DAMAGE DETECTION IN CONCRETE STRUCTURES USING SCATTERED ULTRASONIC WAVES

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APRIL 2020

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DAMAGE DETECTION IN CONCRETE STRUCTURES USING SCATTERED ULTRASONIC WAVES

by

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Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

APRIL 2020

Dedicated

to

My family and teachers

CERTIFICATE

This is to certify that the thesis entitled **"Damage Detection in Concrete Structures using Scattered Ultrasonic Waves"** being submitted by **Mr. Debdutta Ghosh** to the Indian Institute of Technology Delhi is a record of bonafide research work carried out by him under our supervision and guidance. The thesis work, in our opinion, has reached the standard, fulfilling the requirements for the award of **Doctor of Philosophy** degree.

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

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ACKNOWLEDGMENTS

Undertaking this PhD has been a truly life-changing experience for me and it would not have been possible to do without the support and guidance that I received from many people. I would like to thank my teachers who have motivated and guided me so far. Thanks to my parents, ***Mr. Ajit Kumar Ghosh*** *and* ***Smt. Anima Ghosh*** *who supported me in every ups and downs of my life.*

With due respect, I express my profound gratitude and deep regards to my thesis supervisors, ***Dr. Abhijit Ganguli****,* ***Prof. Abhijit Mukherjee*** *and* ***Dr. Shashank Bishnoi*** *for their support, patience, and encouragement. I am deeply indebted to* ***Dr. Ganguli****, for his countless support, speculative monitoring and cautious judgment. It's my great privilege to have his inspiring and thoughtful direction and guidance throughout my PhD work. From the beginning, he has always been generous with his time and efforts. I am grateful to* ***Prof. Mukherjee*** *for his valuable inputs at every point of time. His wisdom, insight, and comprehensive approach to the problem have always stimulated me. I owe my profound gratitude and sincere thanks to* ***Dr. Bishnoi*** *for his valuable time and supports.*

I am grateful to my Student Research Committee (SRC) members, ***Prof. B. R. Chahar****,* ***Dr. A. K. Swamy*** *and* ***Dr. S. Pradyumna*** *for their time and suggestions. I am also thankful to* ***Prof. B Bhattacharjee*** *for his guidance and motivation. A very special thanks to* ***Dr. Surendra Beniwal*** *who has given me lot of encouragement to keep moving on all these years and helped me in every step, from motivating to proof checking of the thesis, without your help and advices, this thesis would have not been the same! I would also like to thank my colleagues* ***Dr. Gopinandan, Rahul,***

***Kamlesh, Ajay, Gopala, Gautham** who have helped me, for my experiments. I would like to express my gratitude to **Nitin Chourasia, Late Mr. Goutam Barai, Mr. Lal Singh and Mr. Biri Singh, Ramesh, Sanjay** for extending their helping hand to access their laboratories and performing the experimental work.*

*It's my immense pleasure to thank my wife **Hina** for her all-time unconditional support, be it motivating me every moment, or taking care during my illness, or tirelessly proofreading my thesis.*

*I am very thankful to my sisters **Kabita, Nivedita**, brother-in-law **Dr. Manabendra, Sh. Uttam**, nephew **Moulik** and niece **Dipanwita** for their love and unconditional support. My heartfelt regard goes to my father in law, mother in law and brother-in-law **Hanish** for their supports**.***

*I would like to extend my thanks to **Dr. N. Gopalakrishnan**, Director CSIR-CBRI for permitting and motivating me to carry out Ph.D. work. I would like to show my gratitude to **Dr. A.K. Mittal** and my **CBRI colleagues** for their supports.*

To conclude, I cannot forget to thank my family and friends for all the unconditional support in these intense academic years.

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Abstract

Concrete is one of the most used materials in the construction of buildings, bridges, tunnels, pipelines, underground spaces, *etc*. These structures get damaged due to overloading, adverse environmental exposure, drying shrinkage, chemical attack, differential settlement, material impurity, ageing or inferior workmanship, *etc*. Such damage affects the strength, durability, and service life of concrete structures. Among these, corrosion of rebars is a critical problem afflicting Reinforced Concrete structures. Since the steel reinforcement is located close to the exposed surface of the concrete, the durability of the cover zone is of critical importance, since it protects the rebar from corrosion damage due to ingress of moisture and deleterious chemicals. A need is therefore felt by the researchers for a reliable non-destructive diagnostic tool for the detection of damages in the concrete near surface.

In the present study, ultrasonic imaging technique has been applied for the detection of subsurface damage in concrete using different ultrasonic wave modes. The study has been divided into two parts: i) imaging of subsurface crack in a concrete slab using the Rayleigh wave field and ii) imaging of corrosion induced damage in a concrete slab using combination of compressional and Rayleigh waves.

In the first part, the detection of subsurface cracks in a concrete slab is presented using the scattered ultrasonic Rayleigh wavefield through a laboratory-based setup. A wedge-based technique for the generation of a Rayleigh wave dominated field is adopted. Two-dimensional (2D) Finite Difference in Time Domain (2D-FDTD) simulations of the concrete medium are also performed to demonstrate: a) generation of Rayleigh dominated surface wave fields in a heterogeneous concrete model with the wedge; and b) interaction of the Rayleigh wavefield with the subsurface crack originating from a rebar. Experimental investigations are performed using the wedged transducer configuration to demonstrate that indeed a Rayleigh dominated field is generated and to validate the observations from the numerical model. Further, concrete specimens with embedded vertical subsurface crack like planar objects are scanned. By recording a series of ultrasonic waveforms in the tied-together mode, the image of the crack is generated, using the *Planar Synthetic Aperture Focusing Technique (Planar SAFT)*. While traditional SAFT with bulk waves has limitations with regard to detection of vertically aligned cracks, the capability of the *Planar SAFT* algorithm is demonstrated through successful imaging of these types of near-surface cracks. The technique is also reference-free and therefore, does not require information regarding the pristine condition of the medium.

In the second part, a combination of *body waves based SAFT* and the *Rayleigh wave based Planar-SAFT* is presented for the detection of corrosion induced rebar damage in a concrete slab. A chloride induced accelerated corrosion setup is developed to induce corrosion in a rebar embedded in a concrete slab specimen. A pitch-catch mode of ultrasonic scanning is performed on a set of grid points on the test specimen, using compressional and Rayleigh wave transducer arrangements. In the first approach, the traditional Synthetic Aperture Focusing Technique (SAFT) is used to produce images in the horizontal and vertical planes, using the compressional wave velocity information and by incorporating corrections related to limited directivity of the transducers. In the second approach, *Planar SAFT* is used for the detection of vertically aligned corrosion cracks, using the Rayleigh wave velocity information. The compressional wave based SAFT images shows the progressive disappearance of the rebar, while Planar SAFT image shows evidence of interactions between the incident field and subsurface cracks, with advancing corrosion activity.

The combination of these two approaches, therefore, has the potential of a powerful nondestructive diagnostic technique for identification and localization of corrosion damage, which may be useful for repair and maintenance activities in concrete structures.

डैमेज डिटेक्शन इन कंक्रीट स्ट्रकचर्स उसिंग स्कैटर्ड अल्ट्रासोनिक वेव्स

सारांश

कंक्रीट इमारतों, पुलों, सुरंगों, पाइपलाइनों, भूमिगत स्थानों आदि के निर्माण में सबसे अधिक उपयोग की जाने वाली सामग्रियों में से एक है। ये संरचनाएं अधिक लदान (ओवरलोडिंग), प्रतिकूल पर्यावरणीय अनावरण, शुष्क संकोचन (ड्रॉइंग श्रिन्केज), रासायनिक आक्षेप (केमिकल अटैक), डिफरेंशियल सेटलमेंट, सामग्री अशुद्धता, उम्र बढ़ने, हीन कारीगरी आदि के कारण क्षतिग्रस्त हो जाती हैं। इस तरह की क्षति कंक्रीट संरचनाओं की ताकत, टिकाऊपन और सेवा जीवन को प्रभावित करती है। इनमें से, रिबारों की जंग (कोरोजन), रेंफोर्सड कंक्रीट संरचनाओं को प्रभावित करने वाली एक महत्वपूर्ण समस्या है। चूंकि स्टील रेंफोर्समेंट कंक्रीट की उजागर सतह के करीब स्थित है, इसलिए कवर ज़ोन का टिकाऊपन विकट महत्व का है, क्योंकि यह नमी और हानिकारक रसायनों के प्रवेश के कारण जंग से होने वाले नुकसान से बचाता है। इसलिए शोधकर्ताओं द्वारा सतह के पास कंक्रीट में नुकसान का पता लगाने के लिए एक विश्वसनीय गैर-विनाशकारी नैदानिक उपकरण (नॉन-डेसट्रक्टिव इवैल्यूएशन टूल) के लिए एक आवश्यकता को महसूस किया जाता है।

वर्तमान अध्ययन में, विभिन्न अल्ट्रासोनिक तरंग (वेव) मोड का उपयोग करके कंक्रीट में उपसतह (सब-सरफेस) क्षति (डैमेज) का पता लगाने के लिए अल्ट्रासोनिक इमेजिंग तकनीक लागू की गई है। अध्ययन को दो भागों में विभाजित किया गया है: क) रेले तरंग क्षेत्र (Rayleigh wave field) का उपयोग करके एक कंक्रीट स्लैब में उपसतह दरार की इमेजिंग और ख) कम्प्रेशनल (Compressional) और रेले (Rayleigh) तरंगों के संयोजन (कॉम्बिनेशन) का उपयोग करके कंक्रीट स्लैब में जंग प्रेरित क्षति की इमेजिंग।

पहले भाग में, एक कंक्रीट स्लैब में उपसतह दरार (सब-सरफेस क्रैक) का पता लगाने के लिए स्कैटर्ड अल्ट्रासोनिक रेले वेवफील्ड का उपयोग एक प्रयोगशाला-आधारित सेटअप के द्वारा प्रस्तुत किया गया है। रेले

वेव वर्चस्व वाले क्षेत्र के उत्पादन के लिए एक वेज (Wedge) आधारित तकनीक को अपनाया गया है। कंक्रीट माध्यम में टू डायमेंशनल (2D) फाइनाइट डिफरेंस इन टाइम डोमेन (2D-FDTD) सिमुलेशन का भी प्रयोग निम्न को प्रदर्शित करने के लिए किया गया है: क) वेज के साथ हेट्रोजेनिअस कंक्रीट मॉडल में रेले की वर्चस्व वाली सतह वेवफील्ड का उत्पादन; और ख) रीबार से उत्पन्न होने वाली उपसतह दरार के साथ रेले वेवफील्ड का इंटरैक्शन। वेज (wedge) ट्रांसड्यूसर कॉन्फ़िगरेशन का उपयोग करके प्रयोगात्मक जांच (एक्सपेरिमेंटल इंवेस्टीगेशंस) की गयी है ताकि यह प्रदर्शित हो सके कि वास्तव में रेले वर्चस्व वाला क्षेत्र उत्पन्न हुआ है और साथ ही संख्यात्मक (न्यूमेरिकल) मॉडल की टिप्पणियों (ऑब्जरवेशंस) को मान्य करने के लिए भी इसका उपयोग किया गया है। इसके आगे, खड़ी उपसतह दरार (एम्बेडेड वर्टीकल सब-सरफेस क्रैक्) की तरह समतल वस्तुओं (प्लैनर ऑब्जेक्ट्स) के साथ बनाये गये कंक्रीट नमूनों को स्कैन किया गया है। एकसाथ बंधे (टाईड टुगेदर) मोड में अल्ट्रासोनिक तरंगों की एक श्रृंखला रिकॉर्ड करके, दरार की छवि उत्पन्न होती है, प्लैनर सिंथेटिक एपर्चर फोकसिंग तकनीक (Planar SAFT) का उपयोग करके। जबकि बल्क वेव्स (Bulk waves) वाले पारंपरिक एस.ए.एफ.टी. (Traditional SAFT) में लंबवत रूप से संरेखित दरारों (वर्टिकली अलाइनड क्रैक्स) का पता लगाने के संबंध में सीमाएं हैं, प्लानर एस.ए.एफ.टी. एल्गोरिथ्म की क्षमता को इन प्रकार के निकट-सतह दरारों की सफल इमेजिंग के माध्यम से प्रदर्शित किया गया है। यह तकनीक संदर्भ-मुक्त (रिफरेन्स फ्री) भी है और इसलिए, माध्यम की पूर्वकालीन स्थिति के बारे में जानकारी की आवश्यकता नहीं है।

दूसरे भाग में, एक कंक्रीट स्लैब में जंग प्रेरित रीबार क्षति का पता लगाने के लिए बॉडी वेव्स (Body waves) पर आधारित एस.ए.एफ.टी और रेले वेव पर आधारित प्लानर-एस.ए.एफ.टी का एक संयोजन प्रस्तुत किया गया है। एक कंक्रीट स्लैब नमूने में एम्बेडेड रीबार में जंग को प्रेरित करने के लिए एक क्लोराइड प्रेरित त्वरित संक्षारण (एक्सेलरेटेड कोरोज़न) सेटअप विकसित किया गया है। परीक्षण नमूने पर ग्रिड बिंदुओं के

एक सेट पर अल्ट्रासोनिक स्कैनिंग की एक पिच-कैच मोड का प्रदर्शन किया गया है, जिसमें कम्प्रेशनल और रेले वेव ट्रांसड्यूसर व्यवस्था का उपयोग किया गया है। पहले दृष्टिकोण में, पारंपरिक सिंथेटिक एपर्चर फ़ोकसिंग तकनीक (ट्रेडिशनल SAFT) का उपयोग आड़ी एवम खड़ी समतल सतहों में छवियों का निर्माण करने के लिए किया गया है, जो कि कम्प्रेशनल तरंगो के वेग (वेलोसिटी) की जानकारी का उपयोग करके और ट्रांसड्यूसर्स की सीमित डाइरेक्टिविटी से संबंधित सुधारों को शामिल करके किया गया है। दूसरे दृष्टिकोण में, प्लेनर एस.ए.एफ.टी (Planar SAFT) का उपयोग, रेले तरंगो के वेग की जानकारी का उपयोग करते हुए, लंबवत संरेखित जंग दरारों (वर्टिकली अलाइनड कोरोज़न क्रैक्स) का पता लगाने के लिए किया गया है। कम्प्रेशनल वेव आधारित एस.ए.एफ.टी. छवियां (SAFT images) रिबार के प्रगतिशील गायब होने को दर्शाती हैं, जबकि प्लैनर एस.ए.एफ.टी. छवि (Planar SAFT images) संक्षारण (कोरोज़न) गतिविधि के प्रगति करने के साथ घटना क्षेत्र और उपसतह दरार के बीच इंटरैक्शन का सबूत दिखाती है।

इसलिए, इन दोनों दृष्टिकोणों के संयोजन में संक्षारण क्षति (कोरोज़न डैमेज) की पहचान और स्थानीयकरण (localization) के लिए एक शक्तिशाली गैर-विनाशकारी नैदानिक तकनीक (नॉन-डेसट्रक्टिव डियगोनस्टिक) की क्षमता है, जो कंक्रीट संरचनाओं में मरम्मत और रखरखाव गतिविधियों के लिए उपयोगी हो सकती है।

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List of Symbols

λ, μ	Lamé parameters
σ_{ij}	Stress tensor at a point
ε_{ij}	Strain tensor
u_i	Displacement component in the i direction
ρ	Mass density
f_i	Body force per unit mass of material
∇	Gradient vector operator / Nabla operator
∇^2	Laplacian
Φ	Scalar potential
$\bar{\Psi}$	Vector potential
c_L	Compressional wave velocity
c_T	Shear wave velocity
c	Phase velocity
c_R	Rayleigh wave velocity
c_i/c_{Lw}	Longitudinal wave velocity of the incident material
c_{rl}/c_R	Longitudinal wave velocity of test material
c_{rs}	Shear velocity of the test material
c_{rr}	Rayleigh wave velocity of the test material
ω	Angular frequency
k	Wavenumber
ν	*Poisson's* ratio
$\bar{u}$ and $\bar{w}$	Normalized displacements in x and z direction
f	Frequency
d	Thickness of slab
θ_i	Incident angle / critical angle of the wedge
θ_{rl}	Angle of the refracted longitudinal wave
θ_{rs}	Angle of the refracted shear wave

θ_{rr}	Angle of the refracted Rayleigh wave
$\boldsymbol{A}_{(m,n)}$	Column vector
R_f	Reflection coefficient
x, y, z	Cartesian coordinates
t	Time
Δt	Size of time step
T	Time period
m, n, p	Unit Vector along x, z and t directions
n	Number of spatial dimensions
$\boldsymbol{Tr}$	Transmitter
$\boldsymbol{Re}$	Receiver
$\boldsymbol{P}_{(m,n)}$	Pixel location
Z	Acoustic impedance
$\left\|\vec{d}_{\boldsymbol{P}}^{S}\right\|$	Distance from the source to the pixel center
$\left\|\vec{d}_{\boldsymbol{P}}^{R}\right\|$	Distance from the pixel center to the receiver location
$\boldsymbol{I}_{(m,n)}$	Image value
N	Number of observed waveforms
M	Number of aperture lines
$f_{ij}(t)$	The amplitude of the *A-scan* acquired by the i^{th} the transmitter-receiver pair situated in the j^{th} aperture line
$\boldsymbol{\mu}_{(m,n)}$	mean
$\boldsymbol{\sigma}_{(m,n)}$	Standard deviation
$\boldsymbol{w}_{(m,n)}$	Weighting factor
$S0, S1, S2$ ...	Symmetric wave modes
$A0, A1, A2$ ...	Anti-symmetric wave modes

List of Acronyms

1D/ 2D/ 3D	One/ Two/ Three-Dimensional
AE	Acoustic Emission
CA	Coarse Aggregate
DC	Direct Current
EMATs	Electromagnetic Acoustic Transducers
ERT	Electrical Resistance Tomography
FA	Fine Aggregate
FD	Finite Difference
FDM	Finite Difference Method
FDTD	Finite Difference in Time Domain
FMC	Full Matrix Capture
FTC	Fourier Transmission Coefficient
GPR	Ground Penetrating Radar
IE	Impact Echo
IRT	Infrared Thermography
NDE	Non-Destructive Evaluation
NDT&E	Non-Destructive Testing and Evaluation
P-waves	Pressure Waves/ Compressional Waves
RC	Reinforced Concrete
RTM	Reverse Time Migration
SAFT	Synthetic Aperture Focusing Technique
SH	Shear Horizontal Wave
S-waves	Shear Waves
ToF	Time of Flight
TRF	Time Reversal Focusing
TRM	Time Reversal Modelling
TTA	Tied-Together Approach
UPV	Ultrasonic Pulse Velocity