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Research Article

Corrosion Assessment in Steel Reinforcement Using Piezoelectric Sensor for Service Life Prognosis of Reinforced Concrete Structures

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ABSTRACT

The deterioration of reinforced concrete (RC) structures due to the corrosion of steel reinforcement poses significant challenges to structural integrity and service life. This study investigates the application of electromechanical impedance (EMI) techniques using piezoelectric sensors for the real-time assessment of corrosion-induced damage and the prognosis of remaining service life in RC structures. By leveraging the sensitivity of EMI-based methods, this research aims to develop predictive models for quantifying corrosion severity and structural deterioration without direct physical measurements of corrosion parameters. The study examines chloride-induced and carbonation-induced corrosion mechanisms, emphasizing their impact on reinforcement integrity. The EMI technique is employed to monitor corrosion progression by analysing variations in mechanical impedance, which serves as a reliable indicator of structural degradation. Structural parameters such as stiffness and mass loss are extracted from impedance signatures to establish predictive models for corrosion assessment. The stiffness-based model enables phase-wise classification of corrosion progression, while the mass loss model facilitates the estimation of corrosion rates and corresponding reductions in rebar cross-section and structural load-carrying capacity. Experimental validation is conducted using RC specimens subjected to accelerated corrosion conditions, demonstrating the efficacy of EMI-based techniques in accurately assessing corrosion severity. The results establish a strong correlation between impedance-derived parameters and actual structural deterioration, enabling reliable service life estimation. By providing a non-destructive, real-time monitoring framework, the proposed approach offers a viable alternative to conventional electrochemical methods, facilitating proactive maintenance and extending the service life of RC structures. This research underscores the potential of EMI-based structural health monitoring for advancing corrosion assessment methodologies, offering a cost-effective and efficient solution for ensuring the long-term durability of RC infrastructure.

Keywords: Chloride and Carbonation induced corrosion, Use of EMI Technique for corrosion detection, Mechanical impedance of structures, stiffness model, mass model, reduction in steel dia, Service life prognosis.

INTRODUCTION

Concrete is a versatile, cost effective and easy to handle construction material, widely used next only to water. Its lack of adequate tensile strength is taken care by steel rebars making the combination reinforced concrete (RC). In most cases, RC structures are durable and strong, performing well throughout its service life. However, in some cases, they do not perform adequately due to various reasons and one of the reasons being corrosion of steel rebars. In fact, corrosion of the steel rebars has become the major cause of deterioration of RC structures around the world. The present study aims to review technique of corrosion measurement for SHM focusing on EMI techniques and also discuss prediction models for determining severity of corrosion damage during various phases of chloride induced corrosion, corrosion rates without need for actual parameters. Furthermore, an attempt has been presented on the prediction of the remaining service life of concrete structures being deteriorated by rebar corrosion. The approach has been made assuming that the "reduction in bar diameter or bar section" is the determining parameter in calculating the loss in load-carrying capacity of the structure

PROCESS OF CORROSION

The time for the chloride ion concentration to reach a critical level for the onset of corrosion is known as the 'initiation Period'. Once the protective layer around the reinforcement has been removed, corrosion can take place in the presence of moisture and oxygen. The time taken for corrosion to result in sufficient deterioration such that remedial action is required is known as the 'propagation period'. Different conceptual models are proposed to describe the corrosion process of steel rebar in concrete (Tuutti, 1982(16(a)). The most suitable scheme for modeling the service life of corroding structures is that presented by Tuutti, shown in Fig. 1. The residual lifetime of the structure depends on the rate of deterioration. An unacceptable degree of corrosion, not quantified by Tuuti, is reached when a repair should be undertaken. The quantification of this deterioration period becomes of crucial importance in the assessment of damaged structures.

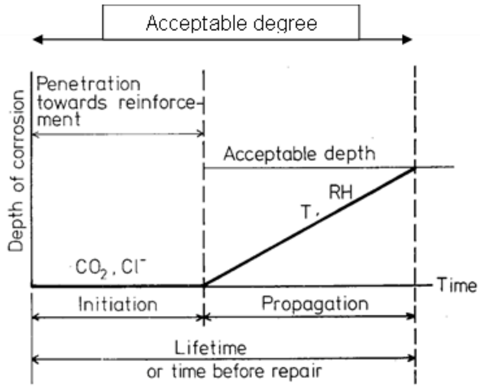


FIG 1 TUTTI MODEL

1. **Chloride Induced Corrosion in Concrete**.

(a) One of the most common causes for rebar corrosion in RC structures is the presence of chloride ions. They cause localized breakdown of the passive film that initially forms around steel because of alkaline nature of the pore solution in concrete.

(b) The main corrosive agents i.e. the chlorides, can ingress into concrete from several sources. The aggressive chloride ions can originate either from the contaminated mixing ingredients (cast into the concrete as part of the ground water/seawater in the mix or contaminated aggregates or due to sea salt spray/direct wetting or deicing salts) in the fresh state or from the surrounding environment in the hardened state (Broomfield, 2007(16(l))). These chlorides, when diffused into concrete, reduce the alkalinity of the pore solution (from the original pH 13 to below 7) thereby initiating corrosion.

2. **Carbonation Induced Corrosion in Concrete**.

(a) Carbonation is the result of the interaction of carbon dioxide gas in the atmosphere with the alkaline hydroxides in the concrete. Like many other gases, carbon dioxide dissolves in water to form carbonic acid. The carbonic acid does not attack the cement paste, but just neutralizes the alkalis in the pore water, mainly forming calcium carbonate that fills the pores.

(b) Calcium hydroxide is not the only substance that reacts with CO_2, the other hydration products and even the residual unhydrated cement compounds also take part into carbonation reactions. The formation of calcium carbonate requires three equally important substances: CO_2, calcium phases (Ca), and water (H_2O). CO_2 is present in the surrounding air, calcium phases mainly calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrate (CSH) are present in the concrete, and water is present in the pores of the concrete.

METHOD

Use of EMI Technique for Corrosion Detection

Corrosion can cause serious failures, potentially causing irreparable economic losses. The most important step in order to hinder or reduce the extent of such failures is to detect corrosion as early as possible and adopt effective preventive measures. The paper discusses, assessing and measuring the rate of corrosion using sensors (Piezo electric sensors).

(a) **Characteristics of Piezo Electric Sensors**.

SerNo	Characteristic	Description
i.	Frequency Range Selection	High frequency of excitation (50 to 500 kHz) which ensures high sensitivity
ii.	Effect of Temperature	Admittance signature obtained are temperature sensitive. Tests need to be performed under controlled laboratory conditions

iii.	Sensing range	High frequency of excitation induced renders the actuation and sensing zone to be localized. Sensing zone is closely related to host material and varies from 0.6m in concrete to 2-3 m in metal.
iv.	Excitation Voltage	Piezo electric patches (PZT) are normally excited by LCR meter with an AC signal of 1 volt r.m.s
v.	Instrumentation	Impedance measurements needs to be done using Tektronix digital function generator and key sight multimeter.

MECHANICAL IMPEDANCE OF STRUCTURES

EMI technique is a prominent damage detection technique, which utilize the direct and converse capabilities of smart piezoelectric materials to non-destructively inspect and evaluate the health of structures. It has recently been integrated into autonomous SHM devices (Bhalla et al., 2003-07(16(b,c,d)). The main aim of this research is to evaluate the EMI technique as a corrosion detection and quantification tool for rebars embedded in concrete. Electrical impedance is a parameter used to characterize electric circuits and components is given as

$$Z = X + yj$$

(a) where the real part of impedance is the resistance *X,* and the imaginary part is the reactance *y*. The electrical admittance on the other hand, is a measure of how easily a circuit or a device allows current to flow and is the inverse of impedance. It is defined as

$$Y = 1/Z = G + Bj$$

where *G* is called the conductance and *B* the susceptance. To understand the EMI technique, it is important to understand the concepts of mechanical impedance as it is analogous to electrical impedance (Bhalla, 2004). A harmonic force, acting upon a structure, is given as: -

$$F(t) = F_o\cos wt + jF_o\sin wt$$

(b) The resulting velocity response $\dot{u}$, at the point of application of the force, is also harmonic in nature. However, it lags behind the applied force by a phase angle, due to the 'mechanical impedance' of the structure. Hence, velocity can also be represented as a phasor, as

$$\dot{u} = \dot{u}_0 \cos(wt - f) + j\dot{u}_0 \sin(wt + f) = \dot{u}_0 e^{j(wt - f)}$$

(c) The mechanical impedance of a structure, analogous to the electrical impedance, at any point, is defined as the ratio of the driving harmonic force to the resulting harmonic velocity at that point, in the direction of the applied force, that is

$$Z = F/\dot{u}$$

(d) A healthy structure may be thought of as a multiple degree of freedom system composed of several mechanical elements i.e., different combinations of mass, spring, and damper elements. If the basic elements are known, they could be combined using superposition theorems. The result would be a single impedance equation which would describe the input (Force) output (velocity) relationship for the structure. The equation would define the frequency dependant structural response of the system which thus identifies the healthy mechanical impedance composition of the structure. Thus, Mechanical impedance composition would deviate if the structure is corroded and it would be possible to see the effect of the damage through the mechanical impedance change.

Analysis Based on Equivalent Structural Parameters. To determine mechanical impedance of the structure, $Z_{s,eff} = x + yj$, at a particular frequency ω, from the impedance signature, values of *x*' and '*y*' can be determined for the entire frequency range of 50 to 400 kHz. A close examination of the extracted impedance components in the frequency range 150-250 kHz revealed that the chosen system exhibited similar system behavior as that of parallel spring-damper-mass (k-c-m) combination (Hixon, 1998) as shown in Fig. 2. This system is chosen to include mass and calculate the rate of corrosion.

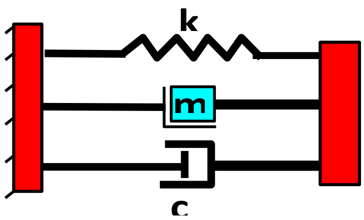
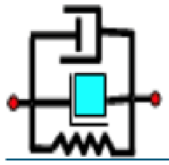
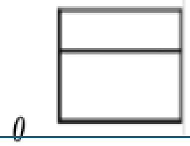
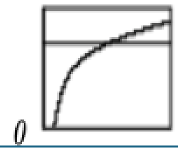


Fig 2 Identified system (Parallel combination of spring-mass-damper)

For this system,

COMBINATION	X	Y	X Vs FREQUENCY	Y Vs FREQUENCY
	C	$m\omega - \frac{k}{\omega}$		

(a) The above relation has been extracted from combine approach for structural damage identification using EMI technique (Manjeet Aug 2016, international journal of science technology and engineering) as suggested by Bhalla 2012(16(j)).

(b) The angular frequency at which y = 0 is denoted by ω_o. The system parameters can be determined by algebraic calculations as: -

$$K = Y\omega\omega_o / (\omega^2 - \omega^2_o) \quad (1)$$

$$M = K/ \omega^2_o \quad (2)$$

$$C = X \quad (3)$$

ANALYSIS MODEL AND RESULTS

Prediction Models

This section will focusses on development of models for predicting corrosion severity and corrosion rates based on structural parameters obtained from impedance.

(a) **Stiffness Model**. The actual stiffness (initial and final) of the rebar can be calculated indirectly based on the minimum cross sectional area (along the length of the bar), before the rebar was embedded in concrete and after the rebar was removed from the concrete specimen by splitting after 120 days (Period for which impedance to be measured at regular intervals, while subjecting specimen to accelerated corrosion process) . The PZT identified equivalent stiffness, both initial and final, can be directly obtained from the Eq. (1) by substituting the impedance parameters of baseline (for initial) and of 120 days (for final).

(i) Knowing the stiffness, the relation between the actual stiffness loss and the PZT identified stiffness loss can be written as

$$(\Delta K/K)_{ACTUAL} = \Delta_K (\Delta K/K)_{PZT}$$

Where Δ_K is a constant relating the non-dimensional PZT based stiffness loss with actual stiffness loss. Using Eq. (1) Δ_K is calculated for all the specimens. The value of Δ_K then can be averaged covering all the specimens. This correlation helps in estimating the actual stiffness loss due to the corrosion (whose measurement is not feasible in a real structure non-destructively) by determining the PZT identified stiffness loss instead using Equations above, which can be achieved non-destructively. Hence, the chloride induced corrosion process can be distinguished into three different phases, namely, corrosion initiation followed by propagation and finally, the cracking, based on the visual inspection and the variation of the dimensionless stiffness parameter, as illustrated in Fig. 3. Phase I, the corrosion initiation phase up to 45th day, during which the dimensionless stiffness parameter (based on PZT identified stiffness) commences from 0. This is followed by phase II, corrosion propagation phase from 45th day to 90th day during which the accumulation of corrosion products (iron oxides and hydroxides), occupying a volume several times larger than that of the original iron (Tutti, 1982(16(a))). This leads to internal stresses that result in cracking and spalling of the concrete cover. At this stage the intrusion of aggressive agents, oxygen and humidity is facilitated. Finally, phase III starts, accompanied by large scale concrete cracking due to the overshooting of the internal stresses caused from the building up of corrosion products, during which the values of dimensionless stiffness parameter are in excess. This can be considered as an alarming situation, where the total loss of the structural integrity occurs. Hence, in an actual scenario, the PZT identified stiffness 'k' parameter alone can thus provide satisfactory information about level of corrosion induced damage non-destructively in term of identifying the relevant phase of corrosion and can be substitute to the conventional electro-chemical techniques.

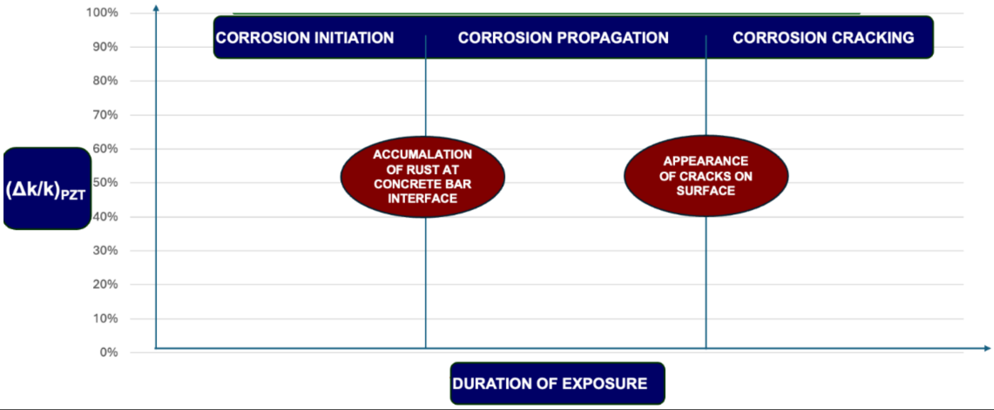


FIG 3 GRAPHICAL REPRESENTATION OF STIFFNESS PARAMETER VARIATION

(c) **Equivalent Mass Model** Gravimetric mass loss technique is a destructive method, which deals with the measurement of mass of the rebar before being embedded into the concrete and after the end of the corrosion experiments, taking it out destructively. The detailed test procedures of preparing, cleaning, and evaluating corrosion test specimens are described in ASTM G1 (ASTM, 2012). The difference in mass (gravimetric loss) is a quantitative average of the attack of corrosion. Although this method is very time-consuming and only applicable to the laboratory studies, it is a useful tool to check the corrosion rates obtained from other techniques.

(i) To determine the corrosion rates, the initial mass of all the rebars is to be measured before embedding them. After splitting all the specimens, the final mass loss of the steel bars can be determined by the gravimetric method after chemically cleaning the corrosion products. The PZT identified mass was also calculated directly using Eq. (2) during the corrosion exposure, without any destructive measure.

Knowing the actual and the PZT identified mass a similar to stiffness relation can be derived relating both as,

$$(\Delta M/M)_{ACTUAL} = \Delta_M (\Delta M/M)_{PZT}$$

(ii) Where Δ_M is a constant relating the non-dimensional PZT based mass loss with actual mass loss. This equation compares the non-dimensional actual mass loss and non-dimensional PZT identified mass loss. Δ_M shall be computed for all specimens and the average value of Δ_M to be worked out. This correlation will be useful in calculating the corrosion rates of the rebar, because measuring the actual mass loss in real life structures is not possible as rebar is inside the concrete. Based on the EMI measurements, this can be achieved non-destructively.
Knowing the mass loss, the corrosion rate (mm/year) can be calculated as:-

$$\Delta_C = K.\ \Delta M/a.T.D$$

where K is a constant equal to $8.76\text{x}10^4$, Δm is the mass loss in grams, a is the area in mm^2, T is the time of corrosion exposure in hours and D is the density of steel i.e.,7.8g/cm^3. The corrosion rates can be calculated using both PZT identified mass loss and actual mass loss.

Experimental Analysis. To validate the model, six RC cubes of M30 grade (as per IS 456, 2000), 150x150x150 mm in size, were cast along with 200 mm long, 16 mm diameter HYD rebar located centrally. The rebars were thoroughly cleaned with a wire brush prior to bonding the PZT at mid length. The concrete cube specimens were then cast with rebars placed centrally using OPC, fine aggregate and crushed coarse aggregate of nominal size 10 mm. Table. 1 below present the details of composition of the concrete mix. The standard moulds were filled with concrete in three layers, taking particular care in pouring the concrete to avoid damage to the PZT sensor. The concrete was compacted carefully using table vibrator, the specimens were demoulded after 24 hours of casting.

Materials/Parameters	**Quantity**
Water-cement ratio	0.4
Ordinary Portland Cement 53 Grade (kg/m^3)	500
Fine aggregate (kg/m^3)	570.5

Coarse aggregate (kg/m3)	1062.2
Slump (mm)	100

Table 1. Concrete Mix Design Details

The corrosion rates were calculated using PZT identified mass loss (Equivalent mass model) and tabulated in Table 2 below.

Specimen	Initial mass (kg)	Final mass (kg)	Mass loss (kg)	$\Delta_{c\,(mm/yr)} = (87.6*\Delta m\ /a*D*t)$
2	0.21	0.14	0.07	1.37
3	0.14	0.07	0.06	1.29
5	0.23	0.11	0.11	2.24
6	0.19	0.091	0.09	1.91

Table 2. Corrosion Rate Value

Reduction in Steel Dia. Corrosion rates have been used by Andrade et al 1990(16(n,o)) in estimating remaining service life of reinforced concrete structures where corrosion is the degradation process. Corrosion rates is converted to reductions in dia of reinforcing steel by the relationship:-

$$\Phi(t) = \Phi - \Delta_C . t$$

Where,

$\Phi(t)$ = Steel Dia at time t in mm

Φ = Initial Steel dia in mm

t = Time t in yrs

The change in dia of steel as a result of corrosion can be further converted into service life predictions by modelling the effects of reduction in cross section of the reinforcement on load capacity of reinforced concrete. Reduction in cross section as a function of bar diameter and corrosion rates is shown below.

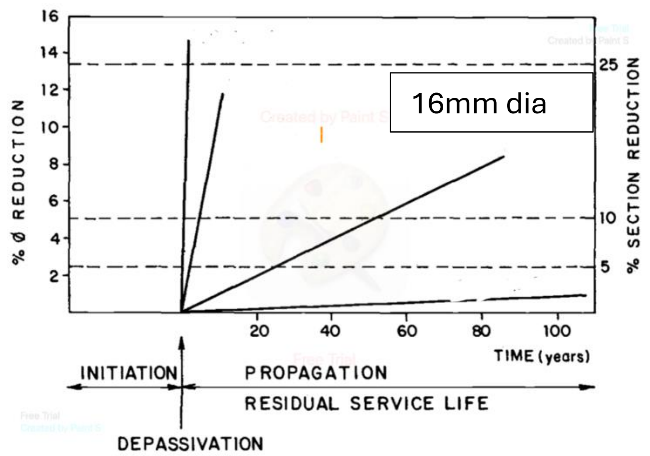


FIG 4 Decrease with time of rebar diameter (left) and X section (right) as a function of corrosion rate

Percentage Reduction of diameter and cross section of steel reinforcing bar of 16mm diameter at different corrosion rates during the propagation period of corrosion (Tutti's model) is graphically represented in Fig 4.

Predicted decrease in the moment of resistance ($MoR = 0.87 f_y A_{st} (d - 0.42 X_u)$) of RCC structure as a function of corrosion due to change in cross sectional area of steel is further shown in the fig 5.

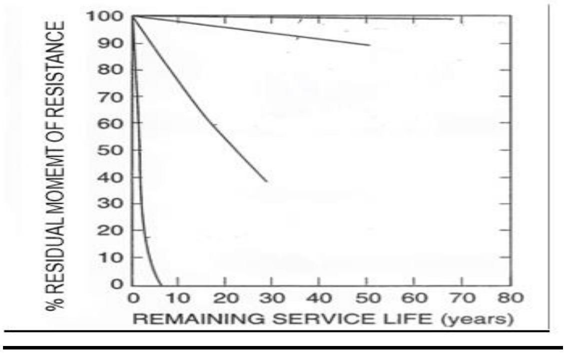


FIG 5 Decrease in moment of resistance with time for different corrosion rates.

Validation. The figures so obtained by calculating the penetration attack in mm per year for bar of 16 mm in diameter, from the values of corrosion rates, were transformed into percentage of reduction in bar diameter or bar section and % Residual Moment of Resistance. Therefore, assuming the corrosion rate remains constant, the prediction of the number of years to reach a deterioration level (either 5, 10, or 25%) is easily attained. The calculated Time Vs % Dia Reduction & % cross section Reduction and Time vs & Residual Moment of Resistance is shown in Fig 6 .

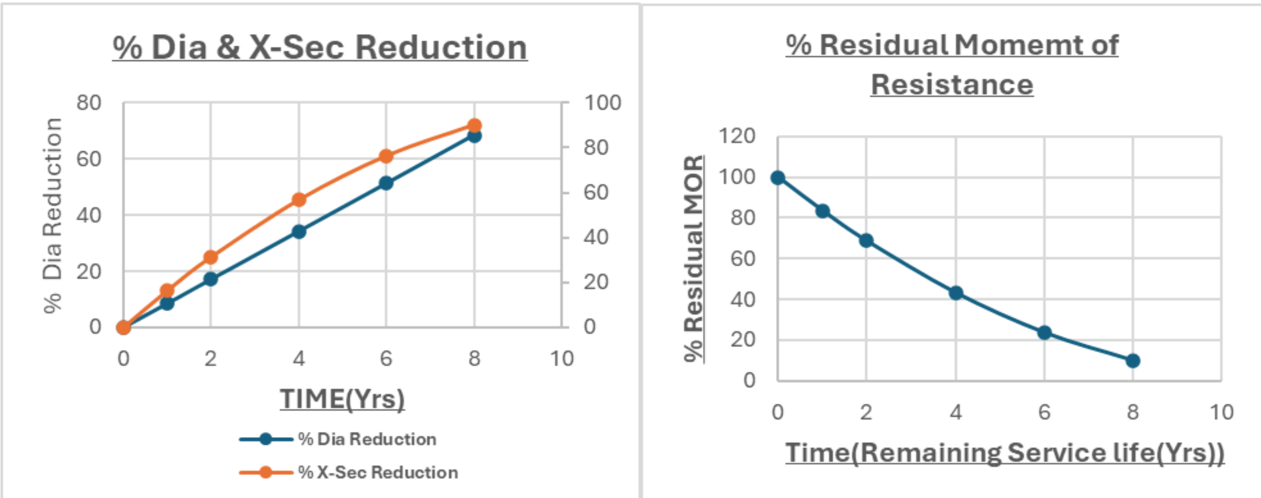


FIG 6. Note: Above Graphs Plotted Assuming a Constant Corrosion Rate of 1.37mm/yr, which otherwise needs to be measured on need basis.

The graph shown in fig no indicates that the % reduction of rebar diameter & cross section of the rebar and %reduction in moment of resistance with time as a function of corrosion rate. Extent of structural deterioration evolution are assessed based on the relationship developed. The structural deterioration which is effecting the lifespan reduction can be addressed by using maintenance technique. This will assist in judging the urgency of intervention.

CONCLUSION

Based on the limited experiment studies and extensive literature svy, following conclusions are warranted.

(a) A new diagnostic approach to carry out the assessment of rebar corrosion based on the equivalent system parameters identified by means of the EMI technique.
(b) The real and imaginary components of the impedance signature are used to extract the damage sensitive equivalent structural parameters.
(c) Empirical models derived between the actual parameters and the PZT identified parameters can be used in real life corrosion monitoring of RC structures, where the determination of actual parameters of rebar is impractical.
(d) Based on the mass model, corrosion rates determined using the PZT identified mass loss correlate well with those calculated based on the actual mass.
(e) Based on stiffness model, utilizing the $(\Delta K/K)_{PZT}$ ratio to differentiate between phases of corrosion and level of corrosion severity non destructively.
(f) Once the relationship between corrosion rate and structural deterioration are developed, damage to the structure can be assessed.

REFERENCES

[1] Tutti, kyosti(1982), "Corrosion of steel in concrete".
[2] Bhalla. (2001), "Smart System Based Automated Heath Monitoring of Structures", M Engg Thesis, School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.
[3] Bhalla, S. and Soh, C. K. (2003), "Structural Impedance Based Damage Diagnosis by Piezo-Transducers", Earthquake Engineering and Structural Dynamics, 32 (12), 1897-1916.
[4] Bhalla. (2004), "A Mechanical Impedance Approach for Structural Identification, Health Monitoring and Non-Destructive Evaluation Using Piezo-Impedance Transducers", PhD Thesis, School of Civil and Environmental Engineering, Nanyang Technological University, Singapore.
[5] Bhalla, S. and Soh C. K. (2004a), "Structural Health Monitoring by Piezo-Impedance Transducers. Part I Modelling", Journal of Aerospace Engineering, ASCE, 17(4), 154-165.
[6] Bhalla, S. and Soh, C. K. (2004b), "Structural Health Monitoring by Piezo Impedance Transducer. Part II Application", Journal of Aerospace Engineering, ASCE, 17(4), 166-171.
[7] Bhalla, S., Yang, Y. W., Zhao, J. and Soh, C. K. (2005), "Structural Health Monitoring of Underground Facilities-Technological Issues and Challenges", Tunnelling and Underground Space Technology, 20 (5), 487-500.
[8] Bhalla, S. and Gupta, A. (2007), "A Novel Vibration Sensor for Concrete Structures", Invention Disclosure Dt. 26thFeb 2007 (FT/IRR/CE/SB/2007/0570), Foundation for Innovation Technology and Transfer (FITT), IIT Delhi, Patent No: 1011/DEL/2011.
[9] Bhalla, S., Gupta, S., Bansal, S. and Garg, A. (2009), "Ultra Low Cost Adaptation of Electro-mechanical Impedance for Structural Health Monitoring" Journal of Intelligent Material System and Structure, 20, 991-999
[10] Bhalla, S., Vittal, A. P. R. and Veljkovic, M. (2012), "Piezo-Impedance Transducers for Residual Fatigue Life Assessment of Bolted Steel Joints", Journal of Structural Health Monitoring, 11(6), 733-750.
[11] Bhalla, S. and Moharana, S. (2013), "A Refined Shear Lag Model for Adhesively Bonded Piezo Impedance Transducers", Journal of Intelligent Material System and Structures, 24 (1), 33-48.
[12] Broomfield, J. P., Rodriguez, J., Ortega, L. M. and Garcia, A.M. (1993). "Corrosion Rate Measurement and Life Prediction for Reinforced Concrete Structures'. Proceedings of International Conference on Structural Faults and Repair, University of Edinburgh, Scotland, 155–164.
[13] Broomfield, J. P. (2007), "Corrosion of Steel in Concrete, Understanding, Investigation and Repair", Second edition, Taylor and Francis.
[14] C. Andrade et al(1990), " Initial effort to use Corrosion Rates in establishing Rebar Durability".
[15] C. Andrade et al(1989), "Remaining service life of corroding structures".