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Research Article

Usage of PZTs for Damage Evaluation of Steel Reinforcing Bar

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Abstract: This study presents an effort for the damage assessment of reinforcing bars using bonded piezoelectric transducers and the implementation of an integration approach based on the electromechanical admittance method. The damage is the result of excessive elongation of the bar due to yielding caused by flexural deformation of are in forced concrete element or by local steel corrosion and it is simulated considering reduced bar diameter along the damaged part of its length. Test measurements of healthy and artificially damaged steel bars have been conducted using the developed monitoring system. The experimental program comprises data acquisition of current density curves for healthy and damaged bars as detected by the test instrumentation and implementation of the adopted admittance-based procedure to evaluate damages at different levels. Analytical simulations of the same healthy and damaged bars have also been carried out using the finite element software COMSOL. It was found that the sensitivity of the piezoelectric transducers greatly depends on the selection of the excitation frequencies. Current density and admittance curves demonstrated discrepancies between the response of the healthy and the damage states. Admittance signatures showed a clear gradation of the examined damage levels.

Keywords: Reinforcing steel, piezoelectric material (PZT), electromechanical admittance, damage detection, experimental testing, finite element method.

INTRODUCTION

The implementation of smart materials in “intelligent” Reinforced Concrete (RC) structures is an emerging concept with a potential impact on the sustainability, security, structural health monitoring and safety of the built environment. The detection of damaged areas of the reinforcement of 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 a structure. 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.

Piezoelectric materials such as Lead Zirconate Titanate (PZT) ceramic have been widely used as sensor due to its high electromechanical coupling factor and piezoelectric coefficients [1, 2, 3].Thus based on the properties of the PZTs 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 topics of RC and earthquake engineering research that are rapidly developed [4]. 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 issue of the design of intervention works.

A PZT sensor produces electrical charges when subjected to a strain field and conversely it produces mechanical strain when an electrical field is applied. A theoretical model of the PZT functioning has been proposed by Liang et al. [5]. The structural health monitoring and damage detection techniques have been developed based on the coupling properties of the piezoelectric materials. The impedance-based structural health monitoring 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 structural health monitoring 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.

Sabet Divsholi and Yang [6] used PZT sensors for the detection of damage location and severity level and Yang et al. [7] used the structural mechanical impedance extracted from the PZT electromechanical 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 [8].

A novel structural health monitoring technique using a self-sensing circuit of piezoelectric sensors for detecting the debonding between concrete and fibre reinforced polymer sheet laminated to a beam surface has recently been reported by Lee and Park [9]. 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 [10] presented a numerical method for structural health monitoring and damage identification of a concrete beam by extracting the electromechanical impedance characteristics of surface bounded self-sensing PZT patches. The damage was firstly quantified conventionally by the root mean square deviation 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 electromechanical admittance using a combination of the finite element method and the Box-Behnken design of experiment analysis [11]. This technique produces polynomial models that relate damage parameters, such as stiffness reduction, to the electromechanical admittance 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 electromechanical impedance approach has also been studied [12].

Recently, the feasibility of the electromechanical impedancesensing technique for the online strength gain monitoring of early-age concrete has been investigated and checked with experimental data [13]. It was found that the electromechanical 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 electromechanical impedancemeasuring chip and a reusable PZT transducer to monitor the concrete strength development at early ages has been proposed [14]. 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 for concrete elements.

In a recent study [15] the issue of structural health monitoring of concrete beams reinforced under flexure with steel bars in the context of the damage index based on the electromechanical signatures in time domain response has been addressed. The purpose of this investigation was to apply analytical models of admittance based signature data, to analyse 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 steel bars of the lower part of the mid-span area of a simply supported RC beam using PZTs has been analytically investigated. 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 have been examined: (i) Flexural cracking of concrete in the middle area of the beam’s span that extend from the external lower fibre of concrete up to the steel reinforcing bars. This damage also causes cracks in the interface between concrete and reinforcement resulting this way to debonding between steel bars and concrete. (ii) Damage observed for higher levels of bending moment and especially damage in the middle area of the beam that corresponds to the occurrence of the yielding of the reinforcing bars. It is stressed that yielding of steel causes decrease of the effective diameter of steel bars along the length of the considered area of yielding allowing this way a sound detection of the observed damage through PZTs. Finite element method simulations for both healthy and damaged areas have also been included. Smeared modeling [16, 17] is used for cracking and yielded materials. The smeared cracking approach has been adopted through the development of constitutive models for the description of cracks in concrete and cementitious materials. Since 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 properties 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 behaviour 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 [16].

This study extends the previous one and demonstrates an effort for the detection of potential damages in the steel reinforcing bars of RC members using piezoelectric transducers and the implementation of an integration approach based on the electromechanical admittance method. The examined damage is considered as the result of excessive elongation of the steel bar due to yielding caused by flexural deformation of the RC 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. The investigation presented herein is twofold; experimental and analytical. Experimental measurements of undamaged (healthy) and artificially damaged steel bar have been conducted using an integrated monitoring system and the electrical readings of two PZTs transducers bonded on the surface of the examined steel bar. Analytical simulations of the same healthy and damaged steel bar have also been carried out using the finite element software COMSOL3.4a [18]. Comparisons between analytical and experimental results are also presented and discussed.

DAMAGE DETECTION PROCEDURE

Experimental implementation

The experimental set-up shown in Fig. 1 is used for the evaluation of the damage on a concrete reinforcement steel bar. It is a specially implemented monitoring system that is based on the electromechanical admittance methodology and utilizes the measurements of two mounted piezoelectric lead zirconatetitanate patches(PZT1 and PZT2) that working separately can serve as both actuators and sensors.

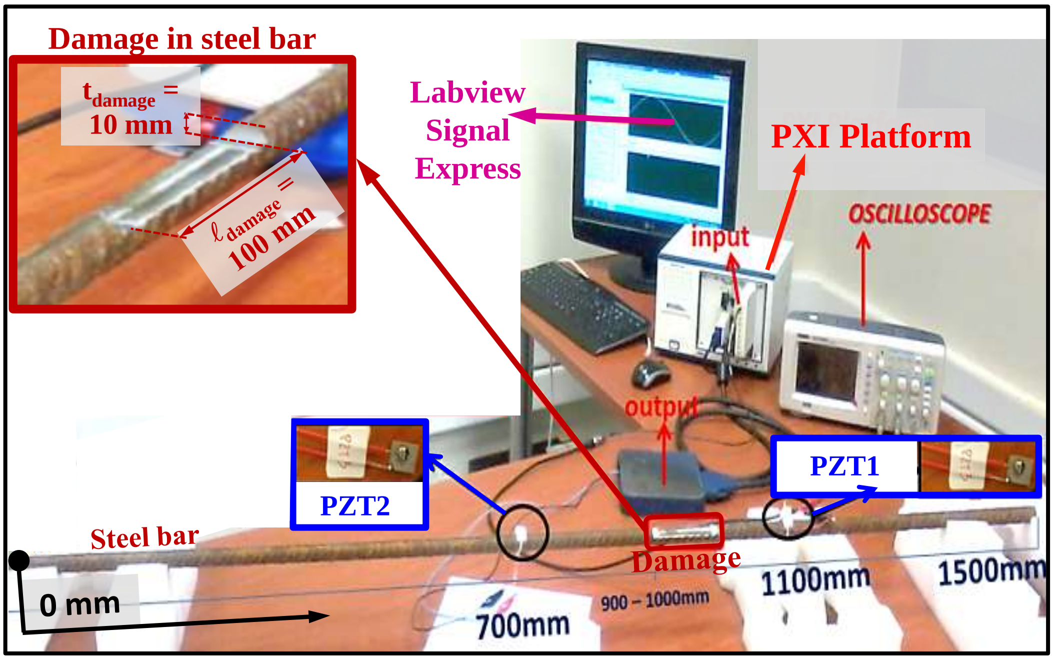
The admittance-based integrated monitoring system includes a PXI platform (see also Fig. 1a)that is a USB-6251high-speed M series multifunction module and is used to excite the PZT transducers. This way, the PZTs are sending out the interrogating wave and receiving the reflected wave at the same time. The PXI platform is running under the Lab view Signal Express program. With the Lab view Signal Express a wide band excitation signal sweeping can also be achieved.

The diameter of the examined steel reinforcing bar is 20 mm (∅20) and the total length of the specimen is 1500mm. The damage examined has been artificially introduced by removing materialalong a length of λ_{damage} = 100 mm andin a width equal to the half of the steel bar diameter: t_{damage} = 10 mm (see also Fig. 1a). The material designation of the PZTs used in this first experimental part is PIC 155.

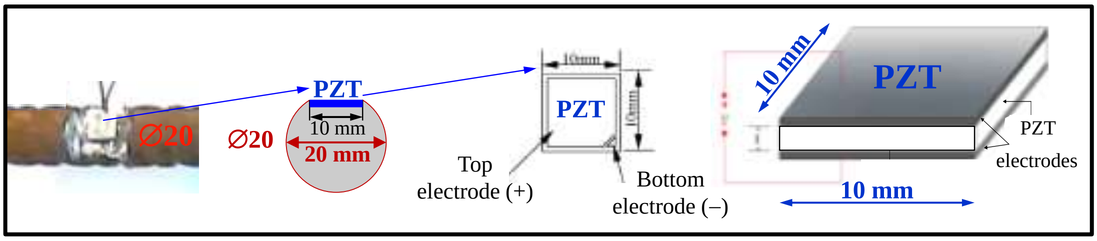
Fig 1b displays the piezoelectric patches used with dimensions 10 mm × 10 mm that are bondedon the surface of the steel bar after a proper flattening of the bar. The distances of PZT1 and PZT2 are 1100 mm and 700 mm away from the left end of the bar, respectively and they are located 100 mm and 200 mmaway from the edges of the 100 mm long damage, respectively (see also Fig. 1a).

The overall concept of the adopted admittance measuring system is based on the one provided by Providakis et al. [19]. In the experimental evaluation of the damage the admittance spectrum of each 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. [19, 20].

The PZT transducers are excited by the PXI Platform for a specific frequency range and their corresponding signals are recorded simultaneously [21]. These measurements are carried out initially on the undamaged steel bar in order to record the healthy condition and to be used as a reference signature. After the artificially introduced damage the same measurements are carried out on the damaged steel bar.



(a) Overall view of the test set-up

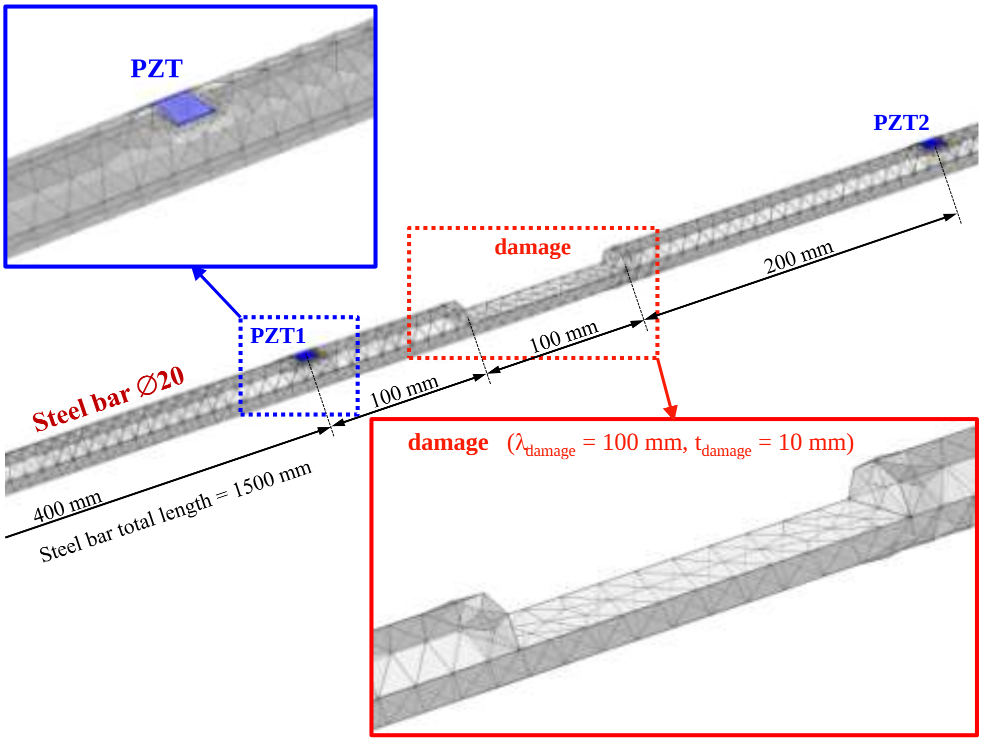


(b) PZT patch configuration

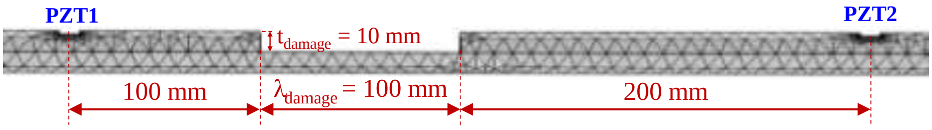
Fig-1: Test rig and instrumentation for EMA method for damage detection in steel reinforcing bar

Analytical simulation

The 1500 mm long ∅20 steel reinforcing bar was also analytically simulated using the software COMSOL 3.4a. Finite element analyses of the undamaged bar (healthy state) and the damaged with λ_{damage} = 100 mm and t_{damage} = 10 mm have been performed. The finite element mesh of the steel bar damaged case is displayed in Fig. 2a that includes details of PZT and damage regions. The distances between two PZTs (PZT1 and PZT2) and the edges of the damage area are shown in Fig. 2b. The geometrical and mechanical characteristics of the steel bar, the examined damage and the piezoelectric transducers of the tests and the analyses were kept the same for comparison reasons.



(a) 3D view of the steel bar finite element mesh (details of the damage and the PZT patches)



(b) Side view

Fig-2: Analytical simulation of the steel reinforcing bar, the PZT patches and the damage

Electromechanical admittance procedure

The electromechanical admittance technique uses piezoelectric materials, such as piezoelectric lead zirconatetitanate transducers (PZTs). The PZTs exhibit the characteristic feature to generate surface charge in response to an applied mechanical stress and 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 [22, 23]. This way a potential damage can be detected by changes in admittance signatures of smart piezoelectric transducers bonded on the structure. Recently, this technique has also been successfully demonstrated by Talakokula et al. [24] to monitor chloride-induced corrosion in RC structures.

Special attention has also been given in the selection of the excitation frequencies. It has been proven that damage detection capability greatly depends on the successful frequency selection of the excitation rather than on the level of the excitation loading itself. This observation demonstrates that excitation loading sequence can have a level low enough that the technique may be considered as easily applicable and effective for real structures. Thus, in this study analyses are performed for a frequency range of 10 kHz to 70kHz per step of 10kHz by using one cycle per 10 kHz.

A harmonic excitation voltage of 1 Volt is amplified to the PZTs in time domain range at every central frequency, as described by the expression:

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

where: V_{PZT} is the excitation voltage of the PZT, isω is the angular frequency of the driving voltage and t is the time domain range.

The experimental project comprises two levels of data acquisition:

i. Current density curves for healthy and damaged bars as detected by the instrumentation.

ii. Implementation of the adopted electromechanical admittance experimental procedure to detect damages at different damage levels.

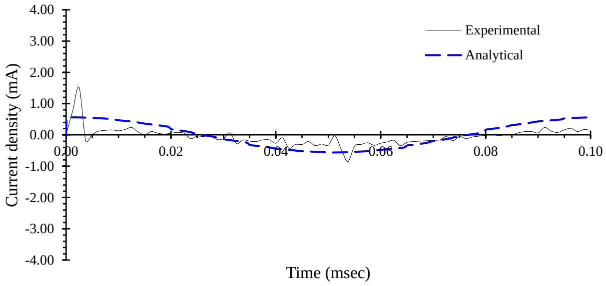
RESULTS AND COMPARISONS BETWEEN EXPERIMENTAL AND ANALYTICAL CURRENT DENSITY CURVES

The experimentally measured and the analytically derived time histories of the current density passing through the PZT1 for the undamaged steel bar (healthy state) are compared in Fig. 3. These results are shown in Figs 3a, b and c for the case of 10kHz, 30 kHz and 50 kHz frequency excitation, respectively. In the same way, comparisons between the experimental and the analytical time history curves of the current density passing through the PZT1 for the damaged steel bar are shown in Figs 4a, b and c for frequency excitation10kHz, 30 kHz and 50 kHz, respectively. Figs 3 and 4 indicate that a satisfactory correlation between analyses and tests can be obtained.

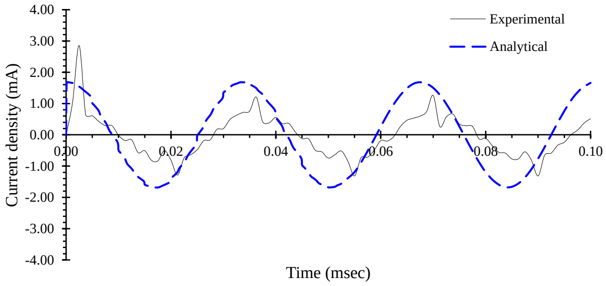
Further, in Figs 5a, b and c the PZT1 current density versus time curves of the healthy and the damage state are compared for both analytical and experimental results and for frequency excitation 10kHz, 30 kHz and 50 kHz, respectively. The comparisons of Fig. 5 diagrams point out that in both procedures, analyses and tests, there are differences between the response of the healthy and the damage state of the steel bar. These discrepancies are observed at the peak current density points.

Thereafter, for the evaluation of the admittance spectrum of the PZTs at the predefined frequencies, a Fast Fourier Transformation (FFT) of the time domain signals of voltage, V(t) and current density I(t) is performed in order to achieve the corresponding frequency domain quantities of V(iω) and I(iω). Since the admittance of a PZT transducer is the ratio of the current density to the voltage of the PZT, the FFT admittance can be evaluated as:

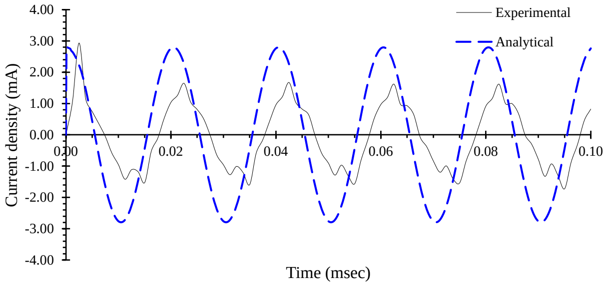
$$\text{FFT (admittance)} = \frac{\text{FFT (I)}}{\text{FFT (V)}} \qquad (2)$$



(a) Excitation frequency 10 kHz

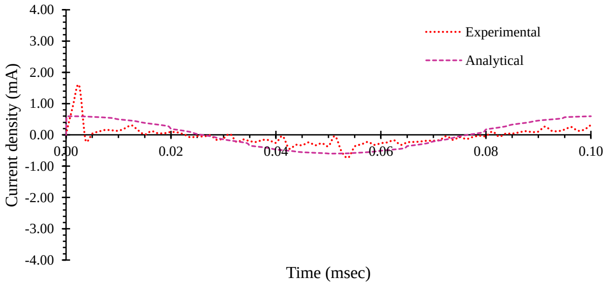


(b) Excitation frequency 30 kHz

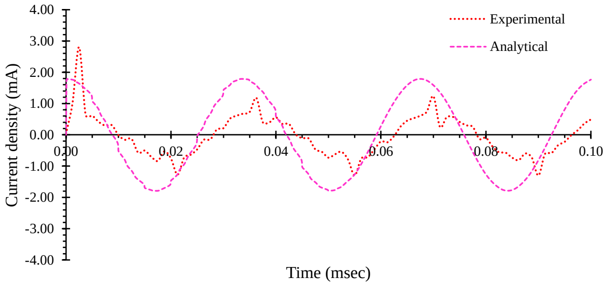


(c) Excitation frequency 50 kHz

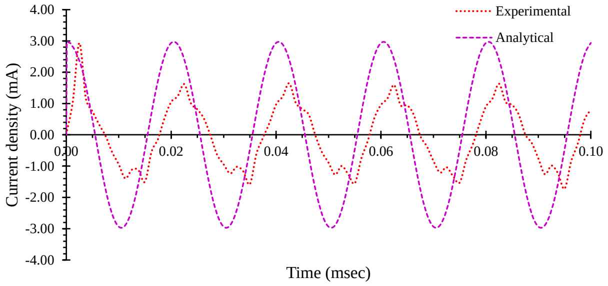
Fig-3. Comparisons between the analytical and the experimental results of the PZT1 current density curves versus time for the non-damaged (healthy state) steel reinforcing bar and for excitation 1 Volt



(a) Excitation frequency 10 kHz



(b) Excitation frequency 30 kHz



(c) Excitation frequency 50 kHz

Fig-4. Comparisons between the analytical and the experimental results of the PZT1 current density curves versus time for the damaged steel reinforcing bar and for excitation 1 Volt

In Figs. 6a, b and c comparative results of the analytically evaluated FFT admittance spectra (absolute values) of the PZT1 between the healthy and damaged state of the steel bar are presented for the case of 10kHz, 30 kHz and 50 kHz frequency excitation, respectively.

Further, it is known that the electromechanical admittance of the PZT transducer, Y, is expressed as:

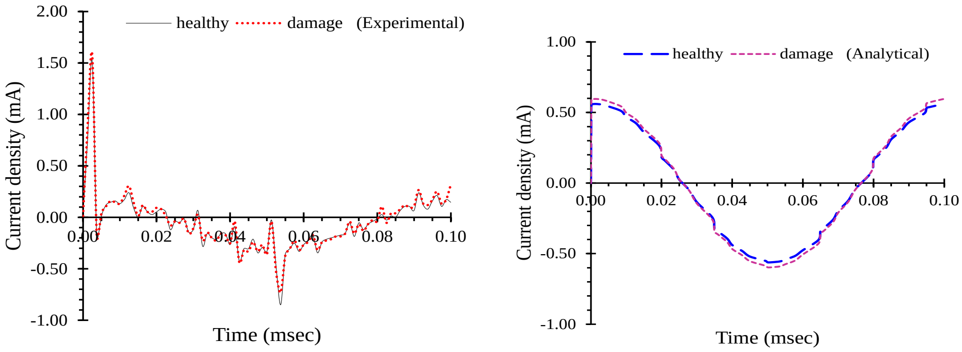
$$Y(j\omega) = G(\omega) + jB(\omega) \qquad (3)$$

where: G is the conductance or the real part real part of admittance,B is the susceptance or the imaginary part of admittance and j is the imaginary unit.

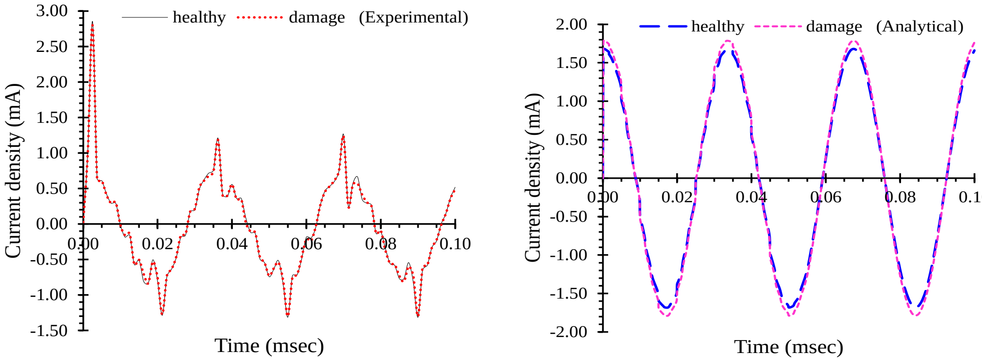
This way the absolute value of the admittance is calculated by the following equation:

$$|Y(j\omega)| = \sqrt{G^2(\omega) + B^2(\omega)} \qquad (4)$$

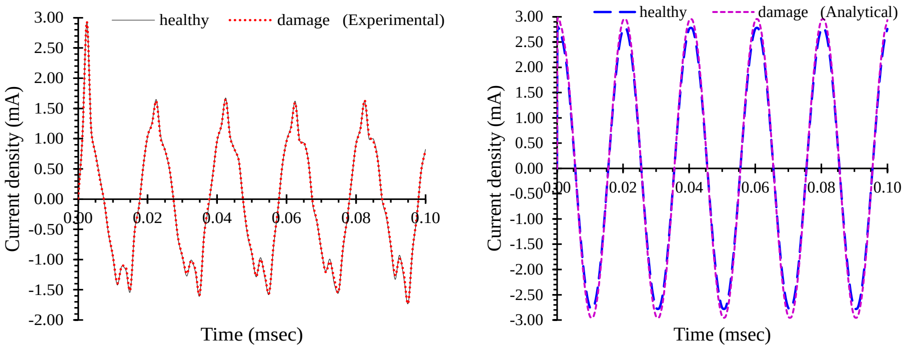
Based on the aforementioned expressions, in Fig. 7 the experimentally obtained relationship of the PZT1 admittance versus the examined frequency range of 10-70kHz for the cases of the undamaged (healthy) and the damaged steel bar are compared. Particularly, diagrams of Figs 7a, b and c present the conductance, the susceptance and the absolute (abs) value of the admittance, respectively.



(a) Excitation frequency 10 kHz



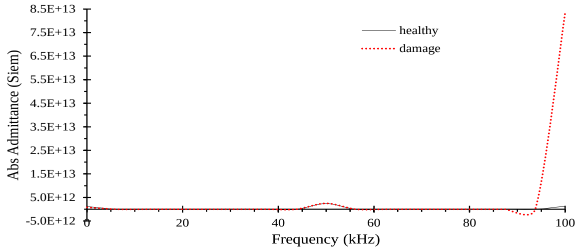
(b) Excitation frequency 30 kHz



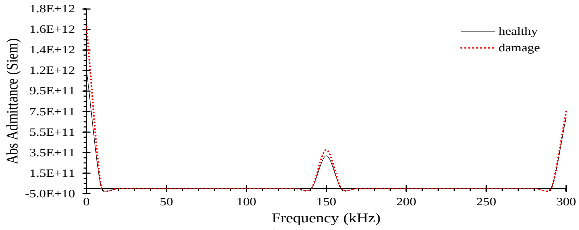
(c) Excitation frequency 50 kHz

Fig-5: Comparisons between the healthy and the damaged state of the steel reinforcing bar using the PZT1 current density curves versus time (excitation 1 Volt)

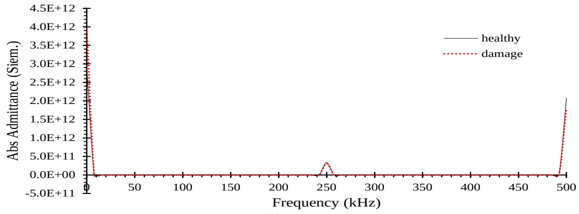
The sensitivity of the PZT1 in damage level of the steel bar is clearly depicted in the admittance curves displayed in Fig. 7. The differences of the typical experimental conductance signatures between the healthy and the damage state are obvious, indicating this way the presence and a level of the damage in the examined steel bar.



(a) Excitation frequency 10 kHz

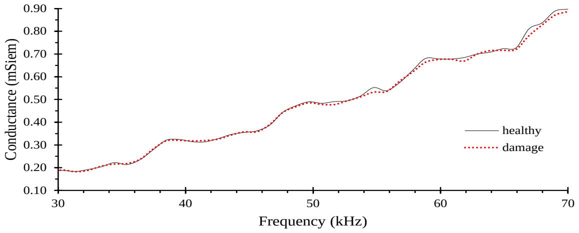


(b) Excitation frequency 30 kHz

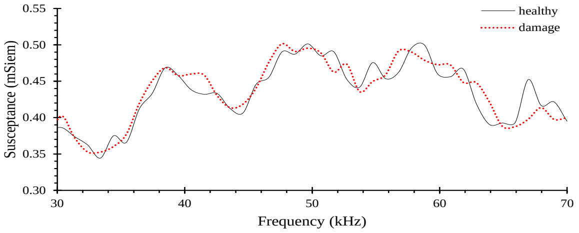


(c) Excitation frequency 50 kHz

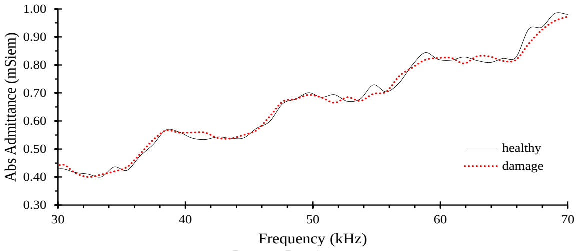
Fig-6. PZT1 Fast Fourier Transform (FFT) analytical diagrams of the healthy and the damaged steel reinforcing bar(excitation 1 Volt)



(a) Conductance



(b) Susceptance



(c) Abs admittance

Fig-7. Comparisons of the PZT1experimental measurements of admittance between the healthy and the damaged steel reinforcing bar(excitation 1 Volt)

Moreover, based on the experimental measurements ofPZT2for frequency excitation 50 kHz, the time domain signals of PZT2 current density of the healthy and the damage state are compared in Fig. 8.

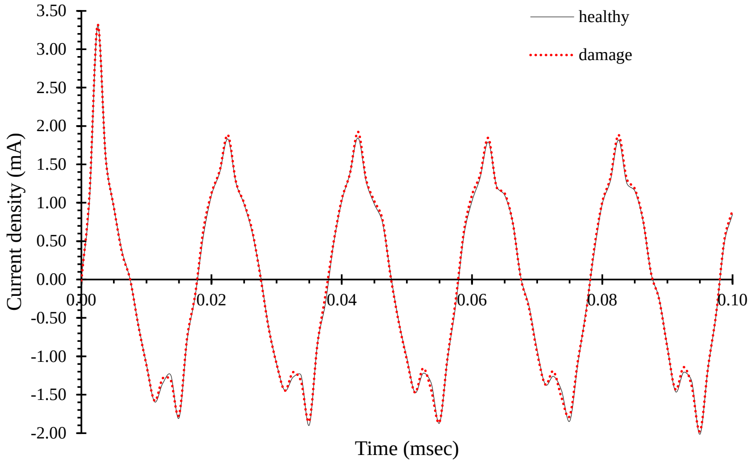


Fig-8: Comparisons of the current density versus time curves between the healthy and the damage state using the experimental measurements of PZT2 for excitation 1 Volt and frequency 50 kHz

IMPLEMENTATION OF ELECTROMECHANICAL ADMITTANCE APPROACH FOR THE DETECTION OF DAMAGE BASED ON TEST ACQUIRED DATA

Test set-up, specimen and damage characteristics

In order to check the sensitivity and the effectiveness of the adopted experimental procedure to detect damages at different damage levels, a second test program has been conducted. The diameter and the total length of the examined steel bar are the same; 20 mm (∅20) and 1500mm, respectively.

Two damage levels in the steel reinforcing bar are experimentally examined, as it can be observed in Fig. 9.Both damages are artificially introduced by removing material along two different lengths: λ_{damage} = 50 mm and 100 mm and for a common width equal to t_{damage} = 5 mm(see also Fig. 9).

The same experimental set-up for electromechanical admittance method shown in Fig. 1 is also used for the detection of the damage levels in the steel bar of this test program. Two mounted piezoelectric lead zirconatetitanatepatches (PZT1 and PZT2) that working separately can serve as both actuators and sensors with dimensions 10 mm × 10 mm are used. The material designation of both PZTs is PIC 255. They are bondedon the surface of the steel bar after a proper flattening of the bar at the same distances as in the first experimental program; 1100 mm and 700 mm away from the left end of the bar for PZT1 and PZT2, respectively.

A harmonic excitation voltage of 10 Volts is amplified to the PZTs in time domain range at every central frequency, as described by the expression:

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

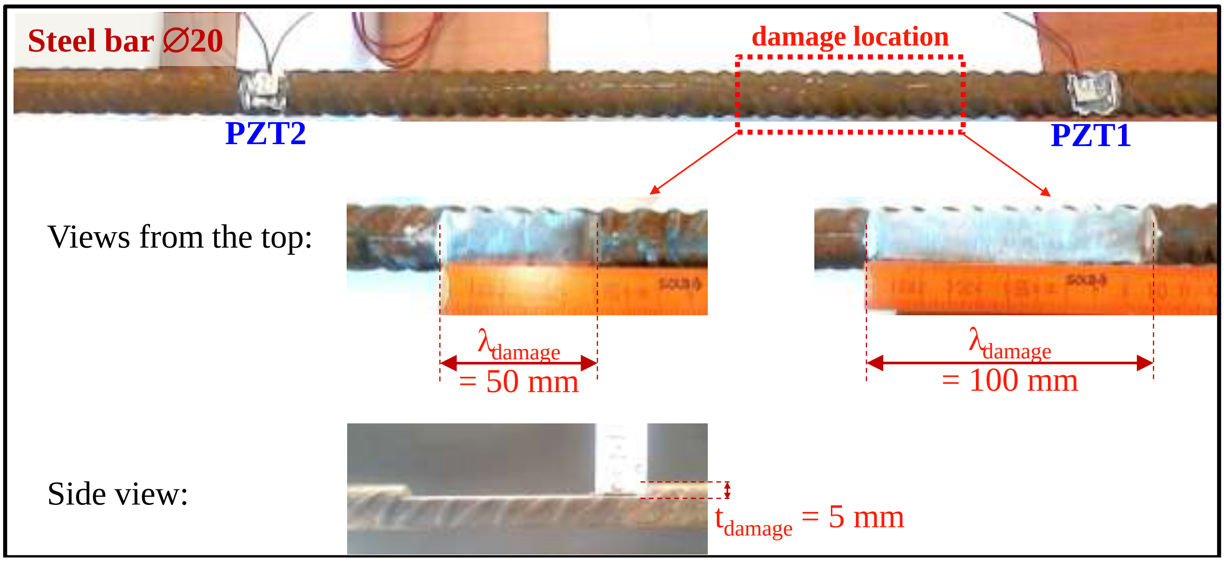
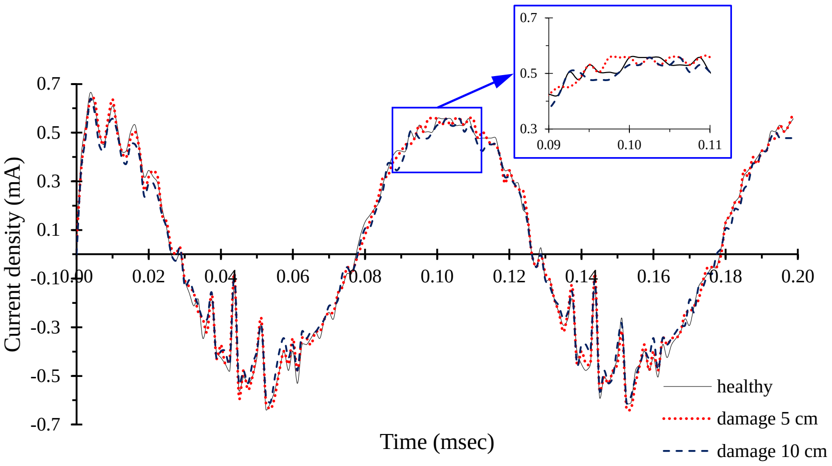


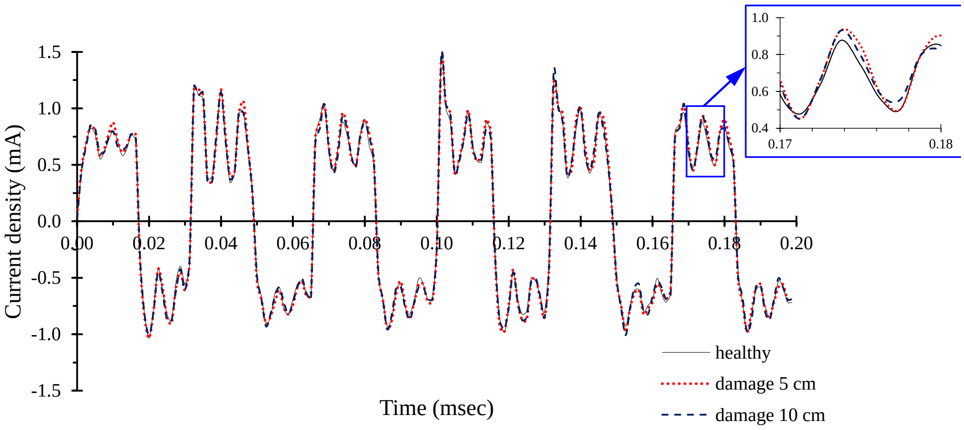
Fig-9: Steel reinforcing bar with the PZT patches and the artificial damages of the second experimental part

Test results and discussion

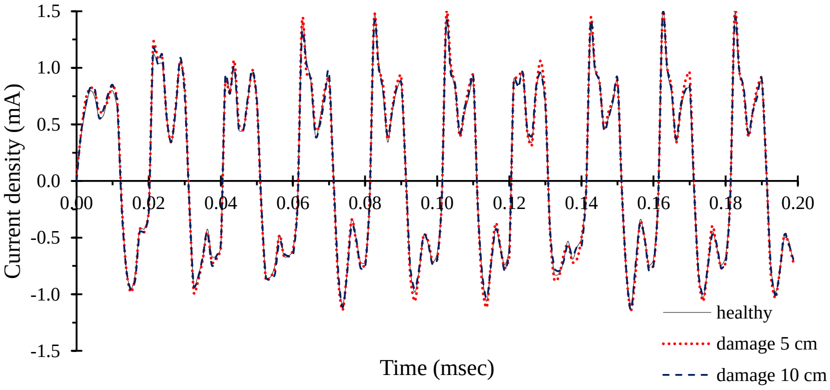
The experimentally measured time histories of the current density passing through the PZT1 for the steel bar without damage (healthy)and corresponding measured time histories for the cases of the two damaged levels are compared in Fig. 10. These results are shown in Figs 10a, b and c for the case of 10kHz, 30 kHz and 50 kHz frequency excitation, respectively.



(a) Excitation frequency 10 kHz



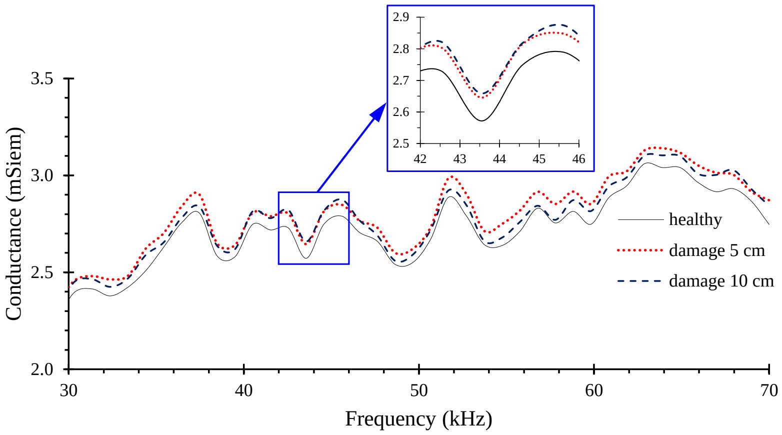
(b) Excitation frequency 30 kHz



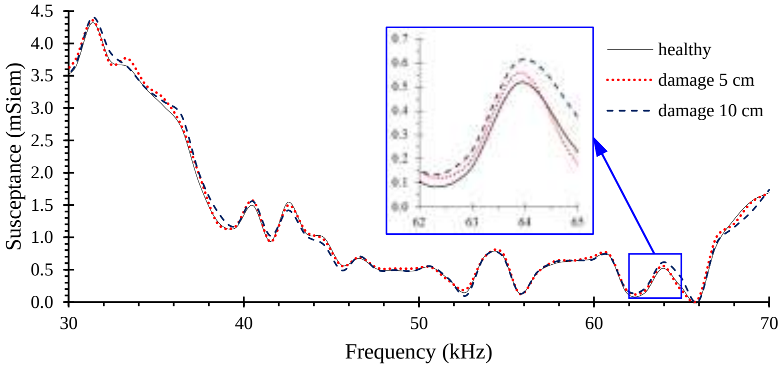
(c) Excitation frequency 50 kHz

Fig-10: Comparisons of the current density versus time curves between the healthy state and the two damage states of the steel reinforcing bar using the experimental measurements of PZT1 for excitation 10 Volt

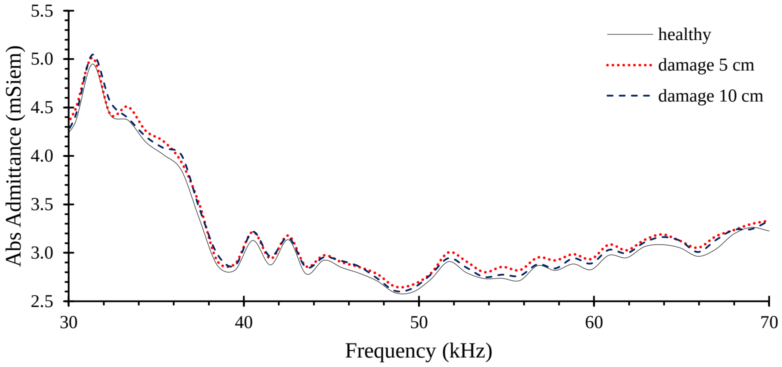
Further, in the diagrams of Figs. 11a, b and c the measured PZT1 admittance versus the frequency range of 10-70kHz for the three examined cases (healthy, 50 mm and 100 mm long damage) are compared in terms of conductance, susceptance and absolute value of admittance, respectively.



(a) Conductance



(b) Susceptance



(c) Abs admittance

Fig-11: Comparisons of the PZT1 experimental measurements of admittance between the healthy state and the two damage states of the steel reinforcing bar(excitation 10 Volt)

Although based on the time domain signals of current density shown in Fig. 10 it is rather difficult to discretize and further to categorize the differences between the examined two levels of damage, a clear gradation of each damage level can be demonstrated from the admittance signatures of Fig. 11. Additionally, experimental results of Fig. 11 seem to verify the claim obtained from previous researches that the conductance (real part of admittance) is considered to be more important as compared to its counterpart susceptance (imaginary part of admittance) and hence it has been used for damage assessment [22, 7] .

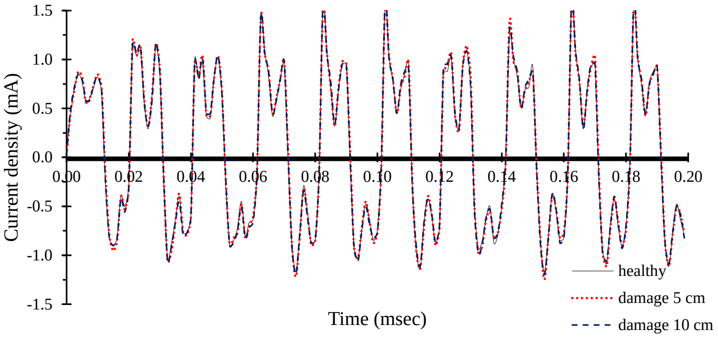
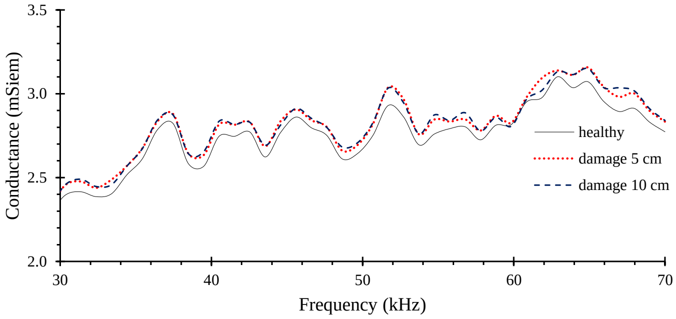
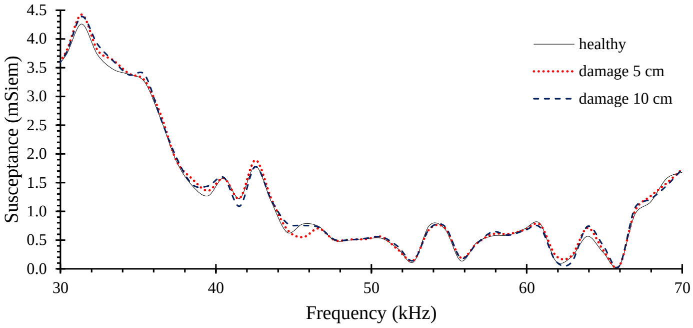


Fig-12. Comparisons of the current density versus time curves between the healthy state and the two damage states of the steel reinforcing bar using the experimental measurements of PZT2 for excitation 10 Volt and frequency 50 kHz

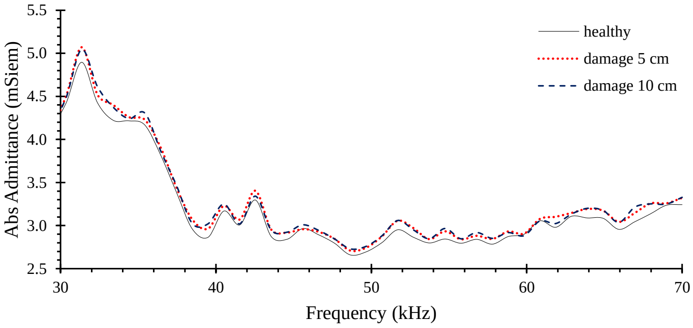
Furthermore, concerning the experimental measurements of PZT2, the time domain signals of current density of the healthy and the two damage level states are compared in Fig. 12for frequency excitation 50 kHz. Moreover, the conductance, the susceptance and the absolute value of the admittance curves for a frequency range of 10-70kHz as measured from the PZT2 for the healthy and the two damage level states are compared in Figs. 13a, b and c respectively. Similar remarks can also be derived based on the differences of the admittance signatures of PZT1 and PZT2 (see also Figs 11 and 13).



(a) Conductance



(b) Susceptance



(c) Abs admittance

Fig-13: Comparisons of the PZT2 experimental measurements of admittance between the healthy state and the two damage states of the steel reinforcing bar(excitation 10 Volt)

CONCLUDING REMARKS

The utilization of the electromechanical admittance methodology for the detection and evaluation of the damage in the steel reinforcing bars of RC members using PZTs has been presented. Experimental measurements of healthy and artificially damaged steel bars have been carried out using an integrated experimental monitoring system and the signatures of two bonded PZTs transducers. Further, finite element simulations of the same undamaged and damaged steel bars have also been performed using the finite element software COMSOL. Both test and analytical results seem to be very promising for damage assessment and comparisons between them showed satisfactory correlation.

Time histories of current density and admittance signatures acquired from test measurements and analytical simulations exhibited obvious discrepancies between the response of the healthy and the damage state of the examined steel bars. This observation indicates that the developed electromechanical admittance procedure using PZT transducers can successfully detect the potential damages of excessive elongation in the reinforcing bars due to yielding caused by flexural deformation of the RC element or by local steel corrosion. It is noted that the sensitivity of the PZTs can be demonstrated more noticeably and soundly in the admittance plots for the selected frequency band.

The selection of the excitation frequencies is of great importance since the derived results demonstrated that damage detection capability significantly depends on the successful frequency selection of the excitation rather than on the level of the excitation loading itself. Thus, the presented technique may be considered as easily applicable and effective for real structures.

Admittance versus frequency curves showed a clear gradation of the examined two different damage levels. Further, experimental results demonstrated that the conductance (real part of admittance) is more important to damage detection and characterization as compared to its counterpart susceptance (imaginary part of admittance).

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