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Damage assessment in concrete structures using piezoelectric based sensors

A. Narayanan[1], K. V. L. Subramaniam*[1]
*Contact Author: kvls@iith.ac.in
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ABSTRACT

Piezoelectric based PZT (Lead Zirconate Titanate) smart sensors offer significant potential for continuously monitoring the development and progression of internal damage in concrete structures. Changes in the resonant behavior in the measured electrical conductance obtained from electro-mechanical (EM) response of a PZT bonded to a concrete substrate is investigated for increasing levels of damage. Changes in the conductance resonant signature from EM conductance measurements are detected before visible signs of cracking. The root mean square deviation of the conductance signature at resonant peaks is shown to accurately reflect the level of damage in the substrate. The findings presented here provide a basis for developing a sensing methodology using PZT patches for continuous monitoring of concrete structures.

Keywords: PZT; electro-mechanical impedance; conductance; microcracks.

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[1] Department of Civil Engineering, Indian Institute of Technology Hyderabad, INDIA.

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Evaluación de daños en estructuras de concreto utilizando sensores piezoeléctricos

RESUMEN

Los sensores inteligentes PZT (Lead Zirconate Titanate) basados en piezoeléctricos ofrecen un potencial significativo para monitorear continuamente el desarrollo y la progresión de los daños internos en estructuras de concreto. Se investigan los cambios en el comportamiento resonante a través de la conductancia eléctrica medida, obtenida a partir de la respuesta electromecánica (EM) de un PZT unido a un sustrato de concreto para aumentar los niveles de daño. Los cambios en la resonancia de la conductancia EM se detectan antes de que aparezcan signos visibles de agrietamiento. La desviación cuadrática media de la raíz de la conductancia en los picos resonantes refleja con precisión el nivel de daño en el sustrato. Los hallazgos presentados aquí proporcionan una base para desarrollar una metodología de detección utilizando parches PZT para el monitoreo continuo de estructuras de concreto.

Palabras clave: PZT; impedancia electromecánica; conductancia; microfisuras.

Avaliação de danos em estruturas de concreto usando sensores piezoelétricos

RESUMO

Os sensores piezoelétricos inteligentes PZT (Lead Zirconate Titanate) oferecem um potencial significativo para o monitoramento contínuo do desenvolvimento e progressão de danos internos em estruturas de concreto. As alterações de ressonância através da medida da condutância elétrica obtida a partir da resposta eletromecânica (EM) de um PZT ligado a um substrato de concreto é investigada para níveis crescentes de danos.

As alterações no perfil de ressonância de condutância EM são detectadas antes de sinais visíveis de fissuras. O desvio quadrático médio da raiz do perfil de condutância nos picos ressonantes é mostrado para refletir com precisão o nível de dano no substrato. Os resultados aqui apresentados fornecem uma base para o desenvolvimento de uma metodologia de detecção usando PZT para monitoramento contínuo de estruturas de concreto

Palavras chave: PZT; impedância eletromecânica; condutância; microfissuras.

1. INTRODUCTION

Structural Health Monitoring (SHM) is a process of assessing the structural integrity of the constituent parts and the level of damage in the structure during its life period. SHM relies on non-destructive evaluation (NDE) procedures and continuous monitoring of structural parameters to determine the intensity and location of the damage. This involves sensors, data acquisition system and signal processing tools. Signs of distress in concrete are often associated with visible cracking. Since concrete is a brittle material, which is weak in tension, cracking is the manifestation of damage in the material which results from tensile stress in the material. Stress induced damage in concrete could result from load application or from internal sources such as shrinkage or corrosion of reinforcing steel. Damage initiation takes place in the form of distributed microcracks, which eventually localize to form cracks. Often the damage, particularly in the incipient stages is not directly visible and by the time signs of distress appear on the surface of the structure, significant damage would have accrued in the structure and there may be significant degradation of the capacity of the structure. Early detection of damage, before visible signs appear on the surface of the structure is essential to initiate early intervention, which can effectively increase the service life of structures. Methods to detect incipient damage in the form of microcracks are required to provide effective methods of monitoring structural health and service life performance of structures.

Use of PZT patches and wafers has become popular in structural health monitoring. Due to the coupled electro-mechanical constitutive response of a PZT material, the mechanical response of a bonded PZT patch subjected to an applied electrical potential is influenced by the elastic restraint provided by the substrate material. Coupling the PST patch to a structure changes the mechanical impedance of the PZT, which produces changes in its vibration characteristics. Monitoring changes in the electrical impedance signature due to changes in the effective mechanical impedance of the substrate is the basis for electromechanical (EM) impedance-based measurements. Information about the surrounding material is contained in the electromechanical impedance (EMI) signature of a PZT. By comparing the impedance signature taken in the pristine state and at any other time, structural damage can be determined. Generally, both frequency and amplitude shifts are produced relative to the pristine state (without damage) (Ayres et al., 1998; Chaudhry et al., 1995; Sun et al., 1995; Park et al., 2000; Zagrai and Giurgiutiu, 2001; Giurgiutiu et al., 2002, 2004; Peairs et al., 2004; Narayanan and Subramaniam, 2016a).

Application of EMI technique for damage detection in concrete structures requires a careful study of the changing compliance of the substrate for different forms of damage in the substrate material from the incipient to the visible stages. The use of PZTs for health monitoring of concrete structure was demonstrated by the ability of EMI technique to register changes due to formation of cracks well in advance of failure (Park et al., 2000; Narayanan and Subramaniam, 2016b). Several other studies of damage in concrete using impedance-based measurements of PZTs have been conducted using embedded defects and artificial damage in the form of machine cuts (Tseng and Wang, 2004; Lim et al., 2006; Dongyu et al.,2010; Wang et al., 2013). The EM impedance method has also been used to determine the location of a crack by inducing crack at different positions and depths and cross correlation as damage index (Wang et al., 2013). While the use of artificial damage provides meaningful insight, it is not representative of substrate compliance with stress/load induced damage in the material.

The potential use of EMI based measurements of surface mounted PZT to identify the formation of incipient damage in concrete structures, is evaluated in the paper. The relationships between forms of material damage, visual indication of damage, mechanical compliance of the material and resonant modes in the conductance signature of PZT bonded to a concrete substrate are investigated. The variation in surface strains for incremental levels of loading is monitored using Digital Image Correlation (DIC) and compared with the conductance plot of the PZT. Root mean square deviation (RMSD) of the EM conductance close to the resonant peak is used as a damage index and variation in RMSD at different damage states is presented.

2. EXPERIMENTAL PROGRAM

Experiments were performed using 150 mm concrete cubes. Six cubes were cast and cured for 90 days before testing. The cubes were bonded with PZT patches exactly at the center of the side face of the cube using a two-component epoxy. The properties of the concrete and epoxy are given in Table 1. Three cubes were tested to failure to determine the compressive strength of the concrete.

Table 1. Material properties

Type	**Average Failure stress (*MPa*)**	**Young's Modulus (*GPa*)**	**Density (ρ) (kg/m^3)**	**Poison's ratio(υ)**
Concrete cube	52	36	2300	0.2
Epoxy	-	2	1400	0.36

The front faces of the cubes were smoothened and a sprayed-on speckle pattern was created for measurement of surface displacements using the full-field optical technique known as digital image correlation (shown in Figure 1a). The baseline signatures of the PZT when attached to the substrate were taken. 20mm x 20mm PZT patches of 1 mm in thickness were used in the experimental study. In a typical impedance measurement, the frequency was varied between 1 kHz and 0.5 MHz at an applied voltage of 1V and data was collected at 800 discrete frequencies. Average of five measurements was collected. Impedance data was collected from the PZT patch in the free-state before attaching the PZT to the concrete cube. The baseline EM conductance signature and image were taken prior to the start of loading. Cubes were subjected to cyclic compressive loading of increasing magnitude where the load amplitude was increased in increments of 10% of the average compressive strength in every cycle. The loading procedure consisted of alternate loading and unloading cycles as shown in Figure 1b. During the loading, the conductance signatures and the image for DIC were recorded on top of the load cycle and after unloading.

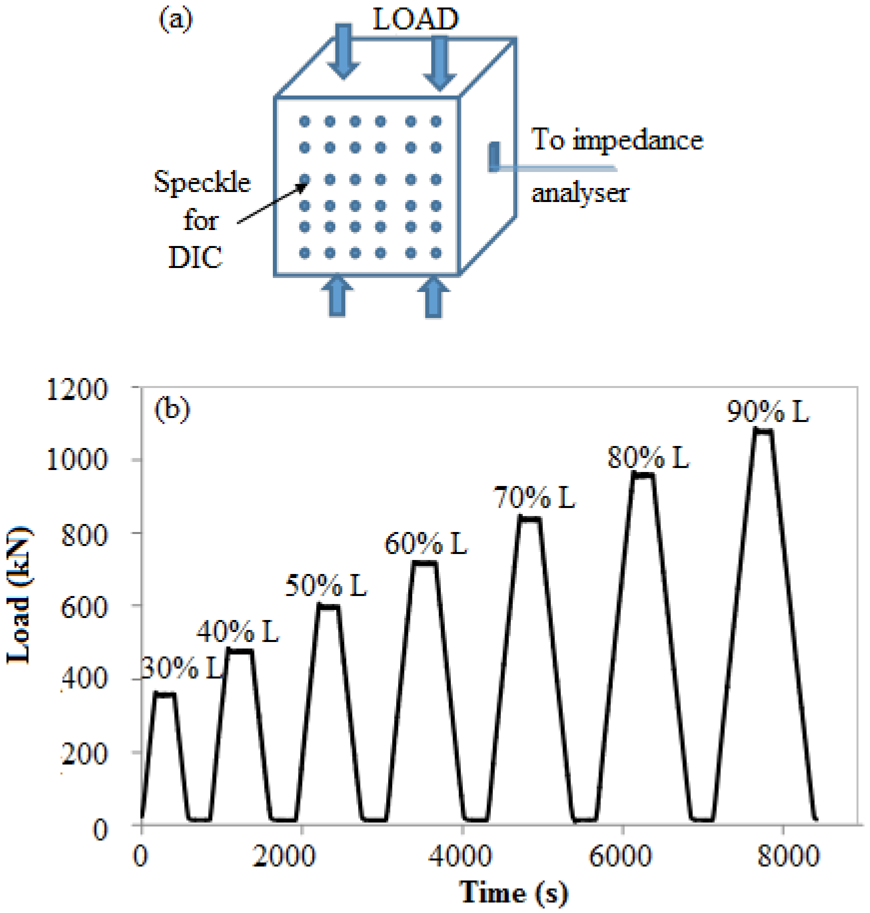


Figure 1. (a). Experimental set-up (b). Applied loading history

3. ELECTRO-MECHANICAL IMPEDANCE OF PZT

In a PZT material, the application of an electrical field results in mechanical strain in the material due to the coupled electro-mechanical constitutive relations. For a PZT patch attached to a substrate subjected to an applied electrical input, the motion of the interface subjected to continuity conditions is governed by the combined mechanical impedance of the structure and the PZT. The constrained motion in turn produces a change in the measured electrical impedance. The first systematic attempt to derive the electrical impedance of the PZT which is mechanically connected to a structure using a 1D idealization of the system was developed by Liang et al., 1994. Subsequent improvements in modelling the PZT response have included the effective 1-D model of the PZT and varying levels of idealization of the structural impedance (Bhalla et al., 2004; Xu and Liu, 2002; Yang et al., 2005,2008). Most of the available analytical solutions are applicable for 1 or 2-D idealizations of the PZT, substrate or both. Typically, the complex electrical admittance ($\bar{Y}$) of the PZT patch for a given electrical input at a frequency can be represented as a function of $\bar{Y}(Z_A, Z_S, \omega, l_i, E)$.where Z_A And Z_S are the mechanical impedance of the PZT and substrate respectively. l_i, represent the dimensions of patch (length, breadth or thickness) and E is the electric field applied for actuation with circular frequency ω .

The conductance, which is the real part of admittance of the free PZT and the PZT bonded to the 150 mm concrete cube are shown in Figure 2. It can be seen that resonance peaks associated with the free vibration of the PZT can also be identified in the response of the PZT attached to the concrete cube. Only three prominent peaks are identified in the conductance spectrum of the bonded PZT. Peaks 1 and 2 in the conductance spectrum of the bonded PZT correspond with modes 1 and 3 respectively of the PZT. The third peak in the conductance response of the bonded PZT has contributions from closely spaced modes 5 and 6 of the PZT. There are several prominent changes associated with the frequency of the resonant modes and the relative magnitude of the resonant peaks. There is a noticeable decrease in values of conductance, an increasing baseline trend which increases the magnitude of conductance with increasing frequency and a change in the relative magnitudes of the resonant peaks in the bonded state. There is also a significant broadening of the resonance peaks compared with the free-state.

The resonance peaks shift to higher frequencies, with a larger frequency shift in lower modes. The resistance to the motion of the PZT by the substrate is reflected in the overall decrease in the value of conductance. While the conductance of the free PZT is essentially zero between resonant peaks, the conductance is non-zero between the resonant peaks for the bonded PZT. The resistance to the motion of a point located on the surface of the cube, given by the driving point impedance, influences the motion of the bonded PZT. The frequency dependency of the substrate driving point impedance is reflected in the relative shifts in the amplitudes and the general increasing trend in the background of the measured conductance. The influence of the substrate can also be identified with the overall increase in the frequency and broadening of the resonant peaks.

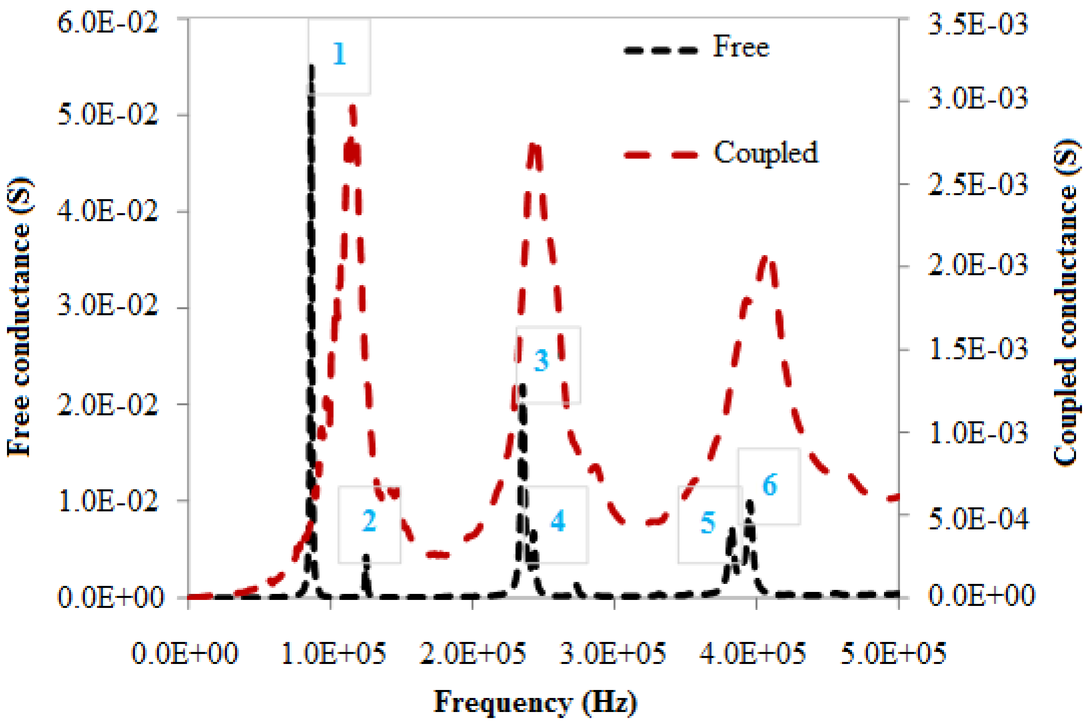


Figure 2. Conductance spectrum of PZT in the free condition and coupled with a 150 mm concrete cube.

4. ANALYSIS OF RESULTS

From the results of the numerical analysis of surface bonded PZT carried out in COMSOL multiphysics^{TM}, the first peak was not well defined for concrete. The second peak was well defined and sensitive to the change in elastic modulus. The second peak in the EM conductance response of the bonded PZT was selected for evaluating the influence of load-induced damage. The conductance signatures at the second peak of the bonded PZT response after unloading from different load levels are shown in Figure 3 a, b.

The second peak is centered on 255 kHz. The response between 245 and 265 kHz is plotted in the figures. Contours of horizontal strain at distinct loading obtained from the DIC technique are shown in Figure 4. It can be clearly identified from the plot that the unloading signature at 40%u shows a shift to lower frequencies. This is due to the incipient damage produced in the concrete. Horizontal strain contour shows an increase in strain levels (Figure 4). As the load level increases, the resonance peak in the conductance signature shows a consistent leftward shift. Comparing with the measured DIC response, there is no visible sign of distress or cracking up to 70% of strength, while some signs of localization are evident at 60% of peak. Localization of damage into a crack occurs at 70% of strength. Significant changes in the resonant peak associated with the localization are observed. After localization, significant changes are observed in the shape of the resonant peak. At 90% of the compressive strength, the peak showed a significant decrease in amplitude and a flattening of the peak. The flattening of the peak is associated with the formation of a major crack on the surface. The conductance signatures associated with the resonant peak has a very good agreement with the indication of damage obtained from surface strain measurements. Further, changes in EM conductance are observed before any visible sign of distress.

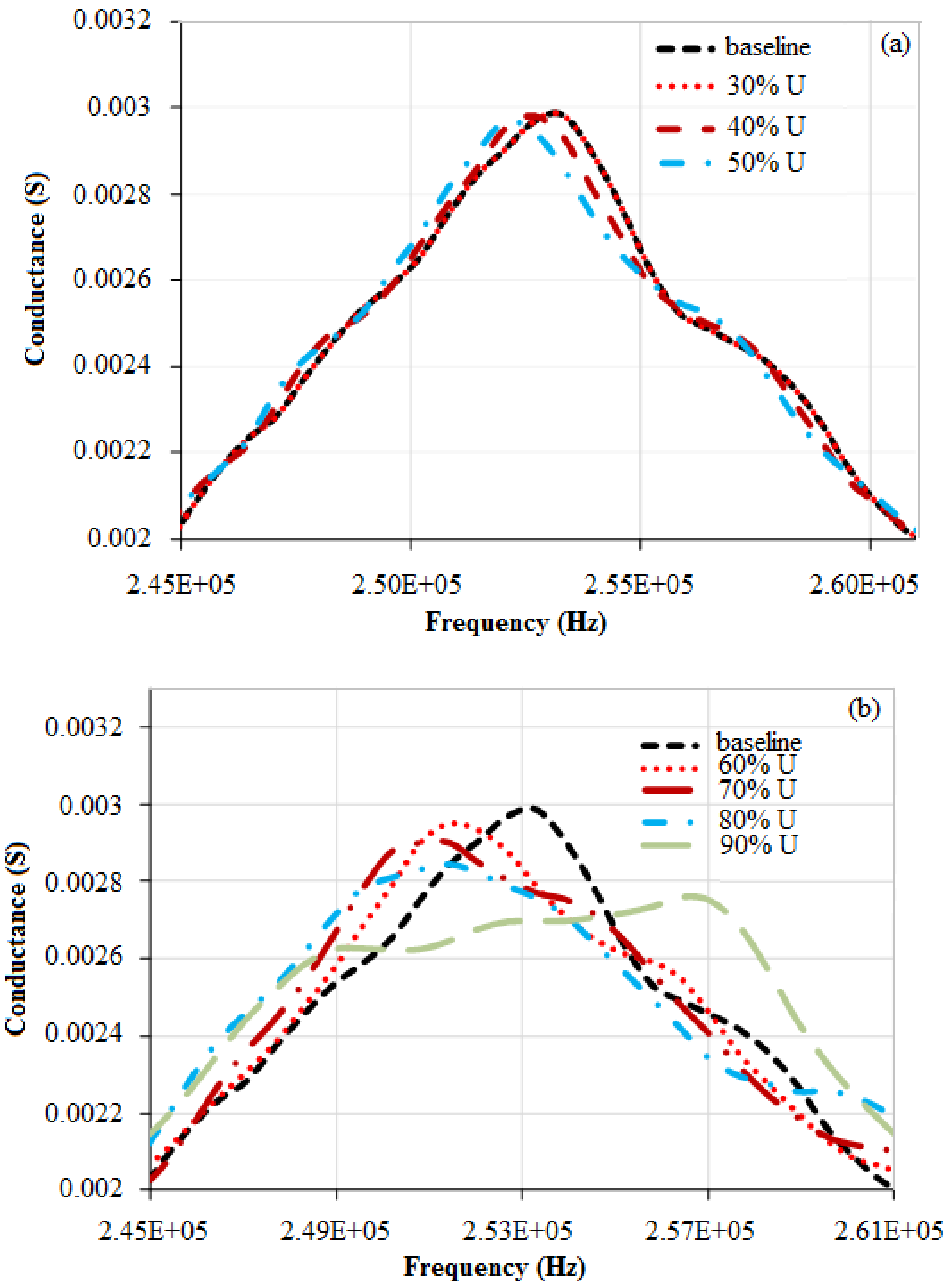
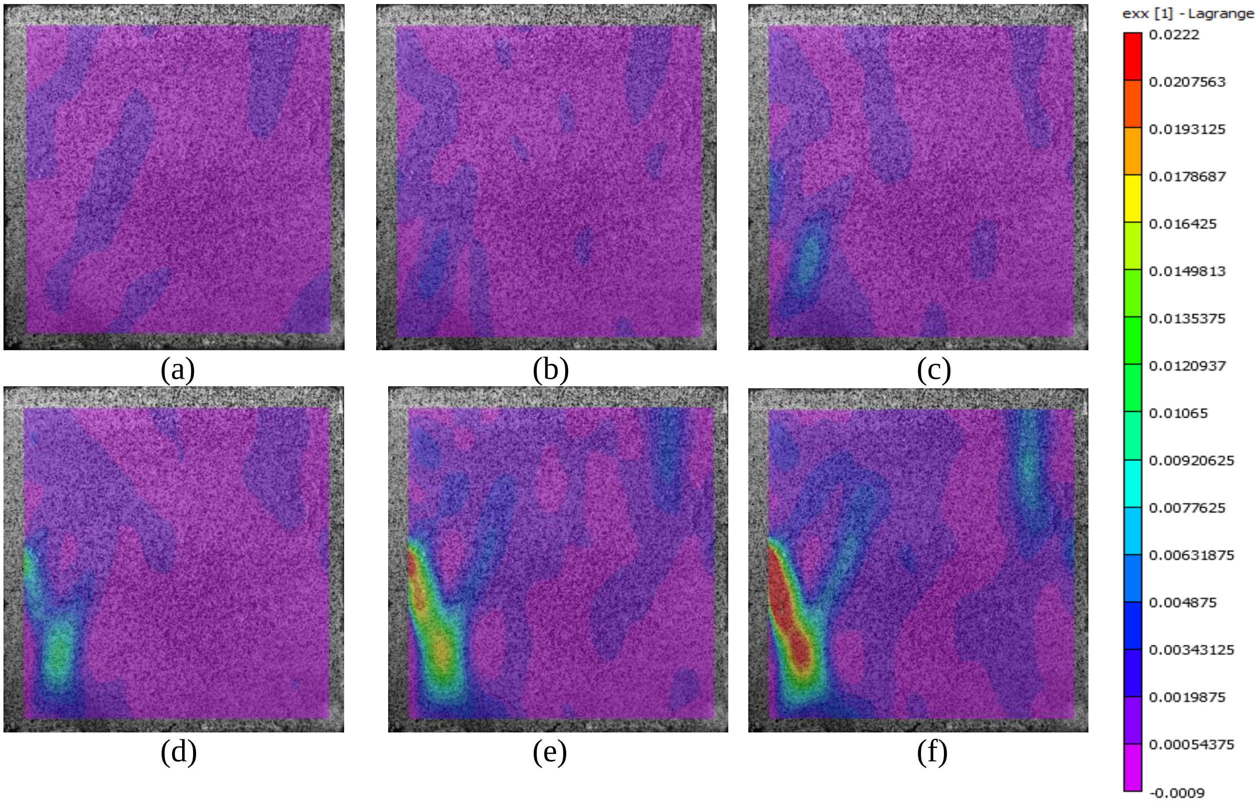


Figure 3. Electrical conductance signatures: a. 30%-50% of strength b. 60%-90% of strength



(a) (b) (c)

(d) (e) (f)

Figure 4. Contours of horizontal strain (e_{xx}) obtained using digital image correlation (a) at 40%; (b) at 50%; (c) at 60%; (d) at 70%; (e) at 80%; and (f) at 90% of Strength.

The root-mean-square deviation (RMSD) is used to measure the differences between values of baseline measurement of conductance signature at the second resonant peak and the corresponding signatures at different load levels. The RMSD for the frequency range 245 kHz-260 kHz with respect to the baseline measurement were calculated using equation (1), where.x_i and y_i are the signatures obtained from the PZT transducer bonded to the structure before and after damage (or loading) with length N. The scatter in the results obtained from all the specimens is also plotted in the figure.

It can be seen that despite the scatter, there is an increasing trend of RMSD with each level of loading as shown in the Figure 5a. The variation in the average vertical strains recorded at the top and bottom of the load cycles obtained from DIC measurements are also plotted in Figure 5b. It can be seen that the level of damage assessed using the RMSD variation of the second resonant peak compares well with the evolution of plastic strain and increase in mechanical compliance. There is an exponential increase in the evolution of plastic strain with loading. Plastic strain is an indicator of level of damage in the material. This corresponds with the observed trend in the RMSD measured with loading.

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N}(y_i - x_i)^2}{\sum_{i=1}^{N} x_i^{\,2}}} \qquad (1)$$

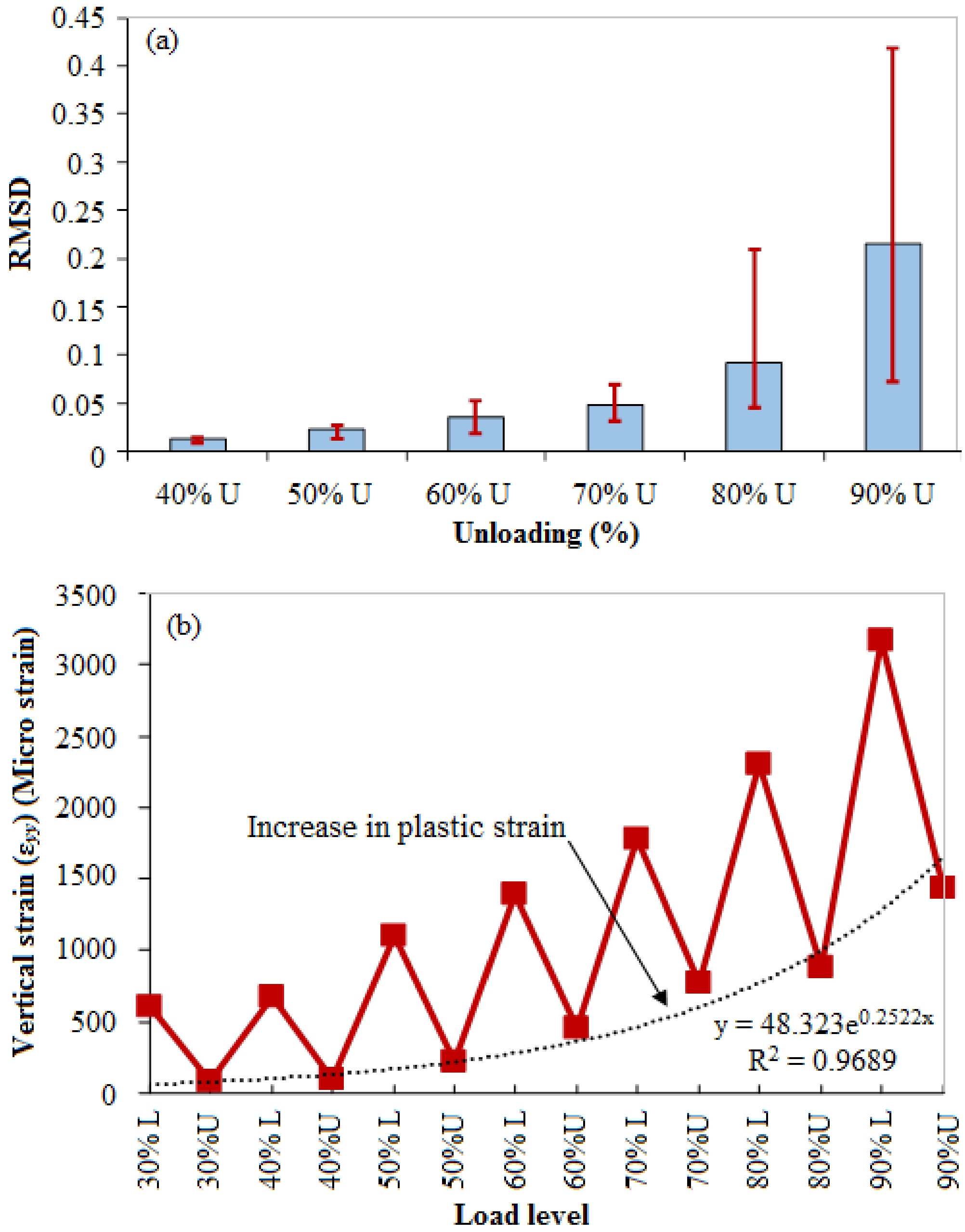


Figure 5. (a). RMSD of the second resonance peak (b). Average vertical strain (ε_{yy}) obtained from DIC

5. CONCLUSIONS

The potential of using EM impedance measurements of surface mounted PZT patches for structural health monitoring of concrete structures is established. It is shown that there are changes in resonant behavior of the EM conductance response of the PZT bonded to a concrete substrate with increasing damage. The PZT sensor detects incipient damage significantly earlier than the appearance of visible signs of damage. There is an amplitude reduction and frequency shift of the PZT resonance peak with an increase in damage in the concrete substrate. At higher damage levels, there is flattening of the resonant peak associated with localization and formation of a major crack.

6. ACKNOWLEDGEMENTS

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