Assessment of Epoxy-Based Repairs in Cementitious Specimens by nondestructive evaluation techniques

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Abstract. Cracking in cementitious materials is a common challenge in structural engineering, requiring effective repair methods to restore integrity and prolong service life. While epoxy resin injection is widely used for this purpose, evaluating the quality and durability of these repairs remains a key issue. Traditional assessment methods, such as visual inspections or destructive testing, provide limited insight into internal damage progression. Acoustic Emission (AE), a real-time non-destructive evaluation (NDE) technique, offers a more advanced approach by detecting crack activity as it occurs. While AE has been extensively used in laboratory studies, its application in monitoring repaired structures and assessing repair performance is still developing.

This study investigates the mechanical behavior of cementitious specimens repaired with epoxy resin. To assess the effectiveness of the repair, specimens were first subjected to four-point bending tests until failure, then repaired with epoxy resin, and reloaded to evaluate their structural recovery. AE monitoring was used to track damage activity throughout the tests, capture crack development and quantify the effectiveness of the repair. The results demonstrate that AE can effectively monitor damage evolution and provide meaningful insights into restoration levels. This combined experimental and numerical approach proves the potential of AE for real-world structural health monitoring, offering a practical tool for assessing repair techniques in civil infrastructure.

Keywords: Structural Health Monitoring (SHM), Non-destructive evaluation (NDE), repair, cementitious materials, fracture, acoustic emission (AE), fiber reinforced concrete.

1 Introduction

Cracking is one of the most common and critical issues affecting concrete structures. Cracks may form due to a range of factors including mechanical loading, shrinkage, thermal effects, or environmental exposure. If not properly addressed, even small cracks can widen over time, leading to reduced serviceability, corrosion of reinforcement, and ultimately, structural failure [1]. Repairing cracked concrete is therefore an important aspect of structural maintenance and rehabilitation strategies. A successful repair should restore the structural state, prevent further deterioration, and extend the service life of the element [2]. Among the available repair techniques, epoxy injection has gained wide application due to its ability to penetrate narrow cracks, bond fractured sections, and restore stiffness. Epoxy resins are known for their high tensile strength, excellent adhesion to concrete, low shrinkage, and good chemical resistance [3]. These properties make them suitable for structural repairs in beams, slabs, columns, and bridge elements, especially when used to address static or durability issue cracks [4]. However, the application of a repair technique does not guarantee structural integrity. If a repair is ineffective due to poor bonding, incomplete crack filling, or premature failure under load, the consequences can be severe, especially in critical structural elements. Assessing whether a repair has truly restored the element's performance is therefore not optional, but essential [5]. Traditional evaluation methods, such as visual inspection or destructive testing, offer limited insight. Visual checks may not detect hidden or progressing damage, while destructive tests are impractical in real structures. There is a clear need for reliable, non-destructive techniques that can monitor the success of a repair in restoring mechanical and fracture resistance [6].

Acoustic Emission (AE) monitoring has emerged as a powerful tool for this purpose. AE detects elastic waves generated during crack initiation, growth, and propagation, providing real-time feedback on internal damage activity [7,8]. By analyzing AE parameters, like amplitude, rise time, energy, and average frequency, it is possible to infer damage mechanisms and classify fracture modes [9, 10]. The ratio of rise time to amplitude (RA value), when combined with average frequency, has proven effective for distinguishing tensile from shear cracking [11]. These AE indicators are particularly valuable when applied to evaluate repaired elements, where the goal is to confirm whether the repair has effectively mitigated cracking or simply just superficially covered ongoing deterioration [12]. Previous research has demonstrated that AE monitoring can detect subtle differences in fracture behavior between damaged and repaired specimens [13,7]. In previous study, Saliah et al. [14] used AE to analyze a reinforced concrete beam before and after epoxy injection, revealing distinct shifts in signal energy and crack mode progression. Similar investigations have shown that AE can track fracture patterns in repaired or strengthened fiber-reinforced concrete and assess the ability of the repair to delay critical crack formation [15 - 16]. These findings highlight AE as a sensitive and non-invasive technique for assessing not only damage but also the functional success of repair interventions. While AE has been used in studies involving concrete repair, its application to epoxy-repaired fiber-reinforced concrete remains limited [17], particularly when it comes to monitoring the damage evolution in real-time and correlating AE data with structural behavior.

In this study, fiber-reinforced concrete elements were subjected to three-point bending both in its damaged and its repaired state, following epoxy injection. AE monitoring was used throughout both states to evaluate damage evolution, with particular attention to AE features that indicate crack type and severity. By comparing AE behavior before and after repair, the aim was to assess the effectiveness of epoxy injection in restoring integrity and delaying critical fracture. The analysis focused on parameters such as signal strength, average frequency, and RA value to trace changes in crack development during loading.

2. Experimental program

2.1. Materials and Experimental Procedure

The concrete mix was prepared using CEM II/A-M(P-LL) cement, crushed sand, fine and coarse gravel, and a water-to-cement ratio of 0.70. Steel fibers with a flat-straight geometry, 25 mm in length and 0.6 mm in diameter, were added at 39.3 kg/m³. The beam was cast in a prismatic mold (100 × 100 × 400 mm) and cured in lime-saturated water at 23 ± 2 °C for 28 days. The specimen was tested in a four-point bending configuration according to ASTM C1609 the configuration of the experimental setup is presented in Fig. 1. Acoustic emission was monitored using two R15 piezoelectric sensors (resonant at 150 kHz), attached with acoustic grease and secured using adhesive tape (Fig. 1).

Fig. 1. Experimental setup of four point bending and AE sensors position indication.

In the first loading stage, the beam was loaded under displacement control until a through-crack formed at mid-span. After unloading, the surface was cleaned, and a two-component low-viscosity epoxy resin was injected along the main crack (Fig. 2). The resin was left to cure for 7 days under ambient conditions. The repaired specimen was then reloaded under the same setup. AE sensors remained in the original configuration to ensure consistency in data collection. Load, deflection, and AE signals were recorded during both phases to allow direct comparison of mechanical and fracture responses before and after repair. Further details of materials and the repair methodology and the experimental setup can be found in authors' previous publications.

Fig. 2. Repair procedure with epoxy resin: (a) specimen preparation, (b) injection with needle for microcrack filling and (c) injection with plastic tube for finishing.

2.2. AE monitoring and signal analysis

The system employed a 40 dB preamplifier, and all signals above this threshold were captured using a PAC PCI-8 board at a 3 MHz sampling rate. Several parameters were presented to characterize crack behavior. These included amplitude (A), which relates to the strength of the emission event, and energy (ENE), which corresponds to the cumulative signal magnitude over time. Rise time (RT), defined as the delay between the first threshold crossing and peak amplitude, is influenced by the fracture mode. The RA value—calculated as RT divided by amplitude—helps differentiate between tensile and shear cracking. Average frequency (AF), computed as the number of threshold crossings per unit time, offers additional insight into frequency content. The AE analysis follows the methodology of signal processing as presented in previous studies conducted by the authors [17, 18] where more information can be found. In general, higher RT values typically indicate shear-dominated events, while higher AF is associated with tensile cracking.

3. Results and discussion

Specimens were classified according to concrete mixture (G), fiber geometry ("F" for Flat-Straight) and condition ("H" for intact, "R" for repaired), yielding two configurations: GF_H and their repaired counterparts GH_R. All specimens underwent four-point bending tests with concurrent AE monitoring to evaluate their mechanical and acoustic response.

Fig. 3 illustrates the mechanical behavior of the flat fiber-reinforced concrete specimen, comparing the flexural performance before and after repair. The repaired specimen (GF_R) demonstrated a reduced load-bearing capacity, reaching approximately 4 kN compared to 16 kN in the intact specimen (GF_H). This reduction reflects the partial recovery provided by the epoxy injection. The bonding at the crack surfaces between the epoxy resin and the concrete microstructure absorbs significant energy, resulting in a smoother load-deflection curve. While the intact specimen exhibits brittle failure characterized by a sudden drop in load post-peak, the repaired specimen demonstrates a more ductile response, lacking abrupt failure and indicating improved energy dissipation characteristics due to the presence of the epoxy.

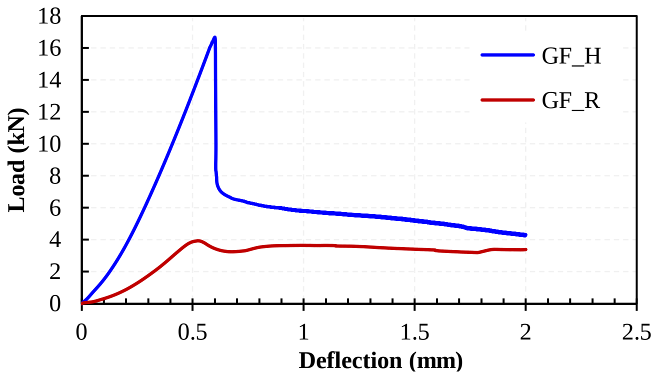
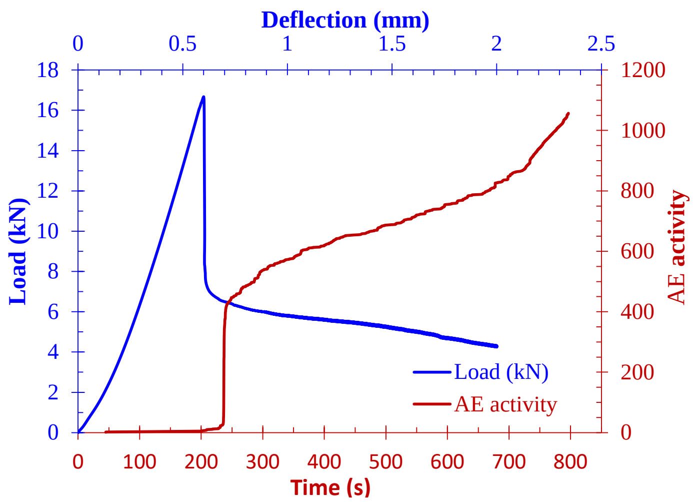
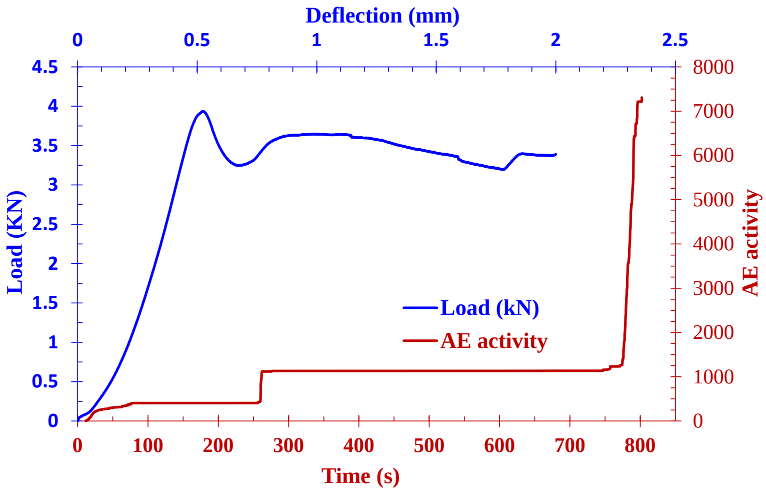


Fig. 3. Load vs flexural deflection for the Intact GF_H vs the repaired GF_R specimen.

The load–deflection curves together with cumulative AE hits over time for the intact (GF_H) and repaired (GF_R) specimens are presented in Fig. 4a and b. In the intact beam (Fig. 4a), AE activity increased sharply around peak load, consistent with sudden crack formation and rapid failure. In contrast, the repaired specimen (Fig. 4b) showed earlier AE onset and more gradual accumulation, reflecting a slower and more distributed damage process. The AE plateau in the repaired case coincides with the stabilization of load, further supporting the observation that the repair delayed active crack reopening. The late surge in AE hits at the end of the test suggests a final failure event, likely associated with shear or interfacial slip.



(a)



(b)

Fig. 4. Load – deflection response and cumulative AE hits over time for (a) the intact specimen (GF_H) and (b) the repaired specimen (GF_R).

A comparative analysis of cumulative AE energy for intact versus repaired flat fiber-reinforced concrete specimens under 4-point loading is presented in Fig. 5. The intact specimen (GF_H) exhibited a sharp increase in cumulative AE energy following peak load, corresponding to rapid damage development and final failure. In contrast, the repaired specimen (GF_R) showed a more gradual energy accumulation and a significantly lower total energy release. This difference reflects the different fracture process introduced by the epoxy repair. The lower AE energy suggests that the crack reopened in a more controlled manner, with reduced intensity, likely due to the restraining effect of the epoxy at the fracture interface. These observations are consistent with previous findings that associate AE energy trends with the effectiveness of crack repair and interfacial bonding.

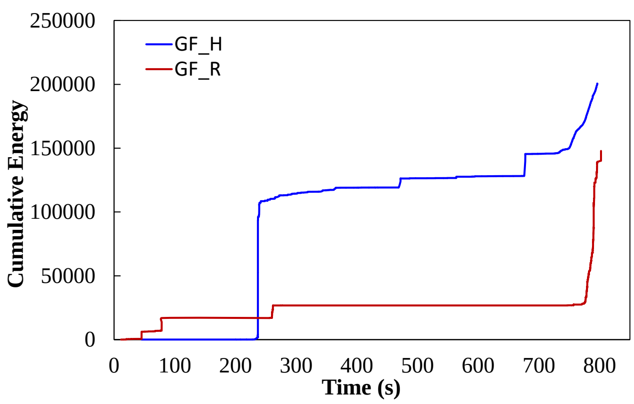


Fig. 5. Cumulative energy per time for the intact (GF_H) and repaired (GF_R) specimens.

In Table 1 the results of the mechanical tests and key values of the AE parameters are presented for both intact (GF_H) and repaired (GF_R) specimens. AE values represent averages from both sensors and are categorized by loading stage: the full loading range (0–100%), the early phase (0–33%), and the near-failure interval (95–100%). Parameters include AE hit count, cumulative energy, amplitude, average frequency (AF), and RA value.

Table 1. Results of flexural performance and AE parameters for intact (GF_H) and repaired (GF_R) concrete beams, measured over full loading, early stage (0–33%), and near-peak (95–100%) intervals.

Monitored Loading intervals	**Concrete type**	**Maximum Flexural** Load (N)	**Sum** COUNT	**Sum** ENERG	**AMP** (dB)	**AF** (kHz)	**RA** (μs/V)
0-100%	GF_H	16673.86	61261	200555	52.94	163.96	3165.97
	GF_R	3935.26	245354	147859	44.62	259.73	17563.10
0-33%	GF_H	5502.38	4.20	0.20	42.80	196.00	939.28
	GF_R	1298.65	12.74	41.65	47.49	247.31	1082.16
95%-100%	GF_H	15840.17	86.21	271.02	51.42	181.65	4506.81
	GF_R	3738.50	23.00	13.59	45.35	222.61	13162.43

The flat-fiber specimen (GF_R) exhibited a restoration ratio of approximately 0.24, indicating only partial recovery of the load-bearing capacity. During early loading (0–33%), the repaired beam exhibited higher average frequency and lower RA values compared to the intact one, which is consistent with the initial response of the lower-modulus epoxy under elastic deformation [17]. However, the continued presence of elevated RA values, already evident at early stages, suggests a dominant contribution of shear or interfacial sliding, pointing to limited bond effectiveness along the epoxy–concrete interface which is consistent with prior findings as presented in literature [5,17]. The cumulative AE energy is a more sensitive indicator of repair efficacy than total hit count, with higher restoration levels correlating with lower emitted energy [6,17]. The results emphasize the importance of interfacial conditions and epoxy adhesion in shaping the failure mechanism and associated acoustic signatures [19].

Fig. 6 and 7 present the evolution of RA and average frequency (AF) values over time for the intact (GF_H) and repaired (GF_R) flat-fiber reinforced concrete specimens. The plotted line represents the connected mean computed over 70 AE hits values during the loading sequence. The repaired specimen shows persistently elevated RA values, even at early stages, indicating a low degree of restoration in straight-fiber reinforced concrete. AF values do not exhibit a consistent trend over the full duration of loading. In the repaired specimen, elevated AF is observed only in the early stages, suggesting that when restoration levels are low, epoxy injection has limited influence in the fracture behavior (as implied by consistently high RA values). Additionally, the repaired specimen shows fewer fluctuations in signal parameters, likely due to a predominant fracture mechanism—the reopening of the epoxy-filled crack—resulting in more uniform AE responses compared to the intact specimen.

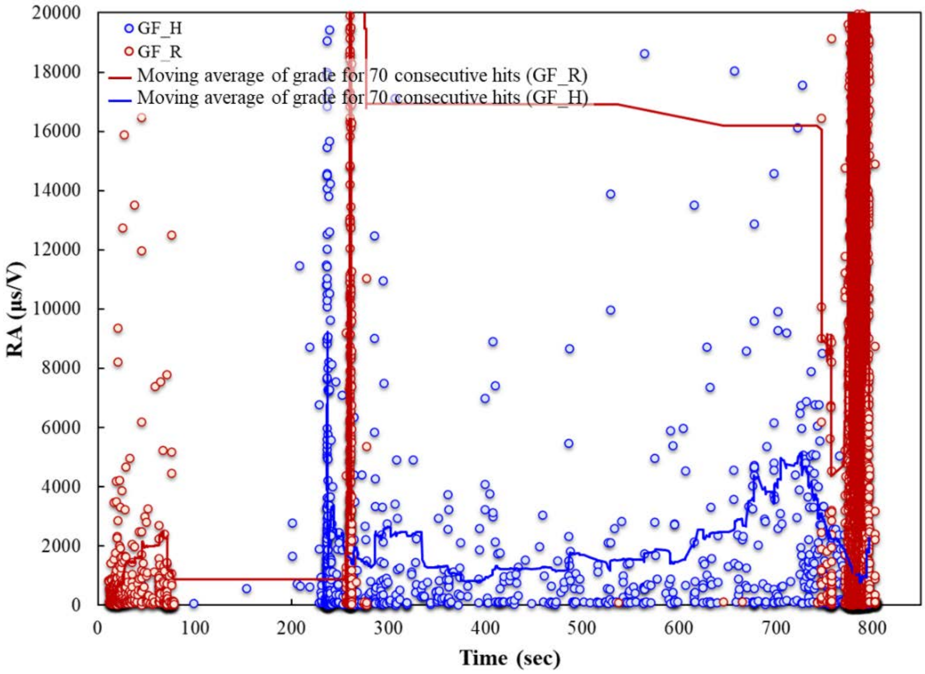


Fig. 6. RA value over time for the intact (GF_H) and repaired (GF_R) specimens.

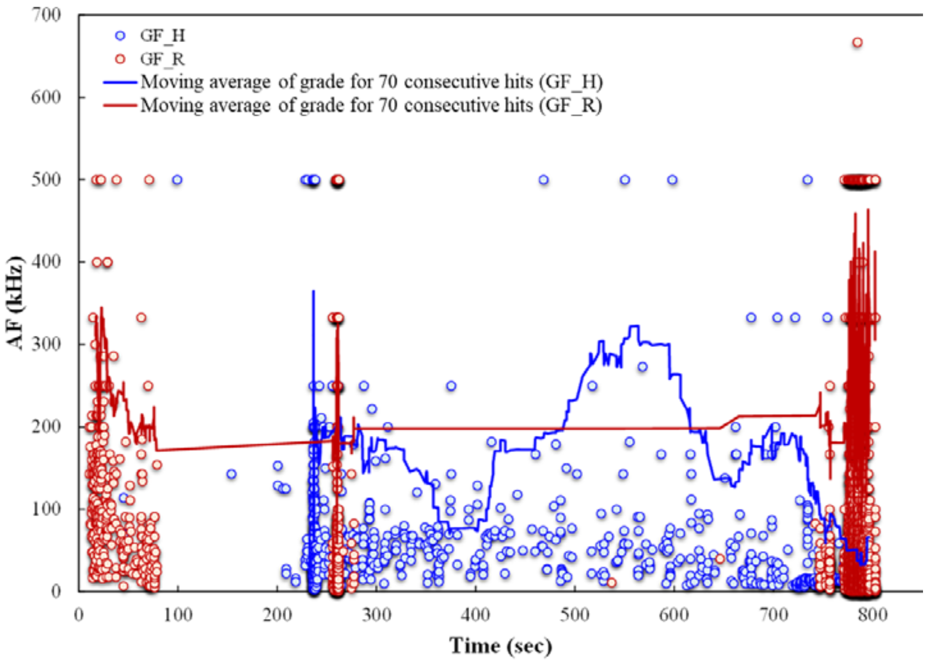


Fig. 7. RA value over time for the intact (GF_H) and repaired (GF_R) specimens.

4. Concluding remarks

This study evaluated the mechanical and acoustic behavior of fiber-reinforced concrete beams, comparing intact specimens with those repaired through epoxy-resin injection. Real-time AE monitoring was used to assess fracture processes before and after repair under flexural loading. The results demonstrate that AE is a reliable method for evaluating repair effectiveness. The following are considered the most important remarks:

- In intact specimens, cumulative AE hits and energy increased abruptly around peak load, reflecting sudden tensile failure. In contrast, repaired specimens exhibited more gradual AE accumulation, with higher AE energy released at early stages but lower total energy post-peak. This shift indicates altered fracture behavior influenced by the presence of epoxy.
- AE parameter trends—particularly AF and RA values—offered valuable insight into damage mechanisms. Repaired specimens showed higher AF and lower RA values during early loading, consistent with tensile-mode microcracking in the epoxy zone. However, persistently elevated RA values and reduced AE energy suggest a transition to interface-controlled or shear-dominated damage. These trends point to the importance of interface quality in shaping the fracture response and acoustic signature.
- AE differences between intact and repaired specimens became less distinct under high-load, post-peak conditions. As cracking progressed and stress fields evolved, AE patterns converged—an effect also noted in previous research. Nonetheless, early-stage AE responses, particularly cumulative energy and AF/RA behavior, emerged as effective indicators of repair quality and fracture mode.

AE monitoring proves to be a valuable, nondestructive technique for assessing structural restoration in epoxy-repaired fiber-reinforced concrete. Its sensitivity to early microcracking and fracture transitions makes it particularly suitable for evaluating interface performance and guiding the development of more effective repair strategies in structural engineering and infrastructure rehabilitation.

Acknowledgements

Author Violetta K. Kytinou acknowledges financial support from the Research Council of Lithuania (LMTLT, Project No S-PD-24-036).

References

1. Carpinteri, A., Lacidogna, G., Corrado, M., Di Battista, E.: Cracking and crackling in concrete-like materials: A dynamic energy balance. Engineering Fracture Mechanics. 155, 130–144 (2016). https://doi.org/10.1016/j.engfracmech.2016.01.013.

2. Thanoon, W.A., Jaafar, Kadir, M.R.A., Noorzaei, J.: Repair and structural performance of initially cracked reinforced concrete slabs. Construction and Building Materials. 19, 595–603 (2005). https://doi.org/10.1016/j.conbuildmat.2005.01.011.
3. El-Hawary, M., Al-Khaiat, H., Fereig, S.: Effect of sea water on epoxy-repaired concrete. Cement and Concrete Composites. 20, 41–52 (1998). https://doi.org/10.1016/s0958-9465(97)00074-7.
4. Issa, C.A., Debs, P.: Experimental study of epoxy repairing of cracks in concrete. Construction and Building Materials. 21, 157–163 (2005). https://doi.org/10.1016/j.conbuildmat.2005.06.030.
5. Saliah, S.N.M., Nizam, K.K., Ariffaizad, M.M.M., Rahman, N.A., Nor, N.M.: Evaluation of severe damaged reinforced concrete beam repaired with epoxy injection and retrofitted with CFRP using acoustic emission technique. Journal of Physics Conference Series. 1349, 012097 (2019). https://doi.org/10.1088/1742-6596/1349/1/012097.
6. Tang, J., Bai, Y., Qian, W., Lv, P.: Non-destructive evaluation of bond strength between epoxy repair material and concrete under wet surface. Case Studies in Construction Materials. e04509 (2025). https://doi.org/10.1016/j.cscm.2025.e04509.
7. Aggelis, D.G., Soulioti, D.V., Sapouridis, N., Barkoula, N.M., Paipetis, A.S., Matikas, T.E.: Acoustic emission characterization of the fracture process in fibre reinforced concrete. Construction and Building Materials. 25, 4126–4131 (2011). https://doi.org/10.1016/j.conbuildmat.2011.04.049.
8. Holsamudrkar, N., Banerjee, S.: Acoustic emission (AE) based health monitoring of RC beams strengthened with mechanically anchored hybrid Fiber Reinforced Cementitious Matrix (FRCM) system. Case Studies in Construction Materials. 21, e03773 (2024). https://doi.org/10.1016/j.cscm.2024.e03773.
9. Li, H., Li, X., Fu, J., Gao, Z., Chen, P., Zhang, Z.: Research on acoustic emission multi-parameter characteristics in the failure process of imitation steel fiber reinforced concrete. Physics of Fluids. 35, (2023). https://doi.org/10.1063/5.0170179.
10. Shahidan, S., Pulin, R., Bunnori, N.M., Holford, K.M.: Damage classification in reinforced concrete beam by acoustic emission signal analysis. Construction and Building Materials. 45, 78–86 (2013). https://doi.org/10.1016/j.conbuildmat.2013.03.095.
11. Ohno, K., Ohtsu, M.: Crack classification in concrete based on acoustic emission. Construction and Building Materials. 24, 2339–2346 (2010). https://doi.org/10.1016/j.conbuildmat.2010.05.004.
12. Kocur, G.K., Vogel, T.: Classification of the damage condition of preloaded reinforced concrete slabs using parameter-based acoustic emission analysis. Construction and Building Materials. 24, 2332–2338 (2010). https://doi.org/10.1016/j.conbuildmat.2010.05.003.
13. Shin, H.-C., Miyauchi, H., Tanaka, K.: An experimental study of fatigue resistance in epoxy injection for cracked mortar and concrete considering the temperature effect. Construction and Building Materials. 25, 1316–1324 (2010). https://doi.org/10.1016/j.conbuildmat.2010.09.013.
14. Saliah, S.N.M., Nor, N.M., Rahman, N.A., Abdullah, S., Tahir, M.S.: Evaluation of severely damaged reinforced concrete beam repaired with epoxy injection using acoustic emission technique. Theoretical and Applied Fracture Mechanics. 112, 102890 (2021). https://doi.org/10.1016/j.tafmec.2020.102890.
15. Garhwal, S., Garhwal, A., Sharma, S., Sharma, S.K., Banik, A.: Monitoring and Restrengthening of Real Sized Corroded RC Beams with Acoustic Emission Technique and GFRP Sheets. Transactions of the Indian Institute of Metals. 77, 1443–1454 (2024). https://doi.org/10.1007/s12666-023-03252-1.

16. Goyal, P., Sharma, S., Kwatra, N.: Acoustic emission monitoring of steel fiber reinforced beams under simultaneous corrosion and sustained loading. European Journal of Environmental and Civil Engineering. 27, 1535–1560 (2022). https://doi.org/10.1080/19648189.2022.2087743.
17. Mpalaskas, A.C., Aggelis, D.G., Matikas, T.E.: Monitoring the fracture behavior of epoxy resin repaired fiber reinforced concrete specimens by acoustic emission. Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2018. 78 (2021). https://doi.org/10.1117/12.2584603.
18. Mpalaskas, A.C., Kytinou, V.K., Zapris, A.G., Matikas, T.E.: Optimizing Building Rehabilitation through Nondestructive Evaluation of Fire-Damaged Steel-Fiber-Reinforced Concrete. Sensors. 24, 5668 (2024). https://doi.org/10.3390/s24175668.
19. A. C. Mpalaskas, D. G. Aggelis, and T. E. Matikas "Correlation between acoustic emission parameters and fracture behavior of repaired marble specimens", Proc. SPIE 11382, Smart Structures and NDE for Industry 4.0, Smart Cities, and Energy Systems, 1138213 (22 April 2020); https://doi.org/10.1117/12.2557351