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Study of fracture evolution in FRP-strengthened reinforced concrete beam under cyclic load by acoustic emission technique: An integrated mechanical-acoustic energy approach

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HIGHLIGHTS

- An RC specimen strengthened with CFRP was tested in the laboratory.
- Sentry function that combines both mechanical and acoustic energy information was employed.
- Fracture mechanisms were identified by applying sentry function.

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ABSTRACT

Acoustic emission (AE) is an effective tool to evaluate the damage progression qualitatively and it can be used to assess important damage mechanism points of a structural element during loading. These assessments are made either by signal-based analyses or parameter-based analyses. In order to investigate the behavior of a reinforced concrete element strengthened with carbon fiber reinforced polymers (CFRP), both mechanical and acoustic information have been considered independently in several studies. However, it is important to combine both the mechanical and acoustic energy information to make a more comprehensive damage characterization. In order to perform a deeper analysis of FRP-strengthened reinforced concrete structure's damage evolution, a unitless function so called "sentry" that combines both the mechanical and acoustic energy information is employed in this study. This function is expressed in the terms of the logarithmic ratio of the strain energy (E_S) and the acoustic energy (E_{AC}).

According to the results obtained in this study, sentry function is proved to be successful and efficient method in CFRP-strengthened reinforced concrete elements that can be used in observing their structural failure mechanism for realistic assessments.

1. Introduction

The need to improve the structural capacity of existing buildings arises from higher load demand than in design process, seismic capacity upgrade or any deficiencies which can be developed in service life of the structural system. It calls for the largest possible number of repairing techniques, from which the most effective one have to be chosen in each particular case. The common principle of these methods is quite simple. It is usually aimed at increasing the strength of bearing system with stiffness enhancement of structural elements. As mentioned above, even though different techniques have been suggested in this area, the most important part of this work is to select which method is effective for cases examined.

Strengthening with composite materials has been employed recently in rehabilitation and repair of elements for better performance in terms of high stiffness to weight ratios and resistance to environmental conditions. CFRP (carbon fiber reinforced plastics) composite materials have been recently introduced as reinforcement elements. Efficient performance of CFRP reinforcement elements have been reported in several studies [1–4]. Due to severe shear stresses separation may occur between CFRP reinforcement element and the concrete which leads to less stress transfer from concrete to reinforcement and contrariwise. Consequently, the load bearing capacity of the structure decreases; thus, the brittle fracture in the concrete takes place subsequently. This phenomenon is the most important problem of CFRP applications. As

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a result, to clarify the failure mechanisms and the time of failure occurrence have a great importance in preventing the catastrophic failures taking place whilst loading the component.

FRP-strengthened reinforced concrete (RC) beams undergo more types of failure mechanisms in comparison to conventional RC beams due to the existence of bond interface between FRP-concrete substrate. The possible modes of failures can be classified into two categories which are premature debonding modes and material failure modes as seen from Fig. 1. If the interface bond between FRP and concrete layer is strong enough, the failure modes will depend only on the strength values of concrete and FRP composite layers. In the category of strong interface failures, the possible failure mechanisms are rupture of FRP layers, crush of concrete in compressive zone and shear failure of RC beam. These modes are similar to those of conventional RC beams. These modes can be easily avoided by using adequate reinforcement bars, higher strength concrete and more FRPs for shear failure. Furthermore, when the strength of bond between FRP and concrete is not sufficient, occurrence of interface debonding leads to a brittle failure of the beam. In the category of weak bond failures, the possible failure mechanisms are plate-end debonding and flexure-shear crack induced interface debonding. Plate-end debonding initiates from the end point and propagates towards the mid-span. This is stem from stress concentration in end points. But, flexure-shear crack induced interface debonding can be much more dangerous than plate-end debonding and this type occurs in the vicinity of an intermediate flexural shear crack within the RC beam. The weak bond failure modes are incomprehensively complicated than strong bond ones. Therefore, extensive studies have been conducted on this mechanism type in order to get realistic assessments in this area [5–11].

Acoustic emission (AE) is an effective method that evaluates the damage progress in a structural element under loading. AE is based on detection of elastic waves that originates due to release of stored strain energy during fracture and propagates inside a material. Numerous studies have been conducted on estimation or assessing the mechanical performance of structural elements [12–15]. Various techniques are available in analyzing AE data in terms of count and count rates such as spectral analysis, amplitude distribution analysis, autocorrelation function and root mean square (RMS) signal analysis [16,17]. One of the most promising and efficient methods in data analyzing in acoustic emission by means of crack characterization is AE-SiGMA (Acoustic Emission-Simplified Green's Functions for Moment Tensor Analysis) [12–15,18–21]. AE-SiGMA is applied to identify AE sources in order to classify micro-crack formations into tensile, shear and mixed mode. By AE-SiGMA, quantitative crack evaluation has been made in reinforced concrete structures by extensive research [18–22] and the success is proved when the experimental results are examined. Therefore, AE has been successfully applied to provide any information about structural systems in the last decade [23–28]. These extensive studies clearly indicate that damage initiation, progression and location of CFRP-strengthened reinforced concrete specimens can be realistically demonstrated. The failure mechanism of CFRP-strengthened RC elements can be simultaneously monitored and valuable contributions are gained from AE results in terms of structural behavior of elements.

In all of the aforementioned approaches, both mechanical and acoustic emission information are applied separately to assess the behavior of the component that undergoes loading. Therefore, application of a method which could simultaneously utilize the potential of both types of information is very important. Sentry function as a novel approach is an integration of both mechanical and acoustic emission information in unique formula.

The idea of sentry function which is applied in this study was firstly presented by Minak in 2007. The capability of sentry function is extensively studied in composite materials and steels [29,30]. Minak et al. applied sentry function to composite tube loaded in torsion after an accidental impact. They reported that the shape and the composition of the sentry function depend on

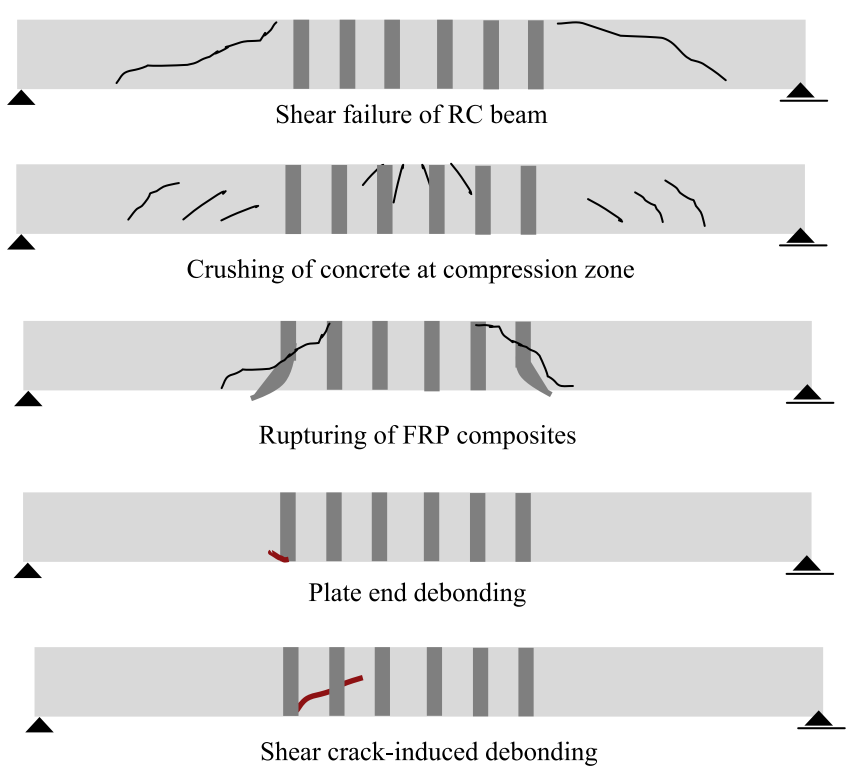

Fig. 1. Possible fracture mechanisms of FRP strengthened reinforced concrete [11].