Monitoring Loading Effects of Construction Steel Structure Using Piezo Transducer for Electromechanical Impedance Techniques

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1 Introduction

The application of piezoelectric smart materials in damage detection techniques is a relatively new and promising innovation in the field of structural health monitoring (SHM) in civil and mechanical infrastructure. The invent of smart materials possess the ability to assess the condition of structures and relay the information about its load and strain usage and any damage (if occurred) target specific areas for inspection. The implementation of piezoelectric material like Lead Zirconate Titanate (PZT) in SHM became more efficient with the advancement of electromechanical impedance (EMI) techniques. Piezoelectric materials are commonly used in structural dynamics applications because they are light weight, long term stability, low cost, and come in a variety of sizes and shapes. Bhalla and Soh [1] derived the following expressions for the bonded/embedded PZT patch's coupled complex admittance signature

$$\overline{Y} = G + Bj = 4\omega j \frac{l^2}{h}\left[\overline{\varepsilon_{33}^T} - \frac{2\,d_{31}^2\,\overline{Y^E}}{(1-\mu)} + \frac{2\,d_{31}^2\,\overline{Y^E}}{(1-\mu)}\left(\frac{Z_{\text{a,eff}}}{Z_{\text{S,eff}} + Z_{\text{a,eff}}}\right)\overline{T}\right] \quad (1)$$

where G and B are the conductance and susceptance, l, w, and h are the dimensions of the PZT patch, μ poisons ratio, and $\overline{\varepsilon_{33}^T}$ complex electrical permittivity, k is wave number, and $Z_{\text{a,eff}}$ and $Z_{\text{S,eff}}$ denote effective impedance of PZT patch and structure, respectively. $\overline{Y^E}$ and $\overline{\varepsilon_{33}^T}$ are the complex young's modulus of elasticity and complex electrical permittivity, respectively. $d31$ piezo electric strain coefficient, T is the complex tangent ratio equal to $\frac{\tan kl}{kl}$, and ω is angular frequency of excitation.

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The EMI technique utilizes a small PZT patch attached to the host structure to impart a harmonic force on the structure by applying an electric field (AC voltage signal) across the patch. The structural response comprises of peaks and valleys in "admittance versus frequency" plot, which is known as the electromechanical (EM) "admittance signature." If damage occurs in the structure, its mechanical impedance will change, which will modify the admittance signature, thereby providing indication of the damage [2, 3]. This equation couples the mechanical impedance of the structure with the electrical admittance which means that any damage to the structure (change of $Z_{s,eff}$) will reflect itself as change in.

From the past studies, many researchers have demonstrated the usage of PZT transducers for detecting incipient damage in structures using high frequency excitations [4–6]. PZT sensors were employed to determine the location and severity level of damage [7]. Many researchers also found the suitability of EMI techniques for various structural applications and incipient damage detection. Impedance-based structural health monitoring gained much popularity among researchers to determine the damage detection, localization, and quantification of concrete, composite and steel structures, where most of the studies utilized PZT patch directly attached to host structure only [8–12]. On the other hand, the brittleness of the PZT patch makes attaching the patch to surfaces with complex geometrics difficult. Furthermore, direct bonding the PZT patch to the structures surface may not be viable if the structure is constantly under impact load or is exposed to high temperature environment and may not be easily accessible. To address these issues, Na and Lee [13] proposed metal wire-based electromechanical impedance (MWBEMI) approaches, in which PZT patch is not directly attached to the structures surface but instead functions from the end of a steel wire that is attached to the structure.

This paper aims to explore non-bonded and reusable piezo configuration in depth through experimental investigations. Naskar and Bhalla [14] only studied MWBEMI approach to successfully identify and localize the two-dimensional structure. This article utilizes multi piezo configuration-based EMI techniques to determine better sensing of *loading and it's consequences* in construction steel sample using tensile test. Three different locations of PZT sensor, i.e., surface bonded, metal wire-based and clamped arrangements is used for HYSD bar of 12 mm to monitor the load action through tensile pull test. Statistical damage metrics (RMSD) are used for better quantification of signature. The prime focus of the current study is to address non-bonded and reusable configuration because of non-assessed and deformed surface of reinforced bar.

2 Materials and Experiments

In this investigations, tensile pull test was conducted for construction steel rebar to assess the loading effects using non-bonded and reusable piezo configuration. The experimental steel rebar has a diameter of 12 mm and a length of 300 mm HYSD bar according to IS 432-1982. After fabrication of test specimen, three different

Table 1 Properties of PZT patch (PI ceramic, 2014)

Property	Unit	Value
Size of PZT patch	m^2	0.010×0.010
Thickness	M	3.000×10^{-4}
Piezoelectric strain coefficient, d_{31}	m/V	-2.100×10^{-10}
Electric permittivity, ε_{33}^T	Farad/m	2.124×10^{-8}
Young's modulus, Y^E	N/m^2	6.667×10^{10}
Dielectric loss factor, δ		0.0224
Mechanical loss factor, η		0.0325
Poison's ratio, μ		0.3000

arrangements of PZT patches were bonded to it. In this studies, The PZT patches (PIC 151) were utilized for evaluating the employability of multiple piezo sensors for monitoring the tensile loading of steel bar through UTM machine. The detailed properties of PZT patch were reported in Table 1. Firstly, an aluminum strip with a length of 30 mm, a width of 10 mm, and a thickness of 1 mm was directly attached to steel rebar, and PZT patches were bonded to strip using epoxy adhesive with clamp tightened at two ends (refer Fig. 1a). A square cut was made in the center of the PZT, and epoxy adhesive was used to attach the PZT to the rebar (refer Fig. 1b). A metal wire with a length of 500 mm, a width of 10 mm, and a thickness of 1 mm was directly attached to 12 mm diameter steel rebar, and PZT patches bonded to foil ends with high strength epoxy adhesive (refer Fig. 1c). Electrical wires were soldered to the PZT electrodes with care after applying the epoxy adhesive and allowing it to cure for about 24 h. *The piezo-impedance signatures were recorded through impedance analyzer with excitation voltage of 1Vrms and frequency swept from 30 to 300 kHz with 100substeps.* The schematic diagram of total system is shown in Fig. 2. As a protective measure, the PZT patch was then coated with a thin coating of epoxy adhesive. Tensile force action is imposed using universal testing machine (UTM). Conductance signatures were obtained via a connection between the impedance analyzer for all three piezo configurations. RMSD index was calculated
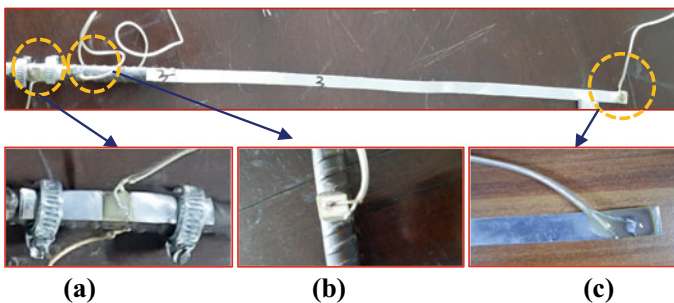

(a)   (b)   (c)

Fig. 1 Specimen with PZT attached for (**a**) clamped, (**b**) surface bonded, and (**c**) metal wire
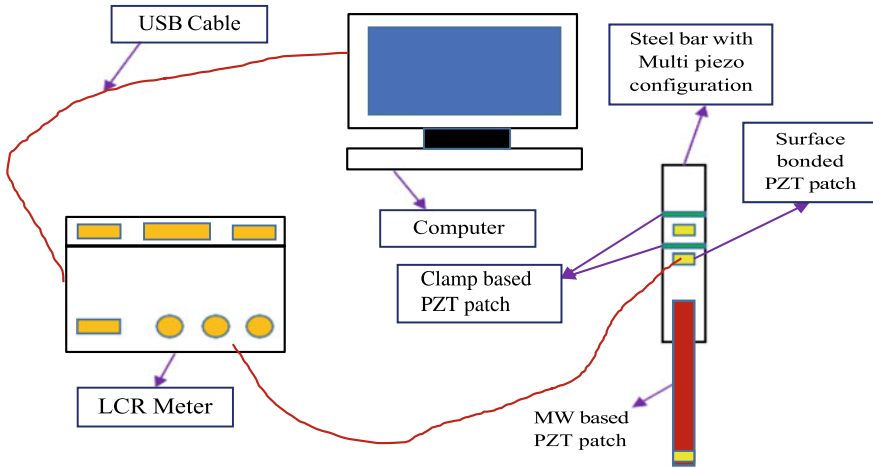
Fig. 2 Schematic diagram of total system

for each tensile load cases and all the lab-sized samples and compared with the baseline signatures. The following section will cover the sensor readings and their quantifications.

3 Results and Discussions

3.1 Sensor Stabilization

The structural deterioration of infrastructure systems may take long time, and it may affect the system's lifespan and reliability. As a result, it is vital to assure sensor stabilization under the same structural health situation. So far sensor stabilization of multi piezo configuration of steel sample is needed to attain the baseline signature required EMI technique. Hence, three different lab-sized instruments with PZT patch have used for acquiring conductance signatures, typically recorded over a finite period time while ensuring a sensor reading and good repeatability. In the same fashion, baseline signature was obtained for three different piezo sensor location (surface bonded, metal wire based, clamped) for the 30–300 kHz frequency range at 27 °C without any structural loading in steel.

The signatures recorded from surface bonded, metal wire-based and clamp-based PZT patches for day 1, day 7, and day 21 are compared in Figs. 3, 4 and 5, respectively. Different days reading are mentioned to signify the bond curing and good sensor bonding quality of proposed experimental approach.

From the above results, it can be seen that all signatures for surface bonded, clamp and metal wire-based PZT patch are coinciding with baseline signature with
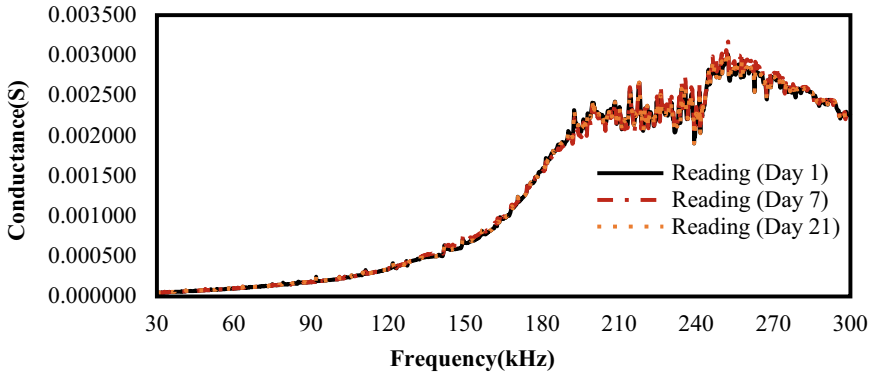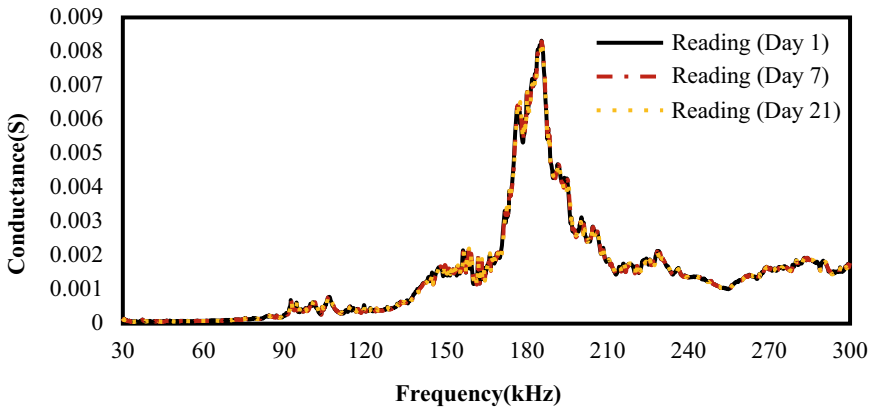
Fig. 3 Sensor stabilization for surface-bonded PZT patch

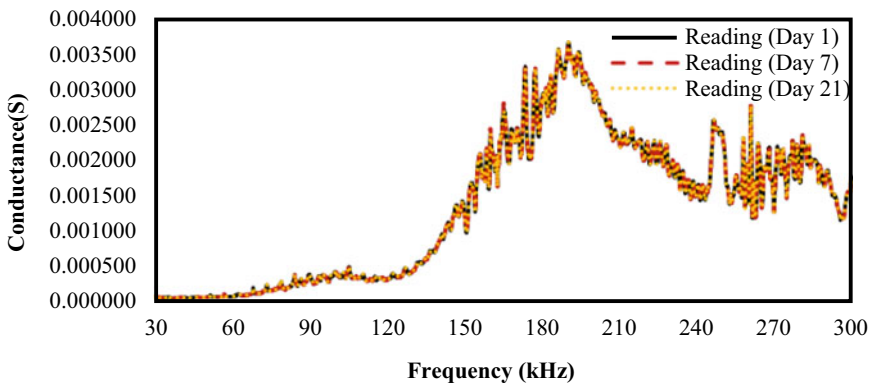**Fig. 4** Sensor stabilization for clamp-based PZT patch

Fig. 5 Sensor stabilization for metal wire-based PZT patch

a repetitive manner. It shows the bond is cured, and all sensor signals are quite stabilized over time. So it is considered as the baseline signatures for the structure.

3.2 Effect of Tensile Strength of Steel Rebar

Mostly concrete and steel are being only one of the most suitable and composite material for new age civil infrastructure construction. In steel concrete composite structure, the ultimate tensile stress is taken care by the steel rebar only but while being embedded, one has to look out anchorage pull dominated with overall shear tensile forces, caused initial dimensional crack, i.e., splitting. Here, the author is limiting the sensor reading for lower strength range (i.e., 0–30 kN). The reason behind for selecting the load is to simulate the anchorage-based shear tensile in HYSD bar, and the main objective of this study is to evaluate the sensor efficiency for the multiple piezo location to detect the shear tensile pull on constructional steel. The overall load deformation graph of lab-sized sample has shown in Fig. 6.

The conductance signatures were acquired for tensile pull on lab sizes steel bars instrumented with sensors for three loading cases, i.e., 9, 18, and 27 kN. The initial load ranges are chosen to evaluate the piezo sensor efficiency toward the detection of incipient force traction on steel bar. The piezo coupled signatures are plotted in Figs. 7, 8, and 9 for the surface bonded, clamped, and metal wire based, respectively. All the sensors are equally participated and the behavioral signature pattern to indicate the tensile force action in steel sample, the conductance peak shifting toward leftward and with the increase of load the frequency is shifting toward left (Fig. 7). For other two configurations though conductance variation is not much prominent but the overall trend (i.e., decrement of frequency and piezo resonance peak) is quite
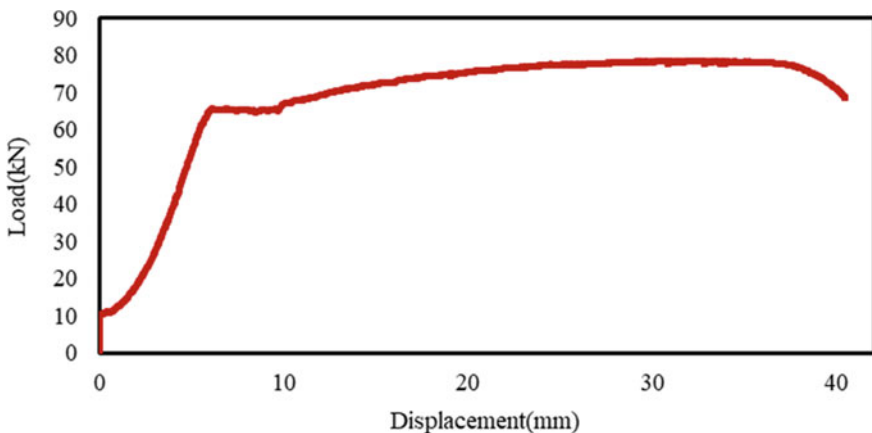

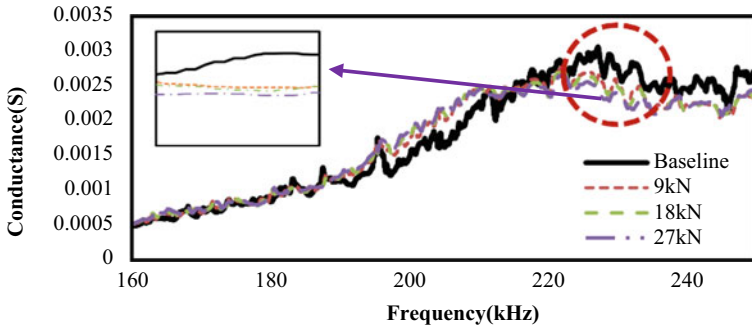**Fig. 6** Load versus displacement curve of lab-sized steel sample

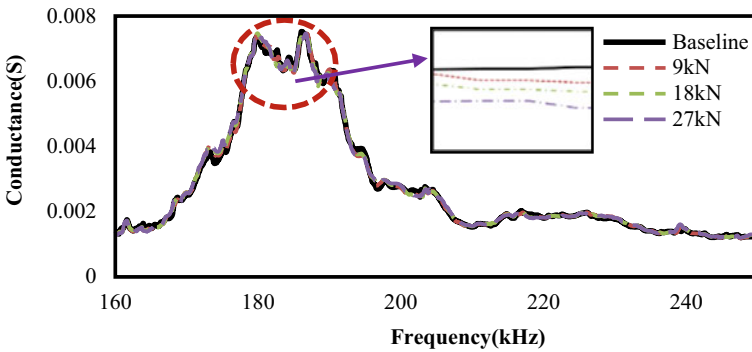**Fig. 7** Effect of tensile pull load on surface-bonded PZT patch

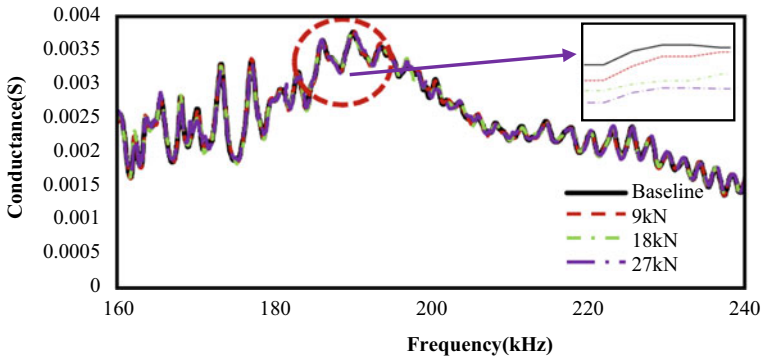**Fig. 8** Effect of tensile pull load on clamp-based PZT patch

Fig. 9 Effect of tensile pull load on metal wire-based PZT patch

evident from the Figs. 8 and 9. Looking for the efficiency of three different piezo locations, we found that clamp and metal wire-based EMI techniques are quite feasible for the ribbed and complex surface of the steel bars, for reusable and non-bonded configuration.

The root mean square deviation (RMSD) index is used to quantify changes in signature due to damage. RMSD index for piezo coupled structure can be expressed as Giurgiutiu and Rogers [15, 16].

$$\text{RMSD} (\%) = \sqrt{\frac{\sum_{j=1}^{N} (G_j^1 - G_j^0)^2}{\sum_{j=1}^{N} (G_j^0)^2}} \tag{2}$$

where G_j^1 is the conductance signatures obtained for various load cases.

G_j^0 is the conductance signatures obtained for baseline signatures.

The RMSD value for all configurations for lab-sized steel samples are shown in Figs. 10, 11, and 12, respectively.

From the RMSD values, it is clearly evident that clamped and metal wired-based techniques are less sensitive (see Figs. 11 and 12) compared to that of surface-bonded case (see Fig. 10). However, it follows same trend like surface-bonded PZT arrangements to detect the loading effects and corresponding structural changes with respect to baseline signatures. Although metal wire and clamp-based PZT has lower sensitivity, but it can be utilized in situations where a standard EMI method is not possible, especially in case of complex structural geometry and inaccessible portion of bridge structure.
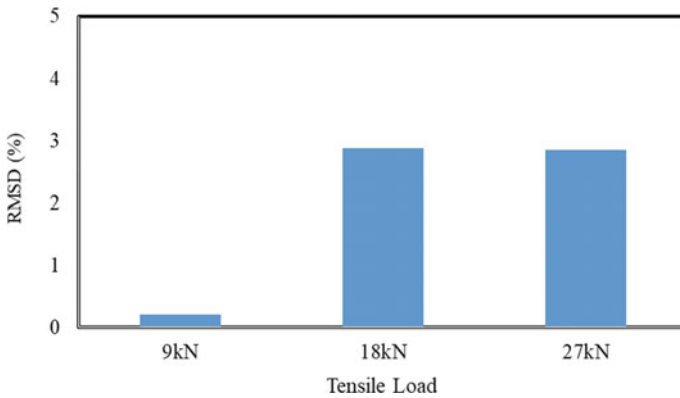

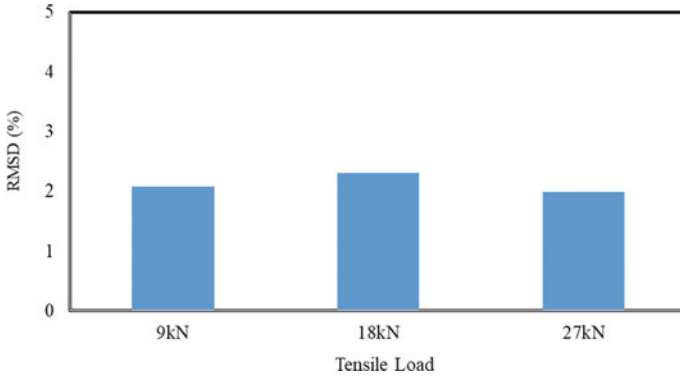**Fig. 10** RMSD values for rebar-bonded PZT patch for tensile load

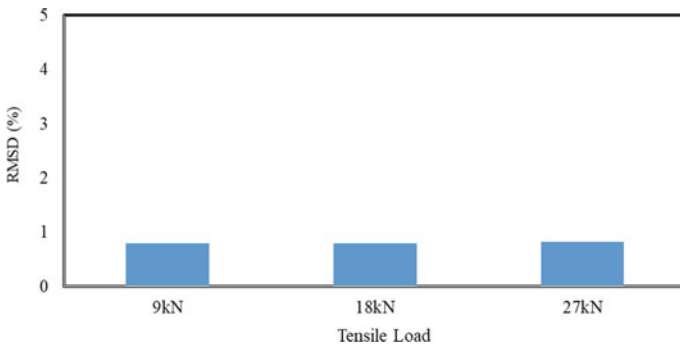**Fig. 11** RMSD values for clamped PZT patch for tensile load

Fig. 12 RMSD values for metal wire-bonded PZT patch for tensile load

4 Conclusions

This current study mainly focuses to evaluate the multiple piezo configuration toward tensile loading of HYSD construction steel bar. It proposes the reusable and non-bonded piezo configuration for curved surface of steel bar subjected to load cases while embedded in concrete for shear tensile to stimulate the anchorage bond behavior. The lab-sized steel samples instrumented with the PZT patches are loaded with tensile pull and conductance signature were acquired. From signatures, it can be found that EMI signatures for three different configurations are capable to detect the tensile pulling (for lower load range). Also, through RMSD quantification, it has been seen that the reusable and non-bonded configuration has ability to detect the internal structural resistance changes against tensile fully successfully. This study may further explored, and its implication can be used for the cases where complex civil infrastructure component which are not assessable or direct assessment of structure is prohibited.

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