Preliminary Experimental and Numerical Studies on PZT Patch and Rock Interaction: EMI Approach

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Abstract. Condition monitoring of underground structures has always posed a challenge to researchers and maintenance engineers. There are many tools and methods available which sometimes becomes tedious when monitoring inaccessible locations. Electro-Mechanical Impedance (EMI) technique is a new condition monitoring technique which is proved to be efficient in detecting damages in reinforced concrete and steel structures in both local and global domains. There have been attempts of using this technique for monitoring rocks under various types of loading. EMI technique involves the deployment of smart piezo-based sensors like Lead Zirconate Titanate (PZT) patches on the host structure which is to be monitored. The present study highlights some numerical and experimental studies on PZT patch and rock interaction which are crucial for developing a monitoring system for rocks. A stage-wise analysis has been presented to develop a better understanding of bonding piezo sensors on rocks. The results of the analysis have helped in composing a method of bonding piezo sensors while taking care of the intricate details. The steps used in bonding has a significant effect on the recorded signals hence, influence the damage detection capability of the bonded piezo sensors.

Keywords: Electro-Mechanical Impedance Technique, Lead Zirconate Titanate, Piezo sensors, Kota Sandstone

1 Introduction

The Electro-Mechanical Impedance technique for health monitoring of civil structures is taking shape into a commercially ready product. This technique involves the use of smart piezoelectric-based sensors for monitoring the structural integrity of a host in a local region. Thin piezo-based patches (0.2-1 mm) are used as transducers and are bonded strongly on the host structure to be monitored (Fig 1). These patches are actuated through a varying AC source which vibrates these sensors. In the present study, Lead Zirconate Titanate (PZT) thin patches were used both as actuator and sensor. PZT is an artificial piezoelectric material having piezoelectric properties hundred times more than the natural piezoelectric materials like Quartz. The generated

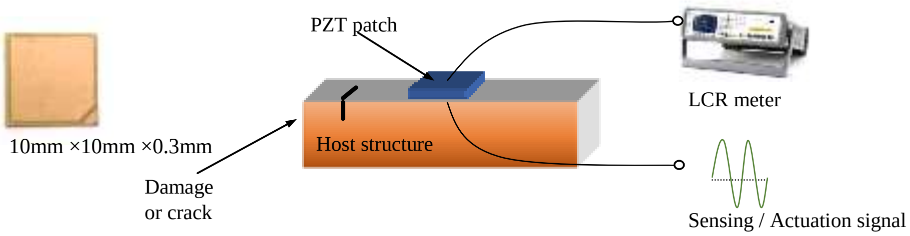

Fig. 1. Schematic diagram of the EMI technique

vibrations excite the local region of the host structure as well. The same sensor senses these vibrations carrying the information of the surrounding region. The data recorded from the sensors is in the form of Impedance vs. frequency of excitation, and is known as an impedance signature. These recorded signatures are unique for a specific case and other conditions like density, temperature, and stiffness of the host structure. Any change in these parameters will be reflected directly as a change in the previously recorded signatures of the pristine condition (Fig 2). This variation can be quantified using any statistical method like Root Mean Square Deviation (RMSD) method, which is widely used in EMI technique. Liang et al [1] first proposed a mathematical interaction between the mechanical impedance of the host structure and electrical impedance of the piezo sensor as following

$$\bar{Y} = 2\omega j \frac{wl}{h}\left[\overline{\varepsilon_{33}^{T}} - d_{31}^{2}\overline{Y^{E}} + \left(\frac{Z_a}{Z+Z_a}\right) d_{31}^{2}\overline{Y^{E}}\left(\frac{tan\kappa l}{\kappa l}\right)\right] \quad (1)$$

where, $\bar{Y}$ is the nverse of impedance (admittance), $\overline{Y^E}$ is the complex Young's modulus of the piezo patch, d_{31} is the piezoelectric strain coefficient, $\overline{\varepsilon_{33}^{T}}$ is the complex electric permittivity of the piezo patch, Z and Z_a, are the mechanical impedance of the structural system and the piezo patch/actuator respectively. ω is the angular frequency of actuation signal, κ is the wave number and w, l and h are the width, length and thickness of the piezo patch.

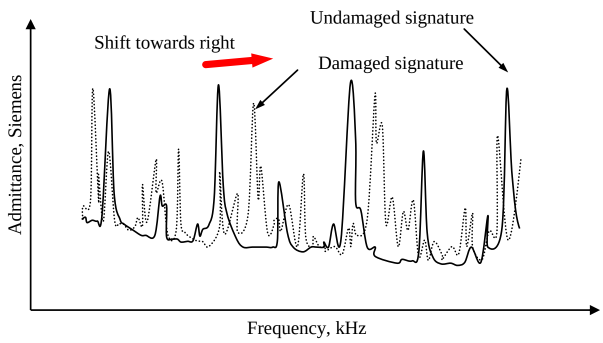

Fig. 2. Admittance signatures of undamaged and damaged structure acquired from a piezo patch [2]

This paper discusses some preliminary studies on the application of EMI technique in the monitoring of rocks. The experimental part discusses the variation in EMI signatures while bonding on a rock specimen and the numerical part discusses the details of modeling a rock-PZT patch interaction in an FE based software (COMSOL).

2 Experimental study: Variation in signatures of bonding stages

The variation in EMI signatures in different stages of bonding the PZT patch has been studied to develop a better understanding of the bonding process. The test has been conducted on cylindrical Kota sandstone specimen of 38 mm diameter and 20 mm length. The properties of Kota sandstone were found and are listed in Table 1. All the signatures were taken in the laboratory conditions at a constant temperature of 27°C and humidity of 35%.

The PZT patch used in the study is of dimensions 10×10×0.3 mm, manufactured by Central Electronics Limited (CEL), India. Its properties are equivalent to PZT material-PIC151 which are listed in Table 2. Both terminals are on the same side of the patch which facilitates in the perfect bonding of the patch on a flat surface. The patches were bonded on the flat surface of the specimen using a two-part (resin and hardener) standard epoxy made by Araldite (properties shown in Table 2). The free signature of the PZT patch was taken first by directly connecting the terminals over it and hanging it freely in the air. The complete experimental setup is shown in Figure 3 for EMI signature acquisition. The conductance signatures of the free PZT patch were acquired using Agilent E4980A LCR [3] meter in the frequency range of 1 kHz to 1000 kHz with a step interval of 1000 Hz. The same frequency range was followed for acquiring the signatures in other stages. For the next stage, the top surface of the rock specimen was completely water sealed using Araldite two-part epoxy adhesive (Araldite 2017), so that water does not come in direct contact with the bonded PZT while saturating the specimen, which might result in short-circuiting or the terminals and malfunctioning of the Piezo patch. After 24 h of applying epoxy, the PZT patch was bonded in the centre of the rock specimen as shown in Figure 3. The next signature was taken after the complete bonding of the patch after another 24 hours.

Table 1: Physical and mechanical properties of Kota sandstone

Properties		**Kota Sandstone**
Specific gravity	(G_s)	2.64
Dry density (kg/m3)	(ρ_{dry})	2190
Saturated density (kg/m3)	(ρ_{sat})	2260
UCS (MPa)	(σ_c)	50-90
Dry elastic modulus (GPa)	(E_{dry})	9.45
Dry Poisson's ratio	(μ_{dry})	0.23

Table 2: PIC-151 material and araldite epoxy technical data (Araldite, 2017; PI ceramic, 2017).

Properties		PIC 151	Araldite epoxy
Density (kg/m^3)	(ρ)	7800	1200
Relative permittivity	(ε_{33} / ε_0)	2400	-
	(ε_{11} / ε_0)	1980	-
Dielectric loss factor	(tan δ)	0.02	-
Piezoelectric strain coefficient (m/V)	(d_{31})	-2.1×10^{-10}	-
	(d_{33})	5.0×10^{-10}	-
Elastic compliance coefficient (m^2/N)	(S_{11}^{E})	1.5×10^{-11}	-
	(S_{33}^{E})	1.9×10^{-11}	-
Young's modulus (N/m^2)	(Y^{E})	6.9×10^{10}	9.79×10^{8}
Poisson's ratio	(υ)	0.34	0.35
Damping ratio	(β)	3×10^{-9}	6×10^{-9}

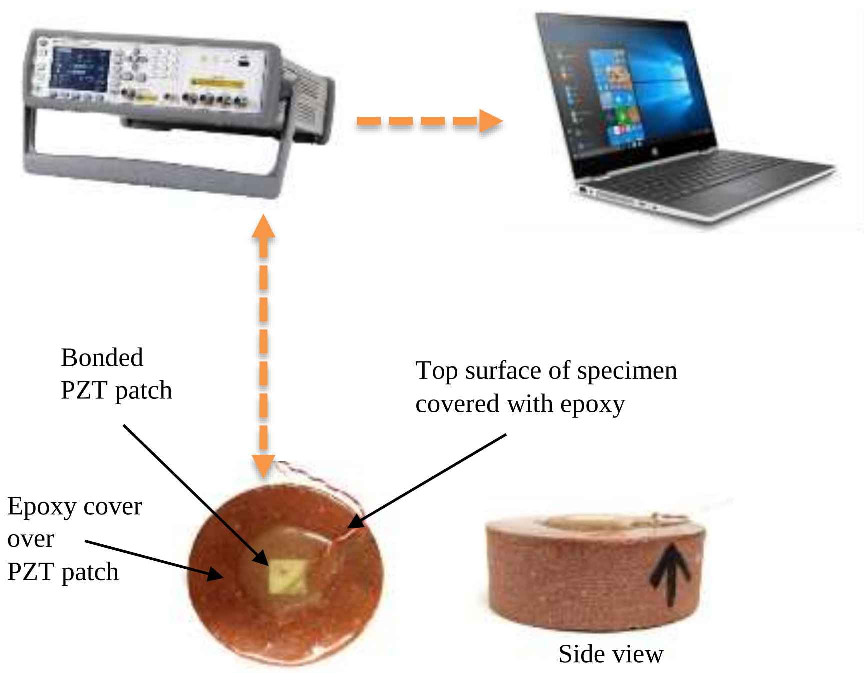

Fig. 3. Complete experimental setup for acquiring EMI signatures

In the next step, the patch was covered with the epoxy from the top (Fig 3), to safeguard the soldering joints and waterproof the PZT patches from the top. Another signature was taken after the curing of the applied layer of epoxy. The specimen was submerged in water for 24 hours and the terminals were kept out of the water carefully. Later, the specimen was taken out of the water and the excess water on its surface was dabbed out before taking the signature in the saturated condition. The saturated specimen was air dried for three days, after which another signature was recorded for the specimen. All the signatures in the range of 1-300 kHz frequency for Kota sand-

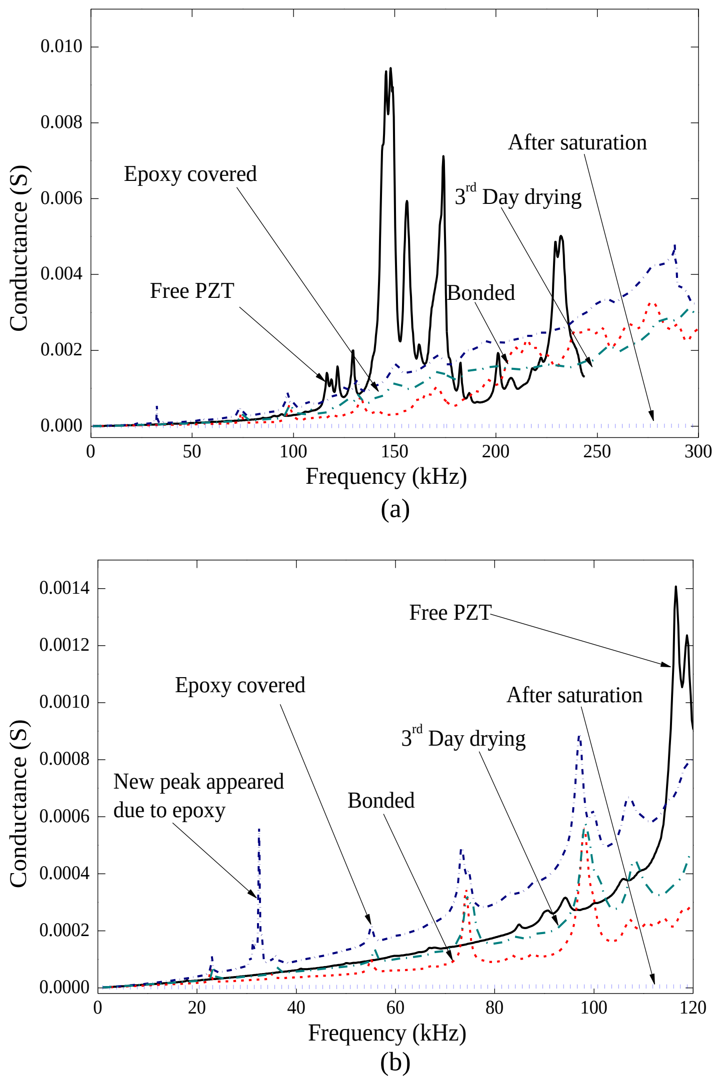

Fig. 4. Kota sandstone: Conductance signatures at different stages of bonding in (a) 1-300 kHz range (b) 1-120 kHz range.

stone specimen are plotted on the same graph and are shown in Figure 4. Sharp vertical peaks corresponding to the first resonance frequency for the free PZT patch can be seen at 150 kHz (Fig.4a). There are multiple peaks instead of single strong peaks. The reason could be the excess application of solder while fixing the patches which acts as an extra mass of the system. As the patch was bonded on the specimen, the resonance peaks reduced significantly, and new structural peaks were developed. These peaks can be seen in Figure 4(b) which shows the conductance signatures for the range of 1-120 kHz. A new peak can also be seen in the epoxy covered signature between 20-40 kHz due to the thick layer of epoxy above the PZT patch. The signature taken after the saturation of the specimen became nearly flat. This shows the PZT patch is not receiving back any response from the structure. The signature taken after three days of drying of the specimen showed recovery of peaks similar to the signature of the bonded condition.

This study shows that the presence of water can be a point of concern while performing SHM of rocks using the EMI technique, as the structural peaks disappear in the presence of water. Also for the signature comparison, while performing SHM, the signature taken after the bonding of the PZT patch is to be considered as the baseline signature.

3 Numerical study: PZT patch and Rock modeling

The interaction of the PZT patch and the host rock was studied through numerical simulations using commercially available finite element (FE) based software COMSOL 4.3. The purpose of this study was to simulate the conductance signature of a PZT patch bonded on the undamaged cylindrical Kota sandstone specimen. For this numerical study, the PZT patch bonded on Kota sandstone specimen was modeled as shown in Figure 5.

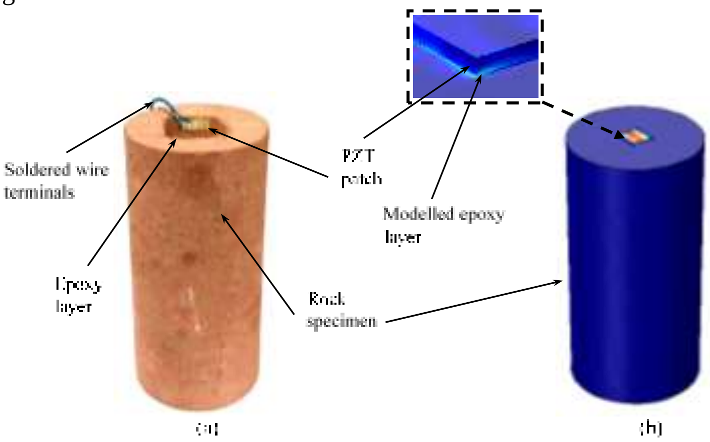

Fig. 5. (a) PZT patch bonded on Kota sandstone cylindrical rock specimen for numerical study (b) von-Mises stresses developed in PZT patch modeled in COMSOL.

In the studies related to damage monitoring of structures, the damage is generally artificially induced in the structure for both the experiment work and the numerical simulations [4, 5]. In the present study, the PZT patch bonded on a concrete beam [4] and on an aluminium beam [6] were modeled first for the purpose of numerical validation. Later the same model was extended for simulating PZT patch bonded on a rock specimen.

Figure 5 shows a square PZT patch (10 mm× 10 mm × 0.3 mm) bonded on a cylindrical specimen of Kota sandstone (54.0 mm diameter and 108.3 mm in length) using Araldite epoxy adhesive. This time the patch was bonded on the top flat surface instead of the curved surface of the specimen, to reduce the complications in modeling. A conductance signature was acquired with an excitation frequency of 1 kHz to 1000 kHz at the step interval of 1000 Hz. The specimen was modeled in COMSOL keeping the minimum element size less than one-sixth of the wavelength of the PZT patch. It may be noted that meshing strongly affects results in such simulations. The minimum element size of the free Tetrahedral element was kept 1mm and

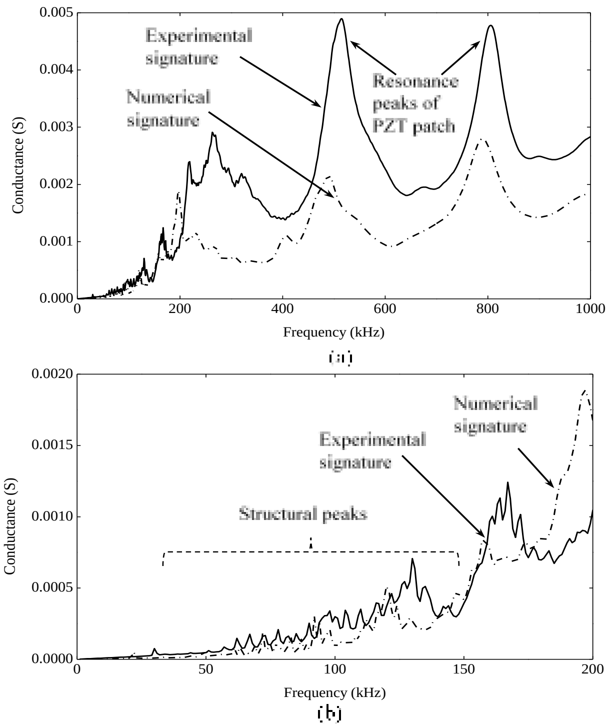

Fig. 6. Comparison of conductance signature of the present signature with numerical and experimental results in the range (a) 1 kHz – 1000 kHz (b) 1 kHz – 200 kHz.

maximum

maximum element size was kept 8.5 mm with a curvature factor of 0.5. Modeling in COMSOL gave an advantage over another finite element (FE) software that the polling direction for the piezoelectric domain is set in the *z*-direction, hence there is no need of changing the coordinate system. The upper surface of the PZT patch was given a potential of 1 V and the bottom surface was kept as ground (0 V). The meshing was kept dense near the PZT patch and epoxy bonding. The mesh was progressively kept sparse for the rock specimen. An epoxy layer of 0.046 mm was also modeled below the PZT patch with properties shown in Table 2. The thickness of the epoxy layer was measured using a dial gauge with a least count of 0.001 mm. However, the thickness was varying between 0.041 to 0.050 mm at different points.

The thickness of the epoxy layer was decided by trial and error. For this, the conductance signature results were compared at higher frequencies with the experimental results. It can be seen in Figure 5(b) that the epoxy layer develops more stress than the host structure due to the vibration of the PZT patch. Figure 6 shows the comparison between conductance signature for results of numerical and experimental studies in 1 kHz – 1000 kHz and 1 kHz – 200 kHz frequency ranges. The signature shows structural peaks up to 200 kHz and beyond that, it carries the information at the very close vicinity of the PZT patch. The two large peaks are shown in Figure 6(a) at 500 kHz and 800 kHz, are the PZT's resonance peaks. In the numerical simulation, the frequencies of these peaks are moderately matched, however, the conductance values are less than the experimental values. This difference can be due to the shear lag effect of the epoxy layer or due to its varying thickness as it was difficult to maintain an even surface of epoxy at micron level. Due to these challenges, it is very difficult to model the exact bonding conditions of the PZT patch and structures made of rock and concrete. Thus, it is not advisable to include higher frequency results for the comparison of numerical and experimental EMI results.

It is seen in Figure 6(b) that the numerical signature below 200 kHz is matching the trend of experimental signature. The rock was modeled here as a homogeneous material, whereas, practically at grain level it carries small fissures and cracks which are difficult to be modeled. This results in a mismatch between the structural peaks in the conductance signature. The difference in the experimental and numerical results of the EMI signature was also reported by Wang et al. [5]. for concrete structures and thus, may be considered acceptable.

4 Conclusions

This paper involves the experimental and numerical study of the interaction of the PZT patch with a rock. This study played a crucial role in applying EMI technique for the condition monitoring of rocks in both dry and saturated conditions [7]. The acquired signature in PZT patch changed at every step of bonding of the PZT patch. Howsoever, the base-line signature for damage monitoring should be taken only after the completion of the bonding process. Any further change in the signature reflects the change in the condition of the host structure and can be used to detect damages. The structural peaks disappeared from the EMI signature on saturating the rock specimen. However, the SHM of saturated rocks can be done by observing the changes in the natural resonance peaks of the free PZT signatures. Providing a water-tight covering is an essential condition for working on structures where water may come in direct contact with the sensor. In the present case, the area below the PZT patch was the possible area from where water had penetrated, as the epoxy layer always had tiny air bubbles which acted as pores after the curing of the epoxy.

In addition, the numerical simulation of the PZT patch bonded on the rock specimen in an undamaged state was performed. The simulation results of the EMI signature on PZT patch interaction with rock having an epoxy layer in between has shown similar results to the experimental EMI signature. This showed that the epoxy layer has also been modeled well. The experimental and numerical results have matched up to 200 kHz of the frequency range. Beyond 200 kHz the variation is quite large as higher frequencies carry the information regarding the very near vicinity of the PZT patch bonding, which is difficult to be modeled exactly.

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