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Analysis of Damage Detection Performance in a Concrete Structure using the Finite Element Method

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ABSTRACT

The field of civil engineering has been witnessing a significant technological revolution through the application of innovative ideas. One such idea gaining widespread attention is the utilization of smart materials for the health monitoring of structures. This study focuses on the feasibility of employing PZT (Lead-Zirconate-Titanate) patches on concrete buildings as a means of real-time health monitoring using an impedance-based technique. In this work, numerical analyses for damage identification in concrete structures that are both healthy and damaged are made. A finite element-based programme was used to model the beams of healthy and damaged concrete in the ANSYS commercial tool. Furthermore, parametric studies were done to determine the impedance signal in concrete structures with PZT. Based on the current results it has been found the Electromechanical Impedance (EMI) technique is useful to detect damage in healthy and damaged concrete structures.

1. Introduction

Civil infrastructural systems frequently use concrete constructions the non-destructive evaluation (NDE) methods for concrete structures are however still in their infancy in comparison to those for metallic or other composite structures. Additionally, standard NDE procedures may be exceedingly time-consuming, expensive, or unreliable due to their extensive and complicated nature. Therefore automated, and more reliable NDE methods are being researched for real-time concrete structure health monitoring. The creation of a built-in diagnostic system is necessary for the implementation of automated NDE techniques allowing for the ongoing surveillance of concrete structures during their operational lifespan. These procedures facilitate the continuous monitoring of various types of buildings even in remote or hard-to-reach areas. One promising approach to developing an integrated diagnostic system is the utilization of a cutting-edge smart material known as piezoelectric

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material. This technology based on impedance measurements has shown considerable potential in constructing a built-in diagnostic system capable of detecting and assessing damage [1].

While the FEM incorporates the scaled boundary finite element method (SBFEM), the image-based quadtree decomposition is utilized to generate the multi-level mesh for the concrete composites automatically. This approach effortlessly handles hanging nodes and the significant variation in element size near the material interface. Furthermore, the integral format of the nonlocal damage model is extended to effectively simulate progressive damage of concrete at the mesoscale while maintaining good mesh independence [2]. The use of image-based concrete finite element models to estimate mechanical properties has been garnering increasing attention. This approach offers a novel method to determine the compressive strength of real concrete, relying on numerical analysis. The generation of three-dimensional mesoscale finite element (FE) models for concrete specimens is accomplished by utilizing computed tomography (CT) images [3].

To monitor alterations in the mechanical impedance of a structure this approach utilizes high-frequency structural excitations typically exceeding 20 kHz applied through surface-bonded PZT patches. Monitoring the electrical point impedance of the PZT patch affixed to the structure forms a crucial aspect of the impedance-based damage detection technique. Any physical changes to the structure may lead to modifications in its mechanical impedance which might lead to modifications to the PZT patches. Electrical impedance changes in the PZT patches can be utilized to spot early signs of structural degradation [4]. Due to advancements in piezoelectric material [5–7], it has been utilized to identify and fix defects in civil concrete structures. Cracks in concrete are considered an important indicator of possible damage durability and are usually observed during structure maintenance. Damage/cracks to concrete structures can be categorized differently and it can be made according to the type of damage the cause, the mechanism of attack the frequency of faults the type of damaged structures, property damage due to various defects the size and scope of the corrective action and much more [8]. In the realm of repairs, the electromagnetic Impedance (EMI) method is commonly employed. However, in practical applications determining the optimal frequency range and interpreting error indications are crucial factors to consider. The EMI technique finds utility across diverse technological domains for evaluating a wide range of material or structural parameters.

In a recent investigation, Kim et al. [9] demonstrated the applications of the piezoelectric-EMI-based technique to evaluate the quality of crack removal in concrete. Where the piezoelectric is a ceramic perovskite material possesses a notable piezoelectric effect, which implies that the substance undergoes deformation when subjected to an electric field Maurya *et al.,* [10] focus on smart materials and their compatibility with structures. The piezoelectric-EMI-based technique can be employed to effectively monitor the freezing, thawing, and crack propagation in concrete. Additionally, it demonstrates that the failure and progression of concrete deterioration can be accurately tracked and monitored by using a built-in piezoelectric sensor based on EMI technology [11]. Using the FE-based programme ANSYS19 the beams of bacterial concrete and control concrete with dimensions of 700 x 150 x 150 mm were modelled. The health of these beams was examined using the EMI Method Quantitative calculations of admittance signatures were conducted using piezo-ceramic PZT sensors placed at the mid-point of the upper surface of concrete beams [12].

An investigation was done to determine how mortar sample damage and repair affected as the damage to the specimen increased the electromechanical response of a surface-mounted PZT transducer exhibited noticeable changes. The resonance frequencies of the admittance signature shifted towards lower frequencies and there was an observed increase in peak amplitude [13]. The two-dimensional digital image correlation (DIC) to find surface cracks in asphalt concrete (AC) pavements was investigated [14]. The authors utilized artificially distorted photos; the strategy was validated. Second, a reliable technique based on displacement fields was created to find cracks. Investigation of concrete deformation and rebar behavior prediction in reinforced concrete with subsequent cracking has been demonstrated [15]. The authors calculated and non-linear findings were considered when generating the numerical results, and their reasonable matching was displayed. To evaluate concrete faults quantitatively utilizing piezoelectric transducers the damage index was developed. The findings show by numerical work that employing the damage index, concrete defect location and quantitative evaluation could be accomplished [16].

After doing an exhaustive review of structural health monitoring systems with PZT actuators it has been found that the PZT has a significant impact on determining the health condition of concrete blocks using EMI technique for experiments. On the other hand, simulation through the FE-based technology was found to be important; therefore, this paper utilized a numerical approach to detect damage in a concrete beam which is a cost-effective and energy-saving approach. A numerical study is conducted using FE models to determine the damage detection in concrete specimens, two types of concrete specimens are investigated in finite element modeling one is healthy another one is damaged.

2. Problem Formulation

The healthy and damaged concrete specimens attached to the PZT are studied in this work. The PZT is attached to the surface of the concrete specimen with glue at a distance of 50 mm from the left. The impedance signal, obtained through the FEM, provides valuable insights into the frequency-dependent behavior of a system. In FEM, numerical techniques are employed to simulate the complex interactions and responses within the system, allowing for a detailed analysis of impedance across different frequencies. However, it is essential to acknowledge that the accuracy of FEM results is contingent upon various factors, including mesh density, material properties, and boundary conditions. The type of PZT patch is PIC151, where dimensions and material properties of the Concrete block and PZT patch are illustrated in Tables 1 and 2 respectively. The healthy with damaged concrete blocks are analyzed using ANSYS finite elements software package (ANSYS Mechanical APDL-18).

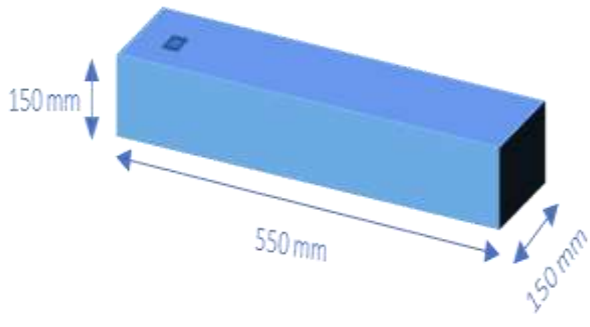


Fig. 1. Dimensions of Concrete Block with PZT

Table 1
Dimensions of Concrete Block and PZT [17]

Dimensions	Concrete Block (mm)	PZT (mm)
Length	550	16
Width	150	16
Thickness	150	0.5

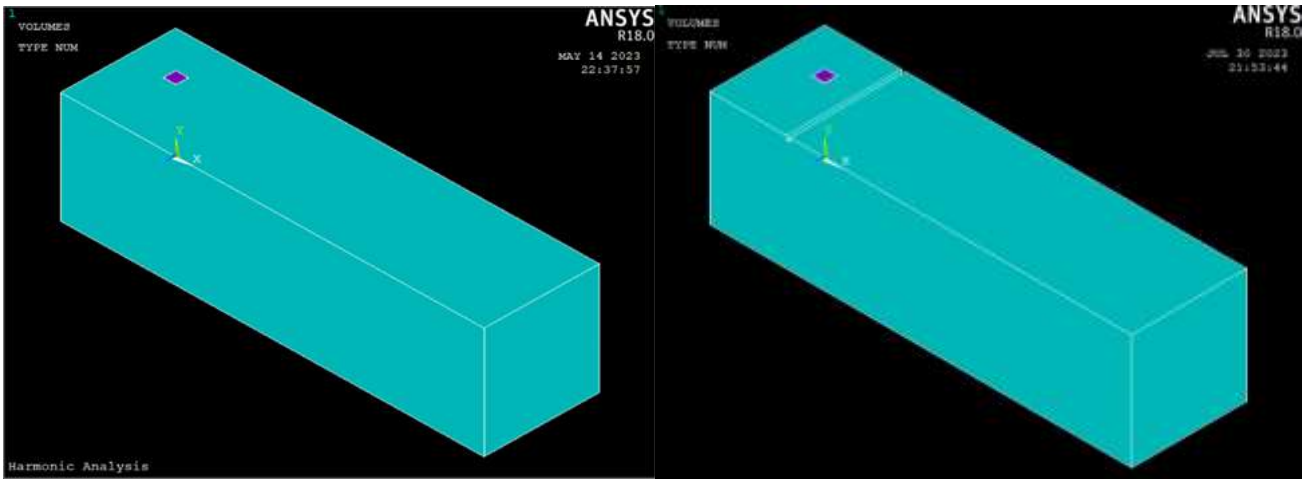
For the PZT patch model in this investigation piezoelectric material properties of type PIC151 were applied. It was necessary to have the following two types of material properties: Table 2 shows the permittivity [ε] (dielectric constant), the piezoelectric matrix [e], the relationship between the electrical field, stress, and various properties is represented by a 6 x 3 matrix. The density of the PZT patch is assumed to be 7,500 kg/m^3. The piezoelectric matrix [e], dielectric matrix [ε], and stiffness matrix [c] are all involved in the characterization. The dimensions of the PZT patch are also considered for this simulation which is taken as 16 x 16 x 0.5 mm.

Table 2
Properties of the concrete block and PIC151 [17]

Parameter	Concrete Block	Adhesive bond	PIC151 PZT patch
Density (kg/m^3)	2400	1160	7500
Poisson's Ratio	0.21	0.345	
Young's Modulus (GPa)	2.25	5.1	
Mass damping factor	0.001		
Stiffness damping factor	1.5 x 10^{-8}		
Dielectric loss factor			0.02×10^{-12}m^2/N
Compliance Matrix			S_{11}=9.6262×10^{-12}m^2/N
			S_{33}=7.8055×10^{-12}m^2/N ε^T_{11}=1977
Electric Permittivity Coefficient			ε^T_{33}=2395
PZT strain coefficient			d_{31}=--8.4746×10^{-10}m/V
			d_{32}=--8.4746×10^{-10}m/V

3. Finite Element Method

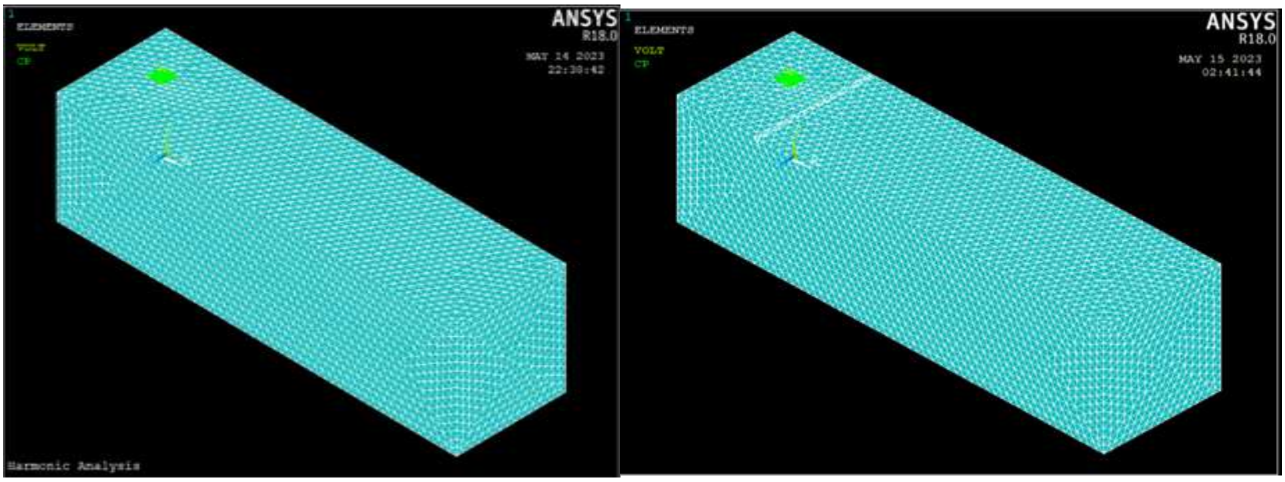
The main objective of this research work is to detect cracks in the concrete structure with healthy and damaged conditions using electromechanical impedance and to develop a structural health monitoring system for crack detection based on EMI and FEM. For which a numerical investigation utilizing FE models was conducted using ANSYS ADPL-18 software. The purpose of this simulation was to model a smart structural system consisting of a concrete beam with a PZT patch and to calculate the electro-mechanical impedance of the system. The study focused on the low-frequency range (20 to 25 kHz) corresponding to the lateral modes of the PZT patch. A coupled field analysis which considers the interaction between different engineering disciplines (specifically the interaction between structural and electric fields in a piezoelectric analysis) was employed to compute the electro-mechanical impedance. Figure 2 (a) and (b) represent models including a plain concrete beam coupled with the PZT patch and a damaged concrete beam respectively. Whereas the PZT patch size used in the FE analysis was 16 x 16 x 0.5 mm and the size for the plain concrete beam in the finite element analysis were used as 550 mm x 150 mm x 150 mm. The procedure is the same as the healthy concrete specimen used for the damaged concrete structure, total distance for the damage from the left is taken as 100 mm. The notch size of the damage is 5 x 5 mm across the width of the specimen i.e., 150 mm.



(a) (b)

Fig. 2. Model of concrete block (a) Healthy (b) Damaged

The FE model mesh needs to be accurate and sufficiently fine to accurately capture the wave characteristics. The concrete specimen with piezoelectric actuators meshing is estimated to be 0.01 mm. Despite operating in the plane dimension, the PZT patch was polarised in the direction of its thickness. As a result, the stiffness, dielectric, and piezoelectric matrices must all be orthotropic and describe the properties of the input material for each of the PZT patch's top nodes a voltage of +0.5 Vpeak has been applied, and for each of the bottom nodes a voltage of -0.5 Vpeak. In the low-frequency region, a harmonic analysis revealed the transverse modes of the PZT patch (20-25 kHz). Figure 3 shows the FE mesh model of healthy and damaged concrete specimens.



(a) (b)

Fig. 3. Mesh model of concrete block (a) Healthy (b) Damaged

The PZT patch was simulated using the SOLID226 element, it includes a three-dimensional (3-D) coupled field solid element with 20 nodes and six degrees of freedom (DOF) at each node. This element includes an electrical voltage as an additional DOF. For modeling the plain concrete beam, the SOLID186 element was utilized. It consists of 20 nodes with three DOFs at each node representing translations in the x, y, and z directions. The concrete material was assumed to be isotropic. Figure 4 shows the FE model of the piezoelectric patch with applied voltage at the master node.

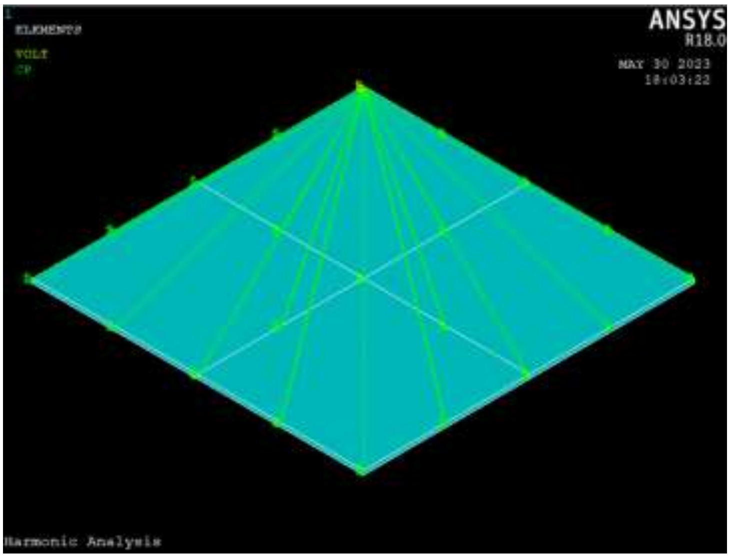


Fig. 4. Meshing and Voltage applied on PZT

Model intelligent construction systems were used to calculate admittance by calculating the ratio of output current to input voltage from the attached PZT to the concrete block. The connected field analysis is used to structure the current flow in the PZT patch while eliminating interactions between two or more engineering disciplines (such as piezoelectric analysis) and controls the interactions between structural and electric fields.

4. Results and Discussion
4.1 Validation of PZT Plate

First ANSYS multi-physics software was utilized to model the behavior of a free PZT patch aiming to gain insights into the effectiveness and principles of FE modeling. The modeled PZT patch is a square with dimensions of 7 x 7 x 0.2 mm^3 produced by the APC-850. In the piezoelectric analysis, additional DOF can be introduced to account for stress alongside displacement. The EMI of the system is calculated based on the electric charge which is determined by applying voltage to the PZT patch. The admittance (Y) can be determined using the current (I) and applied voltage (V) through the following Eq. (1):

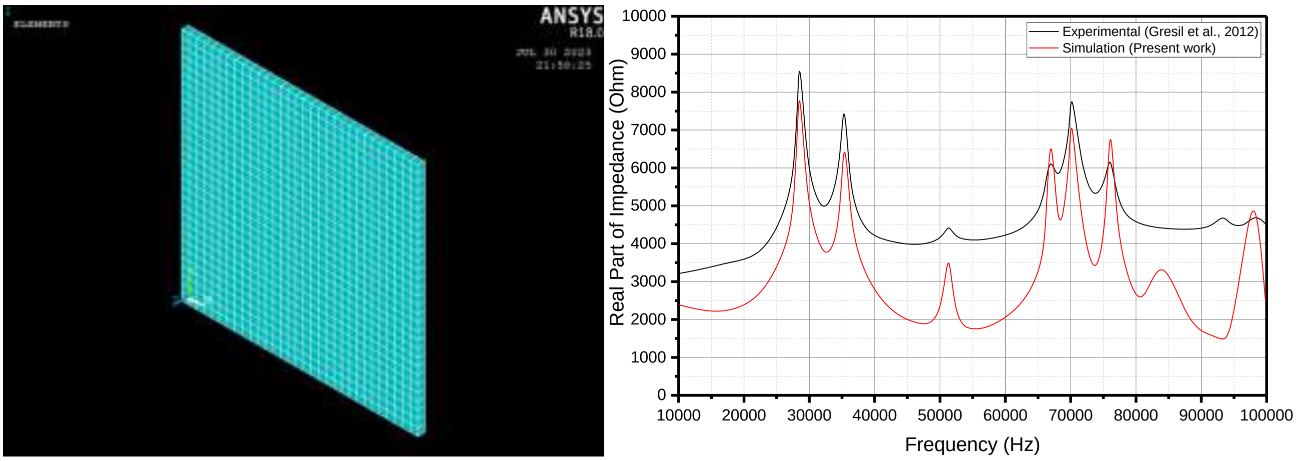
$$Y = \frac{I}{V} \tag{1}$$

The current (I) is represented as a function of the radial frequency (ω) and the complex charge (q) while ω is expressed in terms of the system frequency (f), where (i) is the imaginary component and the following Eqs. (2) and (3) can be obtained.

$$Y = \frac{2\, i\, \pi\, f\, q}{V} \tag{2}$$

$$Z = \frac{1}{Y} \tag{3}$$

The simulation involves conducting 400 partial steps ranging from 0 to 1000 kHz for a square plane that is freely suspended. Figure 5 (a) displays the FE model of the free PZT patch while Figure 5 (b) showcases the experimental results [18] with present simulation work. The real part of the impedance is prioritized over the imaginary part for analysis. This decision was based on the understanding that the real component exhibits greater sensitivity to structural damage or changes in integrity. In summary, the comparison of impedance signatures between the numerical FE model and the experimental results indicates a good match. Both the model and experimental data exhibit a similar resonant frequency, but some differences can be observed. Notably within the same frequency range the impedance in the numerical model is lower compared to the results obtained [18]. It is anticipated that there will be slight disparities between the numerical response and the experimental impedance due to the exclusion of wiring in the model and potential measurement errors. Nevertheless, this comparison demonstrates that the FE method yields a reasonable match which represents a significant advancement compared to utilizing the analytical model alone.



(a) (b)

Fig. 5. (a) Modeling of a square PZT patch in a free configuration (b) Comparison between the numerical and experimental results of the real part of the impedance

4.2 Validation of Healthy Concrete Block with PZT Patch

After applying harmonic analysis in postprocessing the structural damping coefficient is given as 0.005 (no unit for structural damping coefficient). After running the simulation model for healthy concrete, it gives a charge with a negative polarity and a charge with a positive polarity concerning frequency. From parameters frequency and charge we calculated the impedance with frequency. So we validated the impedance behavior for healthy specimens as of experimental results [17] which is represented in Figure 6 with frequency vs impedance for healthy specimens. The comparison shows the same behavior of experimental results of impedance [17] with the present simulation results of impedance concerning the frequency. The impedance signatures have a similar frequency which indicates a good match overall, however, some deviations can be noted. Additionally, since the wiring is not modelled and cannot be avoided there may be modest variations in the numerical output as compared to the experimental impedance. However, this comparison demonstrates that the FE technique may produce a fair fit which is a significant advancement over the analytical model.

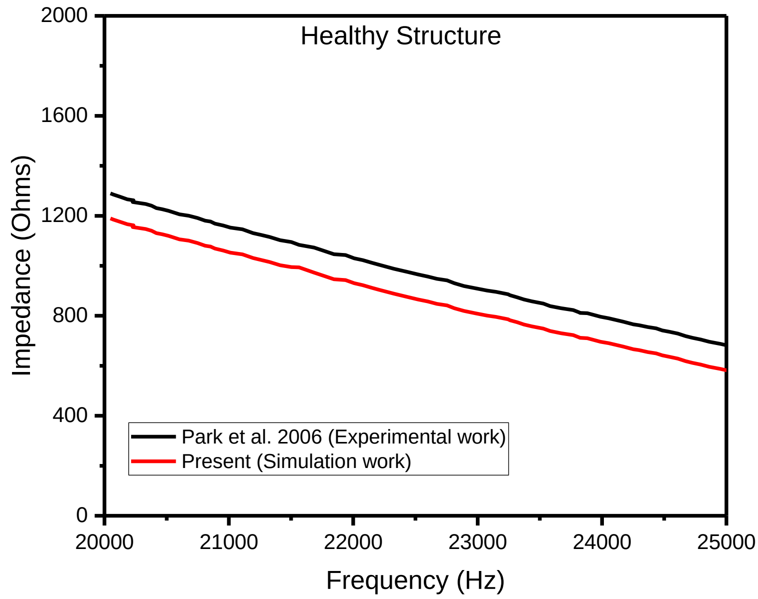


Fig. 6. Impedance for healthy specimen

4.3 Validation of Damaged Concrete Block with PZT Patch

Following the use of harmonic analysis during post-processing it states that the structural damping coefficient is 0.005. The simulation model for damaged concrete generates both a negative and a positive charge for frequency after running. We estimated the impedance with frequency using the parameters charge and frequency. The behavior of impedance to frequency is depicted in Figure 7. So we validated the impedance behavior for damaged specimens as of [17] experimental results. The great agreement between the two outcomes is clarified, which shows that the computational model accurately and faithfully captures the physical experiment. Given the difficulties in conducting physical experiments, the highest relative error of around 10% shows that the variations between the simulation and experimental results are rather minimal. Despite the slight variations it is crucial to remember that several variables including human error in the positioning and alignment of the piezoelectric actuator and concrete specimen could have affected the precision of the experimental results.

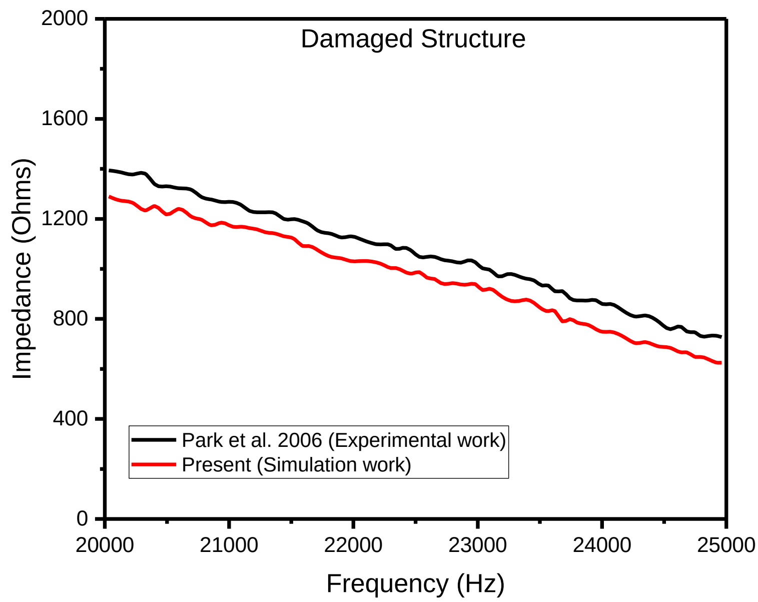


Fig. 7. Impedance for damaged concrete specimen

4.4 Comparison between Healthy and Damaged Concrete Specimens

Figure 8 represents healthy *vs* damaged (cracked) concrete specimens, impedance signal. The impedance signal for healthy concrete specimens is low as compared to the cracked concrete specimen. The crack is across the concrete specimen width with a 5 x 5 mm notch distance from the left of a specimen of 100 mm. The observed differences in impedance between healthy and cracked specimens can be attributed to the presence of lateral modes of thickness and the positioning of the notch in concrete specimens across the width of the concrete block. In healthy specimens, the impedance is lower due to the absence of cracks which results in a more uniform distribution of stress and a smoother surface. On the other hand, cracked specimens exhibit higher impedance values because the cracks introduce irregularities in the stress distribution and disrupt the uniformity of the surface leading to increased impedance measurements. The lateral modes of thickness and the positioning of the notch play crucial roles in influencing the impedance behavior, highlighting the importance of considering these factors in the impedance analysis of concrete structures.

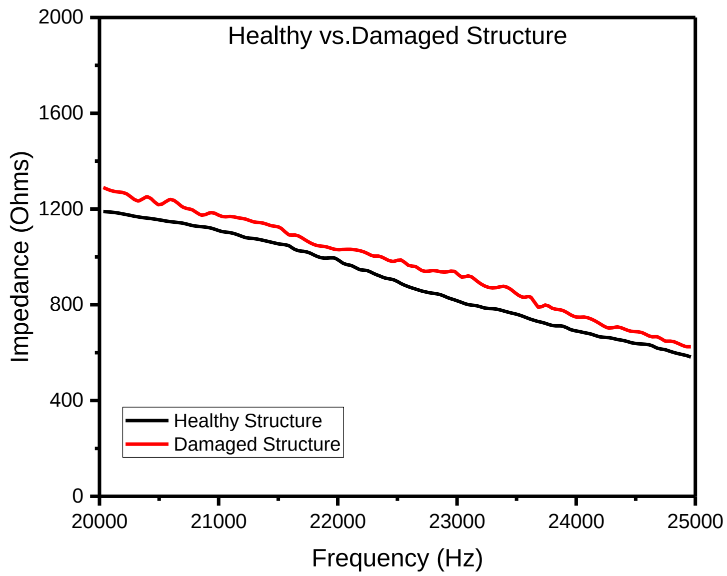


Fig. 8. Healthy and damaged specimens

5. Conclusion

This study explores the viability of employing PZT patches on concrete structures as a component of an impedance-based real-time health monitoring technique. The objective of this research work is to detect cracks in the concrete structure with healthy and damaged conditions using electromechanical impedance and Finite Element Modeling which has been determined. The numerical analysis utilizing finite element models successfully predicts damage with consistent trends observed in the fluctuation of impedance signatures recorded by the PZT patches. The impedance signal for healthy concrete specimens is low as compared to the cracked concrete specimen. The observed differences in impedance between healthy and cracked specimens can be attributed to the presence of lateral modes of thickness and the positioning of the notch in concrete specimens across the width of the concrete block. Moreover, to delve deeper into the subject further examination can be conducted by varying the size and location of cracks at different depths in various types of concrete buildings, thereby expanding the range of scenarios for investigation.

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