Validation and Integration of Non Destructive Evaluation data for the assessment of bridge decks

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Abstract
Non Destructive Evaluation equipment is becoming increasingly affordable and the effective integration of few different nondestructive methods could significantly improve the way infrastructures are assessed. When integrating different Non Destructive methods, however, the effect of changing environmental and operational factors must be properly considered. In this study, the authors leverage two commonly used techniques, Infrared Thermography and Impact Echo, to assess the presence of internal delaminations in small concrete blocks that are representative of common bridge decks. The study shows how Finite Element Method can be used to understand both Infrared Thermography, by using Heat Transfer simulations and to predict wave propagation associated to the Impact Echo test. These simulations show clearly the role that boundaries have in heat transfer and in transient stress wave propagation. Experimentally, the Infrared data and Impact Echo data are extracted and a strategy for fusing information from the two separate techniques is proposed. The approach allows to clearly detect shallow delaminations in the concrete specimen.

Keywords: Infrared Thermography, Impact Echo, Data Fusion, Concrete bridge decks

1. Introduction
Researchers in recent years have successfully leveraged Non Destructive Evaluation (NDE) to assess the condition of civil infrastructures. Federal Highway Administration Long-Term Bridge Performance (LTBP) program is leveraging a robotic platform developed by Rutgers University that combines several NDE modalities to assess concrete bridge deck deterioration [1]. This and many other efforts show how the government, researchers and industry are increasingly relying on NDE to help infrastructure owners in managing their infrastructure. This paper discusses how NDE methodologies could be effectively leveraged while recognizing the various mechanisms of uncertainty that prevail in any field application. Common challenges include environmental and operational variability during data collection, complexity and variability of geometry and materials used in civil engineering assets, operator skills and training, equipment needs and calibration, time and budget constraints, and especially, data interpretation, fusion and proper visualization to provide clear guidance to infrastructure owners. Additional challenges include transforming the bridge inspection industry by making NDE wide spread, proving the value of technology leveraging in terms of payoff. These are only few of the challenges that many recognize The authors will attempt to provide their critical input on how protocols could maximize the accuracy, repeatability, and reliability of NDE data needed to dependably track the degradation of bridge decks over time. However, two key aspects will be addressed in this paper: 1) how individual NDE methods could be properly validated and 2) how multiple complementary NDE probes could be integrated to enhance the diagnosis and prognosis of civil infrastructures.

In this paper, results obtained using two separate NDE approaches (Infrared Thermography
and Impact Echo) applied on small concrete deck specimens with manufactured delaminations will be shown. An approach to fuse the results obtained from the 2 methods will be also discussed.

1.1 Infrared Thermography

Infrared thermography (IRT) is a useful method to detect subsurface delaminations by measuring and imaging surface temperature of an object [2, 3]. A number of research studies have carried out inspections of concrete specimens using IRT approaches. For instance, Maierhofer et al. executed impulse thermography for NDT assessment of concrete specimens [4]. Later they performed quantitative analysis of near surface voids from the same experiment and then explained the effect of different parameters such as environmental conditions, material parameters and geometry on heat transfer and effectiveness of IRT [5]. Several studies have observed the importance of environmental and operational conditions in the use of IRT [6-8]. Abdel-Qader et al. developed an algorithm based on segmentation analysis to automate the detection of subsurface defects in concrete bridge decks using IRT [9]. They tested their algorithm successfully on images collected from concrete bridge deck specimens containing various man-made defects and also on a defect free control model. Kurita et al. applied active infrared thermographic approach for elevated railway concrete structures using a remote heating system [10]. Gosh et al. used IRT for quantitative NDT assessment in FRP strengthened bridge systems [11]. IRT was also used to perform multispectral aerial imaging for infrastructure evaluation [12]. IRT popularity is related to its non contact nature, the relatively simple interpretation of data and the possibility to perform rapid inspection installing IRT cameras on fast moving vehicles and boats [13]. An ASTM standard provides useful guidelines for the use of IRT in the assessment of bridge decks [14].

1.2 Impact Echo

Impact Echo (IE) is another fairly established NDE technique to locate internal cracks and voids in concrete structural components. It is based on monitoring the surface motion resulting from a short-duration mechanical impact [15]. Postprocessing of the motion time histories can be used to generate 2D contour images for locating and estimating size of defects [16]. However, the results of impact echo testing can be affected by the complexity of structures. For this reason, a series of finite element analyses for the impact-echo testing was performed by Cho et al. to obtain a priori information from a composite bridge deck with a steel girder [17]. Later, Huston et al. included IE approach to perform concrete bridge deck condition assessment as part of their automated multi-sensor inspection techniques [18]. Zhang et al developed noise cancellation and damage detection algorithms for non-destructive evaluation of concrete bridge decks using IE signals [19]. ASTM also provides guidelines on test methods to determine the thickness of slabs, pavements, decks, walls, or other plate structures [20]. Recently, Gucunski et al. performed rapid bridge deck condition assessment using an automated vehicle system to construct 3D image of concrete decks with IE data [21]. Efforts in leveraging IE are ongoing to increase its inspection speed. The approach, traditionally requiring contact, has been modified in recent years by leveraging air-coupled sensors that unlike displacement or accelerometer sensors often used in IE, do not require contact and allow faster collection speed of IE data [22].

1.3 Combining different NDE approaches

A combination of few NDE techniques can potentially increase the reliability of damage identification. In 1998, Weil et al. used IRT and IE for nondestructive testing and repair of the
concrete roof shell at the Seattle Kingdome [23]. Yehia et al. performed an experimental investigation to evaluate the ability of IRT and IE to detect common flaws in concrete bridge decks. Cheng et al. fused active IRT with elastic wave techniques to detect defects in concrete structures [24]. Aggelis et al. combined thermography and ultrasound for the characterization of subsurface cracks in concrete [25]. They initially executed IRT to locate the cracks and then they used ultrasonic testing (UT) to perform detailed assessment of the crack depth. Kee et al. applied air-coupled impact-echo and infrared (IR) thermography techniques to evaluate concrete bridge deck containing delamination and cracking defects [22]. They used IR for thermal mapping and IE for representing 2D frequency maps. Recently, Oh et al. applied IRT and IE for assessment of in-situ concrete bridge deck and provided performance characteristics of different NDT approaches to spot delaminations in bridge decks [26]. Although, numerous experiments have been conducted in the field of IRT, IE and their fused application, more studies are ongoing to address the challenges associated with their individual and combined applications. This paper represents the application of IRT and IE techniques to concrete deck specimens by attempting the fusion of the corresponding heterogeneous data sets.

2. Experimental Setup

This experimental investigation has been performed on a set of concrete specimens built and tested at Drexel University. The specimen discussed herein is 0.6m×0.6m×0.2m in dimension and it contains three 0.15m×0.15m×3mm delaminations embedded at 5cm, 10cm and 15cm depth as shown in Figure 1(a).

![Figure 1. IRT on concrete specimen and FEM simulation of heat transfer phenomenon](image)

2.1 IRT setup

An IRT test was performed using a FLIR a325sc camera mounted on a tripod positioned at approximately 2m from the concrete specimen. A calibration procedure was applied to allow accurate absolute temperature measurements on the surface specimen [27]. During the test, the
following experimental settings were used: emissivity 0.93; room temperature 73ºF, humidity 25%. Active thermography was performed on the concrete block leveraging heat lamps to impose heat flux on the front surface of the concrete block. The specimen was heated for nearly 3 hours on the front surface and then it was allowed to cool down for additional 2 hours. Temperature maps were recorded with the IR camera and a snapshot of the temperature distribution after 3 hours is shown in Figure 1(b) where it is visible that the top left corner of the specimen shows a hot spot corresponding to the shallow delamination at 5cm from the front surface.

This expected result was confirmed using Finite Element Method (FEM) simulations with the commercially available software ABAQUS. A transient heat transfer simulation was performed accounting for the properties shown in Tables 1.

Table 1. Input parameters for FEM simulations

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Concrete</th>
<th>Foam Piece</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, ( r ) (kg/m(^3))</td>
<td>2400</td>
<td>52</td>
</tr>
<tr>
<td>Thermal conductivity, ( k ) (W/m.K)</td>
<td>2.7</td>
<td>0.0381</td>
</tr>
<tr>
<td>Specific Heat, ( c ) (J/kg.K)</td>
<td>723</td>
<td>1600</td>
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<tr>
<td>Emissivity, ( e )</td>
<td>0.92</td>
<td>0.87</td>
</tr>
<tr>
<td>Convection heat transfer coefficient to air, ( h ) (W/m(^2).K)</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

The FEM results are shown in Figure 1(c), where the temperature contours of the simulated concrete specimen show excellent correlation with the experimental results.

It should be noted that deeper delaminations are not visible in the experimental and in the numerical study. One possible explanation is that the heat convection and radiation at the lateral edges of the small concrete specimen allow a significant portion of the heat to escape the block. In a larger specimen, these boundary effects will be mitigated and the heat would remain trapped also by the deeper delaminations and consequently temperature increases at the surface could be visible also for a deeper delamination.

2.2 IE setup

The Impact Echo testing was performed using a high-frequency impact hammer (miniature impact hammer PCB model 086E80) that generates stress waves with sufficient energy in a frequency range of DC-20kHz. The impact hammer has a resonant frequency \( \geq 100 \) kHz and a measurement range of 222 N pk. A miniature PCB Piezotronics accelerometer Model 352C67 was used to capture the acceleration motion. The accelerometers had an operating frequency range from 0.5-100 kHz with a resonant frequency \( \geq 35 \) kHz. A LabVIEW based acquisition program was used to record the generated and received waveforms through a National Instrument PXI (NI PXIe-1062Q) unit. The triggering value for this acquisition was 0.1 Volts. The recorded signal length was equal to 100,000 points with a sampling rate of 1 MHz.

A total of 121 waveforms were recorded on a regular grid of 11×11 points. Three features were extracted from the IE test waveforms: (1) the ratio between the maximum amplitude of the recorded acceleration time history in the time domain (after application of the Hanning window to discard the Rayleigh wave) and the maximum amplitude of the hammer time history; (2) the ratio between the energy of the signal in the time domain extracted from the windowed acceleration time history and the energy in the time domain of the hammer time
history; (3) the area underneath the FFT curve of the windowed acceleration time history divided by the area below the FFT curve of the hammer time history. It should be noted that the IE approach commonly uses only the resonance frequency corresponding to the longitudinal wave round trip from the point of impact to the accelerometer. Such wave is reflected multiple times with little attenuation within the thickness of the concrete element. This repeated reflection is visible in the signal with a decaying oscillatory behaviour where the period of oscillation corresponds to the round trip time of the longitudinal wave. The round trip time (inverse of the thickness resonance frequency), is proportional to the thickness of the concrete slab tested. In the presence of a delamination, the round trip time can decrease significantly since the longitudinal wave is soon reflected from the horizontal defect (resulting in an apparent smaller thickness). This is a basic description of the IE method commonly provided in the literature. However, it is well known that when the specimen is approaching a block shape, rather than a slab geometry, the reflection of the waves from the boundaries of the specimen, interfere with the P wave and can complicate the use of IE. For this reason, rather than using the resonance frequency features, in this study other features are leveraged.

To properly extract these features, the authors have performed a number of numerical simulations. For the sake of brevity, only 2 cases are shown here. In the first case, the impact echo is simulated in a block with 3 delaminations located as shown in Figure 1(a).

Figure 2. FEM simulation of IE. Wave propagation in a concrete block (after 41 microsec from the moment of the impact) in: (a) block with horizontal delamination at 5cm from the surface and (b) in a flawless block.
In the FEM model, a total of 1,630,512 linear hexahedral elements (type C3D8R) is used. The impact is simulated using a unitary amplitude force time history, that corresponds to a normalized signal measured by the load cell of the PCB impact hammer during IE test. The model is designed to record displacement and acceleration time histories as well as stresses at each location within the block and at 200 evenly spaced time intervals from 0 to 100microsec. Concrete material is modelled assuming Young Modulus $E=30\text{GPa}$, Poisson's ratio $\nu=0.29$ and density $\rho=2400\text{kg/m}^3$. Foam layers are modelled as follows: Young Modulus $E=2000\text{Pa}$, Poisson's ratio $\nu=0.3$ and density $\rho=51\text{kg/m}^3$.

Figure 2(a) represents the simulated wave propagation following an impact on top of the shallow delamination at 5cm from the surface. In the second case, shown in Figure 2(b), no delamination is considered in the block. In both cases, the wave field is represented at 41microsec after the moment of the impact.

It is clear from the simulation how the delamination has a trapping effect for the IE wave with reflections from the delamination that confine the ultrasonic energy within the surface and the defect at the beginning of the IE phenomena. For this reason, it is expected that the amplitude and energy of the wave signals captured by the accelerometer used in an Impact Echo (commonly few cm away from the impact [20]) would increase when IE is performed on a delamination.

As shown in Figure 2(b), the wave is free to propagate in a flawless specimen. However, if the specimen has width and length comparable to the specimen thickness, complex reflections of the Rayleigh, Shear and Longitudinal waves will occur at the boundaries. The resulting waves will constructively and destructively interfere and the signal from the IE sensor will reveal such complexity. A possible way to mitigate the effect of these reflections is to window the signal (for instance using an hanning window) considering only the first portion of the signal while minimizing the contribution of waves such as the Rayleigh wave, that are not sensitive to the presence of delaminations. This approach could be successful in identifying horizontal cracks also in the proximity of the boundaries of a concrete deck. Leveraging the FEM simulations, the authors have optimized the windowing of the IE signal. The windows have been used to process the 121 signals extracted from the experimental study described at the beginning of this section. The specimen and the location of the 121 IE events is shown in Figure 3(a). The three features extracted from the IE test waveforms are summarized by the contour maps shown in Figure 3(b), (c) and (d). All the features appear sensitive to the shallow delamination (top left corner in Figure 3a), but they appear only marginally sensitive to the presence of deeper delaminations. Additional work should be done by adjusting the window of the recorded signals to improve the sensitivity. It should be observed that the images in Figure 3(b-d) are built using 121 data while the IR image shown in Figure 1(b) contains up to 240x320 temperature data (number of pixels of the FLIR camera used). Consequently, the IR image provides an easier interpretation. Furthermore, with the available equipment, the speed for IE data collection is fairly slow, while the speed of the IR data collection depends on the time needed for the heating process to occur. In a passive IR test, where heat is provided by the sun radiation, the IR data collection can be extremely fast.

Summarizing, both IE and IR show the potential to highlight delaminations, particularly the ones located within 2in (5cm) from the inspected surface. It should be noted that the delamination process frequently starts near rebars, facilitated by the corrosion and consequent expansion of the steel. Such rebars are located within 2-3in from the surface of the deck. It can be concluded that both the approaches can be useful for delamination detection. The next question is how these different NDE approaches can be integrated or in other words, how the data from IE and IR can be fused together. Next section proposes a possible approach to perform this task.
2.3 NDE Data fusion

As previously mentioned, the features shown in Fig.1 and 3 were extracted using different sensors and collected with different resolutions. While IR features are extracted using a FLIR camera rapidly providing 320×240 pixels for each image (76,800 temperature values), contact based IE can be quite time costly and must be repeated at each location (121 points in the case of the concrete block with 2" spatial resolution). To provide a visual representation of these heterogeneous sets of data, a possible approach is provided by the Outlier Analysis [28]. Outlier analysis was performed to fuse the IRT and IE results collected from the small concrete block test.

An outlier is a datum that appears statistically inconsistent with the baseline [29, 30]. A total of four features were used for the small block test: one (temperature shown in Figure 1b) from IRT test and the other three from IE test (shown in Figure 3). The features were fused together to enhance test results and increase reliability. Data from the IE features were first re-sampled through interpolation to reach data sets comparable with the IR data matrix. Mahalanobis
distance [28] was calculated for each pixel using the IRT and IE features. The equation used for this calculation is:

\[ D = (x - \bar{x})^T S^{-1} (x - \bar{x}) \]  

(1)

where \( x \) is the potential outlier, \( S \) is the covariance matrix of the baseline and \( \bar{x} \) is the mean vector.

Figure 4(a) shows the 4 NDE features extracted from the Infrared Thermography and the Impact Echo testing on the concrete block shown in Figure 1(a). The features are fused using the Outlier Analysis by leveraging Equation (1). Figure 4(b) represents the resulting image from the small concrete block test where the map depicts the Mahalanobis distance \( D \). Such scalar quantity is plotted for each pixel of the image and clearly shows the location of the shallow delamination.

Figure 4. NDE data fusion: (a) 4 features extracted from IR and IE testing of the concrete block; (b) map obtained using the Outlier Analysis by applying Equations (1) to fuse the 4 NDE features.

3. Conclusions

This paper presents a combination of two NDE techniques for the evaluation of concrete specimens with thickness comparable to bridge decks and with simulated delaminations. The results from the Impact Echo and Infrared Thermography testing are compared and a strategy to perform data fusion is proposed to effectively detect horizontal flaws. The IR method is used to detect changes in the surface temperature that are due to the heat trapping effects of the subsurface delaminations while IE is commonly employed to observe shifts in the frequency spectrum of the transient wave travelling along the thickness direction of the slab. Given the geometry of the specimen, IE is leveraged by extracting energy and amplitude related features. IR imaging gives high spatial resolution and potentially rapid assessment compared to the IE. IE, unlike IR (that requires heating sources such as the radiation from the sun) is not as sensitive to environmental conditions. The fusion with features extracted from both IR and IE improves the final imaging of the tested specimen and provides a clear indication of existing shallow delaminations. Therefore, the fusion of the two different NDE methods could improve reliability of the inspection and assessment of concrete bridge decks although additional research is ongoing to increase the sensitivity of the approach to deeper delaminations.

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