DEVELOPMENT, IMPLEMENTATION, AND VALIDATION OF HYBRID TESTING METHODS FOR STRUCTURES SUBJECTED TO FIRE AND EARTHQUAKE LOADINGS

by

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Submitted
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CERTIFICATE

This is to certify that the thesis entitled, *"**Development, implementation, and validation of hybrid testing methods for structures subjected to fire and earthquake loadings**"* being submitted by ***Saurabh Sharma*** to the Indian Institute of Technology Delhi, for the award of the degree of ***Doctor of Philosophy*** is a bona fide record of research work carried out by him under my supervision and guidance. The thesis, in my opinion, has reached the requisite standard, fulfilling the requirements for the award of the degree of *Doctor of Philosophy.*

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.

Prof. Dipti Ranjan Sahoo
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The journey I embarked upon to complete the research presented in this thesis is understood by very few. To successfully carry out this work, I had to dive deeply into not just Civil Engineering, but a wide range of disciplines, including control theory, computer science, electronics, signal processing, electro-mechanical systems, hydraulic systems, and many more. From the very beginning, the research demanded countless hours of diagnostics, debugging, trial and error, and the constant repetition of these processes (often in parallel) to learn these concepts from scratch and apply them effectively. For this, I would like to express my deepest gratitude to the people in my life who guided, helped, and supported me every step of the way.

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I dedicate this thesis to my family, for without their love, sacrifices, and encouragement, this journey would not have been possible.

ABSTRACT

Advanced testing methods such as Hybrid Simulation have proven to be more affordable, reliable and repeatable to full scale global structural testing while providing greater accuracy than traditional testing of individual components. Hence, the primary objective of this study was to develop Hybrid Simulation methods in the Heavy structures Laboratory (HSL) of Indian Institute of Technology Delhi (IITD) for structures subjected to fire and seismic loads. Two different frameworks were developed for each hazard.

The hybrid fire testing framework was developed using NICON (Zhan and Kwon, 2015) as a middleware applied to a standard fire testing setup developed in HSL to perform compression testing of a steel specimen subjected to elevated temperatures. A set of custom extension rods were fabricated out of Inconel 713c alloy to prevent heat transfer beyond the specimen and maintain the axial stiffness of the loading frame under elevated temperatures. The hybrid fire simulation method was implemented to experimentally simulate a steel column subjected to fire under axial stress and constraints imposed by the rest of the structure and generate demand-capacity curves for the same using 9 sets of initial stress and 4 sets of axial constraint levels. A set of 48 standard compression tests were performed at regular temperature intervals up to 800 °C, to obtain the capacity curves for steel specimens with three different design slenderness values. Various diagnostic tests were performed to evaluate the sources of errors that could arise in the experimental and numerical setups. As evident from the results obtained, accurate tracking of the specimen displacement under elevated temperatures proved to be inconsistent and unreliable due to relatively high axial stiffness of specimen as compared to the test setup. Hence, a model based elastic and thermal compensation strategy was developed based on the performance of the experimental setup under standard compression testing. The performance of the compensation scheme was validated using virtual hybrid simulation followed by 36 hybrid fire simulation tests to obtain the demand generated on the specimen subjected to temperatures up to 800 °C, as per the parameters defined in the numerical model. The demand-capacity curves obtained experimentally accurately predicted the Demand-Capacity curves proposed by Wang et al. (2021).

Next, a Real Time Hybrid Simulation (RTHS) method was implemented using a real time controller implemented on a Simulink-Real Time operating system. Dynamic hydraulic equipment was configured, purchased and diagnosed for testing specimens under high-speed cyclic loading up to 3 Hz. An elastic single degree of freedom (SDOF) experiment test setup was developed in the lab to act as the experimental sub-structure for performing setup and framework diagnostic tests to understand its performance under real-time earthquake excitation. The SDOF system was tested using the RTHS framework by simulating four sets of natural frequency of vibration, while evaluating the sources of errors and implementing solutions for the same. Tests were conducted at extended timescale (Slow Hybrid Simulation (SHS)), real timescale (RTHS) and reduced timescale (Rapid Hybrid Simulation (RHS) of the El Centro ground motion time-history. A detailed study of actuator delay in the hydraulic system was carried out using virtual hybrid simulation and used for finalizing the parameters for Advanced FeedForward Compensation Scheme (AFC) scheme, which was validated using RTHS tests. The RTHS framework was calibrated, tuned and validated for further studies to be implemented for non-linear SDOF and MDOF structures.

In the end, both Hybrid Fire and Real Time Hybrid simulation frameworks, developed for use in the HSL at IITD, were successfully implemented and validated by incorporating standard test equipment in a hardware-in-loop setup for advanced structural testing.

सारांश

उन्नत परीक्षण विधियाँ, जैसे कि सम्मिलित अनुकरण (हाइब्रिड सिमुलेशन), पारंपरिक व्यक्तिगत घटकों के परीक्षण की तुलना में अधिक सटीकता प्रदान करते हुए पूर्ण पैमाने पर वैश्विक संरचनात्मक परीक्षण की तुलना में अधिक किफायती, विश्वसनीय और दोहराने योग्य सिद्ध हुई हैं। इसी कारण, इस अध्ययन का उद्देश्य भारतीय प्रौद्योगिकी संस्थान दिल्ली (आई.आई.टी. दिल्ली) की हेवी स्ट्रक्चर्स प्रयोगशाला (एच.एस.एल.) में अग्नि एवं भूकंपीय भारों के अधीन संरचनाओं के लिए हाइब्रिड सिमुलेशन विधियों का विकास करना था। अग्नि और भूकंप, दोनों के लिए स्वतंत्र ढाँचों का निर्माण किया गया।

हाइब्रिड अग्नि परीक्षण ढाँचा निकॉन (एन.आई.सी.ओ.एन.) मिडलवेयर (झान और क्रॉन, २०१५) का उपयोग कर विकसित किया गया, जिसे एच.एस.एल. में मौजूद एक मानक अग्नि परीक्षण संयंत्र में लागू किया गया। इसका उद्देश्य उच्च तापमानों पर एक इस्पात नमूने के संपीड़न व्यवहार को समझना था। इनकोनेल ७१३सी मिश्रधातु से बने विशेष विस्तार रॉड ऊष्मा को नियंत्रित करने और लोडिंग फ्रेम की कठोरता बनाए रखने के लिए उपयोग में लाए गए। प्रयोग में एक इस्पाती स्तंभ को अग्नि और संरचना द्वारा लगाए गए प्रतिबंधों के अधीन विषय बनाया गया, और ९ प्रारंभिक तनाव स्तरों तथा ४ प्रतिबंध स्तरों के साथ माँग-क्षमता वक्र तैयार किए गए।

३ भिन्न डिज़ाइन स्लेंडरनेस वाले नमूनों के लिए कुल ४८ संपीड़न परीक्षण किए गए, जिनमें तापमान को क्रमशः ८०० डिग्री सेल्सियस तक बढ़ाया गया। परीक्षणों के दौरान विस्थापन को सटीकता से मापने में समस्याएँ आईं, जो नमूने की अधिक कठोरता के कारण उत्पन्न हुईं। इस चुनौती का समाधान एक मॉडल-आधारित प्रत्यास्थ और ऊष्मीय क्षतिपूर्ति रणनीति द्वारा किया गया, जिसे पहले वर्चुअल अनुकरण और फिर ३६ प्रयोगात्मक हाइब्रिड अग्नि परीक्षणों से सत्यापित

किया गया। प्राप्त माँग-क्षमता वक्र, वांग और उनके सहयोगियों (२०२१) द्वारा प्रस्तावित सैद्धांतिक वक्रों से मेल खाते हैं।

भूकंपीय परीक्षणों के लिए, रियल टाइम हाइब्रिड सिमुलेशन (आर.टी.एच.एस.) को सिमुलिंक–रियल टाइम प्लेटफॉर्म पर विकसित रियल टाइम नियंत्रक के माध्यम से लागू किया गया। इसके लिए तीन हर्ट्ज़ तक की उच्च गति चक्रीय लोडिंग हेतु डायनामिक हाइड्रोलिक उपकरण खरीदे और परीक्षण किए गए। एक प्रत्यास्थ एकल-अवयवी स्वतंत्रता प्रणाली (एस.डी.ओ.एफ.) को प्रयोगात्मक ढाँचे के रूप में उपयोग किया गया। इस प्रणाली का परीक्षण चार प्राकृतिक कंपन आवृत्तियों पर किया गया, जिससे प्रणाली के व्यवहार, त्रुटियों के स्रोत और समाधान को समझा जा सके।

एल सेंट्रो भूकंपीय डेटा का उपयोग करते हुए परीक्षण विस्तारित समयमान (एस.एच.एस.), वास्तविक समयमान (आर.टी.एच.एस.) और संक्षिप्त समयमान (आर.एच.एस.) में किए गए। अधिनियंत्रक की देरी का विश्लेषण वर्चुअल हाइब्रिड अनुकरण द्वारा किया गया और उसी के आधार पर एक उन्नत अग्र-प्रतिक्रिया क्षतिपूर्ति योजना (ए.एफ.सी.) तैयार की गई, जिसे आर.टी.एच.एस. परीक्षणों द्वारा सत्यापित किया गया। इस पूरी प्रणाली को आगे जटिल गैर-रेखीय एस.डी.ओ.एफ. और एम.डी.ओ.एफ. संरचनाओं पर लागू करने हेतु समायोजित और प्रमाणित किया गया।

अंततः, आई.आई.टी. दिल्ली की हेवी स्ट्रक्चर्स प्रयोगशाला में विकसित दोनों ढाँचों – हाइब्रिड अग्नि अनुकरण और रियल टाइम हाइब्रिड अनुकरण – को हार्डवेयर-इन-लूप प्रणाली के साथ सफलतापूर्वक कार्यान्वित और मान्य किया गया।

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ABBREVIATIONS

The following symbols are used in the paper:

Latin lower-case italic

f_n = Natural frequency of vibration

$k_E(T)$ = Reduction factor for the modulus of elasticity at a uniform temperature 'T';

$k_y(T)$ = Yield stress reduction factor for steel at a uniform temperature 'T';

r = Radius of gyration in the weaker axis;

$u_{c,n}$ = Displacement of the column restricted by the axial constraint at n^{th} time-step;

$u_{s,n}$ = Displacement of numerical spring representing axial constraint at n^{th} time-step;

$u_{th,n}$ = Free thermal expansion of the column at n^{th} time-step;

u_{th_setup} = Thermal expansion of the setup at n^{th} time-step;

t = Thickness;

tol = Tolerance;

Latin upper-case italic

A = Cross-sectional area of the member;

E_0 = Young's modulus of elasticity of the material at ambient temperature;

$E_{c,0}$ = Modulus of elasticity of column at ambient temperature;

$E(T)$ = Modulus of elasticity for structural steel at temperature 'T';

$F_{c,n}$ = Force generated in the column;

$F_{s,n}$ = Force generated in the numerical spring;

F_{spec} = Force on the specimen;

F_{sys} = Force on the system;

G = Applied gravity load;

K = Effective length factor;

$K_{c,0}$ = Initial stiffness of the column under investigation at ambient temperature;

K_s = Stiffness of the numerical spring;

K_{setup} = Setup stiffness;

K_{spec} = Specimen stiffness;

K_{sys} = System stiffness;

$P_{cr}(T)$ = Critical buckling strength of the compression member at a temperature 'T';

$P_D(T)$ = Design compressive strength in at temperature 'T';

T = Temperature of the column;

T_n = Period of vibration of a structure;

Latin upper-case

CMF = Current measured force;

CMS = Current measured stroke;

CSD = Current specimen displacement;

CTD = Current target displacement;

CTS = Current target stroke;

D = Depth;

H = Height;

L = Length of the member;

TEF = Target elastic force;

T_n = Temperature at n^{th} time-step;

W = Width;

Greek lower-case

α = Imperfection factor;

α_{T_n} = Coefficient of thermal expansion at temperature T_n;

β = Severity factor;

$\gamma_M(T)$ = Partial safety factor for material,

$\varepsilon_{c,n}$ = Strain induced in the column restricted by the axial constraint;

$\varepsilon_{th,n}$ = Strain induced in the column under to free thermal expansion;

$\varepsilon_{p,n}$ = Strain at the proportional limit for temperature at nth time-step;

η = Initial imperfection factor (Maquoi and Rondal, 1978);

$\bar{\lambda}(T)$ = Non-dimensional slenderness of the column, at temperature *'T'*;

μV = Microvolts;

$\bar{\sigma}_{c,n}$, $\sigma_{c,n}'$ = Stress developed in the column due to temperature at nth time-step;

σ_{ini} = Initial stress on the column under *G*.

σ_{max} = Ultimate stress in the member at ambient temperature;

$\sigma_{p,n}$ = Stress at the proportional limit for temperature at nth time-step;

$\sigma_y(T)$ = Yield stress at a temperature '*T';*

$\sigma_{y,n}$ = Yield stress for temperature at nth time-step;

$\sigma_{y,0}$ = Yield stress at ambient temperature;

ø = Stiffness ratio;

$\chi(T)$ = Strength reduction factor to account for flexural inelastic buckling at temperature '*T'*;

ω_n = Angular frequency of vibration,

Greek upper-case

Δ = Delta;

Ω = Ohms;

Scientific lower-case

cm = centimetre;

kN = kilonewton;

kW = kilowatts;

lpm = litres per minute;

min = minutes;

mm = millimetre;

mV = millivolts;

psi = pounds per square inch;

Scientific upper-case

AC = Alternating current;

Al = Aluminium;

C = Carbon;

Cr = Chromium;

Cu = Copper;

°C = Degree centigrade;

DC = Direct current;

Fe = Iron;

GHz = Gigahertz;

Hz = Hertz;

K = Kelvin;

Mo = Molybdenum;

Mn = Manganese;

MS/s = Million samples per second;

Nb = Niobium;

N = Newton;

Ni = Nickel;

Si = Silicon;

Ti = Titanium;

V = Volt;

W/mK = Watt per meter kelvin;

Zr = Zirconium.