Impedance based service life assessment of corroded structures with Cross correlation analysis

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Abstract. Electro mechanical impedance technique has garnered major significance in structural health monitoring field by integrating with information and sensing technology. Technical advancements in automated smart devices improved the diagnostic evaluation of this monitoring method by incorporating piezoelectric materials. The optimistic coupling property of these materials enhanced the life span of structural members by detecting damages at incipient stage. The intervention of piezoelectric transducers has created potential applications for impedance approach in assessing the structural performance with high feasibility. The present work aims at estimating the service life of simply supported smart beam using piezoelectric sensors in Abaqus Simulia software. Corrosion is deployed at a uniform rate in reinforced concrete beam with impressed current flow and the loss in diameter of rebar is calculated using Faraday's electrochemical equation. With frequency domain based impedance technique numerical analysis is conducted on the modeled beams by exciting the sensor with an external harmonic force and the output electric responses of different piezoelectric locations are captured. The steady state dynamic responses for different cases are compared and quantified with a statistical damage algorithm in MATLAB. The resulted cross correlation indices are analyzed to prevent further deterioration of the corroded beams by setting a limit value. The proposed simulation technology is capable of estimating the residual life span of damage structures with cross correlation analysis.

Keywords: SHM, Impedance technology, Piezoelectric sensor, Corrosion, Cross correlation index

1 Introduction

A recent study on the published literature inferred that service life prediction of structural members subjected to rebar corrosion remains at the parametric stage [1]. It is vital to perform intense research on perilous problems of reinforcement corrosion as it significantly affects the structural performance by reducing its durability. The premature deterioration of corroded structures typically begins with gradual penetration of chlorine and carbon dioxide from atmosphere into the concrete by breaking the impervious protective layer [2]. This intrusion creates an electrical potential difference with pore water as electrolyte leading to electrochemical corrosion of steel. In anodic regions, the surface atoms undergo oxidation and release electrons that combine with polarizer like acids, oxygen and moisture at the cathodic region to form

hydroxyl ions. These ions travel along the electrolyte to combine with positively charged Ferrous ions and forms a mixture of stable Ferric hydroxides which by further oxidation converts into rust whose volume is six times more than the original steel rebar. As a result these end products exert radial thrust on the hardened concrete at the interface causing longitudinal cracking, delamination of concrete, pitting, excessive deflections and make the steel rebar frizzle by reducing its gross cross sectional area [3].

These detrimental agents will cause sudden collapse of the structure by decreasing bond strength, stiffness, load carrying capacity and ultimate strength of the spalled concrete [4]. As the structural integrity is affected with these aggressive effects, it is essential to treat corrosion in initial stages by removing the damaged concrete material,

increasing the reduced steel area, cleaning and applying coating over the steel surface and covering with concrete cover of suitable thickness. All the above steps of treatment must be executed with utmost care because the repaired area in the presence of small contaminated concrete patch will become anodic and begin to corrode. Therefore it is imperative not only to repair the corroded material but also to prevent the entry of depassivating chemicals into the concrete by controlling with metallurgical methods, sacrificial coatings and cathode protection [5]. Rapid development in Nondestructive evaluation techniques enabled Electrical Half cell Potential method to estimate the corrosion activity in steel reinforcement [6]. This method is the most standard and quick test performed to determine the probability of corrosion by calculating the current densities with potential difference values driven by the electrodes of two half cells. The qualitative nature of this traditional method did not give any information about the corroded area location and severity rate as it depends on many external environmental factors [7]. The technical advancements in Structural Health Evaluating methods enhanced researchers to overcome the limitations of visual manual inspection and conventional damage measurement tests by providing reliable and accurate solutions [8, 9].

SHM with the intervention of information and sensing technology has showed an excellent potential of monitoring the corrosion process continuously with various sensors from initial stages [10]. Among them Piezo ceramic materials have attracted a considerable amount of interest due to their easy installation, low cost, high feasibility and resistivity [11, 12]. The piezoelectric sensing system when driven by external electric field gets excited and produces mechanical vibrations which can be converted again into electrical responses [13,14]. This optimistic dual property of converting energies from one form to other implemented piezoelectric materials as sensors and actuators in impedance based approaches for generating high frequency waves [15,16]. The first one dimensional electrochemical impedance equation on 1D host structure was proposed in 1996 [17] which enhanced the application of this technique in various fields for interpreting the structural changes [18]. The simulation technology with the instrumentation of sophisticated transducers is capable of conducting numerical computation analysis on three dimensional finite element models of complicated geometry [19].

The present paper focuses on estimating the residual service life of corroded beams with piezoelectric transducers by conducting EMI analysis [20,21]. Corrosion is simulated uniformly to the reinforced beams by applying a fixed amount of current for a specific varied duration and with Faraday's first law of electrolysis equation the rebar diameter loss is calculated.

$$d(t) = d_i - 0.023 \cdot (i_{cor}) \cdot (t) \quad (1)$$

$d(t)$ = reinforcement diameter at time t (mm)

d_i = initial reinforcement diameter at $t=0$ (mm)

i_{cor} = current density (mA/cm²)

t = applied current duration (days)

These beam models are electrically coupled with piezoelectric sensors in Abaqus Simulia software and excited with an external harmonic force to generate numerical finite element simulations [22]. The output responses in terms of sinusoidal vibration are captured and compared with healthy structure to anticipate the damage severity. The voltage variations are quantified in MATLAB by generating a simple statistical algorithm program for Cross Correlation index and these values are plotted against time to determine the duration up to which the corrosion affected structures remain in service condition [23]. A warning system is developed to prevent further deterioration by setting a limit value of 0.5 to Cc index [24].

2 Numerical study

In the current study, couple field numerical analysis is performed on a simply supported reinforced concrete beam using impedance based sensing technique. With an external current application corrosion is induced in the modeled beams by reducing the mass of the reinforcement. These corroded beams are analyzed to extract the dynamic responses using piezoelectric actuators and are further quantified to calculate the remaining life span.

Initially a three dimensional input file is created in part module of Abaqus software by selecting 8 noded and 2 noded solid extrusion elements for concrete beam and steel rebar. These elements are assigned with suitable material and geometrical properties in section property module as shown in Table 1 and Table 2 and assembled as a single database model by providing a clear cover of 30 mm using embedded constraint.

Table 1. Geometrical and Material properties of Concrete beam

Length of beam	6 m
Cross section of beam	300mm x 400mm
Grade of Concrete (f_{ck})	25 N/mm ²
Density	2400 kg/m ³
Hysteretic Damping ratio	0.05
Modulus of elasticity	2.5×10^{10} N/m ²
Poisson's ratio	0.15

Table 2. Reinforcement properties and detailing

Grade of Steel (f_y)	415 N/mm ²
Density	7850 kg/m ³
Modulus of elasticity	2.1×10^{11} N/m ²
Poisson's ratio	0.3
Main bars	3 bars of 16mm diameter
Hanger bars	2 bars of 12mm diameter

Stirrups	2 legged 8mm with 200mm c/c spacing
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A smart piezoelectric sensor of size 60mm x 60mm x 10mm is modeled as a 3D couple element and attached to the top surface of the host structure in the interaction module using tie constraint. Critical impedance analysis is conducted on the beam by placing the sensor at two different positions from the right support as shown in the Figure 1, electrical and material properties of the PZT are mentioned in Table 3. After modeling, the elements are meshed independently in the mesh module with an appropriate mesh width of 0.01m and 0.05m for piezoelectric patch and beam

Fig.1. Piezoelectric patch locations for different cases

Table 3. Section properties of Piezoelectric sensor

Relative Permittivity (10^{-9} F/m)	PERX = 6.5 PERY = 6.5 PERZ = 6.5
Piezoelectric coupling coefficient(10^{-10} C/N)	$d_{31} = -5.2$ $d_{33} = 15.1$ $d_{15} = 12.7$
Modulus of elasticity (10^{10} N/m ²)	$D_{1111} = 13.9$ $D_{1122} = 7.8$ $D_{2222} = 13.9$ $D_{1133} = 7.4$ $D_{2233} = 7.4$ $D_{3333} = 11.5$ $D_{1212} = 3.05$ $D_{1313} = 2.56$
Density (kg/m ³)	7500

Location	Case 1: PZT placed at 1.5m from right end Case 2: PZT placed at 4.5m from right end
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The embedded steel bars of the healthy beam are subjected to corrosion at a uniform rate by inducing current density and the material loss in the rebar is calculated using electrochemical equation of Faraday. For the present work five stages are considered by increasing the duration of the applied current from 20 days to 100 days with current density of 5mA/cm² and the diameter loss in the reinforcement of partially corroded beam in each stage is represented in the Table 4. These beams are numerically modeled in the preprocessing stage with different corrosion rates and discretized to perform finite element analysis.

Firstly the dynamic features like mode shapes and natural frequencies are extracted from the modeled beams in the step module by conducting frequency analysis as shown in the Figure 2 and this data will act as a pre requisite tool to conduct harmonic analysis in the next step. These beams are excited by applying a voltage of 1V to the surface bonded piezoelectric transducers in the initial boundary conditions and the output electrical responses in the frequency range 20-30 Hz are captured. In the second step dynamic implicit analysis is performed by actuating the piezoelectric with a periodic force of $F = 1.5 \sin(25\pi t)$ for one second time duration with a step size of 100 and the voltage responses with respective to natural frequency and time are recorded from the output field manager of visualization module as shown in the Figure 3.

Table 4. Rebar diameter for different corrosion stages

Corrosion stages in steel	Current density applied(mA/cm ²)	Duration(days)	Rebar diameter loss(mm)	Representation
1 st stage of corrosion	5	20	3.2	S1
2 nd stage of corrosion	5	40	6.4	S2
3 rd stage of corrosion	5	60	9.6	S3
4 th stage of corrosion	5	80	12.8	S4
5 th stage of corrosion	5	100	16	S5

Table 5. Natural frequency of corroded beam at different stages

		Healthy	S1	S2	S3	S4	S5
1	Lateral bending	15.417	15.256	15.228	15.203	15.185	15.179
2	Transverse bending	25.827	24.992	24.923	24.861	24.791	24.712
3	Lateral bending with two nodes	51.982	51.639	51.547	51.469	51.414	51.394
4	Twisting	65.124	65.309	65.078	64.901	64.786	64.747
5	Transverse bending with two nodes	65.783	65.516	65.464	65.382	65.289	65.247

Fig.2. Corroded beam under modal analysis

Fig.3. Corroded beam under harmonic analysis

The sinusoidal responses from different sensor locations for various corrosion stages are captured and analyzed to estimate the damage severity. These signals are further cross correlated in the data acquisition system of MATLAB with damage quantification index as

$$C_c = \frac{\left(\frac{1}{N}\right) \sum_{i=1}^N (H_i - \bar{H})(C_i - \bar{C})}{\sigma_H \sigma_C} \quad (2)$$

where H represents healthy beam signal and C represents Corroded beam signal

3 Results and Discussions

3.1 Frequency analysis

With frequency analysis, the first five modal shape parameters are extracted for different corrosion stages as shown in the Table 5 and in each stage the resonant frequency of the corroded beam is compared with the natural frequency of healthy beam. From Figure 4 it is observed that resonating frequency of the beams got

reduced with increase in corrosion rate from S1 to S5 due to larger reduction in stiffness value than the mass.

3.2 Harmonic analysis

A periodic sinusoidal load of specific harmonic frequency is generated to perform Linear Perturbation analysis and the mechanical vibrations of the beam are captured by the piezoelectric in the form of electrical signal. In harmonic analysis two cases are considered by placing the sensor in corroded and non corroded area at a distance of 1.5m, 3m from right support. The frequency vibrations of the corroded beams in terms of electrical potential for five different stages S1, S2, S3, S4 & S5 with various diameter reduction rates are analyzed and compared for two different locations of PZT as shown in the Figures 5,6,7,8&9.

Fig.4. Natural frequency of beam for different cases

Fig.5. Frequency response of corroded beam in 1st stage

Fig.6. Frequency response of corroded beam in 2nd stage

Fig.7. Frequency response of corroded beam in 3rd stage

Fig.8. Frequency response of corroded beam in 4th stage

Corrosion Stages	Case 1	Case 2
S1	0.8965	0.9342
S2	0.7341	0.8529
S3	0.5978	0.6706
S4	0.3579	0.4628
S5	0.1231	0.2921

Fig.9. Frequency response of corroded beam in 5th stage

With time domain harmonic analysis, the steady state response of voltage with respect to time is recorded for all the cases and using cross correlation method the damage severity is determined by comparing and quantifying the voltage of corroded signal with healthy signal using statistical index as shown in Table 6.

Table 6. Cc values for different sensor locations

From the above graphs, it is noticed that with increase in corrosion rate from Stage 1 to Stage 5 the amplitude of electrical voltage signal got increased with leftward shift of natural frequency. By comparing the results of sinusoidal responses of numerical analysis in both the cases for all the stages it is found that the sensor that is located near to the damaged region has shown a higher peak value of voltage than the other. Moreover from the Table 6 it is noticed that the PZT patch in Case 1 has recorded a less damage index value than the other sensor in Case 2. So to estimate the service life of corroded members the cross correlation values of piezoelectric

sensor that is near to the damage is considered. A graph is plotted between the extracted Cc values of the piezoelectric in corroded area with respect current density duration as shown in Figure 10.

Fig.10. Cross correlation index vs Duration for Case1

From the graph the service life of the different staged corroded beam is predicted by applying linear regression. As 0.5 is taken as limiting value Cc index, the point where linear trend meets the limiting axis is considered. For the present study, beams will take 68 days to become out of service after corrosion initiation.

4 Conclusions

1. The simulation results of proposed technique demonstrated the variation in structural behaviour with corrosion by measuring steady state dynamic responses of piezoelectric patches with couple field finite element analysis.
2. Quantitative evaluation of the present numerical study is achieved by performing computation analysis with statistical damage algorithms of MATLAB.
3. This localization impedance concept of damage assessment with piezoelectric transducers enhanced the structural integrity by incorporating advanced data acquisition systems.

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