

**EXPECTED REMAINING LIFE OF EXISTING REINFORCED
CONCRETE STRUCTURES**

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CONCRETE STRUCTURES**

by

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CERTIFICATE

This is to certify that the thesis entitled, “**Expected Remaining Life of Existing ReinforcedConcrete (RC) Structures**” submitted by **Sushil Kumar Dhawan** to Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him. He worked under our supervision for the submission of the thesis which under the best of our knowledge has reached the requisite standard.

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

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Sushil Kumar Dhawan

ABSTRACT

The possibility of safely extending the service life of existing structures is an idea that has gained increasing importance among structural engineers. This thesis focuses on developing a computational methodology for estimating the expected remaining life of existing reinforced concrete (RC) structures, based on in-situ test outcomes and experimental investigations.

Concrete is primarily used in the form of reinforced concrete (RC) for construction of buildings, bridges and other important structures. RC is an economical, versatile and robust construction material as it can be moulded into a variety of shapes and finishes. In most cases, it is durable, strong and performs well throughout the intended design life. However, due to normal usage related wear and tear and environmental effects, the RC structure would generally deteriorate, the impact of which need to be worked out for the desired performance of the structure, commensurate with the fulfillment of essential requirements from strength as well as serviceability considerations. The expected remaining life of existing RC structures and assessment of an RC structure would depend upon the various parameters, such as the remaining cross-sectional area of steel, Young's modulus of elasticity (concrete and steel) and the *in-situ* strength of the constituent materials: concrete and steel.

The experimental methodology is developed as a part of this doctoral research, consists of damage estimation at component level, based on piezo-identified equivalent parameters for RC flexural components, using EMI technique. The same is thus established in terms of the equivalent parameters sensed by lead zirconate titanate (PZT) patches bonded to the rebar based on the electro-mechanical impedance (EMI) technique. The PZT patch is light weight, low cost, small size and has good dynamic performance, high elastic modulus, high rigidity, brittleness

and low tensile strength. Besides, it exhibits large range of linearity, fast response, long term stability and high energy conversion efficiency. PZT is used as a sensor in structure health monitoring with the EMI technique.

The other part of this doctoral project aims to study the dependence of the expected remaining life of existing RC structures on the design for seismic/windload and the present condition of the structure, encompassing the residual material strength and the residual reinforcement area. This culminated towards the development of a computational methodology to estimate the expected remaining life of existing RC structures. The proposed methodology utilizes seismic and wind considerations to work the design life based on the least probable return period out of earthquake and wind. The methodology has been applied on a model building followed by an illustrative example of application on a real life study of existing five storied RC structure. The influence of various parameters such as concrete strength and the residual area of the rebars have been investigated. As an additional computation, the critical member was completely removed and the structure was reanalyzed, so as to simulate local structure collapse. The proposed methodology provides a simple and rational method of estimation of the residual service life.

The main novelty of the approach is that it takes into consideration the entire building structure as an analytical model for working the expected remaining life of existing RC structures.

सार

मौजूदा संरचनाओं के सेवा जीवन को सुरक्षित रूप से विस्तारित करने की संभावना एक विचार है जिसने संरचनात्मक इंजीनियरों के बीच बढ़ते महत्व को प्राप्त किया है। यह थीसिस इन-सीटू टेस्ट परिणामों और प्रयोगात्मक जांच के आधार पर मौजूदा प्रबलित कंक्रीट (आरसी) संरचनाओं के अपेक्षित शेष जीवन का अनुमान लगाने के लिए एक कम्प्यूटेशनल पद्धति विकसित करने पर केंद्रित है।

कंक्रीट का उपयोग मुख्य रूप से इमारतों, पुलों और अन्य महत्वपूर्ण संरचनाओं के निर्माण के लिए प्रबलित कंक्रीट (आरसी) के रूप में किया जाता है। आरसी एक किफायती, बहुमुखी और मजबूत निर्माण सामग्री है क्योंकि इसे विभिन्न प्रकार के आकार और खत्म में ढाला जा सकता है। ज्यादातर मामलों में, यह टिकाऊ है, मजबूत है और पूरे डिजाइन जीवन में अच्छा प्रदर्शन करता है। हालांकि, सामान्य उपयोग से संबंधित पहनने और आंसू और पर्यावरणीय प्रभावों के कारण, आरसी संरचना आमतौर पर बिगड़ जाएगी, जिसके प्रभाव के लिए काम करने की आवश्यकता है। संरचना का वांछित प्रदर्शन, शक्ति से आवश्यक आवश्यकताओं की पूर्ति के साथ-साथ सेवाक्षमता के विचारों के अनुरूप है। मौजूदा RC संरचनाओं का अपेक्षित शेष जीवन और RC संरचना का आकलन विभिन्न मापदंडों पर निर्भर करेगा, जैसे कि स्टील के शेष क्रॉस-सेक्शनल क्षेत्र, लोच का यंगमॉडलस (कंक्रीट और स्टील) और इन-सीटू ताकत घटक सामग्री: कंक्रीट और स्टील।

प्रायोगिक कार्यप्रणाली को इस डॉक्टरेट अनुसंधान के एक भाग के रूप में विकसित किया गया है, इसमें घटक स्तर पर क्षति का अनुमान है, जो EMI तकनीक का उपयोग करते हुए आरसी फ्लेक्सुरल घटकों के लिए बराबर मापदंडों के आधार पर पहचाना जाता है। इसी तरह से इलेक्ट्रो-मैकेनिकल प्रतिबाधा (ईएमआई) तकनीक के आधार पर रीबार से बंधे लीड जिरकोनेटेटेड (पीजेडटी) पैच द्वारा संवेदी समतुल्य मापदंडों के संदर्भ में स्थापित किया जाता है। पीजेडटी पैच हल्का वजन, कम लागत, छोटा आकार और अच्छा है गतिशील प्रदर्शन, उच्च लोचदार मापांक, उच्च कठोरता, भंगुरता

और कम तन्यता ताकत। इसके अलावा, यह बड़ी संख्या में रैखिकता, तेज प्रतिक्रिया, दीर्घकालिक स्थिरता और उच्च ऊर्जा रूपांतरण दक्षता प्रदर्शित करता है। PZT का उपयोग EMI तकनीक के साथ संरचना स्वास्थ्य निगरानी में एक सेंसर के रूप में किया जाता है।

इस डॉक्टरेट परियोजना का दूसरा हिस्सा भूकंपीय / वायु भार के लिए डिजाइन पर मौजूदा आरसी संरचनाओं के अपेक्षित शेष जीवन की निर्भरता और संरचना की वर्तमान स्थिति का अध्ययन करना है, जिसमें अवशिष्ट पदार्थ शक्ति और अवशिष्ट सुदृढीकरण क्षेत्र शामिल हैं। यह मौजूदा RC संरचनाओं के अपेक्षित शेष जीवन का अनुमान लगाने के लिए एक कम्प्यूटेशनल कार्यप्रणाली के विकास के लिए समाप्त हुआ। प्रस्तावित कार्यप्रणाली भूकंप और हवा से बाहर कम से कम संभावित वापसी की अवधि के आधार पर डिजाइन जीवन को काम करने के लिए भूकंपीय और हवा के विचारों का उपयोग करती है। मौजूदा पांच मंजिला आरसी संरचना के वास्तविक जीवन के अध्ययन पर एक उदाहरण के रूप में आवेदन के एक उदाहरण के बाद मॉडल बिल्डिंग पर लागू किया गया है। ठोस मापदंडों और विद्रोहियों के अवशिष्ट क्षेत्र जैसे विभिन्न मापदंडों के प्रभाव की जांच की गई

है। एक अतिरिक्त गणना के रूप में, महत्वपूर्ण सदस्य को पूरी तरह से हटा दिया गया था और संरचना को फिर से जोड़ा गया था, ताकि स्थानीय संरचना के पतन का अनुकरण किया जा सके। प्रस्तावित कार्यप्रणाली अवशिष्ट सेवा जीवन के आकलन का एक सरल और तर्कसंगत तरीका प्रदान करती है।

दृष्टिकोण की मुख्य नवीनता यह है कि यह मौजूदा आरसी संरचनाओं के अपेक्षित शेष जीवन को काम करने के लिए संपूर्ण भवन संरचना को एक विश्लेषणात्मक मॉडल के रूप में ध्यान में रखता है।

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LIST OF ACRONYMS

A/C	Anode-to-cathode area
AC	Alternating current
ASTM	American society for testing and materials
CDV	Curvature differential values
CTDB	Cold twisted deformed bars
CVS	Concrete vibration sensor
DC	Direct current
EMI	Electro-mechanical impedance
ESP	Equivalent stiffness parameter
FBG	Fiber bragg grating
FCS	Fiber composite sensor
FEM	Finite element method
HYD	High yield deformed
IR	Voltage drop through electrolyte
LPR	Linear polarization resistance
MFC	Macro fiber composite
NDE	Non-destructive evaluation
NDT	Non-Destructive Test
OCP	Open circuit potential
OPC	Ordinary Portland cement
PZT	Lead zinconatetitanate
RC	Reinforced concrete

RMSD	Root mean square deviation
SDV	Slope differential values
SEM	Scanning electron microscopy
SHE	Standard hydrogen electrode
SHM	Structural health monitoring
TMT	Thermo-mechanically treated
USPV	Ultra sonicpulse velocity

LIST OF SYMBOLS

A_{st}	Area of reinforcement (rebar)
E	Young's Modulus of Elasticity
f_{ck}	Characteristic compressive strength of concrete
f_t	Characteristic tensile strength of concrete
f_y	Yield strength of steel
E_c	Modulus of elasticity of concrete
E_s	Modulus of elasticity of steel
ρ	Density
c	Damping
i_{corr}	Corrosion rate (mm/annum)
k	Stiffness
m	Mass
ω	Angular Frequency (rad/s)
w/c	Water Cement ratio
ϕ_o	Undamaged rebar diameter
ϕ	Damaged rebar diameter
Δm	Mass loss
Δk	Stiffness loss
λ_m	Constant relating the non-dimensional PZT based mass loss with actual mass loss for rebars embedded in concrete
Z	Mechanical impedance of structure
Z_a	Mechanical impedance of PZT patch