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MONITORING THE CURING PROCESS OF STRUCTURAL ADHESIVES USING THE ELECTROMECHANICAL IMPEDANCE TECHNIQUE: A NUMERICAL INVESTIGATION

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ABSTRACT

Structural adhesives act as a bonding agent to externally bond fibre-reinforced polymer (FRP) composites onto existing structures for strengthening purposes. The performance of FRP-strengthened systems are therefore affected by the strength and stiffness of the structural adhesive layer. The lead zirconate titanate (PZT)-based electromechanical impedance (EMI) technique was employed in this study to monitor the stiffness development process of structural adhesives. A finite element model was developed to investigate the interaction between the PZT patches and the structural adhesive throughout the curing process. The dynamic elastic modulus of the structural adhesives can be predicted from the simulated EMI signatures. The EMI signatures were compared with experimental results for verification purposes. An empirical equation was established to predict the elastic modulus of structural adhesives from the resonance frequency. The current study can be extended by developing a model that predicts the tensile strength of structural adhesives at different curing durations.

KEYWORDS

Adhesives, curing, elastic modulus, electromechanical impedance (EMI) technique.

INTRODUCTION

Fibre-reinforced polymer (FRP) composites are commonly bonded onto existing concrete structures for strengthening purposes using structural adhesives (Teng et al. 2002). It is critical that the adhesive layer is structurally sound to ensure that the FRP-concrete system can perform to its intended design purpose. Since time is one of the most valuable commodities in the construction industry, being able to load structures once they are fit for purpose is ideal as it will reduce construction times. Being able to monitor the strength gain in adhesives will allow engineers to know precisely when structural members can bear their design loads, ultimately reducing construction times and improving safety. For this reason, a non-destructive monitoring technique is required to determine the strength development of structural adhesives throughout their curing process. Monitoring techniques such as the ultrasonic technique, piezoelectric-based techniques, and the fibre-optic-based technique have previously been used for determining the strength of structural adhesives. Two piezoelectric-based monitoring techniques, namely the electromechanical impedance (EMI) and wave propagation (WP) techniques, have recently been used to non-destructively monitor the curing process of structural adhesives in real-time (Lim et al. 2019). Lead zirconate titanate (PZT) patches can either be surface-bonded onto, or embedded into, structural adhesives to monitor their curing. The EMI technique requires only one PZT patch that acts as both an actuator and a sensor, whereas the WP technique utilises two PZT patches, with one patch acting as an actuator and the other as a sensor (Lim et al. 2018). Both the EMI and WP techniques are able to qualitatively monitor the curing process of structural adhesives by correlating the acquired signatures to the strength of the adhesive (Lim et al. 2019; Tang et al. 2019).

In this study, the EMI technique is utilised for monitoring the curing process of structural adhesives. To date, there is no known finite element modelling study that investigates the interaction between the PZT patch and the structural adhesive. The objective of this study is to patch this knowledge gap. In this study, modelling of the PZT-adhesive system is presented and the simulated EMI signatures are compared with their experimental counterparts.

RESEARCH METHODOLOGY

Sample Preparation

In this study, the structural adhesive Sikadur 330 was selected for monitoring. A rectangular prism sample with dimensions of 15 mm × 160 mm × 15 mm was manually prepared in accordance with the recommendations by the manufacturer. The curing process was considered to have started upon mixing of the hardener and the resin. The rectangular prism was stored in a laboratory and was left to cure for 7 days under a constant temperature of 20°C and a humidity of 70-75%. The EMI signatures were recorded throughout the curing process. More details on this process can be found in Lim et al. (2019).

Finite Element Modelling

In this finite element (FE) modelling study, the FE software package ANSYS 19.1 was used. The FE modelling process to simulate EMI signatures consisted of three steps, namely pre-processing, solution, and post-processing (Gresil et al. 2012). For pre-processing, a three-dimensional (3D) coupled-field PZT-adhesive system was developed (Lim and Soh 2014). The geometrical properties, element types, and material properties were defined. Due to the symmetrical geometric and loading conditions of the specimen in this study, half of the PZT-adhesive system was modelled to reduce the computational demand. The 3D structural solid element, SOLID 45, was used to model the adhesive prism, whereas the 3D coupled-field element, SOLID 5, was employed to model the PZT patch. A uniform mesh size of 1 mm was used on the two materials. The PZT patch was modelled as though it was surfaced-bonded on the adhesive prism, and all the nodes at the interface between PZT patch and the adhesive were merged to connect the two materials. This process was followed by coupling the voltage degree of freedom of both the top and the bottom surfaces of the PZT patch. The coupled nodes were then directed to one of the nodes at the corner of the specimen. Figure 1 shows the pre-processing step.

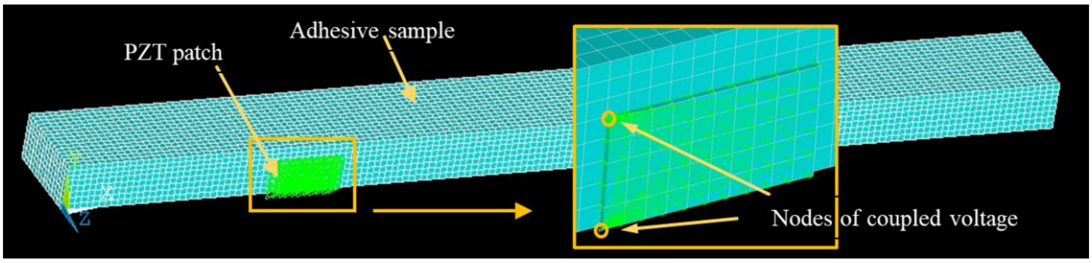

Figure 1. Pre-processing for an adhesive prism with a surface-bonded PZT using ANSYS 19.1.

In the solution step, the coupled node at the corner of the top surface had a sinusoidal voltage applied, whereas no voltage was applied for the node at the bottom. Harmonic analysis was selected for this step. Since only half of the PZT-adhesive was modelled, all the nodes at the symmetrical plane, i.e. x-y plane, were spatially restrained in the y-direction to prevent movement. The node at the centre of the x-y plane was spatially restrained in the x-, y- and z-directions to ensure stability of the system. For the post-processing step, the EMI signatures were acquired and recorded from the coupled node that was applied the voltage. This is due to the vibrational forces of the PZT patch with applied voltage.

RESULTS AND DISCUSSION

The developed FE model was verified by comparing the simulated EMI signatures with the experimental EMI signatures, as shown in Figure 2. The adhesive had cured for 24 hours when the readings in this figure were taken, and the dynamic elastic modulus of the adhesive was calculated as 5.0 GPa. The simulated EMI signatures match closely with the experiment in terms of resonance peaks, slope, and magnitude within the frequency range of 21-35 kHz. The simulated outcome shows that the developed FE model can represent the PZT-adhesive system with a high level of accuracy. Minor variations between the signature acquired from the experiment and the FE model can be explained by geometrical imperfections (Tang et al. 2019).

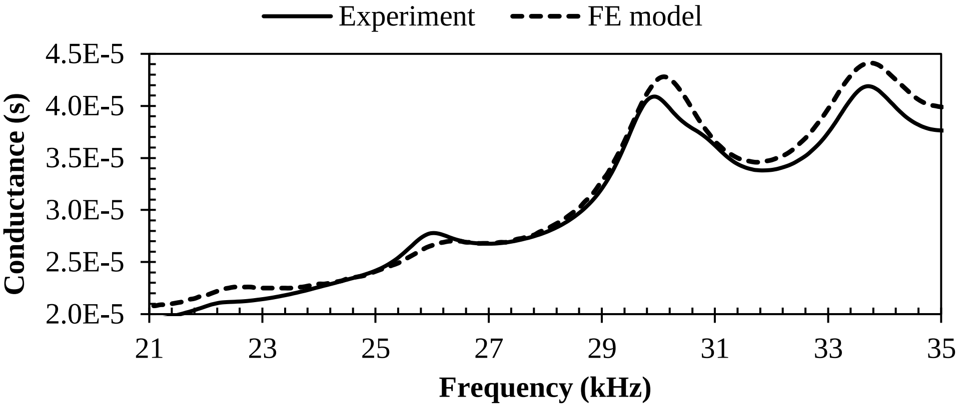

Figure 2. Comparison of the EMI signatures between the experiment and FE model at 24 hours.

Resonance peaks for curing durations of up to 7 days are illustrated in Figure 3. It can be observed that the elastic modulus of the structural adhesive increases as the curing duration increases. Rapid rightward movement of the resonance peaks in the first 24 hours shows that the structural adhesive undergoes rigorous curing. More details on this process can be found in Lim et al. (2019). The elastic modulus was recorded to have increased from 3.60 GPa to 5.00 GPa from the 9-hour duration to the 24-hour duration. Both the resonance frequency and elastic modulus increased at a slower rate from 1 to 7 days of curing.

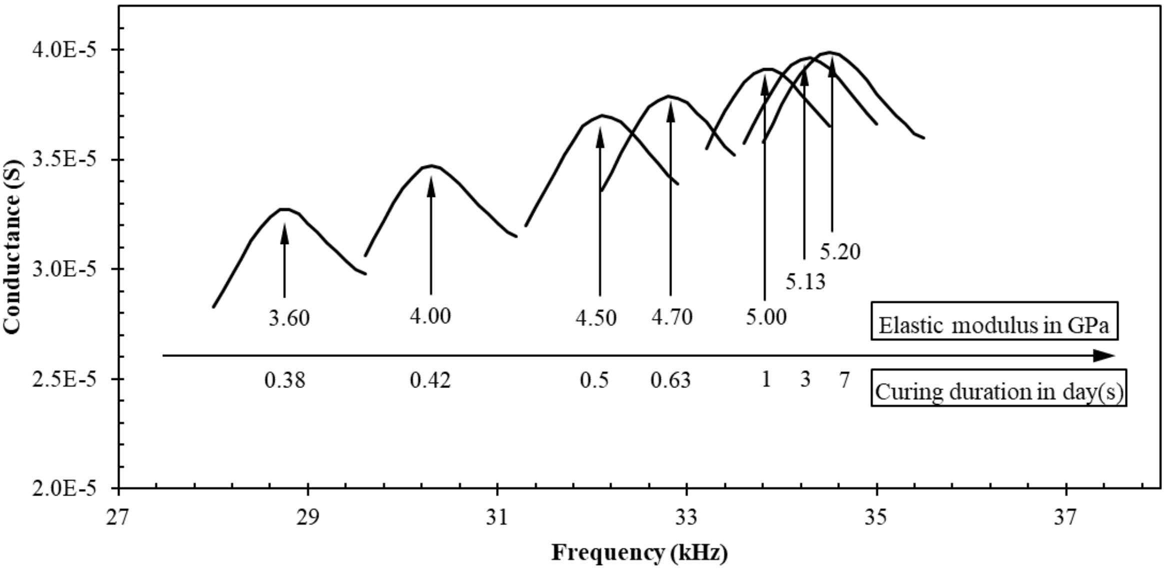

Figure 3. Rightward movement of frequency peaks for a 7-day curing duration, indicating an increase in dynamic elastic modulus

Based on the results in this study, the resonance frequency can be correlated to the elastic modulus of the structural adhesive. The two parameters have a linear relationship, as illustrated in Figure 4. A reliable empirical equation, i.e. Equation (1), was established to predict the elastic modulus of the structural adhesive based on the resonance frequency.

$$E = 0.281f - 4.508 \tag{1}$$

where E is the elastic modulus of structural adhesive (GPa) and f is the resonance frequency (kHz).

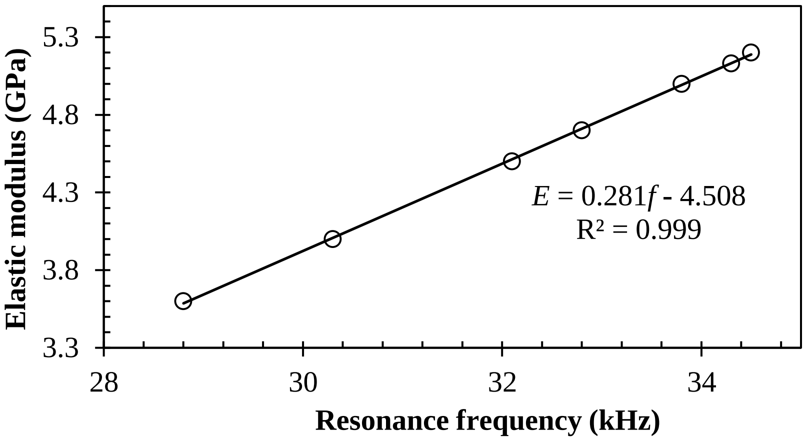

Figure 4. The relationships between elastic modulus of structural adhesives and simulated resonance frequency.

CONCLUSIONS

This paper reported the development of an FE model for monitoring the curing process of structural adhesives using the EMI technique. The FE model was compared and verified with experimental results. In addition, the rightward movement of the resonance frequency peaks shows a good representation of the curing process of the structural adhesive. An empirical equation was developed that accurately predicts the elastic modulus of the structural adhesive from the resonance frequency. This study can be extended to other structural adhesives, as well as adhesives under different curing conditions. Additionally, the current study can be extended by developing a model that predicts the tensile strength of structural adhesives at different curing durations.

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