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Detection of Concrete Reinforcement Damage Using Piezoelectric Materials - Analytical and Experimental Study

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Abstract**—**An effort for the detection of damages in the reinforcement bars of reinforced concrete members using PZTs is presented. The damage can be the result of excessive elongation of the steel bar due to steel yielding or due to local steel corrosion. In both cases the damage is simulated by considering reduced diameter of the rebar along the damaged part of its length. An integration approach based on both electromechanical admittance methodology and guided wave propagation technique is used to evaluate the artificial damage on the examined longitudinal steel bar. Two actuator PZTs and a sensor PZT are considered to be bonded on the examined steel bar. The admittance of the Sensor PZT is calculated using COMSOL 3.4a. Fast Furrier Transformation for a better evaluation of the results is employed. An effort for the quantification of the damage detection using the root mean square deviation (RMSD) between the healthy condition and damage state of the sensor PZT is attempted. The numerical value of the RSMD yields a level for the difference between the healthy and the damaged admittance computation indicating this way the presence of damage in the structure. Experimental measurements are also presented.

Keywords**—**Concrete reinforcement, damage detection, electromechanical admittance, experimental measurements, finite element method, guided waves, PZT.

I. INTRODUCTION

THE detection of damaged areas of the reinforcement of Reinforced Concrete (RC) structures and further the assessment of its damage severity level are traditionally conducted through in situ inspection including optical examination, X-rays and possible partial uncover of reinforcement. Nevertheless it is quite obvious that these procedures cannot be applied in structural members covered by bricks and other building materials or in long prestressed concrete bridge beams or in non-accessible members as the foundation elements of structures.

The fact that most infrastructural systems worldwide are made of RC in combination with the seismic problem in earthquake prone regions and the observation that these structures age with time and deteriorate as a result of fatigue, overloading and insufficient maintenance necessitate the development of new more efficient structural health monitoring.

Thus based on the properties of the Piezoelectric material lead Zirconate Titanate (PZT) the detection of damages, the assessment of their severity level in non-accessible RC members and even more the on-line monitoring of the possible damage evolution with time are new potentials that probably lie ahead to be investigated.

These challenging fields of study have already become special parts of reinforced concrete and earthquake engineering research that are rapidly developed [1]. Research in these areas can be proven essential in the near future since engineers in seismic-prone regions often face the problem of detecting hidden damage of non-accessible RC members and moreover they have to meet the case of designing intervention works.

A PZT sensor can produce electrical charges when subjected to a strain field and conversely mechanical strain when an electrical field is applied. A theoretical model of the PZT functioning has been proposed by Liang et al. [2]. The Structural Health Monitoring (SHM) and damage detection techniques have been developed based on the coupling properties of the piezoelectric materials. The impedance-based SHM approach utilizes the electromechanical impedance of these materials that is directly related with the mechanical impedance of the host structural members, a property that is directly affected by the presence of any structural damage. Thus the impedance extracts and its inverse, the admittance, constitute the properties on which the PZT approach is based for the SHM of reinforced concrete structures. Specifically, the produced effects by the structural damages on the PZT admittance signatures are vertical enlargement or/and lateral shifting of the baseline signatures of the initially healthy structure. These effects are the main damage indicators on for damage detection and evaluation that many researches are based on.

Furthermore statistical techniques and indices have been employed to associate the damage with the observed shifting and alteration in the initial Electro-Mechanical Admittance (EMA) signatures such as the Root Mean Square Deviation (RMSD) [3]. Comparison of the effectiveness of the statistical indices has showed that the RMSD is the most robust and representative index for the damage level assessing [4], [5] and therefore it is used in the present work.

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Sabet Divsholi and Yang [6] used PZT sensors for the detection of damage location and severity level and Yang et al. [5] used the structural mechanical impedance extracted from the PZT electro-mechanical admittance signature as the damage indicator for the detection of structural damages in a 2-story RC frame. Further, PZT sensors bonded on steel reinforcing bars that were embedded in concrete specimens were also applied in order to perform non-destructive monitoring of the bond development between bar and concrete [7].

A novel SHM technique using a self-sensing circuit of piezoelectric sensors for detecting debonding between concrete and fiber reinforced polymer sheet laminated to a beam surface has recently been reported by Lee and Park [8]. Debonding levels have been quantified using damage indices extracted from the impedance and guided wave features of the supervised learning-based statistical pattern recognition.

Providakis and Voutetaki [9] presented a numerical method for SHM and damage identification of a concrete beam by extracting the Electro-Mechanical Impedance (EMI) characteristics of surface bounded self-sensing PZT patches. The damage was firstly quantified conventionally by the RMSD index and then by using a statistical confidence method in system identification advanced routines of a mathematical computational software.

Further, they extended the aforementioned damage detection-characterization approach and proposed a statistical utilization of EMA using a combination of finite element method and Box-Behnken design of experiment analysis [10]. This technique produces polynomial models that relate damage parameters, such as stiffness reduction, to the EMA signature generated at piezoelectric sensors at specific frequency ranges.

Moreover, a finite element modeling technique for the comparison of active constrained layer damping with purely active damping treatments for suppressing the vibrations of smart structures based on the EMI approach has also been studied [11].

Recently, the feasibility of the EMI sensing technique for the online strength gain monitoring of early-age concrete has been investigated and checked with experimental data [12]. It was found that the EMI signature is sensitive enough to the strength gain in early age concrete. In the same scope, an innovative active wireless sensing system that consists of a miniaturized EMI measuring chip and a reusable PZT transducer to monitor the concrete strength development at early ages has been proposed [13]. The effectiveness of this miniaturized sensing system to monitor the concrete strength during the hydration process has been tested using experimental results of standard cubic concrete specimens.

The aforementioned brief review indicates that the recent developments in piezoelectric materials have inspired researchers to develop new non-destructive evaluation and monitoring methods and techniques in concrete elements.

In a recent study [14] the issue of SHM of concrete beams reinforced under flexure with steel bars in the context of the damage index based on the RMSD of electromechanical signatures in time domain response is addressed. The purpose of this investigation is to apply analytical models of admittance based signature data, to analyze their accuracy and validity and check the potential of this technique to become an essential aid in monitoring structural damage in real-time.

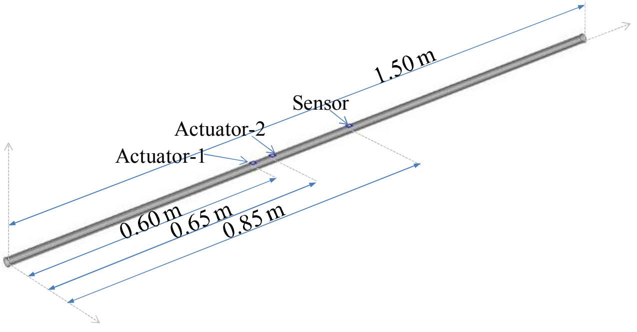
The potential of the detection of the flexural damages in the lower part of the mid-span area of a simply supported RC beam using PZTs is analytically examined. The kind of studied damages are very common in flexural concrete beams reinforced with bars located in the low part of the beam where bending tension prevails. Two severity levels of damage are examined in the paper: (i) Flexural cracking of concrete in the middle area of the beam's span that extend from the external lower fiber of concrete up to the steel reinforcing bars. This damage also causes cracks in the interface between concrete and reinforcement resulting this way to full debonding between steel bars and concrete. (ii) For higher levels of bending moment and further to the flexural cracking in the middle area of the beam yielding of the reinforcing bars is also occurred. Yielding of steel causes decrease of the effective diameter of steel bars along the length of the considered area of yielding.

The study includes the application of the finite element method for both healthy and damaged areas. Smeared modeling [15], [16] is used for cracking and yielded materials. The smeared cracking approach has been realized through the development of constitutive models for the description of cracks in concrete and cementitious materials. Because cracking is a localized phenomenon, severe complications are implied in the establishment of a proper crack model. The smeared crack model is based on the observation that, in reality, concrete cracking consists of systems of parallel cracks that are continuously distributed over the concrete mass, this model considers the cracks to be adequately represented by parallel micro-cracks distributed (smeared) over the finite elements. That is, cracks are merely represented as a change in the material property of the element over which the cracks are assumed to be smeared. Thus, cracked concrete is represented as an elastic orthotropic material with reduced elastic modulus in the direction normal to the crack plane. With this continuum approach the local displacement discontinuities at cracks are distributed over some tributary area within the finite element and the behavior of cracked concrete can be represented by average stress-strain relations. This consideration is computationally very convenient and the smeared crack concept fits the nature of the finite element displacement method, since the continuity of the displacement field remains intact and any orientation of the crack propagation direction is allowed. Thus, the method is suitable for the analytical simulation of concrete members using finite element computation schemes [15].

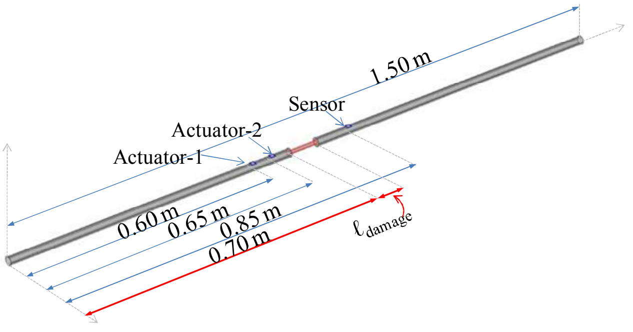
In the present work an effort for the detection of damages in the reinforcement bars of reinforced concrete members using PZTs is presented. The damage can be the result of excessive elongation of the steel bar due to yielding caused by flexural deformation of the reinforced concrete element or by local steel corrosion. In both cases the damage is simulated by considering reduced diameter of the rebar along the damaged part of its length. An integration approach based on both electromechanical admittance methodology and guided wave propagation technique is used to evaluate the artificial damage on the examined longitudinal steel bar. Two actuator PZTs and a sensor PZT are considered to be bonded on the examined steel bar. The FFT admittance of the Sensor PZT is evaluated. An effort for the quantification of the damage detection using the root mean square deviation (RMSD) between the healthy condition and damage state of the sensor PZT is attempted. The numerical value of the RMSD yields a level for the difference between the healthy and the damaged admittance computation indicating this way the presence of damage in the structure. Experimental measurements are also presented.

II. EXAMINED CASES – ANALYTICAL SIMULATION

The test specimen of this study is a longitudinal steel bar of 20mm diameter (∅20) and 1500mm long. Three PZT patches namely as Actuator-1, Actuator-2 and Sensor are considered to be bonded on the surface of the steel bar after a proper flattening in distances of 60cm, 65cm, and 85cm away from the left end, respectively. The geometry, the location of the PZT actuators and PZT sensor are illustrated in Fig. 1 (a).



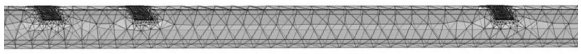
(a) Healthy condition



(b) Damage condition

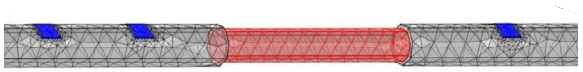
Fig. 1 Concrete reinforcement, geometry and location of the PZT patches and damage location

Five different damage cases in the form of reduced material from the rebar along a certain part of its length are considered (Fig. 2). This kind of damage can be produced by elongation of tensional longitudinal reinforcement due to flexural bending of a reinforced concrete element or due to local steel corrosion.



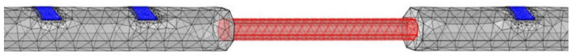
Healthy condition of concrete reinforcement ∅20

(see also *crosssection a*)



Damage Case 1: ℓ_{damage}=10cm – diameter reduction to ∅16

(see also *crosssection b*)

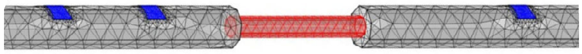


Damage Case 2: ℓ_{damage}=10cm – diameter reduction to ∅10

(see also *crosssection c*)

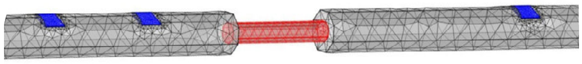
Damage Case 3: ℓ_{damage}=10cm – diameter reduction to ∅6

(see also *crosssection d*)



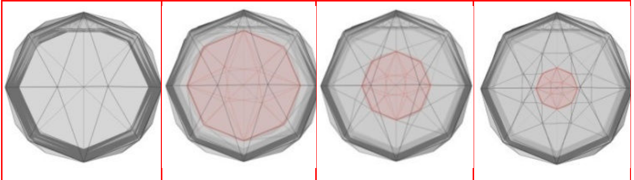
Damage Case 4 : ℓ_{damage}=7cm – diameter reduction to ∅10

(see also *crosssection c*)



Damage Case 5: ℓ_{damage}=5cm – diameter reduction to ∅10

(see also *crosssection c*)



Cross section a *Cross section b* *Cross section c* *Cross section d*

Fig. 2 Damage cases and mesh of the 3-D model of the concrete reinforcement.

Damage Case 1: in a length (ℓ_{damage}) of 10cm (yielding area) the initial diameter of the steel bar (∅20) has been reduced to 16 mm diameter (∅16) due to corrosion.

Damage Case 2: in a length (ℓ_{damage}) of 10cm (yielding area) the initial diameter of the steel bar (∅20) has been reduced to 10 mm diameter (∅10) due to corrosion.

Damage Case 3: in a length (ℓ_{damage}) of 10cm (yielding area) the initial diameter of the steel bar (∅20) has been reduced to 6 mm diameter (∅6) due to corrosion.

Damage Case 4: in a length (ℓ_{damage}) of 7cm (yielding area) the initial diameter of the steel bar (∅20) has been reduced to 10 mm diameter (∅10) due to corrosion.

Damage Case 5: in a length (ℓ_{damage}) of 5cm (yielding area) the initial diameter of the steel bar (∅20) has been reduced to 10 mm diameter (∅10) due to corrosion.

All the damage cases are measured in a distance of 70cm away from the left end (Fig. 1 (b)).

The local decrease of the diameter of the yielded steel bar is simulated in the performed finite element analysis as shown in Fig. 2. The finite element mesh of the examined cases of the steel bar is generated in COMSOL 3.4a [17] using approximately 8900 to 9800 finite elements depending on the case.

In this study an integration approach based on both electromechanical admittance methodology and guided wave propagation technique is used to evaluate artificial damage on longitudinal steel bar. The electromechanical admittance technique uses piezoelectric materials, such as PZT, which exhibits the characteristic feature to generate surface charge in response to an applied mechanical stress and conversely, undergo mechanical deformation in response to an applied electric field. Thus, when a PZT bonded to the structure is actuated, the damage-induced change in the mechanical impedance of the structure is reflected in the electrical admittance of the PZT. When a structure is regularly monitored by extracting the admittance signal to the exciting frequency of the PZT, the changes in this signature become indicative of the presence of structural damage [18], [19]. This way a potential damage can be detected by changes in admittance signatures of smart piezoelectric transducers bonded on the structure. In the guided wave propagation one PZT patch (actuator) is used to generate waves through the structure and a PZT that acts as sensor is recording the received vibration signals.

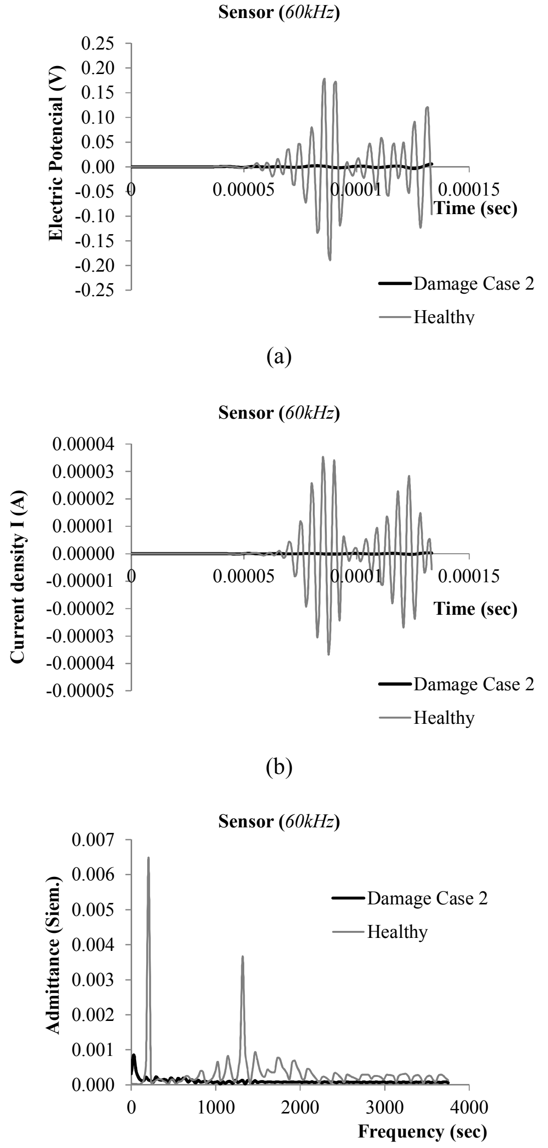
Special attention has also been given in the selection of the excitation frequencies. It has been proven [14] that damage detection capability greatly depends on the frequency selection rather than on the level of the excitation loading. This observation demonstrates that excitation loading sequence can have a level low enough that the technique may be considered as applicable and effective for real structures. Thus, in this study analyses are performed for a frequency range of 10kHz to 100kHz per step of 10kHz by using eight cycles.

A harmonic excitation voltage of 10 Volts is amplified to both Actuator-1 and Actuator- 2 in time domain range, *t*, every central frequency, as described by the expression:

$$V_{PZT}(t) = 10\sin(2\pi\omega t) \tag{1}$$

In Fig. 3 the time histories of the voltage V(t) and the current I(t) passing through the PZT – Sensor are shown for the examined Damage Case 2 in comparison to the corresponding quantities of the undamaged stage (Healthy case). These results are for the case of 60kHz frequency excitation. Thereafter, for the evaluation of the admittance spectrum of the PZT-Sensor at the predefined frequency, a Fast Fourier Transformation (FFT) of the above time domain signals (V(t), I(t)) is performed in order to achieve the corresponding frequency domain quantities of V(iω) and I(iω). Finally the FFT admittance of the PZT Sensor can be evaluated as (see also Fig. 3):

$$\text{FFT (admittance)} = \frac{\text{FFT (I)}}{\text{FFT (V)}} \tag{2}$$



(a)

(b)

(c)

Fig. 3 Time histories of (a) voltage V(t) and (b) current I(t) passing through the PZT – Sensor. (c) FFT admittance spectrum. Comparative results between Healthy condition and Damage Case2 *(frequency excitation of 60kHz)*

Moreover, in order to quantify the damage detection by using the aforementioned integration approach the root mean square deviation (RMSD) between the healthy condition and damage state of the PZT Sensor is calculated as:

$$\mathrm{RMSD} = \sqrt{\frac{\sum_{i=1}^{k}\left[(Y_{i,1}) - (Y_{i,2})\right]^{2}}{\sum_{i=1}^{k}\left[(Y_{i,1})\right]^{2}}} \tag{3}$$

where $Y_{i,1}$ is the admittance of the sensor at the initial undamaged condition (healthy case), ($Y_{i,2}$) is the admittance for the damage state at the i^{th} measurement point and k is the number of the measurement points.

The greater the numerical value of the RSMD the larger the difference between the healthy and the damaged admittance computation indicating this way the presence of damage in the structure.

III. NUMERICAL RESULTS

In Fig. 4 comparative results of the evaluated FFT admittance of the Sensor between the healthy condition of the steel bar and the examined damaged states are presented for the case of frequency excitation that of 40kHz.

The sensitivity of the PZT – Sensor in damage level of the concrete reinforcement is clearly depicted in FFT admittance spectra that presented in Fig. 4. For example, the differences between the damaged Case 3 and the Healthy condition on the FFT admittance amplitudes are greater than the corresponding differences between damaged Case 2 and Healthy state. Further, the distance of the applied PZT-Sensor from the damage location alters different values of damage detection in terms of FFT admittance spectrum. This observation can be deduced by comparing the results between the damage Case 2, damage Case 4 and damage Case 5 (Fig. 4).

As it has already be mentioned special attention has also been given in the selection of the excitation frequencies since damage detection capability greatly depends on the frequency selection. Thus, in this study analyses are performed for a frequency range of 10kHz to 100kHz per step of 10kHz. In Fig. 5 comparative results of the evaluated FFT admittance of the PZT-Sensor between the Healthy condition of the concrete reinforcement and the damage Case 2 are presented for the frequencies of 10kHz, 30kHz, 50kHz, 70kHz and 90kHz. The frequency sensitivity of the PZT-Sensor in the admittance signatures can clearly be observed.

For the examined frequency band (10kHz to 100kHz), in Fig. 6 comparative results of the final admittance of the PZT-Sensor between the Healthy condition of the steel bar and the examined damaged Cases are presented. Based on these results the following observations are noted:

- Large amplitude differences in admittance signatures between Healthy and damage Case 1 are recognized when the applied frequency excitations are 10kHz, 70kHz, 80kHz, 100kHz. In the frequencies of 30kHz to 60kHz these differences may be considered negligible.
- The frequency excitation of 10kHz also gives large differences in admittance signatures between Healthy and damage Case 2. Nevertheless it is also noted that for the frequency of 60kHz in the damage Case 2 the admittance of the PZT-Sensor is greater than the corresponding value in damage Case 1 and when the damage is considered even greater than the damage Case 2 (damage Case3) the admittance of the PZT-Sensor is increased.

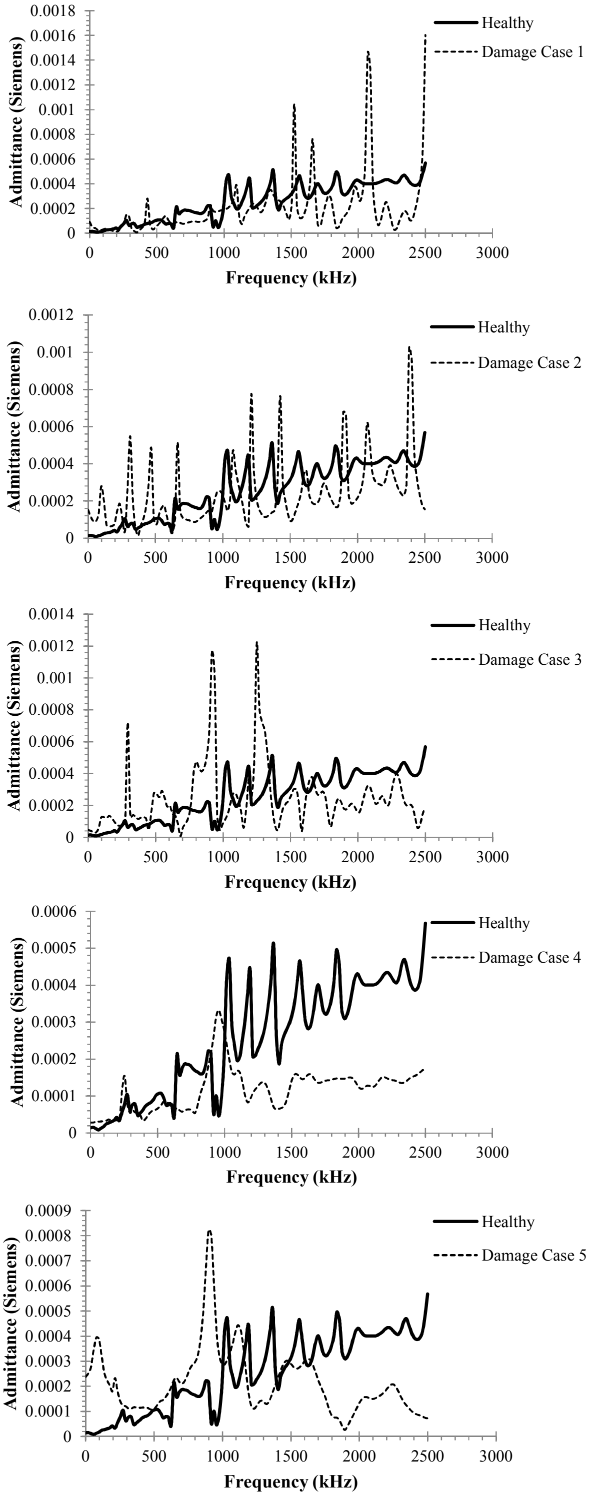


Fig. 4 FFT admittance spectra of the PZT-Sensor. Comparative results between Healthy condition and Damage Cases *(frequency excitation of 40kHz)*

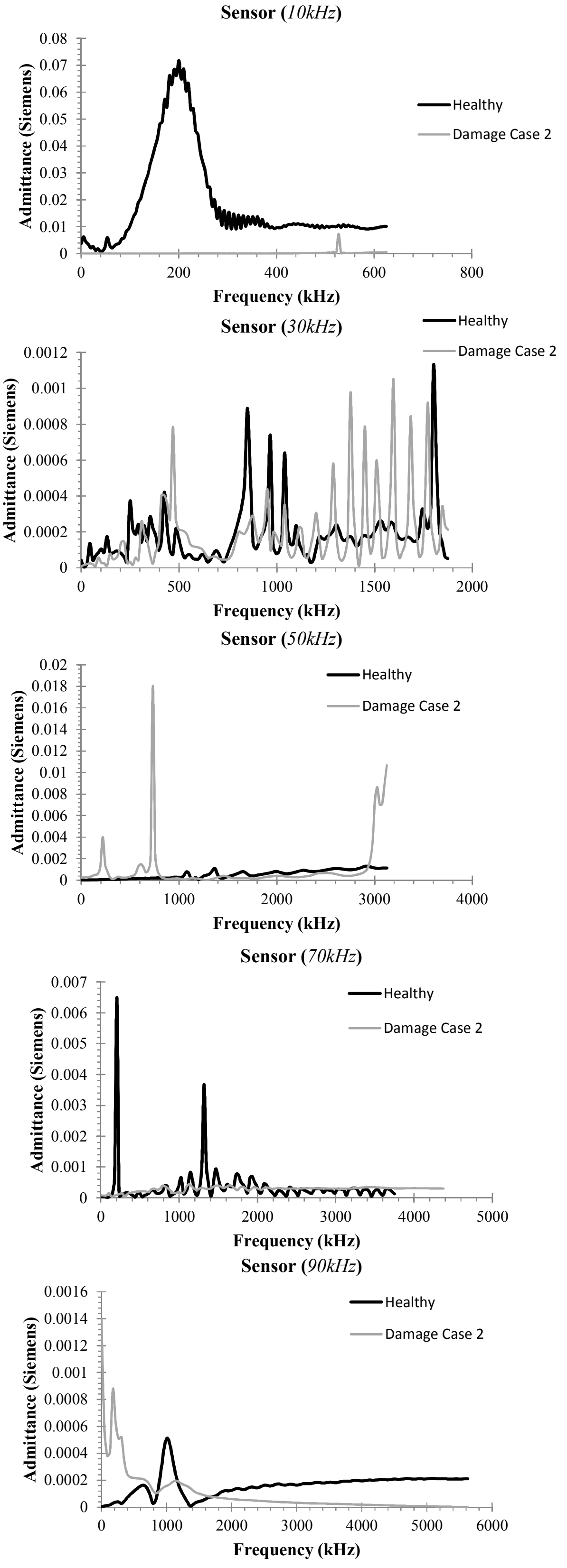


Fig. 5 FFT admittance spectra of the PZT-Sensor. Comparative results between Healthy condition and Damage Case 2 and for values of *frequency excitation that of 10kHz, 30kHz, 50kHz, 70kHz, 90kHz*

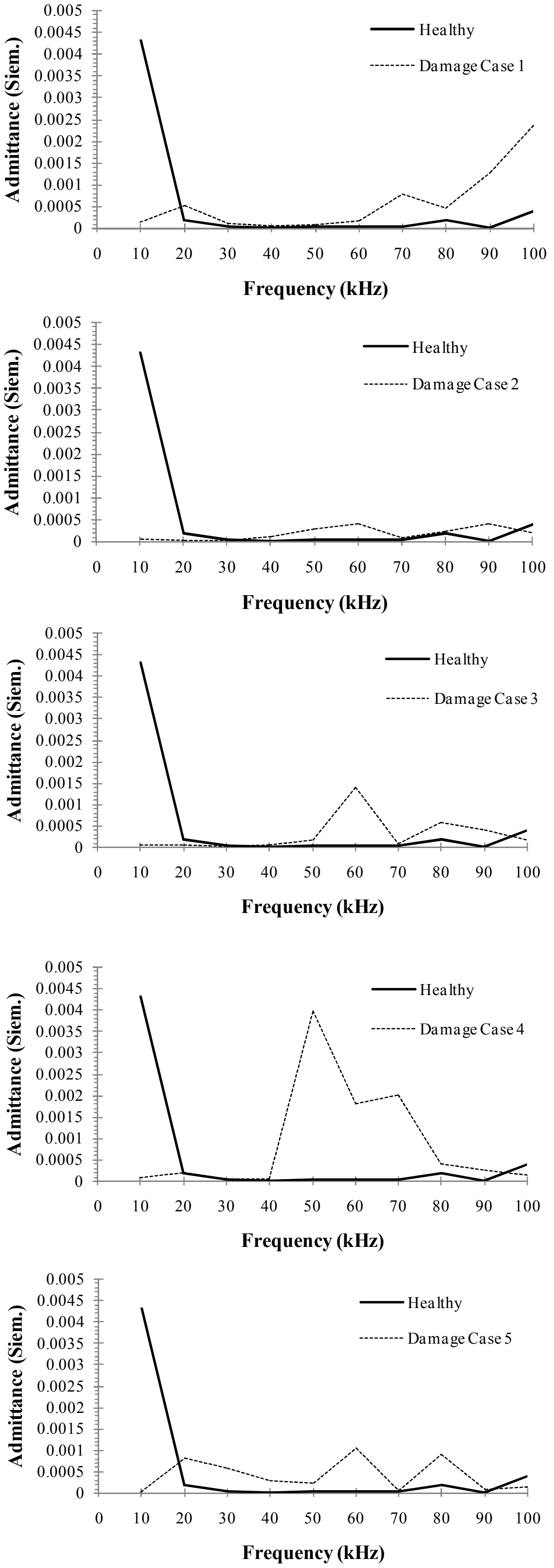
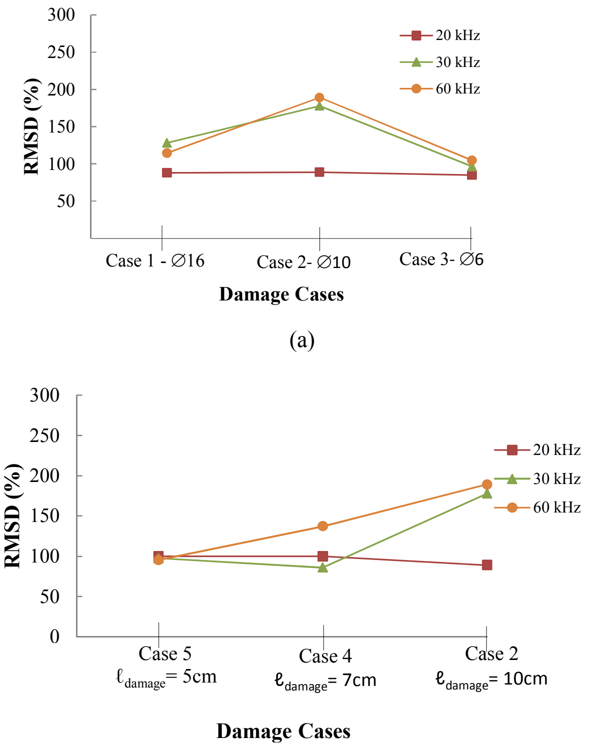


Fig. 6 Final admittance spectra of the PZT-Sensor. Comparative results between Healthy condition and damaged states for the examined frequency band

- Large amplitude differences in admittance between Healthy and damage Case 4 are recognized when the applied frequency excitations are 10kHz, 50kHz, 60kHz, and 70kHz. In the frequencies of 20kHz to 40kHz and 80kHz to 100kHz these differences may be considered negligible.
- Finally, differences in admittance values between Healthy and damage Case 5 are recognized in almost all the frequency excitations (10kHz to 60kHz and 80kHz).

As it has already been mentioned the quantification of the damage detection may be achieved by evaluating the root mean square deviation (RMSD) between the healthy condition and damage state of the PZT-Sensor. Based on the FFT admittance magnitude the calculated damage indexes for the PZT-Sensor for all the damage states are evaluate in terms of RMSD (%). This way the influence of the frequency excitation value on the detection of the damage on the concrete reinforcement steel bar is provided. The results in Fig. 7 are indicative for the frequency excitations of 20kHz, 30kHz and 60kHz.

It can be observed that for frequency values of 20kHz and 30kHz the RMSD index is increased when the diameter of the steel bar is further reduced from ∅16 (damage Cases 1) to ∅10 (damage Cases 2). However, significant changes on the corresponding values of the RMSD index are not observed in the case of 60kHz frequency (Fig. 7 (a)).



(b)

Fig. 7 Influence of the frequency excitation on the RMSD index of the PZT-Sensor in accordance to the level of damage in the steel bar. (*Frequency excitations of 20kHz, 30kHz and 60kHz*)

In Fig. 7 (b) the sensitivity of the RMSD index to detect different damage condition in terms of length (yield penetration) on the concrete reinforcement is examined. It can be observed that in the frequency of 60 kHz the value of the RMSD index for damage length on the steel bar equal to 10cm is greater than the one of 7cm and also greater than the one of 5cm. Similar observations also hold for the frequency case of 30kHz. The values of the damage index are not really affected by changes on the damaged state of the steel for the frequency level of 20kHz.

An effort for the validation of the analytical results and conclusions of this study through experimental investigation is also included. Initial results of the experimental evaluation are presented in the following section.

IV. EXPERIMENTAL EVALUATION

The experimental set-up shown in Fig. 8 is used for the evaluation of the damage on a concrete reinforcement steel bar using the integration approach based on both the electromechanical admittance methodology and the guided wave propagation technique. For this purpose two PZT patches are used one as an actuator to generate the wave signal and the other as a sensor. The PXI Platform presented in Fig. 8 is a USB-6251high-speed M series multifunction module. It is used to excite the PZT actuator and is running under the Labview Signal Express program. With the Labview Signal Express a wide band excitation signal sweeping can also be achieved. The overall concept of the adopted admittance measuring system is based on the one provided by Providakis et al. [20]. In the experimental evaluation of the damage the admittance spectrum of the PZT is equal to Fast Fourier Transform (FFT) of the response signal over the Fast Fourier Transform (FFT) of the excitation signal. Nevertheless, more details about the admittance measuring system can be found in a work by Providakis et al. [20].

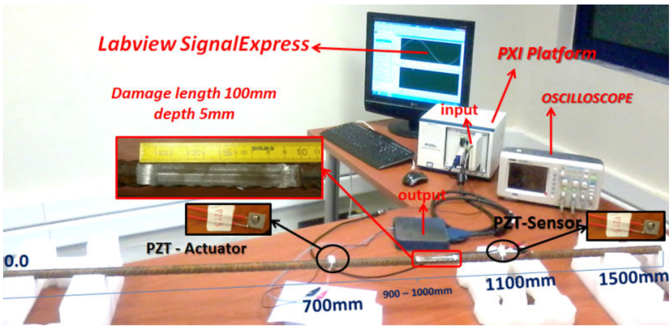
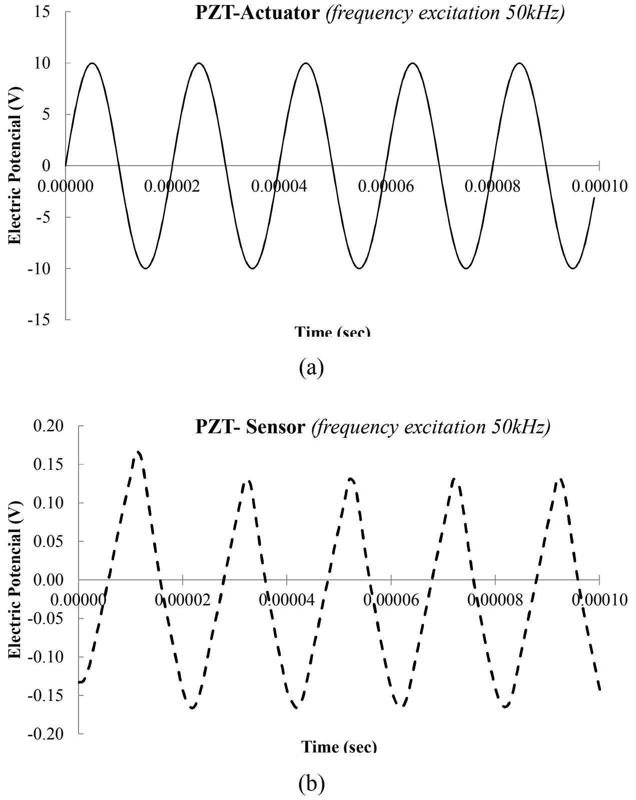


Fig. 8 Experimental set –up

The damage in the steel bar is artificially introduced by removing material as it can be observed in Fig. 8. The diameter of the examined steel bar is 20mm (∅20) and the total length of the specimen is 1500mm. The PZT patches namely as PZT-Actuator and PZT-Sensor are bonded on the surface of the steel bar after a proper flattening in the distances of 70cm and 110cm away from the left end, respectively. The actuator is excited by the PXI Platform in the way it is presented in Fig. 9 (a) for the case of 50kHz frequency excitation. The corresponding recorded voltage signal of the PZT-Sensor is presented in Fig. 9 (b). Finally in Fig. 10 the admittance spectrum of the PZT-Sensor for frequencies range 10kHz to 100kHz is presented. The calculation of the RMSD index qualitatively shows that the same tendency can be traced in the experimental observation as in the analytical results.



(a)

(b)

Fig. 9 Applied voltage excitation V(t)on the PZT-Actuator and recorded signal on PZT-Sensor. (*frequency excitations of 50kHz*)

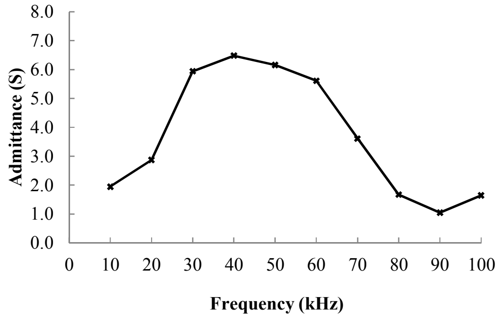


Fig. 10 Admittance spectrum of the PZT-Sensor for frequencies range 10kHzto 100kHz based on the experimental results

V. CONCLUSIONS

The utilization of the electromechanical admittance methodology and the guided wave technique for the detection of damage in reinforcing rebars of reinforced concrete elements using PZTs has been presented. The results are very promising. The numerical value of the RMSD yielded a level for the difference between the healthy and the damaged admittance computation indicating this way the presence and a level of the damage in the examined steel bar. Preliminary experimental measurements have also been presented.

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