Acoustic Emission Monitoring of a Nuclear Containment Wall during Post-tensioning: Data Mining and Knowledge Discovery

Arvin Ebrahimkhanlou[1], Jongkwon Choi[2], Trevor D. Hrynyk[3], Salvatore Salamone[4], Oguzhan Bayrak[5]

[1]*Dept. of Civil, Archit. and Env. Eng., The University of Texas at Austin, Austin, TX, arvinebr@utexas.edu*
[2] *Dept. of Civil, Archit. and Env. Eng., The University of Texas at Austin, Austin, TX, jchoi1022@utexas.edu*
[3] *Dept. of Civil, Archit. and Env. Eng., The University of Texas at Austin, Austin, TX, thrynyk@utexas.edu*
[4] *Dept. of Civil, Archit. and Env. Eng., The University of Texas at Austin, Austin, TX, salamone@utexas.edu*
[5] *Dept. of Civil, Archit. and Env. Eng., The University of Texas at Austin, Austin, TX, bayrak@utexas.edu*

ABSTRACT: Post-tensioned containment structures are widely used in nuclear power plants. In case of any accident, these concrete structures are the last passive barrier against contaminating radioactive materials. During the construction-phase of these cylindrical concrete structures, hidden delamination defects may develop and remain undetected. This study introduces a new method based on acoustic emission (AE) to monitor the onset of delamination in a large-scale experimental model of a containment structure as it is being post-tensioned. In particular, advanced data processing algorithms are used to interpret AE data in terms of the delamination mechanism.

Test Structure and Measured Data

A large-scale experiment was performed on a quarter-circle, post-tensioned curved wall that was approximately 20% of the size of a containment structure (see Figure 1). The design strength of concrete was 3500 psi (24.1 MPa). The diameter, thickness, and height of the wall were 14′ (4.27 m), 12″ (305 mm), and 6′ (1.83 m), respectively. Four ducts each with a diameter of 4″ (101 mm) were installed uniformly every 18″ (457 mm) in the height of the specimen. In each duct, nineteen 0.6” (15-mm) diameter steel strands were provided. To monotonically post-tension the strands, four 800 kip (3560 kN) hydraulic rams were used. To measure the loads, two load cells were installed at the ends of each duct (eight in total). The specimen was continuously loaded to delamination failure at the load of 2850 kip (12680 kN). To measure the delamination of the wall, the through-thickness deformation of the wall was measured using linear strain conversion transducers (hereafter referred to as delamination gauges). The gauges were placed where the delamination was expected to initiate, i.e. at a 15-degree angle from the loading side of the curve.

Acoustic emissions of the specimen were monitored over the course of the structural testing. For this purpose, the specimen was instrumented with eight AE sensors (Physical Acoustic Corporation, R6α) that were held in place with hot glue. The resonance frequency of the sensors was 60 kHz. To record the AE signals, an eight-channel data acquisition system (MISTRAS Micro Express) was used. Before recording, the signals were amplified by 40 dB and filtered with an analog band-pass filter (5 kHz to 400 kHz). To extract common AE features from the signals and localize them, AEwin software (MISTRAS group) was used. The AE features were then post-processed in MATLAB. Figure 1(d) shows the distribution of AE data based on their average frequency and R.A. value (i.e. rise time over amplitude ratio). AEs that stem form tensile micro cracking higher amplitudes, lower frequencies, and shorter rise times than those that stem from micro shear cracking under uniaxial compressive stresses [1]. According to the Japan Construction and Material Standard [2], the two AE source could be discriminated based on the above mentioned features. However, the challenge is that the features of tensile and shear cracks usually overlap.

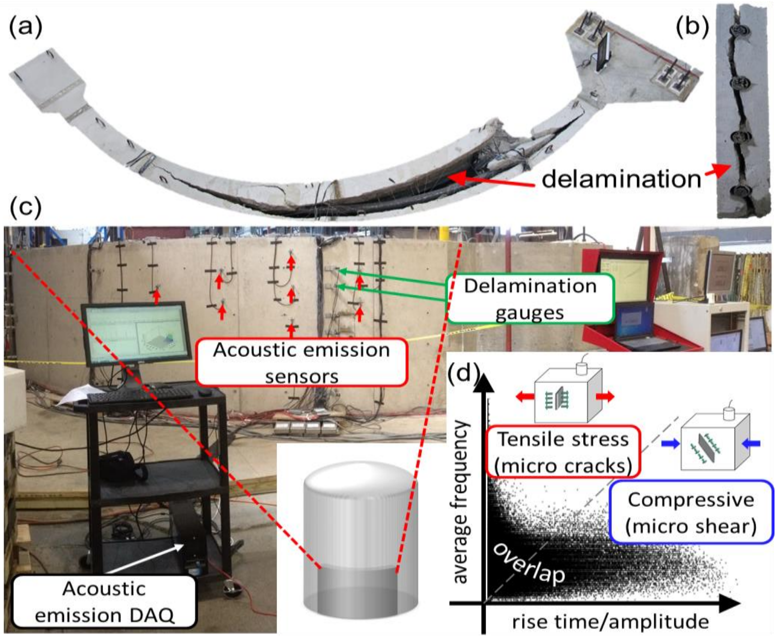

Figure 1. Experimental setup and collected data: (a) top view, (b) cross-section, (c) instrumentation, (d) two AE features.

SHM Methodology and Results

To overcome the challenge of separating AE due shear cracking from those that are due to tensile cracking, this case study uses more AE features, clusters AE hits in a higher dimensional feature space, and shows that the tensile and shear cracks can be discriminated even at the overlapping area.

K-means clustering

K-means clustering is a common algorithm to assign similar data points a common group number. In this study, the optimal number of clusters is determined using the average Silhouette index. To identify the most independent AE features, correlation test was performed, and nine AE features were selected [3]. The results show three clusters were identified in the AE data. To interpret the physical meaning of the clusters, Figure 2 projects the first two clusters on the plots introduced by the Japan Construction and Material Standard [2]. The figure demonstrates that the two clusters respectively match with the description of shear micro cracks and tensile micro cracks. In addition, the overlapping issue has overcome. Figure 3 compares the location of AE events of the first two clusters before and after delamination. In addition, the normalized cumulative number of AE hits are shown as a function of the post-tensioning force and compared with the reading from the delamination gauges. It could be observed that the third cluster is highly correlated with the reading of the first gauge.

Hidden Markov model (HMM)

A hidden Markov model is a probabilistic model that describes a sequence of observed variables based on a sequence of hidden states. In this study, the observed and hidden variables of the model are respectively the clusters and the damage states of the structure: intact or delaminated[4,5]. Figure 4 shows the trained HMM for this study and Figure 5 compares the evolution of the clusters and the hidden damage state (i.e. intact or delaminated) with the readings of the delamination gauges. The figure shows that the HMM made a permanent transition from the intact state to the delaminated state at a post-tensioning load slightly larger than the load at which the first delamination gauge recorded the first indications of delamination. Such results demonstrate that the HMM model can estimate the condition of the wall based on AE signals recorded during the post-tensioning.

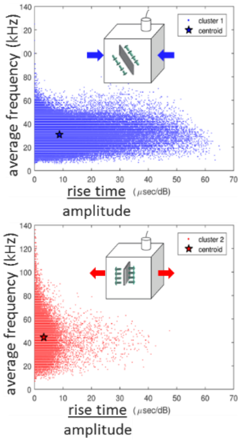

Figure 2. The first two clusters are due to micro shear and tensile cracks.

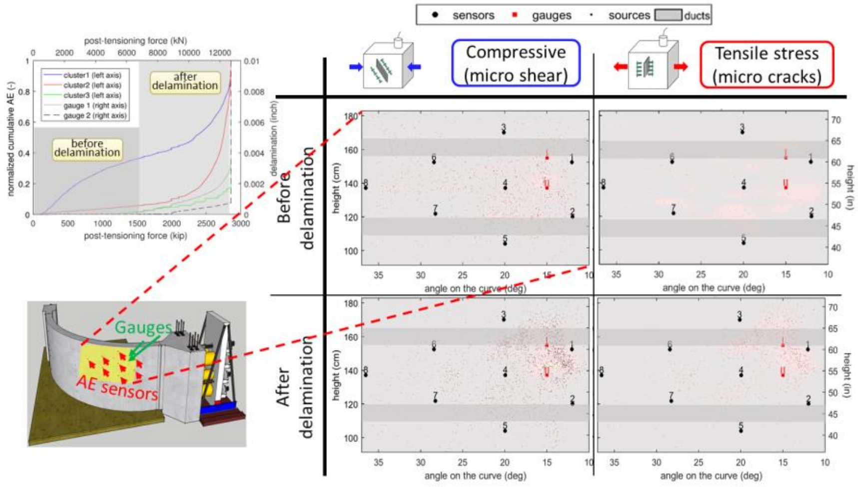

Figure 3. Cumulative number of AE hits and localization results for the identified clusters

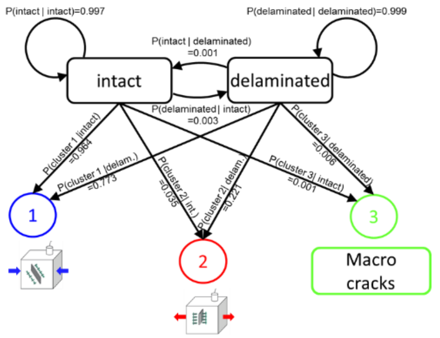

Figure 4. The trained hidden Markov model

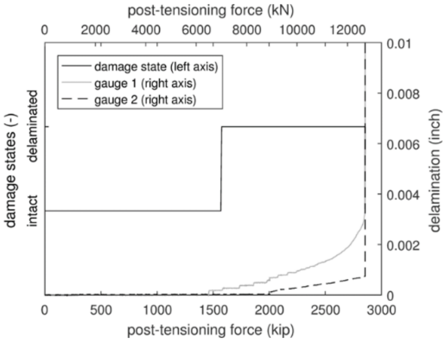

Figure 5. The transition from the intact state to the delaminated state

Lessons Learned

This case study presented AE monitoring of a large-scale experimental model of a nuclear containment structure subject to prestressing loads. The results show that the proposed approach can effectively detect the onset of delamination. Such results suggest that this approach could also be applicable for monitoring the post-tensioning and re-tensioning of other containment structures, such as silos, and storage tanks.

References

[1] Farhidzadeh A, Salamone S, Singla P. A probabilistic approach for damage identification and crack mode classification in reinforced concrete structures. J Intell Mater Syst Struct 24 (2013) 1722–35.

[2] JCMS-III B5706 Monitoring method for active cracks in concrete by AE, Japan, 2003.

[3] Ebrahimkhanlou A, Choi J, Hrynyk TD, Salamone S, Bayrak O. Acoustic emission monitoring of containment structures during post-tensioning. Eng Struct (2019).

[4] Ebrahimkhanlou A, Choi J, Hrynyk TD, Salamone S, Bayrak O. Detection of the onset of delamination in a post-tensioned curved concrete structure using hidden Markov modeling of acoustic emissions. In Proc. SPIE, Sensors Smart Struct. Technol. Civil, Mech. Aerosp. Syst. 1059821 (2018)

[5] Ebrahimkhanlou A, Choi J, Hrynyk TD, Salamone S, Bayrak O. Data mining for acoustic emission monitoring of a nuclear containment wall during post-tensioning. Trans. SMiRT-25, Div. V, Charlotte, NC, USA (2019).