Abstract

In this study lead zirconate titanate (PZT) transducers are employed for damage detection of six reinforced concrete elements (four beams and two columns) retrofitted with carbon fiber reinforced polymer (CFRP) jackets. The PZT transducers were placed externally on the CFRP jackets in an effort to detect the damage underneath the jackets. Measurements of the voltage across the PZT transducers were obtained at various strain values during the experimental procedure. The transducers were placed in positions where the failure of the CFRP jackets was expected to be more intense. The variation of the voltage as the strain increases is the indication of damage. The damage index employed for the quantification of the damage is the root-mean-square-deviation (RMSD) index. The experimental results lead to the conclusion that the measurement system employed in combination with the PZT transducers provide safe evidence that damage detection can be achieved at an early stage.

Keywords: damage detection; FRP jackets; PZT transducers; reinforced concrete; wireless system.

1. Introduction

Recently, a growing interest in retrofitting of existing structures has developed due to their deterioration as a result of ageing but also in order to meet the demands of the contemporary codes. Nowadays one common method for retrofitting of old structures is the application of composite materials and mainly fiber reinforced polymers (FRPs). Although FRPs have been applied in many structures, their application does not provide the ability to detect damage (typically in the form of debonding) underneath. Continuous structural health monitoring of structures retrofitted with FRP is the only way to detect the damage at an early stage by using the appropriate measurement system. One of the most known monitoring techniques is the electromechanical impedance (EMI) or its inverse electromechanical admittance approach (EMA). Recently a new structural health monitoring system was developed by [1]. This system in combination with PZT transducers provides wireless measurements of the voltage across the PZT transducers. Limited research exists combining the damage detection of RC elements retrofitted with FRP sheets, laminates, or jackets, with a wireless measurement system but on small scale specimens. In this study PZT transducers are externally placed on RC beams and columns retrofitted with carbon fiber reinforced polymer (CFRP) sheets or laminates. Each transducer acts both as an actuator and as a sensor. The aim of this research was to detect the debonding of the CFRP sheets or laminates for the case of the beam specimens and also the damage of the RC substrate in the case of column specimens, at an early stage. Measurements of the voltage developed on the transducers for a range of frequencies were obtained. The variation of the voltage as the damage was propagating was
the indication of the damage. The damage was quantified by the use of a simple statistical index, the root-mean-square-deviation (RMSD) index.

2. Electromechanical impedance (EMI) method

The system denoted as WiAMS (Wireless Admittance Measurement System) was used in order to obtain the voltage measurements. The PZT transducers were connected to the system as shown in Figure 1.

![Figure 1. WiAMS](image)

According to the EMI approach a PZT transducer is employed to excite the structure with a high frequency excitation and monitor the changes in the electrical impedance of the transducer. If a PZT transducer placed on a structure is excited with a sinusoidal voltage the area near the PZT (influence radius) will start to vibrate (converse piezoelectric effect). The structure will respond to the vibration by producing electric current on the PZT due to the inverse piezoelectric effect.

The output data of this procedure are the spectra of the voltage versus frequency for a range of frequencies from 160 – 250 kHz. The specific range of frequencies is the appropriate range for reinforced concrete structures as the Voltage – Frequency spectra exhibit peak values of the Voltage at frequency values of 185-195 KHz (1st resonant frequency) and 235-245 KHz (2nd resonant frequency). The resonant frequency is the frequency at which the ceramic element vibrates most readily, and most efficiently converts the electrical energy input into mechanical energy. The WiAMS has a control unit based on a Raspberry pi single board computer which can transfer data without a base station, perform processing-hungry operations and most important to connect to the internet via WiFi. The last feature is very important as it provides the ability to obtain measurements simply by adding the device to the home network and perform structural health monitoring.

In the experimental procedure the output data were uploaded on a database and then downloaded through MySQL (an add-in for Excel). The ability to control the system remotely was achieved by using the free open source application PUTTY. A more detailed description of the system and the EMI method applied in this experimental research is provided as mentioned above by [1].
3. Experimental Procedure

All six reinforced concrete specimens (four beams and two columns) retrofitted with CFRP were subjected to monotonic loading. The beam specimens were subjected to four point bending while the column specimens to uniaxial compression. In this paper the experimental procedure and results of only one specimen (Beam 4) will be presented. More information can be found in [2] concerning the rest of the specimens. Beam 4 was strengthened in flexure with CFRP laminates in the tension zone, tested with the WiAMS. The geometry of the specimen is presented in figure 2 (dimensions in mm).

The average compressive strength of the concrete was 26.76 MPa. The longitudinal and transverse reinforcement had a yield stress of 545 MPa and tensile strength of 600 MPa. The CFRP laminates applied on the beam had a mean tensile strength and modulus of elasticity equal to 3100 MPa and 165 GPa, respectively. The width of each laminate was 50 mm and the thickness was 1.4 mm. Two laminates were applied one next to the other. The length of application was 900 mm. The epoxy resin used was a two-component epoxy matrix with tensile strength equal to 72.4 MPa and tensile modulus 3.18 GPa respectively. Figure 3 shows the arrangement of the transducers on the beam and the failure of the beam. Debonding occurred at the right edge (as seen it can be seen in figure 3) of the laminates as it was expected. The vertical FRP strip at the left edge of the laminates was placed in order to make sure that debonding will occur at the other edge.

The PZTs were placed at the edge of the laminates where the debonding was more intense. The main properties of the PZTs are presented in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7.80 (g/cm$^3$)</td>
</tr>
<tr>
<td>Electric Permittivity $\varepsilon_{33}/\varepsilon_0$</td>
<td>1750</td>
</tr>
<tr>
<td>Piezoelectric Strain Coefficient $d_{31}$</td>
<td>$-180 \times 10^{-12}$ C/N</td>
</tr>
<tr>
<td>Elastic Compliance Coefficients $S_{11}$</td>
<td>$16.1 \times 10^{-12}$ m$^2$/N</td>
</tr>
<tr>
<td>$S_{33}$</td>
<td>$20.7 \times 10^{-12}$ m$^2$/N</td>
</tr>
<tr>
<td>Dielectric loss factor $\tan\delta (10^{-3})$</td>
<td>20</td>
</tr>
</tbody>
</table>
4. Experimental Results and Discussion

As already mentioned, the output data of the measurements obtained with the WiAMS were the spectra of the voltage versus frequency for various displacement or strain values. A representative graph of voltage – frequency is illustrated in figure 4(a). In figure 4(b) the Load-displacement curve of the beam is presented.

\[
\text{RMSD} = \left( \frac{100}{\sqrt{\frac{\sum_{k=0}^{n} [V_0(\omega_k) - V_i(\omega_k)]^2}{\sum_{k=0}^{n} [V_0(\omega_k)]^2}}} \right) \times 100 \quad (\%) \quad (1)
\]

Figure 4. (a) Indicative Voltage – Frequency graph, (b) Load – Displacement graph

The quantification of the damage is achieved by employing the RMSD index, defined by the following equation:

where \( n \) is the number of frequency points, \( V_0(\omega_k) \) is the initial measurement of the voltage of the \( kth \) frequency point (undamaged condition) and \( V_i(\omega_k) \) is the measurement of the voltage at the \( ith \) displacement value of the \( kth \) frequency point.

The RM SD index in relation to the displacement or strain value during the test is an easy and understandable way for quantifying the damage. The increase of the RM SD index indicates that the damage also increases with the increase of the applied displacement on the specimens. All six experiments were displacement – controlled. As the displacement increased the experiment was paused at various displacement values in order to obtain the voltage measurements.

As it can be seen in Figure 5 the transducers PZT2 and PZT3 were placed at the edge of each laminate. PZT1 was placed on the same laminate with PZT2 at a distance of 100 mm. The RMSD index for PZT2 has an increased value since the beginning of the experiment. This fact suggests that the specific area where PZT2 was placed was debonded since the beginning. PZT1 placed at a distance of 100 mm from PZT2 exhibits a different behavior with a smooth variation of its values until it reaches a maximum value at the end of the experimental procedure. The variation of the RMSD index for PZT3 is similar to the one of PZT1 but with one order of magnitude higher almost since the beginning (for low displacement values). This
is possibly due to the fact that PZT1 was placed in an area where debonding occurred later for the other transducers. Hence the debonding was more gradual, leading to a higher variation of the RM SD index.

Figure 5. RM SD index and final image of the area close to the PZTs after the experiment

5. Conclusions

According to the experimental results the following conclusions can be drawn.
• When the PZT transducers are placed close to the area where the failure occurs the damage can be detected at an early stage.
• The variation of RM SD increases with the load. The specific measurement system is quite sensitive to damage detection at an early stage and much more sensitive than the one used in the previous study by [3].

Although the results of the research presented are highly promising, more experimental work should be carried out in the specific research field.

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References

