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# Characterization of concrete matrix/steel fiber de-bonding in an SFRC beam: Principal component analysis and *k*-mean algorithm for clustering AE data

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ABSTRACT

Steel fibers have been used in concrete structures to increase the tensile strength and ductility of concrete. Fibers bridging cracks reduce micro cracking and improve post-cracking strength in concrete. Propagation of damage in a fiber reinforced concrete member occurs by concrete matrix cracking and widening of these cracks, which is accompanied by de-bonding of steel fibers from the concrete matrix. Fiber de-bonding is the main factor affecting the post-peak behavior of these members. Therefore, distinguishing the matrix cracking and fiber de-bonding mechanisms is important in nondestructive structural health monitoring methods. This study is focused on characterizing steel fiber/matrix de-bonding events apart from concrete matrix cracking sources in acoustic emission (AE) method. Two reinforced concrete beams, one of which included steel fibers within the concrete matrix, were tested under three point bending and monitored by AE. Afterwards, Principal Component Analysis (PCA) was applied to AE data and the failure mechanisms were clustered for characterization of steel fiber/matrix de-bonding. Finally, different AE features of these clusters were evaluated and applicable AE parameter distributions, which are useful to clarify steel fiber de-bonding mechanisms, were revealed.

## 1. Introduction

Concrete is a widely used construction material, which has a tensile strength significantly lower than its compressive strength. Typically steel bars are used in concrete structures to overcome this weakness and provide ductility to structural concrete members. In addition to steel bars, natural, synthetic, glass or steel fibers are also used in concrete structural elements due to their function in bridging the cracking surfaces transferring tensile stresses, which significantly increases post-cracking ductility of concrete [1]. Tensile stresses carried across cracks decrease crack widths in such fiber reinforced structural members, increasing their ductility and bending stiffness [2–8].

Steel fibers have its advantages over other types of fibers due to their higher stiffness, higher strength and high aspect ratio. Therefore, they are commonly used in numerous applications where cracking of concrete is of primary concern, such as industrial slabs, precast structural members and tunnel linings [2]. Mechanical properties of concrete members reinforced with steel fibers depend on fiber dosage, geometry, bonding with concrete and orientation of fibers as well as characteristics of concrete matrix

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[3,9,10].

In order to clarify these mechanisms and determine the damage level of a structure, various test techniques can be used. Generally, these techniques investigate the damaged state of the member and they need sampling for testing. However, it is important to make a decision before any visible damage takes place. Nondestructive testing methods have been developed for this purpose, providing information about the state of overall system without inflicting any damage on the structure. Acoustic Emission (AE) is one of the nondestructive test techniques providing information about crack progresses even at low load levels. The method is based on the detection of elastic waves propagating in the body generated by energy discharge due to fracture [11]. By capturing these waves with sensors, location and time of origin of fracture can be determined. A number of studies have been carried out to identify fracture mechanisms and fracture energies of concrete and steel fiber reinforced concrete members [2,12–18]. The studies about steel fiber reinforced concrete conclude that AE activity is proportional to the fiber content [12].

Based on AE parameters, it is possible to determine the failure mechanism of the concrete by various analyses [19–21]. In this paper, cluster analysis was applied to AE parameters which provides grouping objects according to their similarities such that the similarities in the same group are high while in different groups the similarities are low [22]. *K*-means is one of the most popular and widely used clustering algorithms due to its reliability and simplicity. The method aims to separate observations into the clusters in which distance between mean and the observations in the cluster are minimized. In the iterative algorithm, firstly, the clusters are initialized with random centers. Then the distances of each input to the cluster's center are computed and the inputs are assigned to their nearest cluster. Finally, the centers of the clusters are recalculated. Last two stages are repeated until the centers of the clusters converge [23].

Studies show that PCA is an effective tool to correlate clusters using various data [24–29]. Rossiter [30] used principal component regression on infrared spectra of concrete samples in order to predict their properties. Godin et al. [31] conducted tensile tests on pure resin samples and on polyester/glass fiber unidirectional composites and identified mechanisms as matrix cracking and interfacial de-cohesion by *k*-means. Precisely discriminating signals associated with de-bonding and signals associated with fiber failure was difficult, but the researchers regarded the results as encouraging. Ning et al. [32] and Milovanovic and Pecur [33] applied PCA to infrared thermography results obtained in concrete. Calabrese et al. [34] tested AE behavior of concrete beams under four-point-bending and determined their clusters. For this purpose, they used PCA and Kohonen's self-organizing map clustering algorithms and compared them with traditional AE parameter analysis procedures. They pointed out that the methods require the development of validation procedure to optimize a correct interpretation of great amounts of data. Calabrese et al. [35] used AE to monitor hydrogen assisted stress corrosion cracking of post-tensioned strands and distinguished three subsequent damage phases using cumulative hits. Then they confirmed the results with PCA and self-organizing maps and proved them to be particularly effective in identifying the evolution and intensity of corrosion damage on steel wires in the monitored post-tensioned concrete beam. Saliba et al. [36] carried out an experimental investigation to characterize local damages and physical mechanisms underlying creep of concrete. As a result of the study, the researchers obtained two clusters for basic creep and three clusters for desiccation creep. Fotouhi et al. [37] used AE and PCA to investigate different failure mechanisms of delamination in glass/epoxy composite laminates. They found out matrix cracking and fiber/matrix de-bonding dominantly and some fiber breakages took place. Anay et al. [38] monitored cement paste specimens by AE under compression test and classified active crack growth by PCA. They acquired three stages as crack micro crack initiation, stable and unstable crack growth by separating AE data into clusters. Roundi et al. [39] investigated static and fatigue behavior of glass/epoxy composite laminates with AE and classified accumulated damages as matrix cracking, fiber/matrix de-bonding, delamination and fiber breakage by *k*-means method and PCA. Researchers observed matrix micro-cracks as the most dominant damage mechanism and detected few signals representing the fibers breaking.

In this study, differently from the abovementioned studies, it was aimed to distinguish steel fiber/matrix de-bonding events apart from concrete matrix cracking by cluster analysis based on PCA using AE features. For this purpose, two reinforced concrete beams, one of which included steel fibers within concrete matrix, were tested under three point bending and monitored by acoustic emission. Afterwards, cluster analyses were applied to AE data for characterization of steel fiber/matrix de-bonding.

## 2. Acoustic emission (AE)

According to ASTM E 1316 [40], Acoustic Emission (AE) is defined as an event producing transient elastic waves by releasing of a number of local sources in materials under stress. In this context, AE can be considered as a microseism. In the method, stress wave is produced at a source by applied stress. The vibration reaches to sensors located at the surface and is transformed into an electrical signal. Then it arrives to pre-amplifier, filter, power amplifier, and counters, respectively.

In AE procedure, the first purpose is to determine the location of a crack. It can be determined by using the time difference between each sensor and the source. It is also possible to make some predictions about the fracture by using AE parameters as shown in Fig. 1. Here, "amplitude" is the maximum voltage on an AE waveform and it is a significant parameter with regard to constitution of the perceptibility of AE activity. AE amplitude is directly related to magnitude of an event. During the test, a definite amplitude value is specified in order to pick ambient noise. This parameter is defined as "threshold". The number of pulse passing the threshold is "count". "Rise time" is an elapsed time between first and last counts passing the threshold. The area under the rectified signal envelope is named as "MARSE (Measured Area under the Rectified Signal Envelope)", which is the energy.

## 3. Principal component analysis (PCA)

Principal component analysis (PCA) is an approach to discern the patterns in data. Through that, the similarities and differences in