



**Indian Institute of
Technology Delhi**



**THE UNIVERSITY
OF QUEENSLAND**
AUSTRALIA

**EXPERIMENTAL AND NUMERICAL
INVESTIGATION OF FIRE BEHAVIOUR OF
CONCRETE UNDER BIAXIAL STRESSES**

SOUVIK SAHA

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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THE UNIVERSITY OF QUEENSLAND

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**EXPERIMENTAL AND NUMERICAL INVESTIGATION
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STRESSES**

by

Souvik Saha

M. Tech. Structural Engineering, B. Tech. (H.) Civil Engineering



0000-0002-6564-673X

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&

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Dedicated to

my parents, without whose love, sacrifice, and blessings, this journey would have been impossible. At every step of life, their silent strength held me steady – every step of this pursuit is dedicated to them.

বাংলা (Bengali):

আমার মা-বাবাকে, যাঁদের ভালোবাসা, ত্যাগ, আর আশীর্বাদ ছাড়া এই পথচলা অসম্ভব হতো। জীবনের প্রতিটি ধাপে যাঁদের নিঃশব্দ শক্তি আমাকে আগলে রেখেছে – এই সাধনার প্রতিটি পদক্ষেপ তাঁদের প্রতি উৎসর্গিত।

Supervisor Certification

This is to certify that the thesis entitled "**Experimental and Numerical Investigation of Fire Behaviour of Concrete under Biaxial Stresses**", being submitted by **Mr. Souvik Saha** to the Indian Institute of Technology Delhi and The University of Queensland for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him. **Mr. Saha** has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which, to our knowledge, has reached the requisite standard. The results, contained in this thesis, are original and have not been submitted, in part or full, to any other University or Institute for the award of any other degree or diploma.



Dipti Ranjan Sahoo

Professor

Department of Civil
Engineering

Indian Institute of
Technology Delhi

Hauz Khas, New Delhi –
110016, India



Mehdi Serati

Senior Lecturer

School of Civil
Engineering

University of Queensland

St. Lucia – 4076, Australia



Cristian Maluk

Senior Lecturer

School of Civil
Engineering

University of Queensland

St. Lucia – 4076, Australia

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Souvik Saha

Souvik Saha

ABSTRACT

Concrete is the most widely used construction material globally, owing to its strength, durability, adaptability, and excellent thermal performance under fire. Its non-combustible nature, high specific heat, and low thermal conductivity allow it to effectively resist heat transfer, protect internal reinforcement, and limit structural damage during fire events. However, concrete is susceptible to spalling, a failure mechanism involving the sudden or progressive detachment of surface layers, which compromises the structural integrity by exposing reinforcement and reducing cross-sectional area. Fire-induced spalling is influenced by several factors, with the rate of heating recognized as one of the most critical. While experimental studies exist for uniaxial loading, there remains a significant knowledge gap regarding the behaviour of concrete under biaxial stress states during fire exposure, especially under different thermal exposure conditions such as standard (ISO 834) and hydrocarbon fire curves. The current research addresses this gap through a combined experimental and numerical investigation into the thermo-mechanical behaviour of concrete under such conditions.

Two experimental programs were conducted. First, the behaviour of high-strength concrete exposed to both hydrocarbon and standard fire conditions was studied using the Heat-Transfer Rate Inducing System (H-TRIS). This H-TRIS system replicates the total incident heat flux experienced in real fires, enabling controlled, repeatable simulation of realistic thermal environments. Clear differences in spalling behaviour were observed between the two fire curves in terms of spalling onset, depth, and type. Finite element models in ABAQUS were developed to simulate the thermo-mechanical response, which matched well with experimental temperature profiles. These models focused on stress evolution at the time of spalling, excluding pore pressure effects.

The second part of the study focused on biaxial loading scenarios, which remain underexplored. To bridge these gaps, this study proposes a unique testing regime for the assessment of the thermo-mechanical behaviour of concrete under various biaxial load ratios. First, the biaxial mechanical loads are applied to the concrete specimen with a central hole. In the next step, the thermal loading is applied on the hole surface while the specimen is under sustained loading conditions. This approach simulates the realistic tension and compression zones as well as the state of stress near the hole surface under

the applied loading. The setup utilizes a true triaxial machine at the University of Queensland (Brisbane, Australia) to apply biaxial loading on two orthogonal surfaces. Thermal loading was applied using a specially designed heating rod through a central hole inside the cubic specimen. In-depth temperature profiles were benchmarked against H-TRIS experiments and numerical predictions, showing good agreement. The results indicate that in moderate heating scenarios, different biaxial loading ratios significantly influence concrete behaviour at elevated temperatures.

Overall, this research provides new insights into the coupled effects of mechanical loading and thermal exposure on fire-induced damage in concrete. The novel experimental setups and validated numerical models developed in this study offer a robust framework for future investigations and improved fire-resilient design of concrete structures.

ABSTRACT IN HINDI (सार)

कंक्रीट विश्व स्तर पर सबसे व्यापक रूप से उपयोग की जाने वाली निर्माण सामग्री है, जो इसकी उच्च मजबूती, टिकाऊपन, अनुकूलता और आग के दौरान उत्कृष्ट तापीय प्रदर्शन के कारण है। इसकी अग्नि-रोधक प्रकृति, उच्च विशिष्ट ताप क्षमता और निम्न तापीय चालकता इसे गर्मी के संचार को प्रभावी ढंग से रोकने, आंतरिक सुदृढीकरण की रक्षा करने और आग की घटनाओं के दौरान संरचनात्मक क्षति को सीमित करने में सक्षम बनाती है। हालांकि, कंक्रीट स्पॉलिंग के लिए संवेदनशील होता है—यह एक विफलता तंत्र है जिसमें सतह की परतों का अचानक या क्रमिक रूप से टूटना शामिल होता है, जिससे सुदृढीकरण उजागर हो जाता है और क्रॉस-सेक्शनल क्षेत्रफल कम हो जाता है, जिससे संरचनात्मक अखंडता खतरे में पड़ती है। आग से प्रेरित स्पॉलिंग कई कारकों से प्रभावित होती है, जिनमें से गर्मी बढ़ने की दर को सबसे महत्वपूर्ण माना गया है। जबकि एकल-अक्षीय लोडिंग पर कुछ प्रयोगात्मक अध्ययन उपलब्ध हैं, लेकिन आग के संपर्क के दौरान द्विअक्षीय तनाव की स्थितियों में कंक्रीट के व्यवहार को लेकर अभी भी महत्वपूर्ण ज्ञान का अभाव है विशेष रूप से मानक (ISO 834) और हाइड्रोकार्बन अग्नि वक्रों जैसी विभिन्न तापीय परिस्थितियों में। वर्तमान शोध इस ज्ञान अंतर को भरने के लिए प्रयोगात्मक और संख्यात्मक दोनों तरीकों से कंक्रीट के थर्मो-मेकैनिकल व्यवहार की जांच करता है।

इस अध्ययन के दो प्रमुख प्रयोगात्मक कार्यक्रम आयोजित किए गए: पहले भाग में, हाइड्रोकार्बन और मानक अग्नि परिस्थितियों में उच्च-बल कंक्रीट के व्यवहार का अध्ययन Heat-Transfer Rate Inducing System (H-TRIS) के उपयोग से किया गया। यह H-TRIS प्रणाली वास्तविक आग में अनुभव की जाने वाली कुल ऊष्मा प्रवाह को दोहराती है, जिससे यथार्थपरक तापीय वातावरण का नियंत्रित और दोहरावयोग्य अनुकरण संभव होता है। इन दोनों अग्नि वक्रों के बीच स्पॉलिंग की शुरुआत, गहराई और प्रकार के संदर्भ में स्पष्ट भिन्नताएं देखी गईं। ABAQUS सॉफ्टवेयर में सीमित अवयव मॉडल विकसित किए गए जो थर्मो-मेकैनिकल प्रतिक्रिया का अनुकरण करते हैं और जिनके तापमान प्रोफाइल प्रयोगात्मक परिणामों से अच्छी तरह मेल खाते हैं। इन मॉडलों ने स्पॉलिंग के समय तनाव के विकास पर ध्यान केंद्रित किया, जिसमें छिद्र दाब (pore pressure) को शामिल नहीं किया गया।

अध्ययन के दूसरे भाग में द्विअक्षीय लोडिंग पर ध्यान केंद्रित किया गया, जो अब तक कम अन्वेषित क्षेत्र रहा है। इस अध्ययन में विभिन्न द्विअक्षीय भार अनुपातों के तहत कंक्रीट के थर्मो-मेकैनिकल व्यवहार के मूल्यांकन के लिए एक विशिष्ट परीक्षण पद्धति प्रस्तावित की गई है। इसमें पहले एक छिद्रयुक्त कंक्रीट नमूने पर द्विअक्षीय यांत्रिक भार डाला गया। इसके बाद, इस नमूने के छिद्र की सतह पर तापीय भार लागू किया गया, जबकि यांत्रिक भार पहले से ही जारी था। यह पद्धति यथार्थवादी तनाव और संपीड़न क्षेत्रों के साथ-साथ छिद्र के समीप तनाव की स्थिति का प्रभावी अनुकरण करती है। यह सेटअप यूनिवर्सिटी ऑफ क्वींसलैंड (ब्रिस्बेन, ऑस्ट्रेलिया) की टू टायएक्सियल मशीन का उपयोग करता है, जो दो लंबवत सतहों पर द्विअक्षीय लोडिंग प्रदान करता है। तापीय भार एक विशेष रूप से डिज़ाइन की गई हीटिंग रॉड के माध्यम से, घनाकार नमूने के मध्यवर्ती छिद्र में लगाया गया। विस्तृत तापमान प्रोफाइल को H-TRIS प्रयोग और संख्यात्मक अनुकरण से तुलना कर मान्य किया गया, और यह आपस में अच्छी संगति दर्शाते हैं। परिणामों से पता चलता है कि मध्यम तापीय स्थितियों में, विभिन्न द्विअक्षीय भार अनुपात कंक्रीट के उच्च तापमान पर व्यवहार को उल्लेखनीय रूप से प्रभावित करते हैं।

समग्र रूप से, यह शोध यांत्रिक लोडिंग और तापीय संपर्क के संयुक्त प्रभावों को समझने में नई अंतर्दृष्टि प्रदान करता है, विशेषकर आग से प्रेरित कंक्रीट क्षति के संदर्भ में। इस अध्ययन में विकसित नवोन्मेषी प्रयोगात्मक सेटअप और सत्यापित संख्यात्मक मॉडल भविष्य के अनुसंधानों के लिए एक ठोस आधार प्रदान करते हैं और कंक्रीट संरचनाओं की अग्नि-प्रतिरोधक डिजाइन को बेहतर बनाने की दिशा में सहायक सिद्ध होते हैं।

Declaration by author

This thesis is composed of my original work and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution of others to jointly authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

I acknowledge that an electronic copy of my thesis must be lodged with the University Library and, subject to the policy and procedures of The University of Queensland, the thesis be made available for research and study in accordance with the Copyright Act 1968 unless a period of embargo has been approved by the Dean of the Graduate School.

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Souvik Saha

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Publications included in this thesis

1. **Saha, S.**, Serati, M., Sahoo, D. R., and Maluk, C. (2025). Experimental and Numerical Analysis on the Thermo-mechanical Stresses Triggering the Onset of Fire-induced Concrete Spalling. *Fire Technology*, 1-22. <https://doi.org/10.1007/s10694-025-01749-3>.
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Other publications during candidature

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Contributions by others to the thesis

All chapters

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Statement of parts of the thesis submitted to qualify for the award of another degree

No works submitted towards another degree have been included in this thesis.

Research involving human or animal subjects

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LIST OF SYMBOLS

ρ	concrete density
C	specific heat of concrete
λ	thermal conductivity of concrete
ε	concrete emissivity
σ	Stefan-Boltzmann constant
h_c	convective heat transfer coefficient
\dot{q}_{inc}^{ni}	Incident heat flux
\dot{q}_{net}^{ni}	Net heat flux
T_{amb}	Ambient temperature
$\varepsilon_{max,T}$	Concrete strain at peak load at temperature T
f'_c	Concrete compressive strength
$f'_{c,T}$	Concrete compressive strength at temperature T
f_t	Concrete tensile strength
$f_{t,T}$	Concrete tensile strength at temperature T
ε_c^{in}	Inelastic strain in compression
ε_{0c}^{el}	Elastic strain in compression
ε_c	Total strain
ε_c^{pl}	Plastic strain in compression
ε_t^{pl}	Plastic strain in tension
ε_t^{ck}	Cracking strain in tension
E_0	Young's modulus
d_c	Damage parameter in compression

d_t	Damage parameter in tension
β_T	Reduction factor for concrete tensile strength
E_T	Young's modulus at temperature T
E_{RT}	Young's modulus at room temperature
R	Biaxial load ratio
D/W	Diameter-to-width ratio

LIST OF ACRONYMS

HPC	High-performance concrete
UHPC	Ultra high-performance concrete
H-TRIS	Heat-Transfer Rate Inducing System
NSC	Normal Strength Concrete
HSC	High Strength Concrete
PP fibres	Polypropylene fibres
BLEVE	Boiling Liquid Expanding Vapor Explosion
RC	Reinforced Concrete
SF	Short severe design fire
LF	Long severe design fire
MHC	Modified hydrocarbon curve
RWS	Rijkswaterstaat
LVDT	Linear Variable Differential Transformer
CDP	Concrete Damaged Plasticity
FE	Finite Element
PID	Proportional-Integral-Derivative
MAPE	Mean Absolute Percentage Error