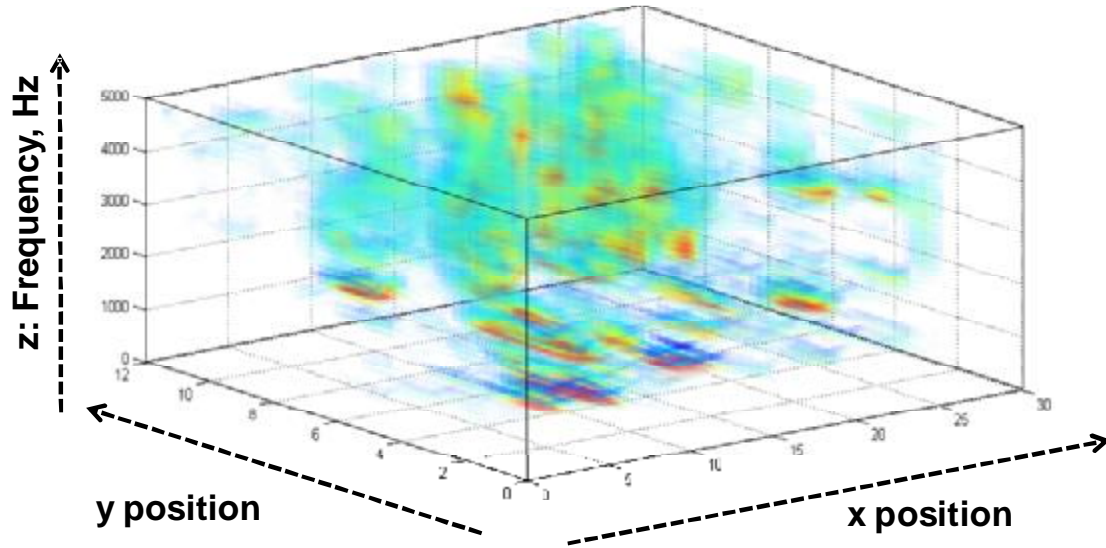


FIGURE 22. 3-D cloud plot image of scan data from the *stationary* testing prototype collected along parallel test lines across defects 1 through 6 shown in Figures 19 and 20. Sensed position points separated by 20cm in x direction and 28cm in y direction.

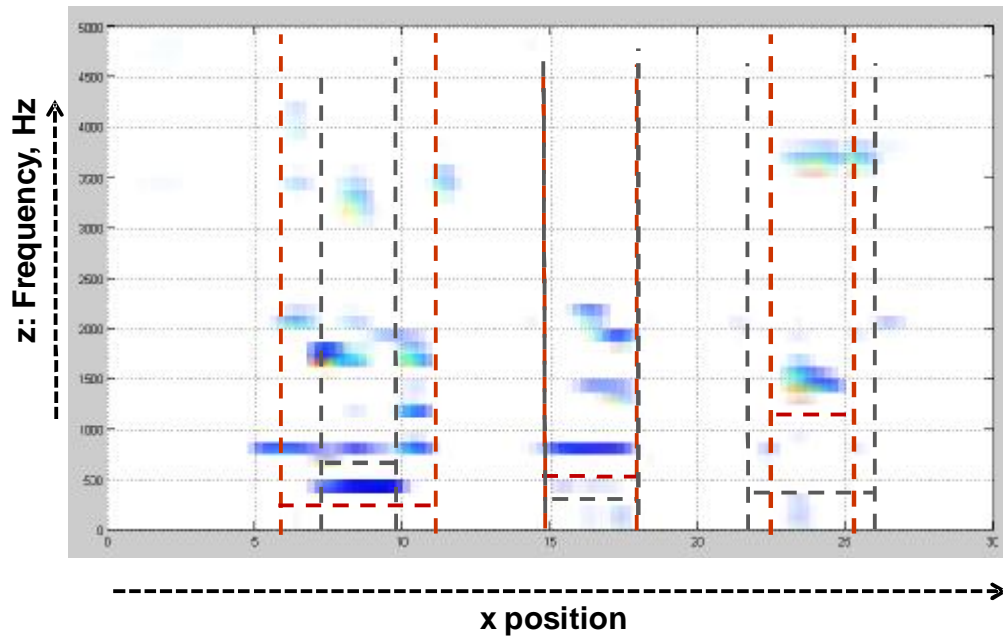


FIGURE 23. x-frequency perspective of the 3-D cloud plot image from the stationary testing prototype shown in Figure 22. The grey vertical lines indicate boundaries of the defects 1,2 and 3 and red vertical lines indicate defects 4,5 and 6. The expected fundamental flexural frequency for each defect, as computed by FEM simulation, are indicated by horizontal dashed lines. Plotted sensed position points (x position) separated by 20cm.

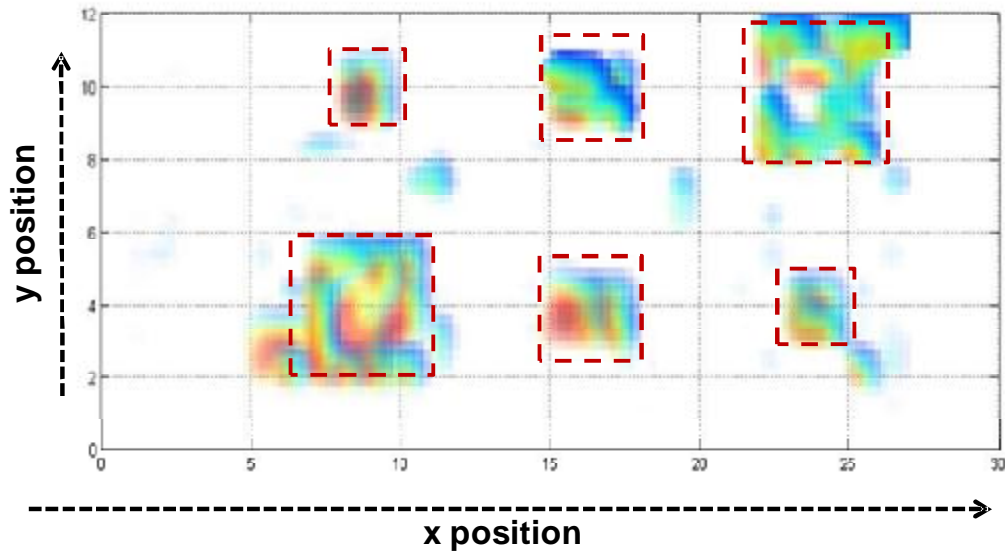


FIGURE 24. x-y perspective of the 3-D cloud plot image from the stationary testing prototype shown in Figure 22. The red dashed lines the actual boundaries of the defects. Sensed position points separated by 20cm in x direction and 28cm in y direction.

PLANS FOR PROTOTYPE IMPROVEMENT AND IMPLEMENTATION

In order to achieve real implementation of the developed technology to the field, several final improvements to the testing prototype must be applied. Then, collaborative and cooperative activities with potential users of the developed technology should be sought. Future efforts to achieve both of these goals are described in this section.

The current area scan prototype shows much promise. However problems associated with the rolling impactor configuration, especially high acoustic noise content from rough pavement surfaces, suggests the need for a re-design of the rolling impactor configuration. Several new designs are being considered, which are based on the concept modular non-contact, rolling impactor elements, allowing a degree of configuration adaptability to optimize different methods and atypical highway configurations. One possible configuration is shown in Figure 25, where innovative features of this equipment include the incorporation of an instrumented high-frequency single-impact mechanical source. This facilitates triggering at the precise excitation time for time-domain data analysis and further allows characteristics of the impact (namely contact duration and force history) to be recorded. The impactor would be mechanically driven with an electromagnetic actuator, favoring both acquisition speed and repeatability of testing results.

In order to be effective and meaningful, the developed technology must be accepted and applied by infrastructure management agencies. We aim to subject the final improved equipment and analysis method to actual in-service bridges under realistic testing environments and damage conditions as they occur in the field. Although this phase of the work extends beyond the formal funded period of the project, the investigators will attempt carry out this work using their own funds, since they feel it is a critical aspect of the whole effort. This effort will include significant cooperation and in-kind contribution from the Illinois Department of Transportation (IDOT); an agreement to this effect has already been established between the investigators and IDOT: IDOT will provide access to several bridge deck structures structure for application of the prototype testing equipment. The specific bridge structures are indicated in Figure 26. These structures have bare concrete bridge decks that likely contain internal damage (e.g. corrosion-induced delamination) and are scheduled to be inspected by IDOT using their conventional inspection methods (visual inspection and chain drag sounding). IDOT will share these findings for comparison with scanning impact-echo data obtained from the testing prototype. Close interaction with IDOT staff (technicians and engineers) will be maintained throughout the tests. IDOT staff will be invited to participate in the testing efforts, and feedback from them about the equipment, analysis and effectiveness will be solicited and incorporated in the final report.

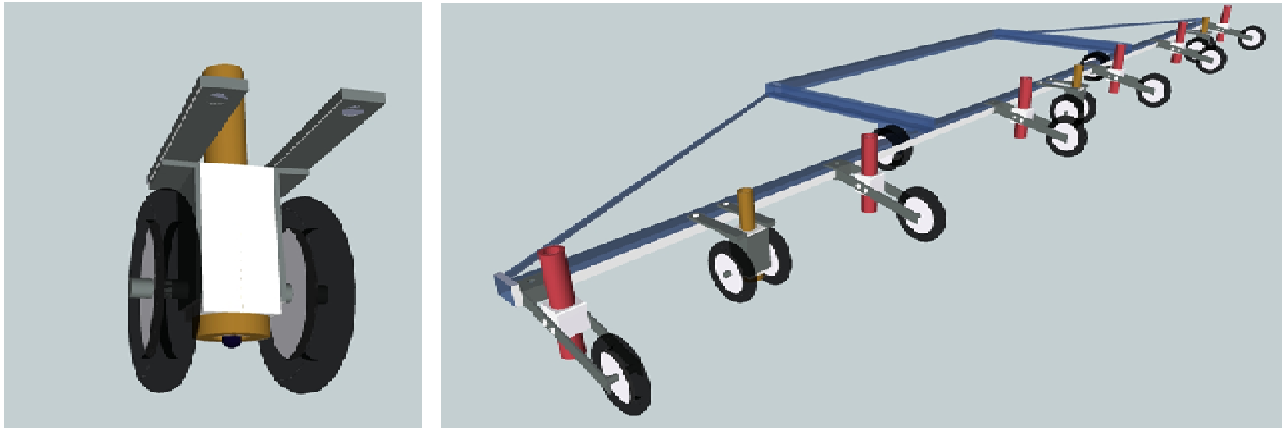


FIGURE 25. Proposed improvements to bridge deck scanning prototype: detail of impactor module (left) and proposed scanning frame (right)



FIGURE 26. Bridge deck test sites proposed by the Illinois Department of Transportation. Specific sites indicated by red stars.

CONCLUSIONS

The following conclusions are drawn, based on the findings presented in this report.

- Viable air-coupled seismic and impact-echo data are obtained when proper sensor, impactor and processing schemes are used. In some cases air-coupled signals are equivalent, and even superior to, data collected by conventional contact sensors. The selection of proper (low acoustic noise) impactors, in particular, is critical for obtaining useful data. Conventional unpowered inexpensive vocal microphones can serve as appropriate impact-echo sensors.
- For rapid and effective detection of delamination defects in bridge deck structures, air coupled impact-echo data presented in an area-scan format are most appropriate.
- Dynamic finite element method (FEM) simulations are helpful when interpreting the complicated dynamic behavior of delamination defects. Our FEM model provides reliable results, which were confirmed by comparison to analytical and experimental data.
- Two different styles of testing prototypes were developed: a line scan prototype and an area scan prototype. The latter was deployed to scan bridge samples. The prototype is designed to be towed behind a vehicle, and allows for full lane width coverage (12 feet) in a single testing pass when the testing wings are deployed. The prototype is self-contained and does not require any external equipment or power. The basic operation of the testing prototype was confirmed through tests on a long stretch of concrete floor.
- The operation of the area scan prototype requires a continuous run of data be collected, which are parsed and processed later on. This approach alleviates triggering and data bleeding problems. The data collection and processing approach works well when the obtained data contain low levels of acoustic noise – i.e. when the prototype is operated over a smooth concrete surface.
- 3-D “cloud” images are an effective way to visualize and characterize delaminations based on impact-echo data collected over a test area. Multiple vibration modes (cloud layers) indicate presence of defect in a clear visual manner and the vibration frequency values need not be known a priori.
- The area scan deck scanning prototype shows much promise, but rolling impactor source noise from rough concrete surfaces must be reduced. Implementation of hardened steel impactor modules in rolling setup appears most promising solution to this problem. The improved testing prototype will be verified on actual bridge deck structures, but these efforts should be carried on in future research and implementation work. Once the acoustic noise in the signal is removed, the proposed prototype technology and approach offers excellent and reliable identification of delamination defects within concrete, which will provide beneficial impact to the transportation community.

INVESTIGATOR PROFILE

JOHN S. POPOVICS

John S. Popovics holds B.S. and M.S. degrees (Drexel University 1988 and 1990, respectively) in civil engineering, and a Ph.D. (The Pennsylvania State University 1994) in engineering science and mechanics. He has been on the faculty of the department of Civil and Environmental Engineering at the University of Illinois since January 2002, and currently holds the rank of Associate Professor. He has also held the positions of Research Assistant Professor at Northwestern University, Assistant Professor at Drexel University, Guest Scientist at the German Federal Materials Research Institute (BAM-Berlin), Visiting Professor at the Polytechnic University of Valencia in Spain and Visiting Researcher, Laboratoire Centrale des Pont et Chaussées (LCPC) in France. Dr. Popovics teaches undergraduate and graduate level courses on materials properties, construction material corrosion and durability, concrete technology, and non-destructive testing. Dr. Popovics has two primary research interests. The first is non-destructive evaluation, imaging and sensing, where he applies mechanical and magnetic field phenomena to assess the condition of infrastructure materials and structures. His second research interest is degradation processes of infrastructure materials, particularly corrosion. His research findings have been published in four chapters in books, forty-five articles in refereed technical journals and over fifty conference proceedings. Dr. Popovics is a member of the Acoustical Society of America, the American Society of Civil Engineers, the American Academy of Mechanics, the American Society for Nondestructive Testing, and he is a named Fellow of the American Concrete Institute. He participates as a voting member in five technical committees and serves as chair in two committees in these societies. He serves as associate editor of the *Journal of Materials in Civil Engineering*. He is affiliated with the Center for Advanced Cement-Based Materials (ACBM). Dr. Popovics was the recipient of the National Science Foundation's CAREER award (1999) and several teaching and advising awards from the University of Illinois.

ALEXANDER GIBSON

Alex Gibson holds a B.Eng. degree from the University of Edinburgh in Scotland, and a Ph.D. in civil engineering from the University of Illinois at Urbana Champaign. Ph.D. research work included an in-depth review and conceptual re-definition of the impact-echo method, for which he was awarded the ACI student paper award in 2004. Alex has been involved in instrument design and structural and geophysical investigations throughout his professional life in Argentina, the United States and Australia. Current research interests include the application of non-contact sensing for rapid NDE scanning, and the quality assurance of shotcrete placement and early-age strength for underground mining operations.

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