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# Damage Detection of Steel Rebars in RC Beams Using Piezoceramic Transducers

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**ABSTRACT:** Health monitoring of reinforced concrete bridges and other large-scale civil infrastructures has received considerable attention in recent years. However, traditional inspection methods (x-ray, C-scan, etc) are expensive and sometimes ineffective for large-scale structures. Piezoceramic transducers have emerged as new tools for the health monitoring of large-scale structures due to their advantages of active sensing, low cost, quick response, availability in different shapes, and simplicity for implementation. This study presents an experimental effort for the detection of damages in the reinforcement bars at lap zone of the reinforced concrete beams using Piezo-ceramic Transducers (PZTs) is presented. An Electromechanical Impedance approach is used to evaluate the damages in the RC beam due to lack of lap length of the steel bars. Tests are performed in i) steel reinforced bars with insufficient lap length embedded in a reinforcing concrete beam of 1.3m span subjected to flexural load for detecting the response and damages ii) steel reinforcing bar with sufficient lap length given to a reinforced concrete beam of span 1.3m subjected to flexural load for detecting the response of healthy state beam. Test measurements of healthy and damage steel bars in the lap zone of the reinforced concrete beam have been conducted using the developed monitoring system.

**KEYWORDS:** Transducers, Damages, Electromechanical, Steel bars, Monitoring.

## I. INTRODUCTION

As new materials and technologies are discovered, buildings get taller, bridges get longer spans and the designs of structures become more ambitious, but more complex. In view of these developments, there is an increased requirement for providing both the costs savings with regard to maintenance and a safer environment for by preventing structural failures. The design, fabrication, and construction of smart structures are one of the ultimate challenges to engineering researchers today. Because, they form the essence of system intelligence, one of the cores of smart structures technology centers around innovative sensors and sensor systems. Structural health monitoring (SHM) represents one of the primary applications for new sensor technologies. Indeed, much attention has been focused in recent years on the declining state of the aging infrastructure, as well as to the limitation of their responses during extreme events (such as wind and earthquakes). These concerns apply not only to civil engineering structures, such as the Nation's bridges, highways, and buildings, but also to other types of structures, such as the aging fleet of aircraft currently in use by Domestic and International airlines. The ability to continuously monitor the integrity of structures in real-time can provide for increased safety to the public, particularly for the aging structures in widespread use today. The ability to detect damage at an early stage can reduce the costs and down-time associated with repair of critical damage. Observing and/or predicting the onset of dangerous structural behavior, such as flutter in bridges can allow for advance warning of such compartment and commencement of removal of the structure from service for the protection of human life. In addition to monitoring long term degradation, assessment of structural integrity after catastrophic events, such as earthquakes, hurricanes, tornados, or fires, is vital. These assessments can be a significant expense (both in time and money).

SHM is, however, not a new concept, as important structures have always been routinely inspected, usually manually, for damages and their effect on the structural performance. But in recent years several research studies have been performed to improve the accuracy and reliability of this approach. Traditionally structural inspections, usually consisting of visual inspections, were carried out by trained or experienced individuals. In some special cases more advanced non destructive methods such as eddy current, ultra sound, and other wave propagation based methods have also been used. The effectiveness of such inspections depends upon the accessibility of the structural location to be examined and to a large extent on the expertise of the individual conducting such inspections. Such approaches tend to be highly intensive and costly. Therefore, alternative methods that can automatically collect and analyze structural data to ascertain its

condition have been sought by practitioners and the research community. In such approaches one usually collects vibration data of the structure caused by natural forces such wind, traffic, earthquakes, etc. This data is then analyzed to identify the damage in the structure, if any. Among other method that use the vibration data, the modal analysis-based methods have attracted special attention. A complete SHM approach consists of four basic steps which are required to be resolved sequentially.

Guided waves based methods are widely used for damage detection and localization in structures. Success of the method application depends on many factors like sensors/actuators location, sensor electronic system design, sensor shape, frequency range of excitation waves and applied signal processing procedures. Developed procedure helps to simulate wave propagation for damaged and undamaged structures for different configuration of sensors and actuators locations, shapes of sensors and frequency range. Simulation results helped to design system including hardware and software for monitoring and diagnostics of plate-like structures. Time and frequency domain methods are implemented in the system for damage detection In this study an integration approach based on the wave propagation technique is used to evaluate the artificial damage on the examined longitudinal steel bars and RC beam. Guided wave testing (GWT) is one of latest methods in the field of non-destructive evaluation. The method employs mechanical stress waves that propagate along an elongated structure while guided by its boundaries. This allows the waves to travel a long distance with little loss in energy. Nowadays, GWT is widely used to inspect and screen many engineering structures, particularly for the inspection of metallic pipelines around the world. In some cases, hundreds of meters can be inspected from a single location. There are also some applications for inspecting rail tracks, rods and metal plate structures..

## II. LITERATURE SURVEY

This chapter presents a review of the related literature on the subject under study presented by various researchers, scholars and authors. It gives an overview of what has been written or researched on different aspects of the subject. It also summarizes selected studies that would be relevant to organization and interpretation of data. Finally it presents the conceptual framework utilized in this study.

In 2004, Bhalla et al.[1] monitored the initial damage of concrete by using the EMI technology, and meanwhile they have also monitored the strength increase of concrete during curing by using this technology and obtained the correlation between concrete stiffness and impedance peaks. Chalioris.C.E (2016), et al.[2] have examined damages of RC beams using wireless based admittance piezo electric transducers.

Chun et al. 2010, [3] studied the importance of compression lap splice as a result of the development of concrete with ultra-high strength. Based on the fundamental structure of design equations for development/splice lengths of deformed bars and hooks in tension, a simpler design equation for splice length in compression was created by re-evaluating the test results of compression splices and performing regression analysis. The correlation coefficient, mean, and COV (coefficient of variation) of the ratios of tests to predictions of splice strengths in compression produce good values when a straightforward linear relationship between  $l_s / d_b$  and  $\sigma_c$  is assumed. A design calculation for splice length in compression was created by including the 5 percent fractile coefficient of 0.83. The proposed equation's splice length calculation has a depend ability comparable to previous provisions for reinforcing bars.

Garcia et al. 2013, [4] examined the bonding behaviour of lapped steel bars utilising fifteen flexure-tested RC beams. There were 10 bar diameters of lapped reinforcement. The factors examined comprise the volume and kind of confinement at midspan (internal, no confinement) externally bonded carbon FRP or steel stirrups), bar size and concrete cover. The findings indicate that the bond strength was improved by the CFRP (Carbon Fiber Reinforced Plastics) confinement. The lapped bars by up to 49% in comparison to unconfined beams, and greatly enhanced the behaviour of the samples as a whole. To make predictions, results are compared to existing models. It is demonstrated that current models overestimate the CFRP strains and exhibit a significant dispersion while projecting the outcomes of experiments. Based upon the test results, a fresh method of bond prediction CFRP confinement results in increased strength that is suggested.

Askar 2016, [5] examined experimentally the behaviour of compression lap splices in circular reinforced concrete columns in this research. The contribution of the work is to determine how end bearing conditions, transverse reinforcement volume, and splice length affect compression lap splice behaviour. Nine circular columns were experimentally tested as part of the inquiry under uniaxial compression stresses. There was constant concrete cover and

contact between every pair of spliced bars. Conclusions have been obtained from the experimental research and test findings, and from these conclusions a design simplified equation for splice length in compression has been created. The experimental and computed findings of the author's specimens and other results found in the literature were correlated, and the results indicated a good agreement. Additionally, the proposed equation has been used to verify the predictions of the compression lap splice length made by various programmes.

Choi et al. 2017, [6] investigated in an experimental study the effect of hybrid fibre, Polyethylene (PE), and steel fibre reinforcement on the bond and cracking characteristics of lap-spliced reinforcing bars embedded in Strain-Hardening Cementitious Composite (SHCC) in the tension zone and subjected to monotonic and cyclic tension loads. The confinement effects on the compressive strength of SHCC mixes with hybrid fibre reinforcement were investigated in this study. The SHCC combinations contained two types of reinforcing fibres with aspect ratios of 1,000 and 79, respectively. For the SHCC mixes, the test conditions include normal compressive strength (30 MPa) and high strength (100 MPa), as well as spliced lengths in tension (40 and 60% of the splice length specified by ACI 318). According to splitting failure control by multiple cracking behaviour of SHCC mixtures, the results show that SHCC mixtures may be employed effectively to reduce the development length of rebar by up to 60% of the splice length required by the American Concrete Institute 318 equations.

Najafgholipour et al. 2018, [7] focused the flexural performance of RC beams with lap splices under reversed quasi-static cyclic loads. The normal design approach specified in ACI 318-14 and the modified splice length, which assumes 1.25fy in design relations instead of the nominal yield strength, were both used in this computation of lap splice length. Nine full-scale RC beams with various splice and reinforcing configurations for two grades of steel were designed and constructed specifically for this use. To assess the performance of lap splices during pure bending, test specimens were put through four-point bending tests. According to test results, the specimen with a splice developed in accordance with ACI318-14 requirements was unable to withstand reverse cyclic loading till flexural failure. However, the specimens with a changed splice length had enough flexural ductility to withstand cyclic loading.

Tarquini et al. 2019, [8] conducted an experimental investigation to determine how lap splice length, confining reinforcement, and loading history affected their ability to withstand deformation. The latter is the average strain attributed to deformations coming from the lap splice zone at the time of the commencement of splice failure. The deformation capacity of lap splices, according to an analysis of the test results, (1) increases with lap splice length, (2) increases with confining reinforcement, but the effectiveness of the confining reinforcement depends on the length of the lap splice, (3) decreases with higher imposed compression levels, and (4) is greater for bottom-casted lap splices compared to top-casted lap splices. Finally, an empirical model that offers a good fit with the experimental results is put forth to estimate the strain capacity of lap splices.

Zheng et al. 2019, [9] examined the behaviour of grouted noncontact lap splices subjected to monotonic tension load. In order to strengthen the splice's tensile strength, a spiral reinforcement was pre-embedded in the connection where deformed bars lapped through a corrugated duct filled with grout. According to the experimental findings, bond failure splices invariably fail when a pre-embedded bar other than a grouted bar is pulled out. Due to the higher confinement that the spiral bar provides when the spiral pitch spacing is less than 75 mm, the tensile strength typically increases as the volumetric spiral reinforcement ratio increases. The spiral pitch distance has a more significant impact on the connection's tensile strength than the spiral bar diameter does.

Gillani et al. 2021, [10] conducted a four-point loading test on twelve full-size reinforced concrete beams that had two tension lap splices. The failure of the bond between steel and concrete at the lap splice region before rebar yielding occurred in half of these beams, which had shorter lap splices than those advised by American Concrete Institute Building Code ACI 318-19. The other half of the beams broke due to rebar yielding and had a ductile behaviour since their lap splice length was somewhat longer than that advised by ACI 318-19. Several strain gauges were mounted to longitudinal bars at the lap splice region to study deformed bar behaviour. The strain in a rebar was greatest at the loaded end of a lap splice and lessened as it approached the unloaded end. At the loaded end, there was a stress flow discontinuity, which resulted in stress concentration. Based on the findings of the tests, this concentration was determined to have an effect. The findings of the comparison between the bond strengths computed by existing equations and those of tested specimens suggested that the two sets of data corresponded well with one another.

### III. METHODOLOGY

Tests are performed in single steel reinforcing bars with insufficient lap length of 5 times diameter of the bars steel reinforcing bars embedded in typical large scale reinforced concrete beams subjected to flexural load at two different loading levels (before and after yielding) that inevitably cause two different damage levels. Test measurements of healthy and damaged steel bars and reinforced concrete beams have been conducted using the developed monitoring system. The experimental program comprises data acquisition of current intensity curves for healthy and damaged bars as detected by the test instrumentation and implementation of the adopted wave propagation procedure to evaluate damages at different levels. Thus, the use of piezoelectric lead zirconate titanate sensors for monitoring and detecting concrete cracking and steel yielding by employing the wave propagation approach can be considered as a highly promising nondestructive structural health monitoring method.

#### Specimen and damage characteristics

The diameter of the steel reinforcing bar tested using the adopted EMI experimental procedure is 12mm and its total length is 1240 mm. Two mounted piezoelectric lead zirconate titanate patches (PZT1 and PZT2) that separately working can serve as both actuators and sensors with dimensions 10 mm X 10 mm are used. They are bonded on the surface of the steel bar after a proper flattening of the bar. Adhesive of high shear modulus and very small thickness, approximately to one-third of the thickness of PZT transducer has been used to bond the PZTs. The distances of PZT1 and PZT2 are 240 mm and 400 mm away from the left end of the bar, respectively. Two predefined damage levels in the steel reinforcing bar are examined. Damages are induced by producing insufficient lap length along two different lengths. The second test program of this study includes the application of the adopted guided wave propagation procedure to 2 large scale RC beams under flexural loading. This way, the effectiveness of the proposed method to evaluate the damages caused on the lapped tensional reinforcing bars of RC beams during a typical flexural test and at different levels of loading is investigated. The geometrical and reinforcement characteristics of the tested RC beams (Beam-1 and Beam2) are shown in Fig:4.1. The total length of each beam is 1.3 m, the shear span is  $a = 150$ mm, the height to the width ratio is  $h/b = 250/200$  mm. The bottom tensional (3nos of 12mm) in order to prevent brittle failure of the compression zone. The measured yield tensile strength values of the tensional steel bars of 10mm and 12mm diameter are 415 MPa. Further, common closed steel stirrups of diameter 6 mm spacing at 200 mm comprise the adequate transverse reinforcement in order to prevent shear failure. The mean concrete cube compressive strength of the beams is  $f_{cm} = 33.9$  MPa.

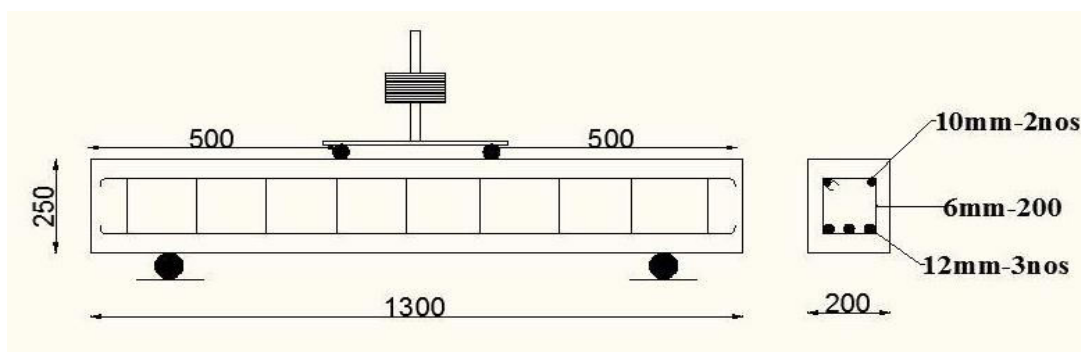


Fig:1 Beam design

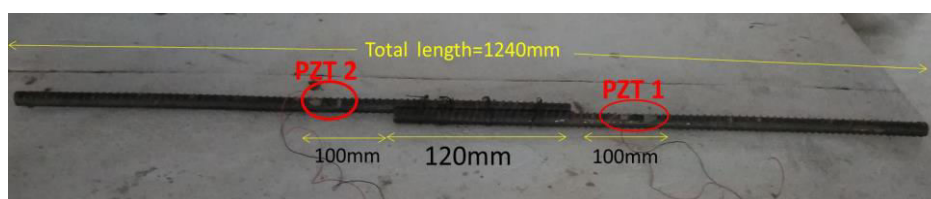


Fig:2 Healthy state

### Experimental Implementation

The overall configuration of the test set-up shown in Fig:3 is used for the damage evaluation of a steel reinforcing bar, single or embedded in a RC element. It is a specially implemented monitoring system that is based on the Electro-Mechanical Impedance (EMI) methodology and utilizes the measurements of two mounted piezoelectric lead zirconate titanate patches (PZT1 and PZT2) that working separately can serve as actuators and sensors simultaneously. Configuration and dimensions of each PZT patch are displayed in fig 4.1 and 4.2. The electromechanical impedance based monitoring system includes an oscilloscope and function generator are simultaneously used to excite the PZT transducers and record the signals. This way, the PZTs are sending out the waves and are receiving the reflected waves at the same time.

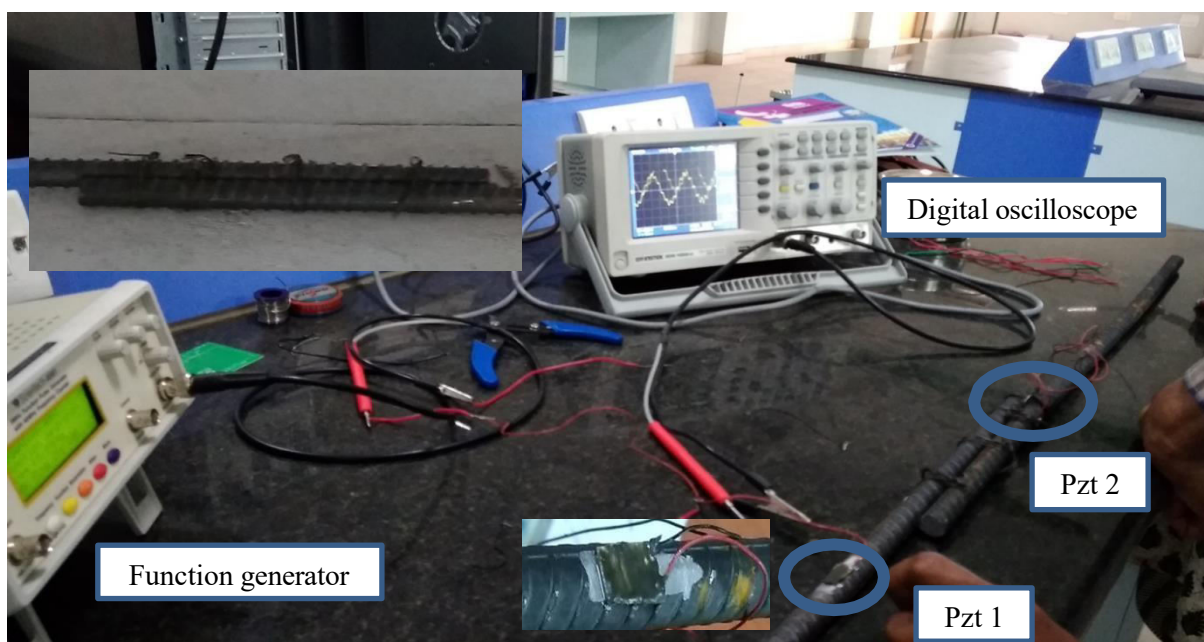


Fig 3 Overall setup

### Test on RC beam using flexural load

The test program of this study includes the application of the adopted wave propagation technique procedure 2 large scale RC beams under flexural loading. this way, the effectiveness of the proposed method to evaluate the damages caused on the tensional reinforcing bars of RC beams during a typical flexural test and at different levels of loading is investigated. Two mounted PZT patches are used on each tensional reinforcing bar diameter 12mm. Thus four PZTs are used per RC beam: PZTs no 1 & 2 bonded on the bars and PZT no 4 is bonded on the shear span and PZT no 4 is bonded on the surface of the beam. They are epoxy bonded on the surface of steel bar after flattening of the bar. A water proof layer of the epoxy adhesive has also been applied meticulously on the top of the bonded PZT transducers in order to protect the patches during concrete casting and to avoid noise in their signature. the PZT located at a distance of 120 mm. A typical two – point bending scheme and setup is adopted for the flexural test of the RC beams, the imposed loading was applied at two points 500 mm apart from the end of the span. The imposed load was consistently increased at that time the signals are recorded continuously. The mounted PZTs were recorded at different levels of the applied flexural loading using the experimental set-up of the adopted wave propagation procedure.

## IV. EXPERIMENTAL RESULTS

The experimentally measured time histories of the intensity of the current (or simply current) passing through PZT1 for the (i) undamaged steel bar (healthy), (ii) damaged steel bar with are compared in Fig:4 and 5 for frequency excitation equal to 1 kHz and 3 kHz respectively. The comparisons of these diagrams point out that there are some differences easily detected between the response of the healthy and the ones of the examined damage states of the steel bar. These discrepancies are mainly observed at the peak current points.

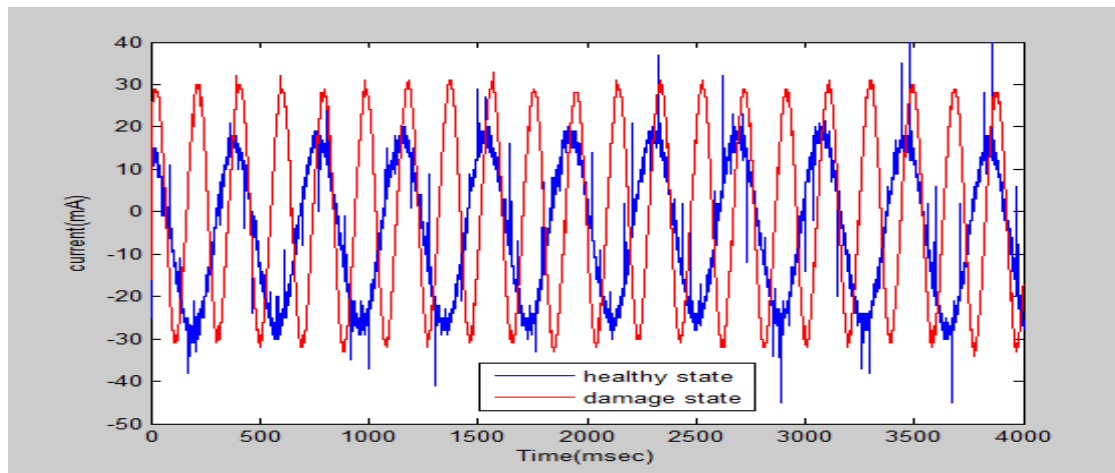


Fig: 4 Comparison of impedance between healthy and damage state of steel rod at 3kHz

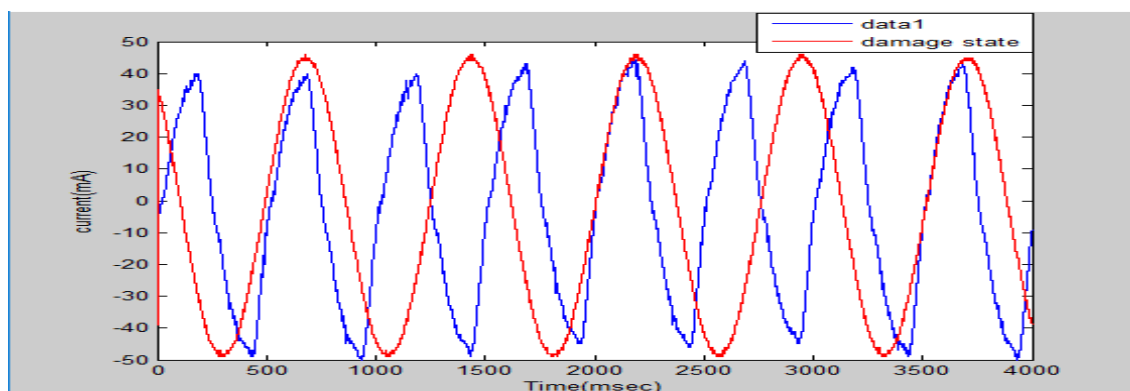


Fig: 5 Comparison of impedance between healthy and damage state of steel rod at 1kHz

Tested RC beams exhibited typical flexural response, as it has been designed and expected. First flexural cracks formed in the mid-span (pure bending region) and perpendicular to the longitudinal axis of the beams. The increase of the applied load caused flexural cracks area to spread and inevitably tensional longitudinal bars to yield. The behavior of beam 1 and beam 2 is presented in fig6.3 and 6.4 respectively. Signature of mounted PZTs on the steel bars of the RC beams were measured at the healthy state and the damage state of the beam (1) and (2) shown in fig 6 and 7 respectively. The frequency excitation of PZT is equal to 1 to 3 kHz. Concerning the test results of Beam-1 and Beam 2, Fig. 6 and 7 display the measured time histories of the current passing through PZT No. 1 and PZT No.2 for frequency excitation equal to 1.3 kHz, under different loading condition(10,15,20,25,30,upto failure). In the same way the Fig 8 demonstrate the current versus time experimental curves of PZT no 1(healthy and damage state) at 30kN. The Fig 9 demonstrate the current versus time experimental curves of PZT no 2(healthy and damage state) at 30kN. The Fig 10 demonstrate the current versus time experimental curves of surface bonded PZT no 4 (healthy and damage state) at 30kN. the Fig 11 demonstrate the current versus time experimental curves of PZT no 1(healthy and damage state)at 80kN(failure). The Fig 12 demonstrate the current versus time experimental curves of PZT no 2(healthy and damage state) at 80 kN. The Fig 13 demonstrate the current versus time experimental curves of surface bonded PZT no 4 (healthy and damage state) at 80kN.

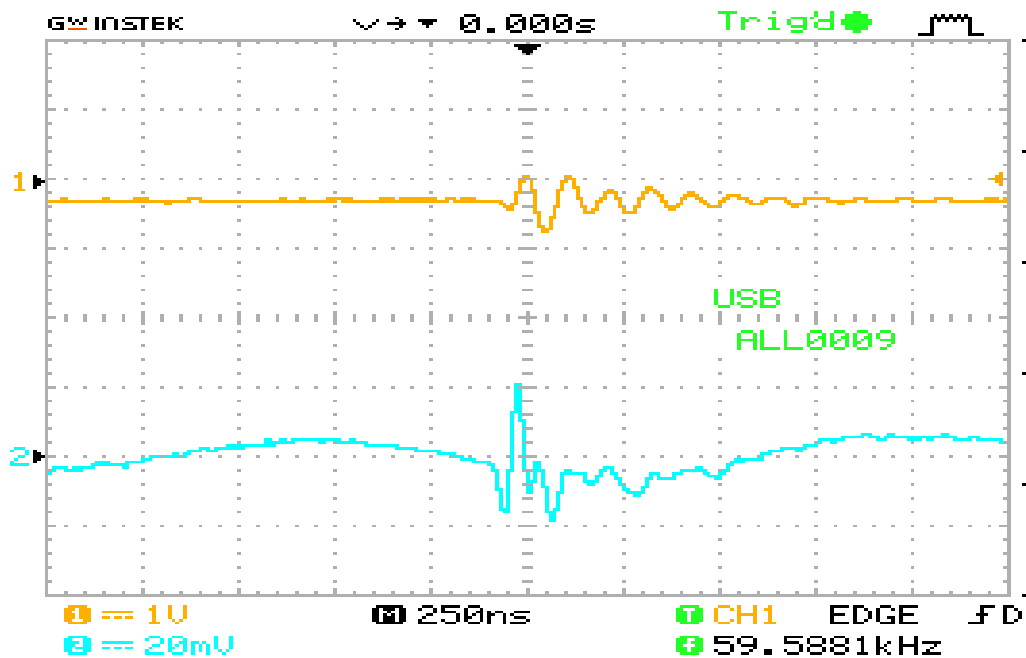


FIG:6 HEALTHY STATE

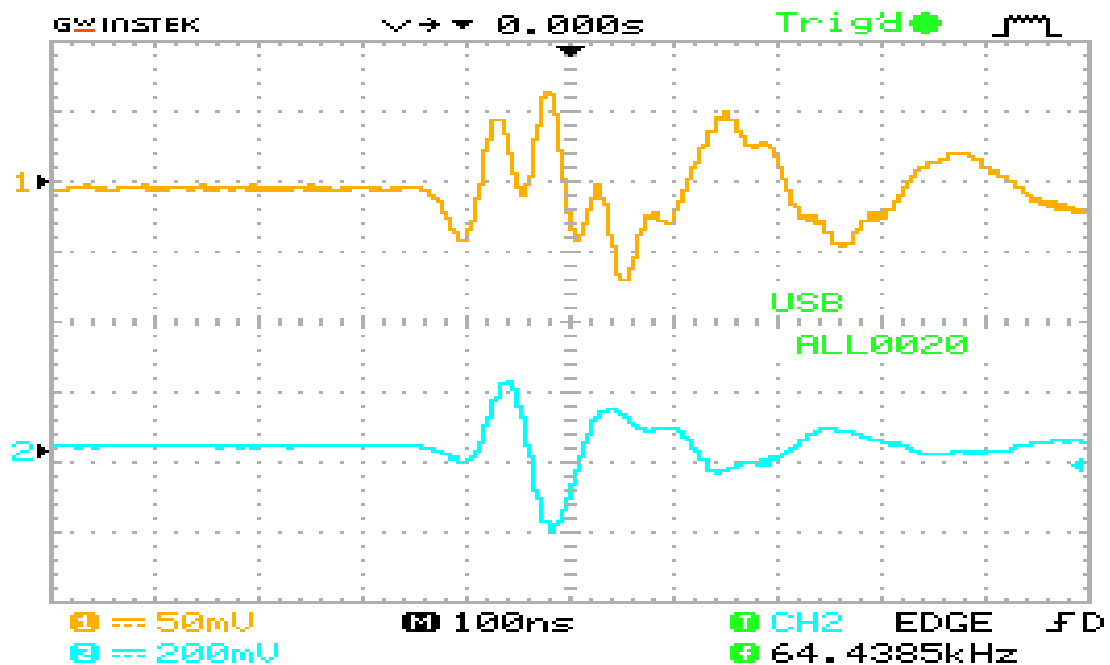


FIG:7 DAMAGED STATE



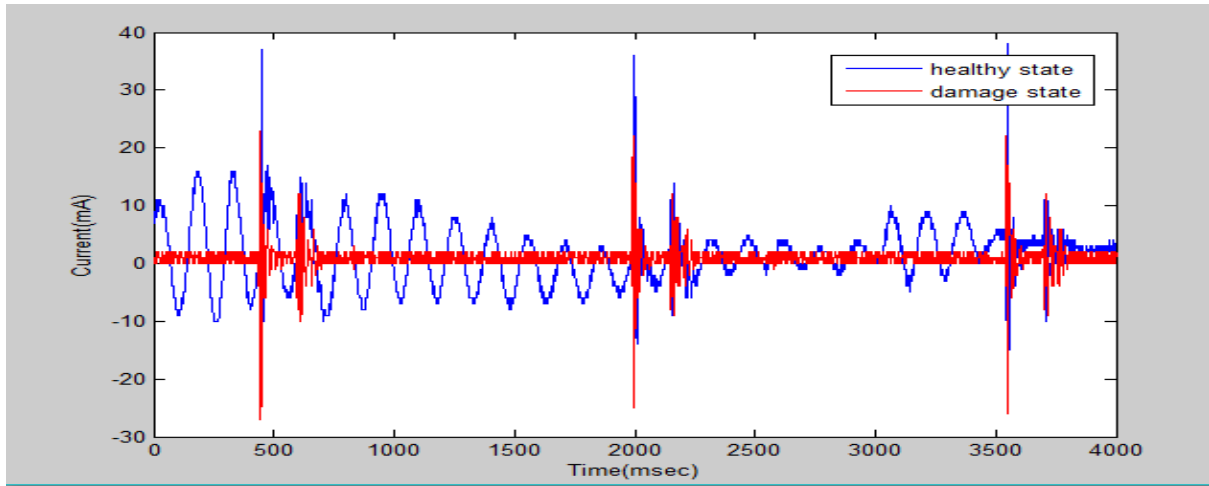


Fig:8 comparison of impedance between healthy and damaged state in RC bar at 30 kN

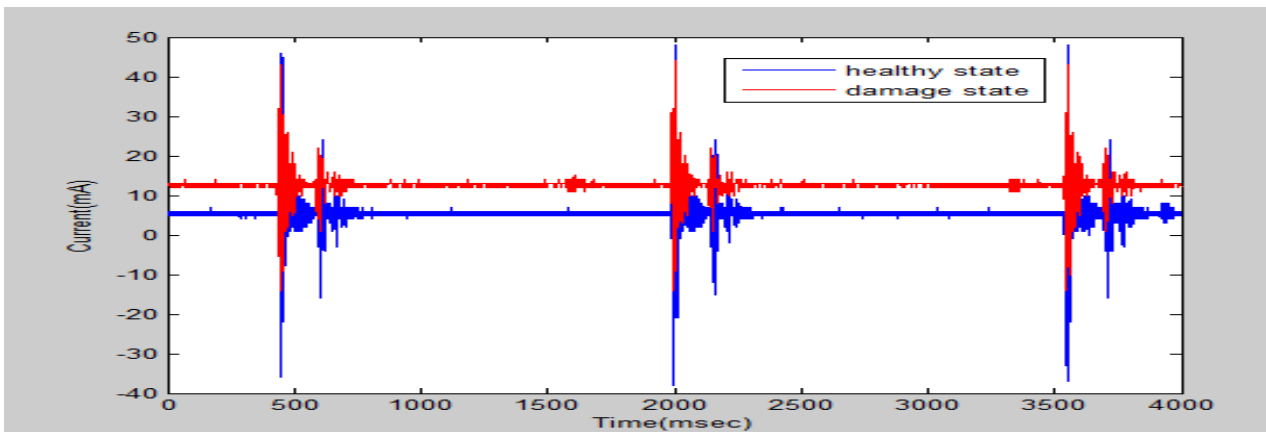


Fig: 9 Comparison of impedance between healthy and damaged state in shear span at 30kN

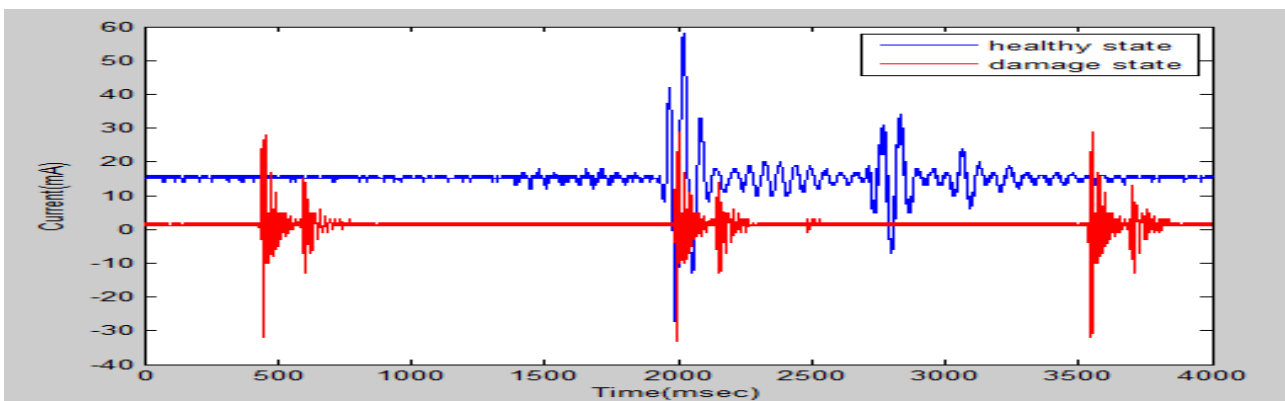


Fig: 10 Comparison of impedance between healthy and damaged state at surface at 30kN

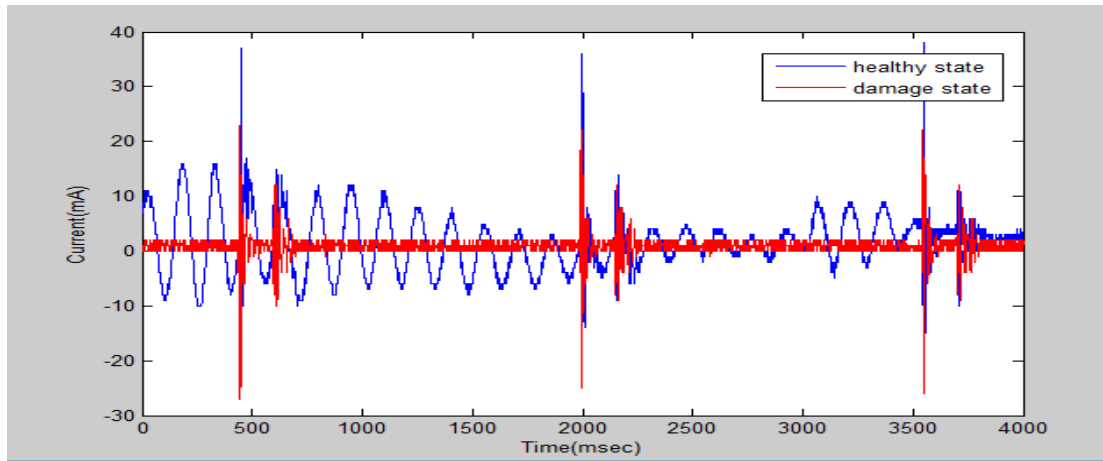


Fig:11 Comparison of impedance between healthy and damaged state in RC beam at 80kN

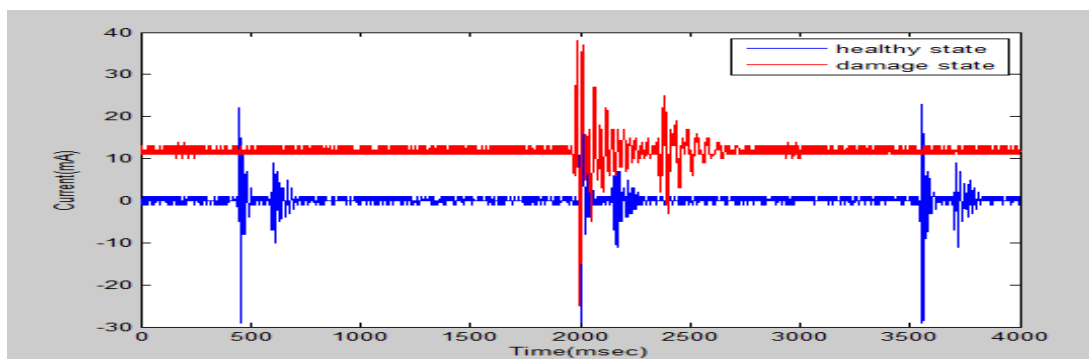


Fig:12 Comparison of impedance between healthy and damaged state in shear span at 80kN

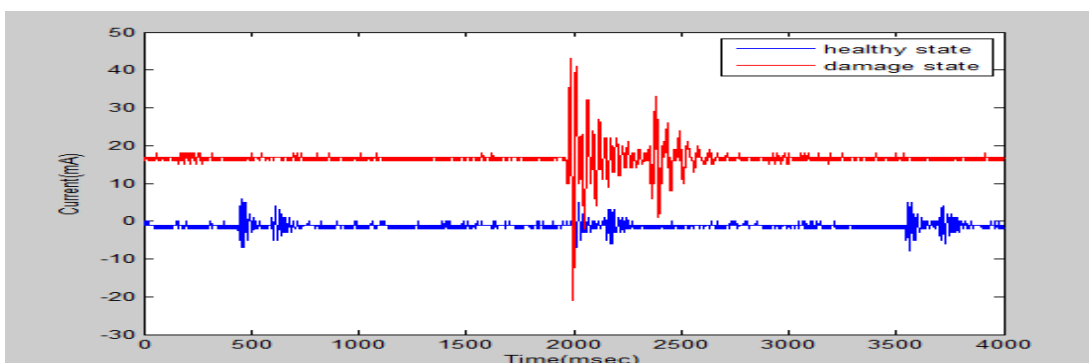


Fig:13 Comparison of impedance between healthy and damaged state in surface at 80kN

Comparisons of Figs. 6.5 and 6.6 indicate that the higher discrepancies between the healthy and the damaged states are observed at the peak current points, as it can be clearly obtained from signatures. Therefore, it can be deduced that as strain increases material properties associated to wave propagation undergo changes and as a consequence the recorded current amplitude decreases compared to the one of the healthy material. This is also attributed to the physical meaning of conductance that is the resistance of the material to electric current in the case of alternating load. It should be noted that the presented SHM procedure has two obvious limitations concerning its application in existing structures: (a) The test

setup of the adopted EMI technique is not portable and (b) bonded piezoelectric transducers on the steel bars are not applicable in existing RC structures, since they should be installed prior concrete casting. However, it would be very useful to practice if this methodology could be properly modified and extended in order to be applied in real and existing structures. A miniaturized, wireless, portable, lightweight, real time impedance monitoring system has already been developed to monitor early-age concrete compressive strength gain and to evaluate the structural integrity assessment of RC members using a smart piezoelectric sensor network.

## V. CONCLUSION

The utilization of the EMA 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, artificially damaged individual steel bars and sincerely damaged steel tensional bars of large scale flexural RC beams have been carried out using an integrated experimental monitoring system and the signatures of mounted PZTs transducers. The signatures of mounted PZTs acquired from test measurements exhibited obvious discrepancies between the response of the healthy and the examined damage levels. Differences clearly indicated the presence of damage. According to flexural tests on RC beams under the different damage levels examined, flexural damages such as concrete cracking and steel bar elongation and their locations could be identified by using PZTs. The sensitivity of the PZTs in damage detection, their influence locus and the determination of damage location is investigated using signature comparisons, and RC beams cracking patterns observations. It is obvious that the level of the applied strain influences the material properties associated with the wave propagation properties; therefore the caused change of wave propagation properties due to strain caused by damage can be considered as the key of the efficiency of the applied technique.

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