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REAL-TIME STRUCTURAL HEALTH MONITORING METHOD BASED ON THE ELECTROMECHANICAL IMPEDANCE APPROACH APPLIED ON CONCRETE STRUCTURES

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Abstract. *In concrete structures, the appearance of cracks could occur due to the combination of residual stresses induced by the hydration process, creep effects, retraction, and temperature effect. To control microcracking during loading and improving the mechanical properties and residual resistance to fracturing of these concrete structures, steel fibers are incorporated into the concrete. It is important to mention that the use of steel reinforced concrete (CRFA) in civil structures has advantages as compared with traditional systems, such as: greater resistance to cavitation, improve the impact resistance and thermal shock, and increase the ductility. In this context, this paper aims to propose a new methodology for real time damage detection in concrete structures by using the method of structural health monitoring based on the electromechanical impedance approach. For this, a smart capsule was used, that is, piezoelectric transducers as sensor and actuator, which is embedded in the monitored structure. Due to the electromechanical coupling between the sensors and the structure, the presence of the damage in the structure changes the PZT patch electric impedance. To quantify this damage, the damage metrics RMSD and ASD are used. In this work, a prismatic concrete specimen was prepared to illustrate the proposed SHM approach, considering the compressive strength of the matrix with $f_{ck} = 40$ MPa and dosage of fibers corresponding to 60kg/m^3 (0.77%). This specimen was subjected to the flexural toughness test to produce damage and the impedance signatures are obtained during the test, with the objective of both identifying and characterizing the damage progression along the ISHM.*

Keywords: *Structural Health Monitoring, Electromechanical Impedance, Piezoelectric transducers, Concrete structures, dynamic test.*

1. INTRODUCTION

In civil engineering, concrete structures are susceptible to several types of damage that may appear since the manufacturing process phase. In the early stage, for example, during concrete cure, cracks could be initiated due to high mechanical stresses induced by the hydration process (Naaman and Reinhardt, 1995). It is worth mentioning that the durability of this type of structures are related to mechanical, physical, and chemical deterioration, namely: corrosion of reinforcing fibers, concrete carbonation, and large temperature differences (Gilber and Ranzi, 2011; Romano et al. 2013).

Thus, researchers have developed structural health monitoring techniques to detect damages in early stages. There are many publications about SHM techniques for concrete structures based on vibration (Dilena et al., 2011), optic fiber (Villalba et al., 2013), and electromechanical impedance (Park et al., 2006; Chalioris et al., 2016). The method based on vibration uses low excitation frequencies (global techniques) and, consequently, it is not possible to detect damages in early stages (Banks et al., 1996). The second technique applied presents some disadvantages, as the concrete is brittle and heterogeneous (several sizes of aggregates). At low level of load the structures cracks, which can result in a break and debonding of the optical fiber (Villalba et al., 2013). The ISHM evaluated in this work shows promise results (Park et al., 2006; Chalioris et al., 2016), since it is simple and easy to implement. However, this methodology has some disadvantages, such as influence of the temperature (Banks et al., 1996).

The electromechanical impedance method for structural health monitoring (SHM) purposes is basic on the verification of changes in the mechanical impedance of the monitored structure, comparing the scenarios with and without damage.

The measurement of the mechanical impedance is performed indirectly, through the electrical impedance by using piezoelectric transducers coupled to the host structure or incorporated into it. The measurements are performed for the pristine condition of the structure (baseline) and during its useful lifetime. Considering that the coupling properties between the PZT patch and the structure are kept constant, the presence of damage can be verified by observing changes on the electrical impedance signatures. This change can be quantified by the so-called damage metrics (Liang *et al.*, 1994).

One of the first published reports on this subject for civil structures showed that the electromechanical impedance method was successful applied for crack detection in the context of loading and unloading of a prototype formed by a part of a bridge. This structure was made with reinforced concrete (Soh *et al.*, 2000). Other studies have also obtained promising results, for example, in detecting damage in concrete plates where the damage was produced from a cutting blade (Na and Lee, 2012). In another study, the influence of the concrete cure on the impedance signals was considered (Quin *et al.*, 2011). For this aim, a piezoelectric transducer was introduced in a concrete plate during its manufacturing. It was found that the impedance signals change as the samples were subjected to compression. However, the authors did not conduct more detailed studies in the presence of incipient damages during the tests. A study about the influence on the impedance signals of the detachment of the piezoelectric transducers was performed by Tawie and Lee (2010). In this case, the sensors were bonded to the steel fibers used to reinforce concrete structures. In another study, the technique was used to detect carbonation in this type of structures (Talakokulaa *et al.*, 2016). The influence of temperature and loading on the impedance signals measured by a piezoelectric sensor coated with a protection capsule of cement and epoxy was also investigated (Dongyu *et al.*, 2015). Therefore, in recent years, the SHM are being used to detect incipient damages with the objective of promoting timely maintenance and extending the operational life of the structures (Rabelo *et al.*, 2016).

The objective of the present work is to develop an experimental test in real time condition by using the impedance signal to detect damage in a prismatic sample of steel reinforced concrete. For this aim, a smart capsule was embedded in the structure analyzed. This specimen was subjected to toughness testing, aiming to produce a damage.

2. IMPEDANCE ELETROMECHANIAL METHOD

The ISHM technique was first presented in 1994 (Liang *et al.*, 1994). The method uses piezoelectric transducers coupled to the structure to monitor changes in its stiffness, damping, and mass. Due to the difficulty of obtaining the mechanical impedance of the structure, the electrical impedance measurements are obtained by using piezoelectric transducers coupled to the host structure. If the properties of the PZT patch (Lead Zirconate Titanate) do not vary over time, changes in the electrical impedance will be directly related to changes in the mechanical impedance, which is affected by the presence of damage (Park *et al.*, 2005). A single-degree-of-freedom (DOF) electromechanical model that describes the measurement process is showed in Fig. 1.

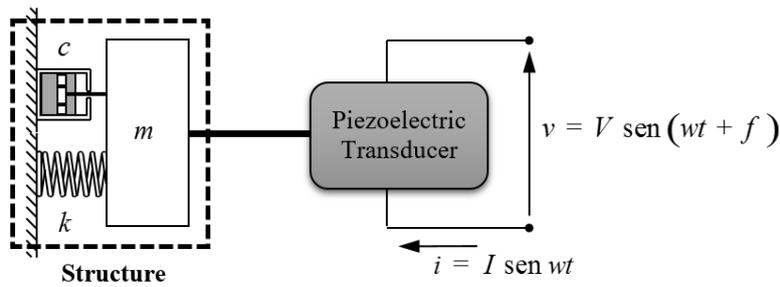


Figure 1. DOF Electromechanical Model of the structural health monitoring method (Liang *et al.*, 1994).

Based on the system showed in Fig. 1, the admittance $Y_a(\omega)$ of the piezoelectric transducer is the combined function between the mechanical impedance of the PZT actuator $Z_{ma}(\omega)$ and the structure $Z_{me}(\omega)$, according to Eq. (1). The impedance is a frequency dependent complex function.

$$Y_a(\omega) = I(\omega)\omega a \left\{ \varepsilon_{33}^T [1 - I(\omega)\delta] - \frac{Z_{ma}(\omega)}{Z_{ma}(\omega) - Z_{me}(\omega)} d_{3x}^2 \hat{Y}_{xx}^E \right\} \quad (1)$$

where \hat{Y}_{xx}^E is the complex Young's modulus of the PZT patch with zero electric field, d_{3x} is the piezoelectric coupling constant in the arbitrary x direction at zero electric field, ε_{33}^T is the dielectric constant at zero stress, δ is the dielectric loss tangent to the PZT patch, a is a geometric constant of the PZT patch, and ω is the frequency. To obtain the electrical impedance, both the direct and inverse effects of the piezoelectric transducer are used. The direct effect (or sensor effect) is characterized by producing a voltage when the piezoelectric transducer is mechanically deformed in the elastic phase,

and the inverse effect (or actuator effect) appears when a piezoelectric ceramic patch is subjected to a voltage, resulting a mechanical deformation (Farrar *et al.*, 2005).

2.1 Damage metric

The detection and evaluation of the structure integrity is based on the comparison between the impedance signatures acquired in the health and damaged (or unknown condition) structure. A visual examination is not enough, since it gives only a qualitative comparison. Consequently, it is necessary the use of a quantitative criterion. Thus, damage metrics are employed, i.e., scalar parameters are properly defined so that they are able to numerically represent the difference between the two signals (without and with damage) (Naidu and Soh, 2004).

For the impedance based SHM approach, a number of damage metrics can be used to evaluate the integrity of the structure (Palomino *et al.*, 2011). As an example, one of the most commonly used metric is the RMSD (Root Mean Square Deviation) and its definition is given by Eq. (2) (Peairs, 2006).

$$RMSD = \left\{ \sum_{i=1}^n \frac{[\text{Re}(Z_{1i}) - \text{Re}(Z_{2i})]^2}{\text{Re}(Z_{1i})^2} \right\}^{1/2} \quad (2)$$

where $\text{Re}(Z_{1i})$ is the real part of the impedance measure without damage (baseline) at the frequency i . $\text{Re}(Z_{2i})$ is the real part of the impedance measurement at the frequency i for a new structural configuration and n is the total number of points used in the measurements.

Another important metric found in the literature is the mean square difference (ASD), given by Eq. (3) (Palomino *et al.*, 2011). The ASD is able to eliminate the effect of amplitude variations due to changes in the environment conditions.

$$ASD = \sum_{i=1}^n [\text{Re}(Z_{1,i}) - (\text{Re}(Z_{2,i}) - \delta)]^2 \quad (3)$$

where δ is the difference of the means of the associated impedance signatures (Eq. 4).

$$\delta = \overline{\text{Re}(Z_1)} - \overline{\text{Re}(Z_2)} \quad (4)$$

3. EXPERIMENTAL PROCEDURE

For the tests, a prismatic concrete specimen 150x150x500 mm with steel reinforcement fibers was used, as shown by Fig. 2. Two smart capsules were embedded in the prismatic concrete specimen. The approximate positions of the capsules can be seen in Fig. 2b. The used concrete mix exhibits 40 MPa of compressive strength (f_{ck}) along 28 days of cure. The materials used in this specimen are specified in Tab. 1, based in Vitor (2017).

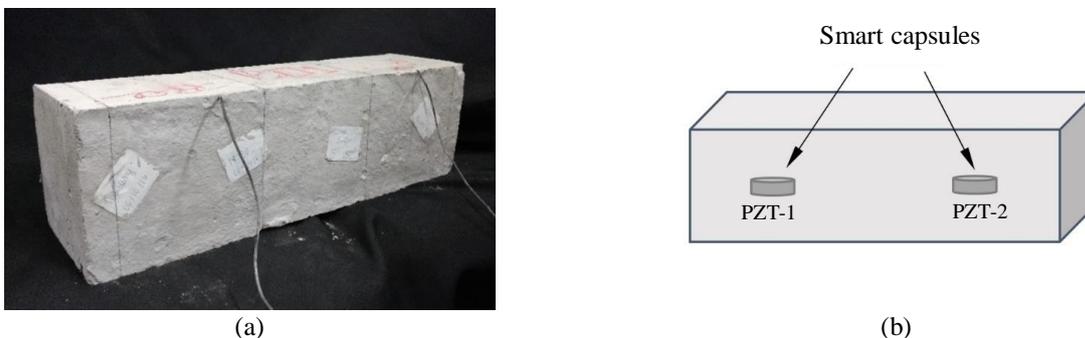


Figure 2. Prismatic specimen: (a) Concrete specimens with smart capsules embedded; (b) Scheme with the position of the smart capsules.

Table 1. Materials used in the specimen (Vitor, 2017).

Materials	Quantity
Cement CP II 40 (kg/m ³)	447,00
Thin sand (kg/m ³)	250,32
Medium sand (kg/m ³)	464,88
Crushed Rock 0 – maximum dimension 12,5 mm (kg/m ³)	268,20
Crushed Rock 1 - dimensão máxima 19,0 mm (kg/m ³)	804,60
Water (l/m ³)	179,80
Superplasticizer (l/m ³)	2,34
Steel Fiber (kg/m ³)	60,00
a/c factor	0,40
Mass trace	1:4

After molding, densification, and finishing, the prismatic specimen was placed inside a humid chamber for 48 hours. The sample was then removed from the mold and placed under submerged curing process along 37 days.

The SySHM impedance meter was used to measure the impedance signatures. For this aim, the equipment was settled with a frequency resolution of 2000 points in a frequency range of 30 to 80 kHz. In each condition evaluated, 30 measures of impedance signatures were performed (mean of 1024 measurements). The tests were performed at ambient temperature (approximately 25 °C). The damage was introduced into the prismatic concrete specimen by a flexural strength test based on the ASTM C1609 method. A MTS hydraulic servo bending machine was used to apply the necessary effort to the concrete specimen in a yoke frame device, as shows the Fig. 3.

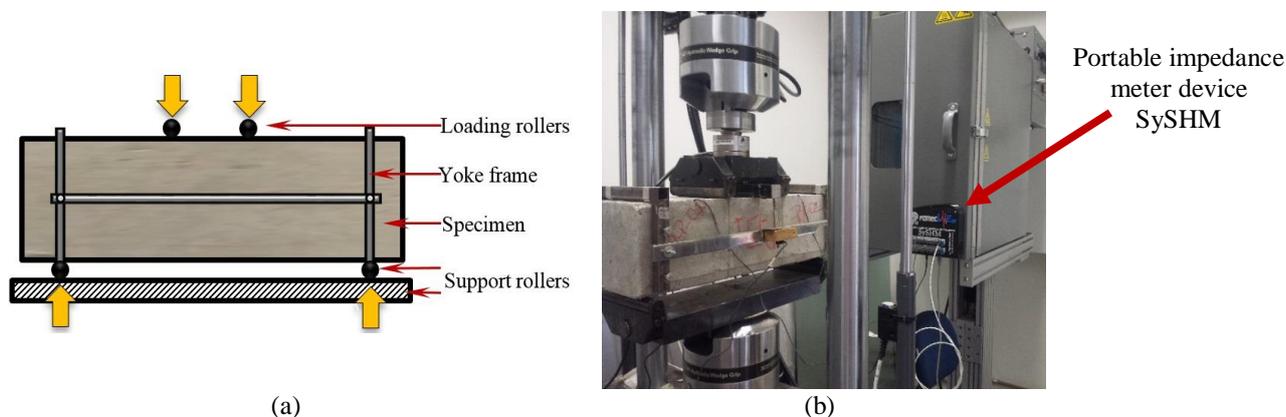


Figure 3. (a) Scheme test as based on the ASTM method C1609. (b) Specimen positioned on the MTS during the flexural toughness test and SySHM impedance meter connected to the smart capsules.

To avoid the tearing of the fibers and a possible collapse of the structure, the test was stopped with a maximum deflection of the structure at 2.0 mm, approximately. In addition, to ensuring safety and integrity of the test machine, the propagation of cracks in the center of the specimen was considered sufficient for monitoring purposes.

4. DISCUSSION AND RESULTS

The peak load of approximately 54 kN observed in Fig. 4 indicates the time in which the structure was damaged. The role of the steel fibers in the concrete matrix allows the increase in the peak force, due to the ability of the fibers to cross the cracks and to work as transfer bridges between the edges of the cracks, increasing also the load capacity after the first fissure.

The role of the steel fibers in the concrete matrix appears very clearly in the test, increasing the deformation in the peak force caused by the ability of the fibers to cross the cracks and to work as transfer bridges between the edges of the cracks, thus increasing the load capacity after first crack. The total time of the presented test was approximately 45 minutes (see Fig. 4b).

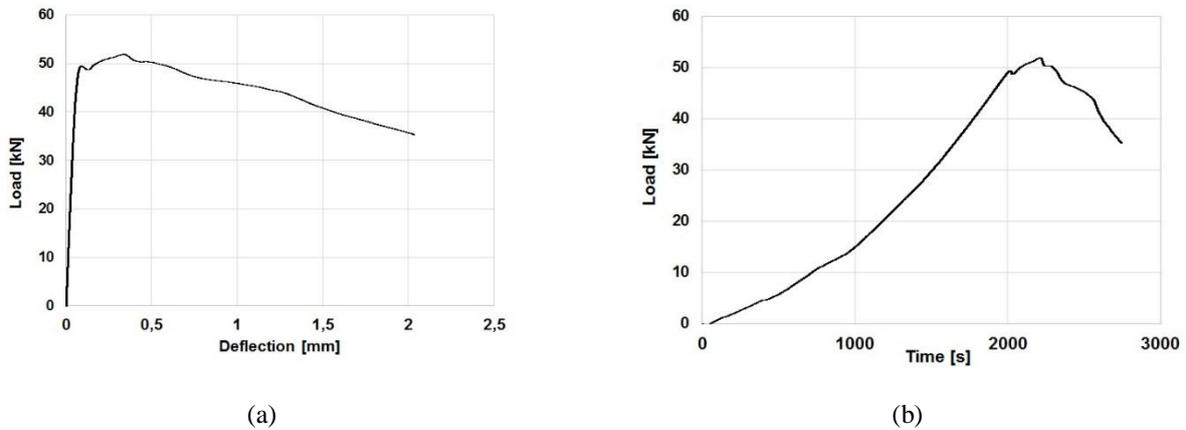


Figure 4. Test ASTM 1609: (a) Load versus deflection; (b) Load versus time.

The SySHM impedance meter was properly configured and before starting the test, four measurements were performed to characterize the reference impedance signature (specimen in pristine condition). In this case, 48 measurements were obtained during the test presented in Figs. 3 and 4. Finally, 9 measurements were performed after the test, resulting in 62 measurements. Therefore, impedance signatures were obtained considering five different configurations for the sensors PZT-1 and PZT-2 (smart capsules in the left-hand side and right-hand side of the specimen presented in Fig. 2b, respectively), which are:

1. PH I (Phase I): reference signal adopted (pristine condition - healthy structure).
2. PH II (Phase II): Initiation of the test, from the 5th to the 20th measurement. Possibly, the formation of multiple cracks and the increase of the tenacity of the structure were started.
3. PH III (Phase III): During the test, from the 21st to the 40th measurement, where the test reached the peak load (54 kN) resulting in the rupture and maximum tenacity of the structure.
4. PH IV (Phase IV): During the test, from the 41st to 52nd measurements, after the matrix rupture, the load capacity of the concrete does not decrease rapidly and presents considerable tenacity.
5. PH V (Phase V): After the end of the test, from the 53rd to 62nd measurements, with the structure in the same position, but free of loading.

Figures 5 and 6 presents the results obtained by the PZT-1. Note that the impedance signatures changed after the damage was generated and, in order to quantify this modification, the RMSD and ASD damage metrics were calculated. The results confirmed the presence of the damage. In this case, the hybrid optimization technique was applied to minimize the temperature effects on the impedance signatures. For the PZT-2, Figs. 7 and 8 present the obtained results, which also confirm the presence of damage.

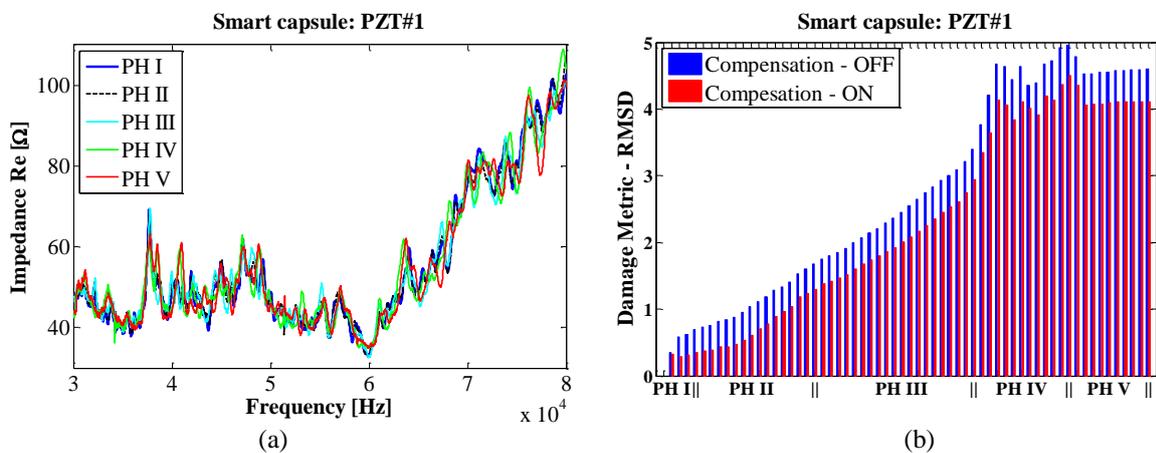


Figure 5. Smart capsule, PZT #1: (a) Impedance signatures for real-time monitoring of concrete prismatic specimen; (b) Damage metric RMSD.

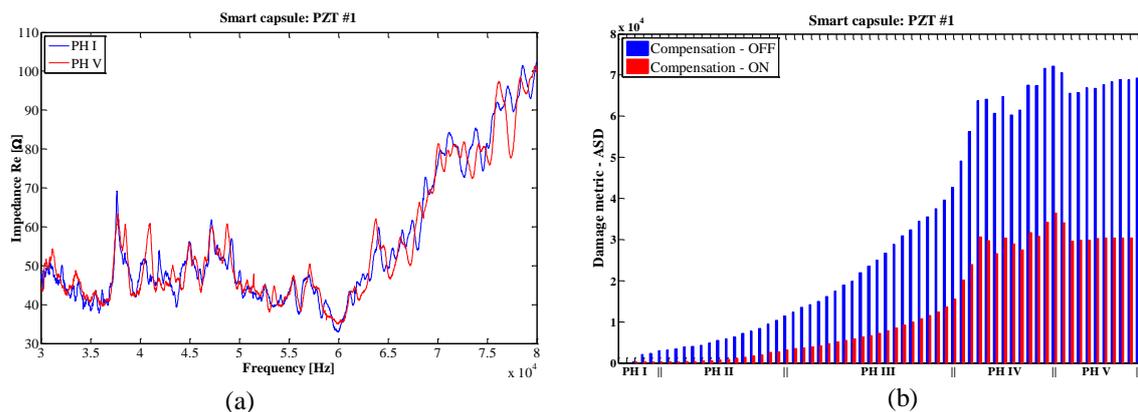


Figure 6. Smart capsule, PZT #1: (a) Impedance signatures for indicative of healthy structure and after the end of the test. (b) Damage metric ASD

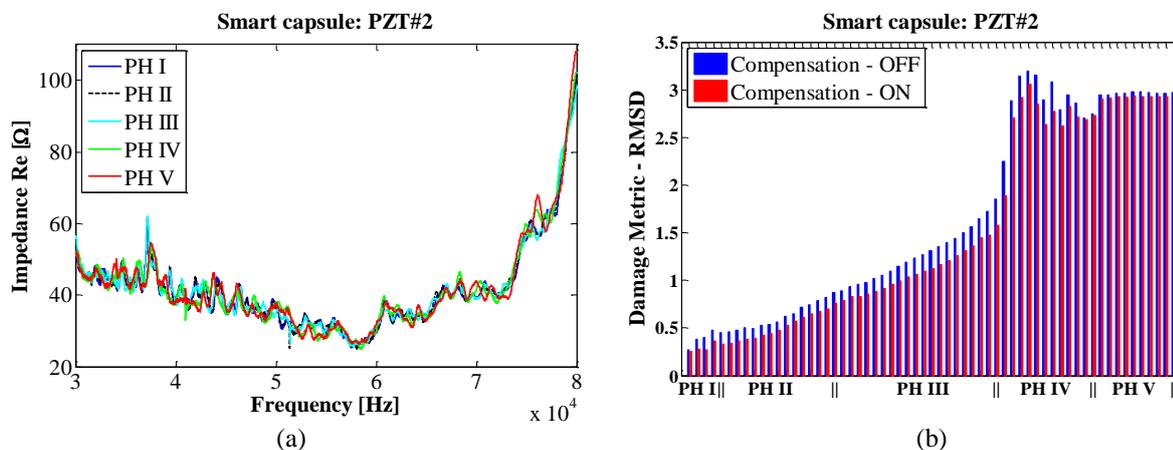


Figure 7. Smart capsule, PZT #2: (a) Impedance signatures for real-time monitoring of concrete prismatic specimen; (b) Damage metric RMSD.

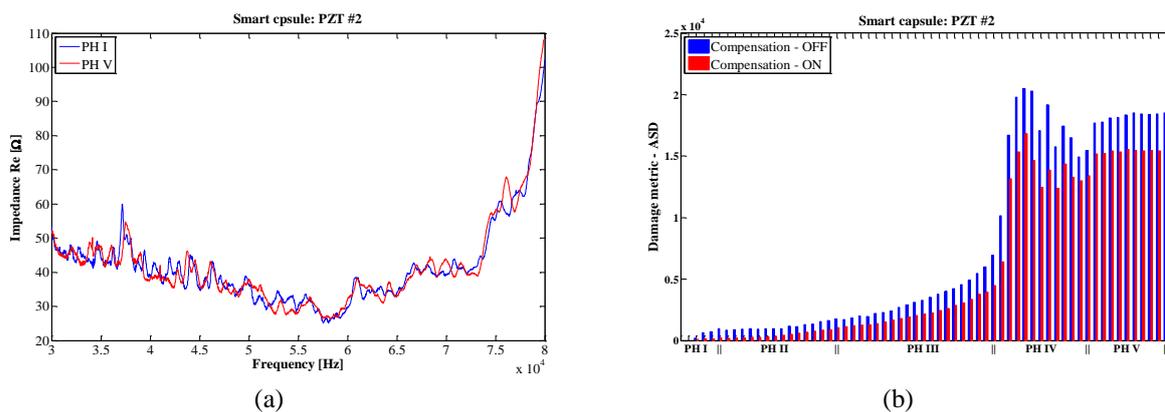


Figure 8. Smart capsule, PZT #2: (a) Impedance signatures for indicative of healthy structure and after the end of the test. (b) Damage metric ASD

As can be seen in the results, the temperature compensation is important to minimize the temperature effect on the impedance signatures, avoiding false positives in the monitoring.

Note that the damage was successfully identified. Therefore, the smart capsule has shown satisfactory performance in damage detection, increasing the efficiency of the monitoring with the impedance technique in civil engineering structures.

5. CONCLUSIONS

In the present contribution, an experimental procedure was performed to evaluate the impedance-based SHM technique to detect damage in a concrete structure. For this purpose, a smart capsule was embedded in the monitored structure. The signatures of the real part of the electromechanical impedance of the specimen were measured during the test by using a portable impedance analyzer SySHM. In addition, to minimize the temperature effect during the test on the impedance signatures, a hybrid optimization procedure was used. After this, to quantify the damage, the RMSD and ASD damage metrics were applied to the impedance signals.

Based on the presented results, it is possible to conclude that the electromechanical impedance method can detect damage in steel reinforced concrete structures. However, it requires more studies to improve the methodology, especially for real civil structures.

6. ACKNOWLEDGEMENTS

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