Structural Health Monitoring to Automate Monitoring and Condition-Based Inspection of Concrete Structures in Nuclear Power Plants

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Concrete structures in nuclear power plants may be affected by a variety of degradation mechanisms over time. Structural health monitoring (SHM) is an established approach to assess the condition of structures and provide high confidence, actionable information regarding structural integrity and reliability. Using a SHM approach may enable nuclear power plants to replace or augment current inspection-based aging management plans with online monitoring capabilities and condition-based inspections of concrete structures. Using an effective SHM approach will provide important information on structural integrity and reliability to support subsequent license renewal.

Currently, researchers from the Light Water Reactor Sustainability (LWRS) Program and Vanderbilt University are investigating alkali-silica reaction (ASR) in concrete, a chemical degradation process that occurs between the alkali hydroxides in the pore solution and the reactive non-crystalline (amorphous) silica found in many common aggregates in a moist environment. This reaction occurs over time and causes the expansion of the altered aggregate by the formation of a swelling gel of calcium silicate hydrate, referred to as ASR gel. In the presence of water, the ASR gel increases in volume and exerts an expansive pressure inside the material, thereby causing transition from micro to macro cracking. As a result, ASR reduces the stiffness and tensile strength of concrete, two properties that are particularly sensitive to micro cracking.

Typically, SHM consists of four stages: (1) detection; (2) localization; (3) assessment; and (4) prediction. An SHM

Figure 1. Casting of medium-sized concrete sample with pockets of reactive aggregates. Numbers in the red box indicate sites where visual cracks were seen after a year of curing and accelerated ASR degradation.

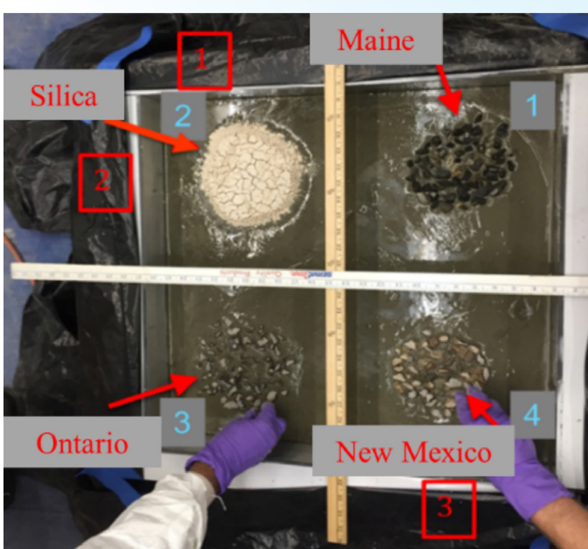
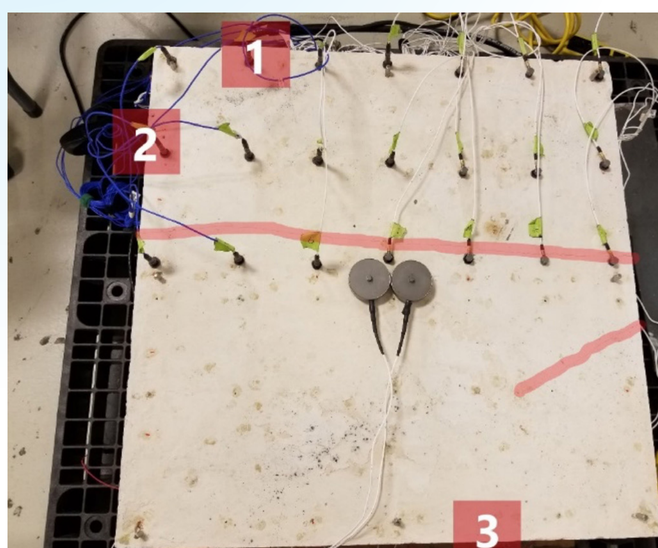


Figure 2. VAM experimental setup with degradation sites identified (marked in red).



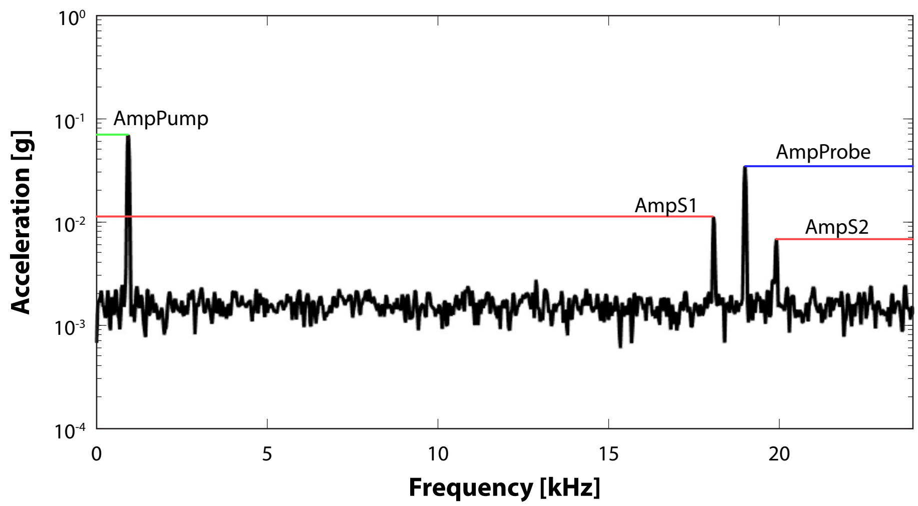


Figure 3. The dynamic response showing sidebands around the probing frequency.

approach based on vibro-acoustic modulation (VAM) testing is utilized to assess the condition of a medium-sized concrete specimen with dimensions of 2 × 2 × 0.5 ft^3, as shown in Figure 1. The medium-sized concrete specimen was cast and cured at the Laboratory for Systems Integrity and Reliability at Vanderbilt University, and contained four types of aggregates at known locations, including three coarse aggregates known to be susceptible to ASR, as well as pure silica powder (see Figure 1). This specimen was placed in an environmental chamber maintained at 60°C and 95% relative humidity to accelerate ASR degradation.

In a VAM test (see Figure 2), the structural component of interest, which is the concrete specimen, is excited simultaneously at two frequencies, while the dynamic response (acceleration) is measured at various locations using sensors (accelerometers). A low-frequency input is termed the "pump" and a high frequency input is termed the "probe." The dynamic response of the structure is used to diagnose (detect) the presence or absence of any degradation. If the dynamic response contains side bands (see Figure 3), it is inferred that measurable degradation is present in the structure; otherwise, the structure has no measurable degradation.

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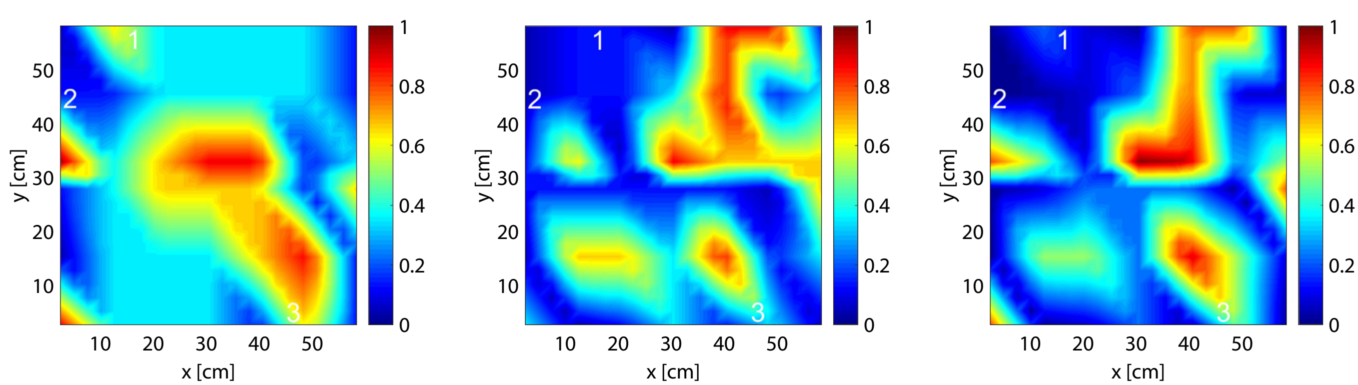
Figure 4. Bayesian-fusion results for the different VAM test parameter settings for pump frequency set at 920 Hz and probe amplitude set at 250 mV. (Left): Probe frequency of 16 kHz. (Middle): Probe frequency of 20 kHz. (Right): Bayesian fusion of the results from (left) and (middle).



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The next step after detecting degradation is localizing the damage. To address this challenge, it was hypothesized that the spatial distribution of the relative magnitude of a sideband-based damage index, such as the sum of sideband amplitudes (AmpS1 + AmpS2), could be used to localize degradation sites on the concrete specimen.

This hypothesis was tested by performing a VAM test in the laboratory using different test parameters, including pump and probe frequencies, pump and probe excitation amplitudes, and their locations on the concrete sample. Accelerometers were distributed uniformly on the surface of the concrete sample to record the dynamic response of the structure for each test parameter setting during VAM testing. The data collected for different parameter settings was used to develop a set of damage maps.

Different test parameter combinations resulted in the identification of different possible ASR damage locations, thereby introducing uncertainty in the localization of the degradation site. To overcome this challenge, Bayesian data fusion was utilized to assimilate the diagnostic information from the VAM tests. Figure 4 shows two damage maps generated for two different test parameter settings and how the fused damage map using Bayesian approach preserved the salient features from each damage map to generate an accurate degradation site localization. The degradation sites identified by the fused damage map were validated using the knowledge on known aggregate sites and visible degradation observed on the concrete specimen.

This example shows that the application of Bayesian data fusion enhances the assessment and prediction capability of the SHM approach. The progress achieved in the research and development of VAM based SHM approach to detect and predict concrete degradation has contributed significantly in enhancing the state of the art of monitoring structures. The approach is generic and can be extended to monitoring vital concrete structures in nuclear power plants with minor modifications and enable online monitoring to ensure performance assurance.

As path forward, for the degradation of interest (ASR in this case), develop a prediction capability, followed by a demonstration and an implementation strategy for concrete SHM to support automation and remote monitoring is required.

Establishing the extent of degradation at the identified site and predicting the future state of the concrete specimen are the topic of ongoing research in the current year.