Advanced NDT Approaches for Performance Evaluation of FRCM-Strengthened Concrete Structures: Insights from Acoustic Emission Monitoring

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ABSTRACT

Ensuring the long-term integrity and safety of reinforced concrete (RC) structures has prompted the development of advanced composite strengthening techniques such as Fiber Reinforced Cementitious Matrix (FRCM) systems. While FRCM offers improved compatibility and breathability over traditional FRP systems, its performance is often constrained by fiber-fiber slip and fabric–matrix debonding. This article provides overview of an integrated methodology combining semi-curing pre-impregnation and mechanical anchorage for improved performance of FRCM strengthened concrete structures. Acoustic Emission (AE) based monitoring is integrated as a non-destructive testing (NDT) approach for real-time performance evaluation of FRCM-strengthened RC beams and confined concrete cylinders. AE analysis, encompassing frequency content, b-value evolution, and sentry function metrics, effectively identifies and localizes damage progression, providing critical insight into tensile cracking, debonding, and fabric rupture mechanisms. The proposed approach demonstrates robust potential for field-scale structural health monitoring (SHM) applications, bridging the gap between laboratory evaluation and practical infrastructure monitoring.

Keywords *: Fiber Reinforced Cementitious Matrix (FRCM); Acoustic Emission (AE); Structural Health Monitoring (SHM); Pre-impregnation; Non-Destructive Testing (NDT).*

1. INTRODUCTION

Reinforced concrete (RC) structures serve as critical elements of civil infrastructure but are susceptible to deterioration under sustained loading, corrosion, and environmental effects. Traditional strengthening approaches using Fiber Reinforced Polymer (FRP) composites have demonstrated effective restoration of flexural and shear capacity. However, these polymer-based systems suffer from poor compatibility with concrete, limited moisture permeability, poor fire resistance and high material costs [1]. Fiber Reinforced Cementitious Matrix (FRCM) systems have emerged as a superior alternative, consisting of high-performance fiber fabrics embedded in an inorganic mortar or cementitious matrix [2]. Unlike FRP, FRCM offers excellent vapor permeability and thermal stability, making it particularly suitable for heritage structures and humid environments. The composite's stress-strain behavior follows a trilinear pattern, i.e. initial elastic uncracked behavior, a multiple-cracking phase governed by matrix micro-cracks, and a post-cracking phase dominated by fabric stiffness [3]. Despite this, FRCM efficiency is often compromised by inter-fiber slip and fabric–matrix debonding, which reduce the effective load transfer between the composite constituents. Researchers have proposed epoxy impregnation as a means to enhance the interface bond; however, conventional curing reduces fabric flexibility and impedes application on irregular surfaces [4]. To overcome these challenges, a semi-curing pre-impregnation methodology has been proposed wherein the epoxy-coated fabric is partially cured before embedding into the cementitious matrix [5]. This approach retains the flexibility required for practical application while ensuring better fabric–matrix interaction. Furthermore, integrating mechanical anchorage systems with FRCM enhances interfacial bond strength and mitigates premature debonding [6]. Given the increasing use of FRCM systems in retrofitting, continuous in-service health monitoring becomes vital. Among available NDT methods, AE has gained prominence due to its sensitivity to micro-level cracking and its capability for real-time

monitoring [7, 8]. By analyzing parameters such as event frequency, amplitude, and energy, AE enables detection and classification of damage events within composite systems. This article presents a comprehensive framework integrating pre-impregnation methodology and AE-based monitoring to assess the structural performance of FRCM-strengthened concrete beams and cylinders.

2. FRCM PRE-IMPREGNATION METHODOLOGY

Fig. 1 : (a) impregnation process with uncured/ semi-cure methodology (b) Single lap- shear specimen preparation steps (c) cylinder strengthening steps (d) Steps for beam flexural strengthening using anchorage

The conventional FRCM system typically embeds untreated or epoxy-coated fabric into a cementitious matrix. While epoxy impregnation enhances the bond strength, it increases the stiffness and compromises the handling flexibility of the fabric. To counter this, a semi-curing pre-impregnation process was developed as shown in Figure 1, enabling improved interface bonding without sacrificing flexibility [9]. Differential Scanning Calorimetry (DSC) was employed to determine the optimal degree of cure, revealing that gelation occurs at a cure level of 0.42, achievable by heating at 100°C for 4 minutes. Laser Raman Spectroscopy confirmed that semi-cured specimens achieved near-complete polymerization, minimizing adverse interactions between epoxy and the moist cementitious environment. Tensile characterization tests on both plain and leno weave FRCM composites indicated trilinear stress–strain behavior, with semi-cured specimens showing higher tensile strength with an increase of approximately 16% over uncured specimens and 166% over pristine fabrics. Scanning Electron Microscopy (SEM) revealed enhanced interfacial bonding and absence of amide blush in semi-cured samples. Additionally, incorporating mechanical anchorages mitigated fabric–matrix debonding and improved load capacity by 20% in flexural applications and up to 49% in confined cylinders. The combined methodology ensures the activation of full fabric capacity and transforms the failure mode from interface debonding to fiber rupture. Table 1 compares experimental and theoretical load capacities, highlighting the improved performance achieved through semi-curing and anchorage integration.

Table 1: Comparison of Theoretical and Experimental Load Capacities for beams and cylinders

	Theoretical Moment Capacity (kN-m)	Experimental Moment Capacity (kN-m)	Thereotical Confining Capacity (kN)	Experimental Confining Capacity (kN)
Uncured Anchored	68.69	69.83	970.4	1038.8
Semi-cured Anchored	69.61	78.65	1102.3	1218.6
Fully-cured Non-anchored	65.32	65.89	-	-

3. AE-BASED MONITORING FOR FRCM-STRENGTHENED RC BEAMS

The study considers four beams: one control RC beam without strengthening, and the other three are prepared with uncured, semi-cured, and fully-cured methodology along with mechanical anchorage [10]. All the beams were partially damaged before strengthening.

FRCM-strengthened beams are monitored with three wide bands (100-1000 kHz) and three narrow-band (20-100 kHz) acoustic emission sensors as a part of the SHM study. The test setup and sensor locations can be observed in Fig. 2. FRCM-strengthened beams are a complex composite system of concrete, steel, cementitious matrix, fabric, and polymer matrix impregnation. Therefore, wideband sensors monitor individual material damage evolution based on frequency content. First, to understand which material damage occurs in which frequency range, individual material characterization was conducted to achieve particular damage modes, such as fabric rupture, fabric-matrix debonding, steel yielding, concrete cracking, and mortar matrix cracking. The test setup for the same can be observed in Fig. 3.

The data collected from AE sensors contains much noise due to the surrounding environment, machine noise, and reflections. Therefore, the data needs to be filtered before analysis. This is done using the sequential denoising method developed in the study. This includes a duration-amplitude (Swansong-II) filter to eliminate noisy signals due to shear/friction and denoising using singular value decomposition (SVD) followed by Discrete Wavelet Transform (DWT). Finally, the data was extracted as signal features and analyzed further.

The results for the frequency content characterization for individual failure modes can be observed in Figure 4. It was found that polymer matrix cracking occurs below the 200 kHz range, fiber pullout/debonding in the 200–400

kHz range, whereas pure fiber ruptures above 400 kHz, which aligns with available literature [7]. Also, for lap-shear specimens, high-frequency content (>400 kHz) was observed post-anchorage activation due to fabric rupture (Fig. 4-b). Meanwhile, for flexurally loaded PCC beams, concrete tensile cracking was observed to occur in the 200-400 kHz range (Fig. 4-c).

The progression of the sentry function, historic index

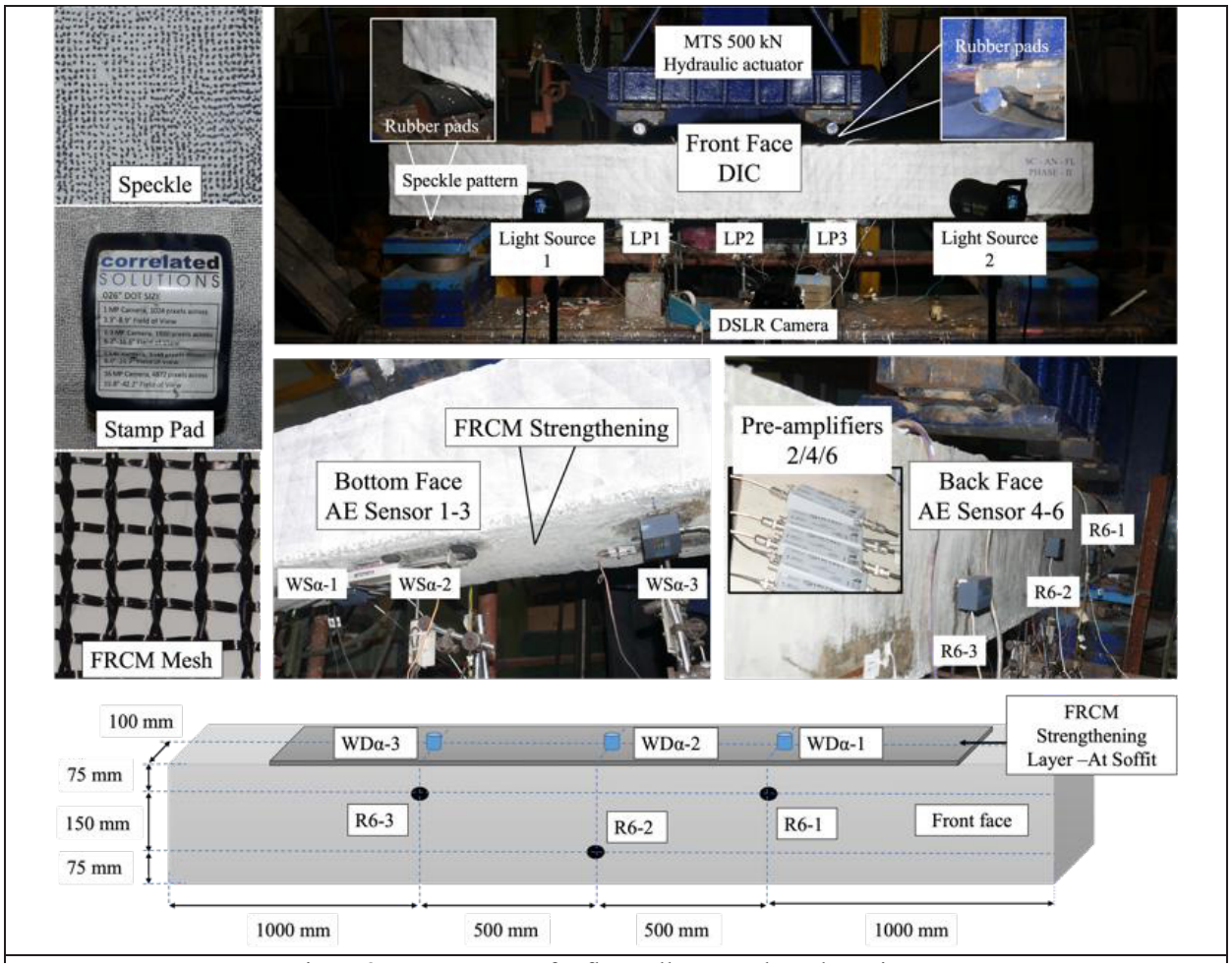

Fig. 2: AE Test setup for flexurally strengthened specimens

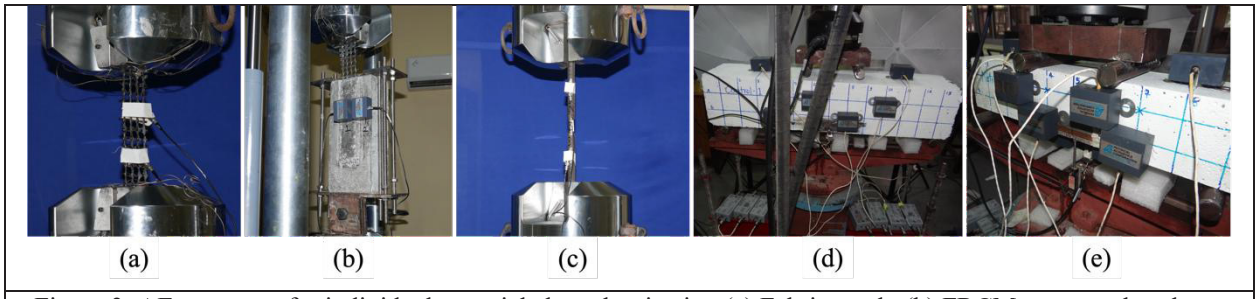

Fig. 3: AE test setup for individual material charachterization (a) Fabric mesh, (b) FRCM-concrete lap shear, (c) steel, (d) Concrete, and (e) Mortar matrix

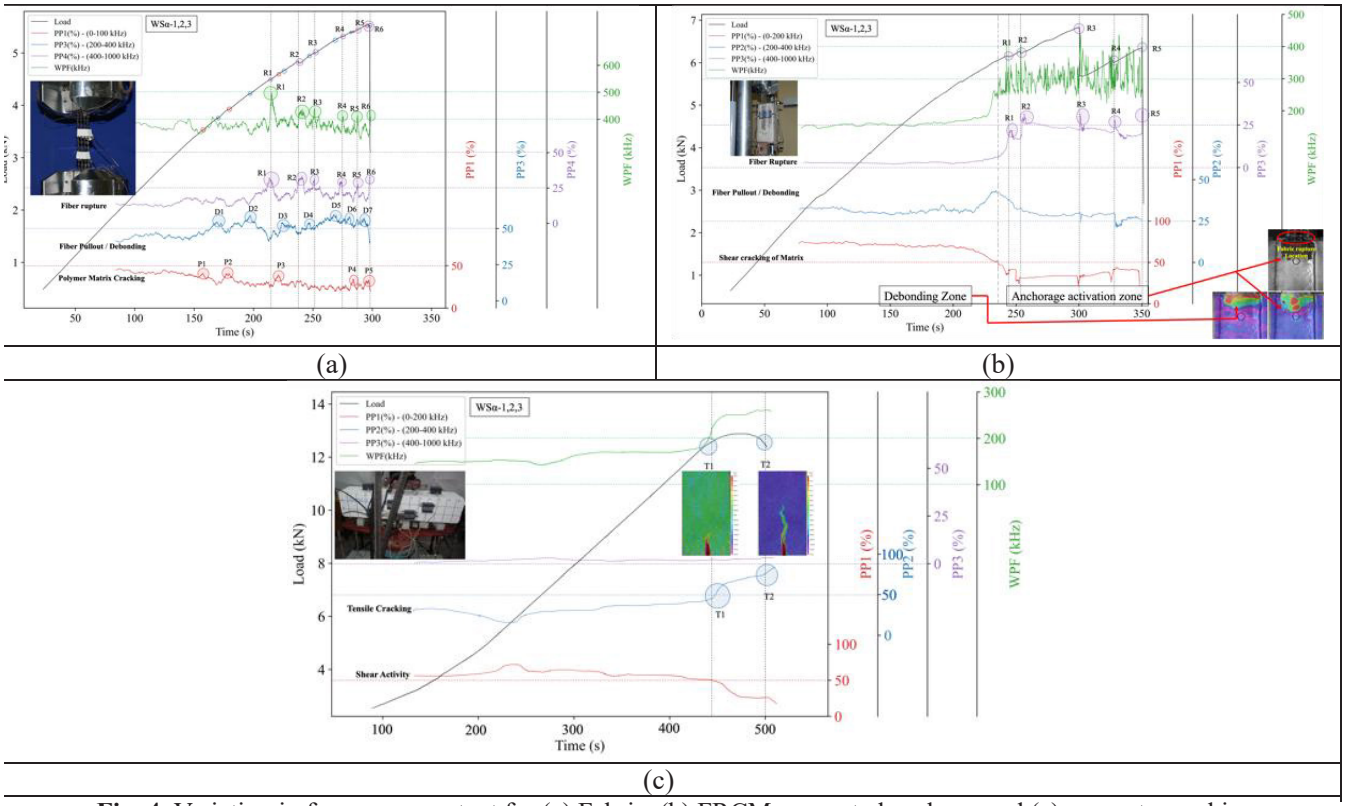

Fig. 4: Variation in frequency content for (a) Fabric, (b) FRCM-concrete lap shear, and (c) concrete cracking

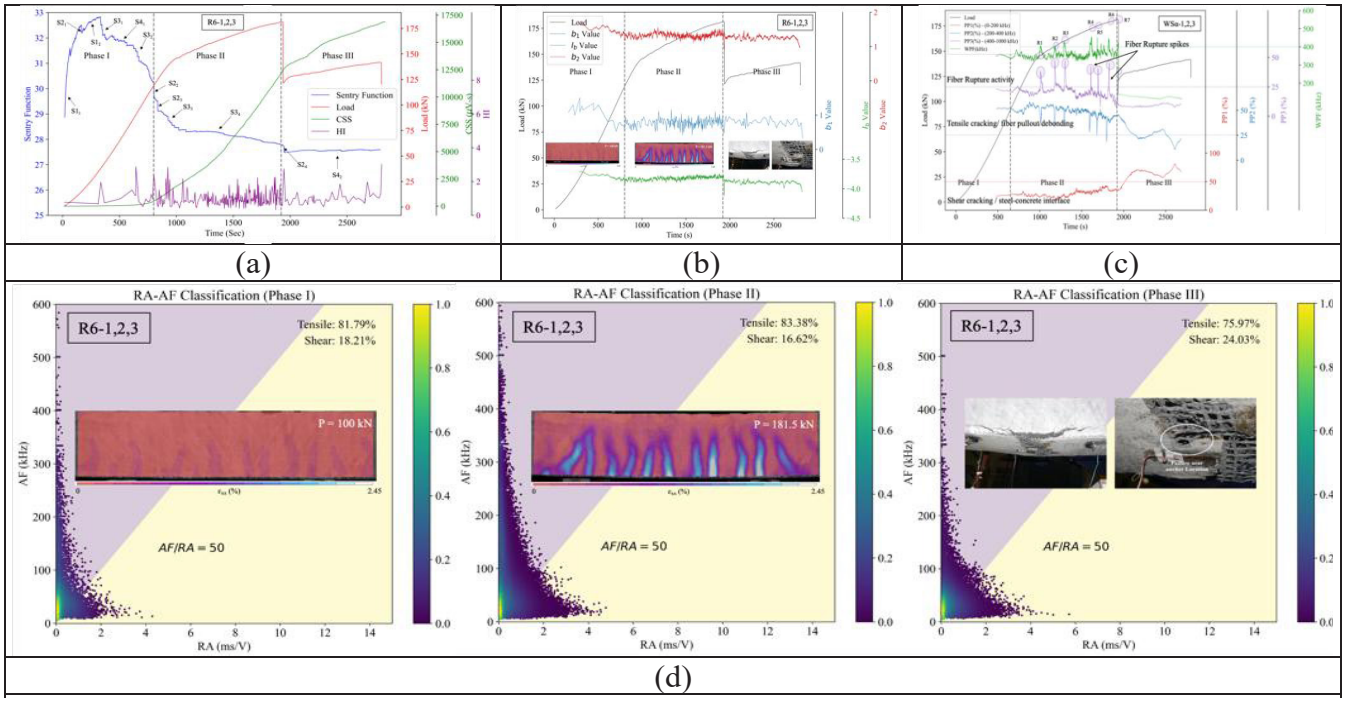

Fig. 5: (a) Sentry function, historic index, (b) b-values, (c) frequency content, and (d) RA-AF variation over time for pre-impregnated mechanically anchored FRCM strengthened specimen

(HI), and cumulative signal strength (CSS) provides a comprehensive framework for interpreting damage intensity over time in FRCM-strengthened specimens. Figure 5-a shows significant damage after steel yielding, marked by a sharp decline in the sentry function and corresponding spikes in the HI for FRCM-strengthened specimens. Simultaneously, the temporal variation of b-values offered insights into the formation of micro-cracks, crack coalescence, and subsequent crack propagation, as depicted in Fig. 5-b. The frequency content analysis of the FRCM-strengthened specimens (Figure 5-c) was conducted based on specific frequency characterizations: the first range (0–200 kHz) was associated with shear cracking in concrete/mortar, mixed-mode cracking in concrete/mortar, polymer matrix cracking, and steel-concrete interface damage; the second range (200–400 kHz) corresponded to tensile cracking in concrete/mortar and fiber pullout or debonding; and the final range (>400 kHz) indicated fiber rupture [8]. Additionally, tensile and shear cracks were differentiated using RA-AF plots, as illustrated in Fig. 5-d.

This integrated analysis approach provided valuable insights into damage evolution and failure modes of concrete, mortar, and impregnated fabric.

4. AE BASED MONITORING FOR FRCM-STRENGTHENED CYLINDERS

The overall strengthening process for cylinders remains the same, i.e., using pre-impregnation and anchorage. AE-based SHM of beams focused on frequency-based material damage detection and classification. However, this study focused on damage localization and detection using the b-value [11].

In this study, differential R6 AE sensors were strategically placed along the cylinder's perimeter for damage localization, as shown in Fig. 6-a. A b-value-based damage localization algorithm, depicted in Fig. 6-b, was developed to locate significant damage in FRCM-strengthened cylindrical specimens. For damage detection, the entropy function derived from waveform analysis was compared with cumulative signal strength obtained through conventional feature-based analysis.

The data was filtered using a methodology similar to that employed in AE-based health monitoring of beams. The results demonstrate that the proposed algorithm effectively localizes damage, as shown in Fig. 7. Moreover, the damage evolution predicted by the entropy-based approach aligns closely with the cumulative signal strength from the feature-based analysis, thereby negating the need for complex and computationally intensive waveform analysis.

5. CONCLUSIONS

The study demonstrates the potential of AE-based non-destructive evaluation for assessing the performance of FRCM-strengthened concrete structures. Key conclusions are summarized as follows:

1. Semi-curing pre-impregnation significantly enhances the tensile and bond behavior of FRCM composites, improving the ultimate strength by up to 49%.
2. Mechanical anchorage converts failure modes from fabric–matrix debonding to fabric rupture, optimizing fabric utilization.
3. AE monitoring effectively identifies and classifies multiple failure mechanisms through frequency domain and b-value analyses.

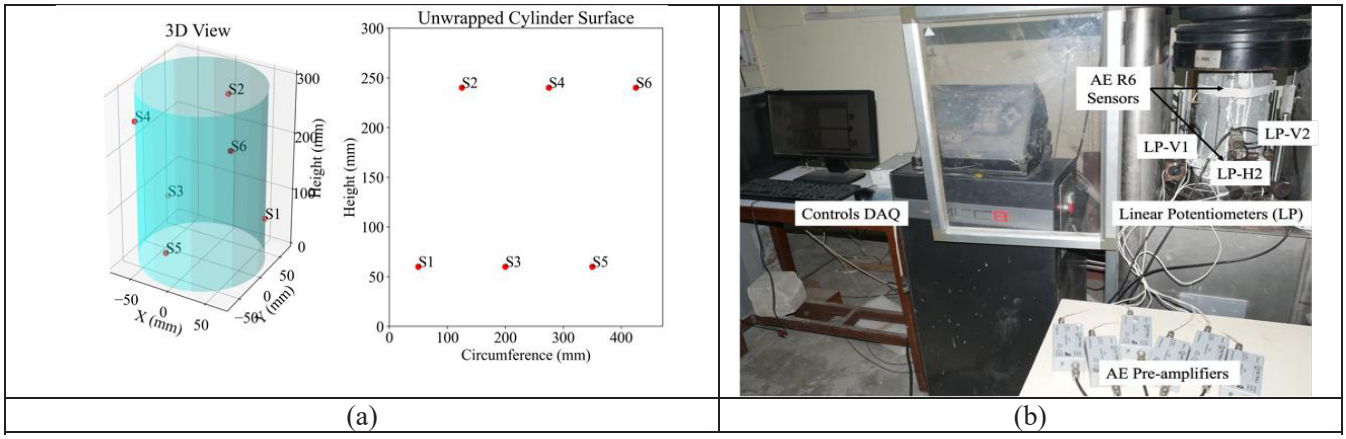

Fig. 6: AE health monitoring flow for concrete cylinders strengthened with pre-impregnated mechanically anchored FRCM

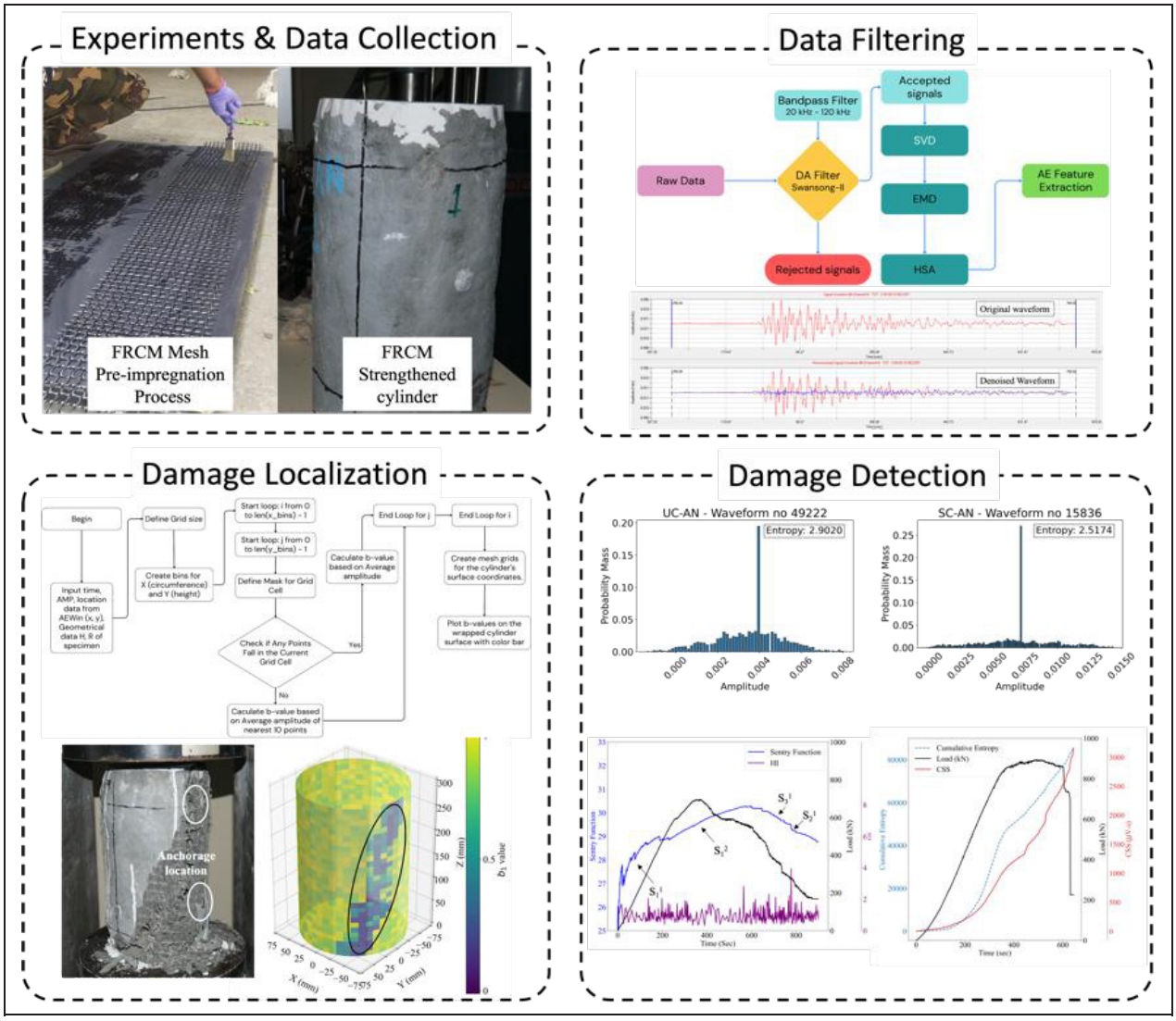

Fig. 7: AE health monitoring flow for concrete cylinders strengthened with pre-impregnated mechanically anchored FRCM

4. The entropy and spatial b-value approaches enable accurate, computationally efficient damage localization.

5. The developed AE-based SHM framework can be readily extended to large-scale structures, including bridges and buildings, for continuous performance evaluation.

Overall, the integration of pre-impregnation methodology and AE-based monitoring presents a robust, field-ready strategy for performance-based assessment of FRCM-strengthened systems.

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