**Experimental Approach for Detection of Multiple Damage and Severity Using the Electromechanical Impedance (EMI) Technique**

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**Abstract**

Detecting and quantifying multiple damages in structures remains a significant challenge in structural health monitoring (SHM), particularly in complex civil engineering systems. This study presents an experimental approach for the detection of multiple damages and their severity using the Electromechanical Impedance (EMI) technique. The EMI method, which utilizes piezoelectric transducers, offers a sensitive and reliable means to monitor structural integrity by measuring the coupled mechanical and electrical response of structures under various damage conditions. In this research, multiple damage scenarios were simulated in concrete specimens, and the corresponding conductance signatures were recorded. particularly shifts in conductance values, were analyzed to identify and localize damages. The conductance signatures (real part of admittance) are obtained in the high-frequency range of 30-400 kHz to assess the damage state using the EMI technique. Conventional statistical metrics such as root-mean-square deviation (RMSD) are employed to quantify the changes in conductance signature. Additionally, a methodology for localizing the damage is presented. Additionally, a severity index based on impedance variations was developed to quantify the extent of damage. The experimental results demonstrate the effectiveness of the EMI technique in accurately detecting, locating, and assessing the severity of multiple damages in complex structural systems. This approach offers a robust, non-invasive solution for real-time damage assessment, contributing to enhanced safety and reliability in structural health monitoring applications.

**Keywords** Piezoceramic Transducer. Electro-Mechanical Impedance. Concrete Damage. Damage Monitoring. Structural Health Monitoring

**1 Introduction**

Structural damage in the buildings occurs due to a variety of reasons such as accidents, natural disasters, deterioration, and normal operations. In order to assess the extent and location of damages, visual inspection is usually the preferred method. However, there are situations where visual inspection may not be feasible. Therefore, it is essential to have a well-coordinated multiple damage detection system to monitor the structures.

In this investigation, we propose to use the Electromagnetic Impedance (EMI) technique for detection of multiple damages in structures. EMI is a non-destructive testing technique that uses electromagnetic waves to detect surface and sub-surface defects in metallic and non-metallic structures. This technique has been widely used in sectors like aerospace and automobiles, construction to detect cracks, corrosion, and other forms of damage.

Recent advancements have focused on the detection of multiple damages in concrete structures using the EMI technique with surface-bonded PZT sensors. For instance, Bhalla et al. [1] demonstrated the capability of EMI-based PZT sensors to detect multiple cracks in concrete specimens, highlighting the technique’s sensitivity to both localized and distributed damages. Similarly, Li and Zhu [2] employed PZT patches to monitor reinforced concrete beams subjected to multiple damage conditions, reporting that the conductance signatures exhibited distinct changes correlating with the extent of the damages. The study showed that statistical indices such as RMSD and correlation coefficient (CC) could effectively quantify damage severity.

While single damage detection using the EMI technique has been well-explored, the detection and quantification of multiple damages remain complex due to overlapping impedance signatures from different damage sites. Recent studies have addressed this issue through advanced signal processing techniques. Zhang et al. [3] introduced an algorithmic approach for distinguishing between multiple damage sites by analyzing shifts in both conductance and susceptance signatures, achieving high accuracy in localization and quantification of damage. Additionally, Wang et al. [4] presented a multi-damage detection framework using surface-bonded PZT sensors, which demonstrated that combining statistical metrics with machine learning algorithms could improve the detection and classification of multiple damages in large concrete structures [5].

The paper is organized as follows: First, the theoretical context of the EMI technique and its application in damage detection are discussed. Next, the experimental setup for multiple damage scenarios in concrete specimens is detailed, followed by the analysis of the conductance signatures. Conventional statistical metrics such as RMSD are employed to quantify the damage. Finally, a methodology for localizing damage and assessing its severity is presented, along with experimental validation of the results.

**Research Significance**

The primary objective of this investigation is to utilize the Electromechanical Impedance (EMI) technique for detecting, identifying, and quantifying multiple damages in concrete structures. By applying this technique, the study aims to accurately locate and assess the severity of damages within a structure. Artificially induced damage was monitored by analyzing the conductance signatures recorded from PZT patches. The RMSD of these signatures was calculated to quantify the extent of damage. By comparing the RMSD values from damaged and healthy states, the study provides a reliable approach for evaluating structural changes, offering insights into early-stage damage detection and enhancing structural health monitoring methods.

**2 Electro-Mechanical Impedance Technique (EMI)**

The Electromechanical Impedance (EMI) technique is a non-destructive method for Structural Health Monitoring (SHM), utilizing piezoelectric materials like PZT patches to detect small structural changes such as cracks and corrosion [6]. It expanded in the early 2000s with methods like root-mean-square deviation (RMSD) to quantify damage [7] and surface-bonded sensors for early-stage damage detection in concrete [8]. Recent developments, including multi-damage detection algorithms [9] and severity indices [10-11], have improved the technique's robustness. Machine learning applications have further enhanced multi-damage detection accuracy [12], and future advancements are expected through integration with wireless networks and IoT [13-16].

The RSMD value is calculated using the expression given below:

(1)

where and represent the conductance at damaged and healthy states, respectively, and N is the number of data points considered in equation 1. Mechanical vibrations occur when a sinusoidal signal excites the structure, and the changes in mechanical behavior are captured as electrical admittance using LCR meters. The admittance is given below equation 2. The mechanical vibrations take place in the structure when a sinusoidal signal actuates it. LCR meters were used to capture changes in mechanical behavior as electrical admittance signatures with the EMI equation is used [18-20].

(2)

where G is conductance, B is susceptance, j is the imaginary unit, and ω is the angular frequency. The formula includes parameters like width w, height h, effective impedance of the PZT sensor Za, eff, effective impedance of the structure Zs, eff​, and Young’s modulus of the PZT sensor ​, along with the electrical permittivity ​.

**3 Experimental study**

**3.1 Experimental Approach for Detection of Multiple Damage and Severity Using EMI Technique**

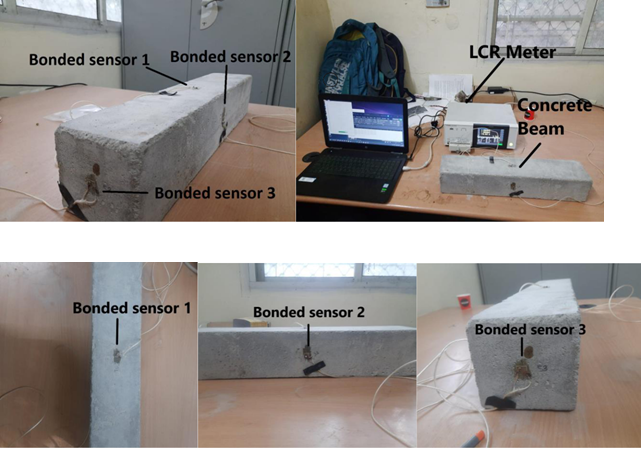
The experiment was conducted using a concrete cube of 150 mm dimensions and a concrete beam of 500 mm x 100 mm x 100 mm. A PZT (Lead Zirconate Titanate) patch was bonded on the top surface of the cube and on three faces of the beam using epoxy adhesive to ensure proper coupling between the sensors and the structure. The experimental setup is illustrated in Fig. 1, 2 and 3. Artificial cracks were induced in both specimens, with the dimensions of the induced cracks provided in Table 1and 2. The signatures of the coupled system were extracted for both healthy and damaged states. Conductance signatures were recorded using an LCR meter across a frequency range of 30-400 kHz. At the healthy state, a one-volt excitation was applied to the nodes of the PZT patch to obtain the baseline signature. After artificially inducing damage, the conductance signatures were again recorded, and the RMSD of the conductance values was calculated to quantify the extent of damage. The RMSD values for the damaged state were compared to those of the healthy state to evaluate changes in the structure. During the experiments, multiple cracks of varying severity were introduced into the concrete cube and beam, with the severity progressively increasing. Conductance signatures were captured for each damage state. These signatures were analyzed and compared to the healthy state signatures to compute RMSD, which provided a metric for detecting and quantifying the presence of cracks in the structure. Due to the high sensitivity of the EMI technique to minor structural changes, even small variations in the conductance graph indicated the presence of damage. This method allowed for the detection of multiple damage points, making it an effective approach for identifying and assessing the severity of damages in the concrete specimens [17].



**Fig. 1** Damaged Cube Sample with multiple damages

**Table 1.** Dimension of Cracks on Cube Sample

|  |  |  |  |
| --- | --- | --- | --- |
| S.No. | Identity | Width(mm) of the | Length(mm) of the |
|  |  | induced damage | induced damage |
|  |  |  |  |
| 1 | C1 | 5 | 98 |
|  |  |  |  |
| 2 | C2 | 4 | 99 |
|  |  |  |  |
| 3 | C3 | 5 | 101 |
|  |  |  |  |



**Fig. 2** Experimental Setup of Beam with Orientation of the Bonded Sensor 1(S1), 2(S2), 3(S3)

**Table 2.** Dimensions of induced cracks in the beam

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| S.No. | Damaged sample no. | Width(mm) of the | Depth(mm) of the | Length(mm) of the crack |
|  |  | crack | crack |  |
|  |  |  |  |  |
| 1 | BD1 | 3 | 21 | 88 |
|  |  |  |  |  |
| 2 | BD2 | 4 | 25 | 85 |
|  |  |  |  |  |
| 3 | BD3 | 3 | 24 | 88 |
|  |  |  |  |  |
| 4 | BD4 | 3 | 23 | 93 |
|  |  |  |  |  |
| 5 | BD5 | 3 | 23 | 91 |
|  |  |  |  |  |
| 6 | BD6 | 4 | 22 | 92 |
|  |  |  |  |  |

**4 Result and discussion**

The Fig. 7 displays the conductance signatures (Siemens) against frequency (kHz) for a concrete specimen in healthy and different damaged states (HS S2, D1S2, D2S2, etc.). The conductance signature changes as damage is introduced, particularly between the frequency range of 30–400 kHz, as indicated by the boxed region. The healthy state (HS S2) has the highest conductance values compared to the damaged states. As the number of damages increases (from D1S2 to D6S2), the conductance values reduce, with the greatest drop observed for D6S2.



**Fig. 3** Multiple damages on the beam surface opposite to sensor 2

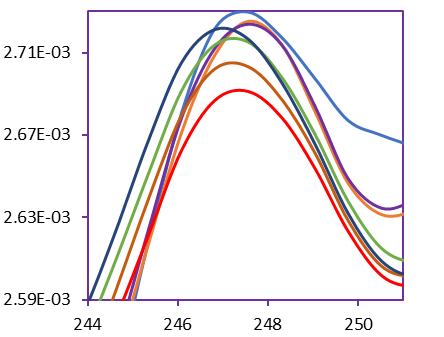
A total of seven artificial cracks were introduced on the beam surface opposite to Sensor 2 to simulate multiple damage scenarios. Of these, five cracks were made along the longer side of the beam (500 mm), while the remaining two cracks were placed on the adjacent smaller side (100 mm) as shown in Fig. 3. This strategic placement of cracks aimed to assess the EMI technique's ability to detect and quantify damage in various regions of the structure. The distribution of cracks on different surfaces allowed for a more comprehensive evaluation of the sensor's sensitivity to structural damage.

**Fig. 4** Plot of conductance vs frequency of healthy state and all damages of concrete cube

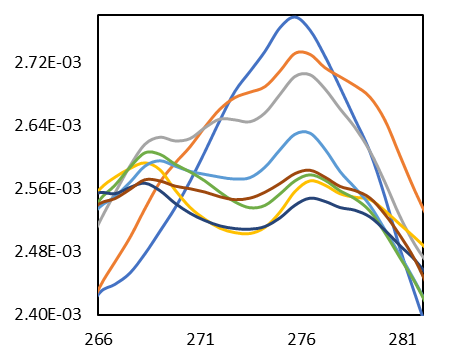
The conductance signatures of a piezoelectric sensor bonded to a concrete specimen across varying damage states. In Fig. 4, the results demonstrate a clear correlation between increasing damage and the conductance signature's downward shift, confirming the effectiveness of the EMI technique for tracking damage progression in concrete structures.

Similarly, a concrete beam of dimension 500 x 100 x 100 mm was considered for experimentation. The PZT patch was bonded at 3 faces of the beam, Ist PZT sensor was bonded in the mid position of the bottom face of the beam as shown in Fig. 2. The crack was induced having different severity and given in Table 2. The signature, graphs and RMSD were extracted from the coupled system. RMSD values were calculated and given in Fig. 9. Similarly, conductance and frequency were plotted and shown in Fig. 5, 6 and 7.

**Fig. 5** Frequency vs Conductance graph of healthy state and all damages of beam (Sensor S1)



**Fig. 6** Frequency vs Conductance graph of healthy state and all damages of beam (Sensor S2)



**Fig. 7** Frequency vs Conductance graph of healthy state and all damages of beam (Sensor S3)

With the help of conductance signatures obtained from EMI technique, RMSD can be utilised to quantify severity of damage. To calculate RMSD for the extracted dataset as shown in Fig. 8, the predicted values would be the conductance signature obtained from the EMI extracted data of the healthy sample, while the observed values would be the conductance signature of the damaged sample in the structure. The RMSD value represents the average deviation between the predicted and observed locations of damage. Therefore, the RMSD value can be used as a quantitative measure of the extent and severity of damage in the structure, which can aid in determining the appropriate maintenance and repair actions.

**Fig.** **8** RMSD values to corresponding damages with healthy state as standard (in Cube)

**Fig. 9** RMSD values to corresponding damages with healthy state as standard (in Beam)

The RMSD value can be used as a quantitative measure for the extent and severity of damage in a structure. A higher RMSD value indicates a larger deviation of conductance signatures obtained from healthy and damaged structure, which indicates a larger change in due to damage. Location and orientation of damage can be determined by installing a sensor opposite to damage that gives the most significant change in RMSD values. As it can be observed from Fig. 6, first 5 damages result in very insignificant change in RMSD computed from BS1 and BS3.

**5 Conclusion**

The investigation demonstrates that the EMI technique, utilizing surface-bonded PZT sensors, is highly effective in detecting and quantifying damages in concrete structures. The RMSD index shows a strong correlation with the number of damages, increasing as the damage severity increases. Conductance signatures also exhibit noticeable changes between the healthy and damaged states, reinforcing the reliability of the EMI-based approach. This technique offers great potential for real-time structural health monitoring, ensuring the early detection of damages and improving the safety and maintenance of civil infrastructure.

* There is a clear distinction between the healthy and damaged states, and the reduction in conductance correlates with the increase in damage severity. The EMI technique can detect subtle changes in conductance, which can be used to assess damage.
* The RMSD index (RMSD values for C1, C2, and C3 range) shows a positive correlation with the number of damages, indicating that the EMI technique can effectively track the progression of damage in concrete structures.
* Both sensors are capable of detecting damage, but RMSD-BS1 demonstrates greater sensitivity. This suggests that the selection of sensor bonding technique or sensor type significantly impacts damage detection accuracy.

For future research, several directions can be pursued to improve the Electromechanical Impedance (EMI) technique for structural health monitoring. One key area is the integration of multiple PZT sensors in a distributed network to achieve more precise damage localization and quantification, especially in larger and more complex structures. Additionally, incorporating machine learning algorithms could facilitate the automatic classification and prediction of damage patterns based on real-time EMI data, enhancing the speed and accuracy of damage detection. The use of wireless sensor networks and IoT platforms can further enable remote monitoring and real-time data transmission, making the technique more scalable for large infrastructure. Furthermore, extending the study to include different environmental conditions, such as temperature and humidity variations, will provide a deeper understanding of how these factors affect EMI readings. Finally, future studies could explore the application of the EMI technique to a wider range of materials and structural systems, increasing its versatility and potential uses in civil engineering.

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**References**

1. Bhalla, S., Soh, C. K., & Wang, S. H. (2020). Multi-crack detection in concrete structures using EMI technique and PZT patches. Journal of Civil Structural Health Monitoring, 10(3), 289-299.
2. Li, X., & Zhu, D. (2021). Monitoring multi-damage scenarios in reinforced concrete using piezoelectric transducers and EMI signatures. Smart Materials and Structures, 30(7), 075021.
3. Zhang, L., Wu, T., & Zhou, J. (2022). Multi-damage detection in concrete structures using EMI technique and advanced signal processing. Sensors, 22(4), 1532.
4. Wang, Y., Liu, H., & Chen, Q. (2023). Multi-damage detection in large concrete structures using PZT sensors and machine learning. Structural Health Monitoring, 22(5), 1579-1593.
5. Liang, C., Sun, F. P., & Rogers, C. A. (1994). Coupled electro-mechanical analysis of adaptive material systems—Determination of the actuator power consumption and system energy transfer. Journal of Intelligent Material Systems and Structures, 5(1), 12-20.
6. Sun, F. P., Chaudhry, Z., Liang, C., & Rogers, C. A. (1995). Automated real-time structure health monitoring via signature pattern recognition. Proceedings of SPIE, 2443, 236–247.
7. Bhalla, S., & Soh, C. K. (2004). Structural health monitoring by piezo-impedance transducers: Modeling. Journal of Aerospace Engineering, 17(4), 154-165.
8. Park, G., Yun, C. B., & Roh, Y. (2003). PZT-based active damage detection techniques for concrete structures. Journal of Intelligent Material Systems and Structures, 14(4-5), 159-167.
9. Raghavan, A., & Cesnik, C. E. S. (2007). Piezoelectric actuator/sensor excitation and sensing of complex structures. Journal of Intelligent Material Systems and Structures, 18(10), 987-997.
10. Koh, B. H., Lynch, J. P., & Sohn, H. (2008). Fault detection of wireless sensors using extreme value statistics. Proceedings of the IEEE Sensors Conference, 1037-1040.
11. Zhang, L., Wu, T., & Zhou, J. (2019). Multi-damage detection and severity assessment in concrete structures using EMI technique. Smart Materials and Structures, 28(5), 055008.
12. Wang, Y., Liu, H., & Chen, Q. (2022). Multi-damage detection in large concrete structures using PZT sensors and machine learning. Structural Health Monitoring, 22(5), 1579-1593.
13. Shanker, R, (2009) An integrated approach for structural health monitoring ( doctroral dissertation). IIT Delhi.
14. Lee, M. M. K., & Barr, B. I. G., (2004). An overview of the fatigue behaviour of plain and fibre reinforced concrete. Cement and Concrete Composites, 26(4), 299-305.
15. Ayres JW, Lalande F, Chaudhry Z, et al., (1998). Qualitative impedance-based health monitoring of civil infrastructures. Smart Materials and Structures 7(5): 599–605.
16. Giurgiutiu V, Zagrai A and Bao JJ, (2004). Damage identification in aging aircraft structures with piezoelectric wafer active sensors. Journal of Intelligent Material Systems and Structures 15: 673–687.
17. Narayanan, K.V.L. Subramaniam, (2016). Experimental evaluation of load-induced damage in concrete from distributed microcracks to localized cracking on elec-tromechanical impedance response of bonded PZT, Constr. Build. Mater. 105 ,536–544.
18. Dixit, S. Bhalla, (2018). Prognosis of fatigue and impact induced damage in concrete using embedded piezo-transducers, Sens. Actua. A 274, 116–131.
19. H.H. Pan, M.W. Huang, (2020). Piezoelectric cement sensor-based electromechanical impedance technique for the strength monitoring of cement mortar, Constr. Build. Mater. 254 (2020),119307.
20. S. Bhalla, C. Soh, (2004). Structural health monitoring by piezo-impedance transducers, J. Aero. Eng. 17, 154–165.