A Novel Use of Frequency-banded Synthetic Aperture Focusing Technique for Reconstructions of Alkali-Silica Reaction in Thick-Reinforced Concrete Structures

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Abstract. As they degrade and age, concrete structures are susceptible to the development of multiple defects, such as alkali-silica reaction (ASR). ASR forms a gel that occurs over time between alkaline cement paste and reactive, noncrystalline silica in aggregates [1]. With the continuing extension of the life span of nuclear power plants, it is important to monitor the structural integrity of concrete structures after 40+ years. Compression strength, modulus of elasticity, flexural stiffness, shear strength, and tensile strength are performance characteristics susceptible to the development of ASR. Current methods for monitoring for defects and degradation within thick concrete structures require damaging the concrete. Oak Ridge National Laboratory, in collaboration with the University of Pittsburgh, has developed a nondestructive evaluation (NDE) and reconstruction technique that enables deep-image reconstruction of damaged concrete. The frequency-banded synthetic aperture focusing technique (FB-SAFT) is an augmented SAFT reconstruction that segments the time-series data into different frequency bands using wavelets immediately before performing SAFT reconstructions [2]. This paper presents the NDE instrumentation and reconstruction techniques applied to thick-reinforced concrete structures and concludes with preliminary results.

THICK-REINFORCED CONCRETE EXPERIMENT

The U.S. Department of Energy's Light Water Reactor Sustainability (LWRS) Program, in partnership with Oak Ridge National Laboratory and the University of Tennessee (UTK), developed a thick-reinforced concrete experiment,

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see Figure 1. The large-scale experiment was designed to be representative of typical nuclear power plant (NPP) structures [3,4,5]. A known issue in concrete structures is alkali-silica reaction (ASR). ASR is the chemical reaction between the aggregates and cement paste in concrete. As early as 2010, ASR was detected in the Seabrook NPP [6]. Two of the thick-reinforced concrete specimens were fabricated using concrete that is known to be prone to developing ASR. One of the ASR specimens was constructed within a rigid steel frame to simulate the passive restraint that could be present in the pressure vessel of an NPP. To ensure the development of ASR in a short 2-year period, when it would normally take many years, a 16,000 ft^3 (450 m^3) environmental chamber was built around the concrete specimens. The environmental chamber was held at 100 °F (38 °C) and 95% relative humidity. The original prediction was 0.5% expansion in 2 years, however, because the expansion accelerated much quicker than the original calculations determined, therefore, the temperature was dropped to 75 °F (23 °C) after the first year. In addition to the two ASR specimens, a control specimen was fabricated using a concrete mixture that was not susceptible to ASR development. The fabricated concrete specimens were 3 x 3.5 x 1 m with two mats of #11 rebar spaced at 25 cm on center.

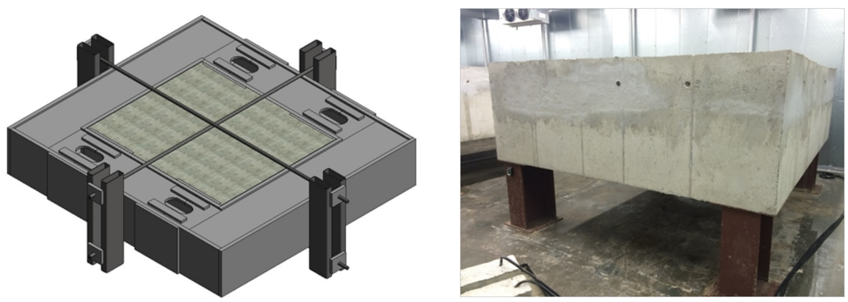

FIGURE 1. Drawing of the confined ASR specimen (left); picture of control unconfined specimen (right).

NONDESTRUCTIVE EVALUATION (NDE) MEASUREMENTS

Several measurements were acquired on the three specimens. Top surface measurements were performed on all three specimens, and side lateral measurements were performed on the unconfined control and unconfined ASR specimens. See Figure 2 for measurement locations S1, S2, and S3.

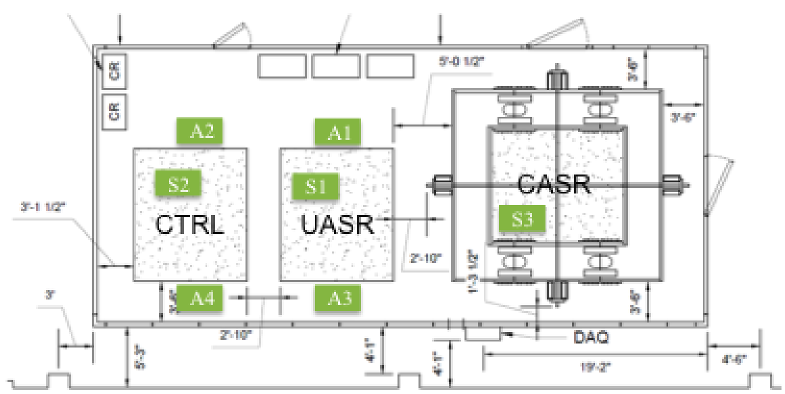

FIGURE 2. Drawing of the specimen with the environmental chamber. From left to right: Unconfined Control specimen (CTRL), Unconfined ASR specimen (UASR), and Confined ASR Specimen (CASR).

A 40 x 40 in square is divided into a 10 x 10 grid (labeled: A-J, 1-10) was drawn on the top surface of each specimen. The grid defines the boundary of the measurements and the scan path, see Figure 3a. MIRA, a commercially available instrument from Germann Instruments, is an ultrasonic tomography unit composed of 40 dry-point-of-contact transducers that form a 4 x 10 matrix (see Figure 4). The instrument transmits ultrasonic pulses from one column of transducers and receives on the other nine columns. Internally, MIRA produces a single entity of averaged data from the four transducers in a column. By cycling through the unique combinations of transmitting column and receiving columns (one column transmits while the other columns receive), a total of 45 unique impulse time-history measurements are acquired (see Figure 5).

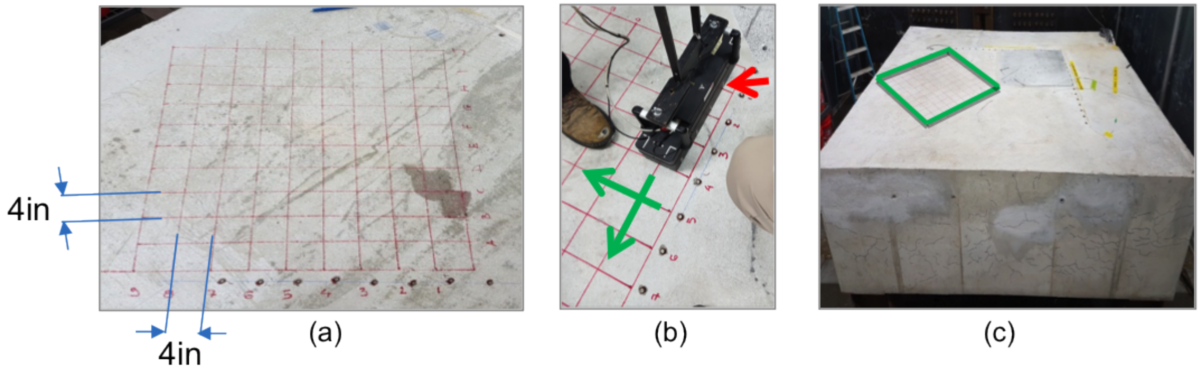

FIGURE 3. Top surface NDE measurement (a) 10 x 10 grid; (b) scan path; (c) image of grid location on top surface of control specimen (CTRL).

FIGURE 4. MIRA ultrasonic tomography instrument

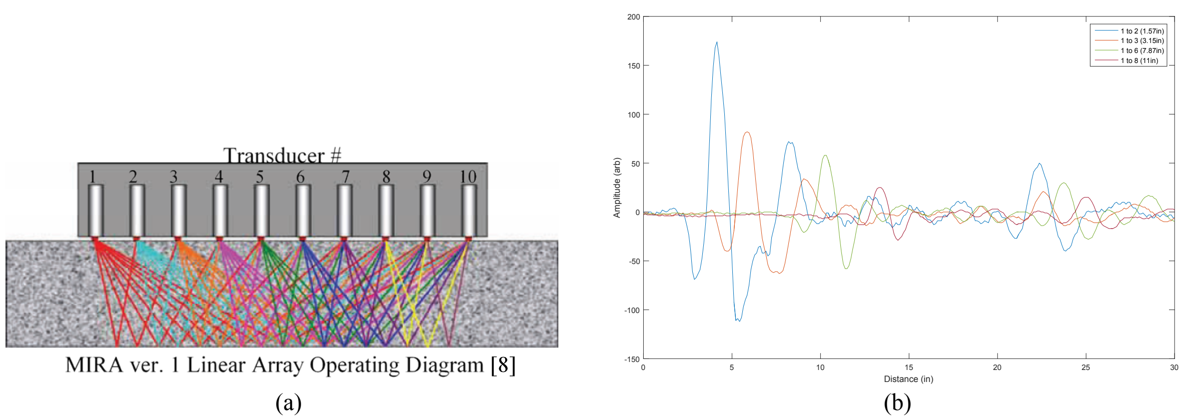

FIGURE 5. (a) MIRA operating diagram. (b) A-scan data with transmission from transducer 1 and receiving at transducer 2, 3, 6, and 8 respectively.

To perform the first scan, the horizontal centerline of the MIRA instrument was aligned on line A, with the first large mark on the device aligned with line 1; then the instrument is stepped along line A, acquiring a measurement at each numbered line (1-10) along line A (see Figure 3b). A complete scan along line A acquires nine measurements each with 45 channels of data. This same process was repeated to create scans for lines B through J. After completion of the scans along the lettered lines, the MIRA instrument was rotated 90°, placed on line 1, and the first large mark aligned on line A. The instrument was stepped along line 1 acquiring a measurement at each lettered line (A-J). The NDE measurements were performed on two occasions (see Figure 6).

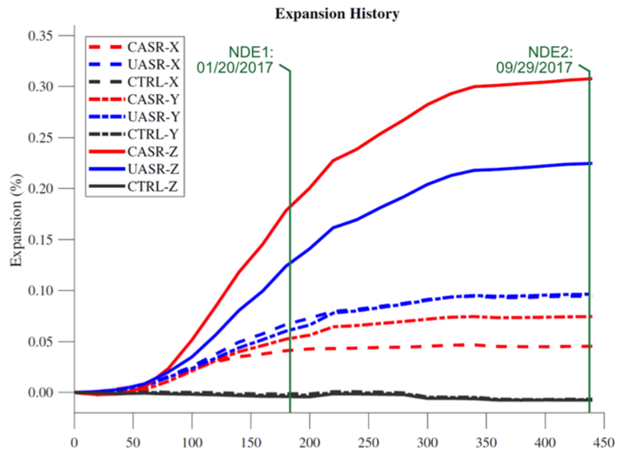

FIGURE 6. Expansion plotted over time.

NDE measurements were also performed on the side surfaces of two of the three concrete specimens; see Figure 2 for the locations of measurements A1, A2, A3, and A4. A 5 x 5 grid was drawn on the side surfaces to register the measurements. To perform the horizontal scans, the horizontal centerline of the MIRA instrument was aligned on line A, with the first large mark on the device aligned with line 1; then the instrument is stepped along line A, acquiring a dataset at each numbered line (1-5). Then this process is repeated for scans (B-E). Again, the MIRA instrument was rotated 90°, and lateral scans along numbered lines (1-5) were made to acquire data at lettered lines (A-E). See Figure 7 for horizontal and lateral surface measurements.

FIGURE 7. Lateral surface grid with lateral MIRA measurements on line A and horizontal MIRA measurements on line 1.

RECONSTRUCTION APPROACH

Processing the data obtained from the NDE measurements produces a 2D image representative of a slice in the concrete at the line segment under evaluation (see Figure 8). Although there are many research facilities investigating image reconstruction techniques, the selection of the correct technique is important for obtaining reasonable and logical images.

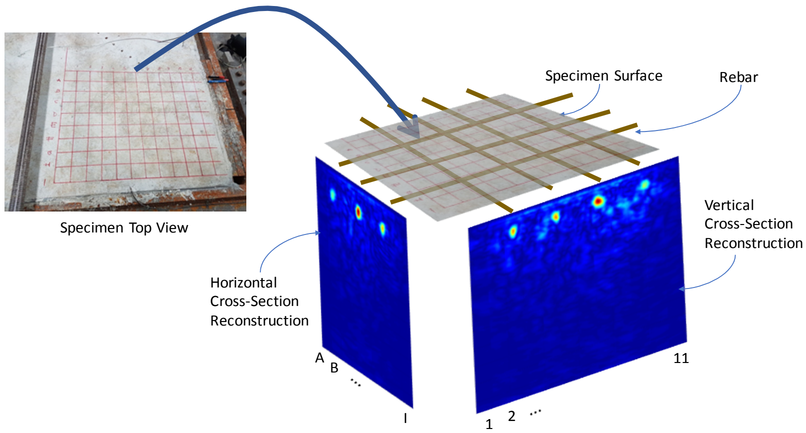

FIGURE 8. Desired reconstruction of Thick-Reinforced Concrete Structure.

ORNL used a Synthetic Aperture Focusing Technique (SAFT) to reconstruct images from the data acquired using the ultrasonic instrument (MIRA). SAFT is the standard method for converting ultrasonic A-scan data into B-scan (see Figure 9). SAFT's ability to improve focusing and the signal-to-noise ratio of the resulting image reconstruction [7] is a key factor in its wide acceptance and application in the field on NDE and testing.

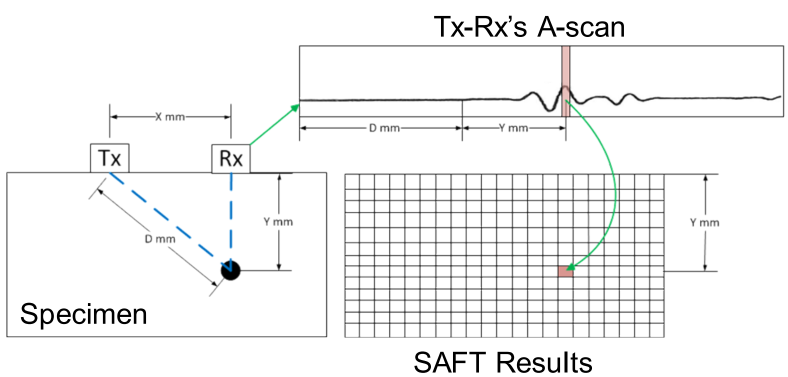

FIGURE 9. Desired reconstruction of Thick-Reinforced Concrete Structure.

Frequency banded-SAFT (FB-SAFT) is an extension of SAFT created to allow the selective incorporation of the ultrasonic energy received based on the frequency/frequency band. In particular, ORNL selected to apply FB-SAFT to reduce the noise in the reconstruction by using wavelets to enable the ability to selectively eliminate or retain bands of frequency [2]. In the case of the MIRA system, the received signals are sampled at 1 M samples per second, yielding a Nyquist frequency of 500 kHz. The nominal transmitted pulse has a center frequency of 50 kHz. The energy of the impulse is contained in bandwidth that is nominally 125 kHz wide [8]. Based solely on MIRA's listed specifications the bandwidth of MIRA is four times the bandwidth of the impulse. By using frequency banding, it is possible to perform a number of advantageous operations in both the operational realm such as defect detection and experimental research realm such as investigating the possibility that the type of a defect, e.g., honeycomb, delamination, etc. may produce an identifiable perturbation of the frequencies reflected by the defect.

Our FB-SAFT approach uses wavelets to selectively eliminate or retain bands of frequency and thus the energy received in those bands while allowing the SAFT reconstruction to continue to operate using time-domain data [2]. In the case of processing MIRA data with FB-SAFT, an immediate advantage comes from simply eliminating energy contributed from frequencies outside the nominal 125 kHz bandwidth of the impulse. By narrowing the bandwidth to retain only the range containing the highest concentration of energy, the noise in the reconstructions is reduced while improving the sharpness [9].

There is currently an overall lack of knowledge regarding the inspection of thick concrete specimens, such as found in NPP containment structures, for ASR using ultrasonics. Therefore, we have based our initial analysis on the knowledge gained in through our previous investigation on applying ultrasonic NDE equipment to inspecting thick concrete structures. The previous investigation sought to determine the capabilities and limits upon a specially designed and constructed thick test specimen containing synthetic analogs representing defects such as cracks, delamination, foreign contaminates (e.g. construction debris), etc. [9]. This specimen was fabricated at the University of Minnesota (UMN)'s Multi-Axial Subassemblage Testing System laboratory. The same MIRA unit was used to collect ultrasonic NDE data from all accessible surfaces of this thick NPP test specimen, see Figure 10.

Based on the lessons learned from analyzing the UMN thick specimen, the same wavelet nodes were used to process the ASR test specimens. Because ASR is a progressive degradation of the concrete host it is occurring in, it is important that the ultrasonic data collection be across a meaningful timeframe. The environmental chambers housing the ASR specimens allow us to decrease this meaningful timeframe from potentially decades to just two years

SAFT RECONSTRUCTION RESULTS

As mentioned previously, the NDE measurements were acquired on two occasions and FB-SAFT was applied to both sets of data. The goal was to make a comparison between the reconstructions to identify areas with changes. The reconstructions were normalized to a fixed dynamic range to enable side-by-side comparison. A visual comparison showing some areas with changes is shown in Figure 11. These changes are subtle and could easily be overlooked. However, the degree, size, and quantity of the internal ASR is yet to be determined. Destructive evaluation of the ASR specimens will be performed as the final step of the ASR experiment. Once this final step is completed, the characteristics of the ASR and location of excised colonies will be used to inform the refinement and improvement of FB-SAFT for ASR detection. The research team has already begun to develop an algorithm that could localize the differences between the reconstruction data sets. This work is underway along with a 3D visualization tool.

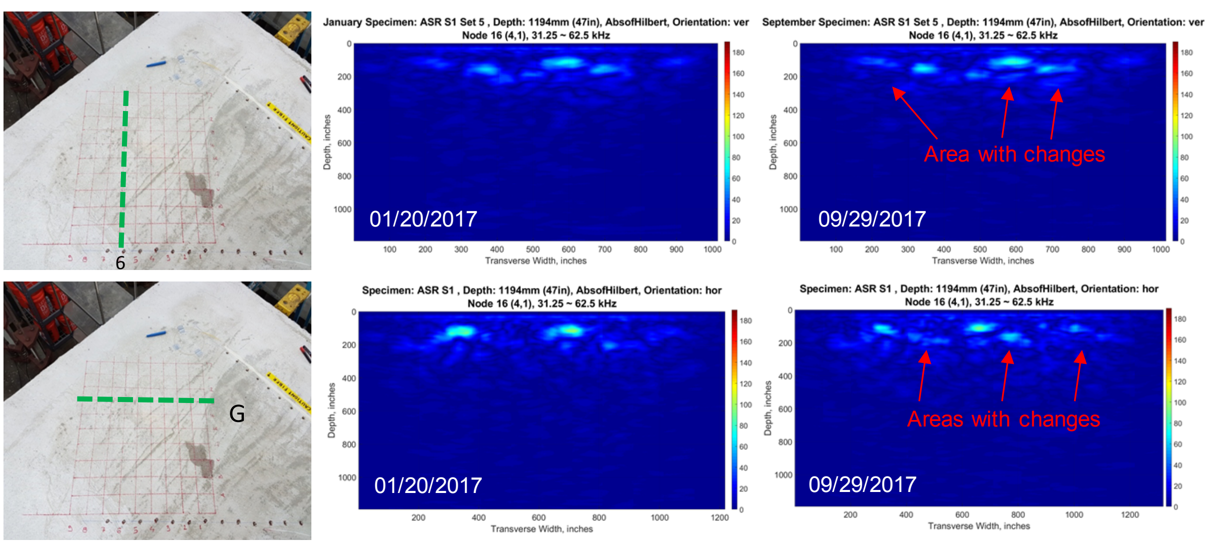

FIGURE 10. Preliminary results from NDE of thick-concrete ASR experiment.

CONCLUSIONS

This paper discusses a large-scale experiment designed to demonstrate the development of ASR in thick concrete. After the confirmed finding of ASR in Seabrook NPP, the LWRS program constructed this experiment to enable a platform for the development of NDE for ASR detection. ORNL has developed a FB-SAFT program that creates 2D image reconstructions of the data acquired using a commercial ultrasonic instrument, MIRA. The procedure followed while acquiring this data is also discussed in detail. The FB-SAFT algorithm was utilized to process data from two NDE measurements. Results from the first and second measurements indicated there were changes in the concrete.

The results from setting a global static dynamic range for the normalization of the FB-SAFT reconstructions, Figure 11, show the need to refine the dynamic range scaled to the maximum and minimum values for a given node, not for all nodes. This will allow more details to show in the reconstructions that are being hidden due to the unnecessarily large dynamic range, while allowing one-to-one comparisons between reconstructions of the same node from different acquisitions.

The next significant step in this work is the pending destructive quantification of the ASR present in the CASR, CTRL, and ASR specimens. This will allow ground truth to be to be derived on the location, amount, and extend of the ASR that has formed. Using this ground truth, the results generated for the wavelet nodes we used with FB-SAFT, based on previous empirical concrete testing experiment, can be corelated with the ground truth data to evaluate the sensitivity and detection qualities of the frequency bands used in FB-SAFT with respect to the detection of ASR.

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