

Shear Wave Method for Concrete Pavement Diagnostics

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Abstract

Field trials involving typical pavement constructability and rehabilitation issues at the Federal Aviation Administration's National Airport Pavement Test Facility, the Minnesota Road Research Project, and various in service pavements using MIRA were verified. The trials indicate that, while the device is a useful portable pavement diagnostic alternative capable of consistent thickness measurement, reinforcement location, and distress evaluation, significant efforts and user expertise are required for measurement and data interpretation of large scale applications. Thus, a couple productive, objective signal interpretation methods are presented for automated analysis of reinforcement location in continuously reinforced concrete pavement as well as an initial distress indicator using two-dimensional ultrasonic signature analysis. This type of automation for multiple applications shows promise for the use of ultrasonic tomography to improve large scale pavement quality assurance, quality control, and rehabilitation projects in the future. Innovative imaging methods such as synthetic aperture focusing technique panoramic reconstructions and synthetic aperture focusing technique three-dimensional visualizations were also introduced to improve the ability to obtain relational information when dealing with larger scanned areas. Ultrasonic tomography is shown to be an accurate, reliable, and convenient alternative/supplement to traditional techniques or can be used to replace or reduce the need for forensic methods such as coring.

Introduction

Ultrasonic testing uses high frequency (greater than 20,000 Hz) sound waves to characterize the properties of materials or detect their defects. Sound waves are generated by transducers, travel through the material, and are received at the surface. Analysis of the signals by the receiving transducer provides information about the media through which the signal has propagated. Recently, dry point contact (DPC) transducers have been developed with the capability of transmitting of relatively low frequency (50 khz) elastic waves that penetrate greater depths in heterogeneous materials such as concrete (Nesvijski, 1997; Mayer et al., 2008). Use of these transducers has been advanced and successfully applied for years in dealing with detailed evaluation of civil structures in Germany (Schubert and Köhler, 2001; Mayer et al., 2008; Khazanovich et al. 2005; Langenberg, K.J. et al., 2001; Marklein, R. et al. 2002).

Some additional commonly used devices include the Ground Penetrating Radar (GPR), Magnetic tomography, infrared thermography, chaining, and seismic methods. All of these methods are based on different physical principles and have strengths and limitations unique to each technique. GPR transmits electromagnetic waves into the tested medium and the reflected energy received at the antenna is

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analyzed. Past studies show that GPR is capable of achieving high speed measurements, although the precision reduces with higher speeds and detecting non-uniform cracks is difficult (Abdallah et al 2009; Chong et al 2003; Gucuski et al 2009 and 2010; Li et al 2008; Maierhofer et al 2003). Magnetic tomography techniques utilize magnetic pulse-induction to estimate metal inclusion location and orientation. It should be noted that this method does not detect any type of non-metallic inclusion or defect (Rao et al 2009; Hoegh et al 2008; Hossain et al June 2006; Khazanovich et al, 2003). Infrared thermography can detect thermal anomalies by measuring infrared emission at the surface (Clark et al 2003; Maser et al 1990; Washer et al 2009).

Ultrasonic tomography can be used for diagnostics of concrete structures, utilizing the same principles that have been successful in medical and metal applications (Hoegh et al 2011a). MIRA utilizes 45 transmitting and receiving transducer pair measurements (see figure 1) in a less than 3 second scan resulting in a 2D depth profile (b-scan). The DPC transducers provide the necessary consistency of impact and wavefront penetration for diagnostics up to 3 ft. deep. The multiple sensor pairs in each scan allows for the required redundancy of information to evaluate heterogeneous mediums such as PCC. Figure 1 shows a manual MIRA measurement on the left in which the transducers are placed flush to the surface for a b-scan measurement. A b-scan is a 2 dimensional reconstruction of the concrete directly below where the scan was taken with high intensity of reflection areas indicating changes in acoustic impedance. On the right side of Figure 1 the increased redundancy of information of MIRA (bottom) over conventional IE (top) can be observed, where the multi-static array of transmitting and receiving transducers creates 45 measurement angle pairs compared to one measurement pair in traditional IE.

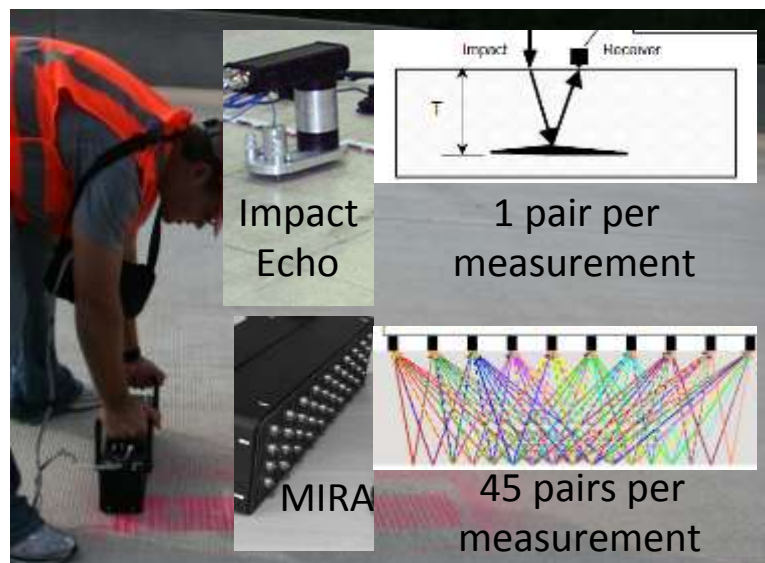


Figure 1. MIRA ultrasonic pitch-catch device and comparison with traditional impact echo method (Carino, 2001; ACYS 2008).

General Analysis

MIRA measures time of signal propagation between the transducers at fixed distances for material velocity calibration, and uses the synthetic aperture focusing technique (SAFT) for analysis in scan mode to reconstruct the medium below the measurement based on the shear wave reflections. SAFT has been found to be a feasible algorithm for use with the ultrasonic pitch-catch technology as well as other applications. The

spatial diversity of the sending and receiving pairs in an array allow for focusing using the SAFT algorithm (Langenberg et al., 2001).

The SAFT algorithm as applied to a MIRA scan creates a cross-section display of echo intensity versus depth along the aperture (SAFT B-scan). The positions with high intensity (red) correspond to areas where there is a change in acoustic impedance, which could be an inclusion, interface between two layers, or damage to the concrete (Hoegh et al 2011a). A brief explanation of a typical signal with multiple 0.75 in. reinforcement bars in concrete pavement is shown in Figure 2. A high intensity reflection can be observed at the three longitudinal reinforcement bar locations where the center of objects shown in the scans corresponds to the center of the longitudinal bars. To compute concrete cover, the radius of the bar (0.375 in.) should be subtracted from the depth of the center of the scatterer. A reflection can also be observed at a depth of about 12 in. at the concrete and base interface. It should be noted the reflection from the PCC/base interface does not extend throughout the horizontal range of the scan as it might be expected for such a continuous interface. This phenomenon is not indicative of any deterioration or lack of continuity, but rather a result of the limited aperture of the scan (Hoegh et al 2011a). The thickness measurements can be made by applying the same method to the oblong reflection at the base as was used for the reinforcement measurements.

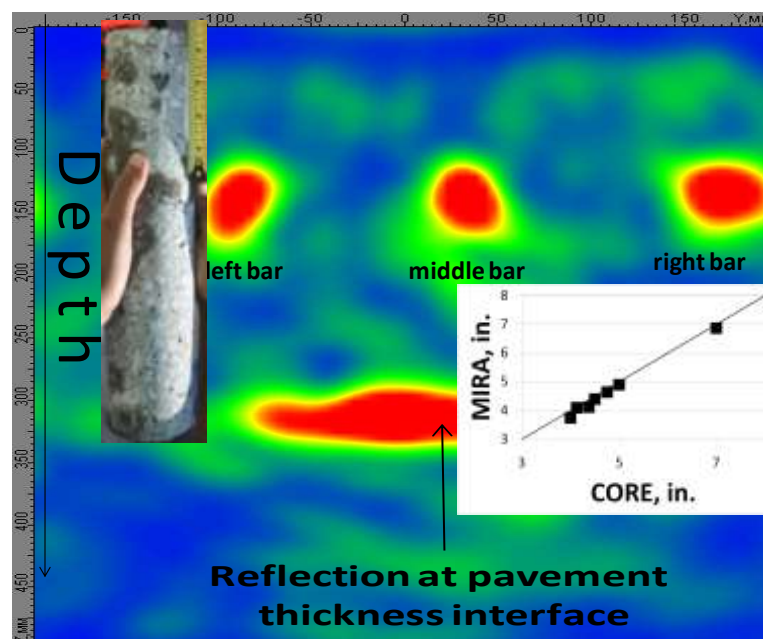


Figure 2. Example SAFT b-scan with reinforcement and PCC bottom surface reflections.

SAFT B-scan Analysis can be used for reinforcement location, concrete thickness estimation, detection of cracking in the PCC layer or de-bonding between PCC layers, as well as joint diagnostics for detection of concrete deterioration, dowel position, spalling, etc, and flaw detection such as honeycombing or poor consolidation.

Figure 3 shows 2 MIRA B-scans taken at unreinforced concrete locations. It can be observed that there is a reflection at a shallower depth on the left. This reflection on the left indicated the presence of a flaw within the concrete since it was at an unreinforced location. This was verified by the core shown in the center of Figure 3. Figure 4 shows B-scans taken at a transverse joint with an uneven backwall

reflection at a shallower depth on the right. This indicated deteriorated concrete which was verified by the “flipped” trench taken at those the corresponding locations. Figure 5 shows a B-scan taken at a location where there was an embedded porous concrete half cylinder was used to simulate honeycombing. The high intensity reflection located on the left side of the B-scan indicated the presence of the fabricated honeycombed condition.

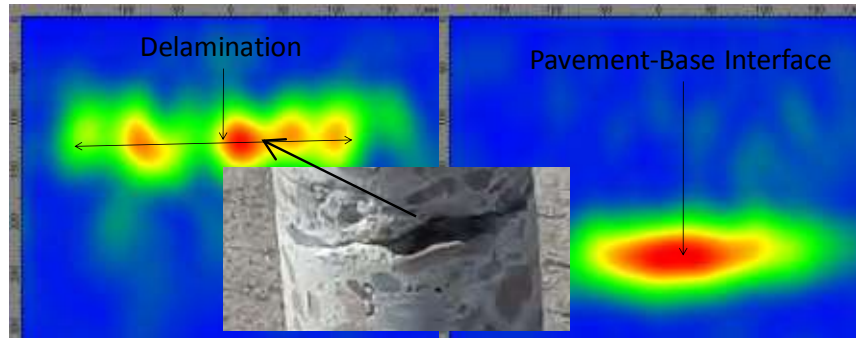


Fig. 3. Delaminating (left) and sound concrete (right).

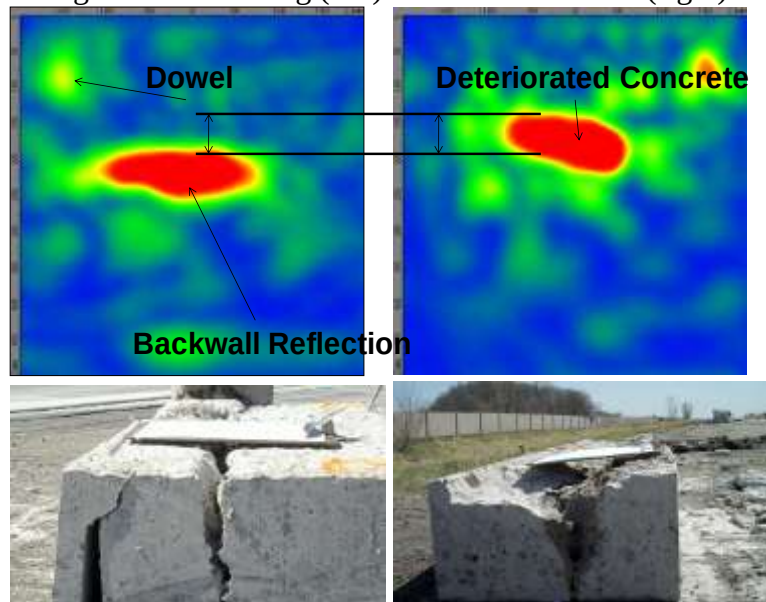


Fig. 4. Forensic verification of MIRA joint diagnostics.

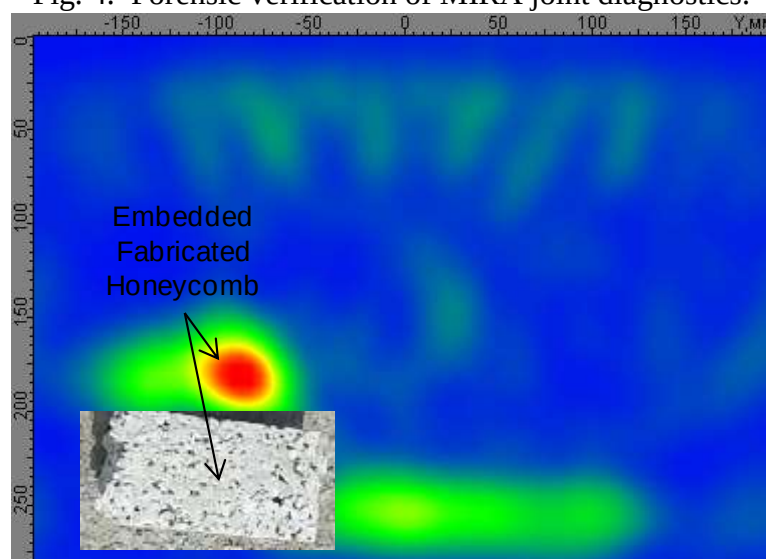


Fig. 5. MIRA identification of honeycombing defect.

Quantitative Analysis

While SAFT B-scans give an accurate picture of the subsurface conditions, the manual data interpretation procedure for certain applications is time consuming and labor intensive. In addition the interpretation process is somewhat subjective and requires a certain experience/expertise. To allow for more efficient objective analysis, software to automate analysis of typical applications should be developed. Figure 6 shows MIRA measurements that were analyzed using the this procedure versus core measured concrete cover at the same seven locations at an in-service continually reinforced concrete pavement (CRCP) on I-85 in Atlanta, GA (Hoegh et al. 2011b). In addition to the good correlation ($R^2 = 0.997$) and accuracy (slope = 0.985) the automated procedure improved the analysis time. For example, the same amount of CRCP data points that took about 2 weeks to manually analyze take less than 3 hours with the automated software.

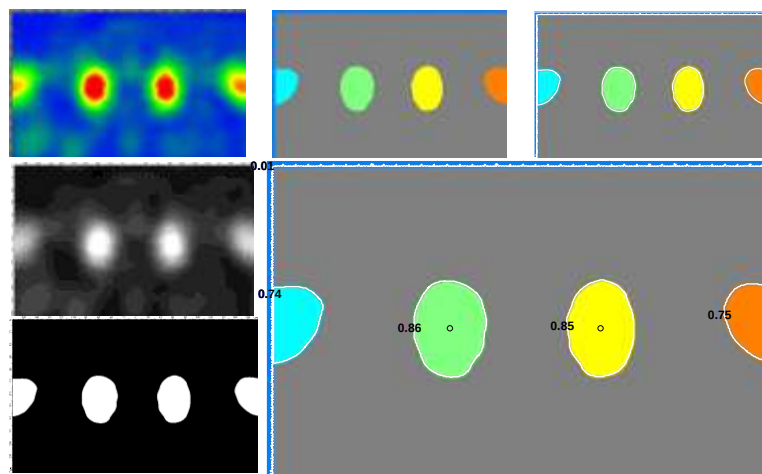


Figure 5. Progression in identifying the centroid of reflections caused by rebar.

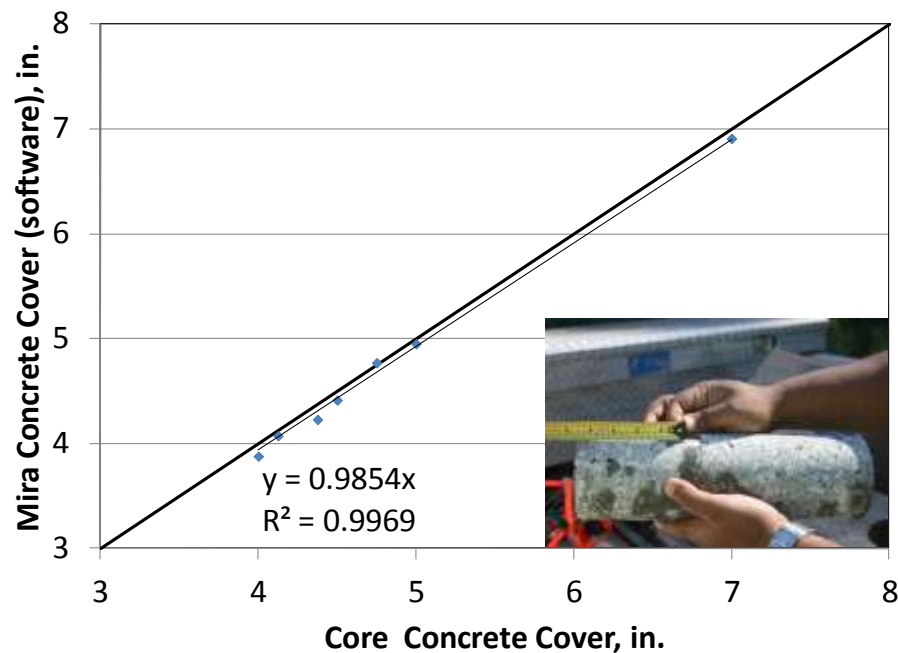


Figure 6. MIRA measured and software analyzed concrete cover versus core measured.

While the shape recognition method shown above is proficient for analyzing systematic inclusions such as reinforcement location, this type of automation cannot be applied for detection of irregular defects in concrete. Signature analysis can be used with impact echo data (IESA) (Shubert et al 2001) or SAFT B-scans (2D-UTSA) (Hoegh et al 2011c) to give a quantitative indication of distress in concrete. While the above referenced papers give a detailed description of Pearson's analysis as applied to signal interpretation of body waves in concrete, a summary of the general concept is presented herein.

Pearson's correlation can be used to provide a similarity measure of various signals as compared to a reference signal in either the time or frequency domain. As applied to SAFT B-scans this is accomplished by comparing the reflection intensity values at each matrix cell location. There is generally very little variation between B-scans of concrete in relatively good condition at different locations, while there is a significant variation between scans where flaws are present at different locations. Two SAFT B-scans taken on relatively sound concrete with similar structural geometry are linearly related resulting in Pearson's correlation values close to 1. A scan taken on flawed concrete as compared to a sound concrete condition are not linearly related resulting in a Pearson's correlation values closer to 0. Therefore, a sound concrete is indicated by a high Pearson's correlation and a significant decrease in Pearson's correlation coefficient indicate dissimilar B-scans, or flawed concrete, especially if observed in a group of adjacent scans.

This type of initial rapid screening can identify areas of interest for further manual evaluation. This reduces the need to manually analyze every scan, which reduces the analysis time for large scale projects where concrete defect identification is necessary. Because information about the type of defect or location within the scan is lost in the method, it should only be used as a filtering method to assist in determination of locations where defects are present. The type of manual B-scan analysis presented by Hoegh et al. (2011b) can then be used to determine the type and location of the defect within the area of interest.

MIRA testing at the National Airport Pavement Testing Facility (NAPTF) was conducted to verify the 2D-UTSA technique in a situation where the presence or type of damage was unknown. Testing was conducted at various locations throughout the facility to determine the concrete condition. Figure 7 shows an example of 100 scanned locations with typical Pearson's correlation variation between scans. It can be observed that Pearson's correlation was typically above 0.95 for these tested cases.

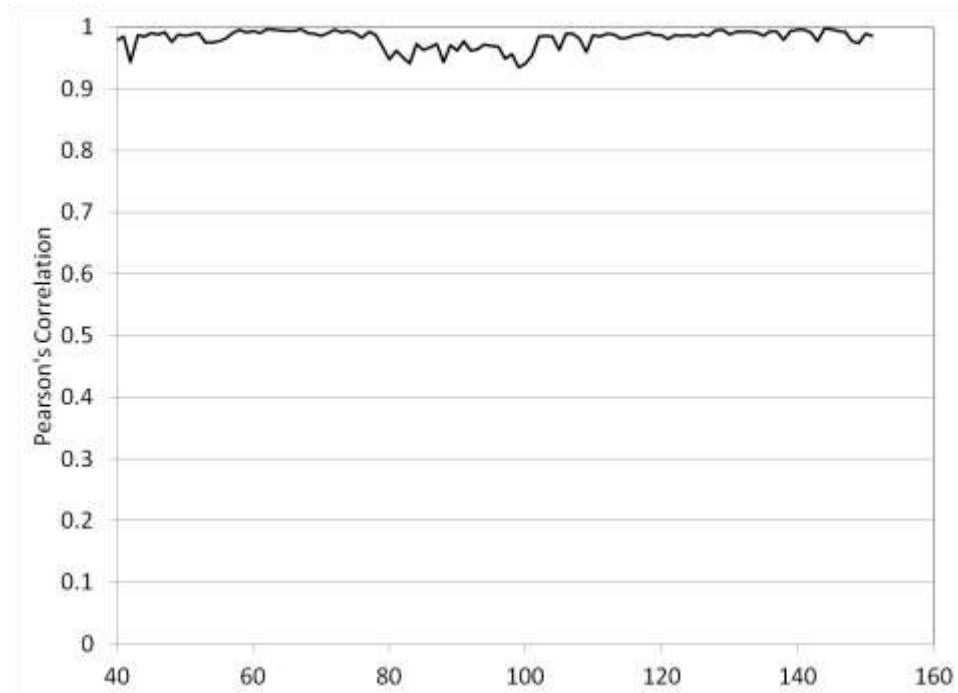


Figure 7. Typical Pearson's correlation values for a set of 100 scans taken at the NAPTF.

Ultrasonic tomography scans were also taken on a slab exposed to a potassium acetate deicer. In one location, a dip in Pearson's Correlation was observed. The core shown in Figure 8 along with the correlogram verified that the 2D-UTSA diagnosis of a subsurface defect was indeed correct.

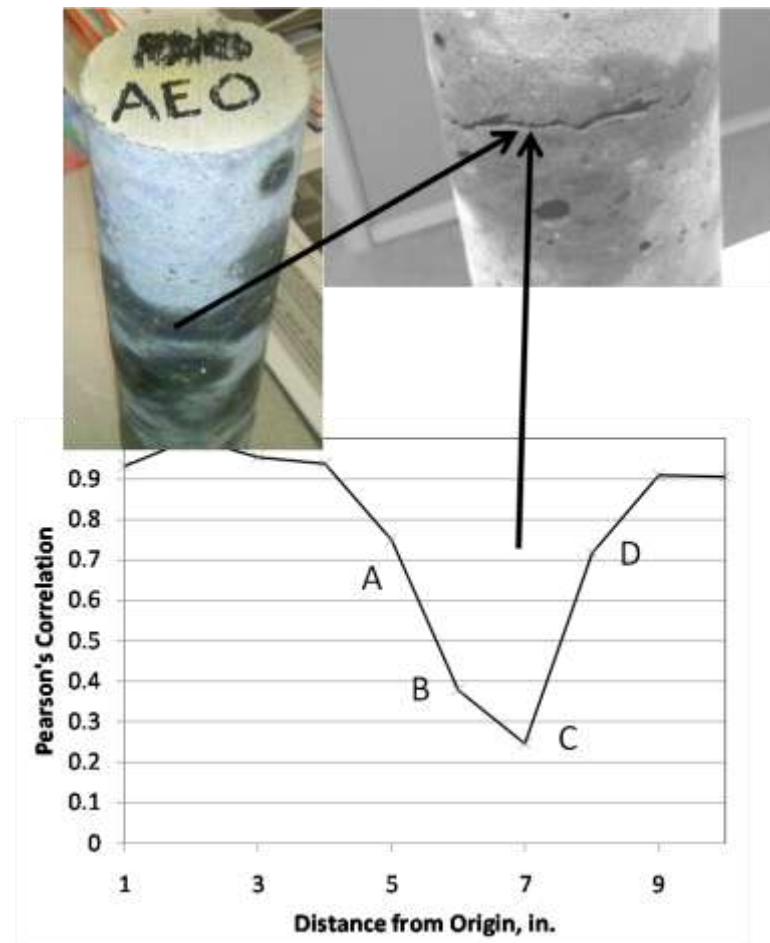


Figure 8. Detection and verification of subsurface distress in airport pavement.

Visualization

SAFT-Panoramic and SAFT 3D reconstructions can allow for a more detailed visualization of subsurface features. To illustrate the value of these methods a series of scans at a PCC joint are presented. The Synthetic aperture focusing technique panoramic reconstructions are based on fusing absolute intensity of reflection from multiple overlapping scans (see Figure 9). The Synthetic aperture focusing technique 3-dimensional reconstructions based on interpolation of threshold intensity reflection locations (see Figure 10). In these cases the high level of reflection intensity are observed at lateral and depth locations where there is a change in acoustic impedance such as a dowel inclusion or at the interface between the concrete and base material.

Figure 9 shows five approximately 3 ft. SAFT Panoramic reconstructions each resulting from 9 overlapping SAFT B-scans taken in 2 inch step sizes after they have been fused together. From top to bottom these 3 ft cross-sections were created with MIRA centered at the following distances from the joint with the overlapping step sizes along the joint:

- 11 in. from the joint
- 9 in. from the joint
- 7 in. from the joint
- 5 in. from the joint
- 3 in. from the joint

The resulting panoramic tomography indicates the subsurface condition of a 3 ft wide section of the pavement. Each panoramic shown in Figure 9 indicates an undamaged condition where the only high intensity of reflection (red) occurs due to features that were as designed including the slightly less than 1 ft concrete depth reflection, circular reflections at the location and depth of the dowels, and reflections at the location and depth of the sensor area. The lack of reflection (blue) at the remaining locations indicates undamaged concrete.

No dowel reflections are observed in the top panoramic because the scans were taken 11 in. from the joint where no dowels are present. Three inches from the joint, a strain gauge was embedded in the concrete at approximately 2 in. depth and fixed using epoxy. Reflections near the surface can be observed in the bottom SAFT panoramic reconstruction corresponding to the embedded strain gauge location. Dowels are observed in the remaining SAFT panoramic reconstructions. The circular red high intensity reflections can be observed at the lateral and depth locations of the dowels under the scan locations. This shows how the dowels from overlapping scans are treated and how fusing data from multiple B-scans can be used to create a clearer picture of the dowel locations in relation to one another using the 3 ft. SAFT panoramic reconstructions as well as for creating a continuous reflection at the depth of the PCC.

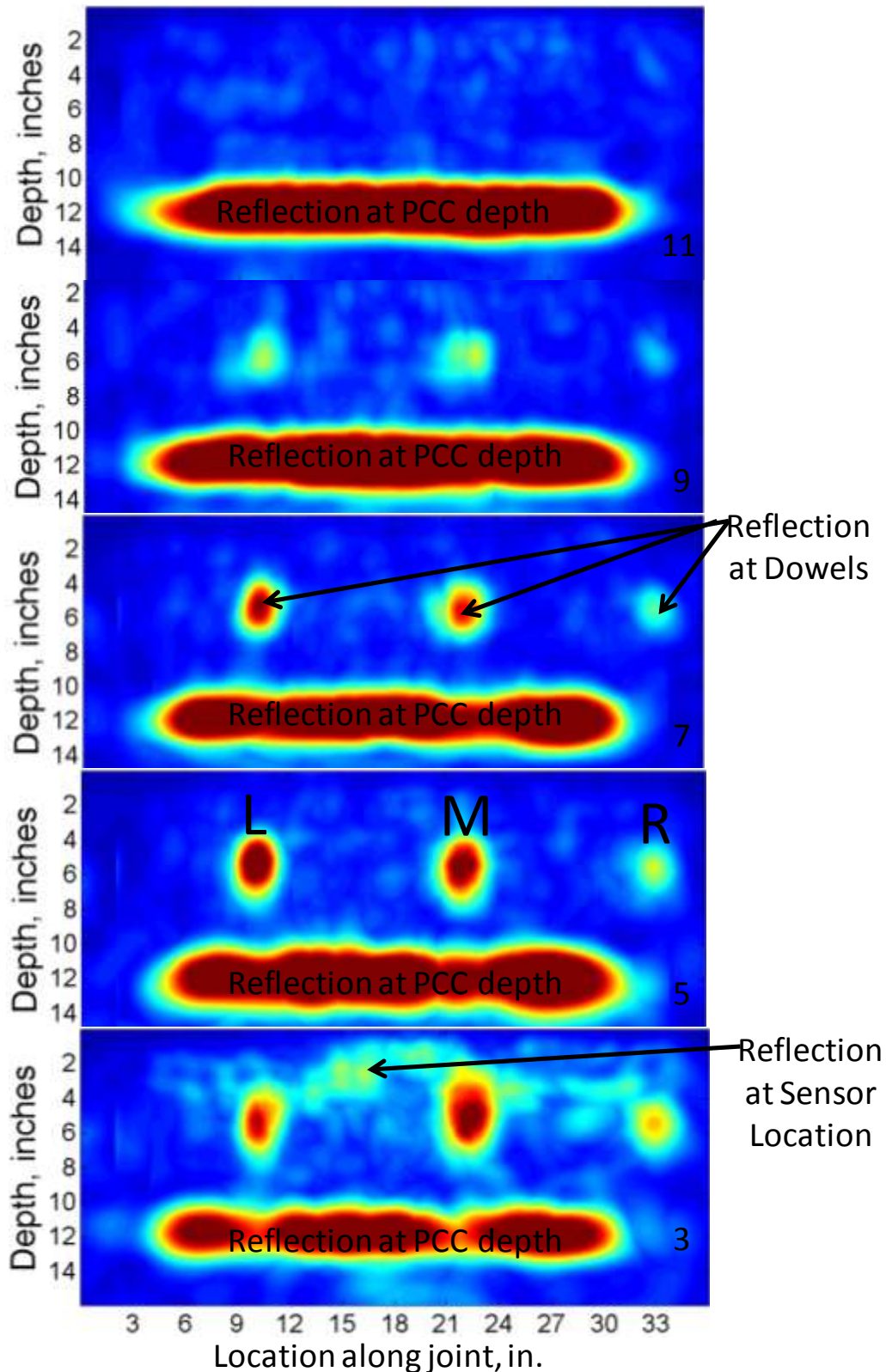


Figure 9. Five SAFT Panoramic examples with the top scan 11 in. away from the joint and each scan below the other 2 in. closer to the joint.

Figure 10 shows the SAFT 3D reconstruction resulting from the SAFT Panoramics shown in Figure 9. This reconstruction was created by using threshold and interpolation techniques to make a three dimensional reconstruction of the 3 ft by

1ft tested location. The approximately 9 in. long dowels can be observed in Figure 7 in addition to some reflections at the sensor location and the continuous reflection at the PCC depth. This type of SAFT 3D reconstruction can be useful for getting relational information about the high intensity reflections to determine if the reflection is caused by an as designed inclusion or damaged concrete.

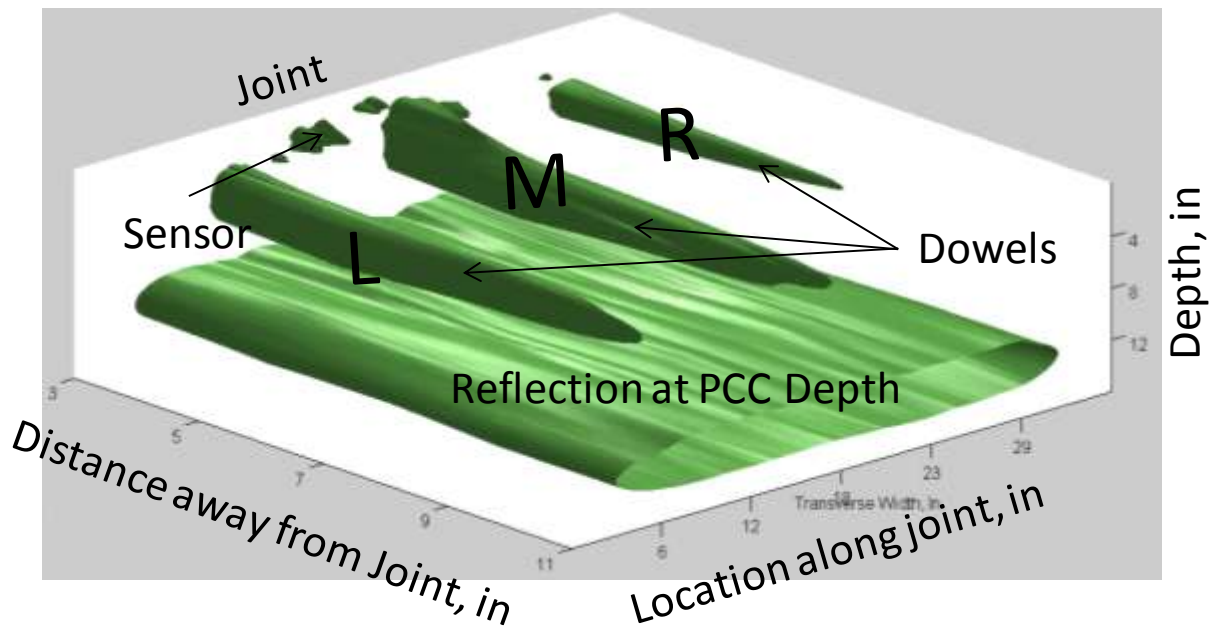


Figure 10. SAFT 3D reconstruction at using the SAFT Panoramic reconstructions shown in Figure 9.

Conclusions

In this study an ultrasonic tomography device was used in conjunction with quantitative analysis techniques. These techniques reduce the need for specialized user expertise/experience and improve the productivity and objectivity of data interpretation. The shape recognition procedure was used for automated reinforcement location. Pearson's correlation was used as a quantitative initial indicator of flaws in concrete. Visualization methods such as synthetic aperture focusing technique panoramic reconstructions and synthetic aperture focusing technique three-dimensional visualizations were also introduced to improve the ability to obtain relational information about larger scanned areas.

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