

Acoustic emission-based assessment of damage evolution in carbon fiber-reinforced polymer-strengthened reinforced concrete beams subjected to moderate elevated temperatures

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ABSTRACT

The assessment of damage evolution in CFRP-strengthened reinforced concrete (RC) beams exposed to elevated temperatures remains a challenge in structural engineering. Conventional mechanical testing provides information on global structural response but offers limited insight into changes occurring at the concrete–adhesive–CFRP interface. This study investigates the use of acoustic emission (AE) for identifying temperature-induced changes in fracture processes. Small-scale RC beams strengthened with externally bonded CFRP strips were tested under three-point bending at ambient temperature and after exposure to 60 °C and 80 °C. Acoustic emission monitoring was performed using 75 kHz sensors. The analysis focused on cumulative AE energy, cumulative AE hits, and RA–AF parameters. Mechanical results showed only a slight reduction in load-carrying capacity after heating. In contrast, AE analysis revealed earlier damage activity, faster energy accumulation, and a higher contribution of shear-related signals in heated specimens, suggesting temperature-related changes in damage evolution potentially associated with the concrete–adhesive–CFRP system. The findings demonstrate that AE provides valuable information on damage evolution that cannot be obtained from mechanical measurements alone and represents a promising tool for assessing CFRP-strengthened RC structures exposed to elevated temperatures.

Keywords: acoustic emission, CFRP strengthening, reinforced concrete beams, elevated temperature, damage evolution, structural health monitoring, fracture mechanisms, non-destructive testing

INTRODUCTION

Externally bonded fiber-reinforced polymer (FRP) composites are widely used for strengthening reinforced concrete structures due to their high strength-to-weight ratio, corrosion resistance, and ease of installation [1–3]. Among available strengthening techniques, externally bonded carbon fiber reinforced polymer (CFRP) strips are commonly applied to improve the flexural performance of reinforced concrete beams [1–4]. Numerous studies have demonstrated significant increases in stiffness and load-carrying capacity resulting from CFRP strengthening [2–4].

The long-term performance of CFRP-strengthened structures depends not only on the properties of concrete and reinforcement but also on the durability of the adhesive bond between the CFRP strip and the concrete substrate [1, 3]. Elevated temperatures may adversely affect this bond by reducing the stiffness and strength of the adhesive layer and altering stress transfer mechanisms at the interface [5–10]. As a result, premature debonding may occur even when the overall reduction in structural capacity remains relatively small [5, 8–10].

The thermal performance of externally bonded CFRP strengthening systems has been extensively investigated in recent years [5–10]. Previous

studies have demonstrated that elevated temperatures may significantly influence the mechanical properties of epoxy adhesives and reduce the effectiveness of stress transfer between the CFRP strip and the concrete substrate [6,8–10]. Even when the global load-carrying capacity remains relatively unchanged, localized deterioration occurring within the adhesive layer or at the concrete–adhesive interface may affect the initiation and propagation of damage during loading. Consequently, the identification of early-stage degradation mechanisms has become an important research topic in the assessment of strengthened concrete structures [8–10,17].

Conventional mechanical testing methods, based on load–deflection or stress–strain relationships, provide information about the global response of structural elements. However, these methods offer limited insight into the initiation and evolution of internal damage mechanisms. Consequently, there is growing interest in the application of non-destructive monitoring techniques capable of detecting fracture processes before they become visible at the structural level [11–18].

Acoustic emission (AE) is one of the most promising techniques for real-time monitoring of damage evolution in concrete and composite structures [11,12,16–22]. AE originates from the rapid release of strain energy associated with microcracking, crack propagation, friction, and debonding processes [11,12]. Previous studies have shown that AE parameters such as cumulative energy, cumulative hit activity, amplitude, and RA–AF indicators can be used to characterize fracture mechanisms and identify transitions between tensile- and shear-dominated damage modes [13–15,18,19,22].

In recent years, acoustic emission has been successfully applied to the monitoring of reinforced concrete structures, fibre-reinforced composites, and CFRP-strengthened structural elements [11–22]. Previous investigations have shown that AE-based parameters can be used to identify crack initiation, distinguish between different fracture mechanisms, and assess the progression of structural deterioration [11,13–18]. In particular, cumulative acoustic emission energy and cumulative hit activity have been reported as effective indicators of damage accumulation, whereas RA–AF-based analyses provide additional insight into fracture mechanisms and crack propagation characteristics [13–15,18].

Despite the growing number of studies devoted to CFRP-strengthened reinforced concrete members, relatively limited attention has been paid to the application of acoustic emission for detecting temperature-induced changes occurring at moderate thermal exposure levels. Most available investigations focus primarily on residual mechanical properties or on temperatures associated with severe thermal degradation and fire conditions [5–10]. Moreover, although AE has been successfully applied to monitor damage and debonding in CFRP-strengthened beams [16–18], studies combining acoustic emission monitoring with moderate thermal exposure conditions remain scarce. Consequently, the influence of moderate temperatures on AE signatures related to damage evolution within CFRP-strengthened systems remains insufficiently understood.

Therefore, the objective of this study is to investigate the influence of elevated temperatures on the fracture behaviour of CFRP-strengthened reinforced concrete beams using a combined mechanical and acoustic emission approach. Particular attention is devoted to the evolution of cumulative AE energy, cumulative AE hits, and RA–AF parameters in order to identify temperature-related changes in damage development and failure mechanisms. The overall research methodology adopted in this study, including specimen preparation, thermal conditioning, mechanical testing, acoustic emission monitoring, and data analysis procedures, is schematically illustrated in Figure 1.

Unlike previous studies, which have primarily focused on residual mechanical performance or severe thermal exposure, the present work investigates whether acoustic emission can detect subtle temperature-induced changes in damage evolution under moderate thermal conditions before they become evident in conventional mechanical measurements.

MATERIALS AND METHODS

Materials

The experimental program was conducted on reinforced concrete (RC) beams with dimensions of $150 \times 150 \times 600$ mm. The beams were cast using normal-strength concrete of class C30/37. Longitudinal reinforcement consisted of four B500S steel bars with a diameter of 12 mm located in the

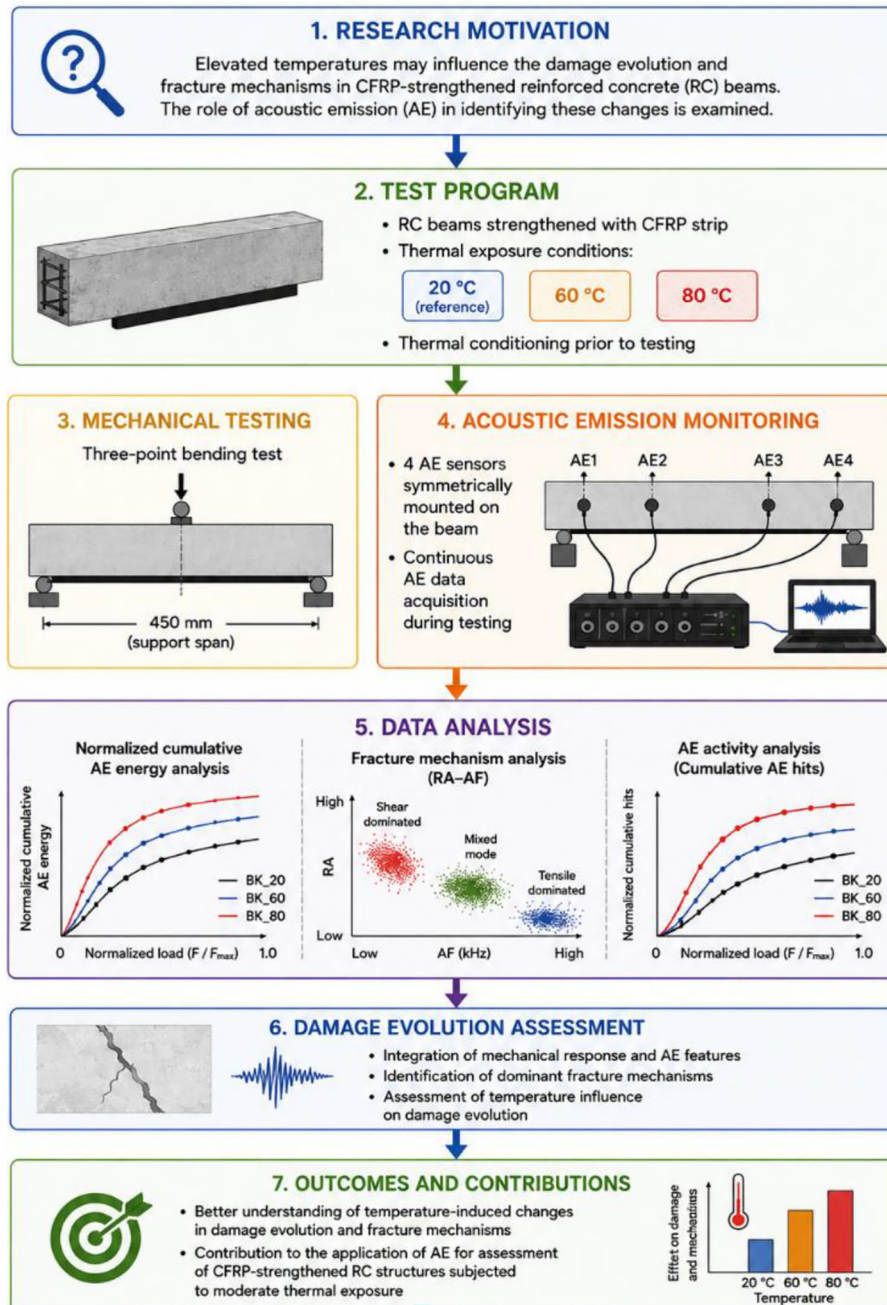


Figure 1. Research methodology

corners of the cross-section. Transverse reinforcement was provided by closed stirrups with a diameter of 4 mm spaced at 200 mm intervals.

After curing, the beams were strengthened in flexure using externally bonded carbon fibre reinforced polymer (CFRP) strips. Sika CarboDur® S512 strips (50 mm wide and 1.2 mm thick) were bonded to the bottom surface of the beams along a length of 500 mm using Sikadur®-30 LP epoxy adhesive. Prior to bonding, the concrete surface was mechanically prepared and cleaned to ensure

adequate adhesion between the CFRP strip and the concrete substrate.

Three series of specimens were investigated. The reference series (BK_20) was tested at ambient laboratory temperature (20 ± 2 °C). The remaining specimens were subjected to elevated temperatures of 60 °C (BK_60) and 80 °C (BK_80), respectively. The target temperature was applied using an electric heating mat installed directly on the CFRP strip.

The heating mat was intentionally positioned directly on the CFRP strip because the objective of the study was to simulate thermal exposure

primarily affecting the externally bonded strengthening system. Heat conduction through the CFRP strip naturally resulted in simultaneous heating of the adhesive layer and the adjacent concrete substrate, as confirmed by the thermocouple measurements presented in Table 1.

Temperature was monitored using thermocouples positioned in the strengthened region. Two K-type thermocouples were installed directly on the CFRP strip and near the concrete–adhesive interface. Mechanical testing commenced immediately after the 60-minute stabilization period while maintaining the target temperature. After reaching the target temperature, the specimens were maintained under thermal exposure for 60 minutes to achieve thermal stabilization before testing.

The average temperatures recorded during the stabilization period are summarized in Table 1.

The selected temperature levels were chosen to represent thermal conditions close to and above the glass transition temperature range typically reported for epoxy adhesives used in externally bonded CFRP strengthening systems. For each temperature level, three nominally identical specimens were tested.

Methods

Three-point bending test

The flexural behaviour of the strengthened beams was evaluated using a three-point bending configuration. The tests were performed using a servo-controlled testing machine under displacement control. The distance between supports was 450 mm, corresponding to a support offset of 75 mm from each beam edge.

The loading rate was maintained at 2 mm/min throughout the entire test. Mechanical testing was initiated immediately after the 60-minute thermal stabilization period while maintaining the target temperature. During testing, the applied load and actuator displacement were continuously recorded. The tests were continued until failure of the specimen.

Based on the recorded data, load–displacement relationships were determined and used to evaluate the mechanical response of the beams. To facilitate comparison between specimens exhibiting slightly different ultimate loads, the applied load was additionally normalized according to:

$$F_{norm} = \frac{F}{F_{max}} \quad (1)$$

where: F is the instantaneous load and F_{max} is the maximum load recorded during a given test.

Acoustic emission (AE) monitoring was performed simultaneously with the mechanical tests. The monitoring system consisted of a Express-8 (Physical Acoustic Corporation) acquisition unit and four resonant VS75-SIC sensors with a central frequency of 75 kHz and integrated 34 dB preamplifiers. The sensors were mounted symmetrically on the side surfaces of the beams using technical silicone as the coupling medium. The sensor arrangement was selected to ensure reliable detection of damage-related signals throughout the monitored region and to enable source localization during the fracture process.

Prior to testing, the quality of sensor coupling was verified using the Hsu–Nielsen pencil lead break procedure. Acoustic emission signals were continuously recorded throughout the loading process. To reduce environmental noise and mechanical disturbances generated by the testing frame, a threshold level of 42 dB was adopted.

The acquisition parameters were as follows:

- threshold: 42 dB;
- sampling rate: 2 MHz;
- digital filter: 25–200 kHz;
- PDT: 200 μ s;
- HDT: 400 μ s;
- HLT: 800 μ s;
- FTBnd: 400 μ s.

All waveforms and extracted signal descriptors were stored for subsequent processing and analysis. The experimental setup and sensor arrangement are presented in Figure 2.

Acoustic emission data analysis

The acoustic emission analysis was focused on both damage evolution and fracture mechanism identification. The following primary AE parameters were considered:

- amplitude (A);
- rise time (RT);
- duration (D);
- counts;
- absolute energy;
- average frequency (AF);
- RA value.

The cumulative acoustic emission energy was used to quantify the progression of internal damage during loading. To enable direct comparison between specimens and temperature levels, cumulative AE energy was analysed as a function of the normalized load.

Fracture mechanisms were identified using the RA–AF approach. The RA parameter was calculated as the ratio of rise time to amplitude, whereas the average frequency was determined from the ratio of counts to signal duration. Tensile-dominated fracture processes are generally characterized by low RA values and high AF values, whereas shear-related mechanisms are associated with high RA values and low AF values. Consequently, RA–AF distributions were used to evaluate temperature-induced changes in damage mechanisms and to assess the relative contribution of tensile and shear fracture modes.

The combined analysis of cumulative AE energy, cumulative AE hits, and RA–AF parameters enabled a comprehensive assessment of damage evolution and fracture development during flexural loading under elevated temperature conditions.

Representative specimens were selected quantitatively as those exhibiting the smallest combined deviation from the group mean values of maximum load, displacement at maximum load, cumulative AE energy, and cumulative AE hits. This objective selection criterion ensured that the presented specimens reflected the characteristic behaviour of each experimental series.

Failure mode analysis

Following the mechanical tests, the failure patterns of all specimens were visually examined. Particular attention was paid to crack initiation, crack propagation, and the interaction between the concrete substrate and the CFRP strengthening system.

All specimens exhibited a similar global failure mechanism characterized by the formation of a dominant shear crack within the constant bending moment region. Crack initiation occurred in

the tensile zone and propagated towards the compression zone with increasing load. Representative failure patterns are shown in Figure 3.

RESULTS AND DISCUSSION

Load–displacement response

The flexural behaviour of the CFRP-strengthened reinforced concrete beams was evaluated using three-point bending tests. During loading, the applied force and corresponding displacement were continuously recorded, enabling the determination of load–displacement relationships for all specimens.

The obtained curves for two representative specimens from each experimental series are presented in Figure 4. The representative specimens presented in Figure 4 were those previously selected according to the quantitative criterion, the smallest combined deviation from the group mean values of maximum load, displacement at maximum load, cumulative AE energy, and cumulative AE hits. Regardless of the thermal exposure condition, all specimens exhibited an initial approximately linear response corresponding to the elastic stage of structural behaviour. As the load increased, deviations from the linear response were observed, indicating crack initiation and progressive damage development within the beams. The final stage of loading was associated with the propagation of the dominant shear crack and subsequent failure of the strengthened specimens.

For clarity, Figure 4 presents two representative specimens from each experimental series, whereas all statistical analyses reported in Tables 2–4 were performed using all three tested specimens.

The reference specimens tested at ambient temperature achieved an average maximum load of 102.8 ± 19.3 kN. The corresponding values obtained for specimens exposed to 60 °C and 80 °C were 102.9 ± 23.8 kN and 87.4

Table 1. Average temperatures measured during thermal conditioning

Series	CFRP surface temperature [°C] (mean $\pm$ SD)	Concrete–adhesive interface temperature [°C] (mean $\pm$ SD)
BK_20	20.3 $\pm$ 0.8	20.1 $\pm$ 0.7
BK_60	60.0 $\pm$ 1.2	57.0 $\pm$ 1.5
BK_80	80.0 $\pm$ 1.0	76.0 $\pm$ 1.7

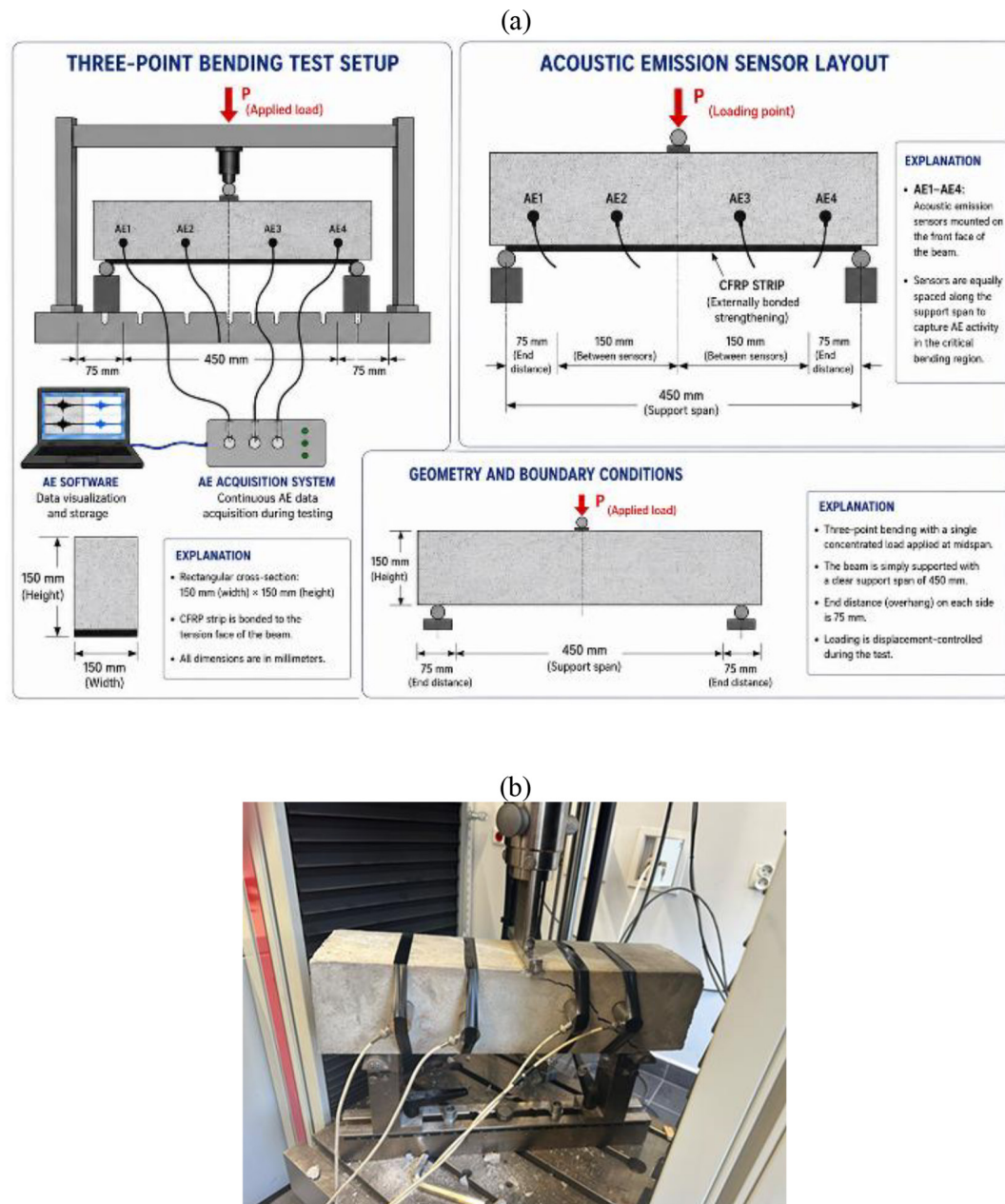


Figure 2. Experimental setup for three-point bending tests with simultaneous acoustic emission monitoring:
 (a) schematic illustration of the test configuration showing the support span, loading point, CFRP strengthening strip, and arrangement of four VS75-SIC acoustic emission sensors;
 (b) photograph of the experimental setup during testing.

± 10.5 kN, respectively. Thus, thermally conditioned specimens exhibited only a limited reduction in load-carrying capacity, with the decrease becoming more noticeable for the 80 °C series. However, the relatively large scatter observed within the BK_20 and BK_60 series indicates that the differences between the investigated temperature levels should be interpreted with caution.

Statistical analysis did not reveal significant differences in maximum load between

the investigated series (one-way ANOVA, $p = 0.541$; Kruskal–Wallis test, $p = 0.430$). The average displacement at maximum load was 4.32 ± 0.50 mm, 4.35 ± 0.47 mm, and 3.32 ± 0.27 mm for the BK_20, BK_60, and BK_80 series, respectively. Although a tendency towards lower displacement at maximum load was observed for the BK_80 specimens, the statistical significance of this observation remains uncertain due to the limited number of

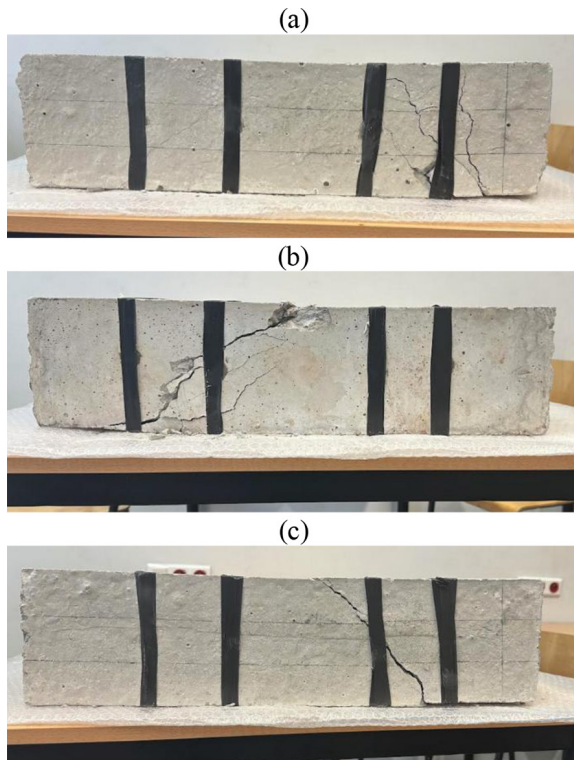


Figure 3. Representative failure patterns observed after three-point bending tests:

- (a) BK_20 specimen tested at ambient temperature,
- (b) BK_60 specimen after exposure to 60 °C,
- and (c) BK_80 specimen after exposure to 80 °C

specimens (ANOVA, $p = 0.040$; Kruskal–Wallis test, $p = 0.066$).

Overall, the results suggest that exposure to temperatures of up to 80 °C did not result in a statistically significant reduction in the global flexural capacity of the CFRP-strengthened beams (Table 2). Therefore, conventional load–displacement analysis alone may not be sufficient to identify temperature-induced changes occurring during the fracture process. Acoustic emission monitoring was consequently employed to provide additional insight into damage initiation, crack propagation, and fracture development during loading.

The mechanical test results constitute the basis for the subsequent acoustic emission analyses presented in the following sections. The representative specimens selected for the acoustic emission analyses exhibited mechanical responses close to the average behaviour observed within the corresponding experimental series and were therefore considered representative of each test group.

Damage characterization based on AE signals

Normalized cumulative AE energy versus normalized load

The evolution of normalized cumulative AE energy as a function of normalized load (F/F_{max}) for representative specimens from each test series is presented in Figure 5. The presented curves are representative of the overall behaviour observed within each experimental series, while the remaining specimens exhibited similar qualitative trends in AE energy accumulation.

For all investigated series, the accumulation of AE energy remained relatively limited during the initial stage of loading, indicating a low level of internal damage development. As the load increased, a progressive increase in cumulative energy was observed, reflecting the initiation and propagation of cracks within the strengthened concrete beams.

The representative BK_20 and BK_60 specimens exhibited similar trends in AE energy accumulation. In both cases, a substantial increase in cumulative energy occurred primarily at high normalized load levels ($F/F_{max} > 0.75$), indicating that intensive damage development was concentrated near the maximum load capacity of the specimens.

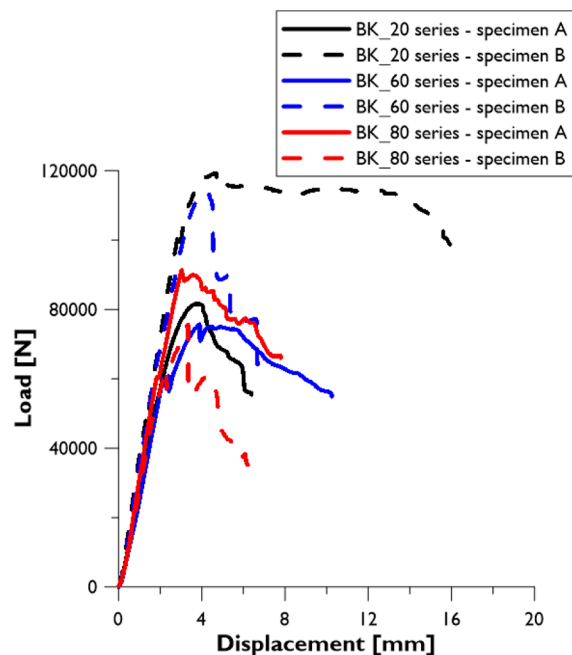


Figure 4. Load–displacement curves of representative specimens from the BK_20, BK_60, and BK_80 series obtained during three-point bending tests

Table 2. Summary of mechanical test results

Series	Fmax [kN] (mean $\pm$ SD)	Displacement at Fmax [mm] (mean $\pm$ SD)
BK_20 mean $\pm$ SD	102.8 $\pm$ 19.3	4.32 $\pm$ 0.50
BK_60 mean $\pm$ SD	102.9 $\pm$ 23.8	4.35 $\pm$ 0.47
BK_80 mean $\pm$ SD	87.4 $\pm$ 10.5	3.32 $\pm$ 0.27

A different behaviour was observed for the representative BK_80 specimens. In this case, the increase in normalized cumulative AE energy occurred earlier and progressed more rapidly than in the remaining specimens. The accelerated accumulation of AE energy at intermediate load levels suggests earlier activation of fracture-related processes and a more intensive damage development during loading.

The step-like character of the curves results from the discrete nature of acoustic emission events. Localized increases in cumulative energy correspond to clusters of AE hits generated within narrow load intervals, reflecting periods of intensified crack propagation and damage accumulation.

Although the global mechanical response of the investigated beams remained relatively similar, the AE results revealed noticeable differences in damage evolution. In particular, the representative BK_80 specimens exhibited earlier and faster accumulation of AE energy compared with the BK_20 and BK_60 specimens,

indicating that acoustic emission monitoring is capable of capturing temperature-related changes in fracture behaviour that are not readily identifiable from conventional load–displacement analysis alone.

Although Figure 5 presents representative specimens for visualization purposes, similar qualitative trends were observed across all specimens within each temperature series. In particular, specimens exposed to 80 °C consistently exhibited earlier cumulative AE energy accumulation compared with the reference series.

RA–AF analysis

The fracture mechanisms occurring during three-point bending were further investigated using the relationship between the RA value and the average frequency (AF) of acoustic emission signals. The RA–AF distributions obtained for representative specimens from each experimental series are presented in Figure 6. Signal classification was performed using the conventional RA = AF criterion commonly adopted in acoustic emission studies of concrete materials. Following common practice in acoustic emission studies of concrete materials, signals located below the classification boundary were interpreted as predominantly tensile-related, whereas signals above the boundary were interpreted as relatively more shear-related. It should be noted that the RA–AF approach provides an indirect classification and should not be considered a direct identification of fracture mechanisms.

For all investigated specimens, tensile-related signals predominated, which is consistent with the flexural loading configuration adopted in the present study. The representative BK_20, BK_60 and BK_80 specimens exhibited tensile signal contributions of 97.4%, 98.3%, and 95.8%, respectively. Correspondingly, the contribution of shear-related signals increased from 2.6% for BK_20 to 4.2% for BK_80.

Among the representative specimens, the selected BK_60 specimen exhibited the lowest median RA value (0.76 ms/V) and the highest

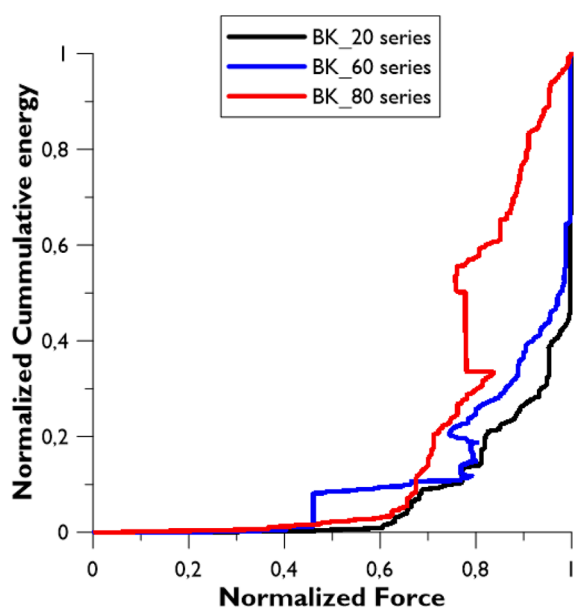


Figure 5. Normalized cumulative acoustic emission energy as a function of normalized load (F/F_{max}) for representative specimens from the BK_20, BK_60, and BK_80 series

median AF value (26.76 kHz), indicating a predominance of tensile cracking mechanisms. In contrast, the representative BK_80 specimen exhibited the highest median RA value (1.37 ms/V) and the largest proportion of shear-related signals. The broader RA–AF distribution observed for BK_80 suggests a more heterogeneous damage process and an increased contribution of fracture mechanisms commonly associated with higher RA values.

Although flexural tensile cracking remained the dominant failure mechanism in all specimens, the results indicate that exposure to 80 °C modified the characteristics of the generated AE signals. The increased contribution of high-RA events and shear-related signals observed for the BK_80 specimen is consistent with the

accelerated cumulative energy development reported in the previous section and indicates temperature-related changes in damage evolution that are not readily identifiable from conventional mechanical measurements alone.

The statistical summary presented in Table 3 is consistent with a gradual increase in the proportion of shear-related signals from $3.70 \pm 2.22\%$ for BK_20 to $5.72 \pm 3.55\%$ for BK_80, accompanied by a slight increase in median RA values. Although the observed differences are relatively small, they are consistent with the trends identified in the cumulative AE analyses.

Normalized cumulative AE hits

Figure 7 presents the evolution of normalized cumulative acoustic emission hits as a function

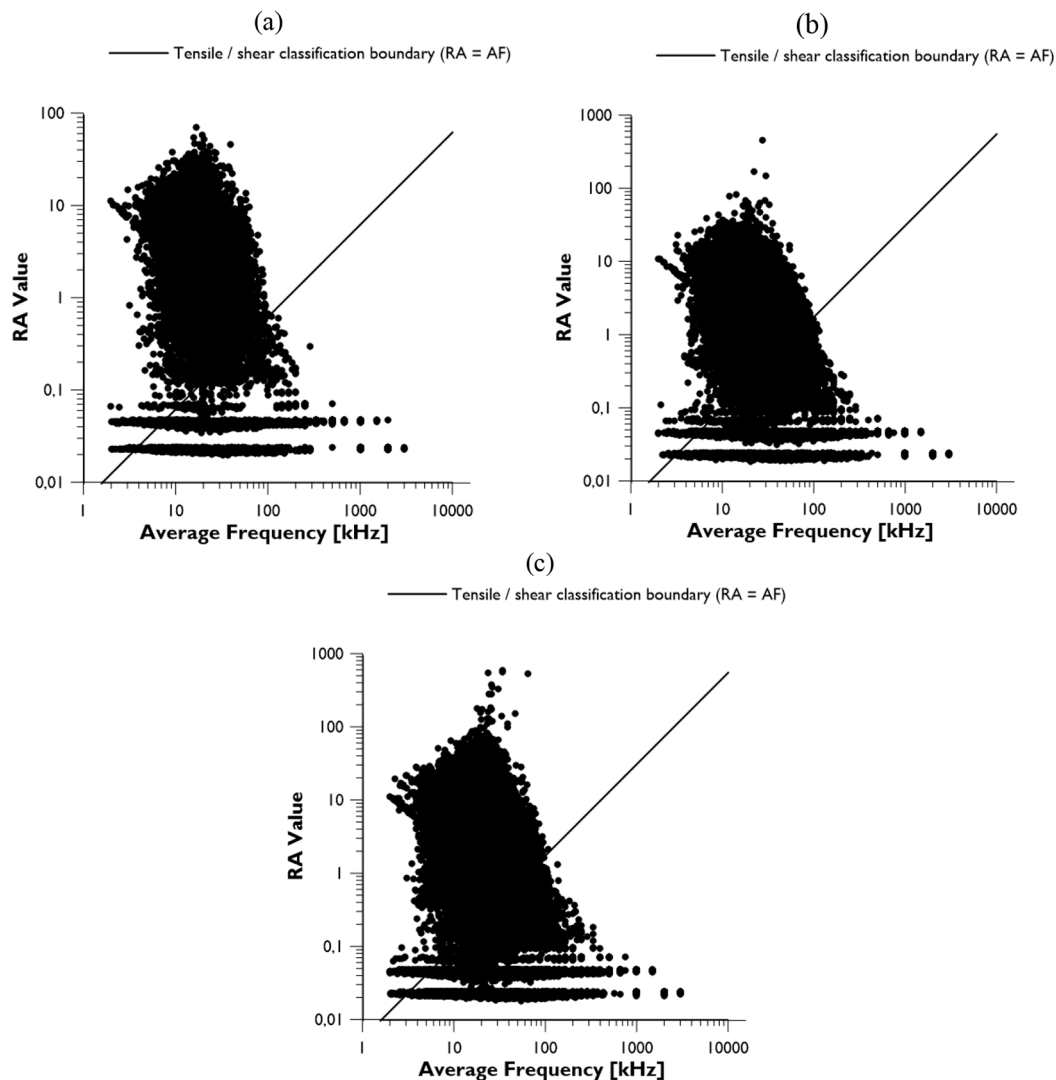


Figure 6. Relationship between RA value and average frequency (AF) for representative specimens from the BK_20 (a), BK_60 (b), and BK_80 (c) series. The diagonal line ($RA = AF$) was adopted as the conventional criterion for distinguishing tensile- and shear-dominated acoustic emission signals

Table 3. Statistical summary of RA–AF parameters for all specimens within each experimental series (mean $\pm$ standard deviation)

Series	Median AE hits	Median AF [kHz]	Median RA [ms/V]	Tensile signals [%]	Shear signals [%]
BK_20	9.5 $\pm$ 2.1	25.24 $\pm$ 3.59	1.28 $\pm$ 0.11	96.30 $\pm$ 2.22	3.70 $\pm$ 2.22
BK_60	8.5 $\pm$ 3.5	24.49 $\pm$ 3.21	1.29 $\pm$ 0.75	95.44 $\pm$ 1.13	4.56 $\pm$ 1.13
BK_80	10.0 $\pm$ 2.8	25.70 $\pm$ 2.66	1.33 $\pm$ 0.05	94.28 $\pm$ 3.55	5.72 $\pm$ 3.55

of normalized load for representative specimens from each experimental series. For all specimens, the accumulation of AE hits remained limited during the initial loading stage and increased progressively as the applied load approached the maximum load level. The representative specimens were selected to illustrate the characteristic evolution of AE activity within each series. Similar qualitative trends were observed for the remaining specimens subjected to the same thermal exposure condition.

The representative BK_80 specimen exhibited the earliest increase in cumulative AE activity. A significant proportion of the total AE hits was accumulated at intermediate load levels, indicating the activation of fracture-related processes at lower normalized loads compared with the BK_20 and BK_60 specimens. In contrast, the reference BK_20 specimen showed a delayed accumulation of AE hits, with the majority of acoustic activity concentrated near the maximum load level.

The representative BK_60 specimen exhibited a cumulative hit evolution generally comparable to that of the reference specimen, although local differences were observed at intermediate load levels. Despite the overall similarity of the curves, the more pronounced accumulation of AE hits observed for BK_80 indicates a more rapid development of damage during loading.

These observations are consistent with the cumulative AE energy results presented previously and indicate that acoustic emission monitoring is capable of detecting temperature-related changes in damage evolution that are not readily identifiable from conventional mechanical measurements alone.

Table 4 quantitatively is consistent with the earlier initiation of acoustic emission activity in the BK_80 series. The load level corresponding to 10% cumulative AE energy decreased from 0.71 $\pm$ 0.04 for BK_20 to 0.43 $\pm$ 0.05 for BK_80. Similar trends observed for cumulative AE hits may indicate accelerated damage evolution after thermal exposure.

The cumulative hit evolution shown in Figure 7 represents the characteristic behaviour of each series. Analysis of all tested specimens confirmed the tendency towards earlier AE activity initiation in the BK_80 series.

DISCUSSION

The limited differences observed in the load-carrying capacity of the investigated beams indicate that exposure to temperatures of up to 80 °C did not significantly affect the global structural response of the CFRP-strengthened elements. From an engineering perspective, such behaviour may suggest that conventional mechanical testing alone is insufficient for identifying the early stages of temperature-induced degradation. This observation is consistent with previous studies showing that moderate thermal exposure may not necessarily lead to substantial reductions in flexural capacity despite progressive degradation of the adhesive layer and interfacial properties [9,10].

It should be noted that the present study employed a three-point bending configuration, in which both bending and shear stresses contribute to the observed failure process. Although a four-point bending configuration could facilitate a clearer separation of flexural and shear damage

Table 4. Statistical summary of selected AE activity evolution indicators

Series	F/Fmax at 10% cumulative hits	F/Fmax at 25% cumulative hits	F/Fmax at 10% cumulative energy	F/Fmax at 25% cumulative energy
BK_20	0.68 $\pm$ 0.04	0.79 $\pm$ 0.03	0.71 $\pm$ 0.04	0.82 $\pm$ 0.03
BK_60	0.61 $\pm$ 0.05	0.75 $\pm$ 0.04	0.66 $\pm$ 0.05	0.78 $\pm$ 0.04
BK_80	0.39 $\pm$ 0.06	0.58 $\pm$ 0.05	0.43 $\pm$ 0.05	0.61 $\pm$ 0.04

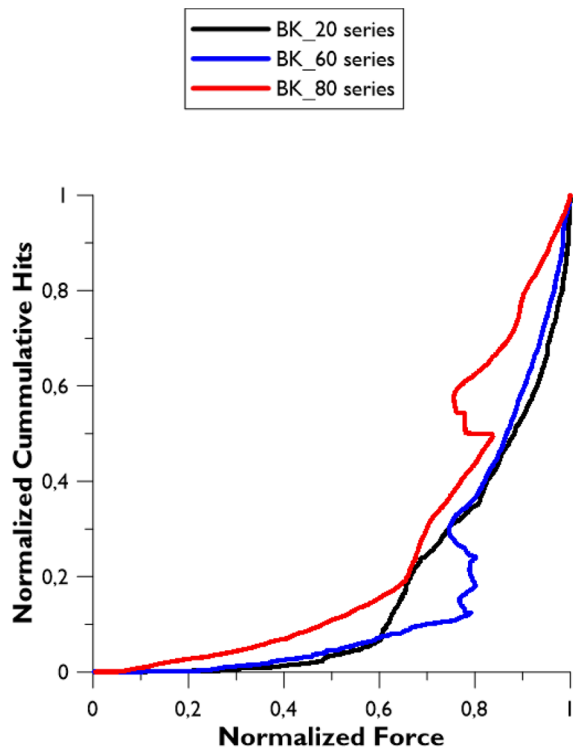


Figure 7. Evolution of normalized cumulative acoustic emission hits as a function of normalized load ($F/F_{\max}$) for representative specimens from the BK_20, BK_60, and BK_80 series

mechanisms, the adopted loading scheme reflects practical structural conditions and enabled evaluation of the overall damage evolution under combined stress states.

The acoustic emission results suggest that moderate thermal exposure influences the fracture process before measurable changes become evident in the macroscopic mechanical response. This finding is particularly important for externally strengthened reinforced concrete elements, where local deterioration of the adhesive layer or the concrete–adhesive–CFRP interface may contribute to the observed AE behaviour, although direct evidence of interfacial degradation was not obtained in the present study. Therefore, the proposed interpretation should be regarded as a plausible explanation supported by indirect AE observations rather than direct experimental confirmation. Future work should include complementary techniques such as pull-off testing, SEM observations, digital image correlation, or microscopic interface characterization. Similar observations have been reported in AE-based studies, where acoustic emission parameters proved more sensitive to early damage development than conventional mechanical indicators [11,12,19,21].

Although the investigated temperatures are relatively low compared with those typically associated with severe thermal degradation of CFRP strengthening systems, prolonged thermal exposure may still influence adhesive stiffness, interfacial stress transfer, and local cracking susceptibility. As a consequence, damage processes can be activated at lower load levels even when the overall load-carrying capacity remains largely unchanged. Previous investigations demonstrated that thermal exposure close to the glass transition temperature of epoxy adhesives may alter stress-transfer mechanisms and initiate local interfacial degradation before significant reductions in structural capacity become visible [9,10].

The RA–AF results suggest that thermal exposure also modifies the character of the generated acoustic emission signals. While tensile cracking remained the dominant damage mechanism, the increased occurrence of high-RA events after exposure to 80°C may indicate a more heterogeneous fracture process potentially involving local crack interaction and interfacial damage development, although alternative interpretations associated with signal attenuation and propagation effects cannot be completely excluded. Such behaviour is consistent with the complex stress redistribution mechanisms typically observed in CFRP-strengthened reinforced concrete members. Similar relationships between increasing RA values and more complex fracture processes have been reported in concrete and composite materials by Aggelis [13] and subsequently confirmed in studies employing AE monitoring of fibre-reinforced composites and CFRP-strengthened elements [18,22].

The present results suggest that acoustic emission monitoring provides information that complements conventional mechanical testing. In particular, AE-based parameters appear to be sensitive to subtle changes in damage evolution that cannot be directly identified from load–displacement relationships alone. This suggests that acoustic emission monitoring may provide a useful diagnostic tool for the condition assessment of CFRP-strengthened reinforced concrete structures subjected to moderate thermal exposure. This finding agrees with previous studies highlighting the capability of AE techniques to detect crack initiation, debonding processes, and damage accumulation at stages when conventional load–displacement measurements remain relatively insensitive [16,17,21].

The earlier accumulation of cumulative AE energy and AE hits observed in the BK_80 series may indicate that temperature exposure accelerates damage initiation within the concrete–adhesive–CFRP system. This tendency was observed consistently across all specimens exposed to 80 °C, although the magnitude of the effect varied between individual tests. Similar tendencies were reported by Hanif et al. [17], who observed accelerated AE activity associated with debonding processes in CFRP-retrofitted RC beams. Although debonding was not directly verified in the present study, the earlier accumulation of AE energy and hits observed for BK_80 specimens may indicate increased susceptibility of the strengthened system to interfacial damage.

The present study is subject to several limitations. The experimental programme included a limited number of specimens per series and considered only moderate thermal exposure levels. Furthermore, the investigated temperature range was limited to moderate thermal exposure levels (60–80 °C), and the results cannot be directly extrapolated to severe fire conditions. The use of representative specimens for graphical presentation may not fully capture the variability observed within individual series. Consequently, the proposed mechanisms should be regarded as indicative and require further verification using complementary experimental techniques. Since heating was applied locally using an electric heating mat, temperature gradients may have existed within the beam cross-section. Therefore, the reported temperatures should be interpreted as temperatures measured in the strengthened region rather than uniform temperatures throughout the entire specimen.

One limitation of the present study is the relatively small number of specimens in each experimental series ($n = 3$). Consequently, the statistical analyses should be interpreted primarily as supporting information rather than as a basis for broad generalization. The observed relationships should therefore be regarded as supportive evidence rather than definitive proof of the identified trends. The observed AE trends were consistent among all specimens, although further studies involving larger experimental datasets are necessary to confirm the quantitative relationships identified in the present work.

No direct microstructural investigations, pull-off tests, or interface characterization

techniques were performed. Therefore, the proposed interpretation of temperature-induced interfacial degradation remains indirect and should be regarded as a hypothesis supported by acoustic emission observations rather than direct experimental evidence.

CONCLUSIONS

Based on the obtained results, the following conclusions can be drawn:

- Moderate thermal exposure of up to 80 °C produced only minor changes in the global flexural response of the investigated CFRP-strengthened beams, indicating that conventional mechanical parameters alone may not be sufficiently sensitive to detect early-stage thermal degradation.
- Acoustic emission monitoring is capable of identifying subtle changes potentially associated with damage evolution within the concrete–adhesive–CFRP system.
- Although tensile cracking remained the dominant damage mechanism, the AE results indicated that exposure to 80 °C modified the fracture process, suggesting a tendency towards more heterogeneous damage evolution and an increased contribution of signals associated with higher RA values.
- The findings highlight the potential of acoustic emission technology as a non-destructive diagnostic tool for the condition assessment of CFRP-strengthened reinforced concrete elements subjected to moderate thermal exposure.

The proposed methodology may contribute to the development of acoustic emission-based diagnostic procedures for the early assessment of temperature-induced damage in CFRP-strengthened reinforced concrete structures.

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