Corrosion assessment of structural components using electro mechanical impedance

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Abstract. Rapid innovation in interdisciplinary technology emphasized the data acquisition system to evaluate the structural integrity by combining with advance sensing techniques. These smart sensors with impedance methodology has shown an excellent potential in assessing the structural health condition and provided an alternative to many sophisticated Non destructive monitoring systems. The sensitivity of electro mechanical impedance technique in detecting local incipient damages is enhanced with piezoelectric mechanism of lead zirconate titanate materials and with conductance signatures these materials can determine the dynamic variations in structural properties more effectively. In the present work numerical finite element analysis is conducted on simply supported RCC beam in Abaqus software with reinforcement subjected to corrosion in five stages with different reduction rates and coupled with piezoelectric transducers along the length to implement the impedance strategy. These surface bonded piezoelectric patches are electrically excited with an external voltage under specific frequency range to conduct linear perturbation harmonic analysis and the output conductance responses of healthy and corroded beams from different sensor locations are captured and compared. The peak shifting nature of signature pattern will serve as an indicator to diagnose the corrosion severity and propagation in structural components. The simulation results of proposed impedance technique showed the feasibility of employing piezoelectric materials to identify corrosion activity in structural members with electromechanical conductivity signatures.

Keywords: Electro Mechanical impedance, Conductance signatures, Piezoelectric transducer, Couple field FEA, Electrochemical steel corrosion.

1 Introduction

Corrosion assessment in reinforced concrete structures has become the focus of research for the past two decades due to its intricate and complex mechanism [1]. The variations in humidity and diurnal temperatures render the steel to undergo corrosion causing premature structural deterioration [2]. The initiation and propagation of corrosion in reinforcement depends on the availability of moisture content, depassivating ions, concrete and steel grade, protective layer thickness and environmental conditions [3]. The electrochemical process of intrusion of chloride, carbon dioxide is a slow dynamic nonlinear mechanism that results in the formation of rust of larger volume at the interface. This expansive nature of the product generates radial stresses that lead to loss of bond between concrete and steel, steel embrittlement, spalling,

cracking and excessive deflections [4]. Due to degradation of the passive layer, the load carrying capacity and ultimate strength of the structure are reduced and causes sudden collapse [5]. Therefore performance evaluation in terms of safety and integrity has to be carried out to determine the residual service life of the structure [6]. Hence the health condition of the structural components has to be monitored in every stage of lifecycle to reduce the detrimental effects.

This led to the development of advance techniques and analytical concepts in Structural Health Monitoring for evaluating the damage severity [7]. With the evolution of Nondestructive methods such as Electro chemical half cell potential method, Linear polarization resistance method, Ground penetrating radar test, Infrared thermography,

Coverometer, Acoustic emissions, the in situ structural inspection is facilitated without destroying the elements [8]. But detailed investigation is not possible with these quality assurance tests as they suffer with distinct limitations such as lack of reliability, portability, trained technicians, costly equipment, complicated mechanism and electromagnetic interferences. It is imperative to choose appropriate monitoring system whose diagnostic analysis can provide complete information regarding damage initiation, proliferation, hairline cracks and impending failure [9]. Rapid advancement in Electronics and Information technology improved data acquisition systems and enhanced their application in Civil engineering [10]. The technical improvements in instrumentation and sensors enabled them to perform efficient maintenance operations [11]. Without human interference, these automated sensors are capable of monitoring the structural health condition continuously from any distant areas.

A variety of sensors like plastic optical fibers [12], accelerometers, ultrasonic [13], moisture, temperature, electro chemical sensors etc are available to measure the material physical and chemical properties. Among these sensors piezoelectric materials have gained a lot of significance due to their special piezoelectric property of converting electrical polarization energy into mechanical strain energy [14,15]. This conversion is a reversible process and was first discovered by French Scientists Pierre and Jacques Curie in 1880 [16]. The inverse effect of piezoelectricity enabled them to act as sensors, actuators, transistors and this optimistic function helps to perform critical EMI analysis [17]. Electro Mechanical Impedance is a local technique which utilizes high frequency waves like ultrasonic, acoustic for carrying analysis which is virtually not possible with traditional modal tests [18]. Intense research is carried out to predict the inhomogeneity of the structure with EMI method by exciting the highly sensitive piezoelectric sensors [19,20]. These materials on application of external voltage can detect the dynamic changes in a structure like mode shapes, damping factor and natural frequencies with electrical conductance signatures which are the real part of electro mechanical admittance signatures [21]. The conductivity signatures with its peak shifting character has emerged as the most reliable and inexpensive technique for monitoring the health status.

Moreover with Impedance based finite element modeling, the complexity involved in analyzing complicated geometry structures is simplified in Numerical methods by offering solutions which are relatively closer to the experimental results [22]. Non linear analysis can be performed in Abaqus CAE software by coupling structural and electrical fields with piezoelectric impedance technique [23]. This software is capable of processing and evaluating the structural models with good visual rendering process.

2 Numerical study

In the present study, a smart simply supported concrete beam coupled with piezoelectric transducers is considered to perform finite element modeling in Abaqus Simulia. Corrosion is induced in the beam from one end by reducing the cross sectional area of reinforcement. Three damage cases are considered for analysis by assuming that corrosion propagates at a distance of one fourth length, half length and three fourth length of the beam from left to right end as shown in figure 1. In each case, the reinforced beam undergoes corrosion in five stages. These stages indicate 20%, 40%, 60%, 80% and 100% reduction in the diameter of bars and stirrups which is shown in Table 1. Numerical simulations are conducted on healthy and damaged beams by impedance based couple field analysis and conductivity signatures are recorded from all the cases with surface bonded piezoelectric patches placed at three different locations. These captured responses are compared with each other to anticipate the corrosion activity.

Fig.1. Corroded beams with piezoelectric at various locations
Table 1. Simply supported beam with various damage cases and piezoelectric positions.

2.1 Geometry and Properties

Initially, a Simply supported healthy concrete beam of length 6m is modeled in part module as a three dimensional 8 noded solid element with a cross section of 300mm x 450mm. Reinforcement is provided to the concrete element with 3-16Ø main bars, 2-12Ø hanger bars and 200mm spacing 2 legged 8Ø stirrups by modeling as 2 noded beam elements. The steel rebars are embedded into the concrete section in interaction module with a clear cover of 30mm. For the present numerical study, a piezoelectric patch of size 50mm x 50mm x 20mm is designed as a 3D couple field element having six degrees of freedom at each node. The piezoelectric sensor and the reinforced concrete sections are assigned with material properties that are mentioned in Table 2 and Table 3. The contact between the PZT and host structure is accomplished using a tie constraint. After assembling, meshing of geometry is done independently by selecting suitable element type. The beam and patch are discretized with an approximate global mesh size of 0.05m and 0.01m in Mesh control module.

Table 2. Piezoelectric material properties

Density (kg/m ³)	7500
Dielectric constant (10 ⁻⁹ Farad/m)	D11 D22 D33 6.5 6.5 6.5
Piezoelectric constant (10 ⁻¹⁰ C/N)	$\begin{bmatrix} 0 & 0 & 0 & 0 & 12.7 & 0 \\ 0 & 0 & 0 & 0 & 0 & 12.7 \\ -5.2 & -5.2 & 15.1 & 0 & 0 & 0 \end{bmatrix}$
Elastic Modulus (10 ¹⁰ Pascal)	$\begin{bmatrix} 13.9 & 7.8 & 7.4 & 0 & 0 & 0 \\ 0 & 13.9 & 7.4 & 0 & 0 & 0 \\ 0 & 0 & 11.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.05 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.56 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3.05 \end{bmatrix}$

Table 3. Reinforced concrete section properties

Material type	Concrete	Steel
Grade	M ₂₅	Fe ₄₁₅
Young's Modulus(Pa)	2.5 x10 ¹⁰	2.1 x10 ¹¹
Density(kg/m ³)	2400	7850
Poisson's ratio	0.15	0.3

Patch Location	Location 1: 1.5m from left support	Location 2: 3.0m from left support	Location 3: 4.5m from left support
Corroded Cases	Extent of damage from left end	Percentage reduction in diameter of reinforcement	Representation
Case 1	1.5m	20%	1A
		40%	1B
		60%	1C
		80%	1D
		100%	1E
Case 2	3m	20%	2A
		40%	2B
		60%	2C
		80%	2D
		100%	2E
Case 3	4.5m	20%	3A
		40%	3B
		60%	3C
		80%	3D
		100%	3E

2.2 Loads and analysis

Boundary conditions are assigned to the beam in the initial step module by selecting pinned support conditions at both the ends. All the member analysis will come under next steps of step module. Linear perturbation analysis is carried on healthy and different corroded beams in step-1 and dynamic responses are obtained in the form of mode shapes and natural frequencies. In Step-2 harmonic analysis is conducted by applying an external voltage of 1V on the top surface of the piezoelectric patch and the beam is excited in the frequency range of 1-200Hz with sub step interval of 100 to extract electrical conductivity signatures.

3 Results and Discussions

3.1 Modal analysis

The natural frequencies corresponding to first five mode shapes are considered for all the cases by conducting frequency analysis using Bloc Lanczos method. For a fixed patch location the natural frequencies of different damage stages A, B, C, D & E are extracted and compared with healthy state natural frequency as shown in Table 4. It is observed that as the percentage of corrosion in beams is increased, the natural frequencies got reduced. The decrease in natural frequency ($\omega_n = \sqrt{k/m}$) of the beams shows that the percentage reduction in stiffness is more than percentage reduction of mass in corroded beams. The natural frequency remains the same in all the cases for various patch locations.

3.2 Harmonic analysis

The Steady state responses of the corrosion induced beams are determined by performing harmonic

analysis in the frequency range of 1- 200 Hz. An external

In first case, one fourth length is considered to

Case	Mode no	Natural Frequency(Hz)				
		A (20%)	B (40%)	C (60%)	D (80%)	E (100%)
Case1	1	15.343	15.295	15.252	15.229	15.182
	2	25.957	25.938	25.912	25.879	25.862
	3	51.639	51.547	51.469	51.414	51.394
	4	65.309	65.078	64.901	64.786	64.747
	5	66.569	66.474	66.282	65.938	65.743
Case2	1	15.256	15.228	15.203	15.185	15.179
	2	24.942	24.921	24.915	24.873	24.857
	3	51.594	51.411	51.325	51.275	51.257
	4	65.154	64.874	64.657	64.524	64.479
	5	66.312	66.191	65.871	65.756	65.649

electric field is generated by applying a voltage of 1V on the top surface of piezoelectric patch with beam attached to the bottom layer. This electrical potential will actuate the beam to produce EMI signatures as response. For analysis conductance signatures that are real part of admittance signatures are considered to identify the corrosion. The signatures from healthy and different damage conditions are captured in 20 – 30Hz frequency range as more number of resonant peaks is observed in this range with 30 sub step interval by placing the sensor at three different locations on the beam.

be corroded with different mass reduction rates by decreasing the steel diameter from 20% to 100%. In each stage, the electrical conductance signatures are captured from the piezoelectric patches placed at a distance of 1.5m, 3m & 4.5m from left end and compared with healthy condition as shown in Figures 2, 3 and 4.

Case3	1	15.232	15.217	15.193	15.177	15.159
	2	24.911	24.812	24.771	24.728	24.712
	3	51.507	51.413	51.317	51.255	51.232
	4	65.116	64.766	64.494	64.322	64.263
	5	66.182	65.889	65.671	65.516	65.458

Table 4. Mode shapes and Natural frequencies of Corroded beams in different cases

Fig.2. Conductance Signatures for 1st Case at location 1

Fig.3. Conductance Signatures for 1st Case at location 2

Fig.4. Conductance Signatures for 1st Case at location 3

In second case, half length of the beam is considered to undergo corrosion with different diameter reduction rates and in each stage the conductance signatures from different piezoelectric patches placed at a distance of 1.5m, 3m and 4.5m from left end are captured. The corroded beams are compared with healthy condition as shown in Figures 5, 6 and 7. In third case, three fourth length of beam is considered to undergo corrosion and signatures are plotted and compared with healthy beam as shown in Figures 8,9 and 10.

Fig.5. Conductance Signatures for 2nd Case at location 1

Fig.6. Conductance Signatures for 2nd Case at location 2

Fig.7. Conductance Signatures for 2nd Case at location 3

Fig.8. Conductance Signatures for 3rd Case at location 1

Fig.9. Conductance Signatures for 3rd Case at location 2

Fig.10. Conductance Signatures for 3rd Case at location 3

From the plotted graphs, it is observed that as the percentage of corrosion activity is increased from Stage A to Stage E, the peak values of the conductivity signatures got reduced. The reduction in natural frequencies due to increase of corroded length from 1.5m to 4.5m shifted the signature peaks to left side. By comparing the Electro Mechanical signatures from surface bonded piezoelectric transducers at various geometric positions it is noticed that the patch which is located near to the corroded area showed a resonant peak of magnitude relatively lower than the other two.

4 Conclusions

Based on the numerical investigations and simulation results the following conclusions are documented:

1. The variation in dynamic properties with natural frequency decrement will indicate the damage presence in a structure.
2. The severity of corrosion is revealed with downward shift in peak values of captured electrical conductance signatures of harmonic analysis.
3. Remarkable aspect of this technique is the possibility to predict damage geometrical location by comparing the responses of various sensors incorporated at different locations.
4. It is concluded that with Abaqus software critical couple field numerical analysis can be performed by bringing good coordination with the host structure and smart system.
5. This method of monitoring with piezoelectric sensors offered a relatively inexpensive and reliable technique to anticipate the corrosion initiation with better robustness.

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