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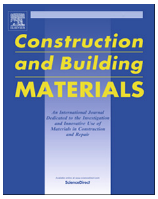

Identifying CFRP strip width influence on fracture of RC beams by acoustic emission

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HIGHLIGHTS

- Three specimens one of which was the reference and two others strengthened with CFRP were tested in the laboratory.
- Due to side bonding, CFRP strips debonded and caused the strengthened specimens fail in shear.
- AE parameter analysis is useful to identify mechanism points by evaluating critical changes in AE parameters.
- Fracture mechanisms of the test specimens were identified by applying AE parameter and SiGMA analyses.

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ABSTRACT

Carbon fiber-reinforced polymer (CFRP) is a widely used material to strengthen deficient structures externally. While CFRP has numerous advantages, debonding is the main problem of CFRP-strengthened reinforced concrete (RC) beams as it causes sudden failure. Thus, to circumvent this problem, failure modes of an RC beam strengthened with CFRP need to be understood. There are various application types of CFRP strips and plates depending on their ease of application and contribution as a strengthening material such as side bonding and wrapping. Using CFRP as a strip is a cost effective way and is widely preferred. Strip width and spacing have a firsthand effect on the mechanical behavior of the strengthened element. Accordingly, in this study, AE parameter analysis and SiGMA analysis were applied for identification of CFRP strip width effect on fracture of RC beams having different CFRP widths. Within the scope of the experimental study, a reference beam and two CFRP-strengthened beams were tested under cyclic loading and monitored by AE. Both mechanical and AE results show that the behavior is not enhanced by increasing the strip width.

1. Introduction

Brittle shear failures in reinforced concrete (RC) elements are caused by lack of shear resistance [1]. To provide a better behavior for deficient elements, strengthening techniques based on the use of fiber reinforced polymer (FRP) materials have been proposed and developed in the last two decades [2–6]. When economic advantages are taken into consideration, using Carbon Fiber Reinforced Polymer (CFRP) strips for external strengthening rather than using CFRP sheets is a practically efficient method for enhancing mechanical behavior of RC members. Shear cracking induced debonding at concrete-CFRP interface, compression crushing of concrete and rupture of CFRP control the ultimate capacity of the CFRP-strengthened beam [7]. By this means, rupture denotes that the full capacity is obtained, while other modes of failure indicate that the full capacity of CFRP is not totally obtained [8]. Thus, the reasons that cause these failure types need to be examined in detail.

Brittle adhesive materials cannot resist high stress concentrations at the bonding interface, thus they activate debonding and a sudden failure occurs due to the debonding of CFRP from concrete surface. Hence, clarification of fracture mechanisms due to debonding is important for the researchers to circumvent this unwanted failure type [9].

Fracture modes of CFRP-strengthened RC beams strongly depend on interface bond between FRP and concrete layer. If this bond is strong, then failure behavior of the RC beam is similar to that of a conventional RC beam including rupture of the FRP layer. If this bond is weak, plate-end debonding and flexure/shear crack induced interface debonding are two possible failure modes. Stress concentrations in the end of FRP cause the plate-end debonding.

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Flexure/shear crack induced interface debonding is the more dangerous one as the failure is sudden. These mechanisms need to be clarified and understood within CFRP-strengthened RC beams.

In previous studies, to comprehend the failure mechanism of reinforced concrete structures strengthened with CFRP, the unit strain obtained from the strain gauges which are placed on the top of CFRP have been used. It has been interpreted that the increase in the strain gauges results from CFRP being pulled due to cracking. Also, decrease in unit strain is related to damage in the bonding. However, the unit strain behavior is directly influenced by the distance to the strain gauge, the crack orientation and the type of crack. Thus, more detailed investigation should be made in order to sort out the cracking mechanisms of CFRP-strengthened RC structures. In this study, AE-SiGMA analysis which is based on moment tensor analysis of Acoustic Emission (AE) signals [10] and parameter-based analysis were applied to determine fracture mechanisms of RC beams strengthened with CFRP.

AE is a well-known NDT method used for damage detection. AE signals have different parameters which are used to detect and evaluate damage in materials [11–16]. Classification of cracks can be made by using AE parameter analysis and AE-SiGMA. Also by using AE-SiGMA, crack types, locations and orientations are quantitatively determined. The method is known to be successfully applied for identification of crack kinematics of RC elements [16–30].

In this study, to determine the effect of CFRP width on fracture mechanism of CFRP-strengthened RC beams, Acoustic Emission method was utilized. For this reason, three RC specimens were tested in the laboratory which one of them was a reference and the others were CFRP-strengthened with similar strip spacing but different strip width. To identify the directions and types of the cracks, AE measurements were taken along with the mechanical observations.

2. Acoustic Emission (AE)

2.1. AE parameter analysis

By evaluating AE parameters such as the number of AE hits, amount of released AE energy, average frequency, rise time and RA value, critical points of the fracture mechanism of a reinforced concrete member can be identified [14,15,29]. For instance, an increase in number of hit and amount of AE energy could attribute to a failure event. Besides, activation of tensile mode event is characterized by rising of average frequency values while RA values decrease. By using AE parameters such as rise time, maximum amplitude, duration time and AE count, cracks can be classified. By using below equation, RA value and the average frequency can be calculated and based on the JCMS-III B5706 code, cracks can be classified into two groups as tensile and shear cracks as shown in Fig. 1.

$$\text{RA value} = \text{the rise time/the maximum amplitude} \tag{1}$$

$$\text{The average frequency} = \text{AE ringdown} - \text{count/the duration time} \tag{2}$$

2.2. AE-SiGMA analysis

Based on moment tensor analysis of AE signals, AE-SiGMA method [10] is developed to classify cracks. SiGMA analysis which is based on the generalized theory of AE and consists of AE source location and moment tensor analysis, is a simplified form of Green's functions. A crack can be modeled by crack-motion vector b and unit normal vector n to crack surface F. Crack motion is defined as b(y)$lS(t)$, where b(y) symbolizes the crack displacement magnitude, l is the direction vector of crack motion, and $S(t)$ is the source-time function of crack motion. Based on the generalized AE theory, wave motion u (x,t) can be defined as [10,16,24,26],

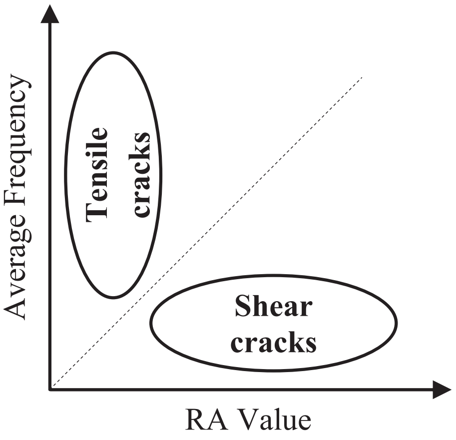

Fig. 1. Crack classification according to JCMS-III B5706.

$$u_i(x,t) = \int C_{pqkl}G_{ip,q}(x,y,t)^{*}[b(y)l_kS(t)n_l]dS = G_{ip,q}(x,y,t)m^{*}_{pq}S(t) \tag{3}$$

where $G_{ip,q}$ is the spatial derivative of Green's function. The following integration over crack surface

F leads to the moment tensor m_{pq},

$$\int C_{pqkl}[b(y)l_kn_l]dS = [C_{pqkl}l_kn_l][\int b(y)dS] = [C_{pqkl}l_kn_l]\Delta V = m_{pq} \tag{4}$$

In the case of isotropic elasticity,

$$m_{pq} = (\lambda l_kn_l\delta_{pq} + \mu l_pn_q + \mu l_qn_p)\Delta V \tag{5}$$

where, λ and μ are Lame constants. By simplifying Eq. (5), following equation is obtained.

$$A(x) = C_s\frac{\mathrm{Ref}(t,r)}{R}r_pm_{pq}r_qDA \tag{6}$$

In Eq. (6), $A(x)$ is the amplitude of the first motion and Cs is the calibration coefficient of the sensor sensitivity and material constants. Reflection coefficient is symbolized by *Ref*, R is the distance from the source and the sensor and r is its direction vector. Moment tensor is m_{pq} and DA is area of the crack surface. For an isotropic material, the moment tensor is second order and symmetric, thus the number of unknown components of the moment tensor is six. Arrival time and amplitude of the first motion are needed from recorded AE waveforms to solve Eq. (6). In order to obtain these parameters, an automated detection method was developed by Ohno and Ohtsu [21,24]. Locations of the sources can be determined by using arrival time differences to different sensors and moment tensor components can be determined by using amplitude of the first motion recorded by at least six sensors.

In order to make crack classification, the eigenvalue analysis of the moment tensor was applied to AE data [10] and these eigenvalues are represented by combination of shear crack (slip motion) and tensile crack (crack-opening motion). Following decomposition is obtained as the relative ratios X, Y and Z,

$$\begin{aligned}
&1.0 = X + Y + Z,\\
&\text{The intermediate eigen value/the maximum eigen value} = 0 - Y/2 + Z,\\
&\text{The minimum eigen value/the maximum eigen value} = -X - Y/2 + Z.
\end{aligned} \tag{7}$$

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