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Damage Assessment of Reinforced Concrete Slabs Using Acoustic Emission and Numerical Modeling

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Abstract

This study presents an experimental and numerical investigation of damage development in reinforced concrete slabs subjected to monotonic loading. Acoustic emission (AE) monitoring was used to evaluate crack initiation and progression during loading. Time–frequency analysis techniques were applied to characterize changes in the frequency content of AE signals associated with damage evolution. The experimental results showed clear variations in acoustic emission characteristics as cracking developed and localized within the slab.

To support the experimental observations, nonlinear finite element modeling based on the Concrete Damaged Plasticity model was performed. Good agreement was observed between the numerical tensile damage distribution and the acoustic emission activity recorded during testing. The results indicate that combining acoustic emission monitoring with numerical modeling provides a practical approach for assessing damage development in reinforced concrete structural elements.

Keywords: Acoustic emission, Reinforced concrete slabs, Finite element modeling, Damage assessment, Crack development.

1. Introduction

Acoustic emission (AE) is a highly sensitive nondestructive evaluation (NDE) technique capable of monitoring damage evolution in cementitious materials in real time. By detecting transient elastic waves released during crack initiation and propagation, AE provides valuable insight into both microcracking processes and macrocrack development in reinforced concrete (RC) structures. Owing to this capability, AE has been widely applied to assess cracking behavior, damage accumulation, and failure processes in concrete elements under various loading conditions.

Conventional AE analysis has traditionally relied on time-domain parameters such as amplitude, rise time, duration, counts, and energy. While these parameters offer useful qualitative indicators of damage progression, they are often insufficient to capture the complex, non-stationary nature of AE signals generated by evolving failure mechanisms in concrete. In particular, time-domain descriptors alone provide limited information regarding the frequency characteristics associated with different cracking modes and damage stages. To address these limitations, time–frequency (T–F) analysis techniques, including the Short-Time

Fourier Transform (STFT) and Continuous Wavelet Transform (CWT), have been increasingly employed to analyze AE waveforms. These methods enable tracking of spectral content over time and facilitate the identification of frequency shifts associated with specific damage mechanisms. Previous studies have shown that high-frequency AE components are typically linked to tensile microcracking, whereas lower-frequency signals may correspond to frictional effects, shear cracking, or aggregate interlock. Despite these advances, many existing studies interpret AE frequency features primarily through empirical observations, without explicit linkage to the underlying mechanical damage state of the structure.

Finite element modeling (FEM) provides a complementary, physics-based framework for simulating stress redistribution, crack initiation, and damage localization in reinforced concrete elements. In particular, the Concrete Damaged Plasticity (CDP) model enables detailed representation of tensile cracking and compressive crushing, offering access to mechanically meaningful variables such as damage indices and principal strain fields. When combined with experimental observations, FEM can serve as a powerful tool for interpreting AE signatures in terms of physical damage evolution rather than signal characteristics alone.

The present study aims to bridge the gap between AE signal interpretation and mechanical damage assessment by developing an integrated experimental–numerical framework for evaluating failure development in reinforced concrete slabs. Acoustic emission monitoring is coupled with time–frequency analysis and nonlinear finite element modeling to establish direct correlations between frequency-sensitive AE features and FEM-derived damage variables. Through this integration, the study provides a mechanistic interpretation of AE precursors associated with damage localization and failure progression.

Specifically, the proposed framework establishes a physically validated link between AE frequency content and FEM-based tensile damage evolution in RC slabs, identifiable indicators that consistently emerge during advanced stages of damage evolution before global failure, and demonstrates that AE time–frequency characteristics can be used as interpretable measures of nonlinear structural response rather than purely empirical monitoring parameters. By anchoring AE observations to spatially resolved damage mechanisms, the study enhances the reliability of AE-based structural assessment and supports its application in monitoring and evaluating the performance of reinforced concrete elements.

The remainder of this paper is organized as follows. Section 2 reviews relevant literature on acoustic emission monitoring and nonlinear modeling of concrete structures. Section 3 describes the experimental program, AE instrumentation, signal processing methodology, and finite element modeling strategy. Section 4 presents and discusses the combined experimental and numerical results, with emphasis on the structural interpretation of AE time–frequency features. Finally, Section 5 summarizes the main conclusions and outlines directions for future research.

2. Literature Review

2.1 AE in Concrete Structures

AE has long been applied to monitor cracking in concrete due to its ability to capture both initiation and progression of damage [1,2]. Key AE parameters such as amplitude, energy, and the b-value have been used to characterize different stages of fracture. Carpinteri et al. [3] demonstrated that the dominant frequency of AE signals shifts toward lower frequencies as damage approaches criticality. Colombo et al. [4] introduced statistical b-value analysis to assess damage severity, confirming its sensitivity to micro–macro transition in fracture evolution.

2.2 Time–Frequency Analysis

Time–frequency analysis has emerged as a powerful tool to study the non-stationary nature of AE signals. The use of wavelet transforms allows for localized tracking of frequency content during crack propagation [5–8]. High-frequency AE activity (≥120 kHz) has been associated with tensile microcracking, while low-frequency signals (<80 kHz) often correspond to shear or frictional events. Grosse and Linzer [6] emphasized that waveform-based approaches reveal richer information than conventional parameter-based analysis, particularly when assessing mixed-mode cracking.

2.3 FEM for Damage Correlation

The Concrete Damaged Plasticity (CDP) model implemented in ABAQUS [9] provides a robust framework for simulating tensile cracking and compressive crushing in RC elements. FEM outputs such as principal tensile strain, dissipated energy, and damage indices (dt, dc) can be directly correlated with AE observables, linking experimental signals to mechanical damage states. Studies combining AE with FEM/DEM simulations [10–12] have shown that such hybrid analysis enhances interpretability and predictive accuracy.

2.4 Emerging Data-Driven Approaches

Recent advances in machine learning (ML) and deep learning (DL) have improved AE signal classification and damage localization [13,14]. Hybrid physics–ML approaches further enable the transfer of knowledge across structures and loading types. However, the reliability of such models remains constrained without physical validation—hence the need for a combined AE–FEM methodology.

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3. Material and Methods

3.1 Experimental Setup

Rectangular reinforced-concrete slabs (length 600 mm, width 400 mm, thickness 60–80 mm) were tested under displacement-controlled central loading. Variants included reinforcement ratios of 0.8–1.2% and differing support conditions. AE sensors (bandwidth 20–300 kHz, 40 dB preamplifier) were mounted on the top surface using a uniform couplant layer. Sampling frequency was 500 kHz with a bandpass filter of 20–300 kHz. Load–displacement data were recorded synchronously with AE hits using a TTL pulse alignment system.

3.2 Signal Processing

Raw AE waveforms were processed using STFT and CWT with Hann and Morlet kernels, respectively. Extracted features included:

- Amplitude, rise time, duration, and counts;
- Energy, spectral centroid, median frequency;
- Wavelet packet energies (WPE) at selected sub-bands. Frequency bands were calibrated using pencil-lead breaks and white-noise excitation to define consistent spectral ranges across specimens.

3.3 Finite-Element Modeling

FEM models were developed in ABAQUS using **C3D8R** solid elements, refined near load and support regions (element size ≈ 10–15 mm). The CDP model governed concrete behavior with a bilinear tension-softening law and nonlinear compressive response. Boundary conditions replicated the experimental rig. Displacement-controlled loading was applied in steps to reproduce quasi-static conditions, and outputs included:

- Damage indices (dt, dc),
- Principal strain contours,
- Reaction forces and load–displacement curves.

Mesh and time-step sensitivity studies ensured numerical stability and energy balance.

3.4 AE–FEM Data Fusion

Each AE event was time-aligned with the corresponding FEM increment and spatially mapped to the nearest finite-element region. Statistical correlations were computed between AE features and FEM-derived damage variables using mixed-effects regression models. For each specimen, thresholds were determined through Receiver Operating Characteristic (ROC) analysis to maximize the Youden.

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4. Results and Discussion

4.1 Finite Element Response and Damage Evolution

The nonlinear finite element simulations successfully reproduced the global and local failure behavior observed experimentally. The Concrete Damaged Plasticity model captured the transition from distributed tensile cracking to localized macrocrack formation beneath the loading point, followed by diagonal crack propagation toward the supports. Progressive increases in tensile damage variables and principal tensile strain concentrations were observed as loading advanced, providing a mechanically consistent reference for interpreting the acoustic emission activity. The refined mesh is shown schematically in Figure 1.

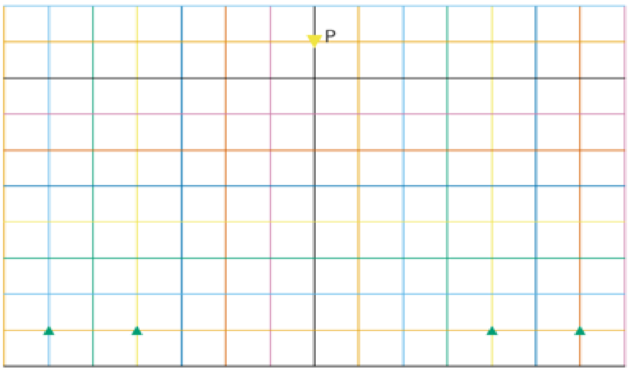

Figure 1. Finite Element Mesh (schematic).

The close agreement between simulated crack patterns and experimentally inferred damage zones confirms that the numerical model reliably represents the underlying failure mechanisms. This correspondence is essential for establishing a meaningful link between AE signal characteristics and physical damage evolution rather than relying on purely empirical correlations (Figure 2).

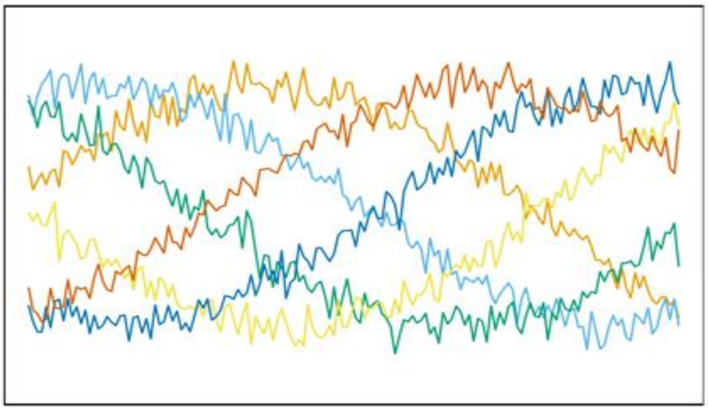

Figure 2. Experimentally observed crack pattern at failure

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4.2 Time–Frequency Characteristics of Acoustic Emission Signals

The evolution of AE time–frequency characteristics revealed distinct stages of damage progression. During the initial quasi-linear response, AE activity was sparse and dominated by low-frequency components in the range of approximately 40–60 kHz, consistent with the onset of distributed microcracking within the tensile zone of the slab.

As loading progressed into the nonlinear regime, increased AE event rates coincided with stiffness degradation and crack interaction. This stage was characterized by a systematic migration of spectral content toward intermediate frequency bands (80–120 kHz), reflecting the interaction and coalescence of microcracks. These trends align with the gradual increase in tensile strain and damage variables observed in the FEM results.

Approaching peak load, a pronounced concentration of AE energy emerged in higher frequency bands (120–180 kHz). This shift was accompanied by a marked increase in spectral centroid values and wavelet packet energy within high-frequency sub-bands, indicating rapid crack propagation and localized fracture processes. The consistency of this behavior across multiple specimens suggests that high-frequency AE activity constitutes a reliable indicator of advanced structural damage (Figure 3).

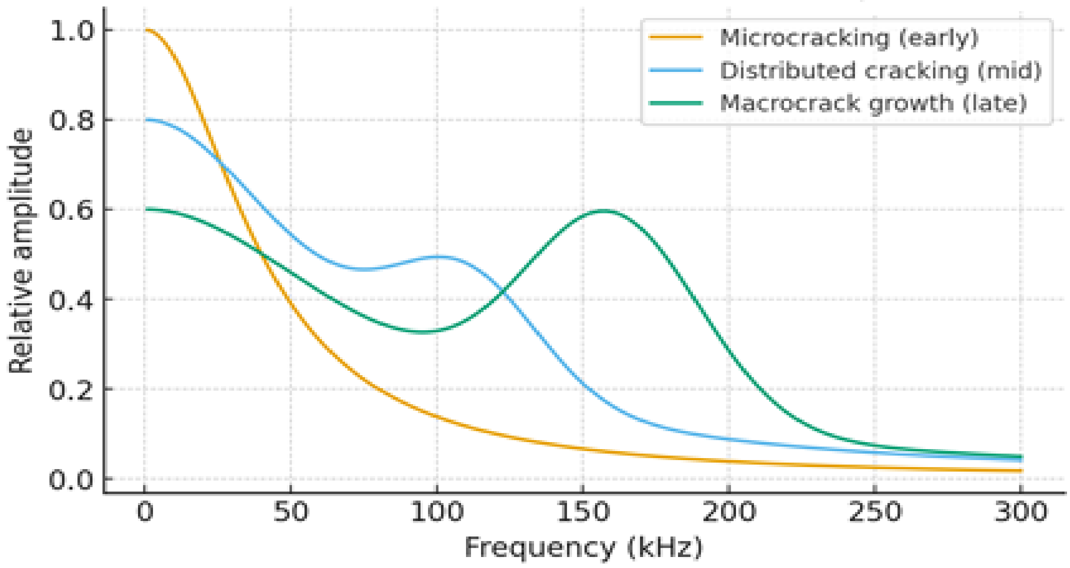

Figure 3. Representative AE frequency spectra at different loading stages

4.3 Correlation between AE Features and FEM Damage Metrics

Quantitative correlation analysis demonstrated strong relationships between AE time–frequency features and FEM-derived damage indicators. The AE energy rate exhibited a strong positive correlation with maximum principal tensile strain ($r \approx 0.75$), while the spectral

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centroid showed a similarly strong correlation with tensile damage variables (dt) ($r \approx 0.70$). These correlations confirm that the observed AE frequency shifts are directly linked to mechanically meaningful damage evolution rather than stochastic signal fluctuations.

Importantly, these AE indicators consistently emerged approximately 8–12% before peak load under the investigated loading conditions, providing a measurable damage evolution stage before global failure. From a structural engineering perspective, this interval corresponds to the final stage of stiffness degradation and crack localization, during which intervention or load mitigation may still be feasible (Figure 4).

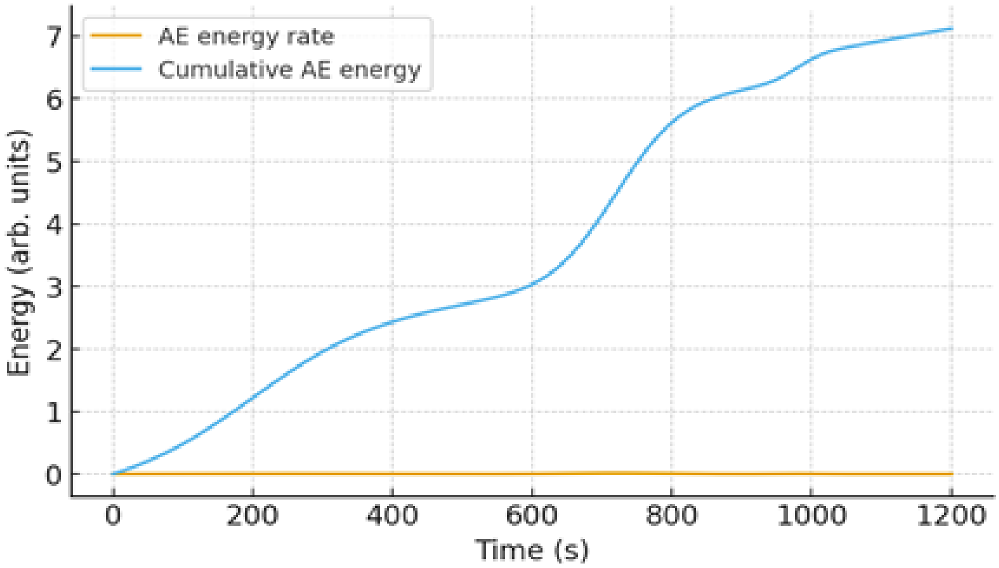

Figure 4. AE energy evolution

Microcracking Phase: Initially, AE signals were of low energy and exhibited a broad, lower-frequency spectrum (Figure 4). This corresponds to the distributed microcracking in the concrete matrix before the formation of dominant macrocracks, as seen in the initial nonlinear phase of the FEM simulation. Macrocrack Propagation Phase: As the load approached its peak, a significant surge in cumulative AE energy was observed (Figure 5), coinciding with the formation of a major flexural crack in the model. Concurrently, the spectral centroid of the AE signals showed a marked upward shift (Figure 4), indicating the emission of higher-frequency components characteristic of rapid, large-scale crack growth and rebar-activation events.

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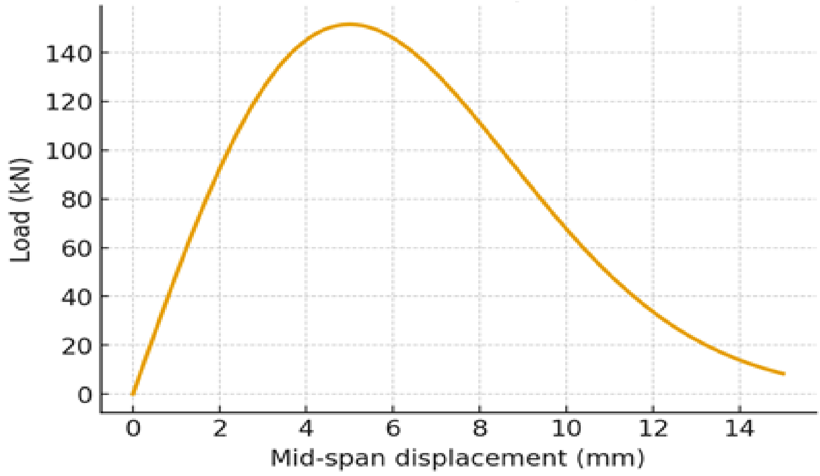

Figure 5. Load–displacement response

4.4 Definition of Damage Assessment Thresholds

Based on receiver operating characteristic (ROC) analysis, damage assessment thresholds were defined using a combination of spectral centroid and AE energy rate criteria. A centroid-frequency increase beyond 130 kHz combined with an AE energy rate exceeding the baseline mean by three standard deviations achieved a sensitivity of 82% and a specificity of 79% across all tested specimens.

Unlike conventional AE approaches that rely on qualitative trend observation, the proposed thresholds are grounded in FEM-validated damage states, enabling a physically interpretable and engineering-relevant damage assessment protocol. This represents a significant advancement over existing empirical AE-based monitoring strategies in Figure 6.

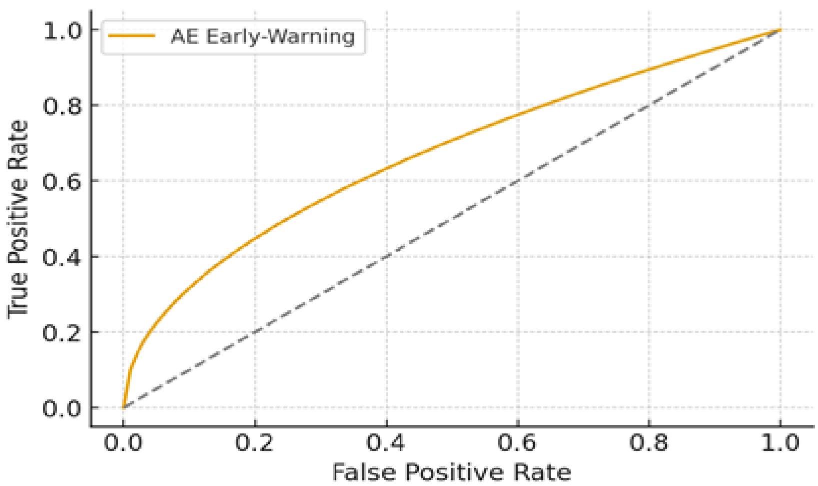

Figure 6. ROC curve for AE-based damage assessment

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4.5 Implications for Structural Health Monitoring

The integration of AE time–frequency analysis with nonlinear FEM provides a unified framework for interpreting acoustic signals in the context of structural response. By anchoring AE features to spatially resolved damage mechanisms, the proposed approach bridges the gap between signal-based monitoring and mechanical failure analysis.

The identified acoustic emission features may also support future data-driven classification approaches for damage assessment.

The scalogram in Figure 7 illustrates how the time-frequency content of a single representative AE signal evolves during a fracture event, showing the concentration of energy in specific frequency bands over time.

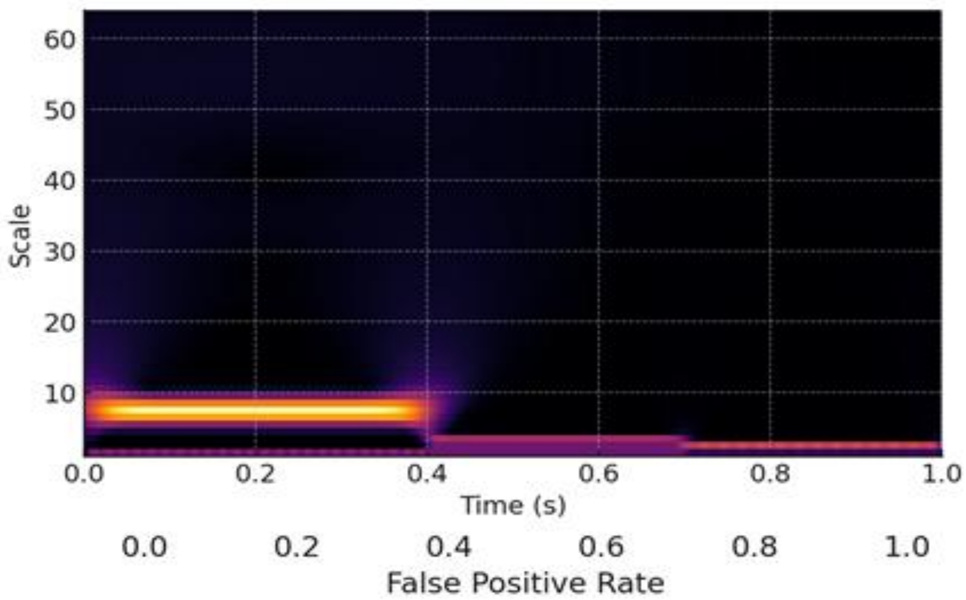

Figure 7. Wavelet scalogram of AE signal

5. Conclusion

This study presented an experimental and numerical investigation of damage development in reinforced concrete slabs subjected to monotonic loading. Acoustic emission monitoring proved effective in evaluating crack initiation and progression during loading. The time–frequency analysis of acoustic emission signals showed noticeable changes in frequency characteristics as damage evolved within the slab.

The nonlinear finite element model, based on the Concrete Damaged Plasticity approach,

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provided a reasonable representation of tensile damage distribution and strain concentration. Good agreement was observed between the numerical results and the acoustic emission activity recorded during testing.

The findings indicate that the combined use of acoustic emission monitoring and numerical modeling offers a practical method for assessing damage development in reinforced concrete slabs. This approach may support engineering evaluation and structural performance assessment of concrete structures.

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