LIFE-CYCLE RISK ASSESSMENT OF REINFORCED CONCRETE STRUCTURES UNDER EARTHQUAKE AND FIRE

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INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

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DOCTOR OF PHILOSOPHY

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&

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Dedicated to

my family

Supervisor Certification

This is to certify that the thesis entitled "**Life-Cycle Risk Assessment of Reinforced Concrete Structures under Earthquake and Fire**", being submitted by **Mr Akshay Satishkumar Baheti** 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 Baheti** 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.

25/06/2024

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I thank the UQ-IIT Delhi Research Academy for allowing me to work at the world-renowned institutes, IIT Delhi and UQ, which proved beneficial for conducting this research. I am indebted to my colleagues and fellow researchers from the Multi-Hazard Protective Structures (MHPS) Laboratory (IIT Delhi) and the Fire Lab (UQ), who have shared their knowledge and experiences, providing inspiration and support throughout the research journey. Their camaraderie has made this academic endeavour more fulfilling.

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Akshay Baheti

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ABSTRACT

Life-cycle assessment of civil engineering infrastructure is necessary for better management of resources during maintenance, strengthening, and repair actions for sustainable development. Current design practices typically consider the structural risk of various loads and their combination at the design stage and do not account for the change in the risk over the service life of a structure. A structure is subjected to multiple hazards over its lifespan, which have a certain permanent effect, though negligible sometimes, which may severely affect its performance to future significant hazard and result in disproportionate structural damages. Therefore, the present doctoral study discusses a holistic risk-based design framework that considers ageing effects in addition to major or minor structural damages on account of independent hazards. The framework is illustrated for independent action of earthquake and fire hazards on reinforced concrete (RC) structures while considering continuous structural deterioration on account of chloride- and carbonation-induced corrosion over the service life.

The earthquake-resistant design is well-developed and applies an objective-based design philosophy through design standards around the world. On the other hand, the response of structures to fire is predominantly articulated in terms of the time of exposure to a nominal fire, such as ISO 834 standard fire. This is despite the fact that this time of exposure is poorly correlated to structural response to fire. The present study discusses a framework for obtaining the most appropriate intensity measure (IM) correlated to the structural response to fire, which in turn is described in terms of an engineering demand parameter (EDP). Such a correlation between IM and EDP leads to reduced uncertainty of structural response to fire. The approach is based on the estimation of certain attributes of the correlation between IM and EDP, including: efficiency, practicality, proficiency, sufficiency, and scaling robustness. The methodology is subsequently demonstrated in application to obtain the most appropriate IM for RC slab, beam, and column elements individually. The appropriateness of a candidate IM is validated through several models that are generated for each member type by varying material and geometric properties, as well as by considering a range of fire models. A single IM is recommended for each structural member at the end of the analysis, independent of any fire model.

Many design regulations around the globe rely on member deflection as a governing criterion for resistance assessment in fire. The deflection evaluation in fire is generally achieved by conducting expensive experiments or computationally expensive finite element analyses, which often restricts practising engineers from using robust performance-based

design philosophy for typical structures in fire. Instead, they rely on objective design guidelines, often resulting in inefficient sizes of RC members. Therefore, semi-empirical relations are derived in the current study to determine the maximum deflection of the RC beam and column in fire. Plausible variables that could affect the overall deflection of the member are first identified, and their proportionality is subsequently determined by performing one-on-one regression analysis. Furthermore, these relations are developed in terms of the most suitable fire IM, which makes them applicable irrespective of the type of fire framework. The credibility of the deflection equations is validated through visual analysis followed by the three popular error indicator parameters – Pearson's correlation coefficient, relative root mean squared error, and performance index. Results indicate that all deflection equations accurately predict the RC member behaviour under fire.

A methodology is devised to obtain building fragility curves for fire using the most suitable IM and regression equations from the current study. The methodology is subsequently used to assess the life-cycle risk in RC structures for independent multi-hazard action of earthquake and fire while considering appropriate structural degradation over the service life. The change in the structure's performance in fire over its service life is also evaluated for the multi-hazard effects of earthquake and fire. The results from this study indicate that there is a significant increase in the risk of post-earthquake fire if minor damage due to earthquake not addressed. Similarly, it is shown that an RC member's performance in fire decreases significantly over its service life due to environmental effects.

ABSTRACT IN HINDI (सार)

शाश्वत विकास के लिए रखरखाव, सुदृढ़ीकरण, और मरम्मत कार्यों के दौरान संसाधनों के बेहतर प्रबंधन के लिए आधारभूत संरचना का जीवन-चक्र मूल्यांकन आवश्यक है। वर्तमान रचना प्रथाएँ आम तौर पर प्रथम चरण में विभिन्न भारों और उनके सम्मिश्रण के संरचनात्मक जोखिम पर विचार करती हैं और किसी संरचना के सेवा जीवन पर जोखिम में बदलाव को ध्यान में नहीं रखती हैं। एक संरचना को अपने जीवनकाल में कई खतरों का सामना करना पड़ता है, जिनका एक निश्चित स्थायी प्रभाव, जो कभी-कभी नगण्य होता है, भविष्य में विशाल खतरों के लिए गंभीर रूप से प्रभावित कर सकता है और परिणामस्वरूप असंगत संरचनात्मक क्षति हो सकती है। इसलिए, वर्तमान अध्ययन एक समग्र जोखिम-आधारित रचना ढांचे पर चर्चा करता है जो स्वतंत्र खतरों के कारण बड़े या छोटे संरचनात्मक नुकसान के अलावा रचनाओंके उम्र बढ़ने के प्रभावों पर भी विचार करता है। सेवा जीवन के दौरान क्लोराइड- और कार्बोनेशन-प्रेरित जंग के कारण निरंतर संरचनात्मक गिरावट पर विचार करते हुए प्रबलित कंक्रीट संरचनाओं पर भूकंप और आग के खतरों की स्वतंत्र कार्रवाई के लिए ढांचे का उपयोग किया गया है।

भूकंप-रोधी उद्देश्य-आधारित रचना अच्छी तरह से विकसित है और दुनिया भर के डिज़ाइन मानक इसे लागु करते है। दूसरी ओर, आग के प्रति संरचनाओंका प्रतिरोध मुख्य रूप से ISO 834 आग जैसी नाममात्र आग के समय के संदर्भ में किया जाता है। यह इस तथ्य के बावजूद है कि यह समय का आग में संरचनात्मक प्रतिक्रिया से बहुत कम संबंध है। वर्तमान अध्ययन में आग के प्रति संरचनात्मक प्रतिक्रिया से संबंधित सबसे उपयुक्त तीव्रता माप प्राप्त करने के लिए एक रूपरेखा बनाई गयी है। तीव्रता और प्रतिक्रिया के बीच इस तरह के सहसंबंध से आग के प्रति संरचनात्मक प्रतिक्रिया की अनिश्चितता कम हो जाती है। यह सहसंबंध कुछ विशेषताओं के अनुमान पर आधारित है, जिसमें शामिल हैं: निपुणता, व्यावहारिकता, प्रवीणता, पर्याप्तता और भार के उतारचढ़ाव के प्रति विभिन्नता। प्रबलित कंक्रीट से बने मंजिल, तंडी, और खम्बे के लिए सबसे उपयुक्त तीव्रता माप प्राप्त करने के लिए इस रूपरेखा का उपयोग किया गया है। एक उम्मीदवार तीव्रता माप की उपयुक्तता को कई सामग्री और ज्यामितीय उदाहरणों के माध्यम से मान्यता दी गई है। यह सहसंबंध विभिन्न अग्नि प्रारूप पर विचार करके उत्पन्न होते हैं। विश्लेषण के अंत में प्रत्येक संरचनात्मक सदस्य के लिए किसी भी अग्नि प्रारूप से स्वतंत्र, एकल तीव्रता माप की सिफारिश की गयी है।

दुनिया भर में कई रचना नियम आग में प्रतिरोध मूल्यांकन के लिए एक शासी मानदंड के रूप में सदस्य झुकाव पर निर्भर करते हैं। आग में झुकाव आकलन में महंगे प्रयोगों या जटिल तकनीको की आवश्यकताए अक्सर सामान्य अभियंता को आग में उद्देश्य-आधारित रचना का उपयोग करने से

प्रतिबंधित करती है। अतः वे वस्तुनिष्ठ रचना दिशानिर्देशों पर भरोसा करते हैं, जिसके परिणामस्वरूप अक्सर प्रबलित कंक्रीट संरचना अनुपयुक्त रहती है। इसलिए, आग में प्रबलित कंक्रीट तंडी और खम्बे के अधिकतम झुकाव को निर्धारित करने के लिए वर्तमान अध्ययन में विशिष्ट समीकरण प्रस्थापित किए गए हैं। सदस्य के झुकाव को प्रभावित करने वाले चीजों को पहले पहचाना गया है, और उनकी आनुपातिकता बाद में एक-पर-एक प्रतिगमन विश्लेषण करके निर्धारित की गयी है। इसके अलावा, इन संबंधों को सबसे उपयुक्त अग्नि तीव्रता माप के संदर्भ में विकसित किया गया है, जो उन्हें अग्नि ढांचे के प्रकार की परवाह किए बिना लागू करता है। झुकाव समीकरणों की विश्वसनीयता को तीन लोकप्रिय त्रुटि संकेतक मापदंडों - पियर्सन के सहसंबंध, गुणांक सापेक्ष त्रुटि, और प्रदर्शन सूचकांक के बाद दृश्य विश्लेषण के माध्यम से मान्य किया गया है। परिणाम दर्शाते हैं कि सभी समीकरण आग के तहत प्रबलित कंक्रीट सदस्य के झुकाव की सटीक भविष्यवाणी करते हैं।

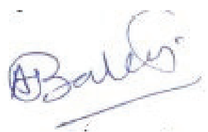
वर्तमान अध्ययन से सबसे उपयुक्त तीव्रता माप और झुकाव समीकरणों का उपयोग करके आग के लिए नाजुकता वक्र प्राप्त करने के लिए एक पद्धति तैयार की गई है। इस पद्धति का उपयोग बाद में सेवा जीवन पर उचित संरचनात्मक गिरावट पर विचार करते हुए भूकंप और आग की स्वतंत्र संयुक्त-खतरे की कार्रवाई के लिए प्रबलित कंक्रीट संरचनाओं में जीवन-चक्र जोखिम का आकलन करने के लिए किया गया है। भूकंप और आग के संयुक्त-प्रभावों के लिए इसकी सेवा अवधि के दौरान आग में संरचना के प्रदर्शन में परिवर्तन का भी मूल्यांकन किया जाता है। इस अध्ययन के नतीजों से संकेत मिलता है कि अगर भूकंप के कारण होने वाली मामूली क्षति पर ध्यान नहीं दिया गया तो भूकंप के बाद आग में भारी नुकसान होने का खतरा काफी बढ़ जाता है। इसी तरह, यह दिखाया गया है कि प्रबलित कंक्रीट सदस्य के सेवा जीवन में पर्यावरणीय प्रभावों कारण आग का प्रतिरोध करने की क्षमता काफी कम हो जाती है।

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 by 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.

I acknowledge that copyright of all material contained in my thesis resides with the copyright holder(s) of that material. Where appropriate I have obtained copyright permission from the copyright holder to reproduce material in this thesis and have sought permission from co-authors for any jointly authored works included in the thesis.



(Akshay Satishkumar Baheti)

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Publications included in this thesis

1. **Baheti, A.**, Lange, D., and Matsagar, V. "Semi-empirical equations to evaluate maximum deflection in RC beam and column under fire", *Journal of Structural Engineering* (*Accepted, In press*).
2. **Baheti, A.**, Lange, D., and Matsagar, V. (2021). "Multi-hazard nonlinear analysis of RC structures under earthquake and fire in its current state", *in Proceedings* of the 12th Asia-Oceania Symposium on Fire Science and Technology (AOSFST), The University of Queensland, Brisbane, Australia.
3. **Baheti, A.**, Lange, D., and Matsagar, V. (2022). "A study to determine suitable and robust intensity measures for reinforced concrete slab subjected to fire", *in Proceedings* of the 12th International Conference on Structures in Fire (SiF), 1219-1229, The Hong Kong Polytechnic University, Hong Kong.
4. **Baheti, A.**, Lange, D., and Matsagar, V. (2024). "Efficient and reliable fire risk assessment of RC column", *in Proceedings* of the 13th International Conference on Structures in Fire (SiF), University of Coimbra, Portugal.

Submitted manuscripts included in this thesis

1. **Baheti, A.**, Lange, D., and Matsagar, V. "A framework to determine appropriate intensity measures for a structure subjected to fire", *Structural Safety* (*under review*).
2. **Baheti, A.**, Lange, D., and Matsagar, V. "Appropriate fire intensity measures for RC beam and column", *Engineering Structures* (*under review*).
3. **Baheti, A.**, Lange, D., and Matsagar, V. "Service-life multi-hazard risk assessment of structures: framework and application", *Structure and Infrastructure Engineering* (*under review*).

Other publications during candidature

- **Baheti, A. S.**, and Matsagar, V. A. (2022). "Wind and seismic response control of dynamically similar adjacent buildings connected using magneto-rheological dampers", *Infrastructures*, 7(12), 167.
- Bhaskar, P., **Baheti, A.**, and Matsagar, V. (2022). "Service-life damage assessment of a reinforced concrete structure under multi-hazard seismic and wind actions", *Transactions of the Indian National Academy of Engineering*, 7(3), 1017-1031.

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Contributions by others to the thesis

All chapters

Editorial suggestions were provided by the candidate's supervisors, Prof. Vasant Matsagar and Prof. David Lange, and the ASMC members, Prof. Puneet Mahajan, Prof. Dipti Ranjan Sahoo, and Prof. Joe Gattas.

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

No animal or human subjects were involved in this research.

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Keywords

service-life assessment, reinforced concrete, earthquake, fire, corrosion, fire fragility analysis; performance-based fire design, regression equations, member deflection in fire, nonlinear structural analysis.

Australian and New Zealand standard research classifications (ANZSRC)

ANZSRC code: 400506, Earthquake Engineering, 10%

ANZSRC code: 400507, Fire Safety Engineering, 70%

ANZSRC code: 401005, Risk Engineering, 20%

Fields of research (FoR) classification

FoR code: 4005, Civil Engineering, 80%

FoR code: 4010, Engineering Practice and Education, 20%

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List of Symbols

Various symbols that are consistent throughout the thesis are mentioned here. Certain local symbols defined only once for explaining a specific theory or equation, e.g., symbols *B*, *C*, *D*, used in Equation 1.1, are omitted from the list.

Latin symbols

A_{st}	Area of steel reinforcement
b	Member width
c	Concrete cover thickness or clear cover to reinforcement
D	Member depth
D_a	Chloride diffusion coefficient
DI	Damage index
dp300	300 °C isotherm depth
d_r	Reduced diameter of the steel reinforcement bar
dt	Time step
E	Young's modulus
f_c	Core concrete strength
f_{ck}	Characteristic compressive strength of concrete
f_d	Fire load density
f_r	Load ratio
f_y	Yield strength of steel reinforcement bar
H	Height
h	Convection heat transfer coefficient
I	Second moment of area
k	Stiffness
L	Length
M	Moment
m	mass
O	Opening factor
ø	Reinforcement bar diameter
P	Concentrated force

P_f	Probability of failure
Q	Energy
$\dot{q}''_{net}$	Net heat flux
R	Pearson's correlation coefficient
RS	Relative sufficiency
s_f	Fire spread rate
T	Temperature
T_a	Ambient air temperature
T_g	Gas temperature
$T_{r,avg}$	Average reinforcement bar temperature
t	Time
V	Base shear
W	Plan width
w	Uniformly distributed load
w_{cr}	Surface crack width
y	Practicality
Z	Decision variable

Greek symbols

$\beta_{EDP\|IM}$	Efficiency
δ	Member deflection
$\dot{\delta}$	Rate of deflection
ε	Emissivity
ε_c	Concrete strain
ϕ	Hazard risk
λ	Hazard intensity
ρ	Performance index
σ	Stefan-Boltzmann constant
ω	Natural frequency
ξ	Damping ratio
$\xi_{EDP\|IM}$	Proficiency

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List of Abbreviations

AUC	Area under time-temperature curve
CA	Cloud analysis
CIR	Cumulative incident radiation
DL	Dead load
DS	Damage state
DV	Damage variable
EDP	Engineering demand parameter
EDSF	Equivalent duration standard fire
EL	Earthquake load
FF	Fixed-fixed
HRR	Heat release rate
IM	Intensity measure
IS	Indian Standard
iTFM	Improved travelling fire methodology
LCFF	Large compartment fire framework
LL	Live load
MSA	Multiple stripe analysis
OPC	Ordinary Portland cement
PBSD	Performance-based structural design
PC	Propped cantilever
PEER	Pacific Earthquake Engineering Research
PF	Parametric fire
PGA	Peak ground acceleration
PL	Point load
RC	Reinforced concrete
RRMSE	Relative root mean squared error
SS	Simply supported
typ.	Typical (same value at similar locations)
UDL	Uniformly distributed load
WL	Wind load