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Interfacial crack-induced debonding identification in FRP-strengthened RC beams from PZT signatures using hierarchical clustering analysis

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A B S T R A C T

The Electromechanical Impedance Method (EMI), based on the use of piezoelectric ceramic patches (PZT) constitutes one of the most promising methods for damage detection and location in the Structural Health Monitoring (SHM) field, more particularly for monitoring structures reinforced with novel FRP strengthening techniques. Many efforts have been made to obtain robust and reliable procedures that lead to a successful damage identification of experimental structures in general, but reliable data analysis and rational data interpretation are still challenges to be overcome in the case of debonding detection in strengthened structures, an approach being necessary that allows direct assessment of these experimental structures without the use of numerical models to compare with. In that way, clustering methods are a useful tool since they provide a classification of the data, based on some kind of similarity after a direct comparison between experimental results. With that purpose, in this study an innovative hierarchical clustering analysis has been proposed in order not only to obtain a set of clusters based on damage patterns found in experimental data obtained with PZT sensors, but also to achieve a graphical representation of this information so that the damage identification can be done qualitatively and quantitatively in an intuitive manner. The performance of the proposed approach has been investigated using three experimental tests including a full-scale reinforced concrete beam strengthened with FRP strip.

1. Introduction

Aerospace, civil and mechanical infrastructures are continuously subjected to both static and dynamic loads, frequently in severe environments, which can lead to the gradual deterioration of the structure. For that reason, developing reliable Structural Health Monitoring (SHM) technologies has become a very attractive area and an important challenge for these kinds of structures, together with the development of repairing techniques based on the use of Fiber Reinforced Polymers (FRP) composites for strengthening applications of reinforced concrete (RC) structures [1–3]. SHM technologies and methods consist in implementing different strategies in order to achieve the evaluation, quantification and, if possible, location of any damage in the structure [4]. This goal is achieved by means of measuring input and output responses of a structure both before and after damage, trying to establish a relationship between the modification of the expected responses and the appearance of the different damages in operational conditions. In this sense, although a lot of research has been put into the use of FRP composites for repairing and strengthening structures in service, few efforts have been made so far in order to efficiently predict the failure of these complex structural systems, usually by some form of debonding in the interface between the FRP and the concrete. Many different SHM methods have been proposed in the literature for all kinds of structures, based on either a global or a local monitoring of structures [5]. Usually, techniques based on the global dynamic response of the structure are applied [6–10]. However, these techniques are based on the lowest modes of vibration and are not appropriate for local structural monitoring, particularly for the early detection of debonding failures in strengthened structures.

Different non-destructive evaluation methods are commonly used as local methods. In Ref. [11], a classification into four main groups has been carried out according to the main physical

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phenomenon on which these methods are based: a) techniques based on mechanical waves (tap test [12], acoustic emission monitoring [13], pulse-echo ultrasonic [14] and the impact-echo method [15]); b) techniques based on electromagnetic field (crack detection using alternating current field measurement [16]); c) techniques based on radiography (X-ray and gamma ray are typically used as the radiation source [17]); d) techniques based on optics and fibre optics (these techniques have been used in order to obtain experimental measurements by many authors [18,19].

However, all these methods share several drawbacks, as pointed out by Bhalla et al. [5], which makes them inadequate for the health monitoring of all kinds of large infrastructures (civil structures among them). Most of these problems are related to the necessity of large transducers and expensive operational hardware, all together with the complexity of the analysis to be carried out of the measurement data provided by the system.

Nowadays, one very promising active non-destructive evaluation method for local damage identification is impedance-based structural health monitoring (SHM) using piezoelectric ceramic (PZT) sensor-actuators [1]. These materials develop an electric response over their surfaces when a certain mechanical stress is directly applied on them, according to the direct piezoelectric effect; but they are also capable of developing the reverse phenomenon, producing mechanical stresses when an electric field crosses through the piezoelectric material, according to the inverse piezoelectric effect [5]. This capability enables the material to be used both as a sensor and as an actuator simultaneously [20]. The electrical impedance of the PZT can be directly related to the mechanical impedance of the host structural component where the PZT transducers are attached. Since the structural mechanical impedance will be affected by the presence of structural damage, any change in the electrical impedance spectra might be an indication of a change in structural integrity (Electro-Mechanical Impedance (EMI) method). This technique was firstly developed by Liang et al. [21], and subsequently has been used in numerous applications [5,22–27]. Ayres et al. [28] demonstrated not only the ability of this technique to detect damage within a bridge joint, but also that it is suitable for large civil infrastructures. Considerable research activity has been thus put on this smart monitoring technology, but little of it has been actually applied to monitor retrofitted structural systems. For that reason, the global goal of this paper has been centered on detecting early debonding symptoms in strengthened structures through a PZT sensors network.

The SHM process basically involves the observation of a structure over time using measurements obtained from an array of sensors so that the structural features can be extracted accordingly. One of the advantages of the EMI method is that it can be implemented for continuous and on-line monitoring. The presence of damage can be known by evaluating the impedance measured over time. However, the large amount of information captured by PZT sensors during the continuous monitoring makes a comprehensive analysis of the entire repertoire of data difficult. Reliable data analysis and rational data interpretation are challenging problems for engineers. The availability of an approach able to analyse and focus the main features of the entire set of observations would be desirable in order to implement a robust and reliable procedure of damage identification based on a series of experimental measurements. Clustering methods allow grouping data based on some kind of similarity. For any series of measurements, the application of sensible measures of similarity among them would make it possible to group or cluster those data with similar patterns and, therefore, detect and locate the appearance of damage. Furthermore, if the clustered data are displayed graphically by using colours that give a qualitative and quantitative information of each data point, the whole set of experimental data might be explored in a fast and natural intuitive manner. To achieve this purpose, hierarchical clustering analysis has been used in this work in order to develop a two-dimensional classification of the information obtained from the impedance measurements [29–31]. Clustering analysis will organize the experimental impedance measurements obtained over time for different PZT sensors according to the similarity or dissimilarity of their profiles, placing the cases with similar patterns in neighbouring rows and columns of a clustergram.

Although this method has been used successfully in a wide range of applications, especially in areas such as medicine, biology and chemistry [29–34], it has never been used in an application as that proposed in this paper, at least to the knowledge of the authors, and we believe it constitutes a very promising tool for the implementation of a systematic methodology for identifying damage based on EMI. In this work, an unsupervised clustering technique has been proposed considering that we do not have a priori knowledge of the expected data patterns for any health condition.

After a brief introduction of the EMI method, the theory behind the proposed approach is firstly presented and then a series of laboratory applications are carried out to validate the feasibility of the technique, firstly through crack damages detection in an aluminium beam, and then loose bolts on a bolt-jointed aluminium beam, which supposes a first approach to simulate debonding between two bodies under controlled conditions. Finally, the conclusions of the controlled experiments are used for crack and minor debonding detection in an FRP (Fibre Reinforced Polymer)-strengthened reinforced concrete (RC) beam experimentally tested.

2. Electromechanical impedance method

In recent years, lead-zirconate-titanate (PZT) materials have been widely applied to structural health monitoring by means of the electromechanical impedance method due to their lightweight and variety of shapes and sizes [20,23,35,36]. Another advantage is that the electrical impedance is measured at high frequencies so that the wavelength of the excited motion is small and sensitive enough to detect local damage. A PZT patch can be used as both an actuator and a sensor, simultaneously. A mechanical strain on a PZT material produces an electrical charge and vice-versa according to the following constitutive equations [20]:

$$S_{ij} = s^E_{ijkl} T_{kl} + d_{kij} E_k \tag{1}$$

$$D_i = d_{jkl} T_{kl} + \varepsilon^T_{jk} E_k \tag{2}$$

where S_{ij} is the mechanical strain tensor, D_i is the electrical displacement, s^E_{ijkl} is the mechanical compliance of the material measured with no electric field ($E = 0$), ε^T_{jk} is the dielectric permittivity measured with no mechanical stress ($T = 0$), and d_{jkl} represents the piezoelectric coupling effect.

The basic idea of the impedance-based structural health monitoring approach is that the presence of damage in the host structure will affect its mechanical impedance, and thus the electromechanical impedance of the PZT patch, which can be directly measured by an electrical impedance analyzer. The coupled relationship between electrical and mechanical impedance was first introduced by Liang et al. [21] as follows:

$$Y(\omega) = \frac{I_0}{V_i} = G(\omega) + jB(\omega) = \bar{\varepsilon}^T_{33} - \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} d^2_{3x} \hat{Y}^E_{xx} \tag{3}$$

where $Y(\omega)$ is the electrical admittance (inverse of impedance), V_i is the input voltage to the PZT actuator; I_0 the output current from the