WORKSHOP ON ADVANCEMENTS IN EVALUATING THE FIRE RESISTANCE OF STRUCTURES

BOOK OF ABSTRACTS

December 6-7, 2018

Washington, DC, USA

Sponsored by ASTM Committee E05 on Fire Standards

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WORKSHOP ON ADVANCEMENTS IN EVALUATING THE FIRE RESISTANCE OF STRUCTURES

Sponsored by ASTM Committee E05 on Fire Standards

December 6-7, 2018
Washington Hilton
Washington, DC, USA

Workshop Chairs:

John Gales
York University
Toronto, ON

Rodney Bryant
NIST
Gaithersburg, MD

Elizabeth Weckman
University of Waterloo
Waterloo, ON

Marc Janssens
Southwest Research Institute
San Antonio, TX

THURSDAY, DECEMBER 6, 2018

1:00 PM
Opening Remarks
John Gales, York University

1:05 PM
Tibor Harmathy's Contribution to the Provision of the Adequate Fire Resistance of Structures
Jim Mehaffey, CHMfire Consultants Ltd.

SESSION 1: EXAMINING FIRE RESISTANCE PRINCIPALS

1:30 PM
Comparative Energy Analysis of Fire Resistance Tests on Combustible Versus Non-Combustible Slabs
Alastair Bartlett and Luke Bisby, University of Edinburgh; Fabienne Robert and Christiane Rottier, CERIB; Robert Jansson McNamee, Brandskyddslaget

1:55 PM
Producing Design Fires in a Furnace for Fire Resistance Testing
Laura Hasburgh, Keith Bourne, and Samuel Zelinka Forest Products Laboratory; Donald Stone, University of Wisconsin

2:20 PM
The Discrepancy of Energy Balance in Furnace Testing, a Bug or a Feature?
Wojciech Węgrzyński and Piotr Turkowski, Building Research Institute

2:45 PM BREAK

3:15 PM
Re-Examination of 'Restrained Vs. Unrestrained'
Kevin LaMalva, SGH, USA; Jose Torero, University of Maryland; Luke Bisby, University of Edinburgh; Thomas Gernay, John Hopkins University; Robert Solomon, NFPA; Ali Morovat, University of Texas at Austin; Cliff Jones, Protection Engineering Consultants; Eli Hantouche, American University of Beirut

SESSION 2: STEEL AND COMPOSITE

3:40 PM
Fire Resistance of Cold-Formed Steel Framed Shear Walls Under Various Fire Scenarios
Blanca Andres, Danish Institute of Standards and Security Technology, Denmark; Matthew Hoehler and Matthew Bundy, NIST

4:05 PM
Modeling the Fire Resistance Performance of Floor Ceiling Assemblies
Kuldeep Prasad and Morgan Burns, NIST; Suman Sinha Ray, Naveen Punati, and Kumar Natesaiyer, USG Corporation

4:30 PM
A Need for Standardized Test Methods for Characterizing Properties of Concrete at Elevated Temperatures
Venkatesh Kodur, S. Banerji, and R. Solhmirzae, Michigan State University

4:55 PM
Evaluation of Standard and Real Fire Exposures to Predict the Temperature Response of a Railcar Floor Assembly
Anil Kapahi, Mark McKinnon, and Brian Lattimer, Jensen Hughes

5:20 PM
Closing Remarks
Rodney Bryant, NIST

5:30 PM RECEPTION AND POSTER SESSION

FRIDAY, DECEMBER 7, 2018

SESSION 3: COMPUTATIONAL STUDIES

8:00 AM
Opening Remarks
John Gales, York University

8:05 AM
Best Practices for Modeling Structural Boundary Conditions Due to a Localized Fire Using a Coupled CFD-FE Approach
Alyssa Desimone and Ann Jeffers, University of Michigan

8:30 AM
Methodology of Hybrid Fire Tests
David Lau, Zhimeng Yu, and Jeffrey Erochko, Carleton University

8:55 AM
An Extended Travelling Fire Method Framework for Performance-Based Structural Design
Xu Dai and Stephen Welch, University of Edinburgh; Asif Usmani, Hong Kong Polytechnic

9:20 AM
Defining the Near-Field and Flame Extension under the Ceiling for Travelling Fires Inside Very Large Compartments
Mohammad Heiadri and Guillermo Rein, Imperial College; Panos Kostivinos, Arup

9:45 AM BREAK

SESSION 4: CONCRETE AND TIMBER

10:15 AM
Development of Simulation Approach for Fire and Structure Interaction of Concrete Highway Bridges
Biswajit Dasgupta, Marc Janssens, and Debashis Basu, SWRI

10:40 AM
Improved Calculation of Fire Resistance of Composite Slabs
Jian Jiang, Adam Pintar, Fahim Sadek, Joseph A. Main, and Jonathan M. Weigand, NIST

11:05 AM
A New Method for Testing Wall Systems Exposed to Real Fire Environments
Jennifer Ellingham, Bronwyn Forrest, Elizabeth J. Weckman, and Haemi Pollett, University of Waterloo

11:30 AM
Experimental Research on the Fire Performance of Glulam Beam-to-Beam Doweled Steel Connections for Tall Timber Structures
MiIlad Shabanian, Nicole Braxton, and Aixi Zhou, UNCC

11:55 AM
A Time-Equivalence Methodology for Exposed Mass Timber Structural Elements
Robert Dixon, Arup, Australia; and David Barber, Arup

12:15 PM
Closing Remarks
John Gales, York University

12:20 PM WORKSHOP ADJOURNS

12:45 PM BUS DEPARTS FOR NIST TOUR

3:30 PM NIST TOUR COMPLETE – BUS DEPARTS FOR WASHINGTON HILTON

POSTERS

Probabilistic strength retention factors for steel and concrete and effect on structural reliability of columns in fire

Negar Elhami Khorasani, University at Buffalo NY; Thomas Gernay, Johns Hopkins University; Alex Stephani, University at Buffalo NY; Ruben Van Coile, University of Ghent; and Danny Hopkin, OFR Consultants

Design of a test fire for large-scale fire tests on a long span steel-concrete composite beam

Chao Zhang, William Grosshandler and Lisa Choe, National Institute of Standards and Technology

Screening tests of fire spalling behavior of ring restrined high-strength concrete during fire

Mitsuo Ozawa, Gunma University; Toru Tanibe, Taiheiyo Materials; and Manabu Kanematsu, Tokyo University of Science

Methods to achieve self-extinguishment for high-rise mass timber buildings

Daniel Brandon, Research Institutes of Sweden; David Barber, ARUP North America

Compartment fire experiments of composite floor beam assemblies

Selvarajah Ramesh, Lisa Choe, Mina Seif, Matthew S. Hoehler, and Matthew Bundy, National Institute of Standards and Technology

Case Study: Using Performance-Based Structural Fire Engineering to Determine the Progressive collapse mechanisms of steel-frame buildings due to moving fires

Erica C. Fischer, Oregon State University; Amit H. Varma, Purdue University

Simplified Calculation Procedure for Evaluating the Fire Resistance of Reinforced Concrete Walls

Duc Toan Pham, Romain Mege, Université Paris-Est, Centre Scientifique et Technique du Bâtiment (CSTB)

Assessment of Tall Buildings Subjected to Multi-storey Fires

Panagiotis Kotsovinos, Graeme Flint, Yavor Panev and Peter Woodburn,Arup, United Kingdom

ABSTRACTS

COMPARATIVE ENERGY ANALYSIS OF FIRE RESISTANCE TESTS ON COMBUSTIBLE VERSUS NON-COMBUSTIBLE SLABS

Alastair I. Bartlett[1], Fabienne Robert[2], Christiane Rottier[2], Robert Jansson McNamee[3] & Luke A. Bisby[1]
School of Engineering, The University of Edinburgh, United Kingdom [1]
CERIB, France [2]
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Introduction and Background

For the past century, standard fire resistance tests such as ASTM E119 [1] and ISO 834 [2] have formed the foundation of prevailing structural fire engineering approaches. Fire safety regulations and guidance internationally typically prescribe required "fire resistance periods" for structural building elements – this is assessed as the length of time that an element is able to withstand exposure to a standard temperature-time curve within the fire testing furnace. Despite significant advances in fire science and engineering during recent decades, these standard fire resistance assessments and requirements remain fundamentally unchanged although from initially the furnace pressure was not regulated and in recent years the ISO 834 [2] requires that the furnace be controlled using plate thermometers.

Structural engineered timber elements (such as cross-laminated timber (CLT) or glued-laminated timber) are becoming increasingly used in construction. Since timber is combustible, upon exposure to sufficient heat it is able to ignite and burn, contributing additional energy to a fire. This raises a number of relevant questions regarding the applicability of the conventional 'standard fire resistance' testing regime for assessing structural fire hazards associated with combustible building materials and systems. This paper explores the implications of any additional energy contributions on standard fire-resistance testing conditions and outcomes for both combustible (CLT) and non-combustible (concrete) materials.

Experimental Programme

Two essentially identical standard fire resistance (furnace) tests were carried out in a floor furnace according to the ISO 834 [2] temperature-time curve; one on an exposed CLT slab, and one on a reinforced concrete slab. Both were 5.9 m x 3.9 m in plan, whereas the concrete slab had a thickness of 0.180 m, and the CLT slab 0.165 m. These thicknesses were selected to ensure that the respective slabs were as representative as possible of those that would exist in practice in comparable real buildings.

Oxygen, carbon dioxide, and carbon monoxide were measured in the furnace exhaust to allow gas analyses. Exhaust flow velocities and temperatures were also measured, as was the rate of furnace fuel supplied (natural gas in this case) to the furnace to allow a direct analysis of the differences in fuel consumption when testing different materials in this particular configuration.

The time-history of natural gas consumption required to produce the standard temperature time curve within the furnace (measured by plate thermometers according to ISO 834 [2]]) during the two tests is shown in Figure 1 for the first 120 minutes. The test on concrete used almost three times as much natural gas than the test on exposed CLT, despite the same furnace temperature being recorded in both tests. Using these data, the energy released inside the furnace can be approximated.

The energy supplied in a furnace comes from one of two main sources: (1) the natural gas burners, and (2) combustion of pyrolysis products from the test sample. The energy contribution from the burners can be calculated from the mass flow rate and the heat of combustion of the fuel (assuming complete combustion within the furnace control volume), giving the heat release rates (HRRs) from natural gas shown in Figure 1. Major differences exist in the external energy provided when testing a concrete slab compared to a CLT slab according to ISO 834 in a floor test configuration.

Calorimetry Analyses

Using the CO and CO_2 concentrations measured in the exhaust, the total HRR (i.e. from natural gas and test sample) can be approximated using carbon dioxide generation (CDG) calorimetry [3]. This yields the results in Figure 1 for the test on CLT. The additional energy comes from burning of the CLT panel itself, and thus the HRR contribution from the timber is included in Figure 1. In this case the timber is estimated to contribute around 2-2.5 MW of additional energy, and thus the total heat release rate is similar to that provided by the burners in the furnace test on concrete (refer to Figure 1).

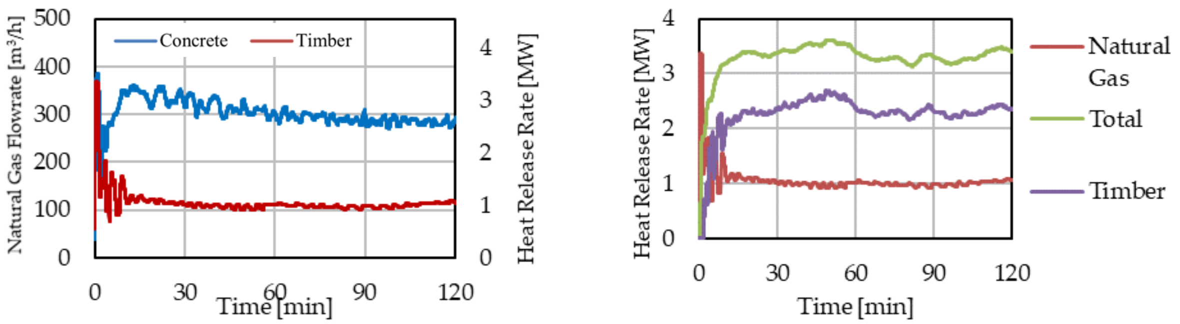

Figure 1. Left: natural gas consumption recorded in furnace tests on a concrete slab and a cross-laminated timber slab and calculated energy contribution from natural gas in each test (assuming complete combustion within the furnace); right: comparison of total HRR (from CDG), and contributions from natural gas and timber for CLT furnace test.

Discussion

The results presented above show that the two different materials tested under the 'same' temperature versus time curves within a standard fire testing furnace do not experience the same energy input if the quantity of fuel available to the 'fire' is used as the comparative metric; (as would be the case in a real building where a fire occurs based on physics, rather than by explicit control of fuel supply). In the case presented herein, the exposed CLT slab is exposed to a ~1 MW 'external' energy source, whereas the concrete sample is exposed to a ~3 MW external energy source. Additional energy contributions from the burning timber (most significantly), as well as differences in thermal inertia of the two materials, resulting in the same furnace temperature being measured by the plate thermometers used to control the supply of natural gas.

This observation may have profound implications for the fire resistance design of both encapsulated and unprotected mass timber elements as when testing combustible materials, they may continue burning without added fuel. Implicit in the traditional fire resistance ratings conventionally required for most building elements is the ability to withstand burnout of the fuel load within the compartment of origin [4]. In the case when the structure itself continues to burn, the traditional fire resistance rating may have little meaning. Fire safety engineering professionals therefore ought to explicitly consider the implications of the above for the fire resistance design of structures that incorporate combustible structural elements, in order to ensure that both explicit (i.e. regulated) and implicit (i.e. expected/perceived) performance objectives in case of fire are openly discussed, and subsequently addressed, by their designs.

References

1. ASTM. ASTM E 119 Standard Test Methods for Fire Tests of Building Construction and Materials. In. West Conshohocken, PA: ASTM International; 2014.
2. ISO. ISO 834-1: Fire resistance tests. Elements of building construction. In. *Part 1: General Requirements.* Geneva, Switzerland: Internatinal Organisation for Standardization; 1999.
3. Tewarson A. Generation of heat and chemical compounds in fires. *SFPE handbook of fire protection engineering.* 2002;3:83-161.
4. Thomas PH. *The Fire Resistance Required to Survive a Burnout.* 1970.

PRODUCING DESIGN FIRES IN A FURNACE FOR FIRE RESISTANCE TESTING

Laura E. Hasburgh[1], Keith J. Bourne[1], Donald S. Stone[2], Samuel L. Zelinka[1]

US Forest Products Laboratory, 1 Gifford Pinchot Drive, Madison, WI 53726, USA [1]
Materials Science and Engineering, University of Wisconsin, 1509 University Ave, Madison, WI 53706 [2]

KEYWORDS: fire resistance, design fire scenario, full-scale fire test, timber construction, fire performance

Introduction

In the United States, wood has been traditionally used in single- and multi-residential construction. However, the combustibility of wood still limits its use as a building material via restrictions found in the prescriptive building codes for building characteristics like height, area, and interior and exterior finishes. To overcome the limitations, performance-based codes can be used and allow for more design flexibility and innovation. In order to properly analyse performance-based designs, more information on the fire performance of materials is required, including the fire resistance under different design fire exposures.

Fire resistance is a measure of the ability to resist collapse or other failure during exposure to a fire.[1] To obtain the fire resistance ratings of structural members and assemblies, wood-based or otherwise, assemblies have traditionally been tested in accordance with ASTM International (ASTM) E119, *Standard Test Methods for Fire Tests of Building Construction and Materials* [2] and similar standards. Among other things, ASTM E119 specifies a time-temperature curve known as the "standard fire" that the furnace needs to achieve. For structural wood components, char rates under the standard fire exposure are well documented and, for practical purposes, a commonly assumed nominal char rate of 0.6 mm/min is used for all exposed wood members in the absence of other data.[3]

While the char rates have been well characterized for the standard fire, much less is known about the rate of char formation under other time-temperature curves. It is known that char rate is significantly affected by the severity of the fire exposure and data on charring rates for non-standard fire exposures have been limited.[3] This lack of information on char rates under these conditions makes it difficult to perform fire resistance calculations under non-standard fires. Recently, several full-scale fire tests on mass timber compartments have occurred and the compartment temperatures obtained. From these full-scale tests a vast amount of data was collected, including real time-temperature curves. Here we present the experimental considerations and initial results of running design fire curves, based on the real fire curves, in an intermediate scale furnace.

Materials and Methodology

Fire Curves

In addition to the standard fire defined in ASTM E119, two design fire curves were chosen for this study. The design fires were based on real fire curves obtained from full-scale fire tests of CLT structures. The first design fire curve was based on Test 3 of the Tall Wood Building (TWB) Fire Tests. Test 3 of this series was a full scale fire test of a cross-laminated timber (CLT) structure with one exposed wall.[4] The second design fire curve was based on two time-temperature curves obtained from tests conducted by Li, et al. on a single room (noted as "Room"). The growth and fully developed phases were from Test 3, a fully exposed CLT room, and the decay phase was from Test 7, a room with one exposed CLT wall.[5] Due to equipment limitations, the real fire curves were followed as closely as possible with the resulting design fire curves provided in Figure 1.

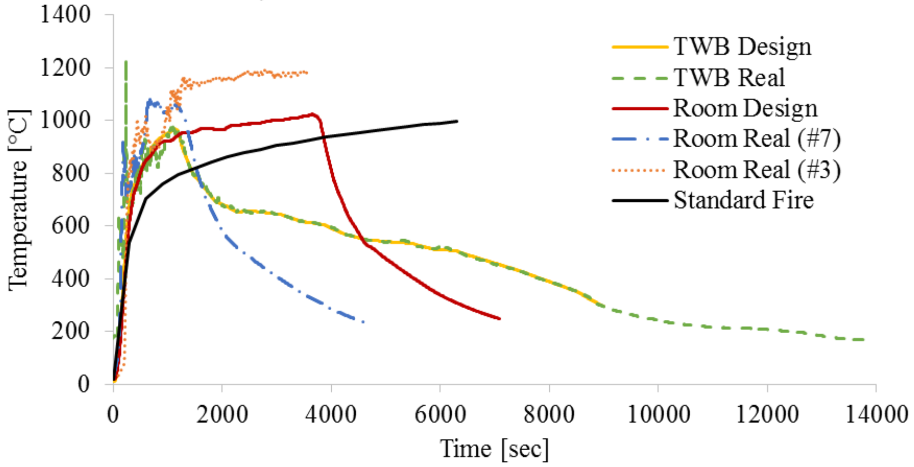

Figure 1. Comparison of real fire curves and the design fire curves tested.

Instrumentation

The design fire curves were tested on the Forest Products Laboratory's intermediate scale furnace which has interior dimensions of approximately 1.1 m wide by 1.8 m long by 1.3 m tall. The furnace temperature is measured by protected thermocouples as described in ASTM E119. The flow rate of the natural gas that supplies the furnaces 8 diffusion flame burners was measured with a mass flow meter (Fox Flow Meter, FT2A-06IE-SS-E2-B0-G3). Wood specimens that were approximately 413 mm square and 83 mm deep had thermocouples installed at various depths to track the char front during each test. The specimens were held on top of the furnace in an insulated rack, in a setup similar to a floor/ceiling test, but without external loading. Additionally, two water cooled heat flux sensors (Huskeflux, SBG01) were installed in two different specimens in each test. The location of the meters varied to determine the effect of location within the furnace on the heat flux incident on each specimen.

Results and Discussion

The results of the fuel consumption for tests with a non-combustible lid when compared to the results with combustible wood inserts will be explored. Additionally, the results of heat flux in the furnace compared to the heat flux measured within the TWB Test 3 and the effect on the char rate of this difference will be discussed.

References

1. Buchanan AH. *Structural design for fire safety.* Vol 273: Wiley New York; 2001.
2. Anon. *ASTM E119 Standard Test Methods for Fire Tests of Building and Construction Materials.* West Conshohocken, PA: American Society for Testing and Materials; 2014.
3. White RH, Dietenberger MA. Fire Safety of Wood Construction. In: Ross RJ, ed. *Wood Handbook. Wood as an Engineering Material.*: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 2010.
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5. Li X, McGregor C, Medina A, Sun X, Barber D, Hadjisophocleous G. Real-scale fire tests on timber constructions. Paper presented at: Proceedings of the 14th World Conference on Timber Engineering, TU Wien2016.

The discrepancy of energy balance in furnace testing, a bug or a feature?

Piotr Turkowski [1], Wojciech Węgrzyński[1] & Paweł Roszkowski[1]
Building Research Institute (ITB), Warsaw, Poland [1]

Introduction

The paradigm of furnace testing – use of prescribed time-temperature profiles, inevitably leads to discrepancies of energy balance in the furnace between tests of various materials, as an effect of the most fundamental physical phenomena related to the conservation of energy and heat transfer between the furnace, and the sample. This factor is rarely taken into account during the assessment of product performance, as most of the standard measures of success refer to temperatures, integrity or load-bearing capacity. The energy supplied in the test furnace is disregarded. However, the differences in the heat transfer may play a significant role in a real fire that occurs in a compartment.

Methodology

This paper aims to present a statistical overview of 237 individual ISO-curve tests performed in one of ITB vertical test furnaces (3.70 x 3.70 m (W x H)). The furnace is methane-gas powered, and the maximum heat supply is 2.70 MW. The furnace is equipped with measurement devices for methane supply, which allows the determination of the heat release rate supplied with a 0.1 MW resolution. As this measurement is performed primarily for statistics/diagnostics, it is burdened with low resolutions and resulting considerable uncertainty. However, it seems sufficient to illustrate the basic differences between the samples. The temperature measurements are performed with plate-thermometers, according to EN 1363-1.

Relevance and conclusions of the study

Results of the study point to a glaring flaw of standardised fire testing, which is disregarding the energy balance to maintain the prescribed temperature of plate thermometers. To preserve the conservation of energy and maintain the required temperature, the furnace is allowed to adapt the fuel supply and ventilation rate freely. This adaptation may sometimes take an extreme form – supply of a large amount of heat in early test phase or overventilation of the furnace to cool it down, Figure 1. The most disturbing observations are made for combustible samples, as in many cases after ignition of the sample, the fuel supply to the furnace is limited or shut down entirely, for an extended period, to not exceed the ISO-curve requirements. A view of the interior of tests of the non-combustible and combustible sample is shown in Figure 2. Important observations were also made for penetration seal samples, which required significantly more heat towards the end of the test, compared to other materials.

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This paper aims to compare the heat supply over a large, statistically valid sample of furnace tests. The findings of this study indicate flaws in the fire testing procedures for some of the materials, which may have a significant impact on how fires develop in real buildings. These findings may be an essential point in the discussion on the future of standardized testing.

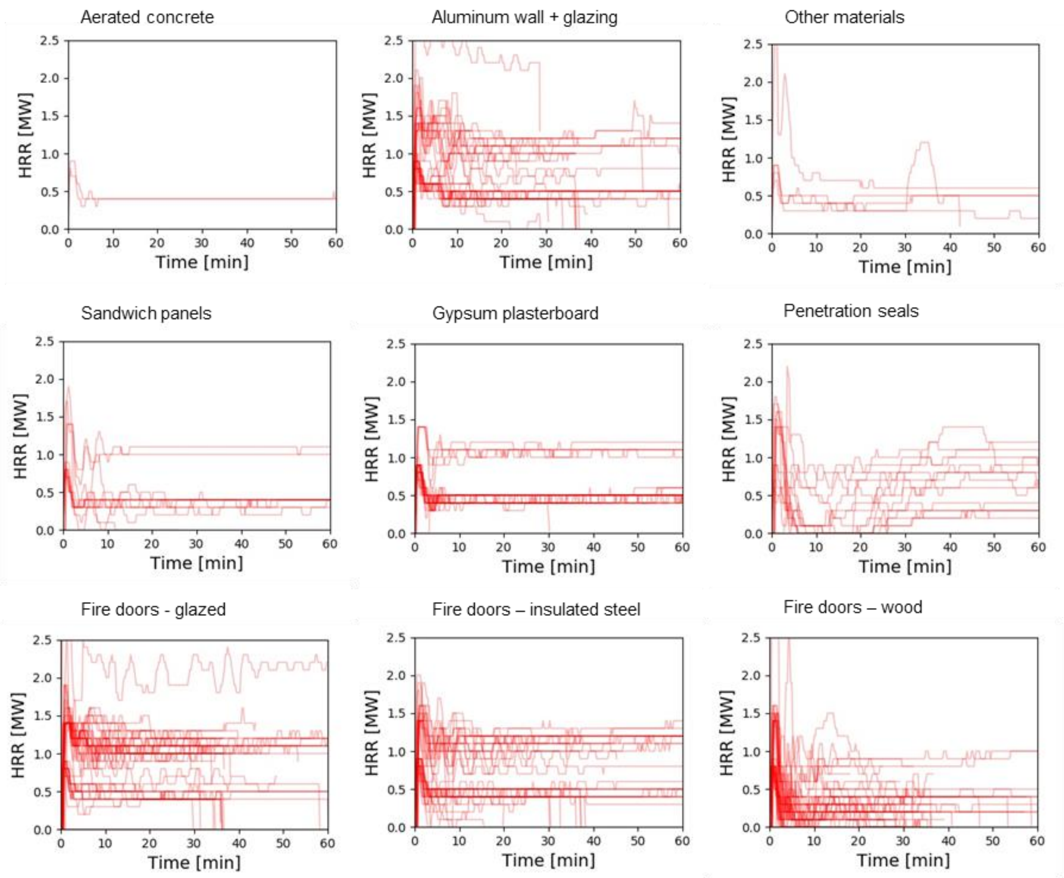

Figure 1. Heat Release Rate evolution in the furnace used to maintain ISO-834 conditions within the furnace for various groups of materials

Fig. 2. View of the test sample inside the furnace left picture – aluminium doors with fire-rated glazing, right picture – wooden doors. Flame visible in the picture indicates combustion of the sample material (furnace burner is visible in the lower right corner of the left picture)

REEXAMINATION OF 'RESTRAINED VS. UNRESTRAINED'

Kevin LaMalva [1], Luke Bisby [2], Thomas Gernay [3], Elie Hantouche [4], Cliff Jones [5], Ali Morovat [6], Robert Solomon [7] & Jose Torero [8]

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University of Edinburgh, UK [2]
Johns Hopkins University, USA [3]
American University of Beirut, LBN [4]
Jensen Hughes, USA [5]
University of Texas at Austin, USA [6]
National Fire Protection Association, USA [7]
University of Maryland, USA [8]

For furnace testing of fire resistant assemblies, ASTM E 119 (Standard Test Methods for Fire Tests of Building Construction and Materials) (and similarly UL 263) permits two boundary conditions: restrained and unrestrained. This distinction was first introduced in 1970, where an assembly is considered "restrained" if it bears directly against the edges of the furnace at the outset of the test and "unrestrained" when it is free to displace laterally (in plane) and is not confined by the furnace frame. Although included as an Annex rather than a mandatory provision in ASTM E119, U.S. based codes and testing protocols began to mandate use of this guidance in 1997 for structural assemblies. When incorporating tested systems into an actual structural system, the designer, oftentimes a fire protection or structural engineer, must judge whether a "restrained" or "unrestrained" classification is appropriate for the application. It is critical that this assumption be carefully considered and understood, as many qualified listings permit a lesser thickness of a given applied fire protection to achieve a certain fire resistance rating if a "restrained" classification is adopted, as compared to an "unrestrained" classification.

In actual building construction, restraint of structural assemblies occurs when the surrounding structural system resists their thermal expansion when exposed to heating. The effect of restraint must be carefully evaluated since it may dominate the behavior of a structural system under fire exposure. A multitude of factors influence restraint conditions (e.g., connection stiffness), and these factors may increase or decrease structural system endurance under fire exposure. For instance, restraint may generate forces sufficient to cause yielding or fracture of connections, perhaps precipitating structural collapse. Alternatively, restraint may limit the deflection of structural members and provide added stability by permitting alternative load-resisting mechanisms to contribute, such as tensile membrane action of floor systems. The effect of restraint from the surrounding structural system becomes even more complex when considering the action of realistic fires which include a cooling phase.

The emerging standardization of structural fire engineering practice in the U.S. will certainly disrupt the century-long norms in structural fire protection. The current edition of the ASCE/SEI 7 standard (Minimum Design Loads and Associated Criteria for Buildings and Other Structures) has commenced a new industry-consensus standard of care for structural fire protection. In addition to providing a legitimatized alternative to the prescriptive method, new standardization prohibits designers from intermingling aspects of the prescriptive method with structural fire engineering.

The new standard of care for structural fire protection will impact how designers consider restraint. For instance, ASCE/SEI 7-16 Section E.2 states that restraint is entirely dependent on adjacent structural framing and connection details, which are not considered under the prescriptive method. Accordingly, Section CE.2 states that furnace testing does not provide the information needed to predict the actual performance of a structural system under fire exposure, since furnace testing qualifies assemblies in isolation without interconnectivity or interaction with the surrounding structural system. In light of these new developments, the industry has begun to reexamine the “restrained vs. unrestrained” concept in order to better serve designers going forward.

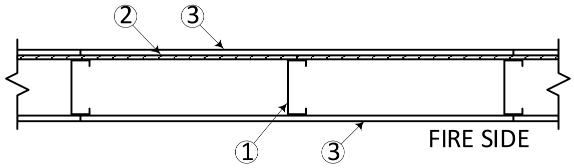
The prescriptive method appears to have served the industry well over the past century, and should continue to be the default option for structural fire protection design. However, ASCE/SEI 7-16 explicitly addresses what designers have known for decades: there is no correlation between assembly performance in a furnace test and in-situ structural system performance under fire exposure. While furnace testing standards provide examples/guidance for restraint classifications, the designer is ultimately responsible for such judgments. Also, restraint conditions of a furnace test differ from those of the in-situ structural system, often significantly. Although consideration of restraint is a common task in the industry, designers are rightfully concerned about the liability associated with making uncertain judgments.

Clarification and/or reform of the “restrained vs. unrestrained” concept would benefit the industry at large. It is envisioned that such clarification/reform would materialize within fire testing standards such as ASTM E 119, and be adopted by building codes. Also, any clarification/reform should relieve designers of the obligation to make judgments concerning restraint when employing the prescriptive method. Such judgments are better reserved within the context of structural fire engineering.

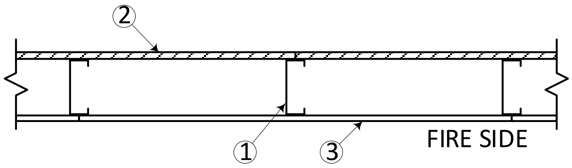
FIRE RESISTANCE OF COLD-FORMED STEEL FRAMED SHEAR WALLS UNDER VARIOUS FIRE SCENARIOS

Blanca Andres [1], Matthew S. Hoehler [2] & Matthew F. Bundy [2]
Danish Institute of Fire and Security Technology [1]
National Institute of Standards and Technology [2]

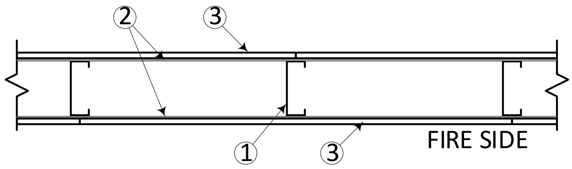
The fire resistance of building wall assemblies is typically assessed using standardized resistance to fire tests [1]. Performance-based fire design requires a sound understanding of the response of building elements to realistic fire conditions; in addition to characterizing their performance in standardized fire tests. There are few published investigations of the full-scale fire behaviour of structural assemblies under various levels of fire exposure. This study extends previous research [2] to investigate the fire performance of the three most common types of lateral force resisting systems (LFRS) used in cold-formed steel (CFS) framed buildings. The investigated LFRS are: (1) Oriented Strand Board (OSB) sheathed walls, (2) gypsum-sheet steel composite panel sheathed walls, and (3) strap braced walls. All 22 wall specimen tested are 3.66 m long by 2.74 m tall and have a 1-hour fire resistance rating per American Society for Testing and Materials (ASTM) standard E119 [1]. The wall cross-sections are shown in figure 1.



1 – CFS stud; 2 – Oriented Strand Board; 3 – gypsum board



1 – CFS stud; 2 – steel composite panel; 3 – gypsum board



1 – CFS stud; 2 – diagonal bracing; 3 – gypsum board

Figure 1. Cross-section of the investigated walls

The three types of walls are investigated under the following levels of fire severity:

1. *Standard Fire*: 1-hour fire exposure with a time-temperature curve similar to ASTM E119.
2. *Mild Fire*: a post-flashover fire of 'short' duration (15 minutes) and a peak upper layer gas temperature of 900 °C.
3. *Severe Fire*: a post-flashover fire of 'long' duration (35 minutes) and a peak upper layer gas temperature of 1100 °C.

The Mild and the Severe fire exposures are based on experimental databases of compartment fires [3,4] and inventories of building contents [5]. The fire is applied using a gas burner located in a compartment adjacent to the specimen. Additionally, a culminating test is performed on an OSB sheathed wall where the fire load is provided by real kitchen furnishings selected based on the prototype room for the Mild and Severe Fires. The dimensions of the compartment are 3.7 m × 2.8 m × 2.8 m with an opening factor of 0.08 $m^{½}$ and a fire load of 804 MJ/m_{floor}^2. The compartment dimensions and fire load are taken as the mean values for kitchens from Bwalyala et al. [5]. The ignition source was a pan oil fire on a cooktop.
Temperatures in the compartment are measured using both plate thermocouples and thermocouple trees. Temperatures through the cross section of the specimens and on the unexposed side of the wall

are measured at several locations. Additionally, measurements of air flow velocity in and out of the wall and pressure at the top of the wall cavity are made. Heat flux to the specimen is also measured in the gas burner tests.

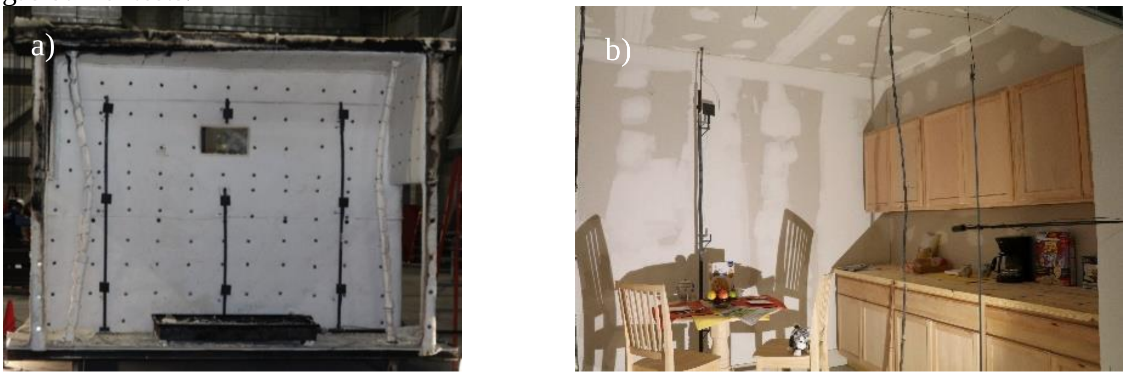


Figure 2. Experimental set up for: (a) Gas fuelled compartment fire, (b) Kitchen furnishings fire.

The results show that all walls withstood the Mild Fire with limited influence on the post-fire structural performance. The Standard Fire was more severe, especially for the OSB sheathed walls, where ignition of the OSB occurred after 42 minutes. Ignition of the OSB during the Severe Fire occurred 19 minutes after burner ignition and during the Kitchen Fire 26 minutes after the compartment flashed over. Figure 3 plots temperature measurements from thermocouples located on the unexposed side of the wall for the gypsum-sheet steel sheathed wall and the OSB wall for the various fire exposures.

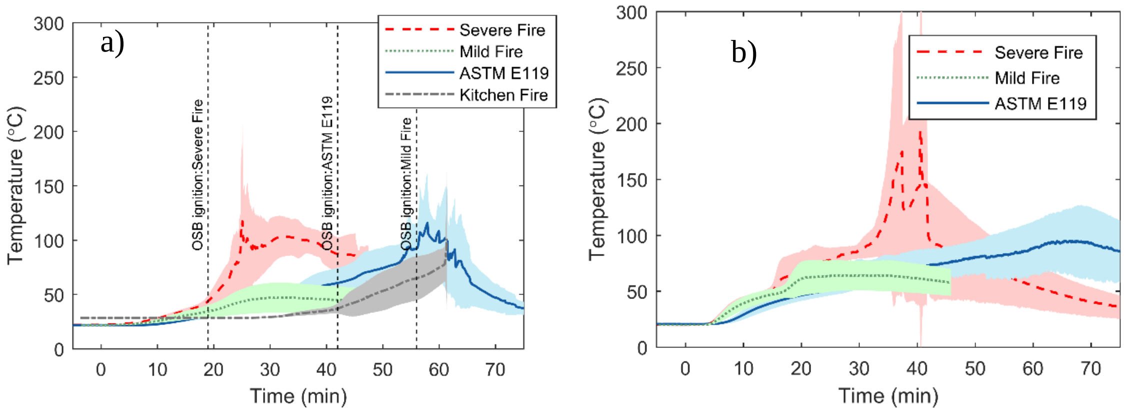


Figure 3. Temperature on the unexposed side as mean value and standard deviation for: (a) OSB sheathed walls, (b) gypsum-steel sheathed walls

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Modeling the Fire Resistance Performance of Floor Ceiling Assemblies

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The construction industry is continually introducing new engineered floor-ceiling systems that span longer distances to meet customer demands, as well as improve structural stability, faster construction time, and efficient use of resources. Under fire conditions, some floor-ceiling systems can lead to structural failure in a shorter time and may not meet the standard 1-hr or 2-hr fire resistance rating prescribed by a standard ASTM E119 test. In this paper, we develop models to predict the fire resistance performance of two floor-ceiling assembly designs using the NIST Fire Dynamics Simulation (FDS). The first design assembly consisted of structural wood joist elements, a plywood subfloor and gypsum ceiling resulting in a 1-hr fire resistance rating. The second assembly includes structural steel joist elements, structural concrete floor sheathing, fiberglass insulation and Type X gypsum ceiling resulting in a 2-hr rating. The physical/mathematical models account for E119 exposure of the gypsum wall boards, dehydration kinetics, convective energy transfer through cracks in the wall board, melting of the porous fiberglass insulation, and heating/dehydration of the flooring material. Testing was performed using a horizontal fire resistance test furnace employing the fire endurance conditions and standard time-temperature curve described in ASTM E119.

Table 1. Material properties required for each material in the floor-ceiling assembly.

Dehydration Kinetics	Thermodynamics	Transport
• Pre-exponential factors • Activation energies • Stoichiometric coefficients	• Specific heat capacity • Heats of dehydration reactions	• Thermal conductivity • Emissivity

The model predictions obtained using FDS require complete specification of the thermophysical properties of the materials used in the floor-ceiling assemblies. The material properties required for each material in the floor-ceiling assembly are summarized in Table 1. In this work, material properties of the various components of the floor-ceiling assemblies were characterized using small-scale testing. In particular, thermogravimetric analysis was used to characterize dehydration kinetics, and the transient plane source method was used to measure room temperature thermal conductivity before and after dehydration. Densities were measured before and after dehydration using direct mass measurements. Other properties were obtained from literature data. The measurements are a demonstration of a method for rapid material property characterization first developed for polymeric materials [1]. The coupling of this rapid material property characterization process with the detailed FDS models allows for predictions of the performance of novel materials in standard furnace tests which could greatly aid in the material design and selection process.

Predicted furnace temperature, finish temperature and unexposed surface temperature were found to compare favorably with thermocouple temperature measurements obtained from the full-scale furnace tests. Results indicate that the models were able to accurately predict the fire resistance rating of floor ceiling assemblies and the results of the standardized furnace tests.

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Need for Standardized Test Methods for Characterizing Properties of Concrete at Elevated Temperatures

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Abstract

For evaluating fire resistance of a structural member, knowledge of temperature dependent thermal and mechanical properties of constituent materials is required. Thermal properties that influence fire resistance are thermal conductivity, specific heat, thermal expansion and mass loss. The mechanical properties affecting fire resistance include compressive and tensile strength, elastic modulus, stress-strain relations, and high temperature creep effects. In the case of concrete, these properties vary significantly with type of concrete (ex: normal strength, high strength, and ultra high performance concrete), specimen conditions (size, age, and moisture content), heating conditions (rate of heating, and transient or steady state) and test procedure (equipment, loading level, etc.).

Relations for variation of temperature dependent thermal and mechanical properties of conventional construction materials, such as concrete and steel, are specified in few codes, standards and manuals such as Eurocode 2 (2004) and ASCE Manual on structural fire protection (1992). For concrete, these relations are mainly derived from property tests on normal strength concrete (NSC) and in some cases on high strength concrete (HSC) specimens. There is significant variation in reported test data on temperature dependent properties of concrete due to differences in test methods, procedures, and equipment adopted in undertaking these property tests. Owing to this reason, there are considerable variations between constitutive relations presented in different codes and standards.

Further, in recent years, as a result of significant research and development activity, number of new concretes with better properties have been developed so as to realize durable, cost-effective and sustainable construction. The high temperature behavior of these new types of concrete is not yet well established. One of the main reasons for limited research on high temperature properties of these new concretes is due to lack of standardized test procedures, test equipment and instrumentation that can withstand high temperature in the range of 20-800°C. Unlike conventional concretes, these new concretes, under fire exposure conditions, are susceptible to temperature induced spalling which has detrimental effect on fire resistance of a concrete structure. In order to account for such spalling in fire resistance calculations, numerous additional properties such as permeability, pore pressure and tensile strength at high temperature are needed. There is absolutely no guidance in current standards for measuring these properties at elevated temperatures.

At present, there are limited guidance or test methods for measuring various properties at elevated temperatures. Many a times room temperature test methods are extended for measuring properties at elevated temperatures, without due consideration to complexities that arise under elevated temperature exposure. The available standards for evaluating thermal and mechanical properties of concrete at ambient and elevated temperature are summarized in Table 1. As can be seen, ASTM standards specify procedure for evaluating thermal conductivity of concrete only up to 85°C and specific heat up to 600°C. No specific

provisions for characterizing high temperature mechanical properties in 20-800°C is given in ASTM standards.

In order to address this gap, available test procedures in ASTM standards [1], RILEM [2] and ISO 22007 [3], along with other published experimental studies are reviewed. Based on the detailed review, the most applicable test methods and procedures for high temperature characterization of concrete in the temperature range of 20-800°C is compiled and presented in this paper.

Table 1. Test standards for evaluation of thermal and mechanical properties

Thermal property	Standards for ambient temperature testing	Standards for elevated temperature testing
Thermal conductivity	ASTM C177, ASTM C1363 ISO 8302	ASTM C1363 (limited to 85°C) ISO 22007
Specific heat	ASTM E1269 ISO 11357	ASTM E1269 (limited to 600°C) ISO 22007
Thermal expansion	ASTM E831 ISO 11359	ASTM E831 ISO 11359
Mass loss	ASTM E1131 ISO 11358	ASTM E1131 ISO 11358
Mechanical property	**Standards for ambient temperature testing**	**Standards for elevated temperature testing**
Compressive strength	ASTM C39	No ASTM RILEM 2007
Tensile strength	ASTM C78 (Flexural) ASTM C1583 (Direct) ASTM C496 (Splitting)	No ASTM RILEM 2007

In the paper, the variability of properties in literature will be demonstrated. The lack of standardized test methods, procedures and equipment for characterizing material properties at elevated temperature will be illustrated. The need for development of standardized test methods and procedures for characterization of new concrete types is highlighted. To this end, the dire need for the development of standards for high temperature material characterization from organization such as ASTM will be laid out.

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EVALUATION OF STANDARD AND REAL FIRE EXPOSURES TO PREDICT THE TEMPERATURE RESPONSE OF A RAILCAR FLOOR ASSEMBLY

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Current standards such as NFPA 130 [1] require railcar floor assemblies to achieve a fire resistance rating according to ASTM E119[2] by exposing the assemblies to a prescribed 30 minutes time-temperature curve using a furnace. Though the ASTM E119 is a standard test procedure, it does not represent a real fire scenario which can have temporal and spatial varying exposure. This work developed a computational framework to evaluate and compare standard fire exposures such as ASTM E119 to real fire exposures to determine the difference in the temperature rise of a railcar floor assembly. The dimensions of the assembly used in this work consisted of the entire width of the railcar ~3.0 m (9 ft) and a length of 3.7 m (12 ft) as described in NFPA 130. The real fire exposures simulated in this work have been identified in a review of incidents involving fire exposures to railcars in the US and internationally over the past 50 years. The fire exposures consisted of a constantly-fed diesel fuel spill, a localized trash fire, and a gasoline spill simulated from a collision of the railcar with an automobile. These realistic fire exposures were applied to floor assembly models in Fire Dynamics Simulator (FDS) which also included the under-carriage equipment to better capture the fire dynamics. A variety of representative undercar configurations were identified from several US railcars and included flat bottom designs with 12 and 22 inches clearance above the top of the rail to represent bi-level railcars and 48 inches clearance above the top of the rail with undercar equipment as representative of single-level cars. All of the configurations modeled in this work included a representation of cables under the railcar with thermo-physical properties of crosslinked polyethylene. The thermal exposure at the underside of railcar assembly was extracted using the heat transfer coefficient and the adiabatic surface temperature provided by FDS. These spatial-temporal exposures were coupled with a detailed railcar floor assembly finite element model in ABAQUS to analyze the thermal behavior of the assembly. This thermal coupling procedure is shown in **Figure 1**.

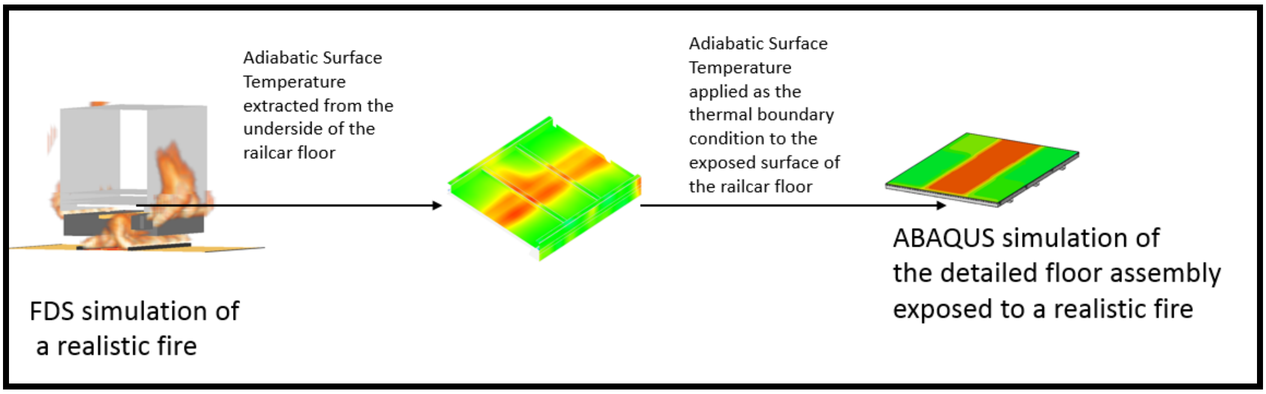

Figure 1. Coupling procedure used to extract data from FDS to apply thermal boundary condition in the ABAQUS model

The thermal model in ABAQUS provided the evolution of temperature in different components of floor assembly consisting of a structural frame, an insulation, and a composite

floor. The standard scenarios were simulated for two hours instead of the typical 30 minutes to identify the appropriate exposure duration in ASTM E119 which can better represent a real fire scenario. The average and maximum temperature predicted at the unexposed surface for both scenarios were compared with the threshold values given in NFPA 130. The work concluded that the ASTM E119 temperatures lagged those of the diesel spill fire by 3-5 minutes. ASTM E119 exposure durations of approximately 34 and 65 minutes are required for a railcar floor assembly to achieve the equivalent fire resistance rating for 30 and 60 minutes respectively for fires due to diesel spills.
In addition to the exposure analysis, this work introduces a novel insulation model to represent temperature dependent shrinkage conforming with the experimental observations. This model assumed that the insulation starts shrinking at 500°C and melts completely at 1500°C which is the melting point of glass. The thermal contraction factor is assumed to be orthotropic with shrinkage occurring only in the direction perpendicular to the exposed surface.

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BEST PRACTICES FOR MODELING STRUCTURAL BOUNDARY CONDITIONS DUE TO A LOCALIZED FIRE USING A COUPLED CFD-FE APPROACH

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Introduction

The standard fire exposure (e.g., ASTM E119) has come under criticism in recent years due to the fact that it does not capture many important features of natural fire exposure. Recent studies have shown that other fire models (e.g., localized fire) may produce structural responses that differ from those observed in standard fire tests [1-2]. Due to the limitations of the standard fire exposure, a number of researchers have made advances toward simulating natural fire effects in numerical models and in structural fire experiments. One approach that shows much promise is the coupled computational fluid dynamics-finite element (CFD-FE) modeling of structures in fire. The approach uses CFD to model the fire behavior and FE analysis to model the heat transfer through the structure. A survey of literature (e.g., [3]-[5]) shows a number of inconsistencies in how the thermal boundary conditions are represented at the fire-structure interface though, and a uniform methodology is needed so that analysts can gain consistency in their results. In this study, a coupled CFD-FE analysis is used with various boundary condition assumptions to show the impact that the modeling assumptions can have on the prediction of the structural response.

Methodology

The heat flux to a surface can be represented by the incident radiative heat flux or the adiabatic surface temperature (AST). Specifying the boundary condition in terms of incident heat flux has increased computational expense because it requires two variable parameters to be outputted from the CFD model (i.e., incident heat flux and gas temperature). Specifying the boundary condition using adiabatic surface temperature reduces the number of variables that must be outputted from the CFD model, thereby reducing computational expense. A third approach is to calculate the net heat flux using CFD and input this directly into the FE model. The main drawback to this approach is that the net heat flux in the CFD model is based on surface temperatures calculated by the crude solid heat transfer model in the CFD code, which may generally be regarded as less accurate than the surface temperatures calculated in the FE model.

Additional inconsistencies can be found in the convective heat transfer coefficient and surface emissivity at the fire-structure interface. This study considers the heat transfer coefficient as equal to either 35 or 9 W/m^2-K, or the value calculated directly from the CFD analysis. The value of 35 W/m^2-K for the heat transfer coefficient was used by [5] and [6] as a conservative value for natural fire exposure. Ref. [3] recommended using 9 W/m^2-K for a CFD-FE model with a localized fire exposure. Lastly, Ref. [4] recommended using the value for the heat transfer coefficient computed from the CFD analysis. Regarding the emissivity of the structure, Eurocode [6] suggests using a value of 0.7 for traditional calculations of steel exposed to fire. The value of 0.9 has been used for the emissivity when considering localized fires [3].

Analysis and Results

This study considers two localized fire scenarios: (1) a SHS column subjected to an adjacent burner fire experimentally tested by [8], and (2) a steel I-beam subjected to a pool fire at mid-span tested at the University of Edinburgh [9]. A CFD model was generated in FDS, and an FE model was created in Abaqus for each case. The thermal boundary conditions were applied according to the various methods described in Section 2. Figures 1-2 show a selection of results from the analysis of Cases 1 and 2, respectively. While the conference paper will show the complete analysis, Figs. 1-2 demonstrate the degree of accuracy that was achieved when adiabatic surface temperature was used as the boundary condition with the heat transfer coefficient calculated by FDS and an emissivity of 0.9. It can be seen that excellent agreement with experiments can be obtained when the boundary conditions are properly modeled. Displacement calculations, which were also part of the study, further demonstrate the importance of accuracy in the temperature calculations.

Conclusions

The study shows that the treatment of boundary conditions in CFD-FE models is not trivial. A wide range of structural temperatures can be obtained depending on the assumptions that are used in the heat transfer model. Given that CFD-FE models are becoming increasingly common in structural fire engineering, it is important that structural fire engineers are aware of the implications of modeling assumptions at the fire-structure interface.

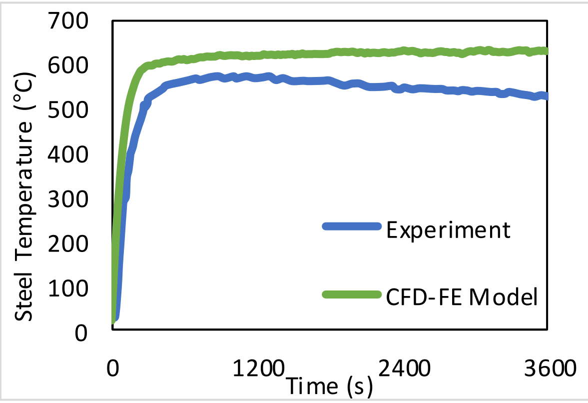

Figure 1. Case 1: SHS column subjected to adjacent burner fire

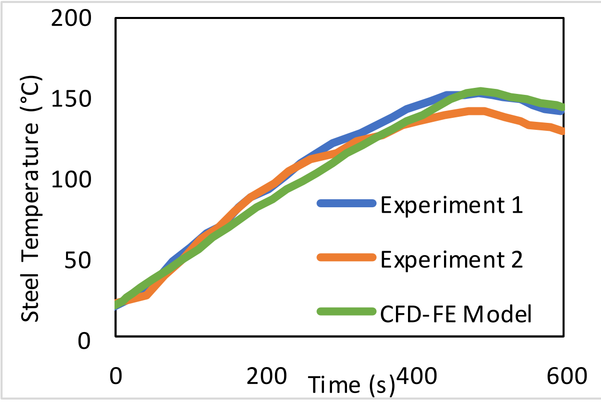

Figure 2. Case 2: I-beam subjected to pool fire at mid-span

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Methodology of Hybrid Fire Tests

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Abstract

To design structures against fire hazards, it is necessary to have detailed information on the material properties and the behaviour and performance of the design structures under different fire scenarios. For this purpose, fire testing is an important tool to investigate structural response in fire. The approach of fire testing has been continuously developed and evolved since the early twentieth century. In conventional fire test, individual structural members or sub-assemblages of different construction materials, such as beams, columns, walls or slabs and connections under elevated temperature, are tested in compliance with the fire standards, e.g., CAN/ULC S101, ASTM E119 and ISO 834. The behaviour and performance of building systems exposed to fire depend on a number of factors in addition to the properties and behaviour of individual structural components, such as the energy source, location and spread of the fire within the building as an integrated system, etc. Furthermore, the redistribution of loads, progressive deterioration in stiffness and strength and increase in deformation of the building system as a whole as fire spread can significantly impact on the performance and resilience of the building under fire hazards. To consider all these complex interaction effects, it is more realistic to conduct fire test of the entire structural system not just of individual structural members. However, it is generally prohibitively expensive or impractical to test full structural system, e.g. entire building under realistic fire loading. Conventional fire test is typically carried out by testing only individual structural elements, which does not account for the interaction effects between separate components of the entire system. Consequently, conventional fire test cannot predict the full system-level performance of complex structural systems. In order to comprehensively evaluate the behaviour and performance of an entire building in a practical and cost-effective manner, a new approach for fire test based on the recently developed methodology of hybrid testing, which combines physical testing and numerical computer modelling, is proposed.

The concept of hybrid simulation or hybrid testing was originally developed in earthquake engineering to investigate the structural response of entire complex structures during earthquakes. In hybrid testing, the complex system is divided into different parts (sub-domains). The parts of the system that cannot be accurately represented by analytical models, or which have high level of uncertainty in their behaviour, are physically tested in the laboratory, meanwhile, the remaining system is simulated by computer models. There are two major advantages of hybrid testing: one is, the capability of representing the complete response of the entire system owing to the fact that the experimental tests and numerical simulations are performed simultaneously as part of a single test; the other is, hybrid testing enables researchers to test full-scale prototype structure without the influence of scaling effect. In this research, the novel hybrid testing technique is further developed for system level fire test to assess the response and performance of entire structural system in fire or fire following earthquake, e.g. triggered by rupture of gas pipes or releasing of combustible materials during or immediately after a seismic event. In this paper, the methodology of hybrid fire testing (HFT) within the framework of performance-based design in fire safety engineering is presented. In the physical test domain of a hybrid fire test, in addition to the fire effects, i.e. the temporal and spatial distribution of the fire loads, the test specimen is also

subjected to the gravity and lateral load and deformation demands from the rest of the structure as determined from the numerical simulation domain of the hybrid test method. Recently, some preliminary hybrid fire tests have been carried out by research groups around the world. However, these tests are mostly either small-scale tests or only partially considered the coupling between the thermal and mechanical loading. [1,2,3] Carleton University (CU) in collaboration with the National Research Council Canada (NRC) is establishing a new hybrid fire test facility with the capacity to conduct real-time hybrid fire tests of large-scale specimens including full interaction effects.[4] This paper presents the framework and the methodology of real-time multi-hazard (post-earthquake fire) hybrid fire test for performance-based assessment of complex building structures based on the OpenFresco (Open-Source Framework for Experimental Setup and Control) and OpenSees (Open System for Earthquake Engineering Simulation) software frameworks.[5,6]

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AN EXTENDED TRAVELLING FIRE METHOD FRAMEWORK FOR PERFORMANCE-BASED STRUCTURAL DESIGN

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In structural fire design, a key principle is to ensure that the fire resistance of a structure is greater than the fire severity. However, this principle would be undermined and difficult to assess, if inappropriate fire exposure models are adopted for the design compartment. The problem for structural engineers is particularly challenging when design compartments are very large and conventional fire exposure models are inappropriate. This kind of problem is beginning to be tackled with 'travelling fire' methodologies in recent years[1], which are related to fires that may burn locally and tend to move across entire floor plates over a period of time in some large compartments. There are three representations of travelling fires which can be found in the literature: Clifton's model[2], Rein's model[3], and an extended travelling fire methodology (ETFM) framework *conceptually* put forward by the authors in 2016[4,5]. The ETFM framework is developed by 'mobilising' Hasemi's localized fire model[6] for the fire plume near the structure (i.e. near-field), and combined with a simple smoke layer calculation by utilising the FIRM zone model[7] for the areas of the compartment away from the fire (i.e. far-field). The heat fluxes generated by the ETFM framework will enable both a heating phase and a cooling phase for each structural member in the large compartment.

The ETFM framework enables the analysis to capture both spatial and temporal changes of the thermal field. Fire temperatures are variable for the near field, contrasting the uniform 800°C-1200°C assumption in Rein's model, while all elements in one firecell share the same fire exposure history in Clifton's model. Furthermore, the FIRM zone model also enables the ETFM to consider smoke accumulation under the ceiling, which is ignored in both previous models. *More importantly*, utilising the FIRM zone model into the ETFM framework, means that the energy conservation and the mass conservation are both satisfied for the design compartment. Previously proposed travelling fire methodologies simply force other existing models to 'travel' (i.e. modified parametric fire curves in Clifton's model, 800°C-1200°C temperature block and the Alpert's ceiling jet model in Rein's model), and have not attempted to explicitly account for the mass and energy balance in the compartment, thus the ETFM framework in principle addressing more of the fire dynamics than Clifton's model and Rein's model. The work presented in this paper is on this basis, to put forward a *complete and executable* performance-based design approach for the structure with large compartment under travelling fires, through a more fire science-bounded travelling fire model with mass and energy conservation, i.e. the ETFM framework.

Moreover, performance-based design for structures in fire requires validated methodologies. Validation of fire spread predictions is very ambitious, nevertheless it is apparent that none of the travelling fire design methods mentioned above have been compared against any travelling fire experiments so far. This paper demonstrates the application of ETFM framework to representation of fire spread in a real building - the Veselí travelling fire test building (a two-storey steel-composite structure[8]). It is achieved through performing a numerical investigation of the thermal response of the structural elements, i.e. comparing member temperatures between the predicted time-temperature histories using the ETFM framework and the test data. In addition, the application of ETFM framework in this test building was also compared against uniform compartment fire models (i.e. standard fire, parametric fires), to explore the inherent limitations of those conventional design methods. Furthermore, the thermal impact of the ETFM parameters (e.g. various fuel load densities, heat release rate per unit area, fire spread rate, etc.) on this structure is investigated, through quantifying the cross-sectional time-temperature evolution of the instrumented steel beam in the test compartment. Besides, compartment aspect ratio, ventilation conditions, and steel beam size are generalised compared with the original Veselí travelling fire test building, to further explore the key sensitivities to the resulting “travelling fires”. All these analyses are performed using SIFBuilder[5], which is an OpenSees-based integrated computational tool for performing automated thermo-mechanical analyses for large structures under realistic fires.

The following are some of the key findings: (1) For ‘slow’ fires (i.e. low fire spread rate), the near-field fire plume brings more detrimental thermal impact compared with the impact from far-field smoke. However, for ‘fast’ fires (i.e. high fire spread rate), the far-field smoke brings more detrimental thermal impact. (2) When the sequential beams (right above the fire trajectory) under a ‘fast’ but ‘thin’ travelling fire scenario (i.e. high spread rate and low fuel load density), the peak temperatures of these beams would be fluctuating. This is because some of the structural members are not given enough time to be heated up by the ‘fast travelling’ near-field fire plume. Hence the relative locations of the structural members in the compartment are taking effect. This peak temperature fluctuation would diminish when the fire spread rates become lower. (3) Fire spread rate and fuel load density are ‘equally’ determinative factors on the time for a structural member to reach its peak temperature. Nevertheless, the fire spread rate is a more determinative factor on affecting the total travelling fire time duration. This is simply due to the length of the predefined fire trajectory for all the scenarios are the same, hence ‘fast’ fires would spread over the entire floor plate with shorter time. (4) Fire spread rate and fuel load density are ‘equally’ influential on the maximum temperature of a steel member at the mid-web, for a design beam would reach. However, the fuel load density produces a stronger impact than fire spread rates, on affecting the temperature difference through the beam depth. (5) For more severe travelling fire scenarios (i.e. high fire spread rates and large fuel load densities), the fire would be entrainment-controlled rather than fuel-controlled. Hence the ventilations cannot be neglected for a design fire severity using travelling fires. (6) Further results highlight the phenomenon of ‘thermal gradient reversal’ due to the near-field fire plume approaching and leaving the design structural member, thereby reversing the thermally-induced bending moment from hogging to sagging. Within the assumed ranges of parameter variation, the maximum thermal gradient due to smoke-preheating is proportional to the fire spread rate and less sensitive to the fuel load density. By contrast, the peak thermal gradients due to approach and departure of the “near-field” are more sensitive to the fuel load density, with larger peak values at lower fuel load densities. (This part of finding published in SiF 2018[9]).

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Defining the Flame Extension under the Ceiling for Travelling Fires inside Very Large Compartments

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Introduction

In large open plan spaces, fires have been observed to travel across the compartment floor plate leading to fire durations of several hours and a non-uniform thermal environment inside the compartment. Such fires have been named as "Travelling fires. The concept of travelling fires has been progressed in the last decade for structural design purposes. [1, 2] One of the newly developed methodologies is the "Improved Travelling Fire Methodology" (iTFM), [2] which provides a family of travelling fire curves in large compartments, where each fire has a different burning area. iTFM considers the 'near field' and 'far field' regions of a fire. The near-field temperature, where the flame is impinging the ceiling, ranges from 800°C – 1200 °C. In the iTFM, the hot gas temperature in far-field can be calculated by Alpert's correlations, which were developed from fire tests with an unconfined ceiling (Fig. 1(a)). [2, 3]As the fire travels throughout the compartment, the structural elements at the ceiling level experience the thermal exposure from the far-field and near-field regions. The assumptions in iTFM aim to produce a simple and reasonably representative of travelling fire scenario that can be used conservatively for structural design purposes. This paper examines the appropriateness of the current near-field assumption of iTFM by considering the effect of flame extension under the ceiling, which is not currently considered. A case study is presented where the thermal response of a concrete slab when subjected to flame extension under the ceiling, is compared with iTFM and the Eurocode 1-1-2 (EC1-1-2) parametric fire curve. [4] Parametric fire assumes uniform temperature and a uniform burning condition for the fire.

Flame Extension Methodology

A methodology that calculates the flame length under the ceiling is presented; thus allowing determining the heat flux along the length of flame under the ceiling; in turn improving the near-field assumption of iTFM to obtain a better boundary condition for a surface exposed to a travelling fire.
When the flame height exceeds the ceiling height, a part of the flame deflects horizontally and become a part of the ceiling jet. Methods to calculate the horizontal part of flame are presented in [5] iTFM methodology assumes that the flame impinges the ceiling just in the near-field region with a flapping angle. This paper assumes that flame impinges the ceiling and extends beyond the near-file region. The Hasemi methodology [6] in EC1-1-2, was used herein to calculate the horizontal flame extension under the ceiling and thus the heat flux received by the fire exposed unit surface area at the level of the ceiling. Hasemi et al. [6] used porous burners below an unconfined ceiling and found the peak heat flux at the ceiling was 100 KW/m² at the stagnation point. This value was also used in this study as an initial estimate.

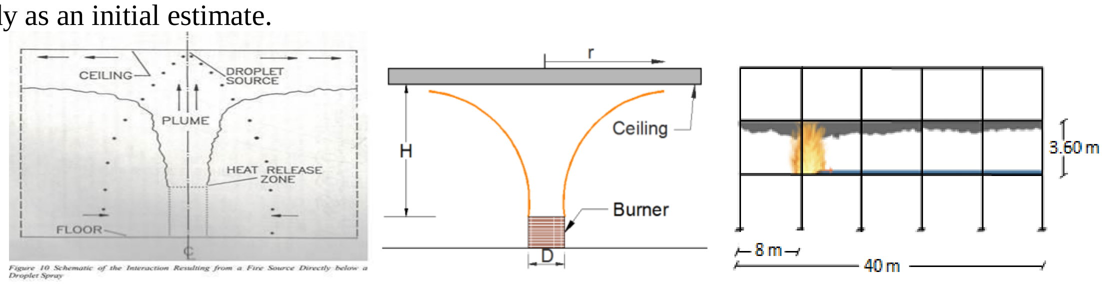

Figure 1. (a) Schematic of ceiling jet from[4]; (b) Flame extension under an unconfined ceiling (c) Structural layout for the case study.

Case Study

The compartment is an open-plan concrete office building with a floor area of 960 m² (Fig. 1(C)). The fire started at the left side and travels along the building. A family of fires were investigated based on the typical fire spread rates in compartments, [3] to generate the heat flux fields across the compartment. The heat flux fields were used to determine the rebar temperature in the concrete slab 180 mm thick with 44 mm axis-distance of the tension rebar and a concrete cover of 36 mm, by applying the finite-difference method for the heat conduction. Fig. 2(a) shows the calculated received heat flux-time curves at the level of the ceiling, in the middle of the compartment (one point is shown for simplicity), using iTFM, iTFM+Hasemi and EC1-1-2 parametric fire. The maximum calculated heat fluxes were 240-254 KW/m² and 85-100 KW/m² from iTFM and iTFM+Hasmi respectively. Fig. 2(b) shows a comparison between the calculated rebar temperatures in the concrete slab using heat fluxes from iTFM, iTFM+Hasemi and parametric fires (one fire size is shown for simplicity in this abstract – full details for multiple fire sizes to be provided).

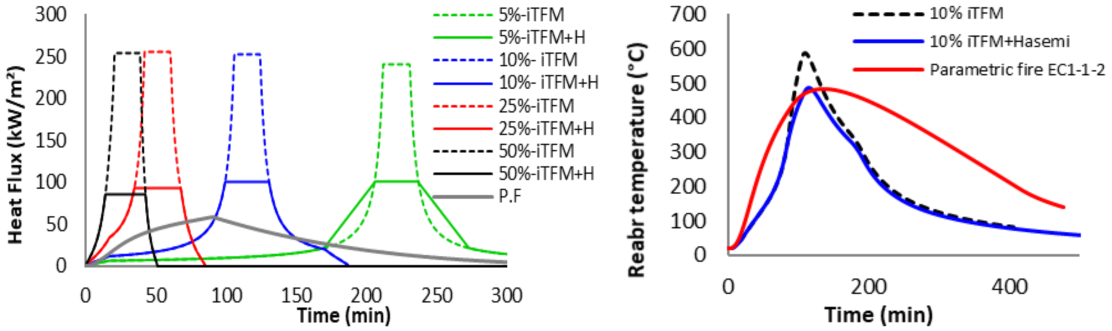

Figure 2. (a) Heat flux received at the level of the ceiling; (b) Calculated rebar temperature in slab using the calculated heat flux

Fig. 2-b shows that iTFM give a higher rebar temperature due to the approximation of near-field temperature in iTFM. iTFM+Hasmi resulted in slightly higher rebar temperature than parametric fire, which emphasizes the need for incorporating the TFM into structural analysis.

PRELIMINARY CONCLUSIONS AND FUTURE RESEARCH

The study considered the flame extension under the ceiling beyond the near-field region and calculated the heat flux received from the flame to the ceiling, as the boundary condition for the heat transfer calculations. The case study showed that iTFM+Hasemi is more critical than parametric fire but less critical to iTFM. Additional research is required to investigate the impact of the family of fire sizes across the compartment. Future research can investigate the effects on protected and unprotected steel structures and the influence of the peak heat flux adopted in the conclusions of the current study. The peak heat flux from Hasemi correlation adopted in EC 1-1-2 is 100 KW/m², which limits the maximum near-field prediction of iTFM+Hasemi. Further sensitivity analysis needed on the peak heat flux at the ceiling level.

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DEVELOPMENT OF A SIMULATION APPROACH FOR FIRE AND STRUCTURE INTERATION OF CONCRETE HIGHWAY BRIDGES

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Introduction

An intense fire on March 30, 2017 underneath Highway I-85 near Atlanta, Georgia, resulted in the collapse of a portion of the concrete bridge. The fire started in a state-owned storage area under the bridge, which contained high-density polyethylene (HDPE) pipes. The heat from the fire caused the collapse of a 30-m section within about 1½ hours from the start of the fire. The fire department took about 2 hours to bring the fire under control. Controlling the I-85 bridge fire posed a significant challenge to the firefighters, not only because of the high flames and large amounts of dark smoke, but also because of the reported spalling of "large chunks" of concrete before the collapse of the bridge deck. Although no injuries were reported, closure of busy highways for an extended period for reconstruction and repair caused significant traffic delays and resulted in devastating effects on area businesses. Similar bridge collapses from fires that were initiated by burning tanker trucks have occurred elsewhere (e.g., I-65 in Birmingham, Alabama in 2002 and MacArthur Maze in Oakland, California in 2007).

Southwest Research Institute Research Project

The Atlanta and other concrete highway bridge fires motivated Southwest Research Institute (SwRI®) to initiate a research program to develop a three-dimensional (3-D) fire-structure interaction simulation approach by coupling simulation of fire dynamics, porous material modeling for hydrothermal response, and mechanical modeling for prediction of response of highway structures exposed to fire. The basic elements of this research are:

(i) Development of a three-dimensional computational methodology for modeling the fire response of concrete bridges by coupling the simulation of the exposing fire, porous material modeling for hydrothermal response, and mechanical modeling for structural integrity
(ii) Development of an algorithm for prediction of spalling potential based on pore pressure (determined from hydro-thermal modeling) and the three-dimensional stress state (from mechanical modeling)
(iii) Validation of the methodology by simulating controlled and well-instrumented previously conducted fire experiments

Our project is different from previous studies to model the behavior of concrete structures primarily because our goals are to (1) have the capability of performing simulations in 3-D so that we can evaluate the fire performance under nonuniform thermal load, (2) be able to model prestressed as well as reinforced structures, and (3) use a commercially available finite element code to model all aspects of the problem. As far as (3) is concerned, we decided to develop a methodology to establish spalling criteria for the concrete under evaluation and chose ANSYS-Mechanical to perform the structural and heat transfer calculations with adjustments to account for the expulsion of spalled material.

Concrete Spalling

The performance of concrete structures in a fire is significantly diminished when spalling occurs. Consequently, extensive research has been conducted on spalling of concrete structures exposed in a fire. However, predicting whether spalling is likely to occur greatly complicates the thermal part of the model because it must account for evaporation of free water in the pores, dehydration of chemically bound water in the cement paste, and movement of water in the liquid and vapor states.
We identified and reviewed about 50 publications (peer-reviewed journal articles, conference papers, reports, and theses) describing various approaches to model the heat and mass transfer and predict spalling in concrete elements exposed to fire. The most comprehensive model was developed by Gawin et al.[1]. However, Gawin et al.[1] wrote a finite element code in FORTRAN to solve the complex set of coupled differential and algebraic model equations. We determined that it might not be possible or too time-consuming to implement the complete Gawin model in ANSYS. Therefore, the SwRI project team focused on the simplified heat and mass transfer model developed by Al Fadul[2]. This model relies on the sorption isotherms developed by Bažant and Thonguthai[3], although we found and corrected an error in Al Fadul's equations.

Subject of Presentation

At the workshop, we will present an overview of the methodology used in the project and discuss the progress made to-date. In this research, we are simulating the response of a 3-D model of a prestressed concrete slab where the post-tensioning tendon and the anchor are explicitly modeled. Heat from fire causes progressive spalling and deterioration of strength and stiffness of the concrete and the tendons, ultimately resulting in structural collapse. Consequently, several computational models are coupled and collectively advanced through the solution time. The main components of the fire simulation consist of exposure of the slab to the standard fire, a transient thermal analysis, a hydrothermal model, and a structural demand and capacity analysis. Thermal modeling determines the temperature distribution in the structural components used for hydrothermal and structural analysis. Hydrothermal modeling is used to simulate moisture desorption, evaporation, and migration, and to estimate the pore pressure for fire-induced spalling calculations. Structural modeling evaluates the demand (stress and strain in concrete and prestressing tendons) to determine the response based on thermally induced material behavior at elevated temperatures. Experimental data reported in the literature (e.g., Ellobody and Bailey[4] and Hou et al.[5]) was used for model validation.

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Improved Calculation of Fire Resistance of Composite Slabs

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1 Introduction

In both ASTM E119-18 [1] and Eurocode 4 [2], the fire resistance according to the thermal insulation criterion, expressed in minutes, is calculated based on the fire duration until a maximum temperature rise of T = 180 °C or an average temperature rise of T = 140 °C, whichever governs, is reached at the unexposed surface of the slab (see Figure. 1). Annex D of EC4 [2] provides simple equations for calculating the fire resistance of composite slabs with profiled steel decking that are based on finite element heat transfer analyses of composite slabs with different geometries exposed to a standard fire [3]. These equations, however, have the following limitations:

- *Limited Range of Applicability:* Although the range of slab geometries considered by Both (1998) spanned an inventory of the commonly used steel decking geometries at that time, it does not encompass the geometries of many composite slabs used in current steel construction practice.
- *Limited Accounting for Moisture Content:* The EC4 method considers normal- and light-weight concrete with moisture contents of only 4 % and 5 %, respectively. The EC4 method does not explicitly consider the effect of the concrete's moisture content on fire resistance. This paper shows that moisture content has significant influence on the temperature rise in the slab, and consequently on the slab's fire resistance according to the thermal insulation criterion.

Thermal analysis of composite slabs exposed to ISO 834 standard fire performed on a wide range of decking geometries, using an experimentally validated high-fidelity finite-element modeling approach, found that the EC4 calculation method significantly underestimated or overestimated the fire resistance of composite slabs when used for geometries outside its range of applicability or for different values of moisture content. Using a rigorous statistical approach (sequential design of experiments) to identify the factors influencing the fire resistance, a new predictive formulae is proposed in this paper for the insulation-based fire resistance of composite slabs, that accounts for full practical ranges of slab geometry and moisture content.

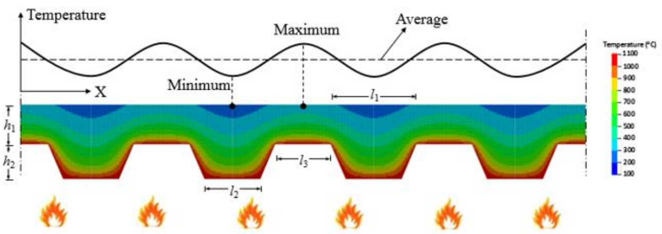

Figure. 1. Typical temperature distribution in a composite slab

2 Sequential experimental design

The design of experiments was formulated in two stages. The initial stage was a resolution IV fractional factorial experimental design, which was used to screen for important main effects and two-factor interactions. The second stage used the Federov algorithm to minimally augment the initial stage runs such that full quadratic response surface could be fitted, separately for each concrete type, to the analysis results. Separate response surfaces for each concrete type were necessary because concrete type was deemed to be an important effect during the initial stage.

3 Effect of moisture content of concrete

The moisture content (m_c) of concrete had a significant influence on the thermal response of the composite slabs. During heating, evaporation of moisture occurs between temperatures of 100 °C and 200 °C, absorbing energy and thus delaying the temperature rise in concrete. This tendency is reflected in the temperature-dependent specific heat of concrete in EC4, which has a spike in the specific heat at a temperature of 115 °C for moisture contents ranging from 3 % to 10 %. A parametric study using high-fidelity finite element models of the composite slabs showed that the moisture content had a significant influence on the temperatures at the unexposed surface of the slab. The fire resistance was found to vary almost linearly with moisture content, where an increment of 1 % in moisture content corresponded to an enhancement of the fire resistance by about 5 min. Thus, for example, assuming a moisture content of 4 % for normal-weight concrete (as is used in EC4) may lead to an underestimation of the fire resistance of the slab by 30 min when compared to a slab with a moisture content of 10 %.

4 New formulae to estimate fire resistance

Two predictive formulae for determining the fire resistance of composite slabs for normal-weight and lightweight concrete were developed based on the results from the high-fidelity finite element model of the composite slab and the sequential design of experiments described above. For each concrete type, four slab geometrical parameters (h_1, h_2, l_2, and l_3, shown in Figure. 1) and moisture content were varied, resulting in 27 runs of the finite element model. Using the Bayesian information criterion, for each concrete type, a subset of the estimated full quadratic response surface was selected to be the predictive formula. For both formulae, the difference between the values from the detailed finite element model and the predictive formulae (i.e., calculated residuals) were generally within ±10 min (Figure. 2).

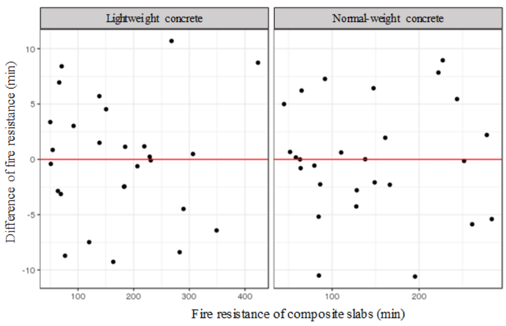

Figure. 2. Comparison of numerical and analytical results of fire resistance of composite slabs

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A NEW METHOD FOR TESTING IN-WALL SYSTEMS EXPOSED TO REAL FIRE ENVIRONMENTS

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Motivation

This research outlines the development of a new intermediate-scale test method designed to address challenges with detailed investigation of the response and endurance of individual materials, as-built wall assemblies, and in-wall systems under thermal exposures similar to those encountered in real fires. For regulatory purposes, full-scale fire performance tests are conducted on individual products or complete assemblies. In the ASTM E119 test,[1] for example, a test component is installed in a large furnace and exposed to a relatively uniform temperature environment where the temperature is increased with time according to a standardized temperature-time curve. Recently, the correlation between the response of a component to the spatially uniform, standard temperature-time exposure and its response to thermal gradients that may be encountered during real fires has come into question. Further, it is expensive and time consuming to add additional instrumentation or to run enough of these certification level tests to investigate effects of design changes on system fire performance. Consistent methods are needed to undertake more in-depth studies of the full response of an in-wall product or system to a real fire in the context of facilitating performance-based design or to make informed decisions around where to invest in R&D related to fire safety design of existing and new product lines.

Experimental Design

The new test apparatus was designed to address some of the above issues. Test walls of varying design are installed in a fire compartment and exposed to an environment where temperatures are relatively uniform from side to side of the wall at a given vertical location, but floor to ceiling temperature gradients evolve with time according to the fire fuel load used. The design is adapted from the ISO 9705 [2] and ASTM E119 [1] test methods. The fire compartment measures 2.3m wide x 3.6m long x 2.3m high. At one end is a 0.8m x 2.0m door; at the opposite is a frame that can hold a 1.8m by 1.8m wall section, up to 0.3m deep. The fuel load and door opening are set to provide a desired temperature-time exposure on the test wall. Previous work has defined various fires in terms of temperature-time exposure on the wall, across a range of wood crib fuel loads and ventilation configurations.[3] For this work, three conditioned, softwood cribs are used, each constructed from 0.6m lengths of 0.05m x 0.05m nominal spruce furring and having a mass of 14-15kg. The cribs are centered in the compartment (Figure 2), starting 0.6m from the wall, spaced 0.05m apart. They are ignited from the end closest to the door using 500ml methanol resulting in a stratified compartment environment characterized by a period of initial fire growth, a thermal plateau, and a decay phase (Figure 2). Vertical temperature gradients and horizontal symmetry are determined using thermocouples positioned at 0.06m below the ceiling as well as spaced 0.3m or 0.6m apart on rakes in each of the four corners. To assess thermal exposures and gradients specific to each test, additional thermocouples are typically attached to the back sides of the exposed and unexposed wall cladding and at key positions within the wall and on any in-wall systems.

Results

Data from walls containing crosslinked high density polyethylene (PEX) pipe will be presented to demonstrate the data that can be obtained using this test apparatus. Testing was conducted using simple stud walls, clad back and front with a single layer of 0.016m Type 'X' drywall. Pipes of various diameter were installed in vertical and horizontal configurations within the walls. To determine thermal gradients from top to bottom of the wall, across the wall cavity, and on the in-wall pipes, thermocouples were installed at the top, middle, and bottom of the backs of the exposed and unexposed drywall, and at the same locations on the in-wall pipe sections. Thermocouples were hung 0.23m out from the exposed wall at corresponding locations to those on the drywall to monitor the evolution of gas temperatures in the compartment on the exposed side of the wall. The temperature evolution over time, from the left chain (visible in Figure 2), is in Figure 3. Initial results indicate that the fire environment is symmetric within the compartment and is repeatable from test to test. Hot gas layer temperatures increase to over 400°C during the first 20 minutes, then range from an average of 700°C closest to the ceiling and 600°C through the depth of the layer during the 7.9-9.4 minute peak burning period. Decay is largely complete within an hour, though data is collected for several hours to properly document the reactions of the in-wall systems to the fire. Results provide new understanding of the overall fire performance of the system being tested, data for development and testing of wall-fire exposure models, valuable reference information to manufacturers for R&D assessments or objective based fire safety design, or aid development of "minimal-risk" installation guidelines for a tested system. Further investigation is required to determine how visible post-fire differences in the drywall at the top versus the bottom of the wall might relate to overall endurance and fire resistance of the wall.

Figure 2: Fuel Arrangement

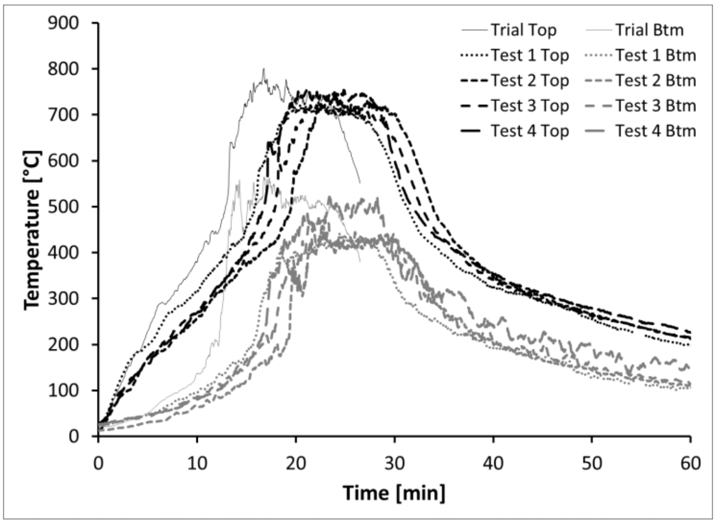

Figure 3. Temperature profile from left chain

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Experimental research on the fire performance of glulam beam-to-beam doweled steel connections for tall timber structures

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Abstract
A recent renaissance of wood construction has led to a desire to design and build tall, heavy timber structures including the use of engineered wood products such as glue-laminated timber (glulam) and cross laminated timber (CLT). Heavy timber construction has advantages in architectural appearance, constructability, cost, and sustainability and as such, the use of heavy timber has been on the rise in Europe and more recently in the US and Canada as well.

Steel connections play an important role in seismic and fire performance of contemporary tall timber structures. The connections increase the ductility of the structure and improve the seismic performance in response to lateral forces. On the other hand, steel connections may be seriously affected by fire if not properly designed – losing strength and stiffness and potentially leading to plastic deformation and even progressive collapse. Current structural fire design guidelines for timber connections follow prescriptive codes based on empirical relationships derived from a limited number of tests on timber members typically loaded in tension, parallel to the grain, and exposed to the standard fire curve (ASTM E-119). Beam-to-beam connections and beam-to-column or wall connections are examples of structural components which were found to be of great importance in improving the structural performance at normal and elevated temperatures. Post fire observations of damaged structures confirm the fact that connections have a remarkable effect on the survival time of the structure in fire.

This work is part of a larger research program focused on developing performance based design guidelines for timber connections in fire. Phase 1 of the research program included a case-study detailing the preliminary design of a 30-story timber structure. The case study provided design schematics and details for the structural system as well as performance based fire safety guidelines. Phase 2 of the research program focused on the fire performance of typical steel connections that could be used in tall timber structures and is the subject of this presentation.

The objective of this research was to determine the temperature distribution in glulam beam-to-glulam girder steel-to-timber dowelled connections exposed to fire and compare structural performance during fire and after fire to the performance at ambient temperatures. Glulam beams were 18 inches long and 5.5 inches by 9.5 inches in cross section. Steel connections were made from two A572 Gr 50 steel plates welded to each other as shown in Figure 1.

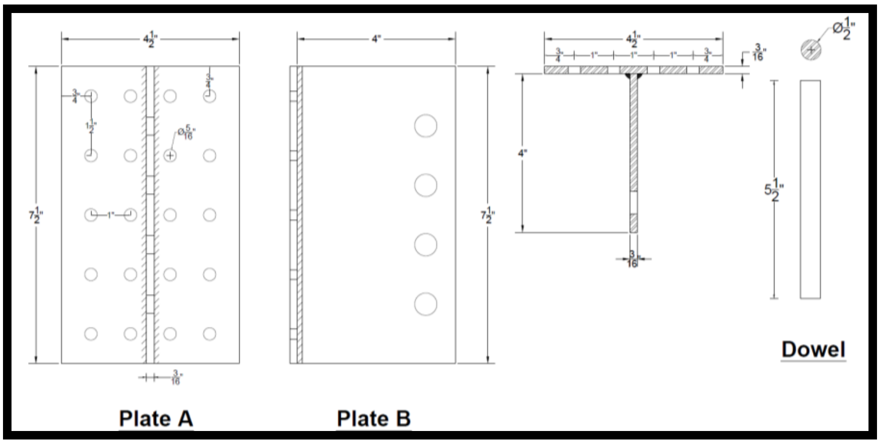
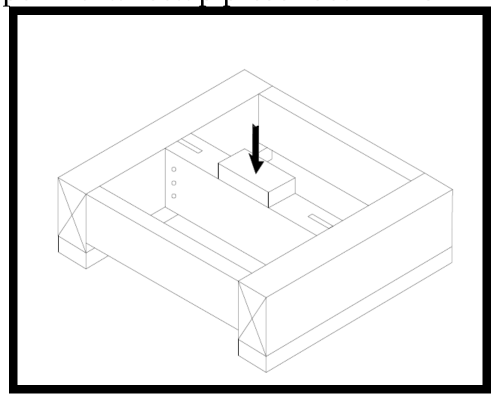
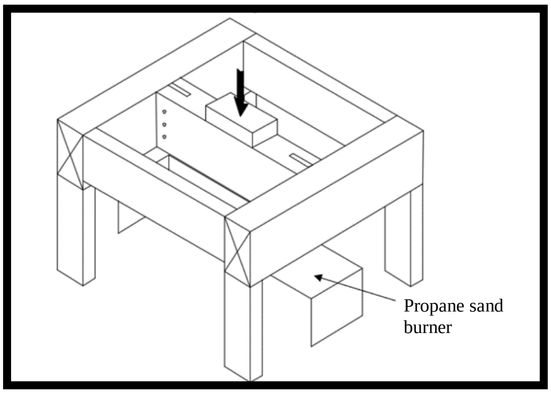


Figure 1: Welded steel connection geometry

Intermediate scale experimental tests were first performed to evaluate the mechanical behavior of the glulam beam-to-beam connections at ambient temperature. Figure 2(a) shows the experimental set-up used for testing the connections at ambient temperature. The imposed load was increased gradually perpendicular to the grain of the glulam bean to find the failure load and mode of the connections at ambient temperatures, following the experimental setup prescribed in ASTM D7147-11.





(a) **(b)**

Figure 2. Test set-up at (a) ambient temperature and (b) elevated temperature

Figure 2(b) shows the similar test set-up used for tests at elevated temperature with the addition of a propane sand burner positioned on the underside of the sample. Testing was then performed on connection assemblages exposed to fire. An unloaded specimen was heated to determine the performance of the connection exposed only to self-weight of the assemblage and loaded specimens were heated while a fraction of the expected ambient temperature failure load was applied to the specimen. The unloaded specimen was also tested to failure after cooling to evaluate the post-fire residual strength of the connection. Thermocouples and thermal cameras were used to record temperatures at various locations in the assembly during testing.

This experimental study addressed the fire behavior of glulam beam-to-beam connections loaded perpendicular to the grain during fire and after fire. Thermal behavior of the connections at elevated temperatures is presented with respect to temperature distributions within the connection assemblies. Temperature distributions will be used in future research to aid in finite element model development for timber connections in fire. Structural behavior is discussed with respect to load carrying capacity at ambient conditions and post-fire residual strength as well as member deformations during fire as exposed to self-weight and reduced superimposed dead load.

A TIME-EQUIVALENCE METHODOLOGY FOR EXPOSED MASS TIMBER STRUCTURAL ELEMENTS

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Abstract: With new mass timber technologies, high-rise timber buildings are being proposed and constructed with architects, developers and building owners requesting more of the load-bearing mass timber structure exposed. This must be rigorously assessed by fire safety engineers to permit safe levels of exposed mass timber structure. Addressing how exposed mass timber influences the fire resistance rating of a building during fire is a complex issue as the fire protection material itself (sacrificial timber) provides additional fuel, influencing the compartment fire. This mechanism has not been considered in traditional time-equivalence methodologies[1], which may not be valid under these circumstances. This paper summarises a methodology whereby equivalent time of exposure can be determined for a building that contains a proportion of the mass timber structure exposed, and not protected. This methodology applies the precise essence of time-equivalence to exposed mass timber structures.

Keywords: Fire resistance rating, time equivalence, fire severity, exposed timber, mass timber, CLT, glulam

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POSTERS

PROBABILISTIC STRENGTH RETENTION FACTORS FOR STEEL AND CONCRETE AND EFFECT ON STRUCTURAL RELIABILITY OF COLUMNS IN FIRE

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Introduction and Motivation

The structural fire engineering community is increasingly adopting the concepts of risk and reliability to support Performance Based Design approaches in fire safety engineering. These concepts will be central to the realization of complex buildings, where reliance on precedent is insufficient, and an adequate level of safety must be explicitly demonstrated. However, probabilistic evaluations of structures in fire require the availability of a well-established set of models to capture uncertainty in the inputs over a range of temperatures, which is currently missing. Probabilistic models for the material strengths are particularly needed to capture the observed scatter in test data at high temperature, as these properties are crucial in evaluating structural fire performance. In this context, the objective of this research is to examine different models to quantify uncertainty in steel and concrete strengths at elevated temperature. Based upon a collection of experimental data from literature, several probabilistic models are proposed for the retention factors of steel yield strength and concrete compressive strength. Then, the different model choices are compared and their impact on the predicted structural fire performance of columns in fire is evaluated through Monte Carlo Simulations. The continuity in reliability appraisals during transition from normal to elevated temperature design is also addressed.

Methodology and Results

The first part of the paper addresses steel yield strength at high temperature. The dataset used in the study is based on collected data by the NIST. A total of 764 data points, covering a temperature range of 20°C to 1038 °C, is used to perform statistical analysis and to quantify uncertainty of steel yield strength at elevated temperatures. The dataset is divided over 17 temperature groups for which histograms are constructed. As a first model, a lognormal distribution (LN) is employed with parameters estimated by the method of moments. A polynomial regression is used to find the best fit for the parameters across the whole temperature range under study. The R^2 values for μ_{ln} and σ_{ln} fits are 0.98 and 0.81, respectively. As a second model, a Beta distribution (B44) is adopted with shape parameters α=4 and β=4. A linear trend in mean and coefficient of variation (CoV) is identified for the different temperature intervals between the 17 temperature groups. The proposed mean and CoV values with linear interpolation in-between closely follow the dataset. Finally, a third model is considered based on a logistic formulation, with unknown parameters calculated using a Bayesian updating rule. A case study of a steel column is then used to investigate the influence of the considered probabilistic models for steel yield strength retention factors on the calculation of the failure temperature. A W14x311 column with a height of 3.56 meters and pinned-pinned boundary conditions is subjected to an axial load equal to 25% of the AISC360 design yielding force at the top and to fire on its four sides. All parameters have deterministic values except the yield strength retention factor at high temperature. The failure temperature is evaluated using the provisions in EC3 for column buckling at high temperature. The probability distribution of the failure temperature depends upon the adopted model for the retention factor. This dependence is limited (Fig. 1), but not insignificant at low quantiles (which are the ones relevant to structural fire reliability analyses). For instance, the Beta distribution predicts higher failure temperatures at low quantiles, with difference of about 20°C and 15°C at 1 and 10% quantiles, respectively.

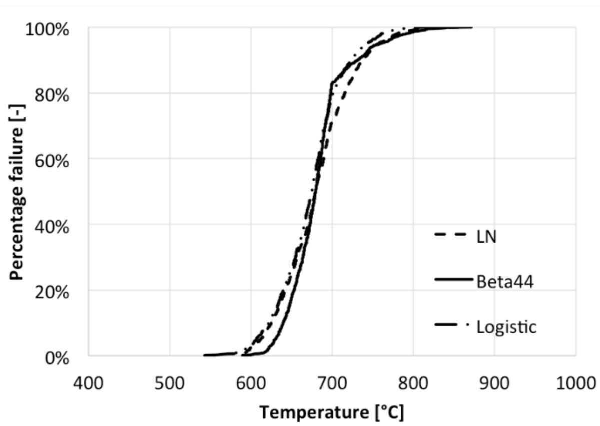

Figure 1. Fragility curve for the steel column case study with different models for steel yield strength retention factor.

The second part of the paper addresses concrete compressive strength at high temperature. The dataset used in the study is based upon collected data from multiple sources in the literature for concrete with both siliceous and calcareous aggregate types. The dataset covers a temperature range of 20°C to 1000 °C. Statistical analyses similar to the steel case are performed on the available test data, yielding several possible probabilistic models for the strength retention factors at high temperatures. The impact of the model choice on the structural fire performance is investigated on a reinforced concrete column subjected to ASTM E119 fire. In this case, advanced finite element modeling is used to evaluate the thermal-mechanical response of the column. The probabilistic retention factor models are implemented in SAFIR. Then, Monte Carlo Simulations are used to establish the probabilistic fire resistance time for the column.

Conclusion

This research provides insights into different modelling strategies to capture uncertainty in material strengths at high temperature from experimental data. It formulates probabilistic models for steel and concrete strength retention factors and discusses the model's efficiency in capturing the failure probabilities through structural fire analysis of columns. The establishment of such models will be instrumental in supporting the rise of probabilistic Performance Based Design methodologies for fire safety engineering.

DESIGN OF A TEST FIRE FOR LARGE-SCALE FIRE TESTS ON A LONG SPAN STEEL-CONCRETE COMPOSITE BEAM

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Abstract

This poster presents the design of a test fire used in the steel-concrete composite beam experiments, recently conducted in the National Fire Research Laboratory (NFRL)[1] of the National Institute of Standards and Technology (NIST). The test program was aimed to evaluate the behavior and modes of failure of five 12.8 m long, mechanically loaded composite floor beam assemblies exposed to a structurally significant fire. Although several fire tests have been conducted on steel-concrete composite floor/beam system, either in a furnace[2] or in a simulated compartment[3,4], designing a realistic test fire is still challenging because of many factors affecting the characteristics of a fire such as heat release of burning fuel loads, ventilation schemes and thermal boundaries of compartmentation. Furthermore, the results from heat transfer and structural analyses are highly sensitive to a given fire condition. Still, there is lack of generally accepted tools to design a realistic fire load that can be used for fire experiments and computational studies on a consistent basis. Existing reports on previous simulated compartment fire tests[3,4] seldom present a full discussion on the design basis of used test fires and on how to determine the most important fire parameter – heat release rate of fuel loads[5]. This paper discusses the design basis and procedure of a test fire used in NIST's long-span composite beam test series in which a structurally hazardous fire was measured and controlled using natural gas fueled burners[6]. The framework of the test fire design includes not only a literature survey of fuel loads and ventilation conditions but also simple and sophisticated models to design a fire load as a function of heat release rate. This framework can be further explored to develop a feasible tool to design test fires for various structural fire tests.

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SCREENING TESTS OF FIRE SPALLING BEHAVIOR OF RING RESTRINED HIGH-STRENGTH CONCRETE DURING FIRE

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Taiheiyo Materials, Sakura, Japan[2]
Tokyo University of Science, Noda, Japan[3]

1. Introduction

The Japan Concrete Institute Technical Committee previously examined the potential performance of concrete in high-temperature conditions (ref. JCI-TC154A) based on a fire-spalling screening test. The study reported to investigate the behavior of high-strength concrete and high-strength concrete with PP fibers based on mixture proportions of RC column concrete in response to the type of extreme heating associated with fire. Ring restrained concrete specimens were used in this study. Comparison with results of spalling test in this study and results of fire tests RC column from previous paper[1] were discussed.

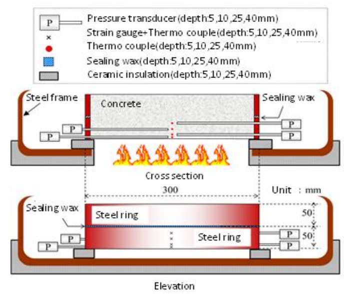

Figure 1. Ring restrained specimen

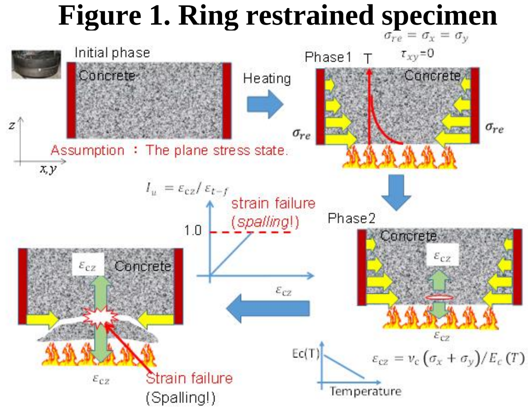

Figure 2. Tensile strain failure model

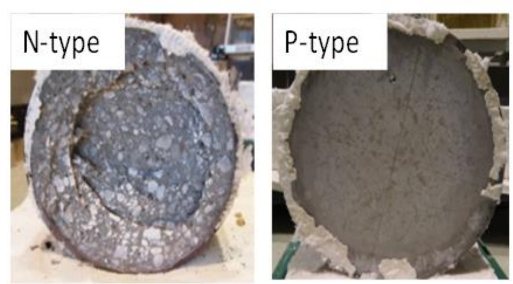

Figure 3. Spalling results of ring specimens

2. Fire tests of RC columns [1]

Morita et al.[1] reported loading and heating tests of RC columns. Cross section of RC column was 450mm*450mm and high:3500mm. Main reinforcement ratio was 1.13% and steel deformed bar and diameter was 19mm, yield point was 345MPa. Stirrup of reinforcement ratio was 0.47% and diameter of steel deformed-bar was 10mm, yield point was 295MPa. Cover depth of concrete was 40mm. Axial loading ratio was 0.33. Heating curve was used for ISO834.

3. Experimental outline

The mixtures were high-strength concrete (N-type) and high-strength concrete with PP fibers (P-type). Limestone was used as coarse aggregate with moderate-heat Portland cement. The compressive strengths of N-type concrete and P-type concrete were 96 and 109 MPa, respectively, at 28 days. Figure 1 shows the configuration and dimensions of the two experimental specimens with a pair of steel rings each (diameter: 300 mm; thickness: 8 mm; length: 50 mm). The heating tests were based on a ISO834 heating curve. Strain gauges and thermocouples were attached 5, 10, 25 and 40 mm from the heated surface and the outer surface of the steel ring.

4. Estimation of Thermal stress and spalling depth

Thermal stress calculation was based on the thin-walled cylinder model theory as shown by Eqs. (1). Vapor pressure was measured at 5, 10, 25 and 40 mm from the heated surface.

$$\sigma_{re} = \varepsilon_\theta \cdot E_s \cdot t / R \quad .... (1)$$

Figure 2 shows a tensile strain failure model of explosive spalling under thermal stress. It assumes to consider the plane stress state. The strain along the z-axis at a depth from the heated surface was calculated using from Eq. (2) to eq.(4), and the index of the strain failure model was determined using Eq. (5).
Tensile strain failure occurred when the index of the strain failure model exceeded 1.0 ($I_u > 1.0$).

$$\sigma_{re} = \sigma_x = \sigma_y \quad ....(2), \qquad \tau_{xy} = 0..... \quad (3),$$
$$\varepsilon_z = \nu(\sigma_x + \sigma_y) / E_c(T) .... (4), \qquad I_u = \varepsilon_z / \varepsilon_{tf} .... (5)$$

5. Results and discussion

Figure 3 and 4[1] show the results of fire spalling tests conducted on the ring specimens at the one-month stage and fire test results from reference at the three months. With N-type concrete, the ring specimen exhibited spalling. The RC column specimen was severely damaged in N-type concrete. The P-type ring restrained specimen exhibited no spalling. The RC column specimen was damaged with corner spalling evident in P-type concrete. Figure 5 shows vapor pressure at 5, 10, 25 and 40 mm from the heated surface with respect to heating time for the N-type ring restrained specimens, respectively. Vapor pressure was drastically increased with N-type concrete, but decreased at 5 and 10 mm when spalling occurred. Vapor pressure in P-type concrete was lower due to the correlation between the build-up of vapor pressure and the melting point of PP fibers. Figure 6 shows the results of restrained stress calculation based on ring strain at 5, 10, 25 and 40 mm from the heated surface for the N-type and P-type specimens with respect to time. The maximum was 20 MPa at 5 mm from the heating surface after 35 minutes for N-type concrete, and the value decreased when spalling occurred. Restrained stress was stable from 10 to 25 minutes, which was the spalling period. Figure 7 compares experimental and estimated spalling depths for N-type concrete, whose maximum was 55 mm at 35 min. The maximum spalling depth in N-type concrete was estimated to be about 40 mm at 33 minutes. These outcomes clearly indicate that the proposed model can be used to estimate spalling depth in N-type specimens up to about 27 minutes from the start of heating.

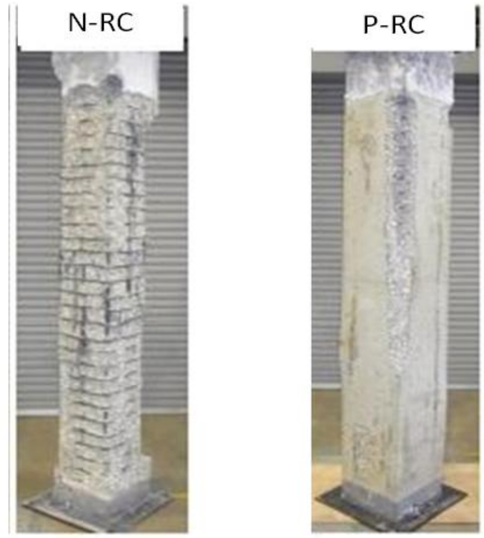

Figure 4. Spalling results of RC columns

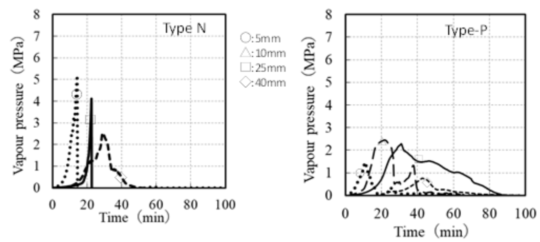

Figure 5. Vapour pressure

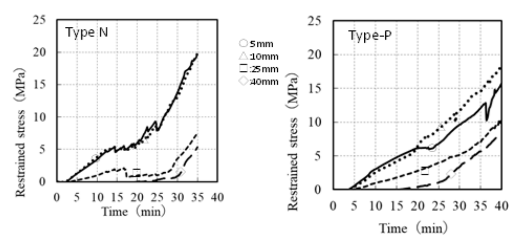

Figure 6. Restrained stress

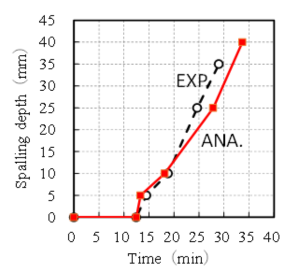

Figure 7. Spalling depth and time

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METHODS TO ACHIEVE SELF-EXTINGUISHMENT FOR HIGH-RISE MASS TIMBER BUILDINGS

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ARUP North America, USA [2]

Introduction

Recent trends have led to an increased number of tall mass timber buildings. This trend is stimulated by an increased emphasis on sustainable building and by changes of regulations in many countries. Cross Laminated Timber (CLT) is a building product that is increasingly used, due to its structural properties and relatively low carbon footprint. High-rise mass timber buildings face a number of fire safety challenges, partly because external firefighting may not be possible, given a high-rise building must remain structurally stable through full fire development until fire self- extinguishment, in the highly unlikely scenario of sprinkler failure.
Multiple recent compartment fire tests with large areas of exposed CLT have indicated that fires may not decay, caused by char fall off (delamination); or caused by protective gypsum board failure. In both situations, the timber surfaces become exposed to the high temperatures and heat fluxes of the fire, preventing self-extinguishment. Preventing CLT char fall off or gypsum protection failure is an important fire safety issue for high-rise mass timber buildings. Self-extinguishment is considered to have occurred when the heat release rate drops below 500kW.

Review of relevant fire tests

A review of 24 recent compartment fire tests was performed (including tests by Fire Protection Research Foundation, NRC Canada, RISE, Carleton University, University of Edinburgh, University of Queensland, TU Delft, International Code Council and Southwest Research Institute). Additionally, small scale experimental studies of the influence of CLT adhesive type were reviewed.

Methods to Allow Self-Extinguishment

There are several options for mass timber structures that use exposed CLT to reach self-extinguishment, in a fully developed fire. These are discussed below.

Adhesive product

Results from one series of full-size CLT compartment fire tests were used as a basis to study the influence of adhesives on char fall off. The fire plate thermometer temperature and the oxygen concentration from a test carried out by NIST was replicated in a small-scale furnace of 1m x 1m x 1m. CLT specimens with four different adhesives, but similar dimensions, species, density and moisture content were tested in the furnace conditions. To validate the test method, gas temperature, incident heat flux by radiation, charring rates and char fall off time, were compared between the full-size compartment test and the small-scale test for the same CLT product. Results show that the use of different adhesives can result in a significantly different fire performance of CLT in natural fires. The tests indicate that CLT with a melamine formaldehyde (MF) adhesive and a specifically formulated polyurethane adhesives (PUR) do not exhibit char fall off, in compartment fire conditions. Compartment fire tests, standard fire tests, and cone calorimeter tests have led to the same conclusion. Studies using different timber, CLT dimension, different production process and different fire exposure, showed that CLT with the identified adhesives do not have char fall off.

Thickness of the outer lamella

Crielaard first proposed a method to avoid char fall off, assuming parametric fire curves and that char fall off does not occur in a bond line if the char layer does not reach the bond line. A compartment fire test performed in Estonia involved exposed CLT with adhesive that is susceptible to char fall off, and an increased thickness of the outer lamella (40mm). The experimental study showed that an increased thickness of the lamella can postpone or potentially prevent char fall off, due to a delay of temperature increase in the bond line. However, it was shown that char fall-off cannot be prevented in all realistic scenarios, as the lamella thickness has an upper limit in practice. As there are multiple uncertainties in this approach, a method to achieve self-extinguishment involving an increased lamella thickness is not considered a reliable solution.

Limitation of exposed surface area

The compartment fire can result in self-extinguishment if the area of exposed mass timber is limited. Based on opening-factor-dependent charring rates for CLT without char fall off, the amount of exposed CLT that would result in a ventilation controlled (fully developed) fire, even after all moveable fuel is consumed, is dependent on the opening factor of the compartment. The maximum allowable area of exposed CLT is directly proportional to the opening factor. While test results available are limited to validate such an expression, the authors are developing work in this area and will present the work to date.

Protection of CLT

A method to prevent CLT char fall off is to protect the CLT with gypsum board that remains in place and prevents charring, for the full duration of the fire, through to decay. The CLT protection must remain in place for the growth, fully developed and decay phase of the fire. The reliability of the gypsum protection must be based on evidential fire tests with CLT. Preventing fall-off of gypsum does not necessarily prevent the timber contributing to the fuel load of the fire, because it is possible that the protected timber still chars. Therefore, a method is proposed involving numerical predictions of temperatures throughout the wall, ceiling or floor, using parametric fires as a basis. The method is compared to experimental results of compartment fire tests and discussed. Conservative empirical relationships between the start time of charring and the opening factor were determined using the predictions.

Conclusions

CLT char fall off and gypsum board failure should be avoided to achieve self-extinguishing fires. To avoid char fall off within CLT, a method involving charring rates corresponding to parametric fires can be used, but has uncertainties. However, the use of adhesive that prevent char fall off provides a robust solution to ensure self-extinguishment. Proposed expressions for failure times of the first and second layer of gypsum board for ceiling and, separately, for walls can be used to determine the number of gypsum boards needed to prevent failure, for a known compartment. Also, conservative limits for the amount of CLT exposed are given, based on test results of compartments involving different opening factors.

COMPARTMENT FIRE EXPERIMENTS OF COMPOSITE FLOOR BEAM ASSEMBLIES

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Abstract

Steel-concrete composite floor systems are widely used in the construction of steel-framed buildings. However, the behavior of the composite floor systems subjected to fire can be complex because of dissimilar high-temperature behavior of individual elements (steel beam, concrete slab, and connections) and due to restraints provided by the adjoining structural framing. Characterizing the structural-fire behavior of composite floor systems through standard fire testing and using available standard equations is very challenging.

A recent test program on the steel-concrete composite beam experiments conducted in the National Fire Research Laboratory (NFRL)[1] of the National Institute of Standards and Technology (NIST) is presented here. The test program was aimed to evaluate the behavior and modes of failure of four 12.8 m long composite floor beam assemblies, designed in accordance with U.S. standards, when subjected to mechanical loads and a structurally significant fire. Each specimen consisted of a W18x35 beam and a 1.83 m wide lightweight concrete slab that were made composite using headed shear studs. The test beam was supported by braced steel columns via shear connections (Fig.1). The steel beams of the fire test specimens were coated with sprayed fire resistive materials for 2-hour fire resistance rating. For fire experiments, the specimens were hydraulically loaded to 45% of bending moment capacity at ambient temperature. A maximum 4 MW of thermal load was produced using three 1 m by 1.5 m natural gas fueled burners to produce an upper layer gas temperature of about 1000 °C. The fire was confined under the specimen using enclosure walls (Fig. 2). The influence of beam connections, including bolted/welded double-angles and single-plate shear connections, and that of slab continuity over primary girders on the fire behavior of the composite beam specimens were experimentally evaluated.

The temperature, displacement, and load measurements were conducted to characterize the behavior of composite beam specimens subjected to fire. The test results indicated that the steel beams of all four specimens bound to the support columns due to thermal elongation and stiffness degradation of the specimen, which resulted in buckling of the beam ends. However, the vertical displacement of specimens reached to the ratio of span length over 20 without collapse, and the connection failure (weld or bolt fracture) occurred during the heating and cooling phases. The results from this large-scale test program will be used for the validation of computational models, for the understanding of complex behavior of structural assemblies, and ultimately, to

help advance the development of performance based design methodologies for structures subjected to fire.

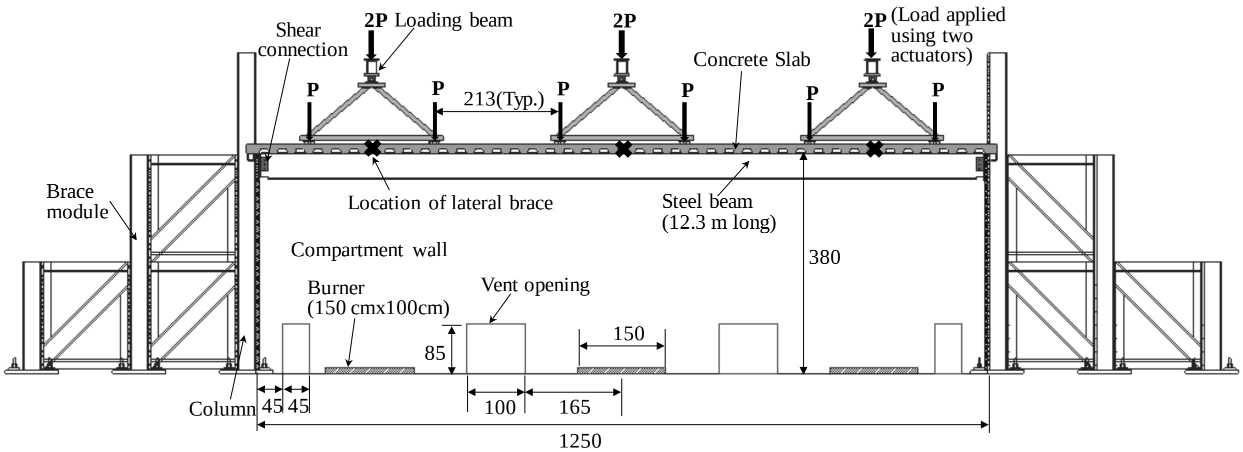

Figure 1. Test setup - Front view (unit: cm)

(a) (b)

Figure 2. Test setup views: (a) outside and (b) inside the compartment wall

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Case Study: Using Performance-Based Structural Fire Engineering to Determine the Progressive collapse mechanisms of steel-frame buildings due to moving fires

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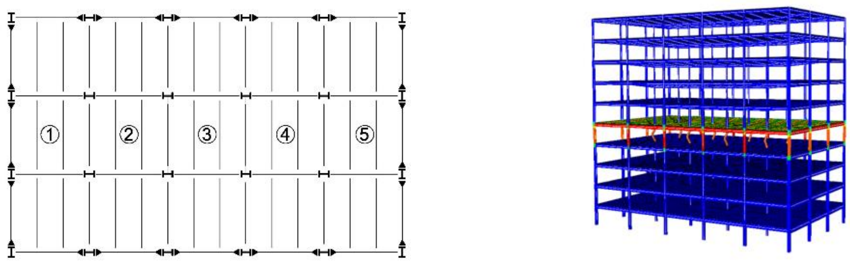
Documented observations from large-scale fire experiments and from real building fires show that accidental fires in large compartments do not burn simultaneously throughout the whole floor plate. Rather, fires move across the floor plate burning specific areas. The tests performed at Cardington[1] showed that large temperature deviations occurred across the floors. Sometimes these temperature variations were in excess of 200°C. In addition, the fires at the World Trade Center[2], the Windsor Tower in Madrid, Spain[3], and the Faculty of Architecture building at TU Delft in the Netherlands[4] all showed that fires travel across the floor plates rather than burn uniformly. These fires (both experimental and accidental) burned well in excess of the time periods designed for using traditional design methods. This is primarily because traditional design methods assume that the fire will burn uniformly on one floor only. This research examined the fire behavior of a building subjected to moving fires using different fire models ranging from simplistic to complex. The objective of the research was to quantify the comparisons between the models to provide feedback to the structural fire engineering community on the benefits of using complex models and the issues that may arise when models are too simplified. This research also highlights when complex models may be necessary to simulate the performance of a building, and when the complexity does not result in a substantial benefit to the project.

The fire models were applied to a ten-story steel-framed building with exterior moment resisting frames (MRF). The displacement of the members was calculated as a result of the moving fires. Three different moving fire models were examined in a building with both prescriptive design fire resistance rating (FRR) on structural members (columns, beams, girders), and performance-based design approaches for the thickness of the fire resistance material. This building represents a typical building found in Chicago, IL and meets the requirements of U.S. codes and standards[5-7]. The building was subjected to three different moving fire models on the fifth floor: (1) simplified fire model where the fire is ignited in neighboring bays and the effect of fire dynamics is ignored[8], (2) the Travelling Fire Methodology[9, 10] developed at University of Edinburgh, and (3) computational fluid dynamics fire modeling using the NIST Fire Dynamics Simulator.

The analysis used Eurocode[11, 12] thermal and mechanical material properties for the structural steel components and lightweight concrete and fire protection thermal properties per AISC Design Guide 19[13]. Each model contained two parts: (1) heat transfer analysis to obtain the temperature distribution through the cross section of each member, and (2) structural analysis to simulate instabilities or failures within the building due to the imposed mechanical and thermal loads. The analysis assumed a one-zone fire model with uniform temperatures along the length of the beams, and fuel evenly distributed across the floor plate. The structural response was characterized by the displacements of each of the structural components. Figure 1a shows the pathway for the moving fire scenarios and Figure 1b shows the resulting quantification of the damaged floor plan due to the moving fire. Each fire is assumed to have a constant burning time (t_b) dependent upon a fire load density and a constant release rate for the area of the fire.

The results of these moving fire simulations were compared with full-story fires using the same FRR on the structural members. Performing advanced fire analysis for moving fires in a building can result in many different permutations for movement of fires around floor plates of buildings The results of this research show that consideration of fire dynamics is imperative to determine the collapse time and temperature of a building subjected to a moving fire. Elevated smoke temperatures greatly influence the gas temperature of a compartment and therefore the collapse mechanisms between the three fire models was different. While consideration of fire dynamics results in column buckling sooner during the *T-t* definition of the fire, it also results at a lower temperature. The progression of column buckling also does not follow the progression of the travelling fire. Whereas the first column to buckle is between Bays 3 and 4 when considering fire dynamics and near and far field.



(a) (b)

Figure 1. (a) Floor plan showing path of moving fire, and (b) FEM results showing damage to structural members

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SIMPLIFIED CALCULATION PROCEDURE FOR EVALUATING THE FIRE RESISTANCE OF REINFORCED CONCRETE WALLS

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Evaluating the ultimate load bearing capacity of reinforced concrete (RC) members subjected to fire loading conditions has gained increasing attention over the last twenty years. Attention has been more particularly focused on the determination of axial force-bending moment interaction diagrams of a reinforced concrete section subjected to a fire induced temperature gradient (see for example Caldas *et al.*, 2010 [1]; Law and Gillie, 2010 [2] or recently Pham *et al.*, 2015 [3]).

This contribution is focused on assessing the structural stability of RC walls subjected to a constant load applied on their top and a uniform temperature gradient along their height. Indeed, when subjecting a structural element such as wall to fire, due to the thermal-induced deformations, such slender structures exhibit out-of-plane (horizontal) displacements, which in turn lead to an eccentricity of the vertical load with respect to the initial plane. As a consequence, bending moments are generated in the wall in addition to the pre-existing compressive axial force, which is usually known as a second order (or P-delta) effect (see for instance the classical textbook of Bazant and Cedolin, 2010 [4]). As the eccentricity increases, the moment due to vertical load eccentricity also increases, thus subjecting the wall to higher bending moments and associated curvature deformations. Simultaneously, elevated temperature leads to a degradation of constituent materials. Consequently, it is the combined effect of fire-induced material strength degradation and developing bending effects due to geometry change, which may trigger the overall failure of the structure.

According to the approach proposed by Pham *et al.*, 2015 [5], the calculation could be performed on a simplified one-dimensional (1D) model of the wall, schematized as an initially straight vertical beam articulated at both ends as shown in Fig. 1, the bottom end being kept fixed, while the top end is free to translate vertically. For evaluating the stability of the structure, the combined bending moments-axial forces distributions resulting from the equilibrium of the wall in its deformed shape, should be compared with the (N, M) interaction diagram modified by the applied thermal loading. More precisely, for a given axial force, the stability of the wall could be ensured as far as the maximum bending moment solicitation (theoretically at the middle height of the wall) remains smaller than the bending moment resistance value corresponding to this axial force.

In the present work, the geometric configuration of the RC wall could be analytically determined from a preliminary thermo-elastic calculation accounting for geometrically non-linear second order effects. The thermo-elastic constitutive behaviour of concrete subjected to temperature increase must take the so-called Load Induced Thermal Strain (LITS: see for example Law and Gillie, 2008 [6]) into account. This is achieved here by considering that the concrete Young's modulus is a decreasing function of the temperature increase, that is by applying a reduction factor to the modulus at ambient temperature. As a result, a closed-form expression of such a deformed shape can be obtained for any prescribed temperature profile. Furthermore, a very good agreement was also obtained when comparing the results of the present formulation with those predicted by numerical simulations.

Due to its simplicity, the model and related calculation procedure are particularly well suited for a preliminary engineering design of RC wall in fire, providing useful guidelines in the crucial matter of structural safety assessment. It allows performing parametric studies in a rather quick way, without it being necessary to resort to complex numerical simulations.

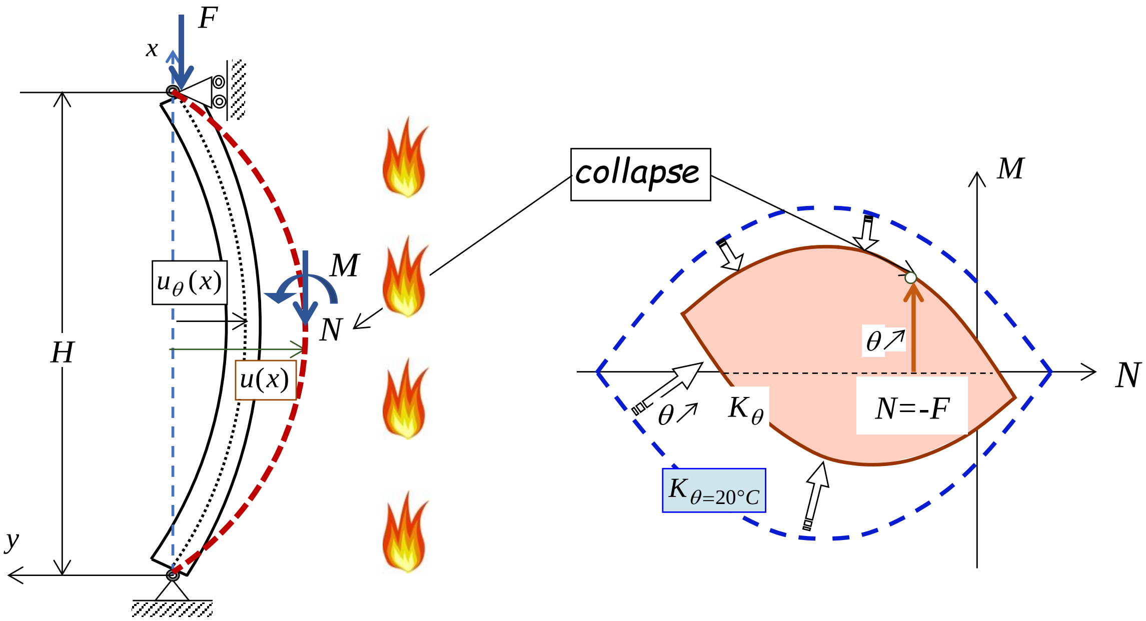

Figure 1. Principle of the stability analysis of the wall in its deformed configuration

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ASSESSMENT OF TALL BUILDINGS SUBJECTED TO MULTI-STOREY FIRES

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INTRODUCTION/KNOWLEDGE GAP

Fire induced progressive collapse of tall buildings represents a high consequence event due to their occupant profile and importance for the surrounding community. The fire induced collapse of a number of tall buildings such as the WTC towers, Windsor Tower, the Plasco Building and the Delft University Building among others have posed questions with regards to the stability of tall buildings in the event of multi-storey fires. For tall buildings, prescriptive guidance generally sets the provision of compartment floors to restrict fire and smoke spread and avoid the potential of a multi-storey fire. However, for modern arrangements with atriums, open stairs or other open voids, designers need to consider the risk of fire spread between storeys (where other passive or active fire safety measures are not provided).

This assessment in addition to other fire safety components such as means of escape or fire-fighting access, although often ignored in practice, needs to consider the potential structural response of the building. The potential thermal expansion effects from multi-storey fires are ignored when isolated elements are tested in accordance with prescriptive guidance or when single element based structural fire engineering methods have been adopted. A holistic methodology for the structural design of tall buildings under multi-storey fires will be presented in this paper based on the authors' experience of research and application on a number of commercial projects.

FAILURE MECHANISMS UNDER MULTI-STOREY FIRES

A number of previous studies have studied the structural response of tall buildings under multi-storey fires. The collapse mechanisms of composite structures similar to the WTC Towers with long-span perimeter truss floor or universal beams were considered by [1,2] and subsequently a closed form equation was proposed by [3] as an assessment method of structural failure under multi-storey fires. The potential for vertical travelling fires with an inter-storey time delay were considered by [4,5] that highlighted that they could introduce different structural responses.

The potential failure mechanisms of different structural forms will be covered in the paper based on a wide range of buildings that have been analysed by the authors and the effect of the number of floors on fire in the resulting structural response and failure mechanism. A discussion on whether simultaneous or vertically travelling fires need to be considered will also be provided in the paper. The applicability of the closed form solution proposed by [3] will be reviewed from a design context and its boundaries of application will be established.

INTRODUCTION/KNOWLEDGE GAP

A discussion will be provided on the conceptual finite element models that need to be adopted drawing from Arup's experience for a number of tall building projects. This will include the definition of boundary conditions, how many storeys need to be considered in the models and which parts of the building are most critical (internal vs perimeter frames). The paper will also consider how different mitigation measures can be assessed through the use of force-moment interaction diagrams in parallel with finite element modelling.

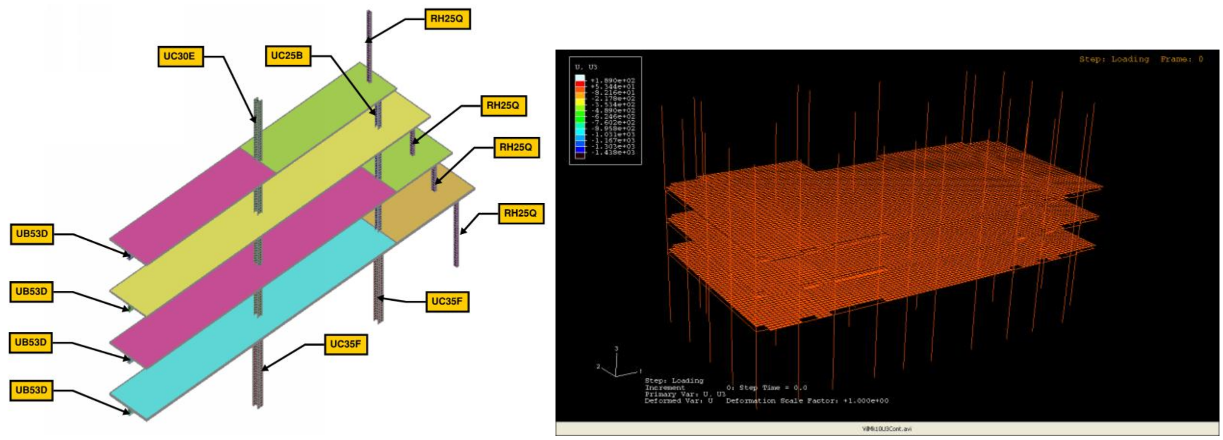

Figure 1 Indicative models that can be adopted depending on the building characteristics

CONCLUSIONS AND NEXT STEPS

This paper presents a holistic methodology for the structural design of tall buildings under multi-storey fires. From the research undertaken and the range of building forms analysed, mitigation measures to the structural and fire protection design typically include: 1) limiting the maximum steel temperature of key structural members by increasing fire protection thickness, 2) increasing section capacities of structural members (typically columns due to p-delta effects) 3) increasing the capacity of connections to accommodate the thermally induced forces.

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