# DEVELOPMENT AND EVALUATION OF REUSABLE BOLTED PIEZO SENSOR (RBPS) FOR STRUCTURAL HEALTH MONITORING USING EMI TECHNIQUE

SUPRIYA

(2016CES2379)

DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY (IIT) DELHI

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***Submitted by***

**SUPRIYA**

**(2016CES2379)**

***Under the guidance of***

**Prof. SURESH BHALLA**


*In fulfilment of the requirement of the degree of*

***Master of Technology in Structural Engineering***


**DEPARTMENT OF CIVIL ENGINEERING**

**INDIAN INSTITUTE OF TECHNOLOGY (IIT) DELHI**


**JUNE 2018**

# CERTIFICATE

This is to certify that the work which is being presented in this report entitled, "**DEVELOPMENT AND EVALUATION OF REUSABLE BOLTED PIEZO SENSOR(RBPS) FOR STRUCTURAL HEALTH MONITORING USING EMI TECHNIQUE** " which is being submitted by **SUPRIYA (ENTRY NO: 2016CES2379**) in the fulfilment the requirements for the award of degree of Master of Technology in "**STRUCTURAL ENGINEERING** " is a record of the student's own work carried out at **Indian Institute of Technology Delhi (IIT) ,India** under my supervision and guidance.

The matter embodied in this thesis has not been submitted elsewhere for the award of any other degree or diploma.

**PROF. SURESH BHALLA**
Department of Civil Engineering
Indian Institute of Technology Delhi

New Delhi
JUNE 2018

# CERTIFICATE

I certify that the work which is being presented in this report entitled, "**DEVELOPMENT AND EVALUATION OF REUSABLE BOLTED PIEZO SENSOR(RBPS) FOR STRUCTURAL HEALTH MONITORING USING EMI TECHNIQUE**" in the fulfilment the requirements for the award of degree of Master of Technology in "**STRUCTURAL ENGINEERING**" is a record of the my own work carried out under the supervision of Prof. Suresh Bhalla, Professor, Department of Civil Engineering at **Indian Institute of Technology Delhi (IIT), India.**

I have not submitted the record embodied in this report for the award of by other degree or diploma.

Supriya

New Delhi

MAY 2018

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# ABSTRACT

This thesis covers the development and experimental evaluation of a novel reusable bolted piezo sensor (RBPS) employing a lead (Pb) zirconate titanate (PZT) bonded to a bolted strip as a damage detection sensor for non-destructive technique (NDT) of plate type structures based on the electromechanical impedance (EMI) technique. The main advantage of the sensor is that the PZT can be simply dismantled from the host structure and reused for repetitive and multiple trials, thereby necessitating minimum number of sensors in real-life applications.

In this project, a novel prototype RBPS sensor has been fabricated and initially its applicability is successfully demonstrated for monitoring the damage detection on a small aluminium based structure. The signatures of the PZT patch have been acquired by changing the torque with which the RBPS is reused to the host structure. Damage has been induced by drilling holes to evaluate the influence of various factors on the damage detection capability. The suitability and reliability of conductance signatures in pristine and damaged conditions for the RBPS are found to correlate well with the corresponding signatures from the conventional surface-bonded piezo. Finally, the experiments have been extended to 2D based steel structure with RBPS for effective damage localization. Also, the Repeatability of signatures is found to be satisfactory with very small variation among signatures. A novel has been proposed to localise damage on steel based 2D structure using RBPS.

Experiments have shown that the proposed reusable bolted piezo sensors(RBPS) technique is very effective, enhancing the damage detection and localisation performance of the EMI technique on large steel structure.

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# LIST OF ACRONYMS

| | |
|---|---|
| 1D | One dimensional |
| EMI | Electromechanical impedance |
| LCR | Inductance, Capacitance, and Resistance |
| MFB | Metal foil based |
| NBPS | Non-bonded piezo sensor |
| NDE | Non-destructive evaluation |
| PZT | Lead zicronate titanate |
| RC | Reinforced concrete |
| RMSD | Root mean square deviation |
| SBPS | Surface bonded piezo sensor |
| SHM | Structural health monitoring |
| RBPS | Reusable Bolted Piezo sensor |

# LIST OF SYMBOLS

| | |
|---|---|
| $A$ | Area |
| $B$ | Susceptance |
| $D_3$ | Dielectric displacements along axis 3 |
| $d_{ij}$ | Piezoelectric strain coefficient of PZT patch |
| $E$ | Modulus of elasticity |
| $E_3$ | Electric field along axis 3 of PZT patch |
| $G$ | Conductance |
| $G_0^i$ | Pre - damage conductance for $i^{th}$ frequency point |
| $G_i^1$ | Post - damage conductance for $i^{th}$ frequency point |
| $h$ | Thickness of PZT patch |
| $S_1$ $(S_i)$ | Mechanical strain along axes 2 (1) |
| $T_1$ $(T_i)$ | Mechanical stress along axes 2 (1) |
| $u$ | Displacement at the interface between the bonding layer and the beam |
| $\bar{Y}$ | Complex electro mechanical admittance (G+Bj) |
| $Ya$ | Active admittance |
| $Y_p$ | Passive admittance |
| $\overline{Y^E}$ | Complex Young's Modulus of elasticity |
| $Z$ | Complex mechanical impedance of |
| $Z_a$ | Mechanical impedance of the PZT |
| $\overline{\varepsilon_{ij}^T}$ | Complex permittivity of the PZT patch for axes $i$ and $j$ at constant stress |
| $\rho$ | Density |
| $\omega$ | Angular frequency |
| $v$ | Poisson ratio |

# CHAPTER 1
# INTRODUCTION

## 1.1 BACKGROUND

Civil Engineering structures may undergo damage during their service life due to factors such as disproportionate usage, severe environmental conditions, fatigue, excessive loads, vehicle impact etc. With time, the necessity to monitor structures surge as the structure ages. The conservative methods of manual or visual monitoring are becoming less feasible for utmost projects as they consume both time and money. So, there is a necessity for constant and continuous structural health monitoring (SHM) for these structures which overwhelms this challenge.

SHM is the measurement of the loading environment and the perilous responses of a structure to timely perceive the structural damage and take remedial actions. It involves the detailed arrangement of the engineered structure by extracting damage data from sensors and investigation of the data to reach at the current state of the system and to detect or to locate the existence of damage if any. Electro-mechanical impedance (EMI) technique is one of the modern approaches used in SHM to detect the incipient damage. However,it needs large number of lead zirconate titanate (PZT) patches which need to be permanently bonded to the structure. Once bonded, they cannot be retrieved and used again for some other structure.

The development of reusable PZT patch is new concept and the idea is to make the monitoring cost effective because the same PZT will be re-used as many times as possible and to ensure better repeatability and reliability in measurements. So far, only limited efforts have been made towards the development of the reusable PZT patches for EMI technique. No dedicated reusable bolted type reusable patch is still available for wide use in piezo- on aluminium and steel structures.

This thesis covers the fabrication and evaluation of reusable bolted piezo sensor (RBPS) on the 2D structure.

## 1.2 OBJECTIVES AND SCOPE

The main objective of this project was to fabricate a reusable bolted piezo sensor (RBPS) to detect and locate the damages 2D structures and develop an algorithm for damage detection and localization on prototype 2D structures. Basically, the primary focus of the project was to validate experimentally the idea of a reusable bolted piezo sensor that will be more effective than conventional piezo sensors and to experimentally evaluate the RBPS for damage diagnosis in large metal structures. An important part of the study was to work out the procedure and parameter (such as tightening torque) for instrumenting RBPS on a structure such that repeatable signature is produced.

## 1.3 ORGANIZATION OF THESIS

This thesis has been divided out into five chapters. The list of figures, table, symbols, and abbreviation are specified after the list of contents. The notations have been well-defined at the place where they first appear. The content of each chapter is briefed below.

**CHAPTER 1**

This chapter covers the background of applicability of RBPS in 2D structures for SHM and damage detection and localization followed by objectives and scope in brief.

**CHAPTER 2**

This chapter contains of the literature review of the EMI technique and previous work on non-bonded piezo sensors. Research gaps are identified and objectives and scopes spelt out in detail.

**CHAPTER 3**

It covers the fabrication of RBPS and experimental setup for evaluating RBPS under different torque range for pristine and damage condition on aluminium based structure. Different versions of RBPS covering the progressive stages are described along with the accuracy achieved.

**CHAPTER 4**

This chapter covers the development and proof of concept experimental verification algorithm for localizing the damage on large 2D structure.

**CHAPTER 5**

This chapter summarises the study and purveys the noticeable conclusions that have been drawn on the basis of the comprehensive study.

Finally, references have been provided at the end.

# CHAPTER 2

# STATE-OF-ART IN EMI TECHNIQUE IN NON-BONDED CONFIGURATION

## 2.1 INTRODUCTION

This chapter covers a brief review of the past research in the field of EMI technique and non-bonded piezo sensors. The basic principle of SHM is described briefly. It also covers the part studies related to non-bonded/reusable sensors.

## 2.2 STRUCTURAL HEALTH MONITORING (SHM)

In procedural terms, structural health monitoring is demarcated as the measurement of the operational and the loading environment and the critical responses of a structure to track and estimate the symptoms of operational incidents, anomalies, and/ or deterioration or damage indicators that may affect operation, serviceability, or safety (Aktan et al., 2000). Another definition by Kessler et al. (2002), states that SHM denotes a reliable system with the ability to detect and interpret adverse changes in the structure due to damage and normal operation.

SHM is important for perilous structures owing to following reasons:

a) To detect structural damages and take remedial actions.
b) To safeguard design validation, since the structural design is often based on parameters affected by statistical variation and uncertainties.
c) Assessment of structure after retrofitting during design life.
d) To deliver an alternative to conventional visual inspection, this is time as well as cost ineffective.
e) By monitoring of external loads and access to stress distributions and deflections etc.
f) To understand overall structural behaviour.

## 2.3 SMART MATERIALS

Smart materials are designed materials which have the ability to modify their physical properties such as shape, stiffness, viscosity, etc. in a comprehensive manner according to the certain specific type of stimulus input. Smart materials are one of the components of smart structures examples of smart materials are shape memory alloys, magneto- or electro-rheological fluids, polymer gels and piezoelectric materials, optical fibers. The goal of this integration is the creation of a material system having better structural performance, but without accumulation too much mass or consuming too much power.

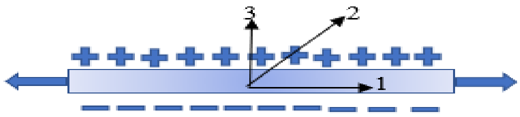
The sensors employed for the SHM are generally alienated into two major categories (a) conventional sensors (b) sensors based on smart materials. Electrical strain gauge, vibrating wire strain gauges, and accelerometers are usually used sensors which can be characterized under conventional sensors. The work presented in this thesis is based on piezoelectric materials, often stated to as piezo sensors. Piezo-sensors are available in two commercial forms: (a) Lead zirconate titanate (PZT) (b) Polyvinylidene fluoride (PVDF). Piezo ceramics (PZT) have higher strength and stiffness, however, they are rather brittle and hence not acquiescent with curved surfaces. They are suitable both as sensors as well as actuators. On the other hand, polymers (PVDF) are categorized by lesser strength and stiffness but are ductile and have shape conformability (Bhalla,2004).

The piezoelectric produce surface charges in response to a mechanical stress applied in the level of the patch, this phenomenon is called the ‘direct effect’ (Figure 2.1a). Conversely, they undergo mechanical Strain in response to an electric field applied across their thickness, which is known as the ‘converse effect’ (Figure 2.1b). Sensor applications are based on the direct effect, and actuator applications are based on the converse effect. The direct and the converse effects exhibited by piezoelectric materials can be expresses by following equations respectively.

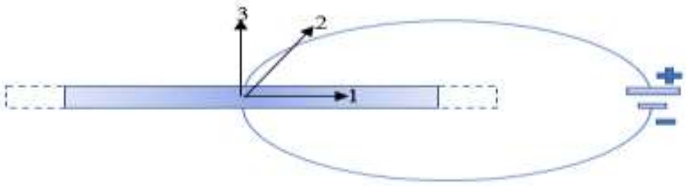
$$D_3 = \overline{\varepsilon}_{33}^{T} E_3 + d_{31} T_1 \quad (2.1)$$

$$S_1 = \frac{T_1}{Y_{11}^{E}} + d_{31} E_3 \quad (2.2)$$

Where $D_3$ (C/m$^2$) is electric displacement along axis 3, $S_1$ is the strain along axis 1, $E_3$ (V/m) is the applied external electric field along axis 3 and $T_1$ (N/m$^2$) is the stress along axis 1 and $d_{31}$(C/N) is the piezoelectric strain coefficient.




(a)




(b)

**Figure 2.1** (a) Behaviour of PZT patch under stress (direct effect)
(b) Behaviour of PZT patch under electric field (converse effect)

The most communal application of the piezo sensor is strain measurement using the direct effect. The most common converse effect application is vibration control. The most common application of piezo patches in the SHM has been in the form of the EMI technique. In this technique, dissimilar to the conventional sensors, piezo sensors do not directly measure the physical parameters such as stresses, strains etc. Rather, they are capable of extracting a signature of the host structure to which they are bonded/ embedded by which damage detection can be done by comparing it with the signature acquired in the pristine stage (baseline signature). Typically, the PZT patch is electrically excited at ultrasonic frequencies (30-400 kHz) and its admittance measured as a function of frequency forms a diagnostic signature of the structure, any nonconformity of which provides an indication of damage (Bhalla,2004). Specific details of the EMI technique are covered in next section.

## 2.4 ELECTRO-MECHANICAL IMPEDANCE (EMI) TECHNIQUE

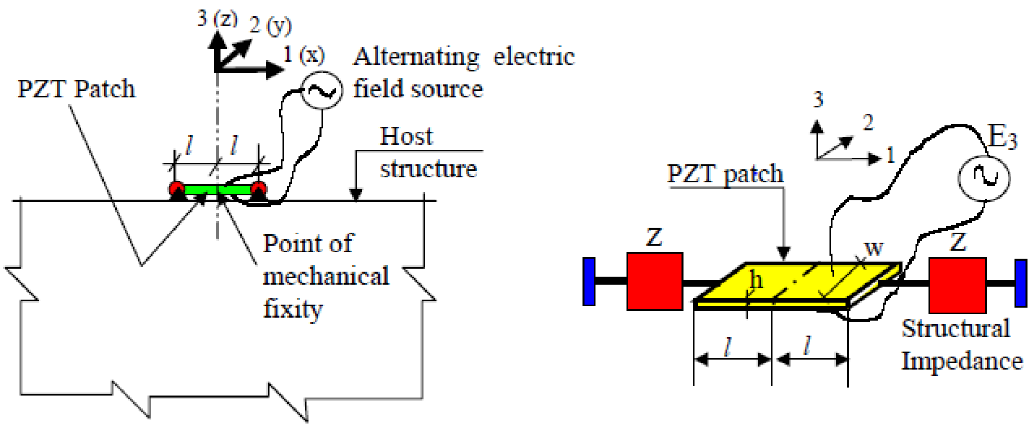
The electro-mechanical impedance (EMI) technique is an interface between the global dynamic techniques and the local NDE technique described above. The technique was first invented by Liang et al. (1994). It uses PZT materials for non-destructive evaluation (NDE) using it as an actuator and a sensor simultaneously. When PZT patch acts as sensor then it is direct effect, i.e. when the mechanical stress is induced in the PZT patch then it produces the electrical charge. Similarly, the PZT patch has converse effect when it acts as an actuator, i.e. when electric field is applied across PZT patch then mechanical strain is induced in the system. Figure 2.1 shows the direct and the converse effect in the PZT patch. As the PZT patches are very light in mass and are available in many sizes and shapes they are being widely used in structural dynamics applications. In the EMI technique, the PZT sensor is bonded on the surface of structure using adhesive layer (epoxy) and subjected to an alternating voltage excitation from an impedance analyser or LCR meter, at particular frequency range, generally 30 to 400 kHz. At the given frequency, the patch actuates the structure and the response is sensed by the patch itself in terms of electromechanical admittance, which consists of real and imaginary components, the conductance and susceptance correspondingly. Any type of damage to the structure shows as a deviation in the admittance signature which is directly obtained in the frequency domain. EMI technique is very sensitive in detecting incipient damages.

Liang et al. (1994) proposed a 1D analytical model of (EMI) technique as shown in Figure 2.2. The two end points of PZT patch can be assumed to encounter equal mechanical impedance from the host structure due to the negligible mass and stiffness of the PZT patch. Basic assumptions of the Liang's model are

i. Force transfer occurs at the end of the PZT patch.

ii. Bending effect, if any, of PZT patch is ignored.

iii. Structure is idealized as a pair of mechanical impedance equal in magnitude.




(Bhalla,2004)

**Figure 2.2**: (a) A PZT patch surface-bonded to a structure.

(b) Liang's 1D impedance model for the system.

The governing one-dimensional wave equation for the generic system comprising one half of the patch and the structure has been solved by Liang et al. (1994) using the impedance approach. Following expression is defined complex electromechanical admittance, of the PZT-structure coupled system based on Liang's derivation (Bhalla,2004).

$$\bar{Y}(\omega) = \overline{Y_P}(\omega) + \overline{Y_A}(\omega) = 2\omega j \frac{wl}{h}\left[\varepsilon_{33}^{T} - d_{31}^{2}\overline{Y^{E}}\right] + 2\omega j \frac{wl}{h}\left(\frac{Z_a}{Z_{s,eff} + Z_a}\right) d_{31}^{2}\overline{Y^{E}}\left(\frac{\tan kl}{kl}\right) \quad (2.3)$$

where $\omega$ the angular frequency, *w* the width of PZT patch, l the half-length of PZT patch, h is the thickness of PZT patch, $\varepsilon^{T}{}_{33}$ is electric permittivity of the PZT material at constant stress, $Z_a$ is the actuator impedance and *Z* the mechanical impedance of the structural system.

The mechanical impedance *Z* is a function of the structural parameters, i.e. the stiffness, damping and mass. Damage to the structure will cause these parameters to change, and hence changes the drive point *Z*. Accordingly, as can be observed from equation, the electro-mechanical admittance *Y* will undergo change, and this serves as an indicator of the state of health of the structure. Measuring Z directly may not be feasible practically, but Y can be easily measured by using an electrical impedance analyser. Hence, the basic concept of EMI method based SHM approach is the presence of damage in the host structure will affect its mechanical impedance which in turn will affect the admittance of the PZT patch (Bhalla,2004). The admittance of the PZT patch, which can be directly measured by an electrical impedance analyser or LCR meter, is compared between the two states i.e. before damage and after damage to the structure. Any change in the admittance signature indicates the damage that have induced in the structure. The measured admittance is a complex quantity consisting of real and imaginary parts, *G* and *B* respectively. A plot of conductance (*G*) over an appropriately wide band of frequency serves as a diagnostic signature of the structure and is called the conductance signature. *B*, on the other hand, was observed weak in the interaction with structure (Sun et al., 1995). Bhalla and Soh (2004a, b) presented the relevance of the imaginary component by introducing the concepts of "active signatures".

### 2.5 NON-BONDED REUSABLE EMI SENSORS

**Yang et. al. (2010)** proposed a reusable PZT sensor setup for monitoring initial hydration of concrete and structural health is established, where a piece of PZT was bonded to an enclosure with two bolts tightened inside the holes drilled in the enclosure. An impedance analyser was used to acquire the admittance signatures of the PZT. Root mean square deviation (RMSD) was working to associate the change in concrete strength with changes in the PZT admittance signatures. The results show that the reusable setup is able to successfully monitor the initial hydration of concrete and the structural health.


(a) (b) (c)

**Figure 2.3** Developed reusable PZT setups

**Tawie and Lee (2011)** proposed reusable sensor, for NDT of cement-based materials based on the EMI sensing technique. The applicability of the sensor was established for monitoring of the setting of cement mortar. In additional experiment, drying-induced moisture loss of a hardened mortar specimen at saturated surface dry condition was measured, and monitored using the reusable sensor to create a correlation between the RMSD values and moisture loss rate. The reusable sensor was also demonstrated for detecting progressive damages reported on a mortar specimen attached to the sensor under several loading levels before allowing it to load to failure.

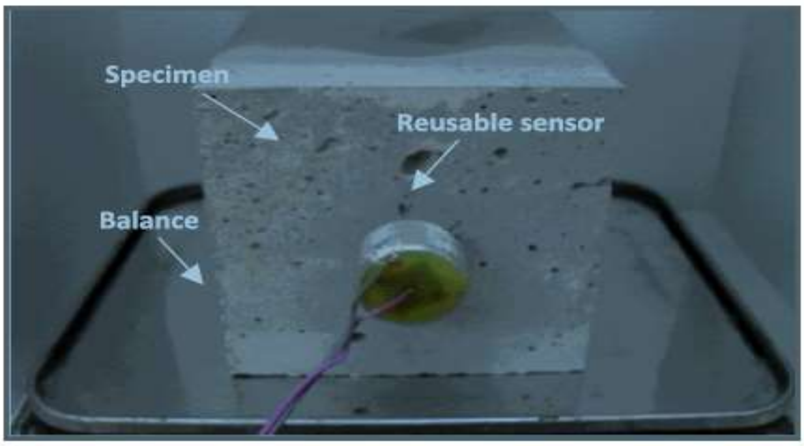



**Figure 2.4** Test set-up for monitoring drying of hardened mortar

**Na and Lee (2012)** proposed approach a new variant of EMI technique, where the patch was first bonded to the end of a metal wire whose other end was attached to the structure (see figure 2.5). After usage, the wire could be reused on other structure.

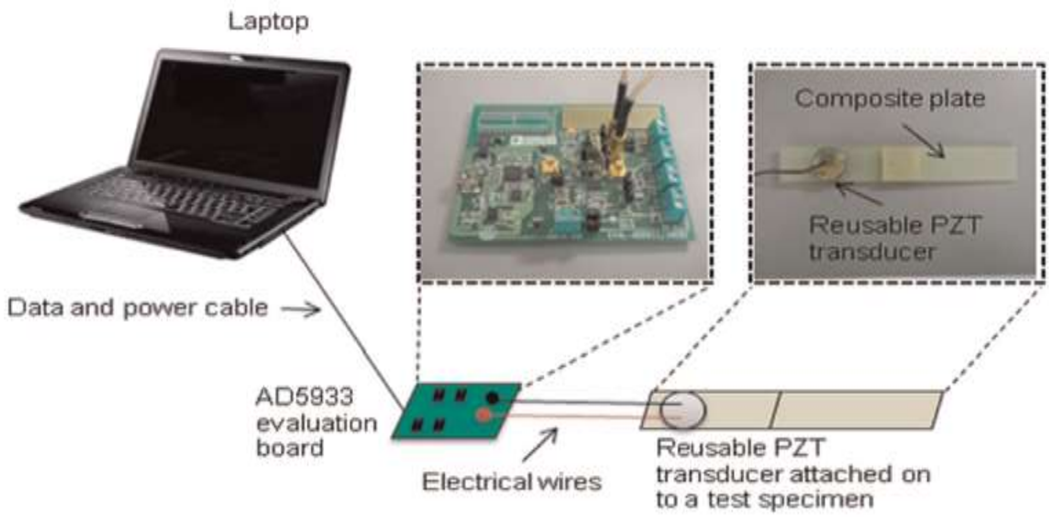



**Figure 2.5** Schematic diagram of the impedance measuring system

**Naskar and Bhalla (2016)** Improved the approach of Na and Lee (2012) by replacing the wire by a foil which showed the better sensitivity of signatures. They also presented a new presented a new field-deployable algorithm harnessing the metal-foil-based (MFB) variant of the EMI technique, warranting drastically lesser number of piezo sensors, for damage detection and localization on large two-dimensional structures such as plates. The MFB based EMI technique was first simulated through finite element method, coupled with the basic impedance model, to test the algorithm on the numerical model of a mild steel plate, 1200mm × 3970mm ×38mm in size. The algorithm was then corroborated through full-scale test on the actual plate, covering damage at various locations.

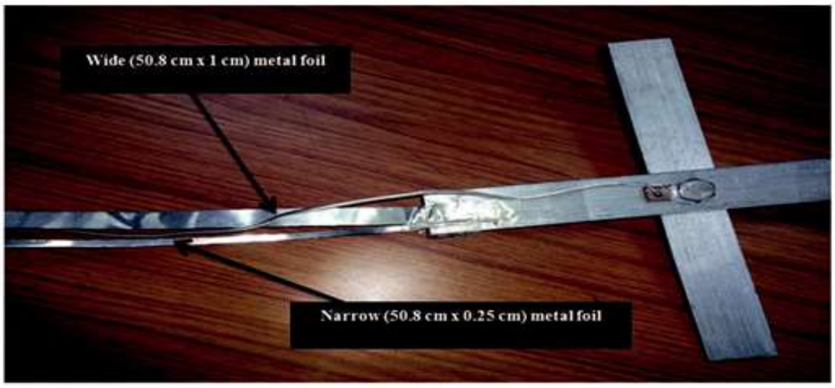



**Figure 2.6** Specimen with wide and narrow foils attached

**Srivastava et. al. (2017)** proposed and evaluated the feasibility of employing PZT patches as biomedical sensors in non-bonded configuration for measuring the physiological conditions of bones. For this purpose, a special design was proposed where the PZT patch is first bonded to a thin aluminium strip, which was in turn clamped securely on the biomedical subject (Figure 2.7). The drift of the conductance signatures in the healthy and the damaged conditions from the non-bonded piezo sensor is found to correlate well with the corresponding signatures from the directly bonded piezo sensor. At the same time, the repeatability of the signatures was also found to be satisfactory. Non-bonded piezo sensor configuration was extended to monitor the condition of bones covered with skin and tissue, simulated in the lab with the aid of silicone-based coating. Also, proof-of-concept experiment on a live human subject was successfully established. The overall results of the study demonstrate very good prospects of employing PZT patches in non-bonded piezo sensor mode for monitoring the condition of human bones and other related biomedical subjects.

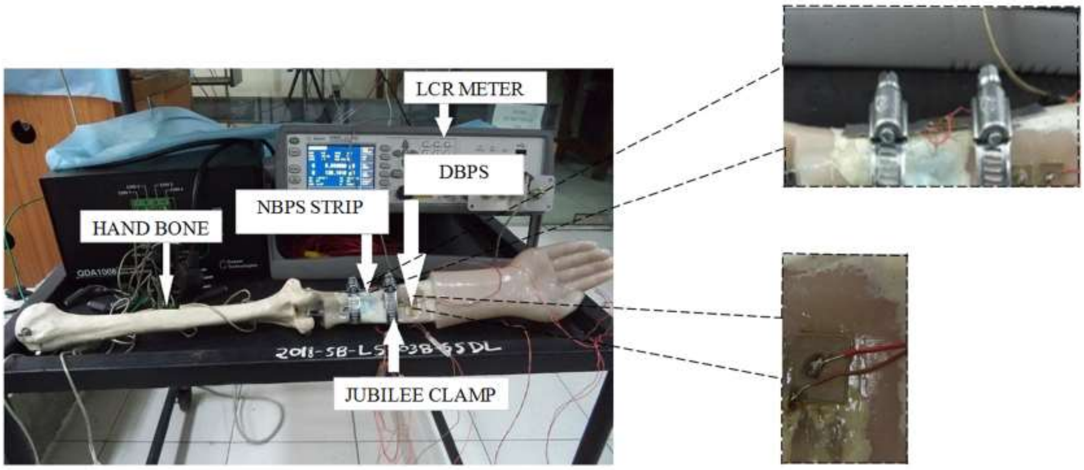



**Figure 2.7** Experimental setup for NBPS evaluation on artificial bone of human hand.

**Thakuri (2017)** presented experimental validation and evaluation of corrosion detection of reusable configurations of PZT patch such metal foil piezo sensor (MFPS) and non-bonded piezo sensor (NBPS) vis-à-vis directly bonded and embedded configurations for corrosion detection. Result shows the considerable variation of real part of the signature i.e. conductance (*G*) of both the types of reusable sensors namely MFPS and NBPS. RMSD variation does not show reliability of results. It may be a good indicator of damage but as far quantification of damage was concerned, structural parameters computation tends to be more reliable as it was correlated with actual variation of mass through gravimetric mass loss. In overall, the study clearly establishes the efficiency of reusable type piezo sensors.

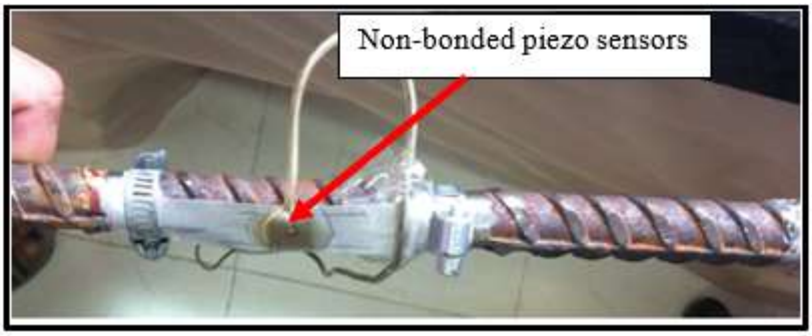



**Figure 2.8** Non-bonded piezo sensors (NBPS) clamed to the rebar

## 2.6 IDENTIFICATION OF RESEARCH GAPS

Although a number of studies had been conducted to study the performance of PZT patches in directly bonded on structure for damage deduction and damage localization in various types structures, no such dedicated study to use reusable piezo based has yet been developed specifically for 2D metal structures. The MFB technique involves cutting the foil reducing its length. NBPS technique can only be applied on thin circular cross section. For Steel structures no study has been done using reusable bolted piezo sensors.

## 2.7 AIMS AND SCOPE OF PROJECT

This project aimed at developing a reusable bolted piezo sensors (RBPS) to detect damage to metal structures.

The specific aims and scopes of the project were:

1 To fabricate REUSABLE BOLTED PIEZO SENSOR (RBPS) for locating the damage induced in structures using EMI technique on plate type structure.
2 To experimentally evaluate RBPS for damage diagnosis in metal structures and work out optional parameter such as tightening torque for best repeatability.
3 Comparison of results from RBPS conventional surface bonded PZT patch technique.
4 Development of algorithm for damage and localization in prototype 2D structures.
5 Experimental validation on large prototype structures.

# CHAPTER 3

# FABRICATION AND EXPERIMENTAL EVALUATION OF REUSABLE BOLTED PIEZO SENSOR (RBPS)

## 3.1 RBPS DESIGN

In the proposed configuration, the PZT patch is not directly bonded on surface of structure but on metal strip example Aluminium, steel etc. and the metal strip is attached to the structure with bolts as shown in the Figure 3.1. Brittleness of the PZT, makes it difficult to be attached to complex geometry and not feasible to attach in the hazardous locations. And also, PZT transducers expensive compare to other sensors. Therefore, for repetitive applications, such as in the precast industry, a method to reuse the PZT transducers is essential . A sensor that can be easily attached and detached will not only reduce the overall cost of monitoring various structures, but the installation time for the sensors can be dramatically reduced as the conventional way of conducting the EMI method requires the PZT material to be surface attached with an adhesive. This can be time- consuming since the adhesive can take more than 24 hours to be fully dried.

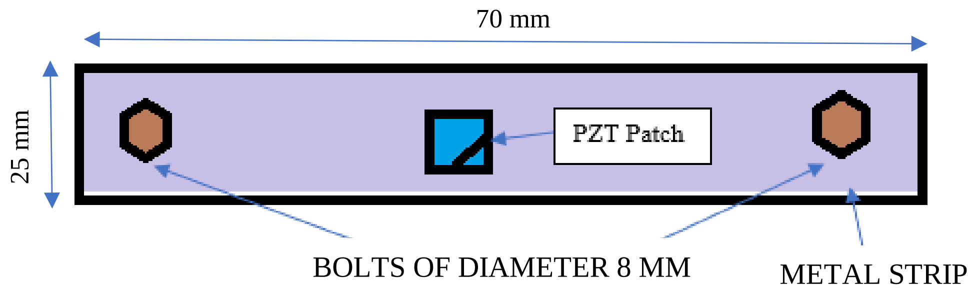



**Figure 3.1** Reusable Bolted Piezo Sensor (RBPS)

## 3.2 EXPERIMENTAL DETAILS

In this investigative study, a bolted connection consisting of one main aluminium plate (397 x 290 x 3mm) was chosen as the test specimens. RBPS was joined to the specimen by bolts of diameter 8 mm and tightened by using standard torque wrench. A conventional PZT patch (10 x 10 x 0.3 mm) was also bonded on the specimen, as shown in Figure 3.3. The two PZT patched were attached to the surface of aluminium strip and steel strip using adhesive layer (epoxy). An LCR meter was connected to the PZT patches on one to one basis controlled by VEE PRO 9.2 software operating in a laptop. Figure 3.2 shows a close-up view of specimen subjected to different torque ranges (5 Nm to 25 Nm).

Signatures were acquired for the frequency range of 100-150 kHz through LCR meter usually frequency range 30-400 kHz for structures. After acquiring signatures at various torque ranges, damage was induced in the specimen of 5 mm diameter hole and then signatures were compared at pristine and damage stage.

**Figure 3.2** Specimen subjected to torque

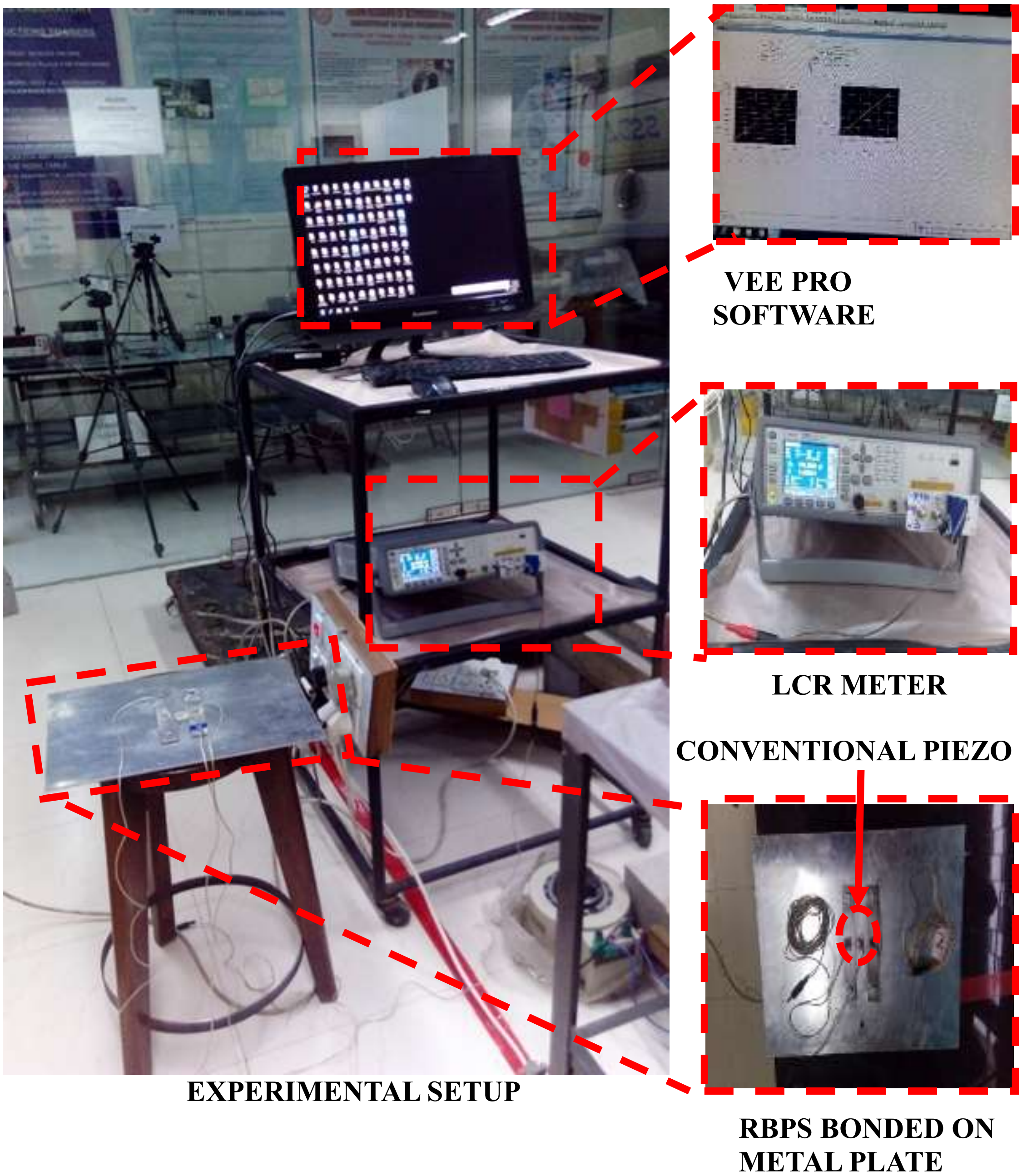



**Figure 3.3** Experimental details of the specimen

## 3.3 ROOT MEAN SQUARE DEVIATION (RMSD)

In the EMI technique, damages are sensed by the amount of change of signatures in the vertical or horizontal directions, or the advent of new peaks or the release of older peaks, which are the key indicators of damage. RMSD is the most commonly used index in SHM to calculate the degree of deviation of the admittance signatures (G) from the baseline signatures. The RMSD index was defined as (Naskar and Bhalla,2016)

$$RMSD(\%) = \sqrt{\frac{\sum_{j=1}^{N}\left(G_j^1 - G_j^0\right)^2}{\sum_{j=1}^{N}\left(G_j^0\right)^2}} \times 100 \qquad (3.1)$$

where $G_j^1$ is the conductance after the damage at $j^{th}$ frequency and $G_j^0$ is the conductance at pristine state at the same $j^{th}$ frequency respectively.

## 3.4 REPEATABILITY OF CONDUCTANCE SIGNATURES

In this study, the repeatability of the signatures was checked by acquiring the conductance signature on the same specimen for both RBPS at torque range 25 Nm. To ensure efficiency of the RBPS it was important to ensure the good repeatability of signatures. Signatures were acquired by fully loosening the bolts once and then fully tightening them at constant torque i.e. 25 Nm. For good repeatability RMSD should be less than 0.5%. Lesser the value of RMSD for repeatability better is the RBPS. During the study three prototypes were made (Prototype-I, prototype-II and prototype-III) which is shown in Fig 3.4 and described in table 3.1. In order to check repeatability following procedure was adopted

a) The RBPS was tightened to a torque of 25Nm
b) Signature I was acquired in 100-150 kHz.
c) Bolts were loosened fully.
d) RBPS was again tightened to 25Nm.
e) Signature II was acquired in 100-150 kHz.
f) Signature I and II was plotted and RMSD was computed.

The results are shown in figure 3.5 ,3.6,3.7for three prototypes. Hence, best repeatability is found for prototype III which will now be used in all future experiments described in this thesis.

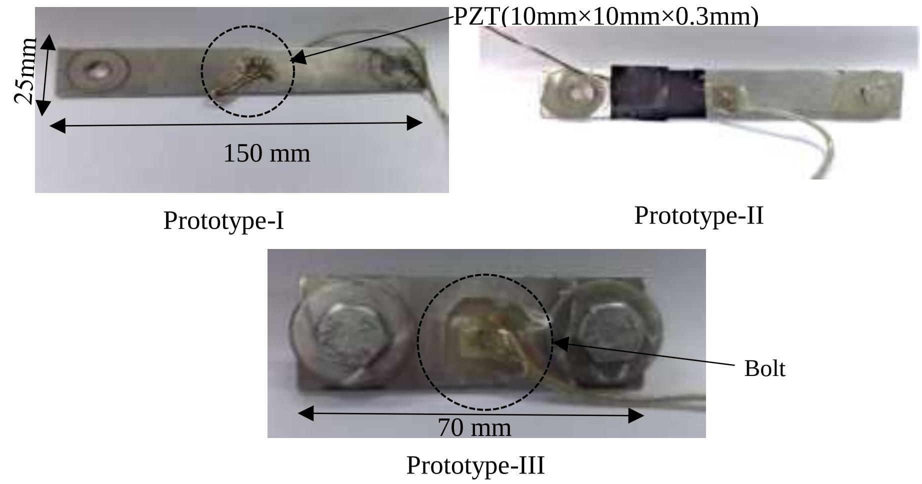



**Figure 3.4** Prototypes of Reusable Bolted Piezo Sensors

**Table 3.1** - Details of Prototypes

| Parameters | Prototype-I | Prototype-II | Prototype-III |
|---|---|---|---|
| Material | Aluminium, Steel | Aluminium, steel | Aluminium, Steel |
| Bolt condition | Not fixed | Fixed with epoxy | Fixed with epoxy |
| Dimensions(mm) | 150 × 25 | 150 × 25 | 70 × 25 |

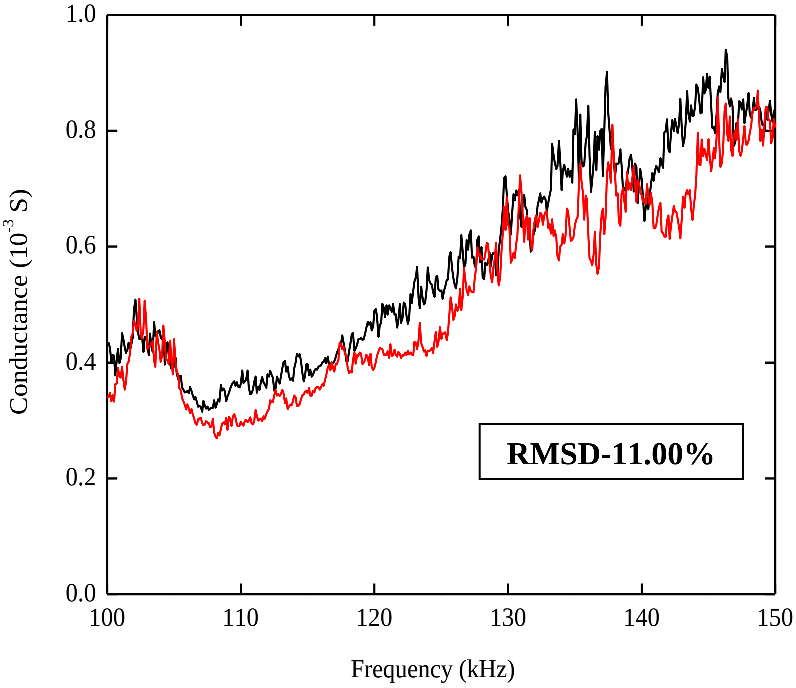



**Figure 3.5** Repeatability of conductance signature of RBPS for prototype I.

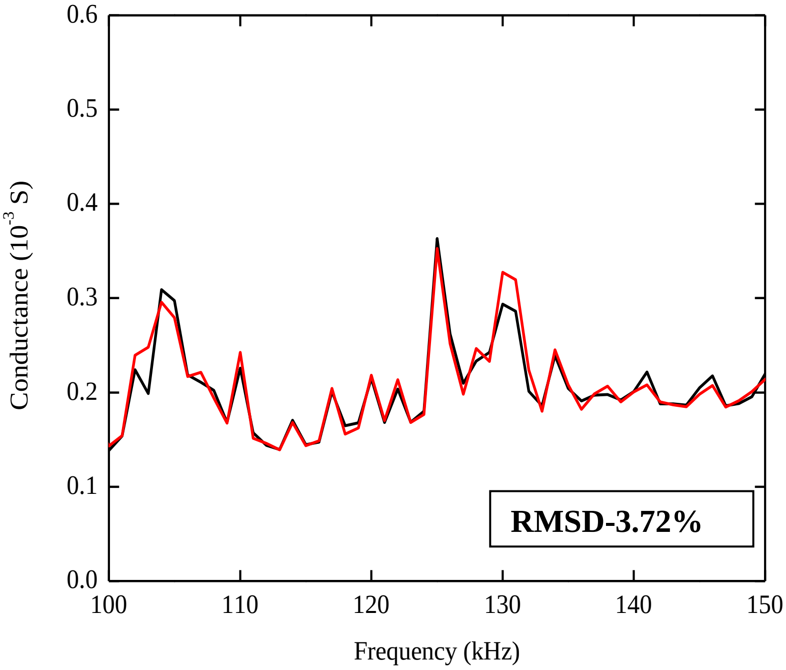



**Figure 3.6** Repeatability of conductance signature of RBPS on for Prototype II.

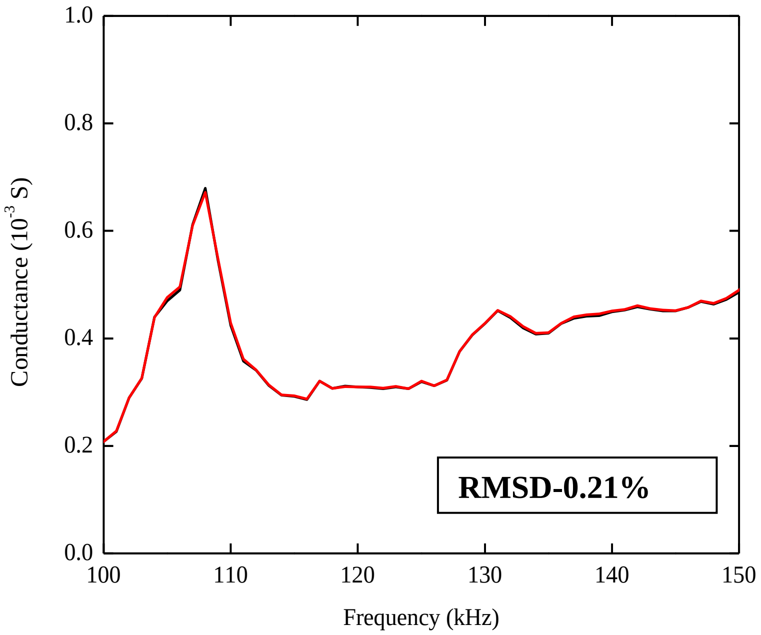



**Figure 3.7** Repeatability of conductance signature of RBPS for Prototype III.

## 3.5 OPTIMAL TORQUE

In this study, the variation of the externally applied torque 5,10,15,20,25 Nm was applied on the bolt joints to determine the minimum torque. Results are shown in Fig 3.8. From this figure, a torque of 25Nm is best.

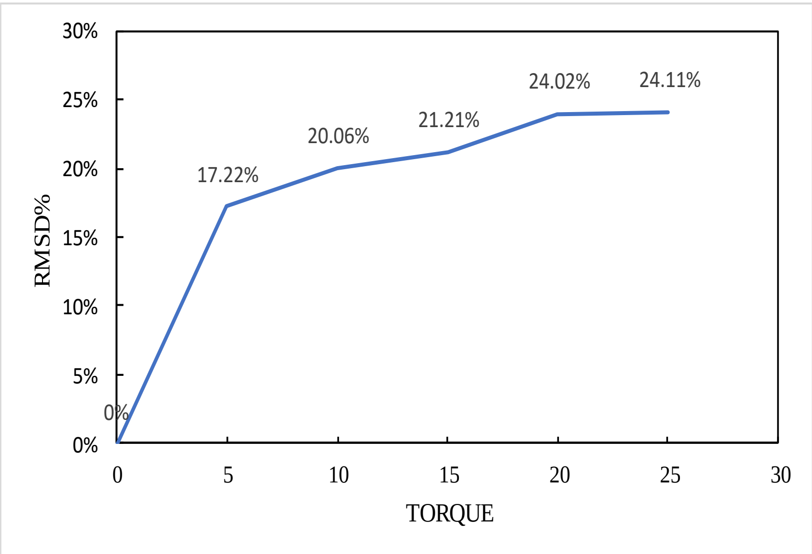
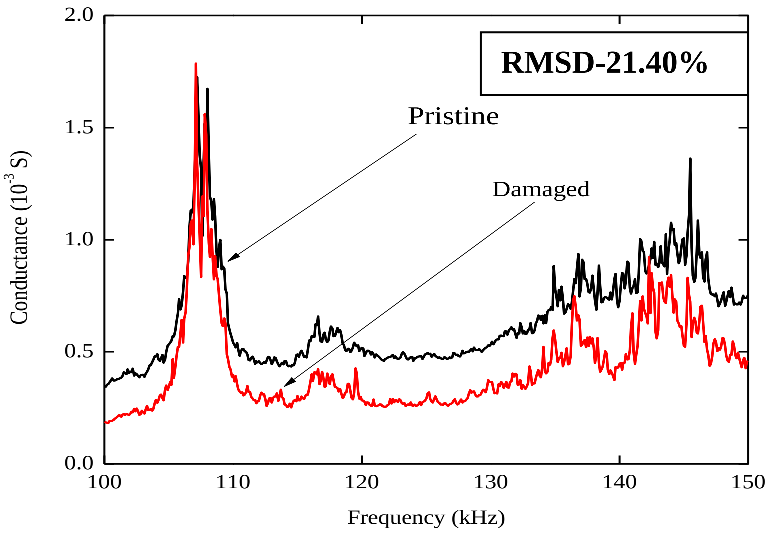


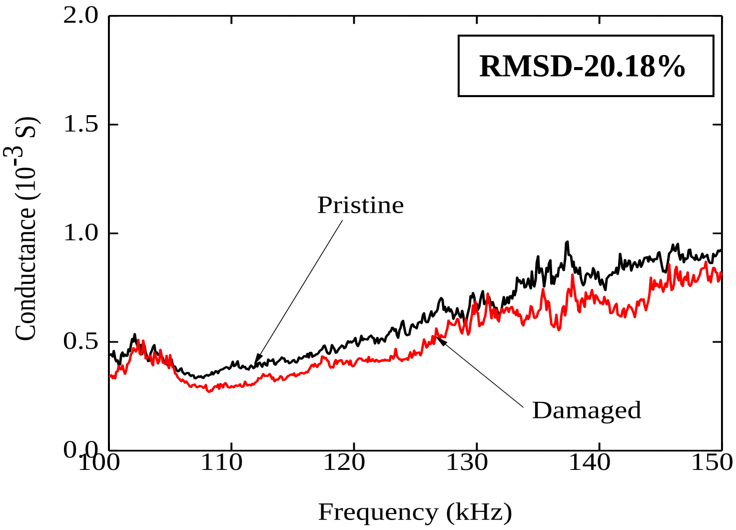

**Figure 3.8** RMSD plot of RBPS on different torque range

## 3.6 EFFECT OF DAMAGE

Damage was induced in the specimen by drilling a hole of 5 mm on the main plate (host structure). The conductance signature for prototype at 25 N m torque range was compared for pristine and damage stage. RMSD variation of over 20% was observed (Fig 3.9 a,b), which is two order of magnitude higher than the RMSD value resulting from tightening related variability.  Hence, the proposed RBPS is proved successful.




(a)




(b)

**Figure 3.9** Conductance signature of pristine and damage stage of RBPS at (a) Aluminium strip (b) Steel strip

### 3.7 SUMMARY AND CONCLUDING REMARKS

A suitable RBPS unit has been successfully fabricated and experimentally validated. In this study, various practical aspects of the RBPS have been investigated for a metal structure subjected to damage and different torque ranges. For damage detection, torque of 25Nm is found best. This matches with the recommendation of Naskar (2016). From the experimental investigation, it can be concluded that the repeatability of signatures is good for prototype III under a torque of 25Nm. The RMSD signature has been successfully calibrated with damage and different torque ranges. A good repeatability with low RMSD around 0.21% for 25Nm of Prototype-III of conductance signature has been achieved. The RMSD for damage was found to be 20.18 %, which is higher than the magnitude of the RMSD for the repeatability test. The RBPS can be used to replace conventional PZT for SHM of metal structures. As the RBPS are reusable, its use, instead of conventional surface bonded PZT patches can make the SHM process economical. Also, their instrumentation is simpler than the conventional patches. Next chapter covers the development of an algorithm for damage detection and localization on large 2D plate type structure.

# CHAPTER 4
# DEVELOPMENT & EXPERIMENTAL VALIDATION OF DAMAGE DETECTION AND LOCALIZATION ALGORITHM USING RBPS ON 2D STRUCTURE

## 4.1 INTRODUCTION

SHM offers great promises for better performance of civil infrastructure. Although it is still mainly a research area, it would be possible to develop successful real-life health monitoring systems for civil infrastructures if all the components of a complete health monitoring design are recognized and integrated. Such health monitoring systems have even been implemented on select bridges, such as Naini bridge etc. In India, the authorities are gearing up for implementing such systems for critical bridges, such as the signature bridge in Delhi (Naskar, 2014).

Steel is used as a major construction material for several centuries and the application of steel is not just limited to civil structures. The connections between steel members have evolved over the decades. This chapter deals with the monitoring of steel structure when subjected to damage, using RBPS by electro-mechanical impedance technique.

The first objective of this study was to test the RBPS algorithm proposed in this chapter on a real-life steel structure. In addition, damages ranging from incipient to serve types and the study aimed for the detection localization, so as to carry out an experimental damage sensitivity analysis.

## 4.2 PROPOSED DAMAGE DETECTION ALGORITHM

The proposed algorithm is essentially an extension of the algorithm proposed by Naskar and Bhalla (2016) for MFB sensors. Fig 4.1 shows the proposed instrumentation of the 2D plate. In this arrangement, RBPS shall be connected to the structure along two adjacent edges, here AB and BC.

Following steps shall be executed for damage detection and localization

i Acquire the baseline conductance signature for all the RBPS instrumented at each location

ii A to D and 1 to 5 totaling 9 locations, one at a time.

iii At any further stage, when assessment of the structure needs to be made, acquire the conductance signatures again.

iv Compute the RMSD index corresponding to RBPS at each location suggested more advanced damage diagnosis based on extraction of mechanical impedance, the RMSD approach has been adopted here since the main objective is damage detection and localization. This step gives the damage metric corresponding to each 'gridline', that is, the line of action of action of the PZT patch. The next step aims to transform the metric corresponding to each 'strip', that is, the region enclosed by two adjacent gridlines.

v Compute the RMSD index corresponding to the strip between sensors i and (i + 1) as the average of the RMSD index of the two RBPS located on either edge of the strip.

vi Plot RMSD histograms along each axis, as shown in Figure 4.1, with each vertical corresponding to a strip. The strip housing the damaged element along each direction can be ascertained by the maximum value of the RMSD histogram. These have been shown shaded in the figure.

vii The exact damage location (panel formed by the intersection of two orthogonal strips) in 2D can be determined as the intersection of the strips corresponding to maxima of the two histograms, as illustrated in the figure.

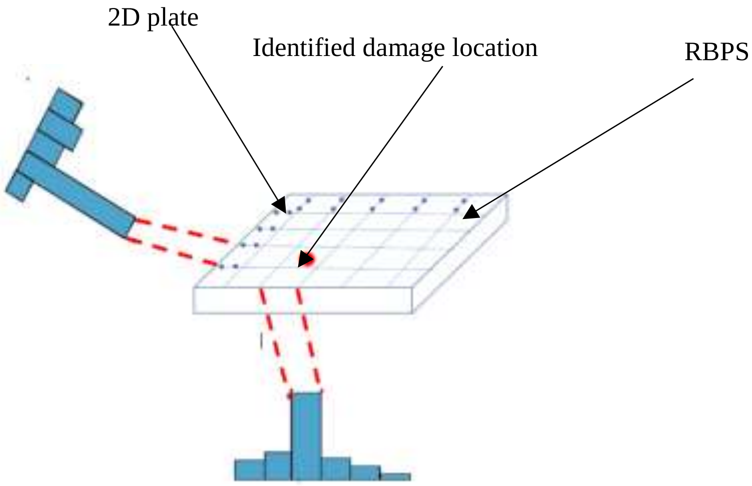



**Figure 4.1** Description of proposed new 2D damage detection algorithm

### 4.3 FABRICATION DETAILS OF EXPERIMENTAL PROTOTYPE STRUCTURE

This project has adopted the experimental specimen used earlier by Chaudhary (2012) and Naskar (2014). The steel plate of size 1200 × 970 $mm^2$ was supported on box type pipe of cross section 38×38 $mm^2$ and 3mm thickness. The pipe was welded along the perimeter of the plate and the entire setup was mounted on four wheels. Details of the experimental setup have been presented in Figure 4.2.

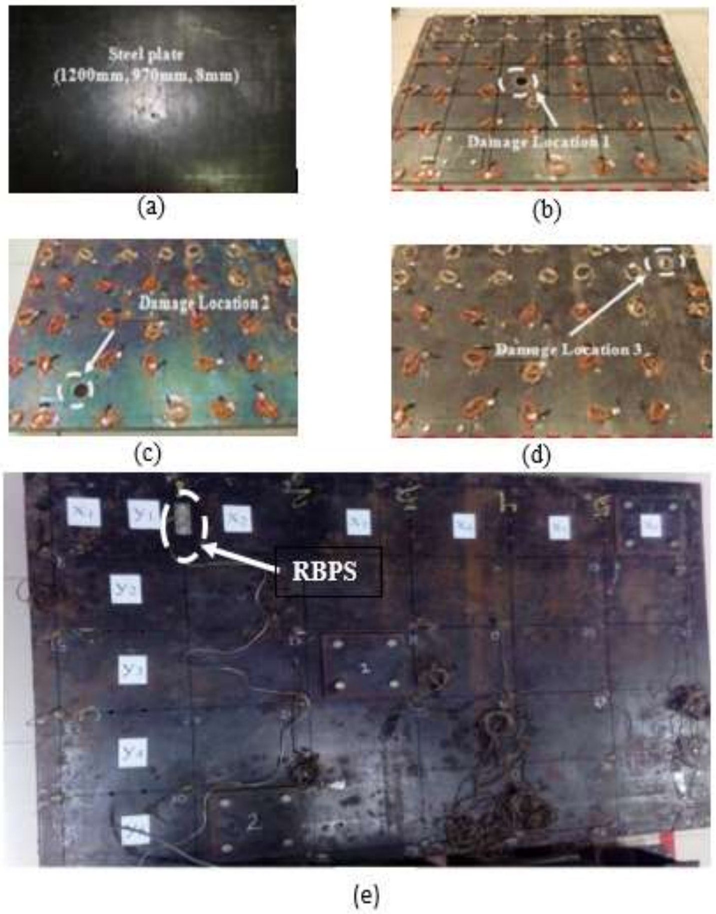



**Figure 4.2**: Fabrication Details of experimental prototype structure

After the fabrication of the test specimen, RBPS was attached to plate using torque wrench in m + n fashion. Three damage locations were chosen, as shown in the Figures 4.1 (b), (c) and (d), respectively. In pristine condition, three holes were covered by plates (150×150 mm in size), attached to the main plate by 4 numbers of 10mm bolts tightened to a torque of 35Nm. Different levels of damage were created by loosening bolts, as illustrated in Figure 4.2. The RBPS was attached to the steel plate, both along the x and y direction, as shown in the Figure 4.1(e).

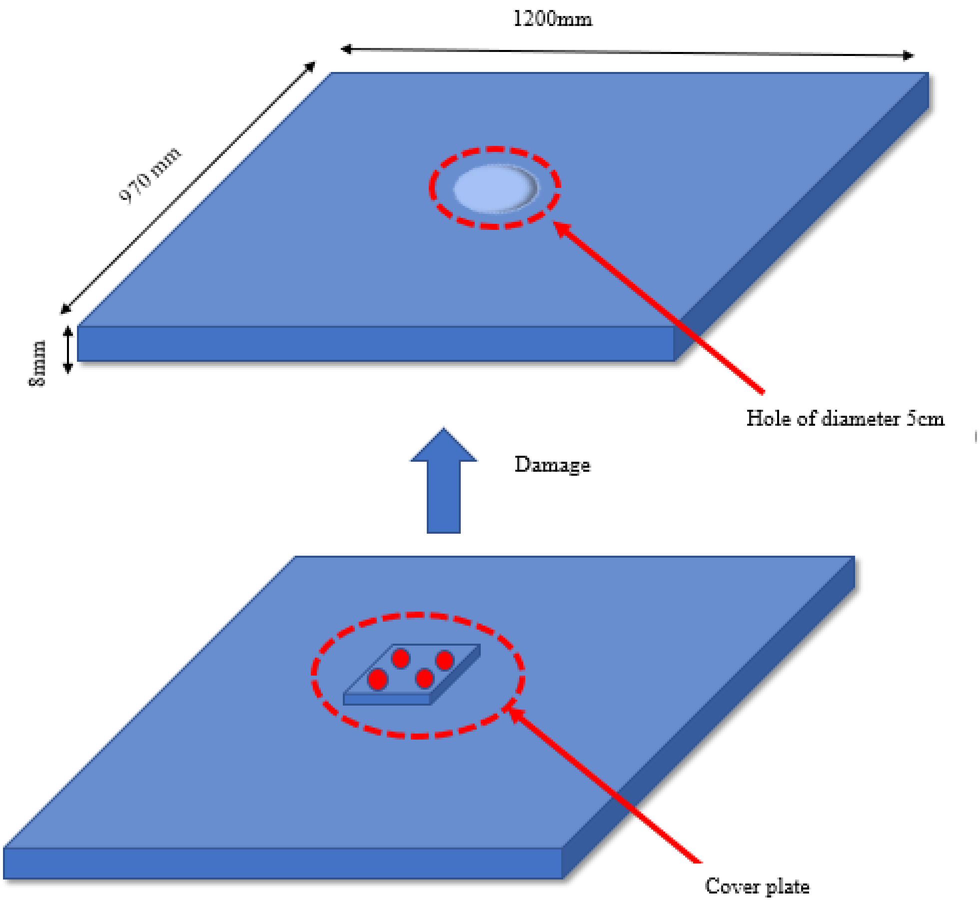



**Figure 4.3**: Illustrating the process of damage simulation

The chemical composition of the steel plate includes carbon of 0.23 %, manganese of 1.5 %, sulphur 0.045%, phosphorus of 0.045% and silicon of 0.40% as per IS-2062, 2006. The key feature of the proposed arrangement is that it drastically reduces the total number of sensors employed for SHM.

## 4.4 EXPERIMENTAL DETAILS

The RBPS using EMI technique employs a PZT patch surface bonded to a strip attached to the monitored structure through bolts, to produce ultrasonic vibrations (in 30-400 kHz range) so as to acquire a characteristic electrical signature of the engineered structure. This signature contains vital information concerning the phenomenological nature of the 2D structure. The electromechanical admittance can be decomposed and analysed to extract the impedance parameters of the structure. In this process, the PZT patch will act as an impedance transducer, which enables the structural identification for SHM. Hence, the PZT patch acts as actuator as well as sensor. The main idea RBPS is that the occurrence of damage in the host structure will affect the mechanical impedance and then the stationary waves on the metal wire, and finally the admittance of the PZT patch, which is directly measured by an LCR meter.

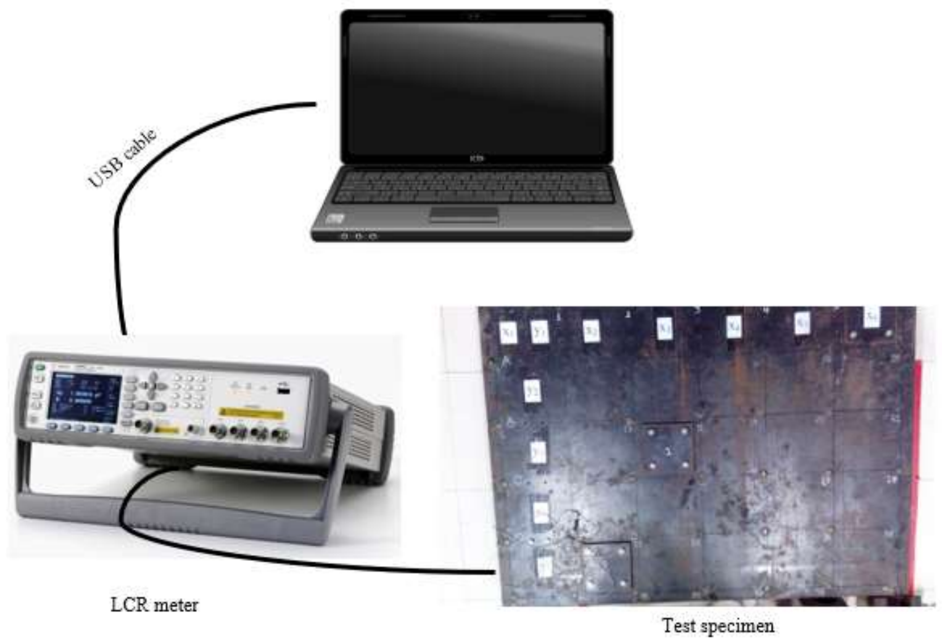



**Figure 4.4**: Overall view of experimental detail

### 4.5 REPEATABILITY OF SIGNATURES

It is very important to ensure the repeatability of the various data sets in the experimentation to ascertain the consistency of the data obtained in various. In this test, repeatability was being checked by acquiring the admittance signature on a same specimen of RBPS for EMI technique at a constant voltage (7v) and temperature (26°C) by tightening the bolts of RBPS at 25Nm torque, loosening them completely and again tightened at same torque. The two signatures are compared in Figure 4.4 for predecided location 1. From this Figure it can be noticed that the RBPS technique has reasonable repeatability. So, it confirms that, RBPS can provide consistent measurements. RMSD percentage obtained was 0.54% for this conductance signature.

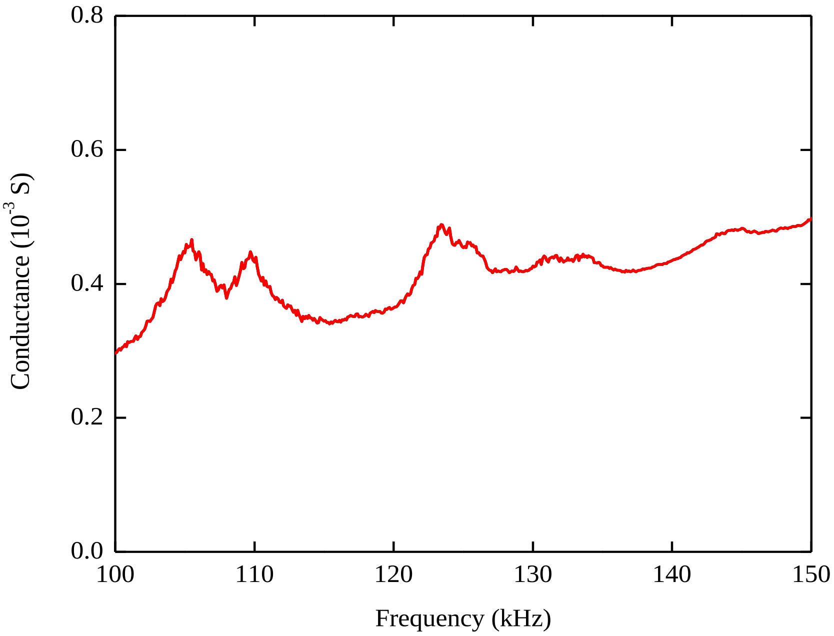
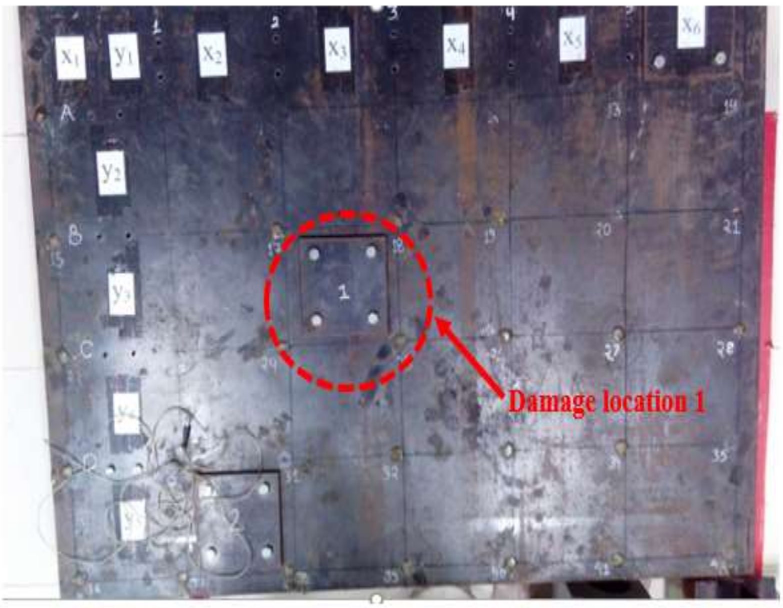


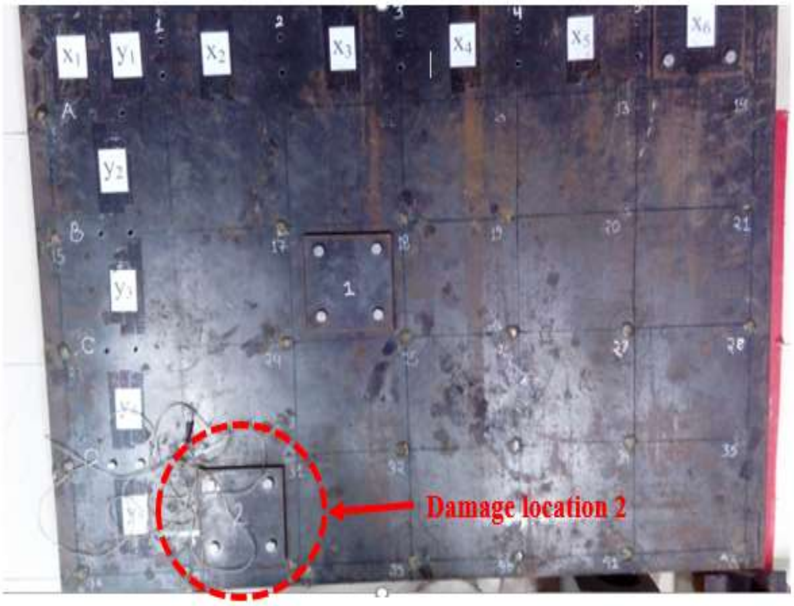

**Figure 4.5** Conductance signature of RBPS for repeatability

## 4.6 EXPERIMENTATION FOR DAMAGE LOCATION IDENTIFICATION

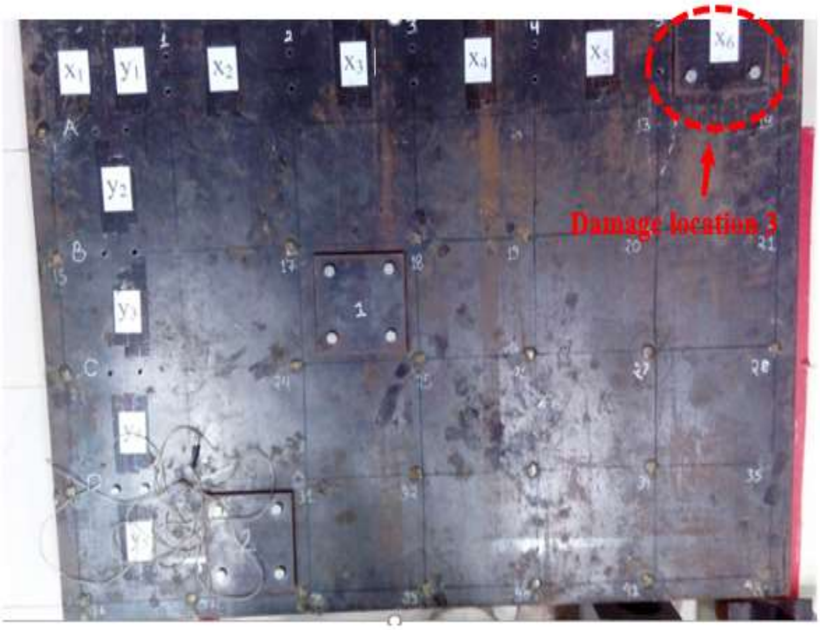
The main aim of this study was to experimentally validate the proposed damage location algorithm. And to detect and locate damage on steel based 2D structure.




**(a)**




**(b)**




**(c)**

**Figure 4.6**: Damage creation at various locations in steel plate (a) Damage1, (b) Damage 2, (c) Damage 3

In this experiment, the three damages damage-1, damage-2, damage-3 in the form of holes of size 5cm diameter were induced in panel as shown in Figure 4.5 (a), (b), (c). The cover plates were placed over all damages, as a retrofitting measure and four 10 mm diameter bolts were tightened at 35 N-m torque to achieve a repaired condition. A total 9 holes were drilled to attach the RBPS as shown in Figure 4.6. The three damage conditions were assessed using EMI technique. For each case the three damage conditions, one hole was uncovered by removing the cover plate completely and other two were kept covered with the bolts tightened with 35 N-m torque

## 4.7 EXPERIMENTAL RESULTS

### 4.7.1 Damage localization for location 1

For the damage location 1 (see in Figure 4.6(a)), for Location of RBPS, the conductance signature was compared for pristine and damage conditions and shown in Appendix A. The RBPS closest to damage (i.e 2, 3, B and C) has undergone the maximum change of signature. The RMSD index was determined and plotted for the damage location 1 and shown in Figure 4.7.

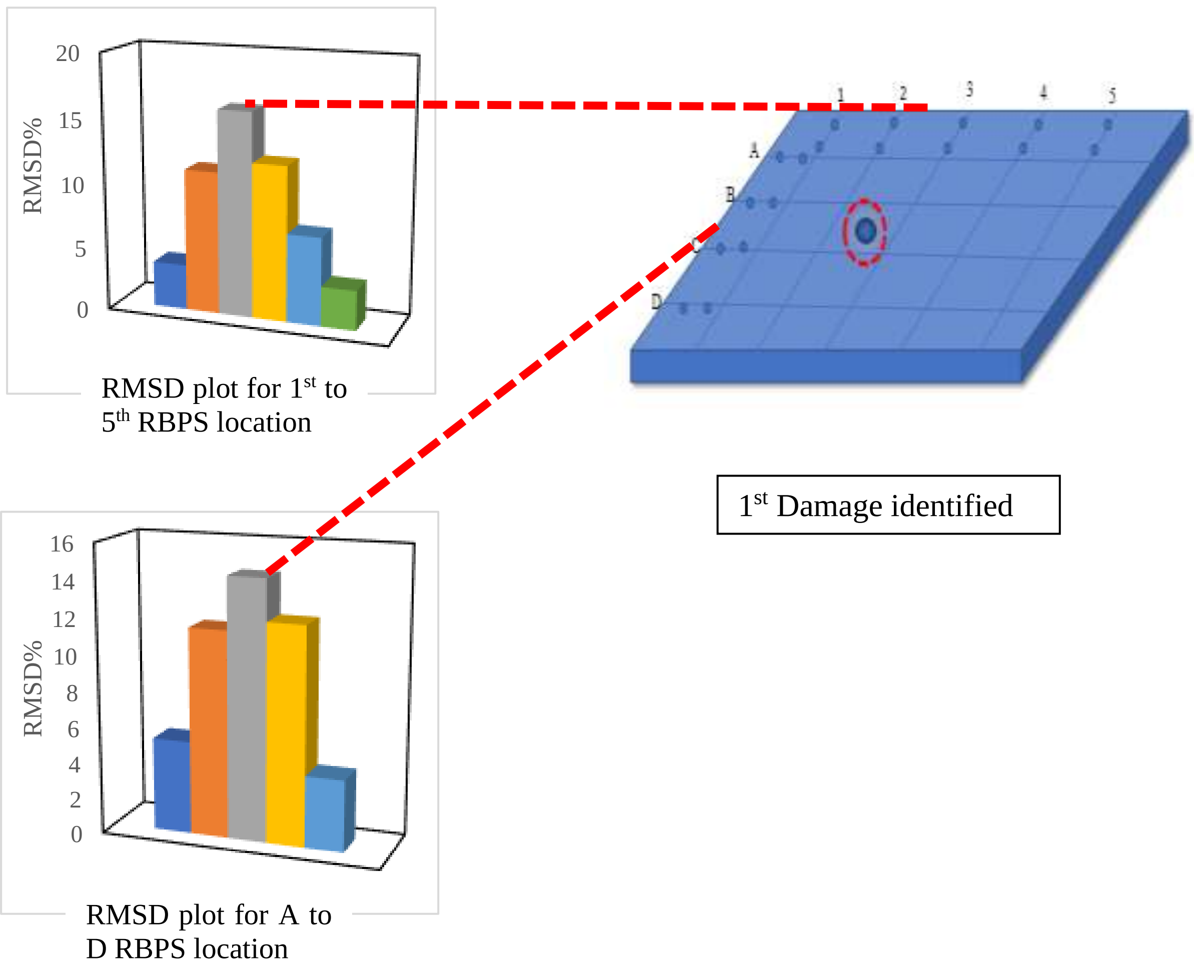



**Figure 4.7** RMSD plot for damage 1 from 1$^{st}$ to 5$^{th}$ location and A to D location.

4.7.2 Damage localization for location 2

For the damage location 2 (see in Figure 4.6(b)), for Location of RBPS, the conductance signature was compared for pristine and damage conditions and shown in Appendix B. The RBPS closest to damage (i.e 1, 2, C and D) has undergone the maximum change of signature. The RMSD index was determined and plotted for the damage location 2 and shown in the Fig 4.8

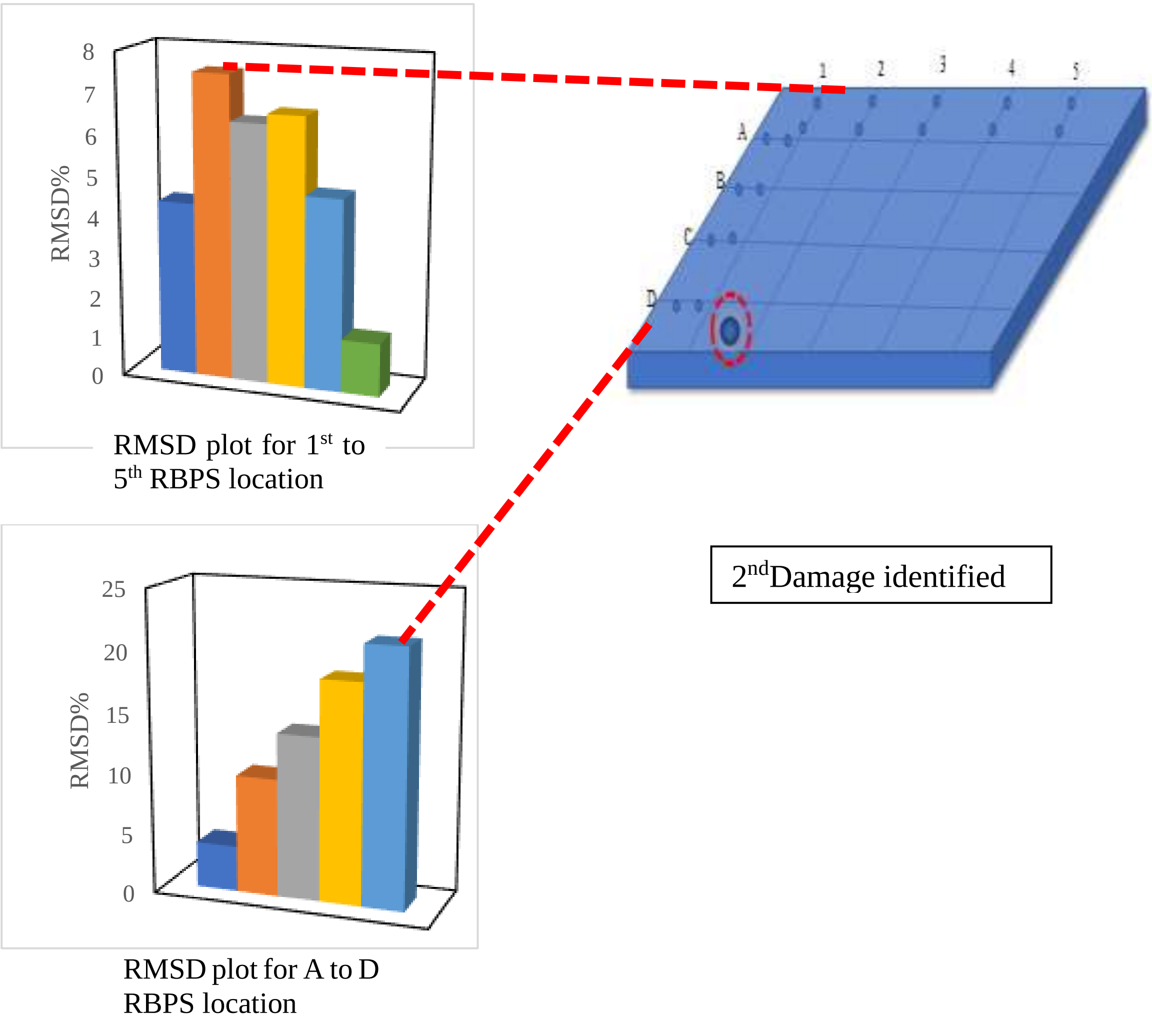



**Figure 4.8** RMSD plot for damage 2 from 1$^{st}$ to 5$^{th}$ location and A to D location

4.7.3 Damage localization for location 3

For the damage location 3 (see in Figure 4.6(c)), for Location of RBPS, the conductance signature was compared for pristine and damage conditions and shown in Appendix C. The RBPS closest to damage (i.e 5, A and B) has undergone the maximum change of signature.

The RMSD index was determined and plotted for the damage location 3 and shown in figure 4.9

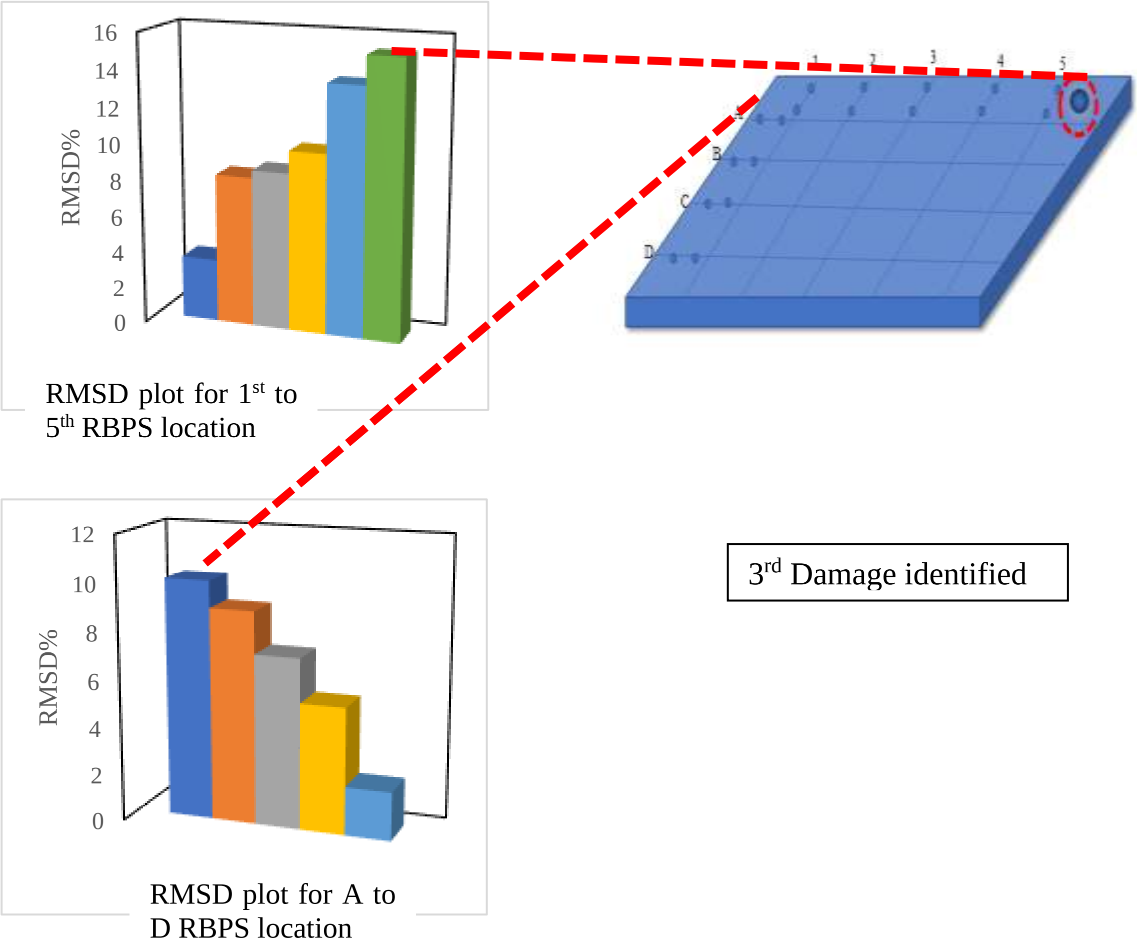



**Figure 4.9** RMSD plot for damage 3 from 1st to 5th location and A to D location

### 4.8 EXPERIMENTAL DAMAGE SENSITIVITY STUDY

This study aimed for carrying out a damage sensitivity analysis by experimental means. For this purpose, steel plate was firstly assessed for pristine condition with 35 N-m torque applied on the nut and bolt system at damage location 1. Damage was created by loosening bolts by torque of 25 Nm. The signal was applied in the frequency range of 100-150 kHz across the RBPS at each predecided location and the resulting values of conductance (*G*) and susceptance *(B)* acquired across the sensor patches were directly stored in the computer by using VEEPRO Software.

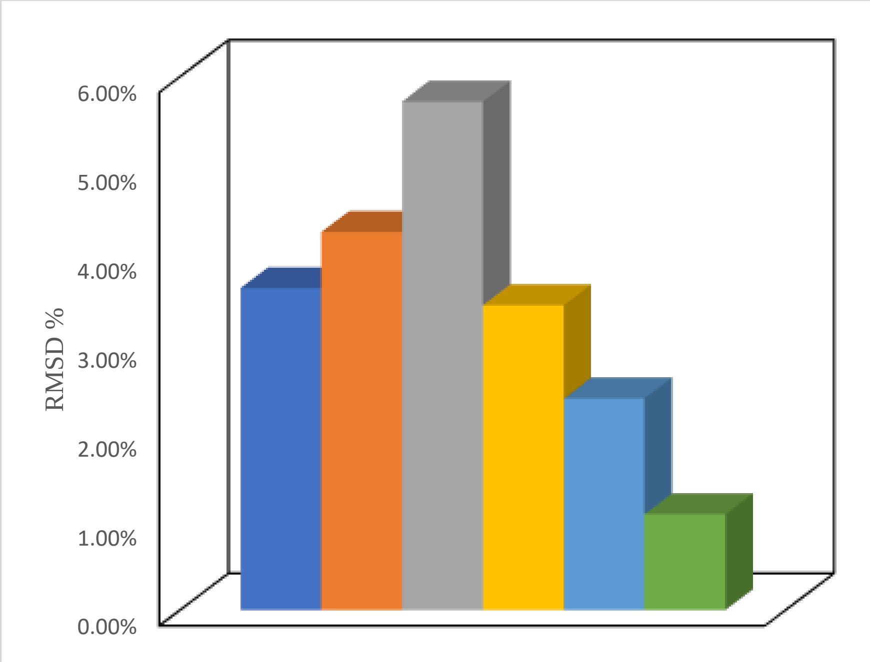



**Figure 4.10** RMSD plot for sensitivity from 1st to 5th location

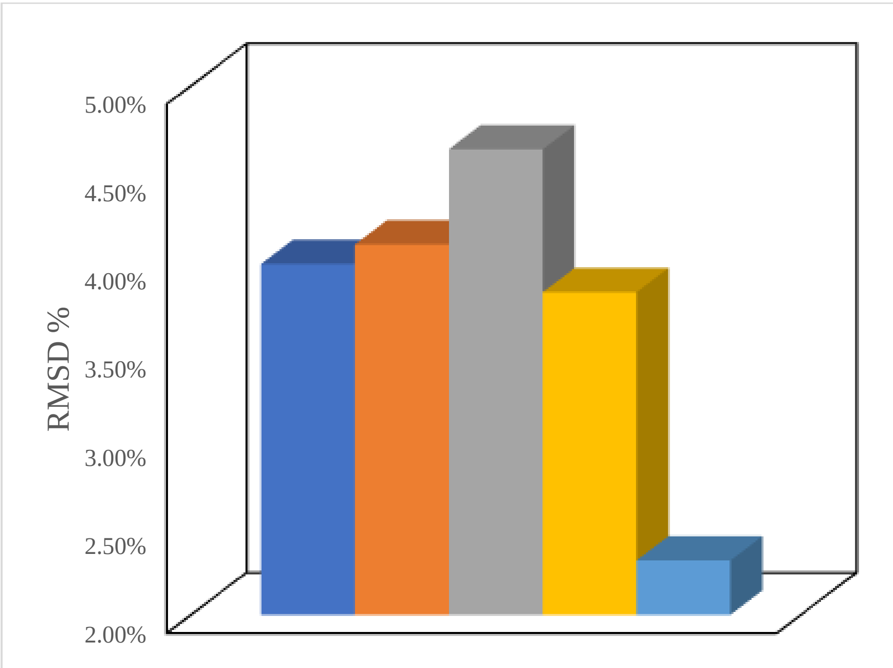



**Figure 4.11** RMSD plot for sensitivity from A to B location

### 4.9 SUMMARY CONCLUDING REMARKS

The experimental results presented in this chapter clearly demonstrated show that the damage detection and localization effectiveness of the RBPS. The damage has been correctly identified. Thus, the proposed RBPS, which has much more advantages than the conventional technique, has proven its viability as a replacement of conventional technique. The time taken for using the RBPS is much lesser than the conventional one because of lesser amount of sensors used at locations and these experimental results shows that RBPS can be used for the larger host structure.

# CHAPTER 5

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 INTRODUCTION

This thesis sums up the development and evaluation of the reusable bolted type piezo sensors based on EMI technique for metal structures, for damage detection. This chapter covers the conclusions and gives the about future work to be done.

## 5.2 CONCLUSIONS AND CONTRIBUTIONS

Major research conclusions can be summarized as follows

1. A suitable RBPS unit has been successfully fabricated and experimentally validated.
2. A good repeatability, characterized by low RMSD less than 0.5% signature has been observed. This is at least one order of magnitude smaller then that resulting from damage. RBPS can be used for large structures.
3. Damage detection and localization has been done successfully by using algorithm.
4. The RBPS can be used in to replace conventional PZT for metal structures for damage detection. Being reusable, their use means savings. Likewise, the need much less skill level from the users.

## 5.3 FUTURE RECOMMENDATION

The following work will be done with the extension of this research

1. To develop an algorithm for extending the RBPS on RC structures.
2. The approach may also be extended for multiple damage scenarios.
3. Magnetic version can be used instead of bolted strips and sensitivity of RBPS can be compared with it.

# PUBLICATIONS

1. Supriya, Negi P and Bhalla S (2018) “Damage Assessment Of 2d Structure by Reusable Bolted Piezo Sensor (RBPS) Using EMI Technique.” International Conference on Geomatics in Civil Engineering (ICGCE-2018), April 5$^{th}$- 6$^{th}$, IIT ROORKEE.

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17. Sun F, Chaudhry Z, Rogers CA, Majmunda M and Liang C (1995) “Automated Real-Time Structure Health Monitoring Via Signature Pattern Recognition.” *Proceedings of the SPIE Conference on Smart Structures and Materials*, 2443, 236–247.
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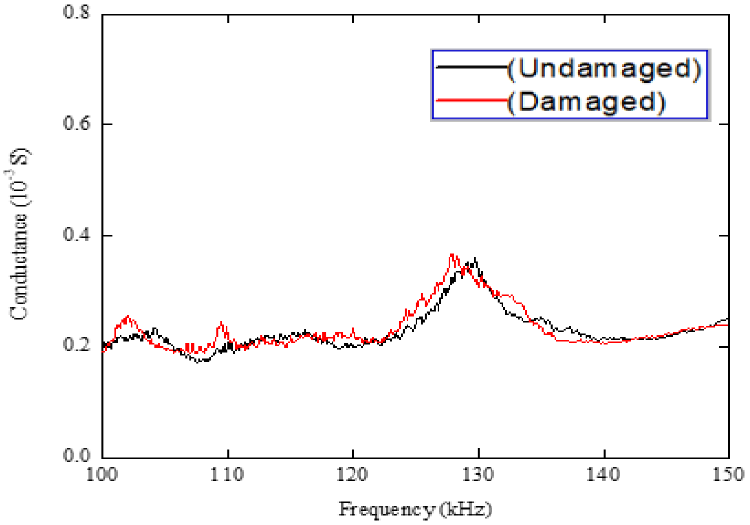
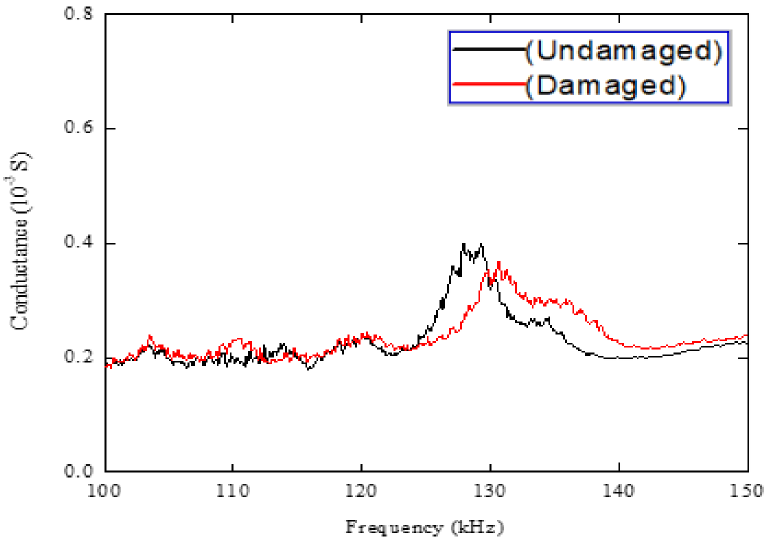
# APPENDIX -A

# CONDUCTANCE SIGNATURES FOR DAMAGE LOCATION 1

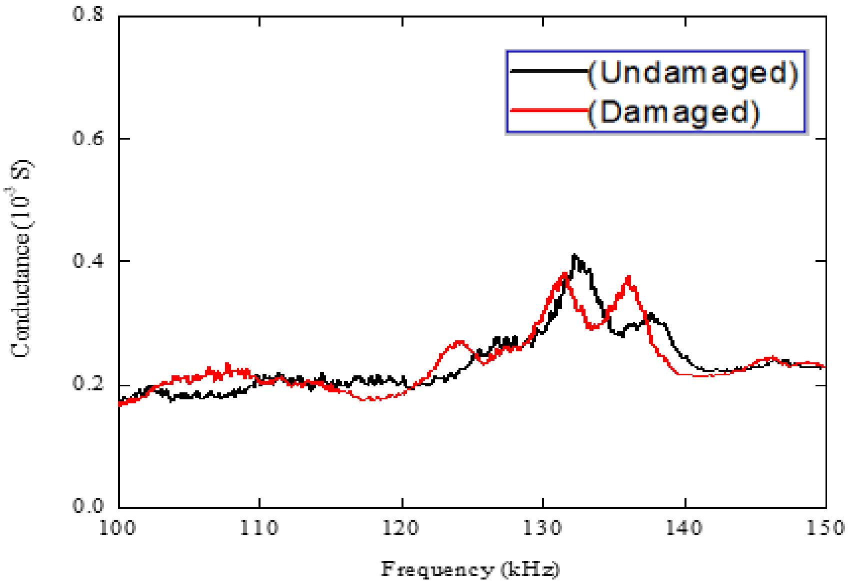



(a)

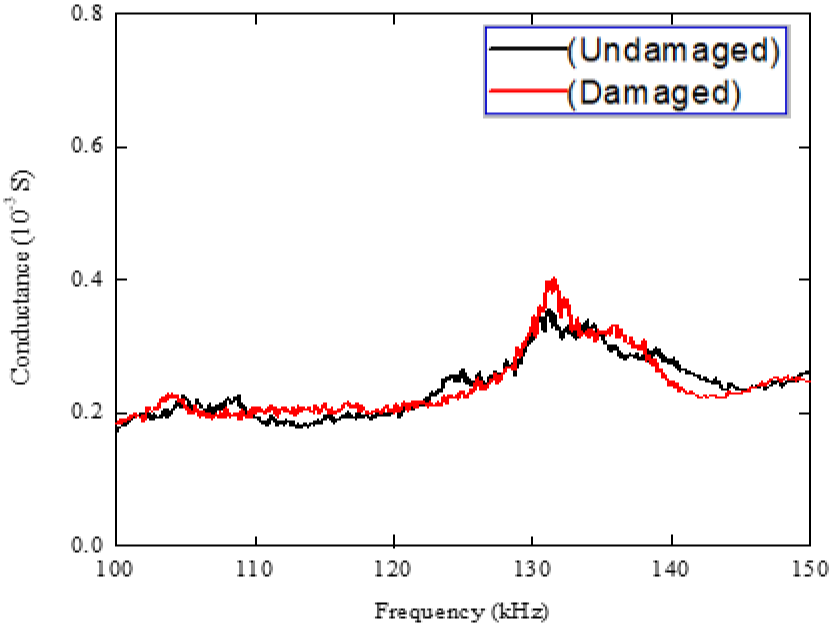



(b)

**Figure A.1** Conductance signature for undamaged and damaged condition at **(a)** location 1 **(b)** location 2

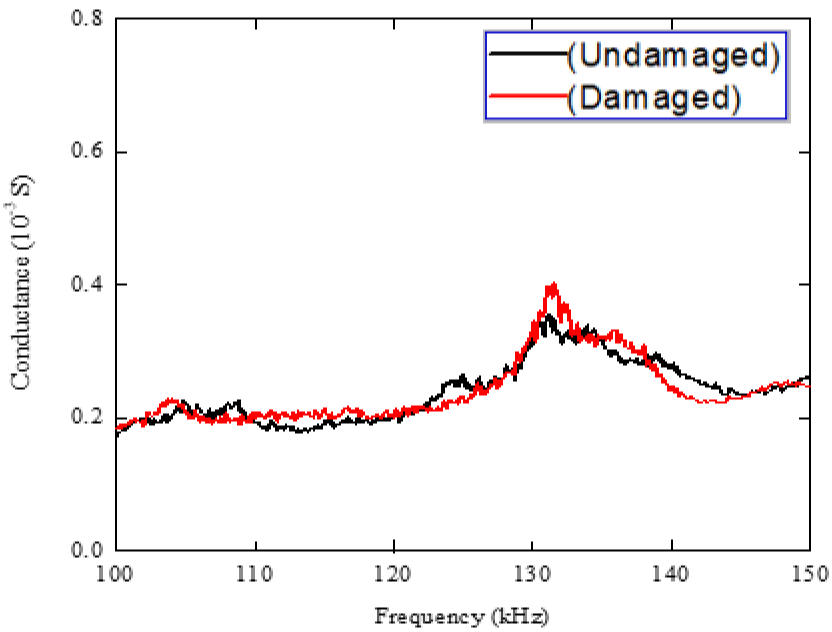



(c)

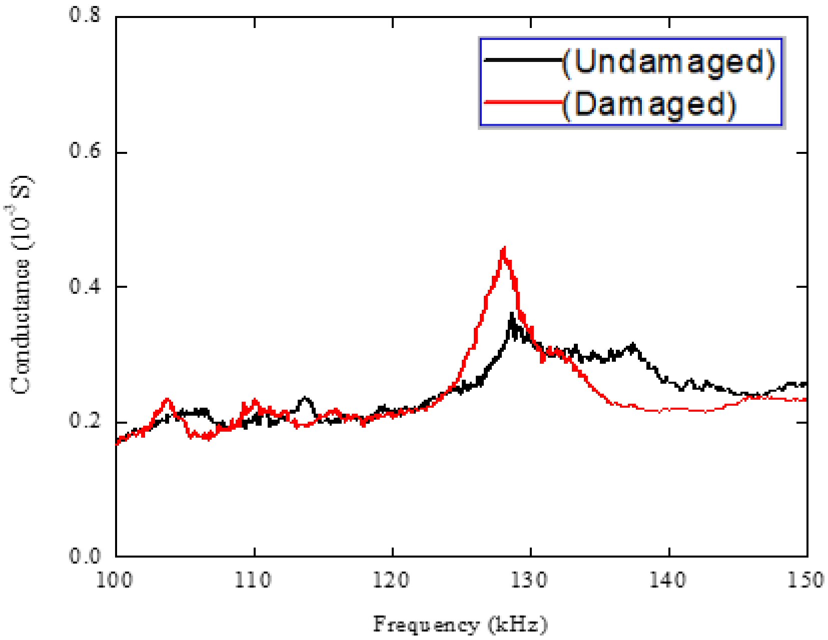



(d)

**Figure A.2** Conductance signature for undamaged and damaged condition at **(c)** location 3 **(d)** location 4

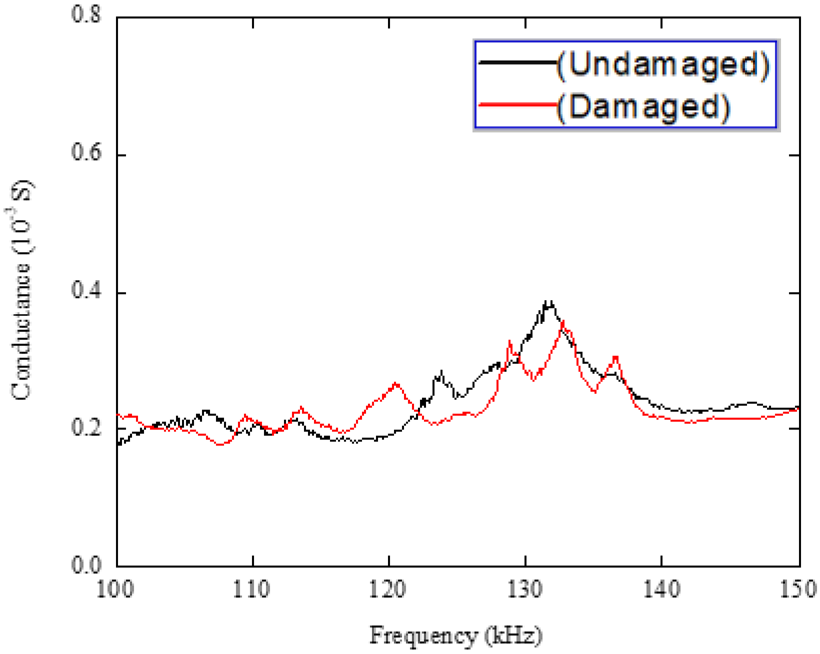



( e)

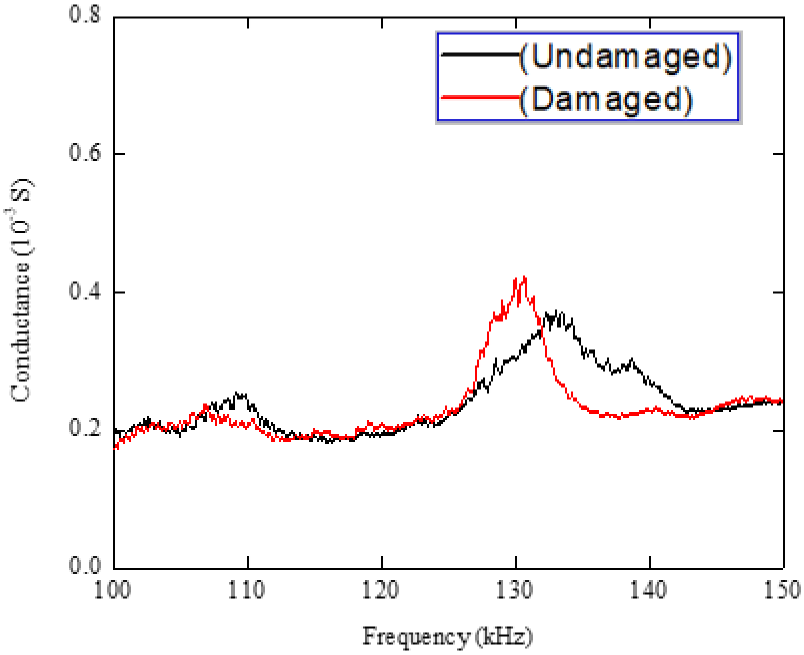



(f)

**Figure A.3** Conductance signature for undamaged and damaged condition at **(e)** location 5 **(f)** location A

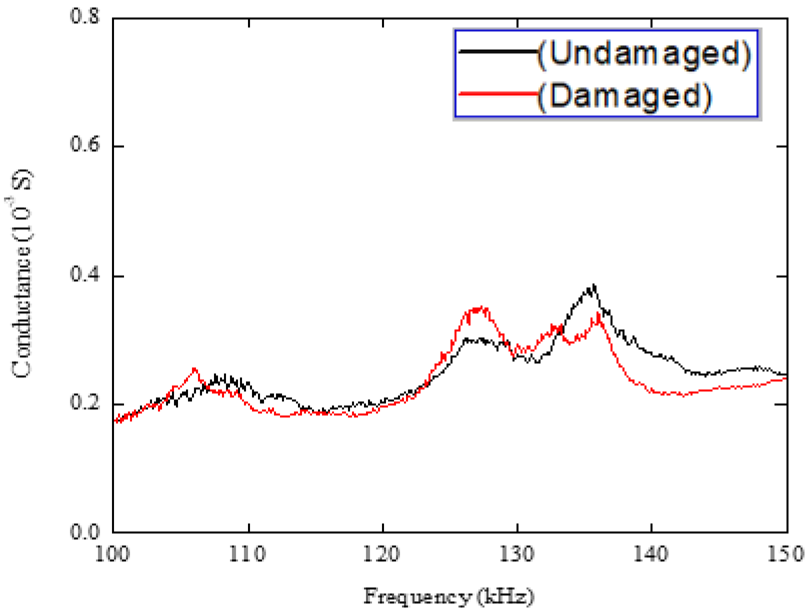



(g)




(h)

**Figure A.4** Conductance signature for undamaged and damaged condition at **(g)** location B **(h)** location C

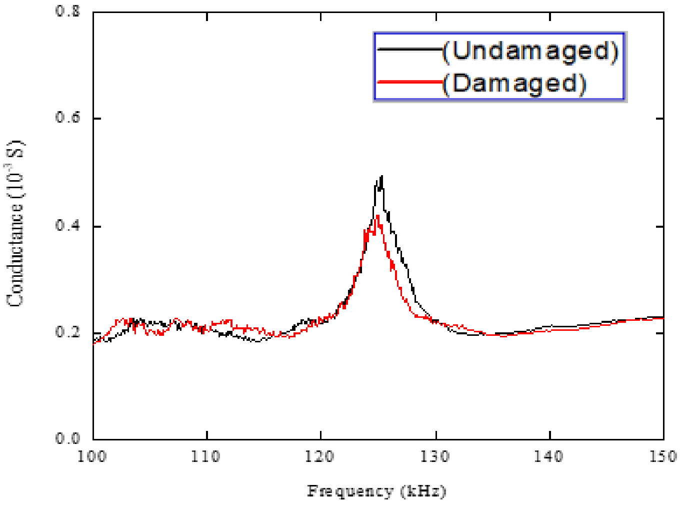



(i)

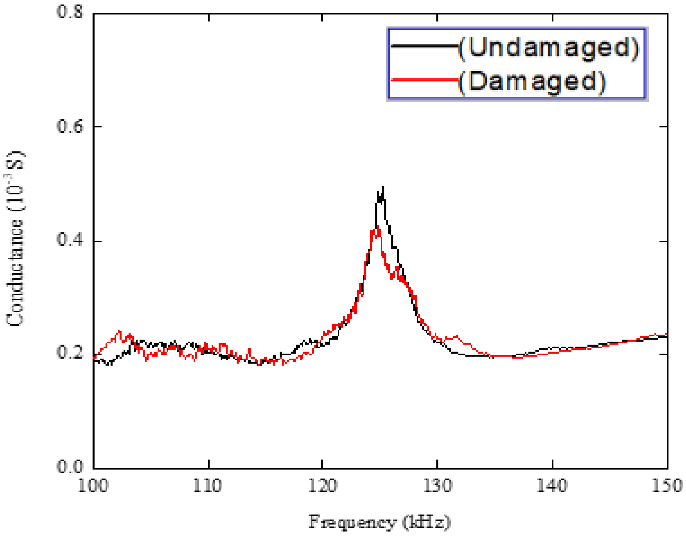
**Figure A.5** Conductance signature for undamaged and damaged condition at **(i)** location D

# APPENDIX -B

# CONDUCTANCE SIGNATURES FOR DAMAGE LOCATION 2

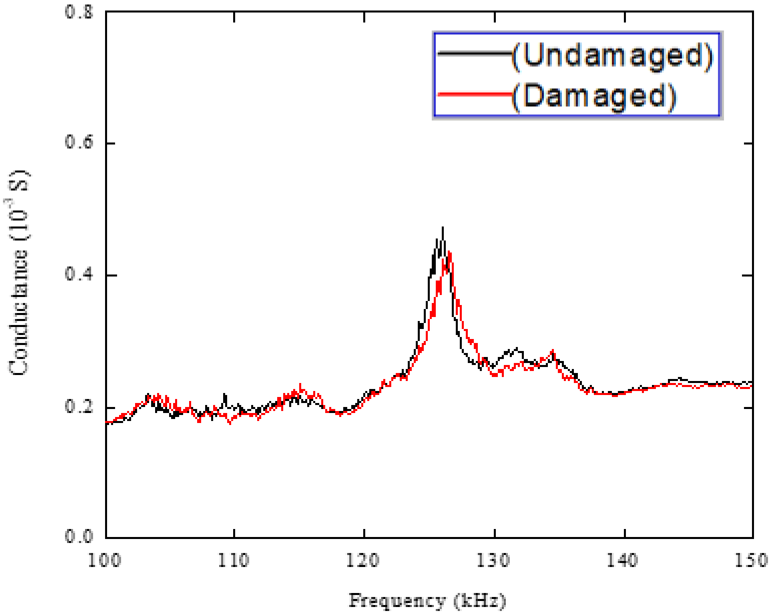



(a)

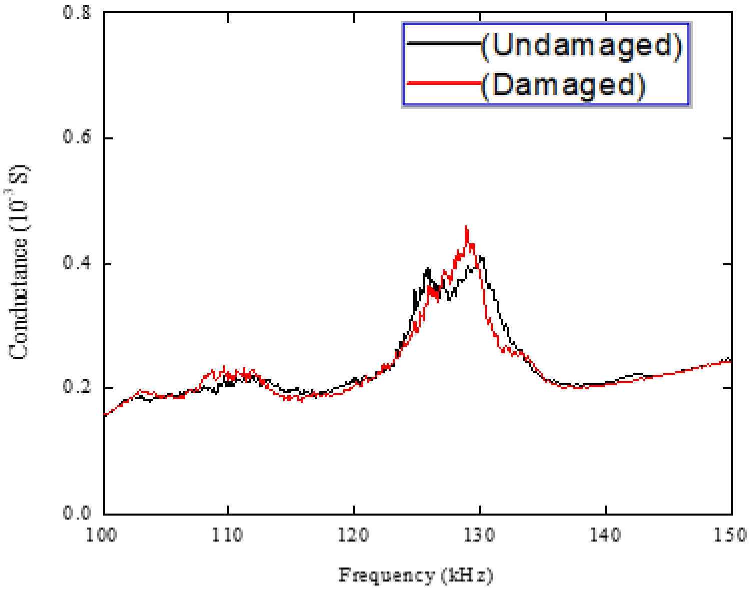



(b)

**Figure B.1** Conductance signature for undamaged and damaged condition at (a) location 1 **(b)** location 2

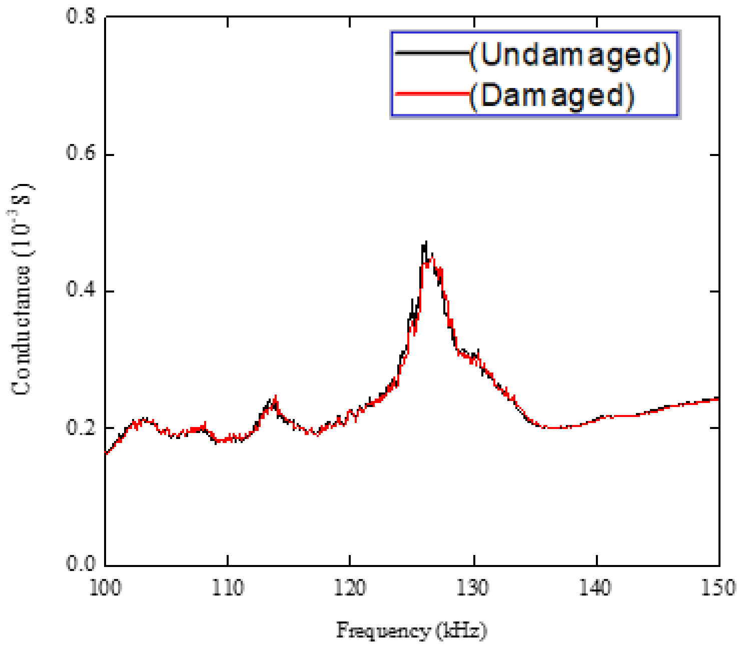



(c)

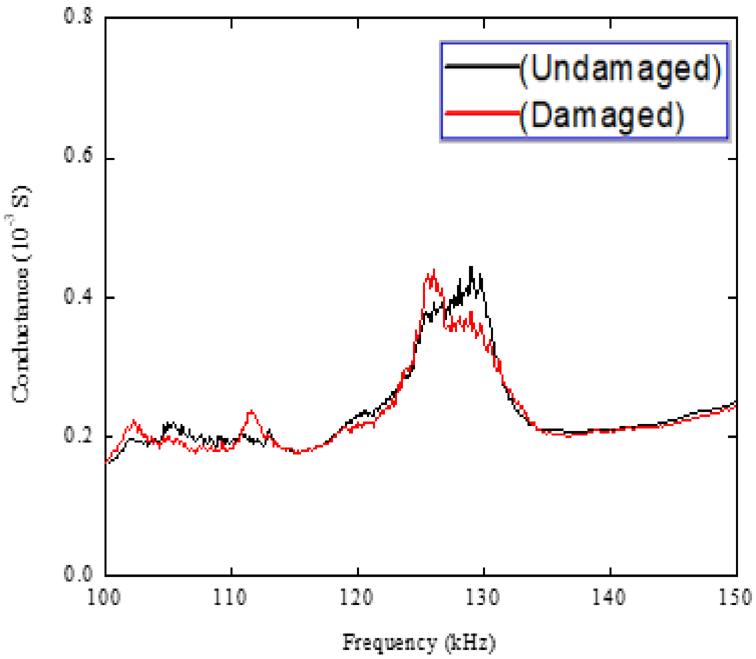



(d)

**Figure B.2** Conductance signature for undamaged and damaged condition at **(b)** location 3 **(d)** location 4

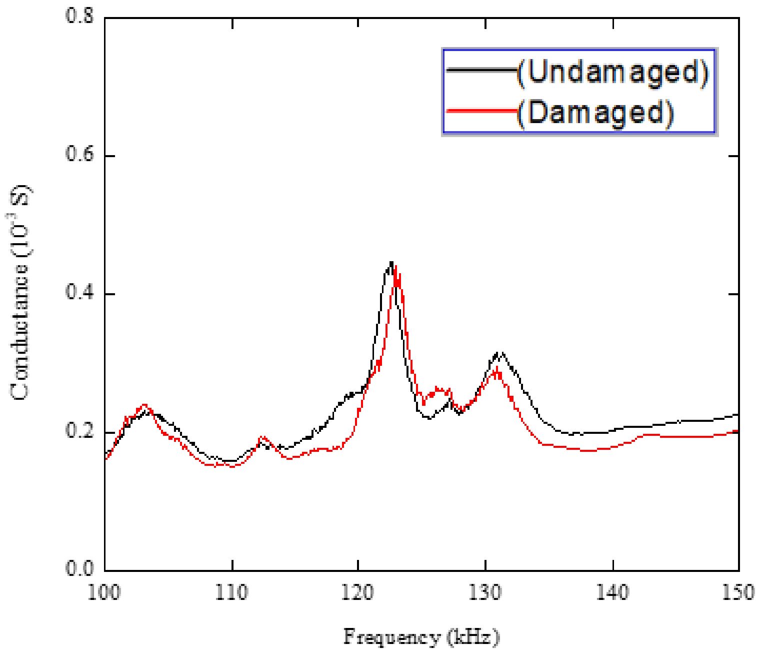



(e)

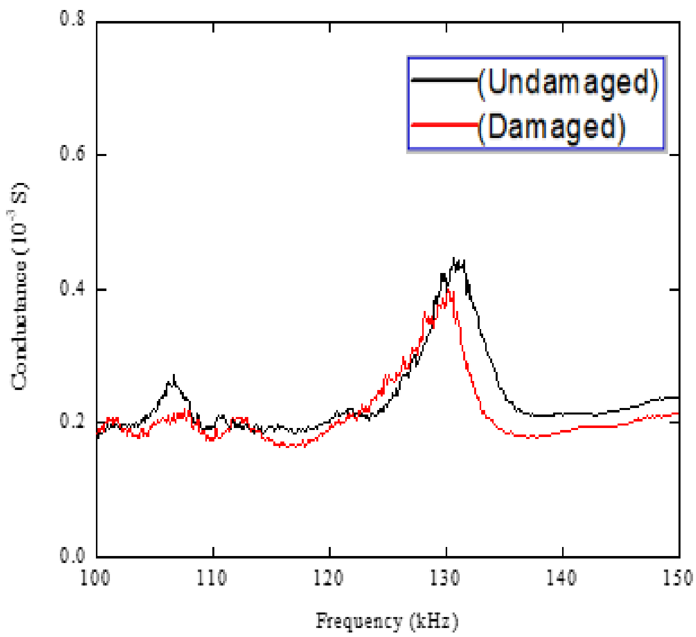



(f)

**Figure B.3** Conductance signature for undamaged and damaged condition at **(c)** location 5 **(f)** location A

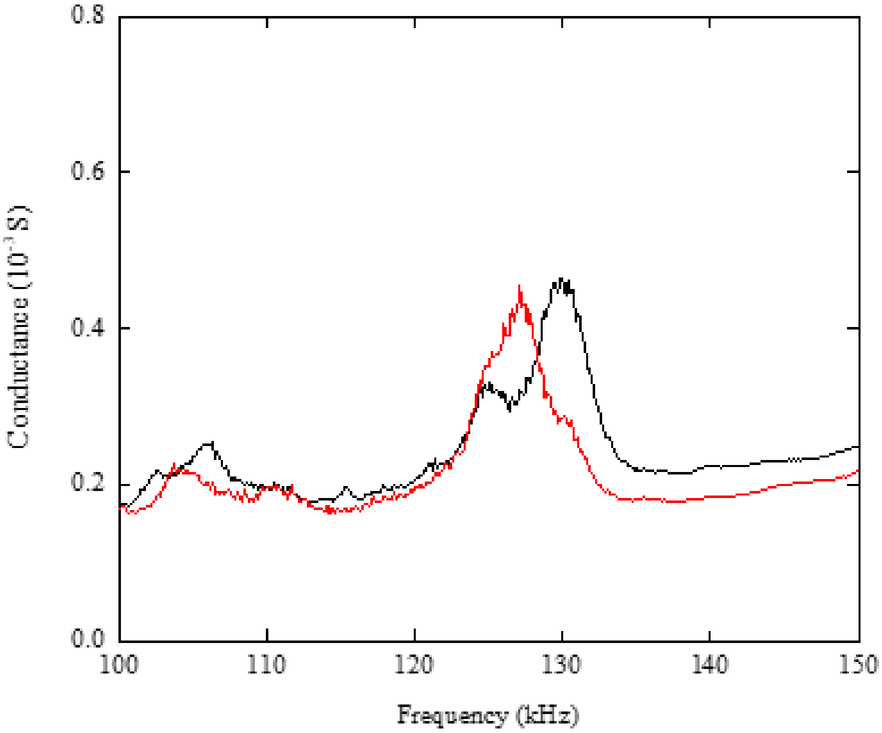



(g)




(h)

**Figure B.4** Conductance signature for undamaged and damaged condition at **(g)** location B **(h)** location C



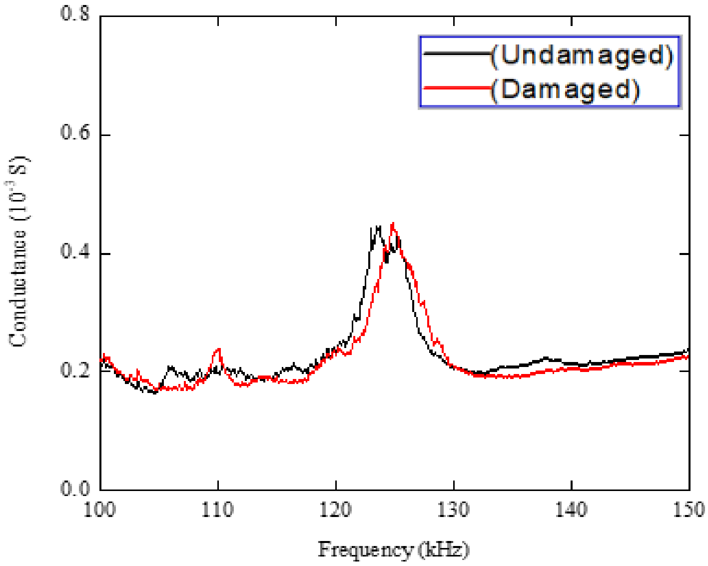

(i)

**Figure B.5** Conductance signature for undamaged and damaged condition at

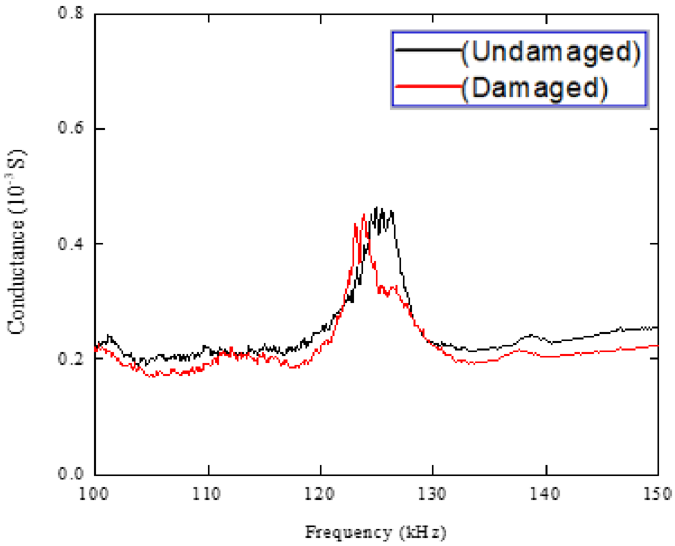
**(i)** location D

# APPENDIX -C

# CONDUCTANCE SIGNATURES FOR DAMAGE LOCATION 3

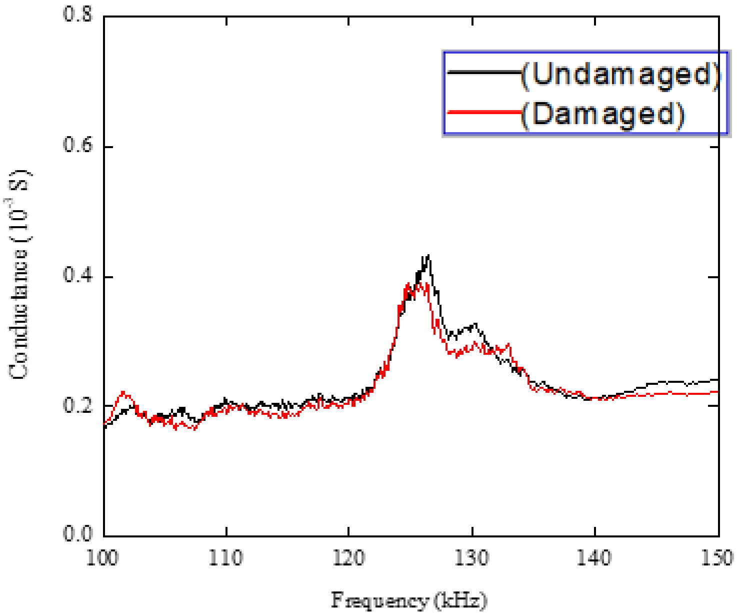



(a)

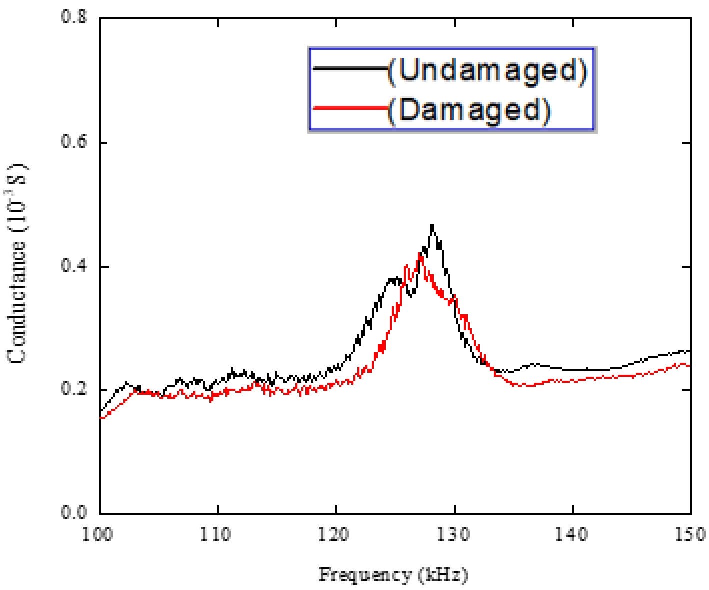



(b)

**Figure C.1** Conductance signature for undamaged and damaged condition at (b) location 1 **(b)** location 2

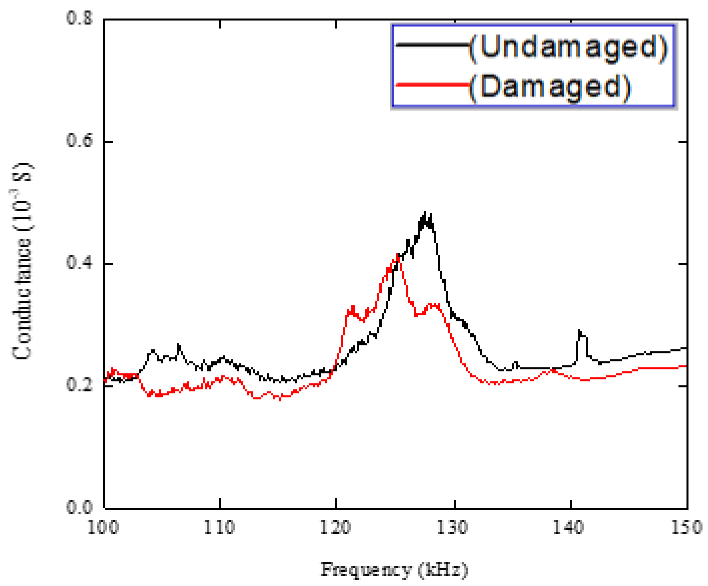



(c)

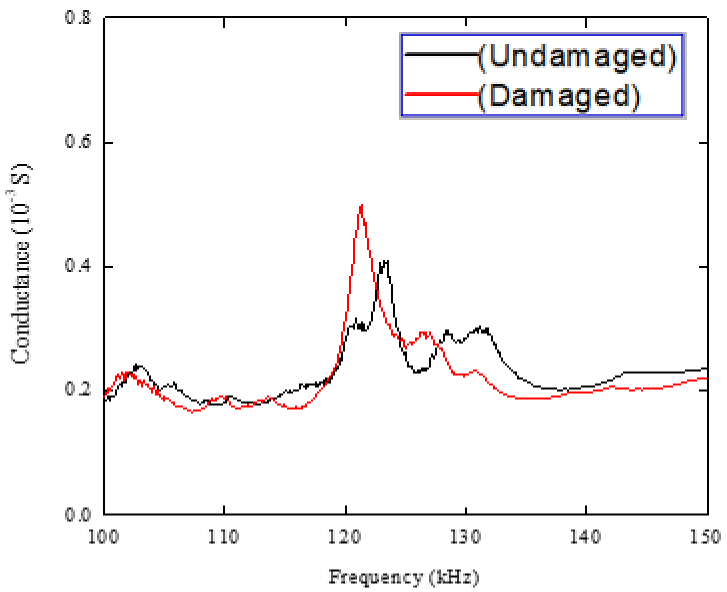



(d)

**Figure C.2** Conductance signature for undamaged and damaged condition at **(c)** location 3 **(d)** location 4

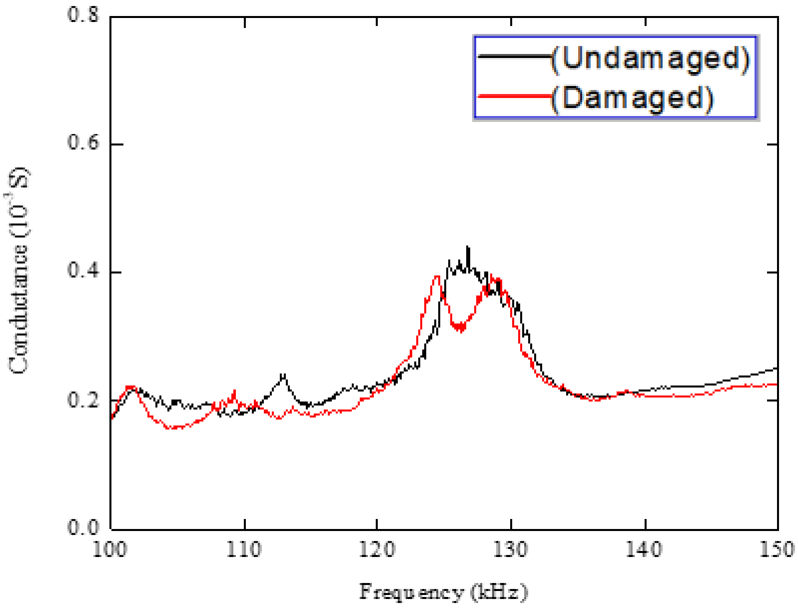



(e)

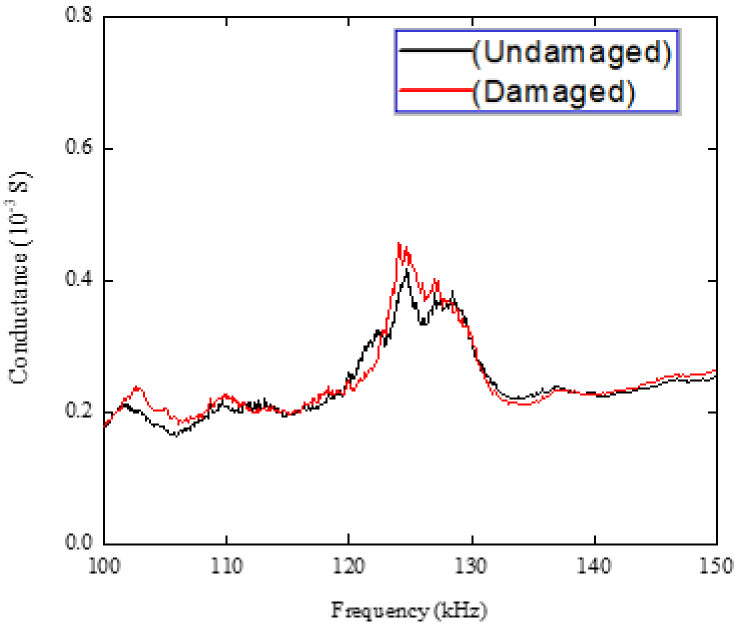



(f)

**Figure C.3** Conductance signature for undamaged and damaged condition at ( e) location 5 **(f)** location A

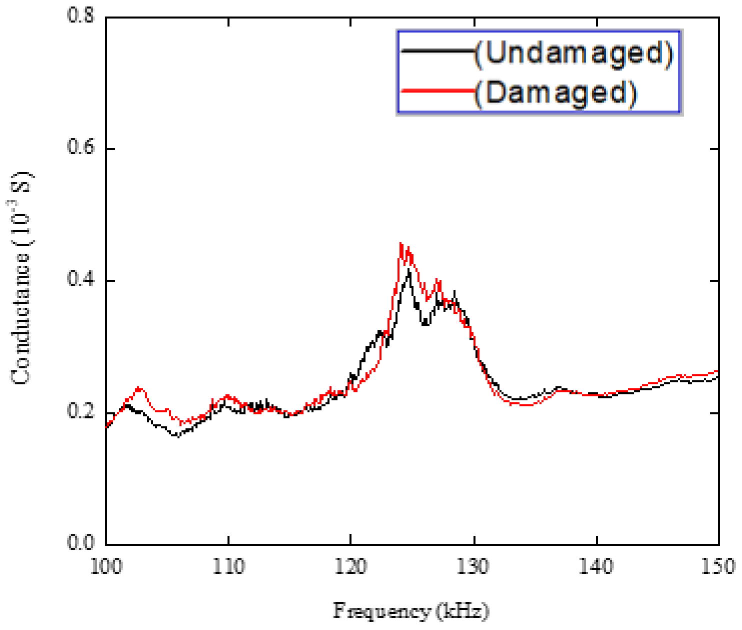



(g)




(h)

**Figure C.4** Conductance signature for undamaged and damaged condition at **(g)** location B **(h)** location C




(i)

**Figure C.5** Conductance signature for undamaged and damaged condition at

(i) location D

# APPENDIX -D

# CONFERENCE PAPER

## DAMAGE ASSESSMENT OF 2D STRUCTURE BY REUSABLE BOLTED PIEZO SENSOR (RBPS) USING EMI TECHNIQUE

Supriya Thakur[1] , Prateek Negi[2], Suresh Bhalla[3]

[1] M.Tech (Structural Engineering), Civil Engineering Department, Indian Institute of Technology (IIT) Delhi, Hauz Khas, New Delhi – 110016,India, phone : +91-7042172185. *Corresponding author 123supriya93@gmail.com

[2] Research Scholar , Civil Engineering Department, Indian Institute of Technology (IIT) Delhi, Hauz Khas, New Delhi – 110016,India, phone : +91-9953919464. negidynamic@gmail.com

[3] Professr , Civil Engineering Department, Indian Institute of Technology (IIT) Delhi, Hauz Khas, New Delhi – 110016,India, phone : +91-011-2658-1117. sbhalla@civil.iitd.ac.in

**Abstract.** In recent years, the electro mechanical impedance (EMI) technique has been proved as an effective non-destructive testing mechanism for monitoring various Civil Engineering structures in both surface bonded and embedded configurations. This paper proposes a novel concept of reusable bolted piezo sensor (RBPS) for monitoring damages in a plate structure. A prototype RBPS sensor is fabricated and its applicability is successfully demonstrated for damage detection on an aluminium thin plate. The admittance signature of the piezo sensor bonded to the aluminium plate is monitored by fixing the RBPS to the plate. Further, suitability and reliability of conductance signatures in pristine and damaged conditions for the reusable bolted piezo sensor are found to perform on same standards of a direct surface bonded piezo. Also, repeatability of signatures is found to be acceptable. Experiments have shown that the proposed RBPS is very effective in damage detection.

**Keywords**: Lead Zirconate Titanate (PZT), Reusable Bolted Piezo Sensor (RBPS), Structural Health Monitoring (SHM), Electro Mechanical Impedance (EMI) Technique, Root Mean Square Deviation (RMSD).

## 1.Introduction

Structural health monitoring (SHM) involves continuous monitoring of civil structures to detect or locate damages and failure due to external loading and environmental conditions. Smart material-based sensors such as lead zirconate titanate (PZT) patches have enhanced the field of SHM. One of latest technique used in SHM is Electro Mechanical Impedance (EMI) technique. EMI technique is an interface between global dynamic techniques and local non-destructive (NDE) technique. In this technique a piezoelectric based transducer is used which acts as an actuator and sensor as well. The PZT patch is surface bonded on structure using adhesive. An LCR meter is used to measure electromechanical admittance (real and imaginary components) at given frequency i.e. 30-400 kHz. It is extremely sensitive to incipient damage and immune to noise. The application of reusable PZT is still new and the idea is to reduce the cost of monitoring because the same PZT could be re-used as many times as possible and therefore ensure better repeatability and reliability in measurements. So far limited studies have been reported on the development of the reusable PZT technique for monitoring hydration and structural health of concrete based on the EMI method. However, no dedicated reusable bolted piezo based study on damage detection has been done on metal structures.

### 1.1 Smart Piezoelectric Materials

Smart materials are designed materials which have ability to change their physical properties such as shape, stiffness, viscosity, etc. in a specific manner according to certain specific type of stimulus input. Smart materials are one of components of smart structures examples of smart materials are shape memory alloys, magneto- or electrorheological fluids, polymer gels and piezoelectric materials, optical fibres. The work presented in this paper is based on piezoelectric materials, often referred to as piezo sensors. Piezo sensors are available in two commercial forms: (a) Ceramics such as (a) PZT (b) Polymers such as polyvinylidene fluoride (PVDF). The piezo patches exhibit two special effects due to the phenomenon of piezoelectricity. They generate surface charges in response to a mechanical stress applied in the plane of the patch, this phenomenon is called the ‘direct effect’. Conversely, they undergo mechanical deformations in response to an electric field applied across their thickness, which is known as the ‘converse effect’. Sensor applications are based on the direct effect, and actuator applications are based on the converse effect

## 1.2 Reusable Bolted Piezo Sensors (RBPS)

In the recent years several researches have attempted to propose non-bonded configurations of piezo sensors. Naskar [1] proposed a new field-deployable algorithm harnessing the metal-wire-based variant of the EMI technique, warranting drastically lesser number of piezo sensors, for damage detection and localization on large two-dimensional structures such as plates. The metal wire-based adaption involves bonding a PZT patch at the end of a wire to other end of which the bonded to the structure. Srivastava et. al. [2] proposed and evaluated the feasibility of employing PZT patches as biomedical sensors in non-bonded configuration for assessing the physiological conditions of bones. For this purpose, a special design is proposed where the PZT patch is first bonded on a thin aluminum strip, which is in turn clamped securely on the biomedical subject. The trend of the conductance signatures in the healthy and the damaged.

This paper proposes a new reusable sensor for EMI technique where the PZT patch is not directly bonded on surface of structure but on metal strip example aluminium, steel etc. and metal is attached to the structure with bolts. Brittleness of the PZT, makes it difficult to be attached on complex geometry and not feasible to attach in the hazardous locations. And also, PZT transducers expensive compare to other sensors. Therefore, for repetitive applications, such as in the precast industry, a method to reuse the PZT transducers is essential. A sensor that can be easily attached and detached will not only reduce the overall cost of monitoring various structures, but the installation time for the sensors can be dramatically reduced as the conventional way of conducting the EMI technique requires the PZT material to be surface attached with an adhesive.

## 2. Fabrication of RBPS

In this investigative study, a bolted connection consisting of one main aluminium plate (397 mm x 290 mm x 3 mm), one aluminium strip, one steel strip was chosen as the test specimen. These were joined together by a bolt of diameter 8 mm, tightened using standard torque wrench so as to ensure a uniform clamping action. A conventional PZT patch (10 x 10 x 0.3 mm) was also bonded on the specimen. The two PZT patches were attached to the surface of aluminium strip and steel strip using adhesive layer (epoxy). An LCR meter was connected to the PZT patches on one to one basis controlled by VEE PRO 9.2 software operating in a laptop. Signatures were acquired for the frequency range of 100-150 kHz through LCR meter. After acquiring signatures at different torques. Damage was induced in the specimen of 5 mm diameter hole and then signatures were compared at pristine and damaged stage.


**Fig. 1** Complete experimental setup

### 2.1 Root mean square deviation (RMSD)

In the EMI technique, damages sensed by the amount of change of signatures in the vertical or horizontal directions. The origin of new peaks or the release of older peaks, which are the key indicators of damage. Root mean square deviation (RMSD) is the most commonly used index in SHM to calculate the degree of deviation of the admittance signatures (G) from the baseline signatures. The RMSD index is defined as

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}({G^1}_i - {G^0}_i)^2}{\sum_{i=1}^{n}({G^0}_i)^2}} \quad (1)$$

### 2.2 Repeatability of signatures

To ensure efficiency of the RBPS it is important to check the repeatability of signatures. Signatures were acquired by fully loosening the bolts once and then fully tightening them at constant torque i.e. 25 Nm. For good repeatability RMSD should be in the range of 0.1-2%. Lesser the value of RMSD for repeatability better is the RBPS. For better results three prototypes were made (Prototype-I, prototype-II and prototype-III). Length of prototype-II was reduced to make prototype III to increase the structural frequency of RBPS and to neglect the effect of vibrations. Prototype-III was the turbo version which gives the RMSD of repeatability 0.3%.

**Table 1.** Details of Prototypes

| Parameters | Prototype-I | Prototype-II | Prototype-III |
|---|---|---|---|
| Material | Aluminium | Aluminium | Steel |
| Bolt condition | Not fixed | Fixed with epoxy | Fixed with epoxy |
| Dimensions(mm) | 150 × 25 | 150 × 25 | 70 × 25 |
| Repeatability | 9.0-11.0% | 3.0-5.0% | 0.1-2.0% |

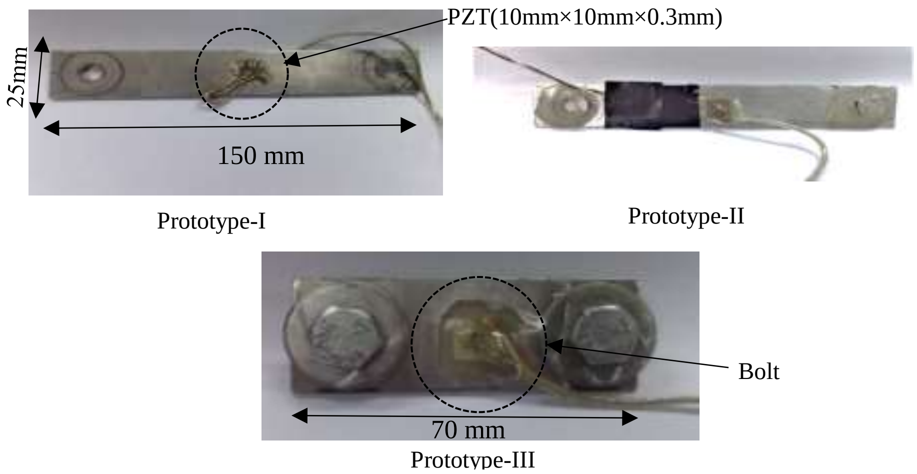



**Fig. 2.** Prototypes

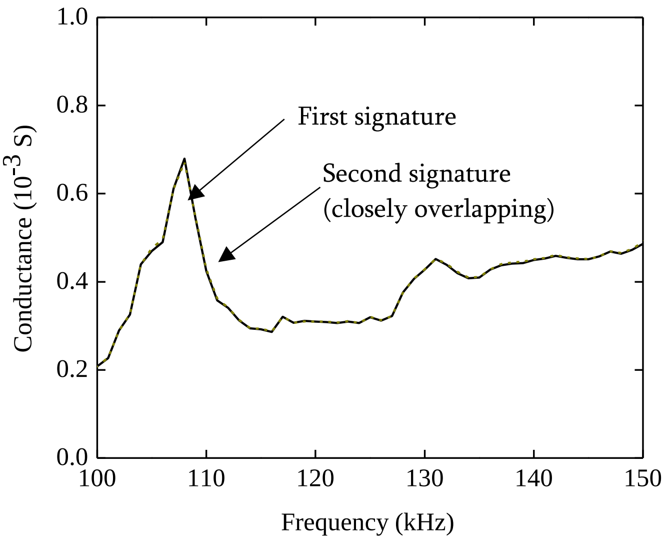



**Fig. 3** Repeatability of conductance signature of RBPS on aluminium strip (70×25 mm) at 25Nm

### 2.3 Effect of Magnitude of Torque

The variation of the externally applied torque 5,10,15,20,25 Nm respectively on the bolt joints to tighten them, is shown in the Fig 4 and 5. It has been observed that above 25 Nm the variation in conductance signatures become constant, therefore it ensures the uniform clamping action. The conductance signature shifted upward and leftward with increase in the torque value by which the bolts of RBPS are tightened.

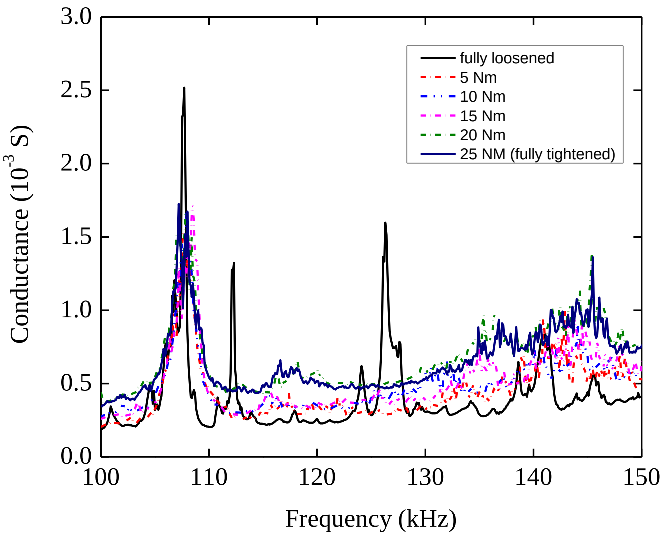



**Fig.4** Conductance signatures of RBPS on aluminium strip at different torque range

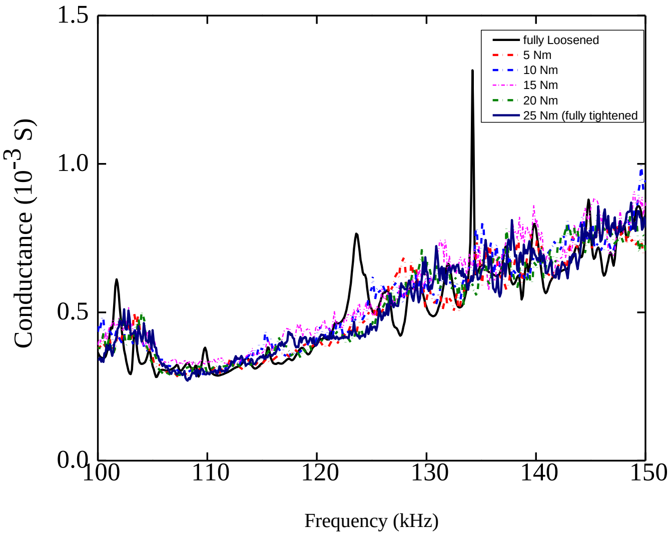



**Fig.5** Conductance signatures of RBPS on steel strip at different torque range

**2.4 Effect of Damage**

A hole of 5mm diameter was drilled in the aluminum plate to resemble a damage as shown in Fig 1. The conductance signature at 25 Nm torque is compared for pristine and damage stage as shown in Fig 6 and 7. The conductance signature shifted downward and leftward. RMSD variation for damage from pristine condition was 20. 2% for Prototype-III which is ten times of RMSD of repeatability test. This shows the Prototype-III can detect a damage to the plate. As the RMSD variation due to repeatability is found to be low in contrast to the RMSD variation due to damage, the Prototype-III can be used for damage monitoring in the host structure

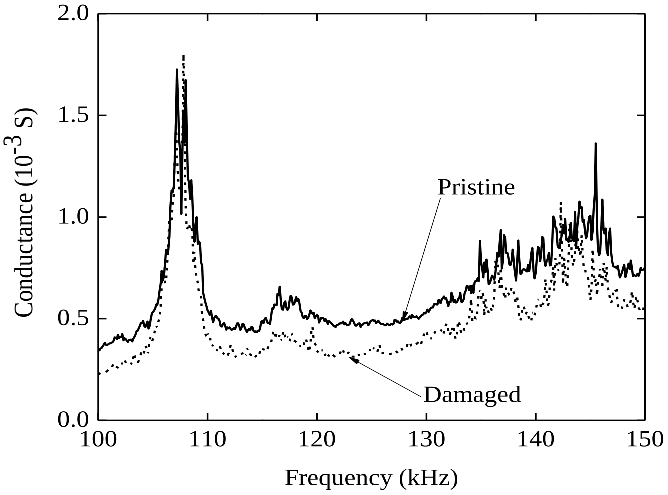



**Fig. 6** Damage detection by RBPS on aluminium strip (70×2.5mm) at 25Nm

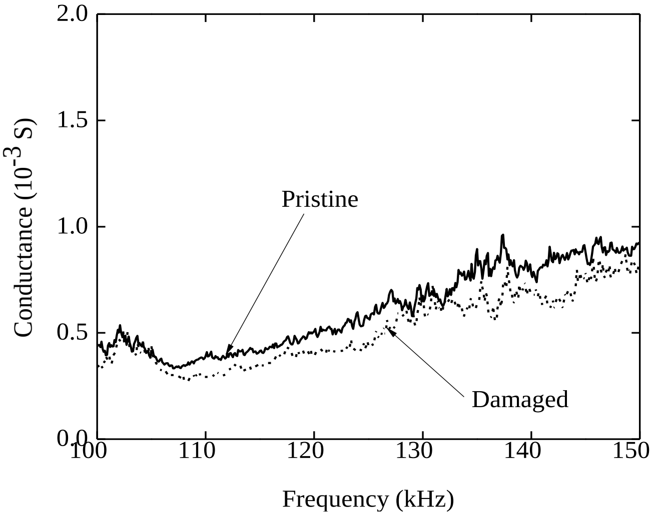



**Fig. 7** Damage detection by RBPS on Steel strip (70×2.5mm) at 25Nm

## 3 Results and Conclusions

From the results of the experiments, following can be concluded –

i. A suitable RBPS unit has been successfully fabricated and experimentally validated.

ii. A good repeatability of RMSD around 0.317% for 25Nm of Prototype-III of conductance signature has been achieved.

iii. The RMSD for damage was found to be 20.18 %, which is higher than the magnitude of the RMSD for the repeatability test**.**

iv. The RBPS can be used to replace conventional PZT for SHM of metal structures. As the RBPS are reusable, its use, instead of conventional surface bonded PZT patches can make the SHM process economical. Also, their instrumentation is simpler than the conventional patches.

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