

CORROSION ASSESSMENT IN REBARS OF REINFORCED CONCRETE STRUCTURES USING EQUIVALENT PARAMETERS EXTRACTED FROM PIEZO-PATCHES

TALAKOKULA VISALAKSHI



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

OCTOBER 2014

© Indian Institute of Technology Delhi (IITD), New Delhi, 2014

CORROSION ASSESSMENT IN REBARS OF REINFORCED CONCRETE STRUCTURES USING EQUIVALENT PARAMETERS EXTRACTED FROM PIEZO-PATCHES

by

TALAKOKULA VISALAKSHI

Department of Civil Engineering

Submitted

in fulfilment of the requirements of the degree of

Doctor of Philosophy

to the



Indian Institute of Technology Delhi

October 2014

CERTIFICATE

This is to certify that the thesis entitled, “**CORROSION ASSESSMENT IN REBARS OF REINFORCED CONCRETE STRUCTURES USING EQUIVALENT PARAMETERS EXTRACTED FROM PIEZO-PATCHES**” submitted by Ms. Talakokula Visalakshi to Indian Institute of Technology Delhi, for the award of the degree of the **Doctor of Philosophy** is a record of bonafide research work carried out by her. She worked under our supervision for the submission of this thesis, which to the best of our knowledge has reached the requisite standard.

The research reports and the results presented in this thesis have not been submitted in parts or in full to any other University or Institute for the award of any degree or diploma.

(Dr. Suresh Bhalla)

Associate Professor

Department of Civil Engineering

Institute of Technology Delhi

(Prof. Ashok Gupta)

Professor

Department of Civil Engineering Indian

Indian Institute of Technology Delhi

Date:
New Delhi

ACKNOWLEDGEMENTS

First and foremost, I would like to extend my sincere thanks and gratitude towards my supervisors, Dr Suresh Bhalla and Prof. Ashok Gupta. It is no overstatement to say that without the consistent guidance, tutelage, support, unparalleled knowledge, and encouragement of my supervisors, this thesis would never have existed. They truly exemplify the role of advisors. I am forever grateful for their kindness and contributions, not only towards my research, but towards my professional growth as well.

Thanks are also due to Prof B. Bhattacharjee, who had given valuable suggestions during the initial days of my research, which helped me a lot. I am grateful to my committee members Prof. K. S. Rao, Dr. A. K. Darpe and Dr G. S. Benipal, who provided useful suggestion and valuable advice regarding my research. Thanks to all the Civil Engineering faculty and other staff members, special thanks to Mr. Lal Singh, Mr. Vinod Sharma, Mr. Mansukh Sureen and other technicians for their keen support in my work. I am extremely grateful to the staff of Smart Structures and Dynamics Laboratory (SSDL), departmental and central libraries for providing books, journals etc., which made this research work possible. Thanks are also due to Dr. R. J. Ball, Dr. G. L. Pesce, Prof. C. R. Bowen and Dr. K. Paine of University of Bath, UK and R. Kurchania of MANIT, Bhopal, India.

A special thanks goes to almighty God and my parents, Last but not least, I wish to express my gratitude to my family, and in particular to my supportive and patient husband Basa Kiran Kumar and to my lovely son Basa Chandraneil for giving me the things that are so much more important in life than the combination of corrosion, steel, concrete and Piezo patches..

ABSTRACT

Reinforced concrete (RC) is an economical, versatile and successful construction material as it can be moulded to a variety of shapes and finishes. In most cases, it is durable and strong, performing well throughout its service life. However, in some cases, it does not perform adequately due to various reasons, one of which is the corrosion of the embedded steel bars used as reinforcement. Concrete provides an almost ideal environment for protecting the embedded steel from corrosion due to the passive film surrounding the steel rebars. However, the breakdown of this passive film, either due to chloride attack or due to carbonation, results in the corrosion of rebars. Thus rebar corrosion is one of the main causes of damage and premature failure of the RC structures worldwide, causing enormous costs for inspection, maintenance, restoration and replacement. Therefore, early detection of corrosion and timely remedial action on the affected portion can facilitate an optimum utilization of the structure, imparting longevity to it.

A large number of investigations have been conducted on the problems related to the deterioration of RC structures due to the corrosion of steel rebars. Usually, the condition of the structure is monitored by visual inspection and remedial measures are resorted to only when the condition becomes very serious. In order to prevent the deterioration levels reaching severe dimensions, it is desirable to monitor the condition of strategic structures right from the construction stage using structural health monitoring (SHM) techniques. The recent advent of the electro-mechanical impedance (EMI) technique for SHM has provided a new paradigm to the maintenance engineers to diagnose the onset of the damage at the incipient stage itself. The EMI technique utilizes the piezoelectric ceramic patches as collocated actuators-sensors and employ ultrasonic vibrations (typically in 30-400 kHz

range) to acquire the characteristic ‘signature’ of the structure, which contains vital information governing the phenomenological nature of the structure, and can signal the onset of structural damages.

Although the EMI technique is well established for damage detection and quantification of various civil and aerospace structures, limited studies have been reported for its application in corrosion detection. This thesis presents a new corrosion assessment models based on the equivalent parameters extracted from the impedance spectrum of concrete-rebar system using the EMI technique via the PZT sensors. The corrosion assessment models are developed based on an accelerated corrosion study carried out on RC specimens covering both chloride and carbonation induced corrosion using PZT sensors that are surface bonded on rebars as well as using piezo-composite concrete vibration sensor (CVS) embedded in concrete near rebar. This is the first ever research reporting such extensive studies on the application of the equivalent parameters for corrosion assessment of rebars embedded in concrete.

Proof-of-concept experiments were performed extending up to 120 days to detect chloride induced corrosion using surface bonded PZT patches as well as CVS. Accelerated corrosion tests were performed in order to obtain the data in a reasonable time frame for a laboratory-based study. Firstly, the equivalent structural parameters were extracted from the admittance spectra of the PZT patches surface bonded to bare rebars for chloride induced corrosion and an empirical model was developed for correlating the actual mass and stiffness with the equivalent mass and stiffness identified by the PZT sensor. Further, the empirical model was extended to the RC specimens to determine the corrosion rates and identify various phases of corrosion using the PZT patches both surface bonded to rebar as well as CVS embedded near rebar. The experimental results indicate that the equivalent parameters and the

developed model are effective in detecting and quantifying the rebar corrosion in a realistic manner.

The research was further extended to the second type of corrosion i.e., carbonation induced corrosion through accelerated carbonation tests conducted on RC cylinders (with rebars surface bonded with PZT patches) in a carbonation chamber for a period of 250 days. The carbonation corrosion assessment models developed were correlated with the progress of depth of carbonation. Imaging techniques such as scanning electron microscopic images and Raman spectroscopy were also used to further establish the onset of carbonation corrosion and correlate with the signal provided by the PZT patches.

Finally, to enhance the efficiency of the proposed model in real life application, the empirical model developed for chloride induced corrosion under accelerated tests was validated by comparing the corrosion rates of RC specimens exposed to natural environment for a period of 420 days. In addition, the influence of mineral admixture, namely fly ash, on the corrosion performance of steel is also investigated non-destructively using the developed model.

The corrosion assessment models developed are empirical and non-destructive in nature. The stiffness model is used to determine the severity of corrosion damage during various phases and the mass model for determining the corrosion rates for both chloride induced and carbonation induced corrosion. These models can be used for non-destructive corrosion monitoring of RC structures in real life with no “a-prior” information regarding the structure and with no modelling required. It is expected that this research will provide a new alternative experimental technique to the researchers and diagnostic engineers working in the field of rebar corrosion.

TABLE OF CONTENTS

CERTIFICATE	i
ACKNOWLEDGEMENTS	ii
ABSTRACT	iii
TABLE OF CONTENTS	vi
LIST OF FIGURES	x
LIST OF TABLES	xv
LIST OF ACRONYMS	xvi
LIST OF SYMBOLS	xviii
CHAPTER 1 : INTRODUCTION	1
1.1 Background.....	1
1.2 Research Hypothesis	3
1.3 Research Objectives and Scope	3
1.4 Research Significance.....	5
1.5 Outline of Thesis.....	6
CHAPTER 2 : LITERATURE REVIEW	8
2.1 Introduction.....	8
2.2 The Corrosion Process	9
2.3 Rebar Corrosion in Reinforced Concrete Structures	10
2.3.1 Chloride Induced Corrosion in Concrete	11
2.3.2 Carbonation Induced Corrosion in Concrete	13
2.4 Techniques for Corrosion Detection.....	14
2.4.1 Electro-Chemical Techniques	15
2.4.1.1 Potential Measurement Technique	15
2.4.1.2 Linear Polarization Resistance Technique	21
2.4.1.3 Alternating current Impedance Spectroscopy Technique	24
2.4.2 Gravimetric Measurement Technique	24

2.4.3 Corrosion Monitoring Using Sensors	25
2.5 Impedance Based Structural Health Monitoring.....	27
2.5.1 Piezoelectric Materials	27
2.5.2 Geometric Details of PZT patches	29
2.5.3 Diverse Applications of Piezoelectric Materials	29
2.6 Electro-Mechanical Impedance Technique Using PZT patches	30
2.6.1 Physical Principles	30
2.6.2 Frequency Range Selection	34
2.6.3 Effect of Temperature	35
2.6.4 Sensing Range and Optimal Placement of PZT Patches	36
2.6.5 Excitation Voltage and Signature Acquisition	36
2.6.6 Instrumentation and Other Considerations	36
2.7 Major Research in Electro-Mechanical Impedance Technique Since 1990's	37
2.8 Limitations in Application of PZT patches for Structural Health Monitoring	41
2.9 Summary: Critical Points of Review	42
2.10 Research Objectives	44
CHAPTER 3 : DIAGNOSIS OF CHLORIDE INDUCED CORROSION IN BARE STEEL REBARS	47
3.1 Introduction.....	47
3.2 Mechanical Impedance of Structures	47
3.3 Mechanical Impedance of PZT patches	50
3.4 Details of Accelerated Corrosion Study	51
3.5 Damage Quantification	56
3.5.1 Root Mean Square Deviation	56
3.5.2 Signature Assurance Criteria	57
3.5.3 Waveform Chain Code Technique	57
3.5.4 Adaptive Template Matching	58
3.6 Analysis of Structural Mechanical Impedance Extracted From Admittance Signature ...	60
3.7 Concluding Remarks	73

CHAPTER 4 :DEVELOPMENT OF CORROSION ASSESSMENT MODEL FOR REBARS EMBEDDED IN REINFORCED CONCRETE STRUCTURES	74
4.1 Introduction.....	74
4.2 Rebar Corrosion in Reinforced Concrete Structures	74
4.3 Specimen Preparation	77
4.4 Accelerated Corrosion Exposure on Conductance Signatures	78
4.5 Analysis Based on Equivalent Structural Parameters	85
4.6 Calibration of Extracted Equivalent Parameters	90
4.6.1 Development of Equivalent stiffness model	90
4.6.2 Development of Equivalent Mass Model for Corrosion Rates	94
4.7 Concluding Remarks.....	97
 CHAPTER 5 : COMPARISON OF CORROSION ASSESSMENT CAPABILITY OF SURFACE BONDED AND EMBEDDED PIEZO SENSORS	 99
5.1 Introduction.....	99
5.2 Advantages of Embedded Sensors.....	100
5.3 Configuration and Application of Embedded PZT Sensors	98
5.4 Experimental Details and Results	102
5.4.1 Comparison of Conductance Signatures	103
5.4.2 Comparison of Root Mean Square Deviation Index	105
5.4.3 Comparison of Equivalent Stiffness Parameters	106
5.5 Concluding Remarks.....	111
 CHAPTER 6 : MONITORING AND ASSESSMENT OF CARBONATION INDUCED CORROSION IN REINFORCED CONCRETE STRUCTURES	 113
6.1 Introduction.....	113
6.2 Accelerated Carbonation Study: Experimental Procedure	114
6.3 Analysis of Results	118
6.4 Correlation With Microscopic Image Analysis and Raman Analysis	123
6.5 Validation of Corrosion Rate Prediction Model	128
6.5 Concluding Remarks.....	129

6.6 Acknowledgements.....	129
CHAPTER 7 : APPLICATIONS OF THE PROPOSED CORROSION ASSESSMENT MODEL ON FLY ASH BLENDED CONCRETE AND ON NATURALLY CORRODED SPECIMENS.....	130
7.1 Introduction.....	130
7.2 Proof-of-Concept Validation 1: Corrosion Assessment in Fly Ash Blended Concrete ..	130
7.2.1 Details of Fly Ash utilized	134
7.2.2 Experimental Details (Concrete and Fly Ash).....	136
7.2.3 Microstructural Analysis.....	138
7.2.4 Corrosion Assessment in Fly Ash Blended Concrete Using the Derived Model	139
7.3 Proof-of-Concept Validation 2: Corrosion Assessment in Naturally Corroded Specimens	142
7.4 Concluding Remarks	143
CHAPTER 8 : CONCLUSIONS AND RECOMENDATIONS.....	144
8.1 Introduction	144
8.2 Research Conclusions and Contributions	144
8.3 Limitations	147
8.4 Recommendations for Future	148
PUBLICATIONS BASED ON THIS RESEARCH.....	149
REFERENCES.....	153
CIRRICULAM VITAE	176