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Summary of Workshop for Fire-Structure Interaction and Large Outdoor Fires

Operation Tomodachi: Fire Research

Samuel L. Manzello
Sayaka Suzuki

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1. Introduction
1.1 Workshop Objectives

NIST's Engineering Laboratory (EL-NIST) hosted "*Operation Tomodachi – Fire Research*" on March 16-18, 2015 in Gaithersburg, MD USA. Tomodachi means friendship in Japanese. This workshop was organized by Dr. Samuel L. Manzello of EL-NIST in partnership with the Japan Association for Fire Science and Engineering (JAFSE). This was a formal continuation of the kickoff meeting held at EL-NIST in June, 2011. Due to the success of the kickoff meeting, EL-NIST signed a Statement of Intent with JAFSE to hold two more workshops, the first held in Tokyo in 2012 (see Manzello *et al*., *Fire Safety Journal* 59: 122-131, 2013, for a summary of that workshop), and this workshop held at EL-NIST, March 16-18, 2015. The objective of the March, 2015 workshop at EL-NIST was to: (1) exchange scientific knowledge to enable its translation into building codes and standards that will be of use to both countries to reduce the devastation caused by unwanted fires, (2) provide a forum for next generation researchers to present their work in order to develop research collaborations, (3) and allow participants a chance to visit EL-NIST's newly expanded National Fire Research Laboratory (NFRL).

Oral presentations were focused on two topics: Large Outdoor Fires (LOF) and Fire-Structure Interaction (FSI). The final program included oral presentations from the following organizations in the USA: NIST, Insurance Institute for Business and Home Safety (IBHS), California Polytechnic University (CALPOLY), University of Maryland, United States Forest Service (Madison and Missoula), Simpson, Gumpert and Heger, University of Michigan, Purdue University, Worcester Polytechnic Institute (WPI), University of Texas-Austin, and Michigan State University. Oral presentation from Japan were delivered by: National Research Institute of Fire and Disaster (NRIFD), National Institute for Land and Infrastructure Management (NILIM), Building Research Institute (BRI), Nagoya University, Toyohashi University of Technology, Tokyo University of Science, Kajima Corporation, Takenaka Corporation, Chiba University, Taisei Corporation, University of Tokyo, Hirosaki University, and Kyoto University (all organizations are listed based on the order of oral presentation). In addition, poster sessions were held in the areas of LOF and FSI, as well as two general fire safety science (GFSS) poster sessions.

This report is organized into specific sections with appendices. Specifically, Section 1.2 is the oral and poster presentation schedule, Section 1.3 is participant listing, and there are four appendices that contain the oral presentation abstracts (Appendix 1), poster presentation abstracts (Appendix 2), oral presentations delivered at the workshop (Appendix 3), and poster presentations delivered at the workshop (Appendix 4).

1.2 Program of Workshop

March 16, 2015 (Green Auditorium, NIST)

9:00 am	***Welcome to NIST*** ***Dr. Howard Harary, Director, Engineering Laboratory, NIST, USA***
9:10 am	***Operation Tomodachi – Fire Research*** ***Dr. Samuel L. Manzello, Organizer, Engineering Laboratory, NIST,USA***
	Plenary lectures – Large Outdoor Fires (LOF)
9:20 am	***Large Outdoor Fires in USA: What is the Problem?*** ***Mr. Nelson Bryner, Engineering Laboratory, NIST, USA***
9:30 am	***Large Outdoor Fires in Japan: What is the Problem?*** ***Dr. Tokiyoshi Yamada, National Research Institute of Fire and Disaster, JAPAN***
9:40 am	**Panel Discussion Bryner/Yamada** **Chair Sayaka Suzuki/NRIFD**
	Physical Aspects of Fire Spread and Ignition **Large Outdoor Fire Session I**
10:00 am	***Fire Spread Caused by Combustible Facades*** ***Dr. Hideki Yoshioka, National Institute of Land and Infrastructure Management, JAPAN***
10:15 am	***Hardening Structures to Wildland-Urban Interface (WUI) Fire Exposures*** ***Dr. Samuel L. Manzello, Engineering Laboratory, NIST, USA***
10:30 am	***A Study on the Urban Fire in Inundated Areas Following a Tsunami*** ***Dr. Tomoaki Nishino, Building Research Institute, JAPAN***
10:45 am	***Evaluating Ember Entry into Attic Vents*** ***Dr. Steve Quarles, Insurance Institute for Business and Home Safety (IBHS), USA***
11:00 am	**Panel Discussion Yoshioka/Manzello/Nishino/Quarles** **Chair Sayaka Suzuki/NRIFD**
11:20 am	**Poster Session – Fire-Structure Interaction (FSI)**
11:50 pm	**Lunch**
	Large Outdoor Fire Hazards **Large Outdoor Fire Session II**
1:00 pm	***Temporal Changes to Wildfire Risk in the Wildland-Urban Interface*** ***Dr. Chris Dicus, California Polytechnic State University, USA***
1:15 pm	***Estimation of Loss Due to Anticipated Post-Earthquake Fires in the Tokyo Metropolitan Area*** ***Dr. Keisuke Himoto, Building Research Institute, JAPAN***
1:30 pm	***Questionnaires Survey on Fires after the Great Disasters in Eastern Japan and its Application*** ***Dr. Yu Hiroi, Nagoya University, JAPAN***
1:45 pm	***Assessing Conditions for the Development of Wind-Driven Horizontal Fire Vortices*** ***Dr. Kathy Butler, Engineering Laboratory, NIST, USA***
2:00 pm	**Panel Discussion Dicus/Himoto/Hiroi/Butler** **Chair Yuji Nakamura/Toyohashi University**

2: 20 pm	**Coffee Break**
	Physical Aspects of Fire Spread and Ignition **Large Outdoor Fire Session III**
2: 40 pm	***Modeling Wildland Fire Propagation: Physical Processes and Real Time Data-Driven Modeling*** ***Dr. Michael Gollner and Dr. Arnaud Trouve, University of Maryland, USA***
2:55 pm	***Overview of NRIFD Fire Research/Development of Evaluation Methods for Firebrand Ignitions*** ***Dr. Sayaka Suzuki, National Research Institute of Fire and Disaster, JAPAN***
3: 10 pm	***The Effect of Wind on the Burning Rate*** ***Dr. Sara McAllister, United States Forest Service – Montana, USA***
3: 25 pm	***Feasibility of Limiting Oxygen Index (LOI) as Material Flammability Classification*** ***Dr. Yuji Nakamura, Toyohashi University of Technology, JAPAN***
3:40 pm	**Panel Discussion Gollner/Trouve/Suzuki/McAllister/Nakamura** **Chair Hideki Yoshioka/NILIM**
4:00 pm	**Fire Safety Science Poster Session 1**
5:00 pm	**Adjourn**

Poster Session – Fire Structure Interaction (Monday 3/16) 11:20 am to 12:00 pm

V. Kodur (Michigan State University), Effect of High Temperature Creep on Response of Concrete Structures Exposed to Fire (Poster file not provided)

T. Mizukami (BRI), Determination of Design Fire Load for Structural Fire Safety Design of Building in the Compartment Subdivided by Non-fire Rating Partitions

A. Amikura (Kyoto University), Experimental Study on Influence of Crack Width on Fire Resistance of Reinforced Concrete Members

M. Nishiyama (Kyoto University), Fire Resistance of Reinforced Concrete Frames Subjected to Service Loads

Y. Shitani (Takenaka Corporation), A Study on the Effect of the Collapse Time of Partition and the Opening Pattern of the Rooms on the Severity of a Fully developed Fire

H. Yamashita (JTCCM), Influence of Water Content on Load-Induced Thermal Strain of High-Strength Concrete

C. Zhang (NIST), New Insights on Thermal Calculation of Structures in Fire (Poster file not provided)

Poster Session – General Fire Safety Science I (Monday 3/16) 4:00 pm to 4:40 pm

R. McDermott (NIST), A Hybrid Cutcell (Immersed Boundary) Method for Low-Mach Flows

C. Zhang (University of Maryland), Towards Data-Driven Operational Wildfire Spread Modeling (Poster file not provided)

C. Weinschenk (NIST), Characterizing the Performance of Firefighter Equipment

X. Liu (University of Maryland), An Investigation of Thermally-Induced Failure of Lithium Ion Batteries (Poster file not provided)

T. Cleary (NIST), Smoke Detector Research at NIST (Poster file not provided)

S. Suzuki (NRIFD), Overview of Research Facilities at NRIFD

K. Matsuyama (TUS), Overview of Research Facilities at TUS

M. Noaki (TUS), Experiments on Suppression of Some Combustible Fire by Sprinkler System under Free Burning Conditions

March 17, 2015 (Green Auditorium, NIST)

	Plenary Lectures Fire-Structure Interaction (FSI)
9:00 am	***The Problem of Fire Safety Design in Japan*** ***Dr. Kenichi Ikeda, Formerly Shimizu Corporation, Tokyo University of Science, JAPAN***
9:10 am	***Fire-Structure Interaction: U.S. Perspective*** ***Dr. John Gross, Engineering Laboratory, NIST, USA***
9:20 am	**Panel Discussion Ikeda/Gross** **Chair Nelson Bryner/NIST**
9:40 am	**Poster Session Large Outdoor Fires (LOF)**
	Fire Resistant Structures **Fire-Structure Interaction Session I**
10:20am	***U.S. Standards that Support Structural Fire Engineering Practice*** ***Mr. Kevin LaMalva, Simpson, Gumpert and Heger, USA***
10:35am	***Development of Fire-Resistant Wooden Structure*** ***Mr. Kouta Nishimura, Kajima Corporation, JAPAN***
10:50 am	***Research Priorities for Structure Fire Interaction – the CIB and NIST Perspectives*** ***Dr. Jiann Yang, Engineering Laboratory, NIST, USA***
11:05 am	**Panel Discussion LaMalva/Nishimura/Yang** **Chair Nelson Bryner/NIST**
11:25 am	**Lunch**
	Physical Aspects of Fire-Structure Interaction **Fire-Structure Interaction Session II**
1:00 pm	***Multiphysics Simulation of Fire-Structure Interaction*** ***Dr. Ann Jeffers, University of Michigan, USA***
1:15 pm	***Thermal Elongation of Steel Beams Constrained by RC Slab and Adjacent Frames*** ***Mr. Tomohito Okazaki, Takenaka Corporation, JAPAN***
1:30 pm	***Behavior and Design of Composite Beams and Floors for Fire Loading*** ***Dr. Amit Varma, Purdue University, USA***
1:45 pm	***A Simple Model for Fire Resistance of Steel Beams Under Non-Uniform Temperature Distribution.*** ***Dr. Takeo Hirashima, Chiba University, JAPAN***
2:00 pm	**Panel Discussion Jeffers/Okazaki/Varma/Hirashima** **Chair Faith Berry/NFPA**
2:20 pm	**Coffee Break**
	Physical Aspects of Fire-Structure Interaction **Fire-Structure Interaction Session III**
2:40 pm	***Fire Performance in Earthquake Damaged Buildings: Overview and Key Outcomes from the BNCS Full-Scale Experiments Project*** ***Dr. Brian Meacham, Worcester Polytechnic Institute (WPI), USA***
2:55 pm	***Experimental Study on Fire Resistance of Mid-Rise Steel Construction Exposed to Post-Earthquake Fire*** ***Dr. Tomohiro Naruse, Building Research Institute, JAPAN***

3:05 pm	***Lessons Learned from the May 13, 2008 Fire and Collapse of the Faculty of Architecture Building, Delft University of Technology*** ***Dr. Michael Engelhardt, University of Texas-Austin, USA***	
3: 20 pm	***Structural Performance of Tunneling Shields in Fire*** ***Dr. Shigeaki Baba, Taisei Corporation, JAPAN***	
3:35 pm	**Panel Discussion Meacham/Naruse/Engelhardt/Baba** **Chair Faith Berry/NFPA**	
4:00 pm	**Fire Safety Science Poster Session II**	
5:00 pm	**Adjourn**	

Poster Session – Large Outdoor Fires (Tuesday 3/17) 9:40 am to 10:20 am

K. Kuwana (Yamagata University), Scale-Model Experiment of Fire Whirl Behind an L-shaped Wall
G. Forney (NIST), Visualizing Outdoor Fire and Smoke Data
E. Johnsson (NIST), Characterization of Fire Spread along Fences
D. Evans (Home Safety Foundation), Hwy 31 Fire – A Study of a Residential Community Attacked by Wildfire in the Night
W. Tang (University of Maryland), Scale Modelling of Wildland Fires Using Stationary Fires
A. Maranghides (NIST), 2011 Wildland Urban Interface Amarillo Fires Report #2 – Assessment of WUI Measurement Science and Fire Behavior (Poster file not provided)
A. Maranghides (NIST), A Case Study of a Community Affected by the Waldo Fire – Event Timeline and Defensive Actions (Poster file not provided)

Poster Session – General Fire Safety Science II (Tuesday 3/17) 4:00 pm to 4:40 pm

K. Ido (Shimizu Corporation), A Simple Method of Burning and Surface Flame Spread of a Cubical-Shaped Polyurethane Foam Block
S. Nazare (NIST), Evaluating Fire Blocking Performance of Barrier Fabrics
M. Zammarano (NIST), Identifying a Near-worst Case Scenario for Smoldering Upholstered Furniture
W. Pitts (NIST), Fire Spread and Growth on Real-Scale Upholstered Furniture Mock-ups (Poster file not provided)
A. Singh (University of Maryland), A Methodology for Estimation of Local Heat Fluxes in Steady Laminar Boundary Layer Diffusion Flames
K. Matsuyama (TUS), A Fundamental Study for Application of THz Electromagnetic Waves to Fire Safety Technology -Absorption and Transmittance of THz Electromagnetic Waves through Artificial Smoke Environments (Poster file not provided)

March 18, 2015 (Green Auditorium, NIST)

	Large Outdoor Fires (LOF)
	Physical Aspects of Fire Spread and Ignition **Large Outdoor Fie Session IV**
9:00 am	***Validation Studies of Home Damaging and Ignitability Modeling of Vegetation Fire Radiant Exposure*** ***Dr. Mark Dietenberger, United States Forest Service –Wisconsin, USA***
9:15 am	***Experimental Study on the Generation of Fire Whirls*** ***Dr. Ritsu Dobashi, University of Tokyo, JAPAN***
9:30 am	***Characterization of Wildland Fire Brush Burning and Ember Generation*** ***Dr. O.A. Ezekoye, University of Texas-Austin, USA***
9:45 am	***Fire Extinguishment by Using Ice Capsule Filled with Liquid Nitrogen*** ***Dr. Hiroyuki Torikai, Hirosaki University, JAPAN***
10:00 am	**Panel Discussion Dietenberger/Dobashi/Ezekoye/Torikai** **Chair William Pitts/NIST**
10:20 am	**Coffee Break**
	Physical Aspects of Fire-Structure Interaction **Fire-Structure Interaction Session IV**
10:45 am	***A Practical Computer Code for Prediction of Thermal Response of Timber Structural Elements During Heating and Post Heating Self-Burning Period*** ***Dr. Kazunori Harada, Kyoto University, JAPAN***
11:00 am	***Simple Calculation Method for Estimating Thermal Resistance of Wall Under Designed Conditions*** ***Dr. Tensei Mizukami, Building Research Institute, JAPAN***
11:15 am	***Fire Resistance of Timber Panel Structures*** ***Dr. Jun-ichi Suzuki, National Institute of Land and Infrastructure Management, JAPAN***
11:30 am	***An Approach for Ascertaining Residual Capacity of Reinforced Concrete Beams Exposed to Fire*** ***Dr. Venkatesh Kodur, Michigan State University, USA***
11:45 am	**Panel Discussion Harada/Mizukami/Suzuki/Kodur** **Chair Rodney Bryant/NIST**
12:20 pm	**Lunch**
	NIST's National Fire Research Laboratory (NFRL)
1:40 pm	***Structural Fire Measurement Capabilities at the National Fire Research Laboratory*** ***Dr. Matthew Bundy, Engineering Laboratory, NIST, USA***
1:55 pm	***Experimental Design of the Large-scale Floor System Subjected to a Fire*** ***Dr. Lisa Choe, Engineering Laboratory, NIST, USA***
2:05 pm	***Dr. William Grosshandler, A Design Fire for Full-scale Steel Structure/Fire Experiments, Engineering Laboratory, NIST, USA***
2:20 pm	**Laboratory Tour**

1.3 Participant Listing

Name	Affiliation
Ankit Agrawal	Michigan State University
Farid Alfawakhiri	American Iron And Steel Institute
Kathleen Almand	Fire Protection Research Foundation
Saleh Alogla	Michigan State University
Ayano Amikura	Kyoto University
Shigeaki Baba	Taisei Corporation
Faith Berry	National Fire Protection Association
Craig Beyler	Jensen Hughes
Jan-Michael Cabrera	Intertek Testing Services
Chris Dicus	Cal Poly San Luis Obispo
Mark Dietenberger	United States Forest Service
Yan Ding	University of Maryland
Ritsu Dobashi	The University Of Tokyo
Michael Engelhardt	University of Texas at Austin
David Evans	Home Safety Foundation
Ofodike Ezekoye	University of Texas at Austin
Michael Gollner	University Of Maryland
Daniel Gorham	National Fire Protection Association
Raquel Hakes	University Of Maryland
Kazunori Harada	Kyoto University
Keisuke Himoto	Building Research Institute
Takeo Hirashima	Chiba University
Yu Hiroi	Nagoya University
Kauzhiko Ido	Shimizu Corporation
Kenichi Ikeda	Tokyo University Of Science
Ann Jeffers	University Of Michigan
Kouta Nishimura	Kajima Corporation
Kazunori Kuwana	Yamagata University
Kevin Lamalva	Simpson Gumpertz & Heger Inc.
Nicola Leyshon	Cal Poly San Luis Obispo
Ken Matsuyama	Tokyo University Of Science
Sara Mcallister	United States Forest Service
Mark Mckinnon	University Of Maryland
Brian Meacham	Worcester Polytechnic Institute
Colin Miller	University of Maryland
Tensei Mizukami	Building Research Institute
Yuji Nakamura	Toyohashi University of Technology
Tomohiro Naruse	Building Research Instiute
Tomoaki Nishino	Building Research Institute

Minehiro Nishiyama	Kyoto University
Masaki Noaki	Tokyo University of Science
Tomohito Okazaki	Takenaka Corporation
Stephen Quarles	Insurance Institute for Business and Home Safety
James Quintiere	University of Maryland
L. Ray Scott	Home Safety Foundation
Yusuke Shintani	Takenaka Corporation
Ajay Singh	University Of Maryland
Stanislav Stoliarov	University Of Maryland
Kuma Sumathipala	American Wood Council
Junichi Suzuki	National Institute for Land and Infrastructure Management
Sayaka Suzuki	National Research Institute of Fire And Disaster
Josh Swann	University of Maryland
Takeyoshi Tanaka	Kyoto University
Wei Tang	University of Maryland
Maria Theodori	University of Maryland
Hiroyuki Torikai	Hirosaki University
Arnaud Trouve	University Of Maryland
Amit Varma	Purdue University
Salman Verma	University Of Maryland
Robert Wessel	Gypsum Association
Tokiyoshi Yamada	National Research Institute of Fire and Disaster
Heisuke Yamashita	Japan Testing Center for Construction Materials
Hideki Yoshioka	National Institute for Land and Infrastructure Management
Cong Zhang	University of Maryland
John Gross	NIST
Jiann Yang	NIST
Anthony Hamins	NIST
Kuldeep Prasad	NIST
William Grosshandler	NIST
Matthew Bundy	NIST
Lisa Choe	NIST
Nelson Bryner	NIST
Rodney Bryant	NIST
Christopher Smith	NIST
Fahim Sadek	NIST
Joannie Chin	NIST
Howard Harary	NIST
Samuel Manzello	NIST
Erik Johnsson	NIST
Glenn Forney	NIST
Shonali Nazare	NIST

Mauro Zammarano	NIST
Matthew Hoehler	NIST
Kathy Butler	NIST
Randall McDermott	NIST
Craig Weinschenk	NIST
William Pitts	NIST
Howard Baum	NIST
Chao Zhang	NIST
Mina Seif	NIST
Ramesh Selvarajah	NIST
Joseph Main	NIST
Jian Jiang	NIST
Jonathan Wiegand	NIST
Thomas Cleary	NIST

2. Summary

The workshop was a success and represented the final workshop, based on a two workshop agreement between the EL-NIST and JAFSE. Plenary talks highlighted the large outdoor fire problem in both countries as well the current approaches to fire-structure interaction research in the USA and Japan. The general fire safety science poster sessions provided a snapshot into various fire safety science research topics ongoing in both countries.

A survey was taken at the completion of the workshop, with 83 % of those that responded suggested that this workshop series (*Operation Tomodachi – Fire Research*) continue in some form. To this end, information will be collected to determine how and if any more workshops will be planned. The organization of such workshops is a huge undertaking and clear benefits to both the USA and Japan must be realized. As a result, all options will be considered to develop future workshops.

Finally, papers that were presented orally are eligible for submission to a special issue of *Fire Technology*, to be Co-Guest Edited by Dr. Sayaka Suzuki of the National Research Institute of Fire and Disaster (NRIFD) in Japan and Dr. Samuel L. Manzello of EL-NIST.

3. Acknowledgements

The local organizing committee (Dr. Matthew Bundy, Dr. Kathy Butler, Dr. Jiann Yang, and Dr. Anthony Hamins) is gratefully acknowledged for their hard work. All are indebted to the staff of the National Fire Research Laboratory (NFRL) for the excellent laboratory tours. The session chairs, Dr. Hideki Yoshioka (NILIM), Dr. Yuji Nakamura (Toyohashi University of Technology), Mr. Nelson Bryner (NIST), Ms. Faith Berry (NFPA), Dr. William Pitts (NIST), and Dr. Rodney Bryant (NIST), did an excellent job moderating the discussions, and their service is appreciated. The assistance of student timekeepers, Ms. Maria Theodori, Mr. Yan Ding, Ms. Cong Zhang, and Mr. Mark McKinnon, all from the University of Maryland, is much appreciated. Dr. Tokiyoshi Yamada, NRIFD, served as the Chair of the Japanese organizing committee for JAFSE. Special thanks are due to all the presenters for a job well done.

Appendix 1 Oral Presentation Abstracts

2015/3/16

Large Outdoor Fires in the USA: What is the Problem?

Nelson Bryner
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The wildland-urban interface (WUI) encompasses housing and other structures that are either co-located or abut wildland vegetation and forest [1]. WUI communities are especially susceptible to destruction from wildland fires. Across the United States, over 80,000 wildfires occur annually and burn approximately approximately19,000 km^2 (7 million acres) of land. Several causes of WUI fires include the upsurge of structures in the WUI, long-term drought, climate change, and build-up of wildland fuel [2]. While the majority of these wildfires are extinguished before exceeding 0.04 km^2 (10 acres), a small percentage, 2% to 3%, of wildfires spread into WUI communities. In the last 100 years, 6 of the top 10 fire loss incidents occurred in WUI areas (5 of the 6 occurred in California). In the United States, more than 46 million homes in 70,000 communities are at risk of WUI fires—which have destroyed an average of 3000 structures annually over the last decade—and this risk is rapidly increasing [3].

WUI fires can also generate huge response and recovery costs. For example, the 1991 Oakland and 2007 Witch Creek fires in California resulted in property losses of $2.7 billion and $1.5 billion, respectively [4]. Federal funding for suppression and wildland fuel treatment has also risen significantly. In the period from 1996 to 2000 to the period from 2001 to 2005, this funding increased from $1.3 billion annually to $3.1 billion annually [2]. In addition, an average of 70 % more area was burned from 2000 to 2005 as compared to the 1990s [2]. In 2012-2013 over 1000 homes were destroyed from three fires in Colorado. Annual costs for WUI fires are estimated at over $14B (2009) [5]. This presentation will describe the trends in large outdoor fires as the number of acres burned annually by wildland fires [6], the number of houses located in the WUI [7], and the costs of suppression are increasing significantly.

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Large Outdoor Fires in Japan: What is the Problem?

Tokiyoshi Yamada
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In Japan, almost 70% of land area is forest and other wooded land. Large forest fires still threaten local residents from time to time. However total number was decreasing in recent. Depopulation in rural area seems to reduce outbreak chance of forest fires. Whereas there were many large city fires in Japan in history under special weather like foehn wind. Development of fire control service, fireproofing of buildings and cities mitigate potential fire risk in cities. Thus the risk of large outdoor fires seems to be controlled under satisfactory level in general.

Major concern related to large outdoor fires in Japan is conflagration following natural disasters such as large Earth quake and/or Tsunami. One of risks of such large outdoor fires is due to neighborhood with vulnerable wooden houses lined so close together in urban cities. The other is due to temporal inability of fire service. For example, 285 fires which burned down total 65 hectare in downtown of Kobe following the Great Hanshin Earthquake in 1995. Ten more town blocks of more than 1 hectare were fully burned down. In Tohoku area 374 fires of total 74 hectare burned area erupted following the Great East Japan Earthquake in 2011.There were at least 10 large outdoor fires observed even in inundated areas swept by devastating Tsunami. Both of large outdoor fires occurred due to above reasons.

Elaborate fire investigations following above earthquakes were made for preventing a recurrence. Results showed diversity of fires in both of fire causes and types. Especially in the Great East Japan Earthquake, countless number s of vehicles, compressed gas cylinders at home initiated fires and large hydrocarbon fuel fires occurred in industrial complex. Those incidents are highly suggestive for mitigating future fires risks in the case of pressing and anticipated large earthquake, i.e. Tokyo metropolitan earthquake and Nankai Trough Quake.

Fire research related in this region is focusing to find out vulnerable area in case of city fires. Some of fire spread prediction methods have been developed and applied to specific area in traditional old cities i.e. Kyoto and Kanazawa etc. Also there are some empirical prediction formulae of fire spread under wind condition. Recent data of fire spread speed and fire occurrence probability following earthquake are somewhat different from those predictions. Further investigation of fire phenomena based on current conditions of social and way of living will be needed to improve the validity. Moreover unprecedented new fire hazards of large outdoor fires related to energy facilities and transportation etc. should be taken in to account.

Fire Spread between Adjacent Buildings Accelerated by Combustible Facades

Hideki Yoshioka, PhD
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With regard to fire safety for exterior walls of a building, fire-resistance performance is considered, according to the current building standard law of Japan. And it is not specifically regulated from the viewpoint of reaction-to-fire performance, such as fire propagation caused by combustible materials or products which are installed at the exterior side of fire-resistant load-bearing walls. Actual fire issues in the world have shown that massive façade fire could occur at the exterior side of building wall even when the wall itself is fire resistant. In previous studies of the authors, a test method of façade fire was proposed primarily for evaluating the vertical fire propagation at an external wall within the same building. On the other hand, especially at the high-density residential areas in Japan, fire spreading would occur mostly from window to window between adjacent buildings when walls are not burning by façade fire. But in case of combustible facades, such as insulating materials, combustible coating, or even sandwich panel are installed at the wall surface, once they are ignited, façade fire would occur and accelerate both the fire propagation in the same building and the fire spreading to the adjacent building. In this paper, results of fire tests on combustible facades are discussed especially from the viewpoint of fire spread between adjacent buildings assuming the crowded residential area in Japan.

Hardening Structures to Wildland-Urban (WUI) Fire Exposures

Samuel L. Manzello, PhD
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Wildfires that spread into communities, referred to as Wildland-Urban Interface (WUI) fires, have destroyed communities throughout the world. WUI fires continue to burn in the USA, and are rapidly getting worse, with attendant increased economic costs [1]. Some recent examples include the Bastrop Complex Fire in Texas in 2011, the Waldo Canyon Fire in Colorado in 2012, and fires in Arizona, Colorado, and California in 2013.

The WUI fire problem can be viewed as a structure ignition problem [2]. Surprisingly, little effort has been spent on understanding the processes of structure ignition in these fires. Scientifically-based building codes and standards are needed to guide construction of new structures in areas prone to WUI fires in order to reduce the risk of structural ignition. Scientifically-based retrofitting strategies are required for homes already located in areas prone to such fires.

Historically, fire safety science research has spent a great deal of effort to understand fire dynamics within buildings. Research into WUI fires, and how to potentially mitigate the loss of structures in such fires, is far behind other areas of fire safety science research. This is due to the fact that fire spread in the WUI is incredibly complex, involving the interaction of topography, weather, vegetation, and structures [2].

When vegetation and structures burn in WUI fires, pieces of burning material, known as firebrands, are generated, become lofted, and are carried by the wind. Interestingly, post-fire damage studies have suggested for some time that firebrands are a significant cause of structure ignition in WUI fires, yet for decades, firebrand studies have focused on understanding how far firebrands fly. This is not helpful to harden structures in WUI communities. Firebrand investigations have not been able to quantify the vulnerabilities of structures to ignition from firebrand showers, as it is difficult to develop a measurement method to replicate wind-driven firebrand bombardment on structures that occur in actual WUI fire events. To address this problem, research has been undertaken in an intricate area involving the quantification of structure vulnerabilities to wind driven-firebrand showers. This type of firebrand research has never been possible prior to the development of the Firebrand Generator (Dragon).

The Dragon technology directly feeds into the NIST developed WUI Hazard Scale [3], since it will be possible to expose any type of building assembly to different levels firebrand flux, thus enabling the ability to design structures to various exposures. It is anticipated that this work will inform test method development for a new generation of effective WUI building codes and standards, since the best way forward to address the WUI problem is hardening of structures [4].

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A Study on the Urban Fire in the Inundated Areas Following a Tsunami

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This study is a basic examination of modeling the fire spread of tsunami fires. Fires that break out in urban areas inundated by a tsunami are collectively referred to as "tsunami fires". The tsunami following the 2011 Tohoku Earthquake, Japan inundated coastal regions of approximately 561 km^2, and many resulting tsunami fires were observed. Some of these tsunami fires developed into spreading fires, and traces of fire damage were found in approximately 67 ha of the total inundated areas. This exceeds the areas destroyed by fire due to the 1995 Kobe Earthquake, 46 ha.

Usual type of this fire is as follows: (1) combustible objects, such as house, automobile, and oil, are washed away by a tsunami and accumulate in urban area as debris; (2) debris are ignited by some kind of cause and fires spread to adjacent debris resulting in urban fire.

The problem of particular concern related to tsunami fires is the ignition of tsunami refuge buildings. In Japan, huge tsunami following the future ocean trench earthquake is of special concern in the coastal areas facing the Pacific Ocean, some public facilities with a certain height have been designated as refuge buildings from a tsunami for local residents who may find it difficult to escape because of the long distance to high ground. If tsunami fires approaches to a tsunami refuge building and cause ignition, evacuees will be forced to remain inside the building because of the surrounding seawater and debris. However, there are no models that can describe the fire spread behavior of the tsunami fire. Therefore, it is difficult for fire safety engineers to plan the safety measures because of the inability to understand a big picture of the fire damage.

Evaluating Ember Entry into Attic Vents

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The objective of this research was to evaluate the vulnerability vents to the entry of wind-blown embers (firebrands). Experiments were conducted in a 45 m x 45 m large-chamber open-jet wind tunnel, having a clear height of 18 m. The inlet jet to the chamber is 19.8 m wide 9.1 m tall and the wind flow is produced using the approximately 1.8 m diameter fans. Active and passive control elements are used to correctly simulate the atmospheric boundary layer to wind speeds approaching58 m/s 10 m above the ground. A 110 m^2 full-scale single story test building, anchored to a 17 m turntable, was used in these experiments.

Embers were generated using seven 0.5 m cylindrical gas-fired burn chambers, positioned across the width of the test chamber. The raw material used to generate the embers consisted of a mixture, by mass, of 85% wood chips and 15% wooden dowels measuring 13 mm in diameter. The wood chips were dried to a moisture content of approximately 6% (oven dry basis) prior to mixing and then stored until use. The wood chip – dowel mixture was loaded into a storage hopper and then fed at a uniform rate of 2.3 kg/min into each burn chamber. Air blowing upwards through the burn chamber carried lofting members through vertical ducting that exited into the wind stream of the wind tunnel.

The current investigation evaluated basic types of inlet and outlet vents commonly used to ventilate attic spaces. Two types of under eave inlet vents were evaluated: soffited (enclosed) eves and open-eaves. Outlet vents included those used in the vertical wall of the gable end area of a building, and those located in either an off-ridge or ridge location. Three wind speed records, with maximum gust speeds of approximately 10, 15 and 25 m/s, were used to evaluate the influence of wind speed to ember entry. Data collection of embers at each wind speed record lasted a total of 15 minutes. The building orientation was varied (by rotating the building on the turn table) to examine the effect of wind direction on the vulnerability of vents to ember entry.

Quantitative measurements of ember entry will be presented, derived from photogrammetric analysis of video collected at exterior and interior vent locations during each experiment. Qualitative observations made by IBHS personnel stationed in the attic during the experiments indicated that vent location, vent type, wind speed and wind direction all influence the potential for the intrusion of wind-blown embers. Vents with openings that are perpendicular to the wind flow (vertical orientation) were more vulnerable to ember entry than vents with openings that were parallel (horizontal) to the wind flow.

Temporal Changes to Wildfire Risk in the Wildland-Urban Interface

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Even with increasing proportions of governmental budgets allocated to fire suppression resources, wildfires annually destroy great numbers of homes and critical infrastructure in the wildland-urban interface (WUI). To aid policy development that reduces these losses, we are evaluating changes to risk through time in dissimilar communities that are expanding into fire-prone areas. Conventional wisdom states that escalating losses are caused, in part, by an expansion of residential development into fire-prone areas. However, various mitigation strategies such as defensible space and improved construction standards have recently been mandated for new developments in California so as to reduce the risk of these losses. Subsequently, older high-risk communities may actually become buffered from wildfires as the WUI expands and lessens their exposure to flames and embers. Thus, expanding WUI may either increase or decrease risk of residential loss dependent upon the extent of altered fire exposure and the application of mandated mitigation strategies. To help elucidate this seeming dichotomy, we are utilizing various GIS strategies to spatially analyze changes to risk of structural ignitions through time in expanding, but demographically dissimilar residential communities in California.

This presentation will describe how we are quantifying changes to risk based on characteristics of community wildfire exposure and characteristics of individual structures, including roofing materials, defensible space, and housing density. Our research is simultaneously (1) quantifying the growth of the WUI over time in multiple, dissimilar communities, (2) analyzing temporal changes to risk based on altered wildfire exposure and structural characteristics, and (3) comparing risk in high-compliance vs. low-compliance communities.

Estimation of Loss Due to Anticipated Post-Earthquake Fires in the Tokyo Metropolitan Area

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Tohoku earthquake event that devastated eastern Japan in 2011 gave alert to people for future catastrophic disasters. Because earthquakes may occur at any part of this earthquake-prone county, municipalities started revising their disaster risk management plans without exceptions. Among many anticipated earthquakes, the one which will strike the Tokyo metropolitan area is one of the most concerned earthquakes because of its high probability of occurrence and high impact on the heart of this country. Thus, municipalities in this area have recently issued loss estimation reports one after another preparing for the occurrence of this unwanted event. However, knowledge of post-earthquake fires that greatly advanced especially after Kobe earthquake in 1995 have not been adequately incorporated in the methodologies of these loss estimations. To add, most of the estimations focus on the classical type of post-earthquake fires that spread in a densely-built urban area; outcome of fires which may start in a high-rise building, a huge underground mall, or an industrial facility which characterizes the area is overlooked. Thus, we develop a new methodology for the comprehensive loss estimation of post-earthquake fires in an urban area by integrating models for ground motion, structural response of buildings, ignition, fire and smoke spread, and evacuation. Result of case studies for selected sites in the Tokyo metropolitan area is presented and effective means of loss mitigation is proposed.

Questionnaires Survey on Fires after the Great Disasters in Eastern Japan and its Application

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The purpose of this study was to investigate the outline of earthquake fire occurred at the time of the Great East Japan Earthquake by carrying out the questionnaire investigation targeting firefighting headquarters. We asked all firefighting headquarters in 17 prefectures in eastern Japan except Hokkaido about the outline of fires occurred during a month from March 11 to April 11, 2011 and the response rate as of December 2013 was 86.9% (258 headquarters). The answers obtained from each firefighting headquarters were compiled and the result showed that the number of fires occurred during the period subject to the investigation was 2,702 and as much as 373 fires among them were considered to be caused by the earthquake. The feature of the earthquake fires occurred at the time of the Great East Japan Earthquake is that many of the fires were caused by the tsunami. The number of the fires caused by the tsunami was 159, and, according to the field investigation conducted by the authors, the total area in the city areas damaged by the fires caused by the tsunami reached about 74 hectares. It also revealed that the fires caused by the tsunami can be divided into the following four patterns according to the regional characteristics where the fire occurred or the cause of the fire: (1) A pattern in which fire occurred due to debris accumulated on a slope (which was observed mainly along the Sanriku coast); (2) A pattern in which fire occurred in the plain region of the city area and its suburbs (which was observed mainly in the Sendai Plain); (3) A pattern in which fire occurred due to hazardous materials that outflowed to the sea (which was observed mainly in Kesennuma); and (4) A pattern in which fire occurred singly due to a problem with the electrical system (which was observed mainly from the second day after the Earthquake). We are required to fully understand in advance which pattern of fire due to tsunami could occur and make use of the understanding to prepare a fire defense plan and an evacuation plan.

Assessing Conditions for the Development of Wind-Driven Horizontal Fire Vortices

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The interaction between wildfires and weather may result in rapid and severe changes in wildfire behavior that take first responders and nearby communities by surprise. An example is the sudden generation of horizontal roll vortices (HRVs) under windy and dry conditions in rolling or flat terrain. The winds in an HRV rotate in a corkscrew manner with a diameter of tens to hundreds of meters, transporting combusting gases from the fire high into the air and downwind. The result is total devastation wherever the vortex touches the ground and embers that travel long distances downstream. Mitigating the hazard from such events requires a better understanding of the conditions under which they occur.

Horizontal vortices oriented with the wind are actually a common phenomenon in the atmosphere. A weak initial disturbance can gain a large amount of energy from the mean wind either by lifting up low velocities near the ground and pulling down high velocities above the vortex or by being pushed by the mean wind from an initial tilt to an upright position. The perturbations that grow optimally on a given mean wind profile can be determined by solving a matrix problem. At maximum energy, the vortices resulting from this analysis agree well with observed atmospheric flow structures. The buoyancy from a fire could help to initiate such vortices and to maintain them after formation.

Optimal perturbations calculated on the mean wind profile at the Bastrop Complex Fire in September 2011 agree well with the scale of the observed HRVs. Because it is linear, the analysis can be performed very quickly. It could eventually be possible to assess the potential for HRVs in wildfires in real time and to estimate their size and orientation. This capability would help to deploy first responders and equipment where they are most effective.

Modeling Wildland Fire Propagation: Physical Processes and Real Time Data-Driven Modeling

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The increasing occurrence of intense wildland fires has challenged researchers to develop solutions to protect property, lives and the environment. One essential tool for both for preventative planning and real-time operational needs is a fire model, providing an accurate means of predicting the spread of a wildland fire. In the early 1970's, Richard Rothermel and his colleagues developed the first operational fire model, using a semi-empirical approach based upon an energy balance of the fire front. This model was calibrated with a significant number of fire spread experiments and, by incorporating properties of the fuel, moisture, wind and slope, a steady spread rate could be calculated for a wide variety of wildland fuels. While this model and its subsequent use in computational tools has been a great leap forward, many of the extreme fire behaviors observed today cannot be modeled with this simplistic steady formulation, leaving significant gaps in our prediction capability, especially during the worst fires.

In order to fill this gap, several research efforts are under way at the University of Maryland both to improve current models of wildland fire spread and to reduce model uncertainties by developing innovative methods that combine computer simulation tools with fire sensor observations. In a joint project with the US Forest Service, recent research has revealed that, despite their large size, wildland fires often spread via small-scale interactions with discrete fuels, dominated by buoyancy-enhanced boundary layer instabilities. Implications from this research towards the current approach to modeling wildland fire spread will be presented. Another avenue being pursued, through a joint project between the University of Maryland and UC San Diego, seeks to develop a cyber infrastructure for real-time sensor-driven modeling of wildland fires. Current fire models are limited in scope because of the large uncertainties associated with the accuracy of physical models, because also of the large uncertainties associated with many of the input parameters to the fire problem. The joint project between the University of Maryland and UC San Diego proposes to overcome these limitations using sensor observations to correct and optimize computer model predictions, an approach that is similar to that used in weather forecasting.

Development of Evaluation Methods for Firebrand Ignitions

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Large outdoor fires in Japan are mainly considered as post-earthquake fires or urban fires due to the urban structure. It was pointed out that scattered fires ignited by firebrands were one of the reasons which caused many fires in Great Kanto Earthquake in 1923. It is hard to predict the locations of scattered fires by firebrands due to complicated natures, which is greatly complicating firefighting capabilities. In order to prevent losing structures by fires, it is important to understand the vulnerabilities of structures to firebrand showers and then, strengthen structures to these exposures in order to reduce ignition and that more ignition resistant structures will also lead to improved firefighting strategies.

Without standard laboratory test methods, it is impossible to evaluate and compare the performance to different building elements ability to resist firebrand ignition. Before such test standards are developed, detailed full-scale experiments that systematically evaluate individual building component vulnerabilities to ignition to firebrand showers are required. To this end, NIST/NRIFD has embarked on pioneering research to begin to determine the vulnerabilities of structures to firebrand showers using the NIST Dragon coupled to a full-scale wind tunnel at the Building Research Institute (BRI). Most recently, Suzuki and Manzello improved the Dragon technology to allow for the generation of continuous firebrand showers, as opposed to the original batch-feed Dragon. With this technology, it is now possible systematically ascertain building component vulnerability to wind-driven firebrand showers of any duration.

As need physical understanding is being collected from the full-scale experiments, work is required to develop reduced-scale test methods that will be able to reproduce results of the full-scale experiments above. Joint USA and Japanese efforts to develop test methods to mitigate ignition from firebrand showers will enable disaster resilient communities in both countries. This presentation will focus on development of this test method and in particular aspects of direct relevance to the fire situation in Japan.

Overview of NRIFD Fire Research, along with non-fire related research will be also provided in this presentation.

The Effect of Wind on Burning Rate

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Wood cribs are often used as ignition sources for room fire tests. As wildland fuels are porous, three dimensional fuel beds, a fundamental understanding of the mechanisms that govern the burning rate of a wood crib may also have applications to wildland fires. The burning rate of unconfined cribs has long been identified to occur in two regimes: the densely-packed regime where the burning rate is proportional to the crib porosity and is ventilation limited, and the loosely-packed regime where the burning rate is independent of porosity and governed by the burning characteristics of the fuel elements. The burning rate is known to reduce when the crib is located in a confined area due to limited ventilation. A more appropriate scenario in wildland fires is an increase in ventilation due to wind, however very little is known about what effect this has on the burning rate of cribs in either the densely- or loosely-packed regime. A further complication is the evidence that the aspect ratio of the crib may change how the densely- and loosely-packed regimes are defined. This paper will examine the effect of forced ventilation on cribs with a wide variety of aspect ratios both in the densely- and loosely-packed regimes.

Feasibility of Limiting Oxygen Index (LOI) as Material Flammability Classification

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Limiting Oxygen Index (LOI) is widely used as the one of material flammability classification. In practical sense, it is recognized as "secured" material against the fire growth if the LOI of the material is higher. In scientific point of view, on the other hand, flammability is the definition whether you can sustain the flame or not. In this way, flammability limit of solid fuel can be recognized as the critical condition at which the flame could spread; i.e., heat balance would be achieved or not. Nevertheless, LOI test is also designed to judge the material is ignitable or not with certain heat input condition.

If this is less than the ignitable one, it is obvious that the flame is not generated so that the subsequent flame spread is no longer expected. However, this is the condition of "not" flammable, but the ignitable (explosive). Therefore, LOI is the value with two meaning; one is flammable (spreadable) and the other is ignitable (explosive). In this study, we look carefully about the how to approach to LOI, then judge that LOI shows really "flammable" condition or not. It turned out that LOI would be more likely representative value of "ignitable", not flammable, depending on the materials. Feasibility of present LOI method is also examined and its application to judge the flammability classification is discussed.

Fire-Structure Interaction: What is the Problem?

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Structural fire safety design became active from middle of 1980's to 2000, and many developments of technologies were made and various new fire resistive building construction members, like the concrete filled steel tube column without fire protection, became in practical use. Several structural fire safety design methods were also developed, and the one method named fire-resistance verification methods was issued as a Notification No. 1433 of the Ministry of Construction May 31, 2000. During these fifteen years, we made remarkable developments in the structural fire safety design field toward next stage. But many problems which must be solved were left.

These problems are classified into a matter of social system such as regulations and a matter of engineering such as evaluating method of fire resistive performance. As for a matter of social system, the produced performance based code only focused on the specified or limited performances of building constructions. Or the codes itself were incomplete. The necessary performances which were implied tacitly were omitted. And the code was not practicable for designers. Lastly, the administration did not make improvement action for it at all, though the administration was aware of those problems. As for a matter of engineering, the new type constructions were applied to real buildings used without sufficient research, development and engineering verifications. Designers and administration are now making effort for improving these undesirable conditions.

Fire-Structure Interaction: U.S. Perspective

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The devastating and widespread effects of fire on the built environment result in losses to human life, property, and national treasure. Traditional approaches to fire protection for buildings and communities include construction restrictions (e.g., zoning and occupancy restrictions), limitation of the spread of fire (e.g., fire resistance rating requirements), and active fire suppression (e.g., sprinklers). While these approaches have worked reasonably well in the past, there are gaps in knowledge and understanding that preclude certainty in engineered structural fire protection design and there remain instances of uncontrolled fires that have led to significant structural damage or collapse. A performance-based approach to design for fire holds great promise to reduce the effects of fire on the built environment. Such an approach allows multiple performance objectives and explicitly considers fire as a design condition. It has the clear potential to improve life safety, property protection, business continuity, and community resilience.

A move toward performance-based design is possible today as a result of advances in predictive computational models used by the fire safety engineering community. These models may be used to characterize building fires, and predict the thermal effects of a fire on a building's structural system. Advanced computational models can also predict the performance of a structural component, assembly or system to the effects of the thermal insult, including the diminishment of mechanical properties. The confluence of technological advances in these three areas: characterization of building fires, prediction of thermal effects, and calculation of structural performance, make possible the vision of a unified performance-based approach to structural fire safety and design.

A fire performance based design approach for buildings and other structures will allow the community to move beyond the prescriptive procedures presently in use, and their attendant limitations. This vision will, for the first time, consider fire as a design condition in the structural design process and treat fire along with other hazards on a risk-consistent basis.

This vision of the future holds the promise of:

- A revolutionary transformation from the current prescriptive approach fire resistance to new performance-based design methods;
- Increased public safety with requisite technical justification;
- Increased innovation and marketplace competition for new products, designs, and services; and
- Cost savings based on a rational and risk-consistent approach to design and use of materials.

U.S. Standards that Support Structural Fire Engineering Practice

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Structural systems protected with qualified assemblies according to prescriptive methods may be resistant to heating during fire events, but they are not specifically designed to endure thermal load effects. The emerging field of structural fire engineering involves the explicit design of structural systems to adequately endure thermal load effects from uncontrolled fire exposure using rationally-allocated means of protection and potential modifications to preliminary structural system designs. In cases where prescriptive methods would not properly address stakeholder objectives, performance-based methods may be judicially employed to provide a rational basis for determination of structural performance during uncontrolled fire exposure. For instance, performance-based methods may be required as part of building code variances in order to demonstrate the adequacy of innovative and/or nonconventional design.

Currently in the U.S., designers and building authorities lack comprehensive guidance for practicing and evaluating structural fire engineering. In spite of this and to a certain extent, structural engineers are presently engaged in performance-based design of structures subject to fire exposure and building authorities need guidance to help them with the approval of proposed designs. In recent years, the American Society of Civil Engineers: Structural Engineering Institute (ASCE/SEI), the Society of Fire Protection Engineers (SFPE), the National Fire Protection Association (NFPA) and other organizations each have endeavored to develop standardized guidance for determination of structural response to thermal load effects from fire exposure. It is envisioned that the aggregate of these standardized documents will provide designers a baseline level of guidance to practice structural fire engineering.

Development of Fire-Resistant Wooden Structure

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The Building Standard Law of Japan became a performance rule in 2000, a building could be recognized as fireproof construction if it have enough fireproof performance even if it is a wooden structure. The authors have made Japanese cedar fireproof glued-laminated timber and have developed wooden fireproof construction (beam, column and beam-column joint).

The structure of the fireproof glued-laminated timber placed nontreatment layers (a load sustain part) centrally. And it placed flame retardant treatment layers (a flaming-die-out part) around a load sustain part. It impregnated flame retardant solvent into nontreatment the flaming-die-out part after incising in laminas of Japanese cedar. The most outer layer is nontreatment layer (dressed lumber).

These members (beam and column) passed a fire resistance test of 1 hour and we are applying for the minister authorization of the fireproof construction for 1 hour. In addition, this member took a quantity of formaldehyde release test, and confirmed that it satisfied an evaluation standard of F☆☆☆☆(best grade)

Research Priorities for Structure-Fire Interaction – the CIB and NIST Perspectives

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An international research and development roadmapping workshop on fire resistance of structures, emphasizing a multi-year multi-institution large-scale experimental program to support performance-based engineering, was convened at NIST on May 21-22, 2014 under the auspices of NIST and the International Council for Research and Innovation in Building and Construction (CIB). The workshop focused on the following issues:

1. identifying research and development needs for large-scale experiments on fire resistance of structures to support performance-based engineering and structure-fire model validation;
2. prioritizing those needs in order of importance to performance-based engineering;
3. phasing the needed research in terms of a timeline, i.e. near term (less than 3 years), medium term (3 to 6 years) and long term;
4. identifying the most appropriate international laboratory facilities available to address each need;
5. identifying the potential collaborators and sponsors for each need;
6. identifying the primary means to transfer the results from each series of tests to industry through specific national and international standards, predictive tools for use in practice, and comprehensive research reports; and
7. identifying the means for the coalition of international partners to review progress and exchange information on a regular basis.

In order to set the stage for the workshop and facilitate the brainstorming and technical discussions in the break-out sessions at the workshop, NIST commissioned three White Papers authored by international experts with emphasis on concrete, steel, and timber built structures respectively. The workshop was attended by over fifty international and domestic participants from academia, industries, professional associations, government, and standard and code development organizations. Working with the CIB W014 Commission (Fire), a roadmap is currently being developed based on the workshop discussions and the three White Papers. The published roadmap will form an international basis to advance performance-based engineering design of structures. The research priorities identified at the NIST/CIB workshop will be presented and discussed.

Multiphysics Simulation of Fire-Structure Interaction

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The understanding of structural performance under realistic fires requires a simulation framework that can capture natural fire effects such as localization, growth, and spread. Computational fluid dynamics (CFD) models are well-established for simulating natural fires; however low-resolution structural models cannot readily take advantage of the data that is produced in the CFD model due to disparities in spatial and temporal scales between the two models. A framework for coupling a CFD model to a low-resolution structural model is proposed that utilizes novel multiphysics algorithms and macro finite elements to bridge the differences in scale in a manner that is accurate and computationally efficient. Macro heat transfer elements are used to simulate the thermal response of the structure in a way that minimizes computational cost and seamlessly transfers temperature data to the structural model. To overcome differences in scale between the CFD model and macro heat transfer elements, spatial homogenization and subcycling algorithms are employed. The multiphysics simulation framework is presented along with an illustrative example to demonstrate that the approach yields excellent accuracy and computational efficiency. The framework is shown to be a viable approach to studying structural performance under natural fire effects.

Thermal Elongation of Steel Beams Constrained by RC Slab and Adjacent Frames

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Thermal deformation of structural members in fire may become the factor to cause the collapse of the building. Above all, thermal elongation of steel beams is one of the most significant considerations for the structural stability of buildings in fire.

In this study, several kinds of full scale furnace tests were carried out. One of the test specimens was composed of only the fire-protected beam, and another test specimen was composed of the same beam connected to RC slab, which was supported by braced lateral frames at two sides. The other four test specimens were composed of fire-protected beam and RC slab. However, the three sides of RC slabs were completely constrained. As each specimen was a model of an external beam of the existing building, one of the heating beam edges was fixed to the reaction truss and the other edge was supported by the roller.

By comparing test results, the suppressive effect of the adjacent frames and RC slab were confirmed quantitatively. It was found that the thermal elongation of a steel beam greatly depends on the in-plane stiffness of RC slab. Assuming that RC slab is rigid, the theoretical thermal elongation in this study becomes around 50% of thermal elongation that is provided in Eurocode 4. However, as for adjacent frames in this study, the suppressive effect was only around 20% of thermal elongation that is provided in Eurocode 4. By the observation during and after the test, wide cracks (width: around 1.0mm) that occurred along the heating beam in the non-heating surface of the RC slab were confirmed.

Because of cracks, it was thought that the in-plane stiffness of RC slab decreased. Therefore, it was suggested the suppressive effect of the adjacent frames for thermal elongation of steel beams greatly depended on stiffness reduction of RC slab. Based on above, evaluation of the in-plane stiffness of RC slab is very important to grasp thermal behavior of actual buildings in fire.

Behavior and Design of Composite Beams and Floors for Fire Loading

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Current U.S. design methods for structures in fire rely heavily upon prescriptive approaches that focus on providing fire protection to keep material temperatures below a given threshold. While these methods are typically conservative, they do not take into consideration the structural performance of such members. In order to move towards a performance-based design approach, it is necessary to quantify not only the thermal response but also the mechanical performance of structural components at elevated temperatures. This paper focuses on the fundamental behavior of composite floor beams and associated beam-to-column connections in fire conditions.

Large-scale experimental tests on composite floor beams were conducted at Purdue University. Designed according to U.S. codes and standards, the specimens consisted of a steel beam that was composite with a flat, lightweight concrete slab through the use of shear studs. The beam was connected to a portal frame using either shear tab or double-angle, all-bolted connections. The specimens were subjected to vertical loading combined with both controlled heating and cooling using high-temperature ceramic radiant heaters. Results provided insight to the failure modes of the composite beam and connections, including concrete compression failure at moderate temperatures (below 500°C) as well as connection failure during cooling.

A two-dimensional fiber-based modeling technique was developed to further evaluate the section moment capacity of composite beams at elevated temperatures. After benchmarking the model with experimental test data, a parametric study was conducted to determine the influence of variations in cross-section geometry, level of composite action, and temperature distribution. Results revealed that at ambient conditions, shear stud fracture is a failure mode of concern for partial composite beams, particularly for those with large span-to-depth ratios. When cross-section temperatures increase as the result of fire, shear stud temperature remain at lower temperatures with respect to the steel beam. As a result, steel beam yielding or concrete compression governs as the failure mode, rather than shear stud fracture. A simple design method for determining the nominal moment capacity of a composite beam at elevated temperatures was developed based upon the parametric study results. Referencing the steel beam bottom flange temperature, a reduction factor can be used with the ambient nominal moment capacity to estimate the moment capacity of the composite beam at elevated temperatures.

A Simple Model for Fire Resistance of Steel Beams Under Non-Uniform Temperature Distribution

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In case of a building fire, beams are exposed fire heating on three sides, and therefore their temperature distributions through the beam height are necessarily non-uniform. Moreover, the steel temperature is generally lower for the beam ends than for the beam mid-span because of the heat transfer from the beam end to the column base on the upper floor. This paper discusses, on the basis of previous experimental results, a simple model for fire resistance of non-composite steel I-beams under non-uniform temperature distribution. These experiments are load-bearing fire tests of simply supported beams, fixed-end beams with moment-resisting beam-splices connections and a rigid steel frame. The simple model is on the basis of the theory of simple plastic design and is improved from the model of Recommendation for fire resistant design of steel structures by Architectural Institute of Japan. This paper also discusses the margin (i.e. the partial safety factor) for the design fire resistance of the beams from the viewpoint of load, time and temperature domains.

Fire Performance in Earthquake Damaged Buildings: Overview and Key Outcomes from the BNCS Full-Scale Experiments Project

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To investigate the performance of structural and nonstructural components and systems (NCSs) in buildings subjected to earthquake loads and post-earthquake fires, a five-story reinforced concrete test specimen was constructed on the Large High-Performance Outdoor Shake Table (LHPOST) at the University of California San Diego (UCSD) and subjected to thirteen different test motions and six room-scale fire tests. NCS of particular focus were interior and exterior walls, ceilings, fire stop systems, swinging doors, roll-down fire doors, stairs, elevator, mechanical ventilation, automatic sprinklers and standpipes. Outcomes from the test series illustrate the extent of damage to the structural system, compartment barriers, façade systems, egress systems and fire protection systems that could occur given different levels of ground motion, and how such damage could impact occupant life safety and emergency response during fires in earthquake-damaged buildings. An overview of the building specimen, earthquake motions, fire tests, and performance of NCS critical to building fire safety are presented.

Experimental Study on Fire Resistance of Mid-rise Steel Construction Exposed to Post-Earthquake fire

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Damage of structure and fire compartmentation of mid-rise steel construction by post-earthquake fire was examined experimentally. The size was about 2.5m height and 5m width. Compartment wall, constructed by light gauge steel stud and gypsum board, surrounded by column and beam, was constructed in the fire furnace. Box shaped steel(BCR295) of 300×300×t12mm was used for column and H shaped steel(SN400) of 294× 200×8×12mm was used for beam. Column and beam were covered by calcium silicate insulation (t15mm) supposing one hour fire resistance performance.

First horizontal static load was applied supposing earthquake motion till it remained some deformations, we observed crack and opening of fire covering materials and member. Next it was heated by ISO standard curve. Temperature of the structural member and wall was measured to discuss the damage of structural integrity and fire compartmentation.

Lessons Learned from the May 13, 2008 Fire and Collapse of the Faculty of Architecture Building, Delft University of Technology

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On May 13, 2008, a fire occurred at the Faculty of Architecture Building at the Technical University at Delft in the Netherlands. The fire started in a coffee vending machine on the 6th floor of the 13-story reinforced concrete building, spread rapidly, and ultimately led to the collapse of a major portion of the building. This event represented a rare opportunity to study the collapse of a major reinforced concrete building in fire. Data was collected on this fire event by an international team that included researchers from the U.S. and the Netherlands. The data collection effort was followed by a preliminary structural analysis to identify possible contributing causes to the structural collapse. This presentation will provide an overview of this fire event, a description of the structural system of the building, and results of preliminary analysis of structural response to the fire. The presentation will conclude with a discussion of broader lessons learned on structural fire safety from this event.

Structural Performance of Tunneling Shields in Fire

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In the shield tunneling, there is the case that the secondary lining is omitted for the purpose of short duration and rationalization of construction. One of the major concerns of such shield segment is its fire resistance in this case because the shield segment is exposed to the high temperature of a fire. From the fire safety perspective, it is known that the failure of concrete members occurs sometimes rapidly due to the explosive spalling of concrete cover exposed to fire, so the fire performance of road tunnel structure must be investigated and verified to ensure that it meets or exceeds the design specification. In this regard, the fire test for shield segments was conducted by the authors for extracting their performances. This paper is intended to provide a summary of the findings obtained from the fire experimental and analytical results in two tunnels.

1. A specimen for a full-scale shield segment was fabricated and fire-tested using the German RABT fire curve. The specimen is made of high strength concrete mixed with organic fibers for the prevention of explosive spalling. Fire resistance test of shield segment was carried out, no spalling occurred and its internal and steel temperatures were clarified in this test. In addition, the bending strength of specimen after heating is investigated, and the comparison between the experimental test and numerical analysis showed that the numerical analysis was reliable to experimental result.

2. The outer shell structure of Multi-Micro Shield Tunneling (MMST) method is a composite structure consisting of steel shell parts (SRC structure) and segment joints and connections between the elemental tunnels (RC structure). The shell's steel parts were subjected to a rapid-heating test to clarify the explosive fracturing conditions of the concrete used for the shell and the restraining effect of the incorporated organic fiber. To meet fire safety requirements, the yield strengths of the segment joints and connections were evaluated using a full-scale shield segment model. An elasto-plastic thermal stress deformation analysis also was carried out using the test result data in order to confirm the structural safety of the MMST shell structure in a fire.

Validation Studies of Home Damaging and Ignitability Modeling of Vegetation Fire Radiant Exposure

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Computer models were partially validated using simple tests of forest litter burn and a propane burn under FPL's enhanced heat release rate (HRR) hood and simple mockup setups. Simple open pool-like diffusion flame burns of either propane or forest litter were used that can be modeled by the Fire Dynamic Simulator, Ecosmart Fire Model, and the Furniture Fire Model for determining radiant exposure to adjoining surfaces. To help calibrate the flame characteristics needed for input to the three models, the tests were done under HRR hood that was enhanced to measure low levels of mass loss and heat release rates along with production rates of oxygen consumption, carbon dioxide, carbon monoxide, water vapor, and soot production. Two exposure mockups were used in conjunction with the pool burns to verify the modeling of surface heating of vertical surfaces predicted by the three fire models. On one side is an inert vertical board with two heat flux gauges used. The other side is a mockup of redwood decking boards mounted vertically instead of horizontally with thin thermocouples attached to the exposed surface. Surface temperatures were achieved in the wood that promoted sap leakage indicating damage to the wood material. However, surface temperatures corresponding to piloted ignition were not achieved as there was a lack of charring on the surface. With the Ecosmart Fire Model predicting damage and ignition on a surface cladding of a building due to a collection of burning trees nearby for a worst case scenario, means that the burning of the forest litter (which is primarily dried leaves) in a chicken wire basket with the instrumented vertical walls nearby offered both a calibration and validation to the model on a small scale.

On the Mechanisms of Flame Height Increase at Fire Whirls

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Fire whirls occur occasionally in wild land fires and large scale urban fires. When a fire whirl occurs, the height of flame increases significantly and the fire damages could become more severe. In this study, small scale experiments are performed to understand the mechanisms of the flame height increase at fire whirls. In the experiments, fire whirls are established on a fuel pool using a fixed-frame-type fire whirl generator. The flow fields near the fire whirl are measured in detail. The measured flow fields are analyzed comparing with the change of flame shape, and the flame height increase mechanisms are examined. It is found that the increase of flame height is induced mainly by two mechanisms. One is the increase of heat feedback to fuel in the pool, which makes enhancement of vaporized fuel supply into the flame. The rotating flow makes the base part of the flame approach to fuel pool, which induces the increase of heat feedback. The other is the change of flow field near the flame, which changes the flame shape to increase the flame height. This phenomenon is effective when the fire scale becomes larger.

Characterization of Wildland Fire Brush Burning and Ember Generation

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The increasing frequency of severe droughts has, among other effects, caused an increase in the occurrence of severe wildland fires. Wildland fire management is being used to affect and mitigate the consequences of accidental fires. For both accidental and prescribed fires, it is useful for emergency management authorities to be able to better predict the fire evolution. For any given prediction challenge, we expect the computational model to contain the appropriate physical submodels. Fire in general, and wildland fire particularly, is a multiscale physics problem. The fundamental challenge in characterizing multiscale physics problems is to rationally separate the scales so as to identify the essential physical processes governing evolution at a particular scale. In describing wildland fires, important physical processes take place at levels from the fuel pyrolysis and flame scales to geological and meteorological scales. In our wildland fire work, we have focused on characterization of what we consider to be an intermediate scale. For us, the intermediate scale is the plant scale. In this talk I will discuss the wildland fire problem in general terms and then focus on our results in characterizing the burning process of a native Texas prairie grass, little bluestem. I will also discuss our work on characterizing the ember generation process for grasses and trees. Ember generation, lofting, and deposition are considered to be one of the primary mechanisms for fire growth and for wildland fires to ignite structures at the wildland urban interface. In both the plant burning and ember generation work, we are working to determine the appropriate/essential physical processes needed to characterize these phenomena.

Fire Extinguishment by Using Ice Capsule Filled with Liquid Nitrogen

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Liquid nitrogen which is a cryogenic fluid can be used as a fire extinguishing agent. This is because liquid nitrogen vaporizes rapidly under atmospheric condition, which results in cooling of burning materials and its surroundings in firefighting, and also the volume of the vaporized nitrogen becomes approximately 700 times larger than that of its liquid state, which results in reduction of oxygen concentration in air or fuel concentration in combustion zone. Moreover, liquid nitrogen has no water damage and can extinguish fires more cleanly than dry chemical extinguishing agents. However, it is difficult to delivery liquid nitrogen over long distance from the extinguishing equipment to fires through the surrounding air because of its rapid vaporization. If liquid nitrogen is filled into a capsule and the capsule wall suppresses heat transfer from the surroundings to the liquid nitrogen, it will be easy to transport liquid nitrogen to the targeted fire area without rapid vaporization. Moreover, by using the capsule, it may be possible to increase the extinguishing effectiveness of liquid nitrogen. In the present study, in order to clarify the fundamental characteristics of flame extinguishment by using the capsule filled with liquid nitrogen, blowout experiments of a methane-air jet diffusion flame have been performed. The spherical hollow ball made of ice was used as the extinguishing capsule and the ice capsule was formed by rotating casting machine. The wall thickness and the outer diameter were 2 mm and 20 mm, respectively. The filling volume of liquid nitrogen was 20 cm3. The ice capsule was dropped freely from the height of 800 mm and impacted on the aluminum plate, in which the round burner to form a jet diffusion flame was embedded. The blowout probability was measured by varying the distance from the impact point of the ice capsule and the flame. The extinguishing processes were recorded with high-speed camera.

A Practical Computer Code for Prediction of Thermal Response of Timber Structural Elements during Heating and Post Heating Self-Burning Period

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A computer code has been developed to predict the thermal response of large-sectioned timber structural elements during heating and subsequent cooling period. The model consists of two-dimensional heat conduction equation and shrinkage model. The effects of water evaporation around 100^{o}C, decomposition of volatile compounds between 200 and 350^{o}C and oxidation of char layer over 400^{o}C were considered. The rates of evaporation and decomposition are described by thermally controlled processes that the rates of reactions are described by the rate of temperature rise. The rate of oxidation is described by a single step, first order Arrheius equation. As the burning and oxidation proceeds, the char layer shrinks followed by cracking. The shrinkage ratio was given as a function of residual ratio. By accounting for shrinkage of surface char layer, crack initiation and propagation was estimated. Internal surface created by crack is subjected to heating, which produce further deterioration of material.

The model was solved by a two-dimensional finite element method. The results were compared with model-scale experiments on 88mm thick walls made of laminated larch lumber. The walls were heated in accordance with ISO 834 standard time-temperature curve for 60 minutes. After heating, the walls were kept attached to furnace and cooled down at different air supply rates of 0.04, 0.06 and 0.12 kg/(s·m^2). Heat release rate during cooling period was measured by oxygen consumption calorimetry. The experimental and calculation results were compared. By adjusting the rate of oxidation, agreement of the results is improved. An empirical relationship was derived to correlate the rate of oxidation with the rate of air supply during cooling. Using the model, thermal response during complete process of fire could be predicted with reasonable accuracy.

Simple Calculation Method for Estimating Thermal Resistance of Wall Under Designed Conditions

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In the long history of prescriptive fire safety design, the database of structural fire resistance (FR) ranked by FR test has been compiled. On the other hand, Performance-based fire safety design (P-b FSD) allows assuming different fire scenarios depending upon the design conditions of a space and fire load, and the structural response under certain fire condition is estimated by computer model. It sounds like efficient process, but in reality, it requires detailed thermo-physical properties which are measured by separately setting up a steady-state, linear flow of heat through the materials to apply Fourier's equation. And it is different from those in realistic fire conditions and not enough to evaluate the effect of cracking and ablation.

In this research, a simple equation is introduced to evaluate the FR under designed conditions. The key parameter, thermal diffusivity, can be obtained as temperature-dependent effective value including the effect of cracking and ablation by existing FR test result using the same equation. Therefore, using this method, it requires neither continual material tests nor complicated mathematical simulations but only one accustomed FR test for P-b FSD. And it is valuable as a bridge between prescriptive code and P-b FSD.

Fire Resistance of Timber Panel Structures

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Timber buildings with construction methods using newly developed engineered woods, e.g. CLT (Cross Laminated Timber) and LVL panels have been encouraged because of potentially high construction and cost efficiency, sufficient load bearing capacity with heavier timber use in structural elements than conventional construction systems. However, there are not substantial data to comprehend the structural and thermal behaviors of timber panel elements with cross laminations/layers exposed to fire in Japan. This study focused on acquisition of fire testing data of timber panels to understand thermal properties and failure modes of structural elements under fire.

A series of experiments, which consist of heating tests and load bearing tests for walls and floors with various parameters, was conducted in the study. Differences among timber panel specimens such as adhesive types, thickness of laminations and panels, species of wood, fire protections and applied loads were arranged as the experimental parameters. As the result of the experiments, it became obvious that timber panels with typical configuration had sufficient thermal insulation and integrity in standard fire testing. Timber floor with a thickness of 150mm also had enough fire resistance exceeding 60min but delamination of almost all charred timber layers was observed in fire testing for CTL panels. As for the load bearing capacity of timber walls, fire exposure on a one-side surface caused eccentric load with disproportionate charring and resulted in buckling.

An Approach for Ascertaining Residual Capacity of Reinforced Concrete Beams Exposed to Fire

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Reinforced concrete (RC) structural members exhibit high fire resistance due to relatively low thermal conductivity, high thermal capacity, and slower degradation of mechanical properties of concrete with temperature. Statistical data clearly suggest that while fires do occur in buildings, complete collapse of structural members due to fire is a rare event. This is primarily due to the presence of active protection systems in buildings combined with better fire-fighting strategies adopted in recent years. In such cases, RC structural members retain much of their structural capacity after a fire incident. However, this does not ensure safety of the building for immediate reoccupation after fire is extinguished. Unlike fire induced spalling, which is a visible sign of damage, structural deterioration due to degradation of mechanical properties at elevated temperatures and redistribution of stresses within the member is not too apparent. Thus, it is imperative to ascertain the residual capacity of structural members through rational engineering methods in order to ensure that the desired residual capacity is present in structural members even after fire. Such an assessment would be indispensable for subsequent retrofitting strategies as well. This paper develops a methodology for assessing residual capacity of fire exposed reinforced concrete beams through numerical studies.

To develop such an approach for evaluating residual capacity of reinforced concrete members, a set of numerical studies were conducted using finite element software ABAQUS. The analysis is carried out in three stages as illustrated in a flow chart in Fig. 1.

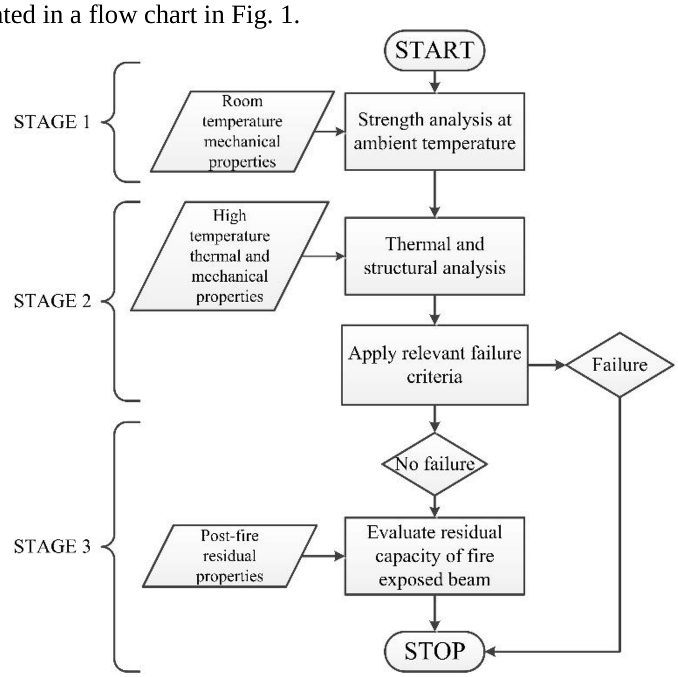
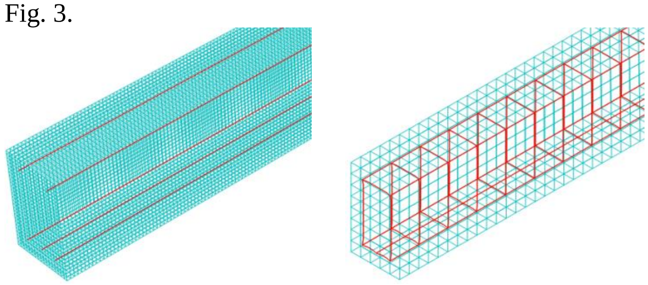


Fig. 1. Flow chart describing the three stages involved in residual capacity analysis.

The first stage is a mechanical analysis of to evaluate room temperature capacity of RC beam utilizing ambient temperature mechanical properties. The second stage comprises of a sequentially coupled thermal stress analysis of the loaded beam exposed to a given fire scenario. The thermal analysis generates cross sectional temperatures and associated thermal gradients in the section during the complete heating and cooling regime of the fire in incremental time steps. Knowing the temperatures, and corresponding strength degradation in concrete, steel rebar, and FRP reinforcement, moment capacity of RC beam is evaluated utilizing an approach similar to that at room temperature but incorporating temperature dependant strength and stiffness degradation in properties of concrete, and steel rebars. Following this, at each time step, the failure of the beam is checked in terms of exceeding applied moments due to loading during fire, or an allowable deflection limit. If the beam survives fire exposure, the residual plastic deformations from the second stage analysis are carried over into the third stage of analysis wherein residual response is traced via incremental loading to failure. This way the residual load carrying capacity of the beam is determined in third stage of the analysis.

The above procedure was applied to a number of NSC beams of 3.96 m span and of rectangular cross section with different boundary conditions. A combination of standard and design fires was adopted to account for common heating regimes encountered in practice. For the thermal model (Fig. 2. (a)), the concrete section was discretized using DC3D8 element (8 node linear brick element) and the steel reinforcement was discretized using DC1D2 element (2 node link element) with nodal temperature as the only active degree of freedom. The structural model (Fig. 2. (b)) utilized C3D8 (8-node linear brick) element, and longitudinal reinforcement and stirrups were discretized using T3D2 (truss) element available in ABAQUS library. The numerical model was validated against measured data from fire tests as shown in Fig. 3.



(a) Thermal Discretization (b) Structural Discretization

Fig. 2. 3-D discretization of the selected beam for numerical simulation.

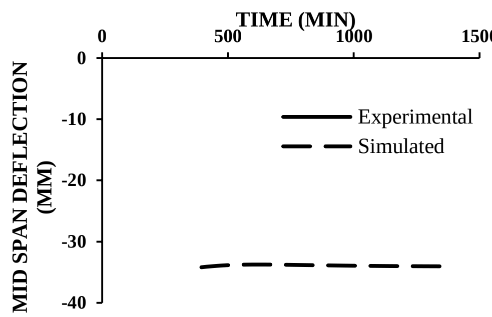


Fig. 3. Comparison of simulated mid span deflections for Beam NSC2 (Table 1.) with experimental results in literature.

Representative analysis results, one for the standard ASTM E119 fire and the other for a short design fire (SF), reveal the significance of fire intensity and duration of exposure on residual capacity. Under ASTM E119 standard fire, failure of the beam occurs during the fire itself. However, the same beam under a more realistic short design fire (SF), with a distinct cooling phase, retains almost 90% of its room temperature capacity when peak rebar temperatures experienced remained below 500 ^{o}C.

Table 1. Description of test parameters and results chosen for numerical studies

Beam	**Support Condition**	**Fire Exposure**	**Load Ratio**	**Maximum rebar temperature (^{o}C)**	**Residual Deflection (mm)**		**Residual Capacity (kN)**	
					Measured	**Simulated**	**Measured**	**Simulated**
NSC1	Simply Supported	ASTM E119	0.55	598	-	-	-	-
NSC2	Axially Restrained	SF	0.55	483	13.8	22.4	119	117

Results from the analysis infer that accounting for distinct cooling phase properties for concrete and steel in the analysis significantly improves predicted response of fire exposed beams. Data from the numerical studies is being used to develop a simplified approach with maximum experienced rebar temperatures and post fire residual deformations as governing parameters in ascertaining post fire residual capacity of RC beams. It will be demonstrated that the proposed approach can be applied in practice to evaluate residual capacity of fire exposed RC beams.

Structural Fire Measurement Capabilities at the National Fire Research Lab

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The National Fire Research Laboratory (NFRL) is a unique facility that is used to conduct research on advanced firefighting technologies, engineered fire safety, material flammability and wildland-urban interface fires. In 2014, the NFRL was expanded to allow research on the response of real-scale structural systems to realistic fire and mechanical loading under controlled laboratory conditions. The laboratory was designed to meet the several performance objectives. The NFRL can accommodate experiments on real-scale structural systems and components up to 2 stories in height and 2 bays × 3 bays in plan. This lab allows the study of realistic fire conditions up to 20 MW that grow, spread and decay. Researchers at NFRL can apply controlled loads to simulate true service conditions. Measurement capabilities were developed to characterize the response of the structural system and components up to failure and to characterize the fire heat release rate and thermal environment in real time. The scientific objectives of the NFRL are to develop an experimental database on the performance of materials, components, connections, assemblies and systems under fire loading. This data can be used by the international research community to validate and verify physics-based predictive models. The lab features two high bay test areas, a 18 m x 27 m strong floor with 1218 anchor points, a 9 m x 18 m strong wall with 420 anchor points, a hydraulic loading system, four large exhaust hoods instrumented for fire calorimetry, an emission control system for scrubbing acid gases and particles generated by real fuels, controlled gas and liquid fuel burners, water suppression systems, overhead cranes and conditioning space. A detailed description of the laboratory will be presented with emphasis on measurement capabilities.

Experimental Design of the Large-scale Floor System Subjected to a Fire

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The National Fire Research Laboratory (NFRL) at the National Institute of Standards and Technology (NIST) is the unique facility which enables experiments on the performance of a full-scale building structure subjected to controlled mechanical loads and real fires up to 20 MW. This paper presents the design of the first series of experimental tests on the building floor system subjected to a fire, which will be conducted in the NFRL. As part of experimental design, earlier structural fire tests on the large-scale floor system, which were conducted in the past few decades, are thoroughly reviewed. The preliminary test plans are developed based on the research needs discussed in literature. A prototype steel-framed building structure (2 story x 2 bay x 2 bay) with composite floors is designed in collaboration with practicing engineers and academic researchers. Test parameters include the various three-dimensional beam-to-column and beam-to-beam connections, floor span length, and degree of composite action (floor stiffness). Various test fire conditions are also considered including localized or compartment fires, heat release rate, and cooling phase. A test fire is simulated using fire dynamics calculations for mechanical design of a test burner. The predictive finite-element models are developed to conduct sequentially coupled non-linear heat transfer and structural analyses. The predictive models are used to develop instrumentation layout and other technical requirements, including hydraulic loading schemes and measurements for temperatures, strains, and displacements. Overall, this project will create a test data to better understand the performance of large-scale floor systems under fire, and the experimental results will be used for validation of predictive models.

A Design Fire for Full-scale Steel Structure/Fire Experiments

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NIST is preparing for a series of experiments proposed to be conducted in 2016 to determine the behavior of a prototype steel-framed building with composite floors subjected to a large fire. Companion papers at this conference describe the laboratory facility [1], the overall objectives of the NIST program [2], and the details of the structural design [3]. The current presentation deals with the design of the fires that will provide the thermal loading on the structure. The fires to be used in this series are intended to stress the floor system, beams, and connections beyond the point of failure (but not to collapse). The experiments will provide data on the structural temperatures, deformations, and failure modes as a function of time and position, all while maintaining (to the extent possible) known boundary conditions. These fires are not intended to represent a specific "Design Fire Scenario" in the sense of one to be used in Performance-based Engineering. The response of the structure will be simulated ahead of the actual experiments using FDS and FEA numerical models. The plan is to replicate the experiments and to quantify the uncertainties associated with the various measurement methods. The results will indicate how steel structures with composite floors of the type evaluated might behave in a beyond-design fire condition (i.e., beyond the fire resistance rating required by current building codes), and will identify weaknesses in the experimental and numerical procedures on which continued research may be necessary.

The thermal load will simulate a growing fire in an over-loaded office setting, up to and beyond a flashover situation, confined to the 6.10 m by 9.15 m bay. The heat release rate (HRR) will be applied based upon knowledge gained in previous full-scale experiments done at NIST with multiple workstations [4] and at Cardington [5] using wood pallets. Following the initial buildup to a maximum HRR, the fire will level off and then be moderated to provide upper gas layer temperatures close to what would be encountered in a parametric fire such as that proposed in the Eurocode [6]. This approach will account for a large fire that is growing throughout the space and will provide insight on the impact of actual structural restraints (as opposed to the choice between having either a fully restrained or totally unrestrained boundary such as prescribed in ISO 834 [7]) on the response of the floor system and connections above the fire.

Natural gas will be used as the fuel source in the structural fire experiments for the following reasons:

- natural gas allows independent and instantaneous control of HRR during an experiment;
- NIST has extensive experience with high accuracy flow rate measurements and independent means of HRR calculation when using natural gas;
- the major constituent of natural gas (CH_4) has the lowest tendency to soot of any hydrocarbon, providing the best environment for optical measurements of displacement;
- natural gas fires are best suited for accurate FDS simulation;
- natural gas provides a baseline for comparison to future solid fuel fires.

Multiple natural gas burners will be required to distribute the fire and to handle the anticipated maximum heat release rate of about 7500 kW during the experiments. The current thinking is to use four sand burners each with a rating of about 4 MW to simulate a fire which travels through the room and when combined can exceed the maximum HRR requirement. One external wall is proposed to have an opening that will provide a vent-area-to-square-root-of-height equal to 10 $m^{5/2}$. The enclosing walls will have a four-hour rating to ensure their integrity over the maximum anticipated time for the experiment. Initial isolated fire experiments also are to be conducted on a restrained beam and on connections of the beam to the fire-protected columns.

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Appendix II Poster Presentation Abstracts

Section: Fire-Structure Interaction

Effect of High Temperature Creep on Response of Concrete Structures Exposed to Fire

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Reinforced concrete structures exhibit higher fire resistance due to superior thermal and mechanical properties of concrete compared to other materials. When exposed to fire, concrete structural members experience significant deformations due to the development of mechanical and thermal strains. In addition, concrete members can develop high level of creep and transient strains at temperature above 500 °C. It is hypothesized that creep and transient strains primarily govern the failure mode in concrete structures when temperatures exceed 600 °C in concrete. While the characterization and quantification of thermal and mechanical strains is well established for different concrete types, there is very limited data on high-temperature creep and transient strains.

A limited number of studies have been carried out to characterize high temperature creep and transient strains of concrete. Current models representing creep and transient strains are based on data resulting from tests performed during the 1970's and 1980's on conventional concrete, and do not represent concrete mixes in today's industry. These models for creep and transient strains are primarily functions of stress level, temperature, concrete constituent materials and time. A considerable variability is shown by these current creep and transient models due to the various adopted concrete types and test conditions. Moreover, current creep and transient strain models have number of drawbacks such as the utilized techniques of creep and transient strain isolation from measured total strain, and the assumptions which are made separate them.

This paper presents a critical review of models for predicting creep and transient strains of concrete at high temperatures. A comparison of creep and transient strains from different models is presented. To illustrate the variability of current creep and transient strain models, two reinforced concrete columns, with different sizes, are analyzed under fire utilizing ABAQUS finite element program. In the analysis different creep and transient strain models are considered to generate comparative response for fire resistance of reinforced concrete columns based on strength and deflection criterions.

Results from numerical analysis shows considerable increase in the predicted fire resistance for reinforced concrete columns compared to experimental results when utilizing constitutive relationships that implicitly accounts for transient and creep strains of concrete. Including transient and creep strains explicitly improves the numerical results of axial deformation with time of tested columns. Moreover, utilizing different transient and creep strain models in the analysis shows considerable variability of the predicted fire resistance and axial deformations in reinforced concrete columns. The numerical results indicate that transient and creep strains constitute to most of the deformation when the temperature in concrete exceeds 600 °C. As temperature and stress level increases higher transient creep strain is experienced and lower fire resistance time is predicted.

Determination of Design Fire Load for Structural Fire Safety Design of Building in the Compartment Subdivided by Non-fire Rating Partitions

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In Performance based approach, engineering calculation method is available for the prediction of fire condition and the verification of structural stability as the condition of fire compartment is finalized. However, it is difficult for office building to guarantee the condition of fire compartment since design change of partition is frequently occurred at replacement of the tenant. And there is an anxiety about extended fire duration time in case of fire spread beyond partition. This poster shows probabilistic risk-based approach to determine the design fire load density for structural fire stability design of buildings when a fire compartment is subdivided into multiple rooms by non-fire rating partition. The point is the failure scenario consists of two events, 1) fire spread beyond the partition, and 2) structural failure caused by extended fire duration time. And the probability occurrence of these two events is balanced out with retardation time of the partition. Three main variables, retardation times of the partition, space division ratio and burning rate, are revealed to affect the probabilistic risk of failure scenario. Furthermore, number of partitions and allocation ratio of fire resistance of these partitions are considered. A case study for office building and residential building were conducted for the compartment with non-fire rating partitions changing these parameters. Results are presented and necessity of adding the design fire load is discussed.

Experimental Study on Influence of Crack Width on Fire Resistance of Reinforced Concrete Members

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Background:
Almost all recent big earthquakes have been followed by fires such as the 1995 Great Hanshin-Awaji earthquake and the 2011 Great East Japan earthquake. The latest was an earthquake hit the Bay Area in California in August 2014. Reinforced concrete structures would be damaged by earthquakes whether it is light or severe. Residual crack width and cover concrete spalling may have some influence on temperature distribution in reinforced concrete members in a fire after an earthquake.

In Kyoto University, we conducted fire resistance tests on cantilever beams. One of them was subjected to upward load, which resulted in tensile cracks at the bottom. The other was loaded downward, therefore tensile cracks were observed at the top of the beam. 30 minutes after heating started the beam heated from the cracked surface showed 100 degree Celsius higher temperature than the beam heated from the compressed surface. The results imply that cracks in concrete damaged fire resistance of the reinforced concrete beams.

Objectives:
The objective of the experiment is to investigate how cracks influence the rise in temperature and, therefore, load carrying capacity of reinforced concrete members in fire.

Experiments:
We constructed four reinforced concrete beams with notches at the bottom. The notches were made every 150 mm in the constant moment region. They were vertically loaded and fire tested in the furnace. Beam *BN* was not loaded. Beam *BL* and *BS* were subjected to service load and short-term load, respectively. Beam *BE* was loaded to the deformation angle of 1/60, and then unloaded to service load.

Flexural cracks were formed as we intended. All the beams except BS were heated for 120 minutes. BS failed at about 100 minutes. Thermocouples were installed to measure temperature distribution in the beam.

Conclusions:
Temperature distribution in the beams indicated that higher temperatures were recorded at the location of the longitudinal reinforcing bars at the bottom side of the cracked sections than at the uncracked sections. However, the difference in temperature at the bottom center reinforcing bars was not so significant between at the cracked and uncracked sections.

Fire Resistance of Reinforced Concrete Frames Subjected to Service Loads

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Two reinforced concrete frames were constructed and tested to investigate fire resistance of statically indeterminate reinforced concrete beam-column subassemblages. The 1/3-scale frames consisted of a beam of 200x300 mm cross-section and columns of 300x300 mm. They were settled in a furnace that was constructed for testing of beams and floors. The inner size of the furnace was 4,000 mm long, 2,050 mm wide and 880 mm high. The testing method we used has been developed in order to test a beam-column subassemblage subjected to service loads in a furnace constructed for beams and floors. The frames were heated on their bottom and both sides. 100 mm thick ALC panels were placed on the top of the beam and covered the furnace along with incombustible seal material on them.

One of the frames was tested to failure, which was defined by losing service load carrying capacity. The other was heated for approximately 30 minutes when the beam longitudinal reinforcement was assumed to yield based on the temperature measurement.

Temperature distributions in the members and the joints by embedded thermo-couples, and deformations and displacements of the frames by displacement transducers during the tests were measured and obtained. We observed that the beam pushed the columns outward, which was typical for a beam-column subassemblage like the frames used in the tests.

Finite element analyses were also conducted. Their results were compared with the test results.

A Study on the Effect of the Collapse Time of Partition and the Opening Pattern of the Rooms on the Severity of a Fully developed Fire

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A model was proposed to calculate the severity of fully developed fires in a multi room spreading scenario and some parameter studies were conducted. The model developed earlier consists of a heat balance of rooms, networks ventilation for mass flow rates through openings, heat conduction in enclosure walls and was extended to consider the burning of the unburnt fuel and the collapse of the partition. Two rooms are consolidated when the partition between the rooms collapses.

The calculation results of the model were compared with the results of the small scale model experiments on fire spread between two rooms with openings. The patterns of the openings were varied. Urethane blocks were set in each room and one of them was ignited. The burning rate of each urethane block, the room temperatures and time for a fire to spread were measured. The model could reproduce the trend of the room temperatures of the experiments.

Some parameter studies on the severity of fully developed fires in two rooms were conducted. The ventilation factors, the patterns of the openings, the collapse time of partition and the floor area were adopted as parameter. The severity was evaluated by the total amount of energy absorbed in the concrete slab. The severity is almost proportional to the collapse time of the partition and the gradient depends on the ratio of the opening factor to the fuel surface area in the fire room ignited at first.

Influence of Water Content on Load-Induced Thermal Strain of High-Strength Concrete

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Numerical analyses on the behaviour of concrete structures exposed to fire heating needs the accurate constitutive model of the concrete underelevated temperature. This is an experimental study on influence of evaporable water in concrete, water/binder ratio and loading level on the load-induced thermal strains (LITS) of high-strength concrete. These cylinder specimens were preconditioned by air dryingor oven drying in 105℃. Water/binder ratios (W/B) were 0.18, 0.24and0.35. In the tests, specimens were subjected to each constant load and heat whose rate is 1.5-2.0°C/min up to 700°C. During the test, an axial relative displacement between both ends of the specimen was measured. Thermal strain of the concrete was also obtained from the un-loading test.

The thermal strain increased with temperature increase. The thermal strain at 700°C was more than 1.2%. In case of the loading tests, the total strain, which includes thermal strain, mechanical strain and transient creep, depended on the loading level. Total strains were larger to contraction for air-drying specimens than for oven-drying specimens between 100°C and 500°C.Influence of W/B was not clear. LITS is a strain that subtracts the thermal strain from the total strain. Therefore, LITS is a contraction strain containing an elastic strain caused by decrease of a modulus of elasticity with temperature increase and creep strain caused as time passes. In all tests, LITSwere larger for air-drying specimens than for oven-drying specimens up to 300°C. Under high loading level tests, absolute values were larger for LITS than for the thermal strain above 200°C.

New Insights on Thermal Calculation of Structures in Fire

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This paper presents some new insights on the thermal calculation of structures in fire, which include:

1) There are formulae in design codes for predicting the temperature of both bare and insulated steel members in fire. New understanding on the applicability of those formulae is produced from an investigation on the theory of lumped heat capacity method.
2) New insight to explain the variation of measured temperatures of steel members with the same cross section but at different locations in a fire compartment is provided by using the theory of thermal radiation in participating medium.
3) There is a lack of calculation methodology in current design codes to predict the temperature of structures in large enclosures where flashover is unlikely to happen. A theoretical model is provided to calculate the thermal radiation from a fire plume to a horizontal surface and is used to answer the question of whether or not gas temperatures can be used to predict the temperature of horizontal members in large enclosure.
4) In large enclosures, if a column is far away from any combustion materials, the column may be left unprotected. A theoretical model is provided to determine the required safe distance from a steel column to a localized fire source. If the horizontal distance from a steel column to a localized fire source is greater than the equivalent diameter of the source, the bare steel column will not fail due to the localized fire.

National Research Institute of Fire and Disaster (NRIFD), Japan

The NRIFD, under Fire and Disaster Management Agency, Government of Japan, is the unique institute in Japan engaged in comprehensive research on firefighting and disaster prevention. Our mission is to provide scientific and engineering support to assist firefighting in their work and respond to society's demand for safety and security. In the poster, research activities, especially fire safety research, in NRIFD are introduced. In addition, research facilities in NRIFD are briefly introduced.

Center for Fire Science and Technology, Tokyo University of Science (TUS), Japan

Tokyo University of Science (TUS) has long been at the forefront of fire science. TUS established the Center for Fire Science and Technology (CFSaT) in 1981 and hasn't looked back since. Today, the CFSaT carries on research to help reduce the damage and impact of fires. The CFSaT cooperates with other leading institutions—academic and otherwise—working in areas of fire safety research, education and engineering worldwide. Today, the CFSaT carries on this tradition of research at the Fire Research and Test Laboratory, which was established in 2005 and boasts world-class facilities and equipment.

Smoke Detector Research at NIST

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Current research at NIST regarding smoke detection will be presented. Research activities include multi-angle, multi-wavelength smoke light scattering, smoke alarm performance measurements, very early warning fire detection and spacecraft smoke detection.

An Investigation of Thermally-Induced Failure of Lithium Ion Batteries

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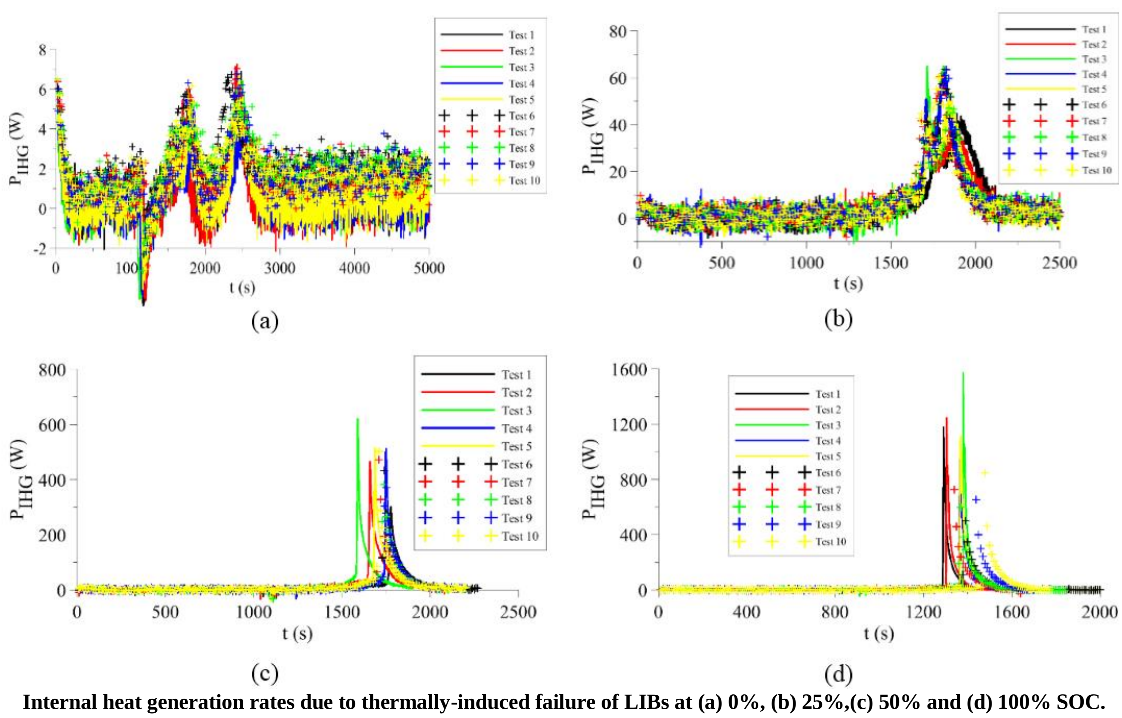
As Lithium Ion Batteries (LIBs) are being deployed in a wide range of energy demanding applications, their fire safety becomes an important consideration. An LIB subjected to an external heat vents potentially combustible gases and aerosols (safety venting), and subsequently, self-heats rapidly while simultaneously ejecting core electrode materials (thermal runaway). These two stages of thermally-induced failure can considerably contribute to hazards associated with developing fire.

In this study, thermally-induced failure of LIBs (type 18650) at different states of charge (SOCs) have been examined. The LIB Calorimeter was designed in our laboratory where LIB thermally-induced failure could be initiated. A systematic procedure was developed to measure the rates and integral amounts of internal energy generation (IHG) during the battery failure. The history of internal energy generation (shown below) due to thermally-induced failure was determined from the temperature rise and mass loss of the battery. Simultaneously, the LIB calorimeter experiments were conducted inside a cone calorimeter to measure the heat produced in flaming combustion of vented products from the battery. These data were then utilized to construct a thermophysical model of the thermally-induced battery failure which purpose was to enable prediction of the battery behavior beyond the range of heating conditions realized in the experiments.



Internal heat generation rates due to thermally-induced failure of LIBs at (a) 0%, (b) 25%,(c) 50% and (d) 100% SOC.

A Hybrid Cutcell-(Immersed Boundary) Method for Low-Mach Flows

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The Fire Dynamics Simulator (FDS) is a low-Mach, large-eddy simulation (LES) code designed specifically to model thermally-driven, buoyant flows. FDS is a structured solver using a Cartesian, staggered grid arrangement for velocity and scalars. Historically, flow obstructions in FDS have been confined to align with the rectilinear grid. A direct-forcing immersed boundary method (IBM) is employed by the flow solver. As pointed out by Fadlun (2000), such a simple IBM method exhibits zeroth-order errors for curvilinear geometry. In recent work, a higher-order IBM approach has been implemented for momentum in FDS. IBM approaches are, however, notoriously diffusive for scalar fields. This limitation prevents the use of immersed boundaries for scalar transport in FDS where the slightest bit of spurious (non-physical) mixing between fuel and oxidizer may lead to catastrophic simulation results. The present work combines the well-established cutcell method (Berger and Aftosmis) for scalar transport with the advantages of direct-forcing immersed boundary methods for momentum. The key challenge is getting the formulation to handle so-called ``thin" obstructions (zero thickness), which are planes that may have arbitrary orientation relative to the Cartesian grid used for the gas phase flow solver. The geometry is input to the code using geometry groups similar to an XML schema. The unstructured geometry is then ``flattened", computationally, within the flow solver. The geometry nodes may move either explicitly or through coupling with a finite element code.

Characterizing the Performance of Firefighter Equipment

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Current test methods and standards do not fully characterize the performance of firefighter equipment in high temperature, rough duty environments. Representative test methods are needed to characterize the performance of fire fighter equipment under the extreme environments in which firefighters operate. The three major areas of study include: performance of firefighter electronic equipment in rough-duty fire fighting environments, performance of firefighter self-contained breathing apparatus (SCBA), and performance of firefighter protective clothing.

Towards Data-Driven Operational Wildfire Spread Modeling

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The challenges found on the route to developing quantitative fire models are two-fold. First, there is the classical modeling challenge associated with providing accurate mathematical representations of the multi-physics phenomena that determine the fire dynamics. Second, there is the less common data challenge associated with providing accurate estimates of the input parameters required by the models. Current fire models are limited in scope because of the large uncertainties associated with the accuracy of physical models, because also of the large uncertainties associated with many of the input parameters to the fire problem. A possible approach to overcome the limitations found in numerical simulations of fires is data assimilation (DA): DA consists in combining computer simulation tools with sensor observations, or more precisely in using observations to correct and optimize computer model predictions. While still original in the field of fire and combustion, DA is an established approach in several scientific areas, for instance in the field of numerical weather predictions.

The objective of this project is to develop a prototype sensor-driven wildfire simulation capability capable of forecasting the fire spread dynamics. The project builds on a collaboration between CERFACS in France and the University of Maryland that led to the development of a prototype wildfire spread simulator called EnKF/FIREFLY. EnKF/FIREFLY features the following main components: a level-set-based fire propagation solver that adopts a regional scale viewpoint, treats wildfires as propagating fronts, and uses a description of the local rate of spread (ROS) of the fire as a function of vegetation, topographical and meteorological properties based on Rothermel's model; a series of observations of the fire front position; and a data assimilation algorithm based on an Ensemble Kalman Filter (EnFK). The DA algorithm also features a choice between a parameter estimation approach in which the estimation targets (the control variables) are the input parameters of the ROS model and a state estimation approach in which the estimation targets are the spatial coordinates of the discretized fire front. The prototype data-driven wildfire spread simulator has been previously evaluated in a series of verification tests using synthetically-generated observations as well as a first validation test corresponding to a small-scale controlled grassland fire experiment. It is currently being evaluated in large-scale controlled prescribed fires as well as large-scale wildfire events.

Experiments on Suppression Performance of Sprinkler System Against Different Fuels

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A series of experiments were carried out to comprehend suppression performance on heat release rate of different fuels under operation of sprinkler system in fire. The fuel was used such as wood cribs (900mm x 900mm, weight:50kg/m^2), urethane foam (1000mm x 1000mm x 1000mm, weight:8kg), sofa (1200mm x 690mm x 710mm, weight:24kg), and n-heptan (Fuel tray dimensions: 300mm x 300mm, 500mm x 500mm, 800mm x 800mm).The conditions of sprinkler were set as typical system in Japan, namely amount of water supply: 80 L/min, pressure at sprinkler head : 0.1 MPa, radius of sprinkler spray: 2.6m. The distance between fuel surface and sprinkler and sprinkler activation time were changed as experimental conditions.

As the results of this experiment, if n-heptane was used as fuel, the heat release rates when sprinkler activated or not were almost the same time-history. In experiments used wood crib, though the maximum heat release rate was approximately 1500kW when sprinkler system didn't activated, the maximum value was 1200kW-1300kW when sprinkler system activated. Besides the change of the distance between fuel surface and sprinkler and the sprinkler activation time didn't have much influence on heat release rate.

In the case of urethane foam set as fuel, although the maximum heat release rate without sprinkler system was approximately 1000kW, the heat release rate became 0kW after sprinkler activated. In the case where sofa was used as fuel, the heat release rate under sprinkler activation was about 200-400 kW lower than one without sprinkler system.

Session-Large Outdoor Fires

Hwy 31 Fire – A Study of a Residential Community Attacked by Wildfire in the Night

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Of the U.S. housing stock, 32-percent are located in the Wildland-Urban Interface that covers one-tenth of all the land in the U.S. with housing. Housing developers are establishing new communities built on patches of land cleared from surrounding forest. Historically these areas have experienced repeated wildfire. Now, new communities consisting of closely spaced, light-weight construction homes are subject to that threat. Americans have become accustomed to major fires in the western U.S. threatening and destroying homes. Less so are major events in the eastern U.S. This poster presents facts gathered from an on-scene study of the 2009 Highway 31 fire that spread in the night, predominately by wind-driven brands, to the Barefoot Resort, a newly established retirement community in South Carolina. As there were a large number of homes lost, the Home Safety Foundation pursued information about the wildland fire, its spread, community preparations, and the community evacuation through interviews with fire department officers, and residents that chose not to evacuate. These residents were eye-witnesses to the fire spread in the community. Some chose to fight the fire spread with garden hoses and were able to save structures. This information supplements and enriches publically available material. This study illustrates the hazards faced by new communities built in areas that historically have experienced wildfires. The poster will include visuals from the community before, after and during the fire.

A Case Study of a Community Affected by the Waldo Fire – Event Timeline and Defensive Actions

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The National Institute of Standards and Technology (NIST) has a suite of research projects addressing risk reduction in Wildland Urban Interface (WUI) communities. The NIST WUI Team and the United States Forest Service Fire and Environmental Research Applications Team (USFS FERA) were invited by the Colorado Springs Fire Department (CSFD) to collect post incident data from the Waldo Canyon fire. The case study is focused on the Mountain Shadows development in Colorado Springs. There were 1000 homes in the Mountain Shadows community that were within the fire perimeter and of these, 346 homes were completely destroyed. The data collected and the data analysis are divided into two papers. This first paper, addresses the event timeline reconstruction and general fire behavior observations. This second paper investigates specific parts of the Mountain Shadows community and how fire propagated though them.

The primary objectives of this work were to reconstruct the fire timeline and show where the fire was in the community as a function of time, document the extent and type of defensive actions that were undertaken during the first ten hours after the Waldo Fire reached the Mountain Shadows community, quantify structural loses as related to local weather conditions and begin the characterization of fire and ember exposures from burning structures. The level of fire and ember exposure was identified as having played a significant role in the survivability and destruction of structures with a pattern of increased destruction of residential structures with increased exposure. Additionally, exposure was found to play a significant role in structure survivability with respect to the effectiveness of defensive actions.

2011 Wildland Urban Interface Amarillo Fires Report #2 – Assessment of WUI Measurement Science and Fire Behavior

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On February 27, 2011, three fires began in the outskirts of Amarillo, Texas, two of which destroyed or damaged buildings in multiple housing developments. The National Institute of Standards and Technology (NIST), as part of its Disaster and Failure Studies Program, began gathering electronic data for the incident within 6 hours of the Tanglewood fire front moving through the Pallisades Community in Lake Tanglewood. NIST and the Texas Forest Service (TFS) integrated a field data collection team into the Incident Command System (ICS) within 48 hours to conduct a post-fire assessment. Initially, both the Willow Creek South Complex and Tanglewood Complex fires were assessed. Within 72 hours after ICS integration, the Tanglewood Fire became the focus of the deployment. The deployment also supported local and state damage assessment efforts.

This assessment represented the first deployment of the NIST WUI 2 field data collection method where logistics and standard operating procedures (SOPs) were integrated into the ICS. Information was collected in the field related to residential structures, combustible features, non-combustible features, fire direction, fire timeline, burned vegetation and defensive actions. Documentation included over 29,000 ground photographs, 2,330 geolocated man-made features, 281 distinct records of burned vegetation and discussions with 48 first responders and homeowners. Pre-fire and post-fire aerial imagery as well as radar data was acquired for the study area.

This report represents the second report for the Tanglewood Complex Fire. The first report provided information on all three fires and provided an overview of possible technical factors responsible for the damage, failure, and/or successful performance of buildings and/or infrastructure in the aftermath of the fire. This study was also used to define areas of future research. This summary report addressed the particulars of the deployment and the data collection methodology used. Additionally, this report provided a summary of the primary structures lost.

This, second report provides the event timeline reconstruction and general fire behavior observations. Additionally, a general assessment of defensive actions is presented to show the spatial extent of these actions and identify potential ignition mechanisms. Topographic characteristics within the affected communities are discussed. This report also details structural and vegetative element ignition mechanisms throughout the communities affected by the Tanglewood Fire. A discussion of current WUI mitigation advice is conducted in context of applicable advice for the affected communities and an assessment of WUI Measurement Science is presented.

Characterization of Fire Spread along Fences

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A series of experiments were conducted to examine the spread of fire along wood fences subjected to wind at various angles. Specifically, 2.4 m long sections of western red cedar or California redwood privacy fences were ignited with a propane burner near one end while wind fields of 9 m/s, 13 m/s, or 18 m/s were applied with the fence aligned with the wind field, perpendicular to the wind field, or at a 45° angle to the wind field. The experiments were conducted at the Montgomery County Fire and Rescue Training Academy grounds near NIST. An airboat owned by the Sandy Spring Volunteer Fire Department provided the wind. To simulate fine fuels typically present in real installations, dried shredded hardwood mulch beds were placed under some of the fence sections. Also, some fence sections were coated with fence preservative to see if it had an effect on fire spread. Pans of mulch were placed downwind as targets for embers produced by the burning fence and/or mulch bed. It was determined that at all wind speeds tested, a mulch bed was required for flames to spread. Fastest flame spread was achieved with the fence in line with the wind field. Many of the conditions tested produced embers which ignited spot fires in the mulch targets. These experiments demonstrated that ignited wood fencing assemblies can be a fast conduit of fire along themselves and potentially to any attached or adjacent structure and can produce spot fires from their own ember generation.

Visualizing Outdoor Fire and Smoke Data

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Several techniques are presented for visualizing outdoor fire and smoke data. One technique involves visualizing changing terrain using satellite images with modeling results overlaid. For example, level set contours are drawn on a sloped terrain. These level set contours represent a fire line. A fire line is used with wildland fire simulations as an efficient means for visualizing the motion of fire across terrain. A thin red line represents the location where burning is currently taking place (the fire line). The grey region represents where burning has occurred and the green region represents where burning has not yet occurred. Level sets are used to quickly (relative to a complete computational fluid dynamic calculation) model fire spread and fire line locations. A second technique makes use of geometric objects for representing modeling elements such as trees or building structures. These two techniques use data generated by fire models such as FDS.

A third technique involves visualizing data obtained from measurement devices rather from modeling data. For example, wind sensor data is visualized using flow vectors along with visual indicators of data uncertainty. A vertical array of green spheres represents measurement locations, the distance from these spheres to spherical shells gives a relative measure of the wind speed. The shell diameter gives a measure of the uncertainty in wind direction. Likewise the shell thickness gives a measure of the uncertainty in wind velocity.

Scale Modelling of Wildland Fires Using Stationary Fires

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Recent experiments of flame spread in discrete fuel beds have revealed the presence of buoyant instabilities which may lead to increased convective heating of fuel particles (Finney et al. 2013). Unfortunately, detailed fluid dynamics and convective heating measurements in spreading fires remain difficult to capture because of the moving burning region of the fire. This is compounded by changes in the flame front and fuel burnout with time, causing non-steady burning rates and dynamic fire behavior that require dozens of expensive, large scale fire experiments to investigate. Stationary burners have long been used to study fires in the built environment, therefore they offer an ideal configuration to study non-steady fire effects in a thorough, statistical manner, in essence capturing a snapshot of a moving fire front.

Experiments were performed using stationary gas burners and liquid fuel-soaked wicks to study fundamental wildland fire behavior, including unsteady flame heating. Stationary fire experiments in forced flow and on inclined surfaces exhibited instabilities similar to those observed in spreading fires but allowed for more detailed analysis of the mechanisms responsible. Large scale inclined experiments were performed using an ethylene gas-fed burner at angles from 10 to 60 degrees. Forced flow experiments were performed on liquid-soaked wicks and small scale gas burners at wind speeds from 0.2 to 3 m/s. Results presented include observations of the general flame structure, including streamwise streak spacing and flame fluctuation frequencies which relate to instabilities observed in large spreading experiments. A description and correlations of flame geometry, useful for predictions of wildland fire spread are also presented.

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Scale-Model Experiment of Fire Whirl Behind an L-shaped Wall

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When a pool fire interacts with a circulating flow, a fire whirl is generated. The generation of a fire whirl tends to increase the fire damage mainly because of induced strong wind and increased flame height and burning rate. This paper studies the occurrence of a fire whirl behind an L-shaped wall. Under the presence of lateral wind, a fire whirl is generated by the interaction between a pool fire and the recirculation region behind the wall. A recently conducted large-scale experiment, in which the height of generated fire whirl exceeded 10 m, is reproduced using a scale model. The scale-model experiment uses a wind tunnel, and the range of wind velocity tested is determined from the wind condition of the large-scale experiment based on scaling analysis. It is found that there is a narrow range of wind velocity that generates an intense fire whirl. The present result supports the scaling analysis conducted. Then, the effect of the location of pool fire on the intensity of generated fire whirl is studied. The intensity of a fire whirl is quantified by the measured average burning rate.

Session-General Fire Safety Science II

A Simple Method of Burning and Surface Flame Spread of a Cubical-Shaped Polyurethane Foam Block

Kazuhiko IDO[1], Ji Junghoon[2], Yoshifumi Ohmiya[3], Ken Matsuyama[3]and Kazunori Harada[2]
[1]Shimizu Corporation, [2]Kyoto University, [3]Tokyo University of Science
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A simple calculation method of burning rate of a polyurethane block is proposed. The method considers flame spread towards multiple directions, i.e., horizontal spread over top surface, downward and lateral spread over vertical side surfaces. After leg of side surface is ignited by dripped melt, upward spread over vertical surface and lateral spread on the vertical surface is considered. Due to burning, shape of the material changes. Downward and lateral shrinkage velocities are calculated directly by burning rate. The actual burning area is calculated by the difference between spread area and burnt-out area considering the shape change of material. Burning rate is calculated by flame radiation to burning surface.

The calculated result was compared with an experiment on a cubic polyurethane block. The size of block is 500mm x 500mm x 500mm. Density was 15.6kg/m^3. The block was ignited at the center of top surface. Heat release rate (HRR) was measured by an open calorimeter. After ignition, flame spread over top surface. After reaching the edges, flame spread down to vertical surfaces. During vertical spread, part of molten material dripped, which ignited the leg of block. After spread to all surfaces, HRR is decreased due to the decrease of burning area.

During the period of flame spread over top and side surfaces, the calculated flame spread area and burnt-out area agreed well experiment. The peak HRR was predicted well. During the decay period, calculated HRR is in accordance with the experiment, but exhibit slight overestimation due to the uncertainties in calculation of shrinking shape. In summary, the model could be used for calculation of burning rate of a polyurethane foam block for modelling early stage of fire source in performance-based design of buildings.

Evaluating Fire Blocking Performance of Barrier Fabrics

Shonali Nazaré, William Pitts, Szabolcs Matko, John. R. Shields and Rick D. Davis
Fire Research Division, Engineering Laboratory, National Institute of Science and Technology,
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Barrier fabrics (BF) are strategically interposed between a cover fabric (CF) and the soft cushioning to modify the thermal response of the upholstery by limiting heat and/or gas transfer in the upholstered assembly [1]. These materials have been successfully used in mattresses and upholstered seating in mass transport vehicles to comply with open-flame flammability regulation. A range of commercially barrier materials including highloft, nonwoven battings, knitted, and woven structures have been studied. This study provides insight into the quantitative properties of the BFs that define their flaming and smoldering propensity when used in combination with non-flame retarded, flexible polyurethane foam (FPUF) and CF.

Fundamental fabric properties that influence the heat transfer properties (HTP), as they relate to thermal protection of cushioning components in upholstered products have been quantified. A thermal protective index (TPI) has been derived and used to rank the BFs. Cone calorimeter experiments were performed to distinguish between BFs with respect to ignition times, peak heat release rate (PHRR), total heat released (THR), and char yield. Additionally, fire blocking performance of barrier fabrics was tested with and without the CF using a new bench-scale composite test. The BF was placed between the CF and a FPUF. The back side of the foam was not covered with BF and the CF to duplicate upholstery sequence. The extent of damage to the underlying foam and flame spread was assessed qualitatively.

In order to improve upholstered product fire safety, a BF must protect the cushioning layer from both flaming and smoldering ignition sources. Smoldering propensity of BFs has been assessed in a small-scale upholstered seating using FPUF/BF/CF mock-up systems and smoldering cigarette was used as ignition source. Smoldering behavior is examined considering char lengths, the mass loss of the complete mock-up assembly, and the fraction of the FPUF used in the mock-up assembly which smoldered during a set time period. A smoldering index for BFs has been derived from the measured char volume fraction (CVF) of the FPUF by varying the BF component in the FPUF/BF/CF mock-up systems, while holding the other two components constant.

This work has demonstrated that the derived TPI value can be used to rank BFs such that the higher the TPI value, the better is the thermal protective performance of a BF [2]. When tested as a composite in a mock-up assembly, the fire blocking barrier materials considered in this study showed a clear distinction between active and passive BFs. Results from this study suggest that if the BF is not an active fire barrier, then the amount of heat transferred through BF is critical, *i.e.*, the material should be thermally thick to protect the underlying foam. Smoldering experiments indicate that the smolder-prone CFs, when placed on top of a number of BFs, are capable of releasing sufficient heat to initiate the char-oxidation smoldering process of some of the BFs and subsequently transmit the heat to the underlying FPUF [3]. Smoldering index of zero or close to zero values correspond to cases where the FPUF is protected by the BF, and sustained smoldering does not develop. BFs with smoldering index of 1 or more resulted in self-sustained smoldering in the FPUF.

References

[1] Nazare S and Davis R. A Review of fire blocking technologies for soft furnishings, Fire Science Reviews 2012, **1**:1
[2] Nazaré S , *et al*., Evaluating fire blocking performance of barrier fabrics, Fire and Materials. Article first published online : 31 OCT 2013, DOI: 10.1002/fam.2210.
[3] Nazaré S, *et al*., Evaluating smoldering performance of barrier fabrics, Journal of Fire Sciences, Published online before print July 14, 2014, doi: 10.1177/0734904114543450.

Identifying a Near-worst Case Scenario for Smoldering Upholstered Furniture

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Corresponding author email: mauro.zammarano@nist.gov

Smoldering poses a serious fire hazard. A large number of residential fire deaths can be attributed to smoldering materials, such as flexible polyurethane foams (FPUFs), commonly found in upholstered furniture and bedding [1].
Smoldering of residential upholstered furniture (RUF) is a complex problem that varies based on the properties of the components (e.g., FPUF, cover fabric, etc.), the layering sequence of the components and the construction of the product. It follows that the possible combinations are almost limitless and, thus, real-scale testing for assessing the smoldering propensity of RUF is not an economically viable solution [2].

Bench-scale tests are more economically feasible than real-scale tests but do not necessarily represent a realistic smoldering scenario. It would seem to be desirable to adopt a small-scale test offering a near-worst-case configuration so that variation from this scenario in actual furniture would most likely lead to less severe smoldering.

The bench scale tests that are currently used in the USA (here referred to as the “standard mockup”) do not offer such a scenario [3]. In fact, they severely underestimates smoldering propensity of household furniture where the buoyant airflow within the foam is not hindered. Here, we propose a modified test that has proven to be a more severe test than the standard mockup. It may offer a near-worst-case scenario, useful for identifying upholstery materials that are less likely to result in smoldering ignition in actual furniture independently of its configuration and/or geometry.

References

[1] Ahrens M. Home structure fires that began with upholstered furniture. Quincy, MA: National Fire Protection Association; 2011.
[2] Gann RG. The challenge of realizing low flammability home furnishing. In: 13th international fire science and engineering conference. London: Interscience Communications; 2013.
[3] Zammarano M, Matko S, Pitts W M, Fox DM, Davis RD, Polymer Degradation and Stability 106 (2014) 97-107

Fire Spread and Growth on Real-Scale Upholstered Furniture Mock-ups

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The burning behaviors of real-scale furniture mock-ups constructed from two 46 cm × 46 cm ×10 cm (seat and back) and two 46 cm × 36 cm ×10 cm (arms) upholstered cushions have been investigated. The four cushions were arranged in a chair configuration on an iron stand and were ignited at the center of the intersection of the seat and back cushions using a succession (depending on whether or not a substantial fire developed) of three flame ignition sources having increasing size and time of application. The materials used in the upholstered cushions were chosen to have a wide range of properties. These included two cover fabrics (cotton and polypropylene/polyester blend), two polyurethane foams (non-fire retarded and fire retarded, satisfying British Statutory Instrument 1324), barrier fabrics (either none, a non-woven high-loft fire-retarded rayon, or a woven blend of aramid and melamine-based-polymer fibers), and polyester fiber wrap (either enclosing the polyurethane foam or not included). Twenty different combinations of materials were investigated, and a minimum of two tests were run for each.

The experiments were performed under the Fire Products Collector (a type of furniture calorimeter) located at the ATF Fire Research Laboratory in Ammendale, MD, which is equipped with oxygen-depletion measurement equipment for heat release rate measurements. Other instrumentation included a load cell for mass measurement, eight video cameras (one infrared) for recording the fire behaviors from various angles and distances, and six gauges for recording heat fluxes at distances of 0.75 m and 1.5 m from the mock-ups along three paths for the front, side, and back. Analysis of the videos was employed to determine the fire front locations on the back and seat cushions as a function of time, which allowed fire spread rates and burned areas to be characterized. Additional parameters determined from the heat release rate and mass measurements included the total heat released, fire growth rate parameter (FIGRA, heat release rate divided by time), mass loss rate, and time varying heat of combustion.

A range of fire spread and growth behaviors were observed for the various cushion types. Maximum heat release rates varied from greater than half a megawatt to levels below the detection limit of the experiment. The fastest fire spread and highest heat release rates were observed for cushions constructed from non-retarded polyurethane foam that did not include a fire barrier. Generally, the fire behavior was somewhat improved (reduced fire spread and heat release rates) when cotton was used as the cover fabric. Replacing the non-fire-retarded polyurethane foam with the fire-retarded material also resulted in improved fire performance. Inclusion of either of the barriers fabrics also reduced the fire spread and heat release rates. The best fire performance was observed for cushions incorporating the cotton cover fabric, fire-retarded polyurethane foam, and the aramid/melamine barrier fabric.

A Methodology for Estimation of Local Heat Fluxes in Steady Laminar Boundary Layer Diffusion Flames

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Department of Fire Protection Engineering, University of Maryland, College Park
Corresponding author email: mgollner@umd.edu

A simple methodology has been developed for the estimation of local mass burning rates and flame heat fluxes over a laminar boundary layer diffusion flame with a high accuracy by utilizing micro thermocouple measurements in the gas phase close to the condensed phase surface. These measurements and this methodology are useful for validation of theoretical and numerical models of laminar flames in the canonical wall fire problem. Results for both liquid and solid fuels will be presented including separation of convective and radiative heat fluxes to the surface and local mass burning rates.

Convective and radiative heat feedback from the flames were measured both in the pyrolysis and plume regions by using temperature gradients near the wall. As expected, for small laminar flames, convective heating was found to be the dominant mode of heat transfer to the condensed fuel surface and accounted for nearly 85-90% of the total flame heat flux in both liquid and solid fuels. The total average incident flux to the condensed fuel surface was estimated to be approximately 22, 20 and 27 kW/m^2 for methanol, ethanol and Poly Methyl Methacrylate (PMMA) wall-bounded flames, respectively. The average convective heat flux from the flame to the wall in the pyrolysis zone was estimated to be 18.9, 17 and 22.9 kW/m^2 for methanol, ethanol and PMMA, respectively. The radiative component in these small flames was observed to be small, never accounting more than 20% of the total wall heat flux. Temperature gradients normal to the wall were found to decrease from the leading edge towards the trailing edge in the pyrolysis zone and were found to remain relatively constant in the combusting plume region (450 K/mm) until the tip of the flame was reached. Thereafter, they were found to decrease significantly as one moves downstream of the combusting plume. The work presented here also discusses the selection of transport properties at appropriate temperatures that allows researchers to calculate convective fluxes by using a crude approximation as opposed to detailed temperature measurements in such flames.

A Fundamental Study for Application of THz Electromagnetic Waves to Fire Safety Technology -Absorption and Transmittance of THz Electromagnetic Waves through Artificial Smoke Environments-

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[1]Center for Fire Science and Technology, Tokyo University of Science, Japan, [2]NTT Microsystem Integration Laboratories, Nippon Telegraph and Telephone Corporation, Japan
Corresponding author email: kmatsu@rs.noda.tus.ac.jp

THz wave has a frequency band between light wave and electric wave, where is about 0.1 - 10 THz. This gives them both the spatial resolution of light waves and the ability of millimeter waves to penetrate non-metallic material. In addition, it resonates with the vibration of gas molecules like infrared ray region. Therefore, THz technology is applied in many industrial fields. This study is a part of application of THz electromagnetic waves to fire safety technology such as Imaging and Gas sensing systems.

First of all, the experiment was carried out by using artificial environment of smoke in order to investigate the properties of transmission and find out the appropriate frequency range of THz wave for fire and smoke environment. By scattering the six kinds of spherical resin minute particle which are different in size of diameter from particle seeder into acryl case, each artificial environment was set up. In these experiments, 4 types electromagnetic (Visible ray, near-Infrared ray, mid-Infrared, Sub-THz wave) were used to compare with the deference of transmission trough the smoke. As the result, the electromagnetic with longer wavelength such as THz region has high transmission properties. And when particle size approximated the range of wavelength, transmission loss changed rapidly. Furthermore, the simple calculation model of transmission loss was developed by using the Mie theory. As the result, when particle size approximated the range of wavelength, calculated scattering coefficient also changed rapidly. The scattering coefficient and transmission tend to be similar.

The above interesting experimental data and effectiveness of the development fire safety technology using THz electromagnetic waves will be shown in the poster. This work was supported in part by the Japan Science and Technology Agency.

Appendix3 Presentations Delivered at Workshop

Operation Tomodachi – Fire Research

Dr. Samuel L. Manzello
Engineering Laboratory (EL)
National Institute of Standards and Technology (NIST)

Guest Researcher, Building Research Institute (BRI)
Tsukuba, JAPAN

Guest Researcher, National Research Institute of Fire and Disaster
Chofu, Tokyo JAPAN

samuelm@nist.gov
manzello@kenken.go.jp
manzello@fri.go.jp

Gaithersburg, MD USA
March 16th, 2015

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ありがとうございます

Thanks for coming!

Tomodachi – Friendship

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History of Japan/USA Fire Research Collaboration

- **From 1976 to 2000, the United States Japan Natural Resources Panel (UJNR) on Fire Research and Safety allowed for more in depth, detailed discussion of shared research findings between both countries**
- **UJNR activities became a mirror image of fully developed conferences within the fire safety science community**
- **At the final UJNR meeting in 2000, it was recommended that future activities be focused on small workshops related to topics of great interest to specific countries**
- **In 1976, when the first UJNR panel on fire research was established, the International Association for Fire Safety Science (IAFSS) had not yet been founded**
- **UJNR was really the first mechanism for research exchange among countries actively engaged in fire safety science research**

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Large Outdoor Fires

- Wildfires fires that spread into communities, known as Wildland-Urban Interface (WUI) fires have destroyed communities throughout the world
- Japan numerous earthquakes - many fires produced in the aftermath
- Large outdoor fires that pose risk to built environment are urban fires in Japan

2014 Chile Fires

1995 Kobe Earthquake

2007 Southern California Fires

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WUI Fires: Growing International Problem

- Fire safety science research has spent a great deal of effort to understand fire dynamics within buildings
- Research into WUI and urban fires is far behind other areas of fire safety science research
- Due to the fact that large outdoor fire spread is incredibly complex, involving the interaction of topography, weather, vegetation, and structures

Europe
2007 fires in Greece
Several hundred structures destroyed
More than 70 people perished

Australia
2009 Fires in Victoria
More than a 1000 structures destroyed
More than 170 people perished

South America
2014 Chile
More than 1000 structures destroyed

USA
2003, 2007 Southern California Fires
2011 Bastrop Complex Fire in Texas
2012 Waldo Canyon Fire in Colorado
2013 Fires in California, Colorado, Texas

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Kick-Off Japan-USA Workshop

Bring WUI and Urban fires Communities Together

Held at NIST June, 2011

Presentations:
NIST
Worcester Polytechnic Institute (WPI)
University of California- Berkeley
University of Delaware
Northern California Fire Prevention Officers/CALCHIEFS
Tokyo University of Science (TUS)
Kyoto University
National Research Institute of Fire and Disaster (NRIFD)
Kobe University

Phenomenological similarities between these fires

Research on urban fires in Japan and WUI fires in the USA has been conducted in each country independently

Little chance of constructive research collaboration


Fire Safety Journal
Preface

Special Issue in Fire Safety Journal

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NIST/JAFSE Agreement
STATEMENT OF INTENT
ON
INTERNATIONAL COOPERATION
BETWEEN
JAPAN ASSOCIATION FOR FIRE SCIENCE AND ENGINEERING (JAFSE)
AND
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST)
日本火災学会
Japan Association for Fire Science and Engineering
For JAFSE:
Prof. Kenji Sato, President
JAFSE
For NIST:
Dr. S. Shyam Sunder, Director
Engineering Laboratory,
National Institute of Standards Technology
Date
Date
Expand to Two topics:
Large Outdoor Fires (LOF)
Fire-Structure Interaction (FSI)
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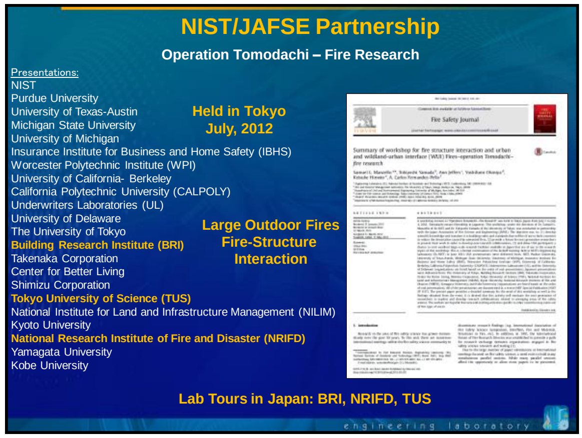
NIST/JAFSE Partnership
Operation Tomodachi – Fire Research
Presentations:
NIST
Purdue University
University of Texas-Austin
Michigan State University
University of Michigan
Insurance Institute for Business and Home Safety (IBHS)
Worcester Polytechnic Institute (WPI)
University of California- Berkeley
California Polytechnic University (CALPOLY)
Underwriters Laboratories (UL)
University of Delaware
The University of Tokyo
Building Research Institute (BRI)
Takenaka Corporation
Center for Better Living
Shimizu Corporation
Tokyo University of Science (TUS)
National Institute for Land and Infrastructure Management (NILIM)
Kyoto University
National Research Institute of Fire and Disaster (NRIFD)
Yamagata University
Kobe University
Held in Tokyo
July, 2012
Large Outdoor Fires
Fire-Structure
Interaction
Fire Safety Journal
Lab Tours in Japan: BRI, NRIFD, TUS
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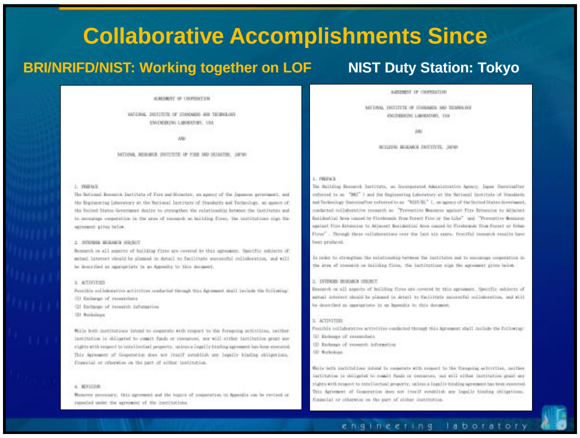
Collaborative Accomplishments Since
BRI/NRIFD/NIST: Working together on LOF
NIST Duty Station: Tokyo
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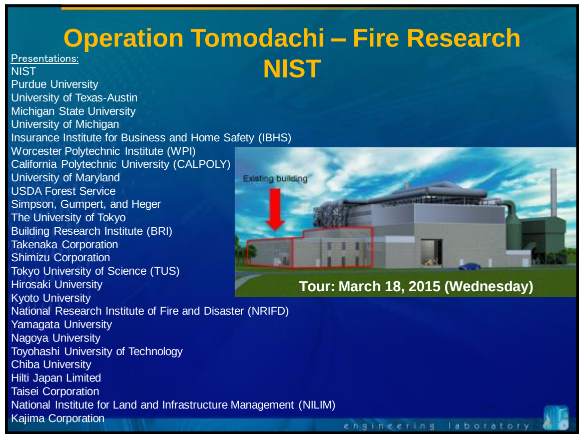
Operation Tomodachi – Fire Research
NIST
Presentations:
NIST
Purdue University
University of Texas-Austin
Michigan State University
University of Michigan
Insurance Institute for Business and Home Safety (IBHS)
Worcester Polytechnic Institute (WPI)
California Polytechnic University (CALPOLY)
University of Maryland
USDA Forest Service
Simpson, Gumpert, and Heger
The University of Tokyo
Building Research Institute (BRI)
Takenaka Corporation
Shimizu Corporation
Tokyo University of Science (TUS)
Hirosaki University
Kyoto University
National Research Institute of Fire and Disaster (NRIFD)
Yamagata University
Nagoya University
Toyohashi University of Technology
Chiba University
Hilti Japan Limited
Taisei Corporation
National Institute for Land and Infrastructure Management (NILIM)
Kajima Corporation
Existing building
Tour: March 18, 2015 (Wednesday)
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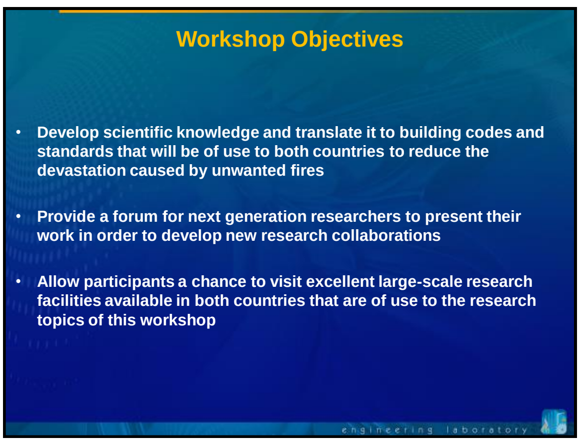
Workshop Objectives
• Develop scientific knowledge and translate it to building codes and standards that will be of use to both countries to reduce the devastation caused by unwanted fires
• Provide a forum for next generation researchers to present their work in order to develop new research collaborations
• Allow participants a chance to visit excellent large-scale research facilities available in both countries that are of use to the research topics of this workshop
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Papers to be Published in Fire Technology
ONLINE FIRST
FIRE TECHNOLOGY
Springer
Oral Presentations:
Special Issue Fire Technology
Guest Editors:
S. Suzuki (NRIFD) and S. Manzello (NIST)
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Closing Survey

- Useful?
- Not useful?
- More workshop?
- No more workshops?
- Happy to no longer receive any emails from Manzello?

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Special Thanks

Arigato Gozaimasu

- Dr. S. Sunder (former EL Director, NIST)
- Dr. K. Sato (former JAFSE President)
- Dr. T. Tanaka (JAFSE President)
- Dr. H. Harary (EL Director, NIST)
- Dr. J. Chin (Deputy Director, EL, NIST)
- Dr. A. Hamins (Chief, Fire Research, NIST)
- Dr. J. Yang (Deputy Chief, Fire Research, NIST)
- Dr. M. Bundy (NRFL Director, EL, NIST)
- Dr. T. Yamada (Vice Director, NRIFD; Japan Chair Organizing Committee)
- Dr. I. Hagiwara (Director, Fire Research, BRI)
- Dr. S. Suzuki (NRIFD – devoted to all three workshops)
- Dr. K. Butler (WUI Group, EL, NIST)

- All presenters and attendees!!

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Large Outdoor Fires in USA – What is the Problem?

Operation Tomodachi – Fire Research
March 16, 2015

日本火災学会

Nelson Bryner
Engineering Laboratory
National Institute of Standards and Technology (NIST)
Gaithersburg, MD

Tokyo University of Science

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Top 15 U.S. Fire Loss Incidents (NFPA)

Incident	Date	Adjusted Loss (2012 dollars)	
1. World Trade Center, New York	2001	$43 billion	5.2 trillion ¥
2. Earthquake and Fire, San Francisco	1906	$8.9 billion	1.1 trillion ¥
3. Great Chicago Fire	1871	$3.2 billion	380 billion ¥
4. Oakland Hills Fire, CA	1991	$2.5 billion	300 billion ¥
5. So. California Firestorm, San Diego County	2007	$2.0 billion	240 billion ¥
6. Great Boston Fire, Boston	1872	$1.4 billion	170 billion ¥
7. Polyolefin Plant, Pasadena, TX	1989	$1.4 billion	170 billion ¥
8. Cerro Grande Wildland Fire, Los Alamos	2000	$1.3 billion	160 billion ¥
9. Wildland fire Cedar, Julian, CA	2003	$1.3 billion	160 billion ¥
10. Baltimore conflagration, Baltimore, MD	1989	$1.3 billion	160 billion ¥
11. "Old" Wildland Fire, San Bernadino, CA	2003	$1.2 billion	140 billion ¥
12. Los Angeles Civil Disturbance	1992	$0.9 billion	110 billion ¥
13. Cerro Grande Wildland Fire, Los Alamos	2000	$0.9 billion	110 billion ¥
14. Southern California Wildlfires	2008	$0.9 billion	110 billion ¥
15. Laguna Beach Wildland Fire, CA	1993	$0.8 billion	96 billion ¥

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What is WUI?

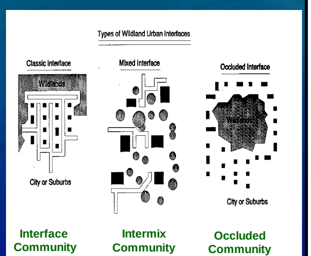
- Wildlands
- Urban

- WUI – "where humans meet with wildland fuel"

Interface Community
- Structures directly abut wildland fuels. 250 people /sq. mile

Intermix Community
- Structures are scattered throughout a wildland area. 28-250 people /sq. mile

Occluded Community
- Structures abut an island of wildland fuels (e.g., park or open space) – often within a city.



The initial definition of urban wildland interface and the descriptive categories used in this notice are modified from "A Report to the Council of Western State Foresters—Fire in the West—The Wildland/Urban Interface Fire Problem" dated September 18, 2000. Under this definition, "the urban wildland interface community exists where humans and their development meet or intermix with wildland fuel." Paragraph Citation 66 FR 753

Ecological Applications, 15(3), 2005, pp. 799–805 q 2005 by the Ecological Society of America
THE WILDLAND–URBAN INTERFACE IN THE UNITED STATES V. C. RADELOFF,1,5 R. B. HAMMER,2 S. I. STEWART,3 J. S. FRIED,4 S. S. HOLCOMB,1 AND J. F. MCKEEFRY1
http://silvis.forest.wisc.edu/old/radeloff_etal_ea2005.pdf

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Where is the WUI in the US?

- All states have WUI - some 75% WUI
- Across US, 9.4% of land is WUI
- WUI is concentrated on eastern US
- Western states have the highest percentage of their homes in WUI
- Across US, 38.5% of homes in WUI

- 70,000 communities at risk of WUI fires
- 46 million structures at risk
- 3000 structures lost in a typical year

- 2 M acres/year becoming WUI

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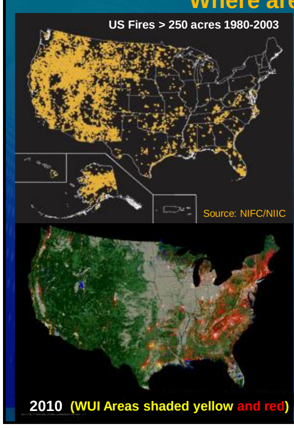
Where are the Fires?



- **Most of fires in western US**
- **Most of WUI in eastern US**

- **Fuel load increasing –**
  structural
  vegetative accumulation

- **Extreme environmental conditions including high winds, hot weather, & low humidity**

- **Climate Change**

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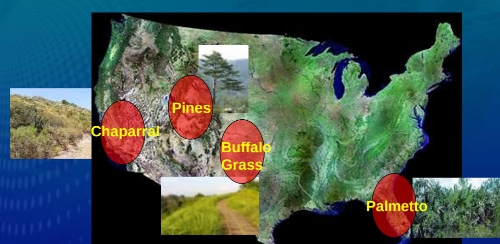
WUI Fuels Across the US



Vegetation	Character
Shrubs	- mixed homogeneous/heterogeneous
Trees (canopy)	- Heterogeneous (multilayered)
Grasses	- Homogeneous

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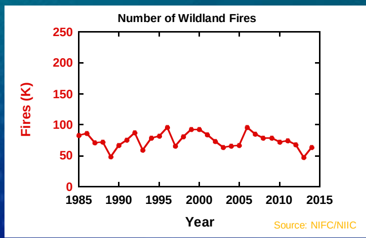
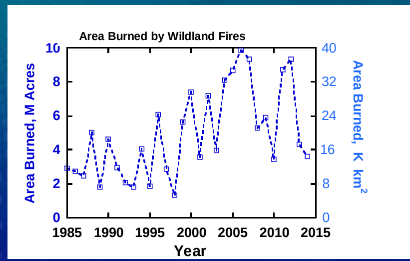
How Many Wildland Fires?



•75,000 (average) wildfires annually in the U.S.

- 97% contained < 10 acres
- Remaining 3% (2300) of fire spread further
- Only 3% of the remaining fires, < 100 fires spread into communities

What Area has been Burned?



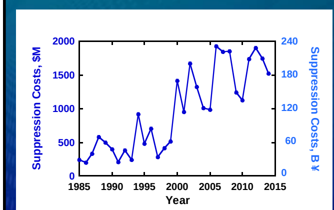
•Average Area Burned: (10 year)

•1985-1994: 3 M acres 12 K km^2

•1995-2004: 5 M acres 19 K km^2

•2005-2014: 7 M acres 28 K km^2

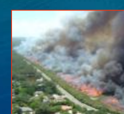
What are the Suppression Costs?



- Costs of wildland and WUI fire incidents less established and comprehensive
- most readily available cost associated with a wildland or WUI fire is suppression cost

Average Cost (10 year):			
	1985-1994	\$ 400 M	50 B ¥
	1995-2004	\$ 880 M	110 B ¥
	2005-2014	\$1600 M	190 B ¥

Summary – Impact of a Growing Problem



WUI Communities
- at least 46 million structures
  - (60% of new homes)
- over 70,000 communities at risk
- Over 120 million people affected

WUI Community Fires
- About 3000 homes lost in “average” year (38,601 homes since 2000)
  - 2003 - 5781 structures lost
  - 2007 - 4900 “ “
  - 2011 - 5850 “ “
  - 2012 - 4244 “ “
- Suppression Costs - \$4.5B (2013)
- Total cost \$14B (2009)

Summary – Additional Impact

Air Quality - Greenhouse Gases –
- 200 % more carbon dioxide than all vehicles in California
- Feed climate change
- Particulates –
  - Compromises respiratory health of exposed population

Water Quality - Run off from fires contaminating water supply

Cascading Damage -
- Fires this year result in mudslides next year
- Evacuation causes transportation related fatalities

Ecosystem Degradation
- Predisposes areas to insect and pathogen attack
- Accommodates invasive species

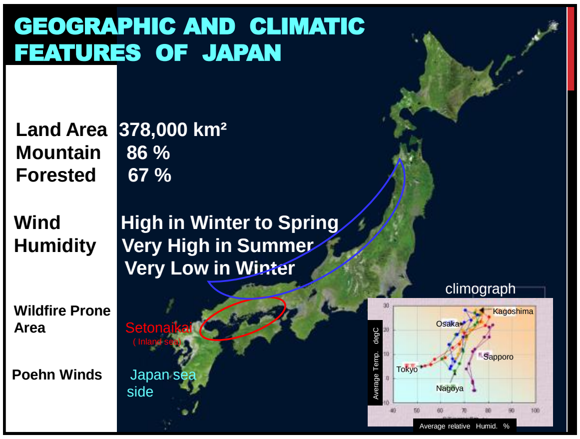
Endangered Species- loss of conservation areas, Loss of habitat, Specie extinction

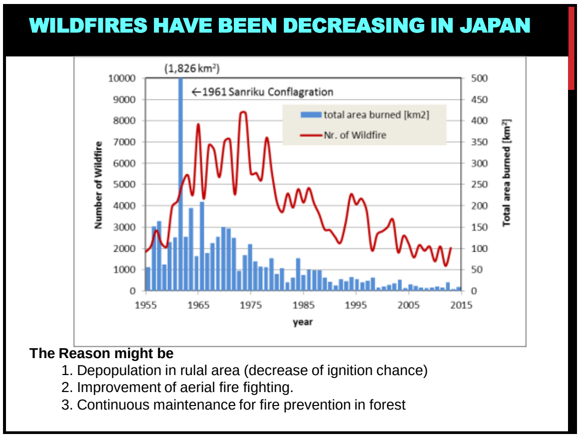
Questions or Comments?

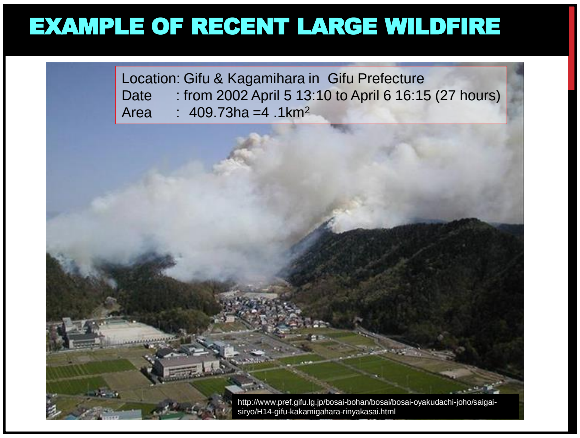
•Thank you for the opportunity to discuss large outdoor fires

•nelson.bryner@nist.gov
301.975.6868

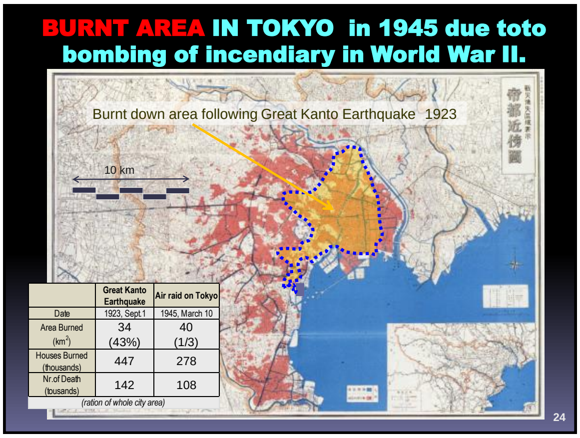

LARGE OUTDOOR FIRES IN JAPAN:
WHAT IS THE PROBLEM ?
TOKIYOSHI YAMADA
NATIONAL RESEARCH INST. OF FIRE & DISASTER
http://www.library.metro.tokyo.jp/digital_library/collectionthe45/the46/tabid/3612/Default.aspx
1855 Nov.11 Fires following the Ansei Edo(Tokyo) Earthquake


GEOGRAPHIC AND CLIMATIC
FEATURES OF JAPAN
Land Area 378,000 km²
Mountain 86 %
Forested 67 %
Wind High in Winter to Spring
Humidity Very High in Summer
Very Low in Winter
Wildfire Prone Area
Setonaikai
Poehn Winds
Japan sea side
climograph
Kagoshima
Osaka
Sapporo
Tokyo
Nagoya
Average Temp. degC
Average relative Humid. %

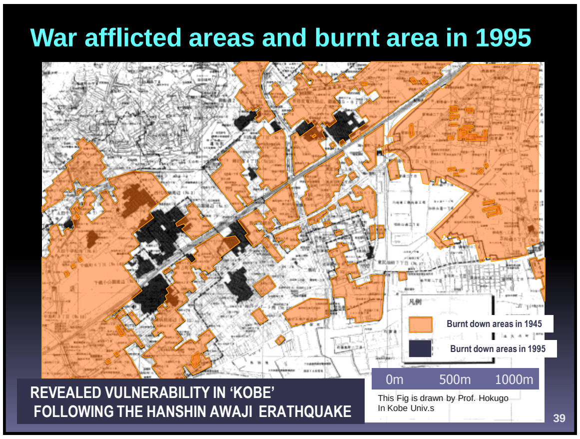

WILDFIRES HAVE BEEN DECREASING IN JAPAN
(1,826 km²)
←1961 Sanriku Conflagration
total area burned [km2]
Nr. of Wildfire
Number of Wildfire
Total area burned [km²]
year
The Reason might be
1. Depopulation in rulal area (decrease of ignition chance)
2. Improvement of aerial fire fighting.
3. Continuous maintenance for fire prevention in forest


EXAMPLE OF RECENT LARGE WILDFIRE
Location: Gifu & Kagamihara in Gifu Prefecture
Date : from 2002 April 5 13:10 to April 6 16:15 (27 hours)
Area : 409.73ha =4 .1km²
http://www.pref.gifu.lg.jp/bosai-bohan/bosai/bosai-oyakudachi-joho/saigai-siryo/H14-gifu-kakamigahara-rinyakasai.html

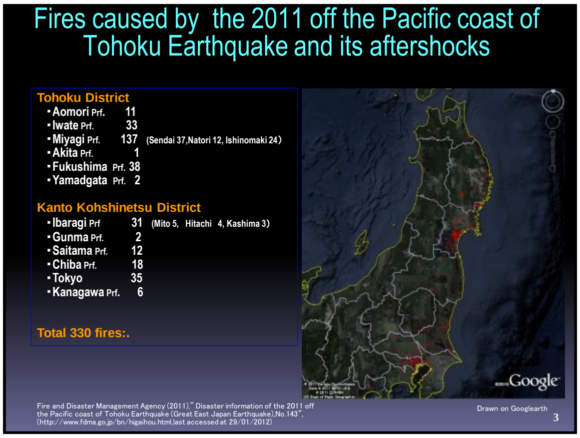

CAPITAL 'TOKYO' WAS BURNED
DOWN TWICE IN JUST 25 YEARS
1923 1st Sept.
1945 10th March
Great Kanto Earthquake | Air raid on Tokyo
Date | 1923, Sept.1 | 1945, March 10
Area Burned (km²) | 34 (43%) | 40 (1/3)
Houses Burned (thousands) | 447 | 278
Nr.of Death (tousands) | 142 | 108
(ration of whole city area)
http://dailynewsagency.com/2011/03/19/1923-kanto-earthquake/
http://www.geocities.jp/torikai007/war/seidan.html
http://www.asahi.com/photonews/gallery/130214_100years/05.html
http://showa.mainichi.jp/photo/2008/06/post-0dcd-5.html


BURNT AREA IN TOKYO in 1945 due toto
bombing of incendiary in World War II.
Burnt down area following Great Kanto Earthquake 1923
10 km
Great Kanto Earthquake | Air raid on Tokyo
Date | 1923, Sept.1 | 1945, March 10
Area Burned (km²) | 34 (43%) | 40 (1/3)
Houses Burned (thousands) | 447 | 278
Nr.of Death (tousands) | 142 | 108
(ration of whole city area)
24


THE KEY ISSUE OF LARGE FIRE IS
URBAN FIRE FOLLOWING GREAT EARTHQUAKE
Ruined Kobe 1945 due to bombing of incendiary in World War II.
1995 Kobe Earthquake
January 17, 1995
http://www.asahi.com/articles/photo/AS20150315001010.html


War afflicted areas and burnt area in 1995
Burnt down areas in 1945
Burnt down areas in 1995
0m 500m 1000m
REVEALED VULNERABILITY IN 'KOBE'
FOLLOWING THE HANSHIN AWAJI ERATHQUAKE
This Fig is drawn by Prof. Hokugo
In Kobe Univ.s
39


LARGE FIRES FOLLOWING THE GREAT EARTHQUAKE AND TSUNAMI 2011 3.11
the Great East Japan Earthquake March 11, 2011


Fires caused by the 2011 off the Pacific coast of Tohoku Earthquake and its aftershocks
Tohoku District
・Aomori Prf. 11
・Iwate Prf. 33
・Miyagi Prf. 137 (Sendai 37,Natori 12, Ishinomaki 24)
・Akita Prf. 1
・Fukushima Prf. 38
・Yamadgata Prf. 2
Kanto Kohshinetsu District
・Ibaragi Prf 31 (Mito 5, Hitachi 4, Kashima 3)
・Gunma Prf. 2
・Saitama Prf. 12
・Chiba Prf. 18
・Tokyo 35
・Kanagawa Prf. 6
Total 330 fires:.
Google
Fire and Disaster Management Agency (2011)," Disaster information of the 2011 off the Pacific coast of Tohoku Earthquake (Great East Japan Earthquake),No.143", (http://www.fdma.go.jp/bn/higaihou.html,last accessed at 29/01/2012)
Drawn on Googlearth
3


Wide Diversity of Fires
(City Fires and Wildland Fires)
SANRIKU COASTAL REGION
Iwate Prf.
• Noda Village
• Yamada Town
• Miyako City
• Ofunato City
Miyagi Prf.
• Kesennuma City
• Minamisanriku Town
• Rikuzentakata City
PLAIN COASTAL REGION
Miyagi Prf.
• Miyagino ward in Sendai City
• Ishinomaki City
• Natori City (Yuriage)
• Watari Town
Fukushima Prf.
• Iwaki City
• Soma
Kesennuma Shishiori city fires
http://www.asahi.com/photonews/gallery/110312tsunami/312tsunami103.html
Yamada machi City Fires
http://www.yomiuri.co.jp/feature/graph/201012wind/garticle.htm?ge=863&gr=3497&id=105147
http://mainichi.jp/select/jiken/graph/20110311/64.html

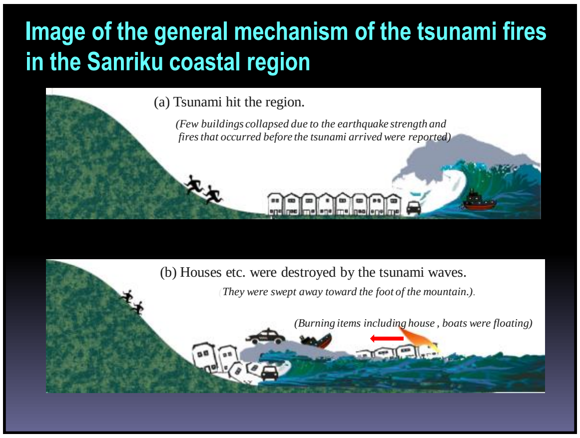


Image of the general mechanism of the tsunami fires in the Sanriku coastal region
(a) Tsunami hit the region.
(Few buildings collapsed due to the earthquake strength and fires that occurred before the tsunami arrived were reported)
(b) Houses etc. were destroyed by the tsunami waves.
They were swept away toward the foot of the mountain.).
(Burning items including house , boats were floating)

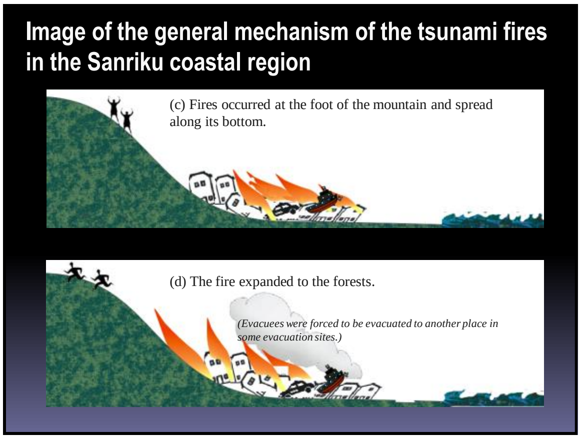
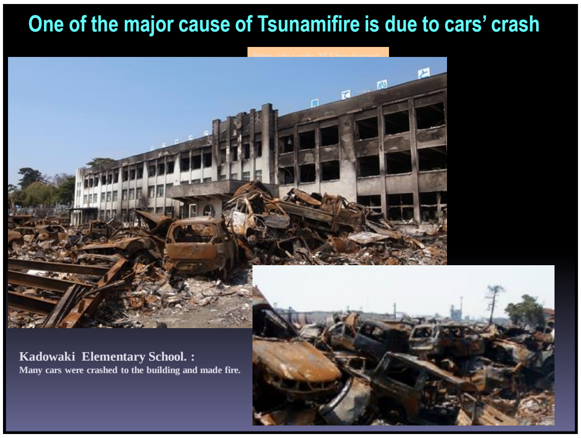
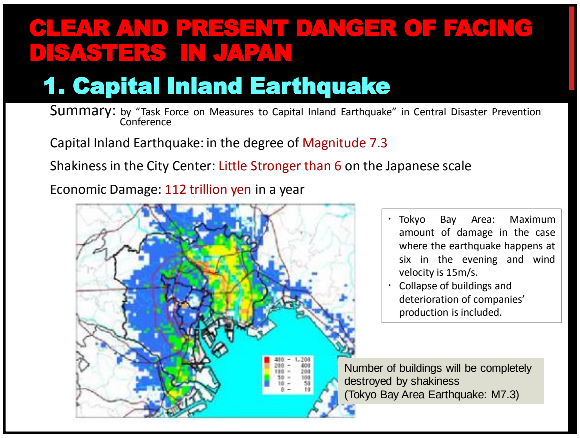
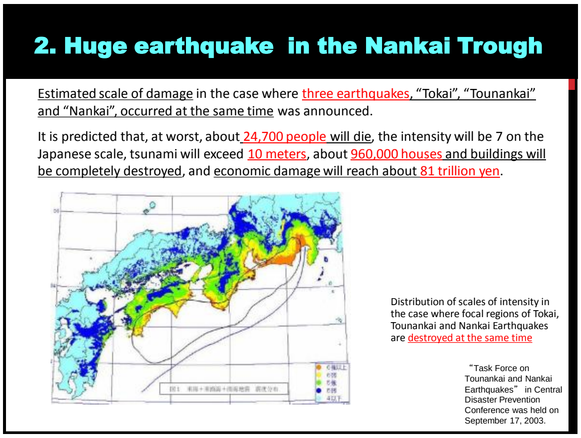


Image of the general mechanism of the tsunami fires in the Sanriku coastal region
(c) Fires occurred at the foot of the mountain and spread along its bottom.
(d) The fire expanded to the forests.
(Evacuees were forced to be evacuated to another place in some evacuation sites.)


Forest fire near the cetral community center
（Ostuchi town）


One of the major cause of Tsunamifire is due to cars' crash
Kadowaki Elementary School. :
Many cars were crashed to the building and made fire.


CLEAR AND PRESENT DANGER OF FACING DISASTERS IN JAPAN
1. Capital Inland Earthquake
Summary: by "Task Force on Measures to Capital Inland Earthquake" in Central Disaster Prevention Conference
Capital Inland Earthquake: in the degree of Magnitude 7.3
Shakiness in the City Center: Little Stronger than 6 on the Japanese scale
Economic Damage: 112 trillion yen in a year
・ Tokyo Bay Area: Maximum amount of damage in the case where the earthquake happens at six in the evening and wind velocity is 15m/s.
・ Collapse of buildings and deterioration of companies' production is included.
Number of buildings will be completely destroyed by shakiness
(Tokyo Bay Area Earthquake: M7.3)


2. Huge earthquake in the Nankai Trough
Estimated scale of damage in the case where three earthquakes, "Tokai", "Tounankai" and "Nankai", occurred at the same time was announced.
It is predicted that, at worst, about 24,700 people will die, the intensity will be 7 on the Japanese scale, tsunami will exceed 10 meters, about 960,000 houses and buildings will be completely destroyed, and economic damage will reach about 81 trillion yen.
Distribution of scales of intensity in the case where focal regions of Tokai, Tounankai and Nankai Earthquakes are destroyed at the same time
"Task Force on Tounankai and Nankai Earthquakes" in Central Disaster Prevention Conference was held on September 17, 2003.

16th March 2015 – NIST, USA

Fire Spread Caused by Combustible Facades

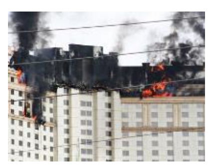
Hideki Yoshioka, Ph.D., Senior Researcher
National Institute for Land and Infrastructure Management (NILIM), Japan

Contents

Background

- With regard to fire safety for exterior walls of a building, fire-resistance is considered, according to the current building standard law of Japan. And it is not specifically regulated from the viewpoint of reaction-to-fire performance, such as fire propagation caused by combustible materials or products.
- Actual fire issues in the world have shown that massive façade fire could occur at the exterior side of building wall even when the wall itself is fire resistant.
- In case of combustible facades, such as insulating materials, combustible coating, or even sandwich panel are installed at the wall surface, once they are ignited, façade fire would occur and accelerate both the fire propagation in the same building and the fire spreading to the adjacent building.

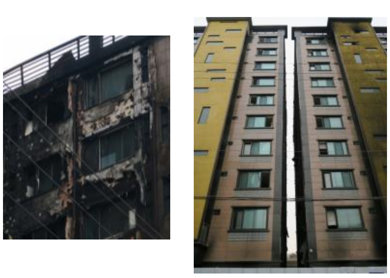
Actual fires



Las Vegas
January 25, 2008

Tokyo
November 3, 2014

Actual fires



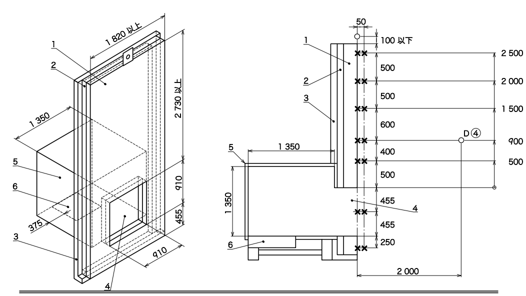
Seoul
January 10, 2015

JIS A 1310:2015 Façade Test

"Test Method for Fire Propagation over Facades", published on January 25, 2015.

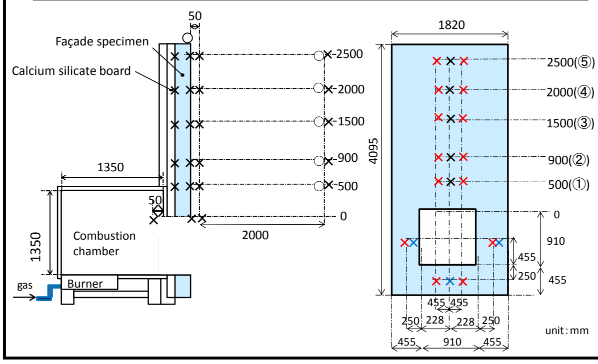
Primary aim:
Vertical fire spread over façade.

Secondary aim :
Horizontal fire spread to adjacent building.

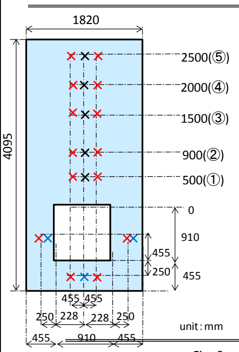


JIS A 1310:2015 Façade Test combined with heat flux meters at opposite side

Measurement



Calibration test result



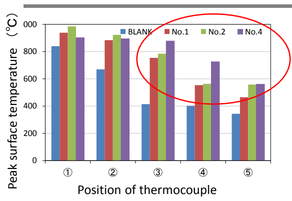
Max. temperature					Max. HF	Max. flame height	
表面最高温度（℃）					試験体上端熱流束	最高火炎高さ(mm)	
①	②	③	④	⑤	最大値（kW/㎡）	連続火炎	間欠火炎
839.6	669.5	414.5	402.2	343.5	11.6	1500	1750

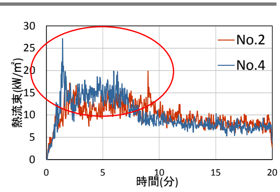
Specimens

試験体	分類	詳細				
BLANK	ブランク試験					
	Exterior insulation (wet type)	芯材	厚さ	密度	バックラップ処理	その他
NO.1		EPS	100mm	15kg/㎥	あり	
NO.2		EPS	100mm	30kg/㎥	あり	
NO.3		EPS	150mm	15kg/㎥	あり	
NO.4		EPS	200mm	15kg/㎥	あり	
NO.5		EPS	150mm	15kg/㎥	なし	開口廻りのみEFR※
NO.6		EFR※	150mm	15kg/㎥	なし	
NO.7		EPS	100mm	20kg/㎥	あり	ピンネット工法 ファイアストップあり (厚さ60mm ALC板)
NO.8	Resin painting	Water resistant exterior finish paint, on calcium silicate boards.(Coated thickness:2~3mm)				
NO.9						
NO.10	Al Composite panel	Core: Polyethylene, with vertical joint between the panels				
NO.11		Core: $Al(OH)_3$ + PE, with vertical joint between the panels				
NO.12	Wooden facade	Vent layer	Japanese cedar, without treatment			
NO.13			Japanese cedar, with flame-retardant treatment			
NO.14	Insulation + siding		Without horizontal furring strip			
NO.15			With horizontal furring strip, as fire-stop, in vent layer			

※ EFR = EPS + Phenolic + $Al(OH)_3$

Test result (Exterior insulation, wet-type)

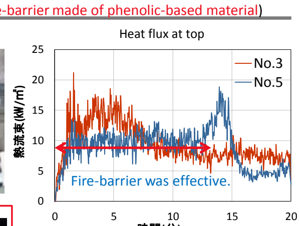




NO.1	EPS	100mm	15kg/㎥
NO.2	EPS	100mm	30kg/㎥
NO.3	EPS	150mm	15kg/㎥
NO.4	EPS	200mm	15kg/㎥

Test result (Exterior insulation, wet-type)

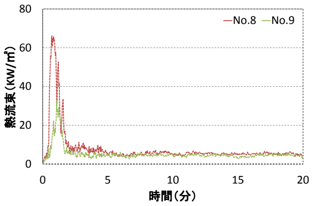
No.3(芯材:150㎜ 15kg/㎥,opening edges: back-wrapped by glass-fiber mesh)
No.5(芯材: 150㎜ 15kg/㎥,opening edges: fire-barrier made of phenolic-based material)



Fire-barrier (phenolic-based) above opening top was effective for 12 min, but no more after that. Improvement needed, such as material for fire-barrier, and installation tecnique.

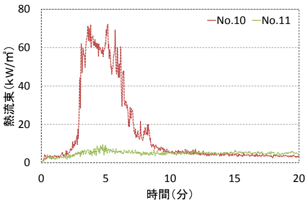
Test result (resin painting)

Heat flux at top end of facade



Test result (Aluminum composite panel)

Heat flux at top end of facade



Test result (Aluminum composite panel)

No. 10

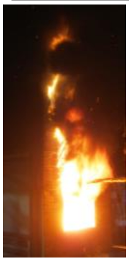
No. 11

Test result (Aluminum composite panel)

No. 10

No. 11

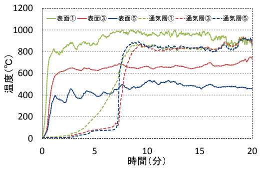
Test result (wooden facade)



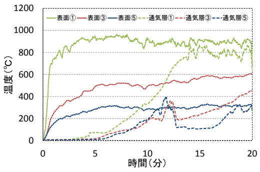
No. 12
Japanese cedar, without treatment

No. 13
Japanese cedar,
with flame-retardant treatment

Test result (wooden facade)



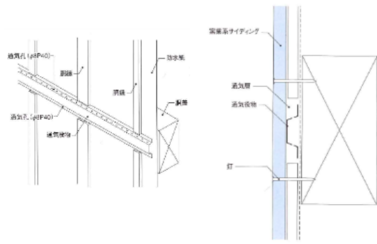
No. 12
Japanese cedar, without treatment



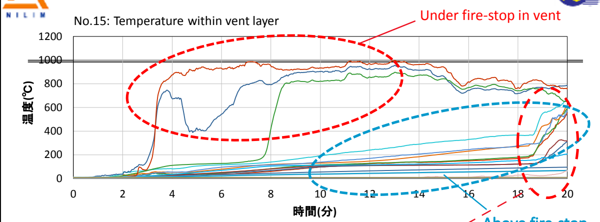
No. 13
Japanese cedar,
with flame-retardant treatment

Calcium silicate boards, wooden mullions, wooden facades.

Insulation + siding board



Test result (Insulation + siding board)

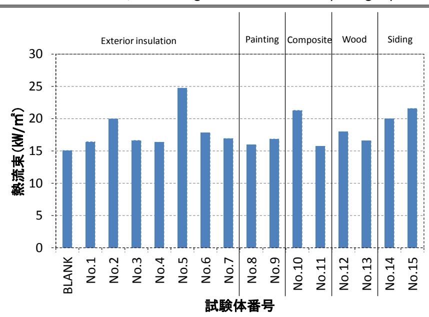


No.14(without fire-stop) No.15(with fire-stop)

Fire-stop (perforated-metal) was effective at least for 18 minutes.

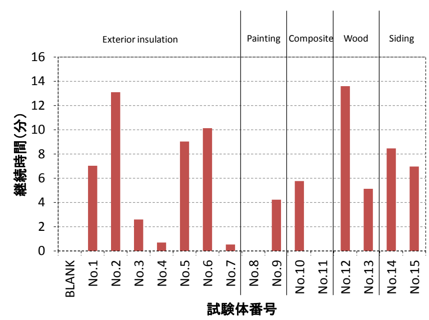
Heat flux at Opposite-side

"Peak" values, at the height of 500 mm from opening top



Heat flux at Opposite-side

Duration time while a certain specimen's peak value exceeds that of calibration test.



Conclusions

- JIS A 1310 was established in January 2015, and this time used for fire tests on combustible facades, from the viewpoints of both vertical and horizontal fire spread.
- Test method was effective in differentiating the fire safety of combustible facades, with respect to traits, such as thickness and edge-treatment of insulation material, core-material of composite panel, flame-retardant of wood, fire-stop in vent layer.
- Incident heat fluxes at 2m from façade were measured, and these data would be used for improving the accuracy of urban fire spread simulator.

Hardening Structures to Wildland-Urban Interface (WUI) Fire Exposures

Dr. Samuel L. Manzello
Engineering Laboratory (EL)
National Institute of Standards and Technology (NIST)

Guest Researcher, Building Research Institute (BRI)
Tsukuba, JAPAN

Guest Researcher, National Research Institute of Fire and Disaster
Chofu, Tokyo JAPAN

samuelm@nist.gov
manzello@kenken.go.jp
manzello@fri.go.jp

Operation Tomodachi – Fire Research
Gaithersburg, MD USA
March 16th, 2015

NIST WUI Group Presentations

- *Dr. Kathy Butler*
- *Mr. Alexnader Maraghides*
- *Dr. Glenn Forney*
- *Mr. Erik Johnsson*

Exciting WUI Group Presentations!

Structure Ignition in Large Outdoor Fires

- Post-fire studies – firebrands a major cause of ignition
- Understanding firebrand ignition of structures – important to mitigate fire spread in communities

Improved understanding of structure ignition in WUI fires

Major recommendation (GAO 05-380)
National Science & Technology Subcommittee on Disaster Reduction
Homeland Security Presidential Directive (HSPD 8; Paragraph 11)
Royal Commission in Australia

Researchers: Who Cares?

- Codes and standards
  - ICC
  - ASTM
  - NFPA
  - CALFIRE
  - ISO
- GAO
- USFS
- DHS
- Insurance industry
- Homeowners
- Construction Industry

Challenges

- Firebrands: generation, transport, ignition
- Research focused on how far firebrands travel for 40 yrs!!
- Nice Academic Problem – Not helpful to design structures
- Vulnerable points where firebrands may enter structure
  - Unknown/guessed!
- Difficult to replicate firebrand attack!
- Entirely new experimental methods needed!

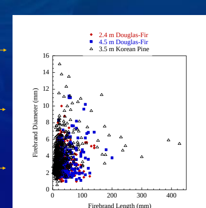
Goals
Science - Building Codes/Standards; Retrofit construction
Harden structures to resistant firebrand ignition

Development of NIST Dragon

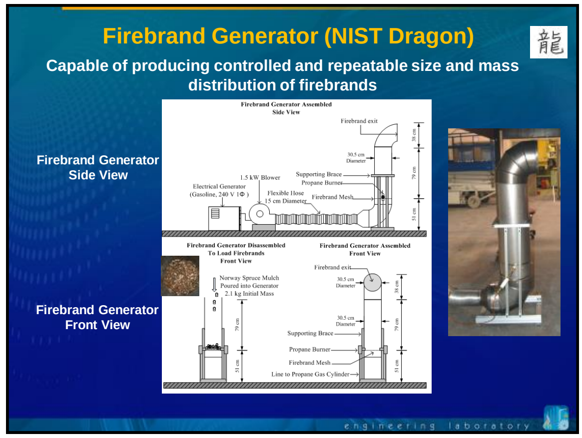
Douglas-Fir Tree Burns at NIST

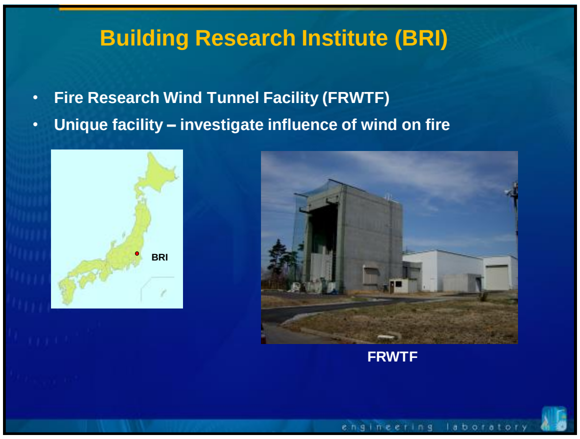
- Firebrand Collection using water pan array
  - Range of crown heights: 2.4 m – 4.5 m
  - Different moisture regimes
- Mass loss using load cells

4.5 m Douglas Fir



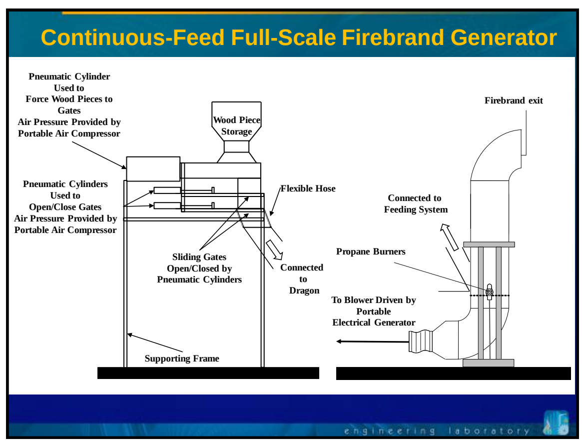

Firebrand Sizes from Angora Fire
Fire Spread
Trampoline
Angora Fire
Trampoline
Determine Firebrand Size from Burn Patterns
NIST and CAL FIRE
Partnership
engineering laboratory


Firebrand Generator (NIST Dragon)
龍
Capable of producing controlled and repeatable size and mass distribution of firebrands
Firebrand Generator
Side View
Firebrand Generator
Front View
engineering laboratory


Building Research Institute (BRI)
• Fire Research Wind Tunnel Facility (FRWTF)
• Unique facility – investigate influence of wind on fire
BRI
FRWTF
engineering laboratory


NIST Dragon
龍
Firebrand size/mass commensurate to full scale tree burns
and actual WUI fire (2007 Angora Fire)
engineering laboratory


NIST Dragon Technology – Cloned Around the World
龍
UL (USA)
NRIFD (Japan)
IDAI – Largest WUI Fire Research Institute in Europe
Cloned Bench-Scale Continuous Feed Dragon
IBHS Cloned
Full-Scale (NIST Dragon)
engineering laboratory


Continuous-Feed Full-Scale Firebrand Generator
Pneumatic Cylinder
Used to
Force Wood Pieces to
Gates
Air Pressure Provided by
Portable Air Compressor
Wood Piece
Storage
Firebrand exit
Pneumatic Cylinders
Used to
Open/Close Gates
Air Pressure Provided by
Portable Air Compressor
Flexible Hose
Connected to
Feeding System
Propane Burners
Sliding Gates
Open/Closed by
Pneumatic Cylinders
Connected
to
Dragon
To Blower Driven by
Portable
Electrical Generator
Supporting Frame
engineering laboratory

Standard Laboratory Test Methods

- Without standard laboratory test methods:
  - Impossible to evaluate/compare performance of building elements ability to resist ignition
- Before test standards are developed - detailed full-scale experiments required:
  - Determine necessary size of building component sections for standard laboratory test methods

ASTM/NIST Building Vent Studies

Full-scale experiments used to guide Standard laboratory test methods

NIST Prior Mulch Studies

- Creation of defensible space around structures is a common mitigation strategy
  - In many areas the requirement for defensible space:
    - Not popular due to resistance to modify the natural environment/landscaping
    - Not practical due to limited lot size
- Of particular concern are landscape mulches located adjacent to buildings

Accumulated Firebrands May Ignite Mulch Beds

Shredded Hardwood Mulch (11 % MC; 8 m/s)

Mulch Studies

- *Are wind-driven firebrand showers capable of igniting common wood mulches found in WUI communities?*
  - Data collected for only shredded hardwood mulch
- *Once ignited, are wood mulches capable of igniting building components?*
- *What about siding treatments?*

Mulch to Wall Ignition Studies

First-step – possible for mulch to ignite walls with no siding?

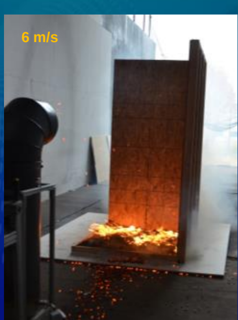
Re-entrant corner (wood studs with OSB)
1.2 m by 1.2 m by 2.44 m (H)

Shredded Hardwood Mulch (51 mm depth)

Wood Chip Mulch (51 mm depth)

Pine Bark Nugget Mulch (51 mm depth)

Mulch to Wall Ignition Studies



Shredded Hardwood Mulch (oven dried)

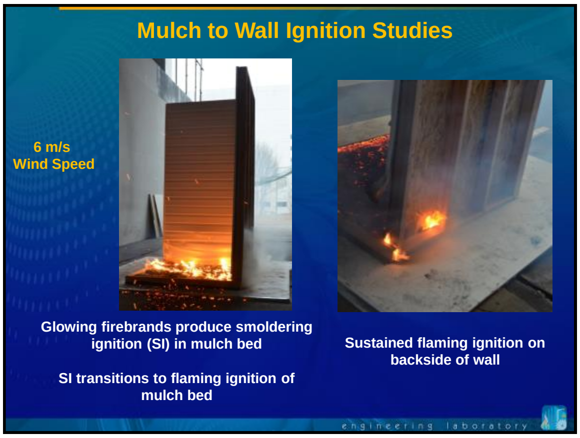
Mulch to Wall Ignition Studies

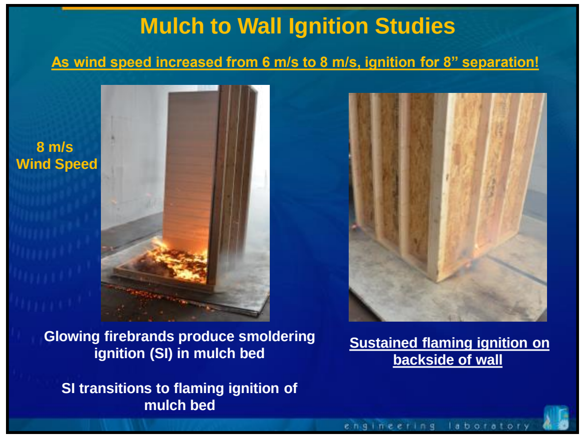
What about the addition of siding?

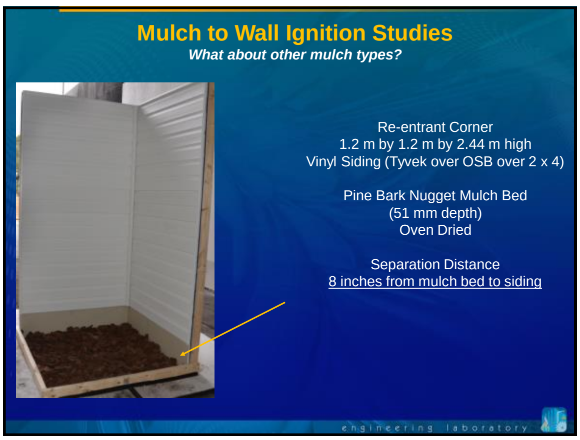
Re-entrant Corner
1.2 m by 1.2 m by 2.44 m high
Vinyl Siding (Tyvek over OSB over 2 x 4)

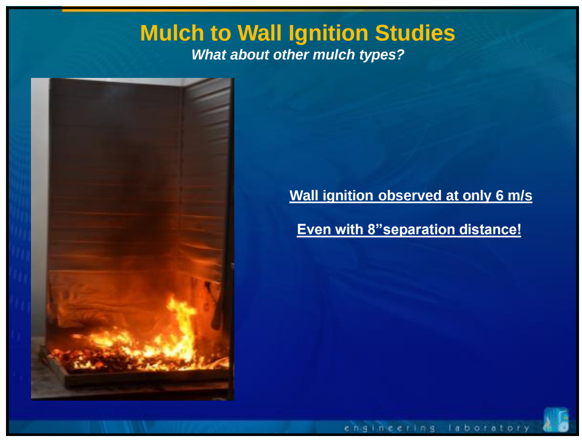
Shredded Hardwood Mulch Bed
(51 mm depth)
Oven Dried

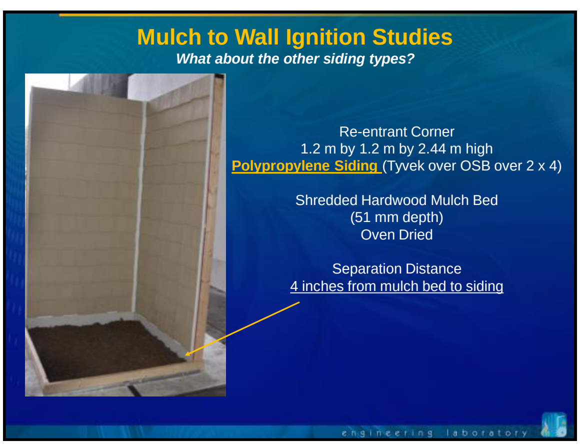
Separation Distance
4 inches from mulch bed to siding

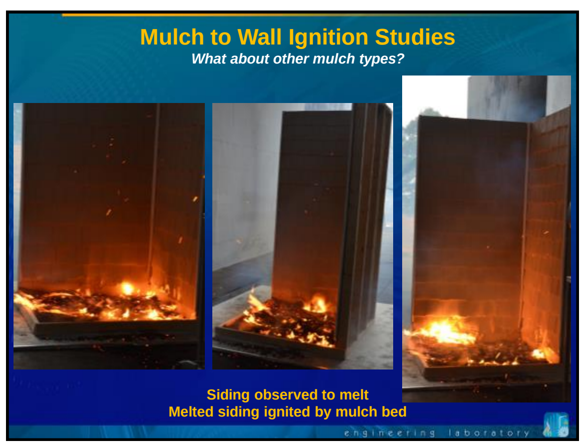

Mulch to Wall Ignition Studies
6 m/s
Wind Speed
Glowing firebrands produce smoldering ignition (SI) in mulch bed
SI transitions to flaming ignition of mulch bed
Sustained flaming ignition on backside of wall
engineering laboratory


Mulch to Wall Ignition Studies
As wind speed increased from 6 m/s to 8 m/s, ignition for 8" separation!
8 m/s
Wind Speed
Glowing firebrands produce smoldering ignition (SI) in mulch bed
SI transitions to flaming ignition of mulch bed
Sustained flaming ignition on backside of wall
engineering laboratory


Mulch to Wall Ignition Studies
What about other mulch types?
Re-entrant Corner
1.2 m by 1.2 m by 2.44 m high
Vinyl Siding (Tyvek over OSB over 2 x 4)
Pine Bark Nugget Mulch Bed
(51 mm depth)
Oven Dried
Separation Distance
8 inches from mulch bed to siding
engineering laboratory


Mulch to Wall Ignition Studies
What about other mulch types?
Wall ignition observed at only 6 m/s
Even with 8"separation distance!
engineering laboratory


Mulch to Wall Ignition Studies
What about the other siding types?
Re-entrant Corner
1.2 m by 1.2 m by 2.44 m high
Polypropylene Siding (Tyvek over OSB over 2 x 4)
Shredded Hardwood Mulch Bed
(51 mm depth)
Oven Dried
Separation Distance
4 inches from mulch bed to siding
engineering laboratory


Mulch to Wall Ignition Studies
What about other mulch types?
Siding observed to melt
Melted siding ignited by mulch bed
engineering laboratory

Roofing Assemblies

- *Is the current requirement mandated in California on the use of a non-combustible cap sheet under roof tiles adequate?*
- *May legacy ASTM E108; UL 790 roofing test be modified to consider wind-driven firebrand exposure to roofing assemblies?*

engineering laboratory

Decking Assemblies

- *Is the current decking test method that uses Class A firebrand exposure adequate?*
- *If decking assemblies are ignited, are they able to ignite building components?*

First experiments to quantify wood decking ignition vulnerabilities to wind-driven firebrand showers

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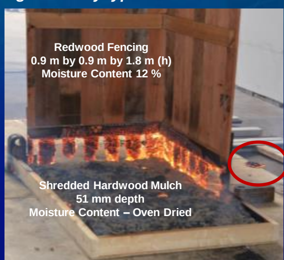
Fencing Assemblies

- *Do fencing assemblies, ignited by firebrand showers, transfer or link the fire to the structure ?*
- *Are certain fencing assembly types more amenable to firebrand generation?*



Firebrands Generated From Ignited Fencing

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Translating Full-Scale Experimental Results to Laboratory Test Standards

Experimental Designation	Wind Speed (m/s)	Firebrand size distribution	Ignition Testing
Composite Decking Assemblies	4-10	Measured	Performed
Wood Decking Assemblies	4-10	Measured	Performed
Untreated Wood Roofing Assemblies	4-10	Measured	Performed
Treated Wood Roofing Assemblies	4-10	Measured	Performed
Concrete Tile Roofing Assemblies	4-10	Measured	Performed
Terracotta Roofing Assemblies	4-10	Measured	Performed
Ceramic Tile Roofing Assemblies	4-10	Measured	Performed
Wood, Vinyl Fencing Assemblies	4-10	Measured	Performed
Mulch: shredded hardwood, pine bark, pink bark nuggets, pine straw	4-10	Measured	Performed
Wall Assembly with Vinyl, Polypropylene Siding	4-10	Measured	Performed
Wall Assembly with Cedar Siding	4-10	Measured	Performed
*Attach decks, fencing, and mulch beds to combustible structure elements to investigate fire spread	4-10	Measured	Performed

Full-Scale Experiments Needed

Collaboration Across Three Institutes

Access to wind facilities designed for fire testing

BRI – full-scale

NRIFD – sections of assebiles

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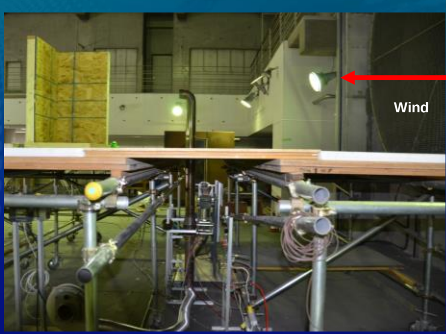
NRIFD Setup

- Reduced-Scale Continuous Feed Dragon Interfaced with NRIFD Wind Facility



Wind

More details in Dr. Suzuki's presentation – stay tuned!

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Summary

- Research into WUI fires, and how to potentially mitigate the loss of structures in such fires, is far behind other areas of fire safety science research
- Fire spread in the WUI is incredibly complex, involving the interaction of structures with topography, weather, and vegetation, and other structures
- Attempted to delineate a series of current research gaps in order to be able to begin to harden structures to firebrand showers, an important aspect of WUI fire exposures

Physical understanding collected from full-scale experiments will be used develop reduced-scale test methods that will be able to reproduce results of the full-scale experiments

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NIST (USA)
University of Maryland (USA)
University of California – Berkeley (USA)
University of Edinburgh (UK)
USDA Forest Service (USA)
National Research Institute of Fire and Disaster (Japan)
COWI AS (Norway)
Center for Forest Fire Research – ADAI (Portugal)

Hope to see you there!

ASTM Workshop
Structure Ignition in WUI Fires
Manzello and Quarles (Co-Chairs)
June 18-19, 2015 (Anaheim, CA)

Fire Safety Science Needed!

Accepted Papers will be submitted to special issue
Fire Technology

engineering laboratory

Special Thanks

- **Dr. Sayaka Suzuki, NRIFD**
- **Dr. Tokiyoshi Yamada, NRIFD**
- **Dr. Daisaku Nii, BRI**
- **Dr. Ichiro Hagiwara, BRI**
- **Dr. Anthony Hamins, NIST**
- **Dr. Jiann Yang, NIST**
- **Mr. Marco Fernandez, NIST**

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A Study on the Urban Fire in Tsunami Inundation Area

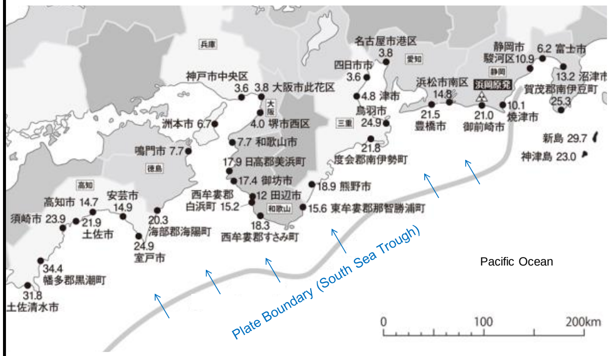
Tomoaki NISHINO
(Building Research Institute, Japan)

Tsunami Fires in the 2011 Tohoku Earthquake

- New Type of Urban Fire
  - Fires that break out in tsunami inundation area.
  - Traces of fire damage were found in 67 ha of the inundation area.
  - This exceeds the areas destroyed by the 1995 Kobe EQ Fire (46 ha).

Overview of Fire Damage in Yamada, Iwate

Risk of Future Mega Tsunami



※ Number is the expected height of tsunami at each city.

Preparedness for Future Mega Tsunami

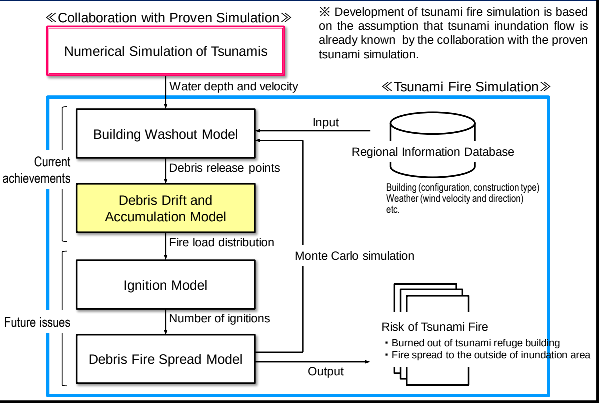
Issues of Disaster Prevention Plan

- Risk of tsunami fire cannot be evaluated quantitatively.
- This reason is the lack of damage estimation method of tsunami fire.
- This makes it impossible to do reasonable risk assessment and disaster planning.


Fire spread to tsunami refuge building


Fire spread to the outside of inundation area

Concept of Tsunami Fire Simulation (BRI Research)



Collaboration with Numerical Simulation of Tsunamis

Mainstream of Tsunami Simulation

- Two dimensional incompressible and inviscid fluid assumption.
- Conservation equations of mass and momentum are solved by FDM.
- Effect of onshore structures is considered as a form of bottom friction.

$$\frac{\partial \eta}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0$$

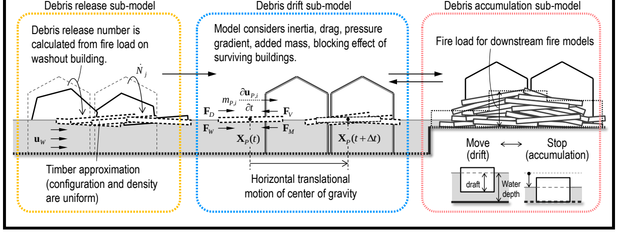
$$\frac{\partial M}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M^2}{D}\right)+\frac{\partial}{\partial y}\left(\frac{MN}{D}\right)+gD\frac{\partial \eta}{\partial x}+\frac{gn^2 M}{D^{7/3}}\sqrt{M^2+N^2}=0$$

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(\frac{MN}{D}\right)+\frac{\partial}{\partial y}\left(\frac{N^2}{D}\right)+gD\frac{\partial \eta}{\partial y}+\frac{gn^2 N}{D^{7/3}}\sqrt{M^2+N^2}=0$$

Debris Drift and Accumulation Model

Particle Trace Model

- Tsunami : structured grid (Euler), Debris : particle (Lagrange).
- Locations of individual debris are predicted in time series.
- Particles have no influence on fluid (one way coupling).



Debris Drift Sub-Model

Translational Motion Model of Center of Gravity

- Described by (1) inertia, (2) pressure gradient of water flow, (3) added mass, (4) drag, (5) blocking effect of surviving buildings, (6) diffusion (random walk).
- Force due to blocking effect of surviving buildings is proportional to own momentum and density of surviving buildings.

$$m_{P,i}\frac{\partial \mathbf{u}_{P,i}}{\partial t}=\mathbf{F}_{D,i}+\mathbf{F}_{W,i}+\mathbf{F}_{M,i}+\mathbf{F}_{V,i}$$

Rotational motion and interaction between debris are neglected.

$$\mathbf{F}_{D,i}=\frac{1}{2}C_D\rho_W A_{P,i}\left(\mathbf{u}_{W,i}-\mathbf{u}_{P,i}\right)\left|\mathbf{u}_{W,i}-\mathbf{u}_{P,i}\right|$$

$$\mathbf{F}_{W,i}=\rho_W V_{P,i}\frac{\partial \mathbf{u}_{W,i}}{\partial t} \qquad \mathbf{F}_{M,i}=\rho_W C_M V_{P,i}\left(\frac{\partial \mathbf{u}_{W,i}}{\partial t}-\frac{\partial \mathbf{u}_{P,i}}{\partial t}\right)$$

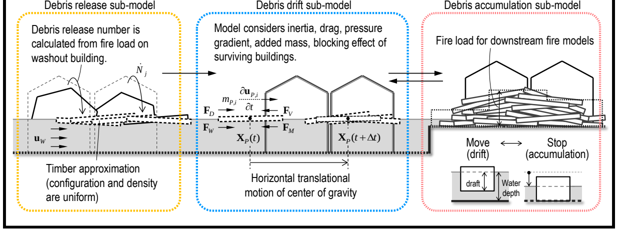
$$\boxed{\mathbf{F}_{V,i}=-\phi_1\phi_2 d_{P,i} m_{P,i}\mathbf{u}_{P,i}\left|\mathbf{u}_{P,i}\right|}$$

Φ_1 is the proportional constant (unknown).

Debris Drift and Accumulation Model

Particle Trace Model

- Tsunami : structured grid (Euler), Debris : particle (Lagrange).
- Locations of individual debris are predicted in time series.
- Particles have no influence on fluid (one way coupling).

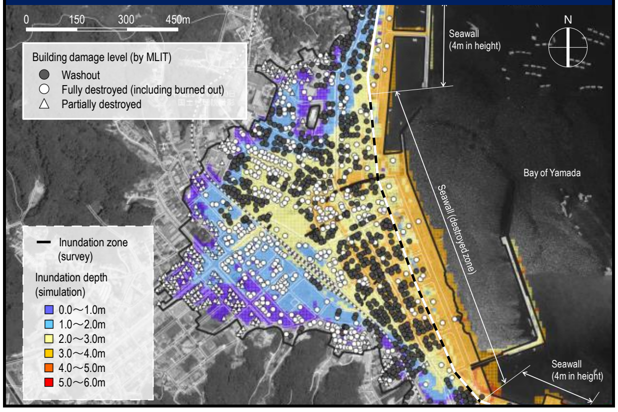


Validation of Debris Drift and Accumulation Model

◻ Simulation in Yamada in 2011 Tohoku EQ Tsunami

Number of fires	2
Date and time of fire	3/11 15:30 - 3/12 11:10
Average wind velocity	0.1 - 2.7 m/s
Number of fire trucks	6
Fire-damaged area	16 hectares

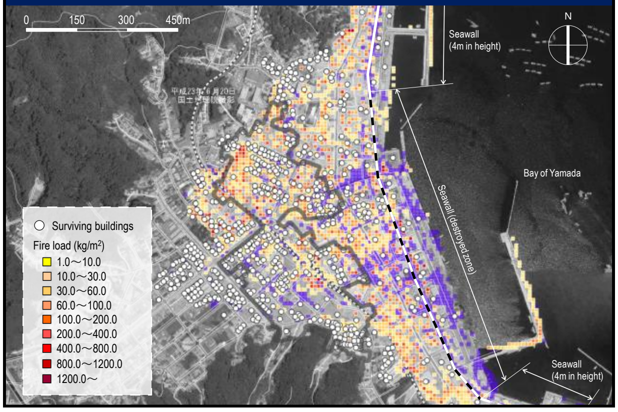
Reproducibility of Numerically-Simulated Tsunami



Numerical Conditions (Debris)

Computational period	2011.3.11 14:46～20:46
Time step	0.6s
Debris configuration and density	0.1m×0.1m×2.4m, 380kg/m^3
Coefficients drag and added mass	Based on the previous hydraulic model experiment on cylinder
Combustible density on buildings	W and S :130kg/m^2, RC :30kg/m^2
Number of debris (washout bldgs.)	1,850,560 (827)
Unknown constant ϕ_1 (blocking effect of surviving buildings)	Calibration by trial and error to maximize the eventual amount of debris in fire-damaged zone
Density of surviving buildings ϕ_2	Calculated in 10m meshes

Eventual Distribution of Accumulating Debris



Conclusion

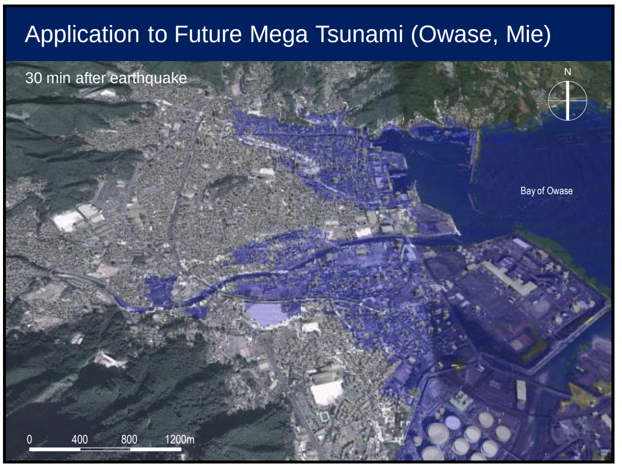
◻ Achievements of This Study

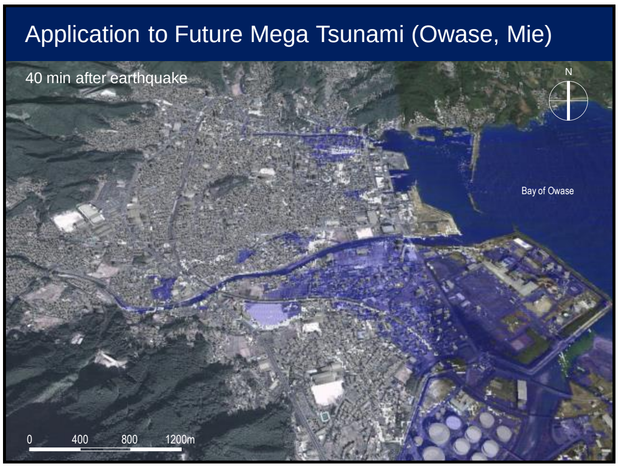
- Debris drift and accumulation model is developed.
- Model was validated through the simulation in the 2011 Tsunami.
- Model can predict how combustible objects accumulate in inundation area even in future tsunamis by the collaboration with tsunami simulation.

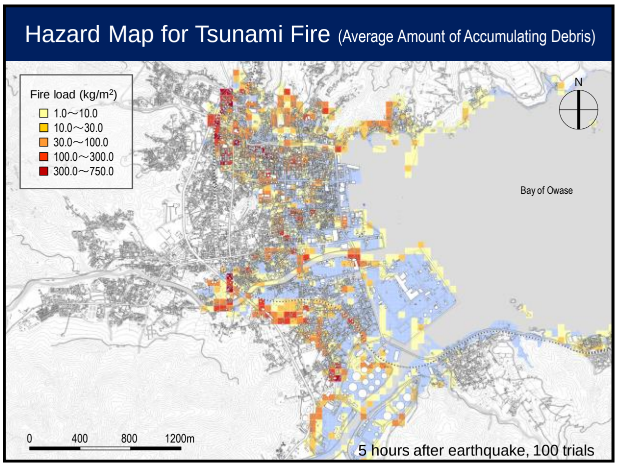
◻ Future Issues towards risk evaluation of tsunami fire

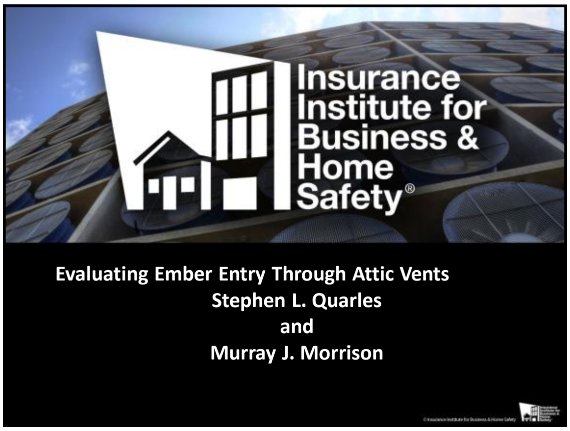
- Ignition modeling.
- Fire spread modeling.

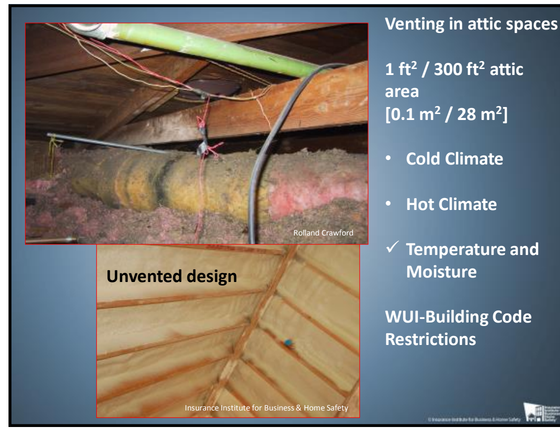
Application to Future Mega Tsunami (Owase, Mie)

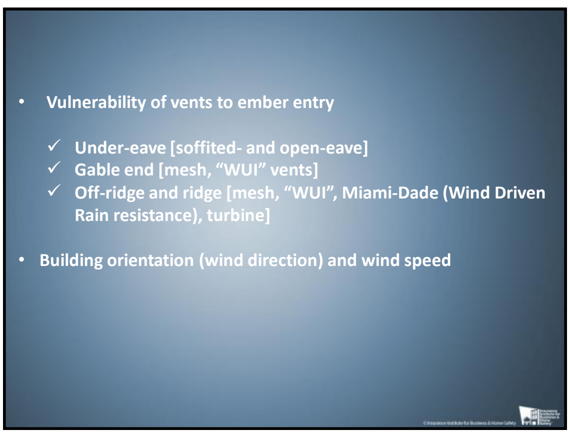

Application to Future Mega Tsunami (Owase, Mie)
30 min after earthquake
N
Bay of Owase
0
400
800
1200m

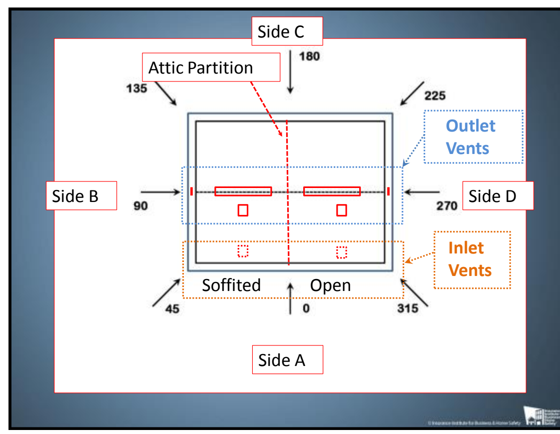

Application to Future Mega Tsunami (Owase, Mie)
40 min after earthquake
N
Bay of Owase
0
400
800
1200m

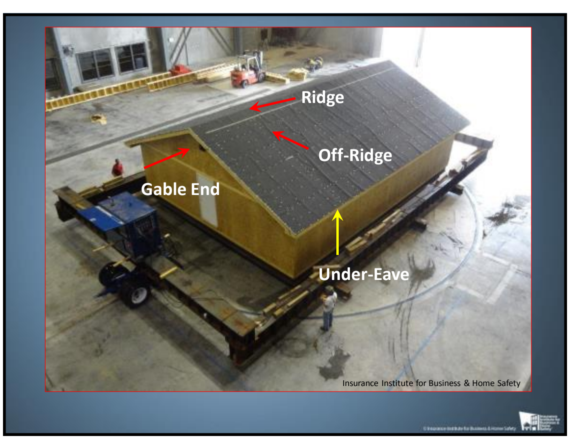

Hazard Map for Tsunami Fire (Average Amount of Accumulating Debris)
Fire load (kg/m2)
1.0～10.0
10.0～30.0
30.0～100.0
100.0～300.0
300.0～750.0
N
Bay of Owase
0
400
800
1200m
5 hours after earthquake, 100 trials

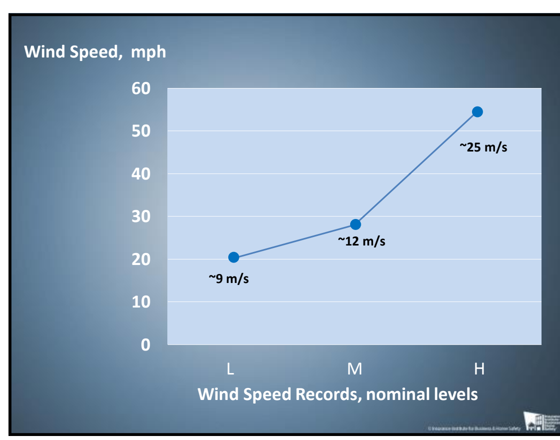

Insurance Institute for Business & Home Safety®
Evaluating Ember Entry Through Attic Vents
Stephen L. Quarles
and
Murray J. Morrison

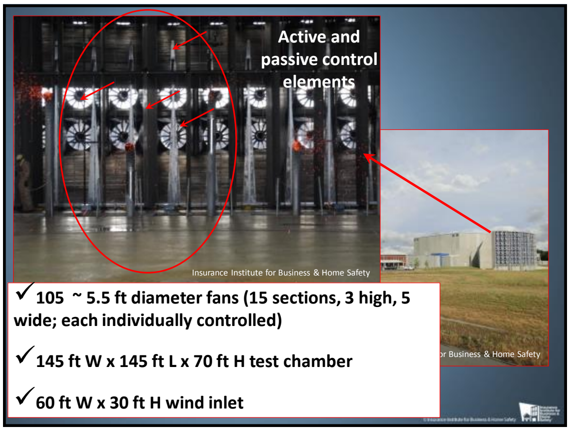

Venting in attic spaces
1 ft² / 300 ft² attic area
[0.1 m² / 28 m²]
• Cold Climate
• Hot Climate
✓ Temperature and Moisture
WUI-Building Code Restrictions
Rolland Crawford
Unvented design
Insurance Institute for Business & Home Safety


• Vulnerability of vents to ember entry
✓ Under-eave [soffited- and open-eave]
✓ Gable end [mesh, "WUI" vents]
✓ Off-ridge and ridge [mesh, "WUI", Miami-Dade (Wind Driven Rain resistance), turbine]
• Building orientation (wind direction) and wind speed

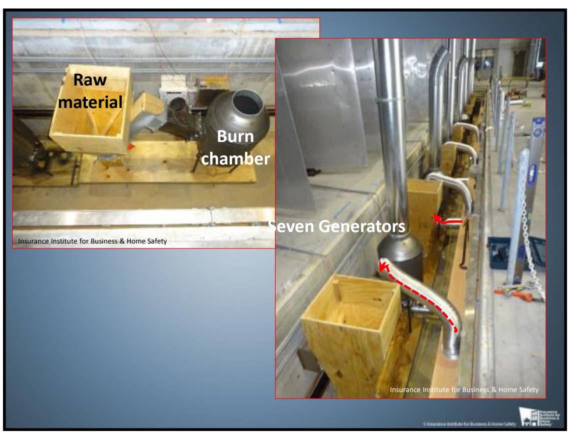

Side C
180
Attic Partition
135
225
Outlet Vents
Side B
90
270
Side D
Inlet Vents
Soffited
Open
45
0
315
Side A


Ridge
Off-Ridge
Gable End
Under-Eave
Insurance Institute for Business & Home Safety


Wind Speed, mph
60
50
40
30
20
10
0
~25 m/s
~12 m/s
~9 m/s
L
M
H
Wind Speed Records, nominal levels

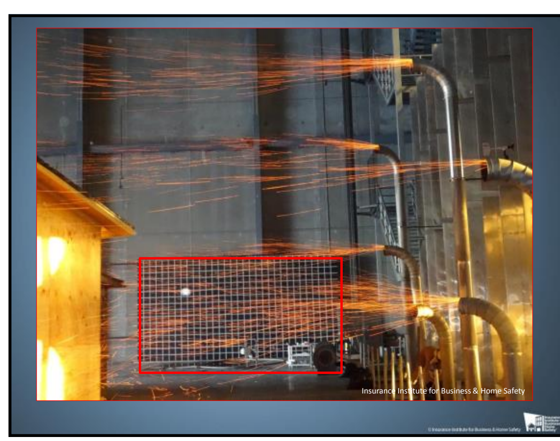

Active and passive control elements
Insurance Institute for Business & Home Safety
105 ~ 5.5 ft diameter fans (15 sections, 3 high, 5 wide; each individually controlled)
145 ft W x 145 ft L x 70 ft H test chamber
60 ft W x 30 ft H wind inlet

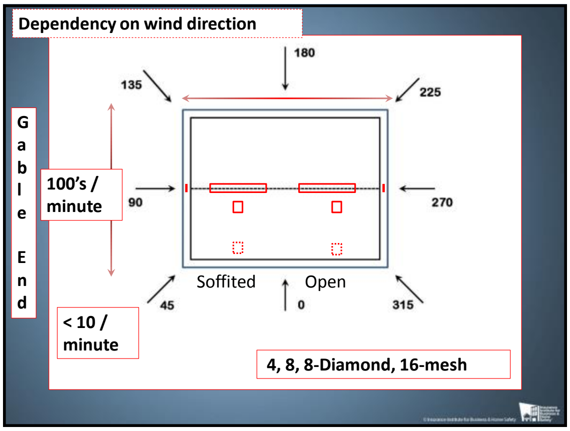

Seven Generators
Air Supply
Insurance Institute for Business & Home Safety

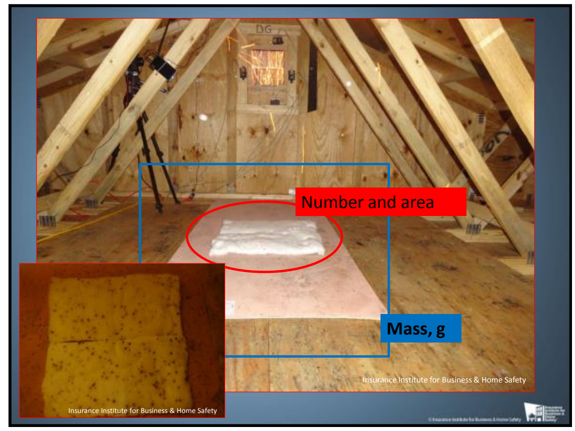

Raw material
Burn chamber
Insurance Institute for Business & Home Safety
Seven Generators
Insurance Institute for Business & Home Safety

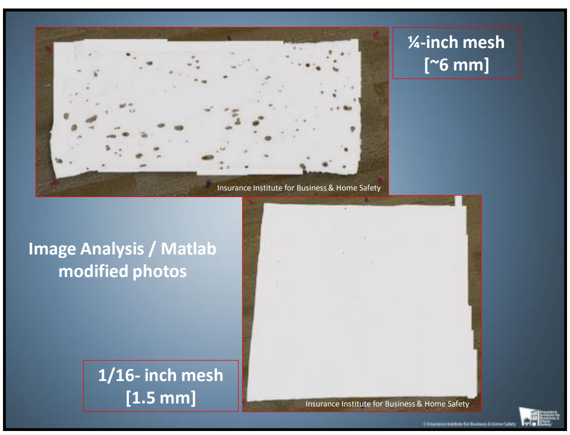

Insurance Institute for Business & Home Safety
Insurance Institute for Business & Home Safety
Raw material consisted of a mixture of dried wood chips and dowels

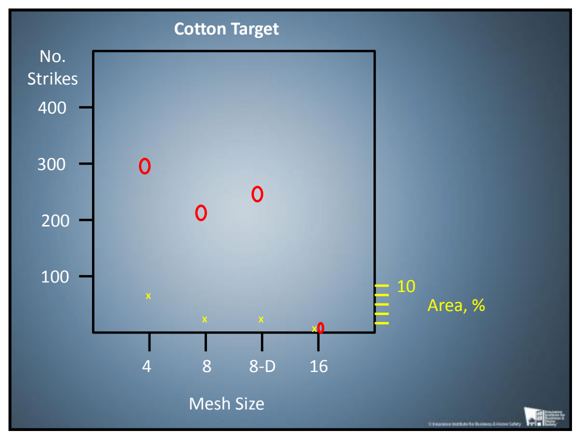

Matlab - Computer Vision Toolbox
Particle Tracking
Insurance Institute for Business & Home Safety

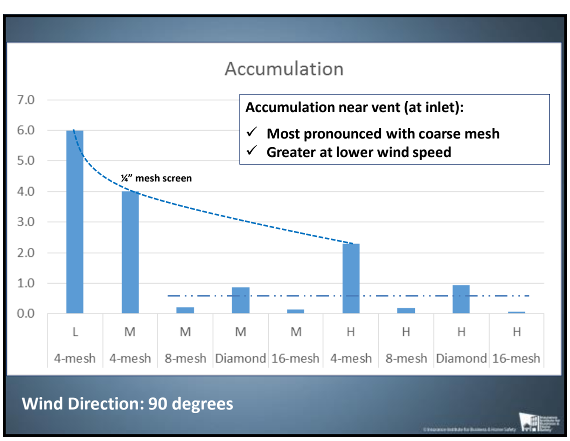

Insurance Institute for Business & Home Safety











Summary of Observations to Date:

- Building orientation (wind direction) influences how vulnerable a vent will be to entry of embers / firebrands.
- General trend regarding wind speed:
  - ✓ Inlet vents (under-eave) - Increase in wind speed, increased potential for ember entry.
  - ✓ Outlet vents (ridge & turbine) - Increase in wind speed, decreased potential for ember entry.
- Vents with vertical orientation relative to wind direction were more vulnerable.


Thanks for your attention!
Steve Quarles
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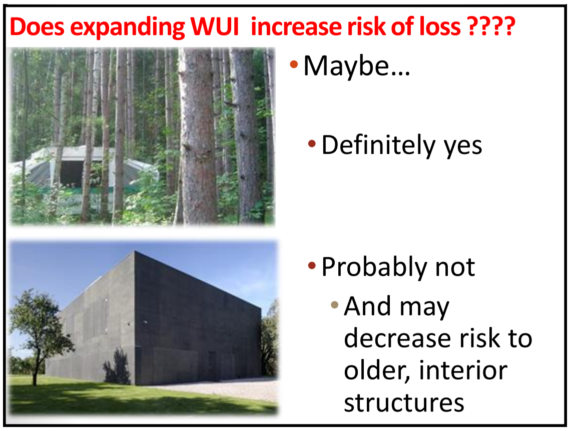
Insurance Institute for Business & Home Safety

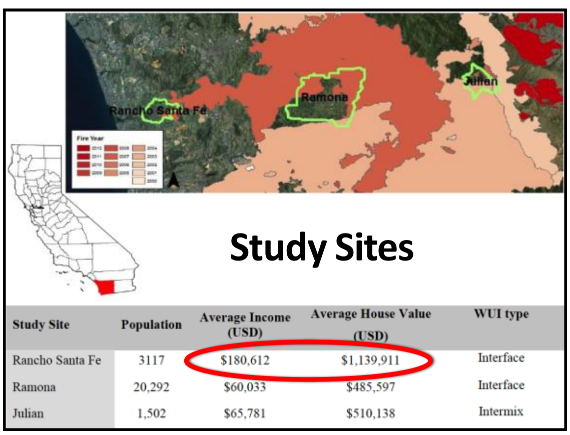
20 Largest California Wildland Fires (By Structures Destroyed)

	FIRE NAME/*CAUSE*	DATE	COUNTY	ACRES	*STRUCTURES*	DEATHS
1	CEDAR *(HUMAN)*	October 2003	SAN DIEGO	273,246	4,847	15
2	TUNNEL *(REKINDLE)*	October 1991	ALAMEDA	1,600	2,900	25
3	WITCH *(UNDER INVESTIGATION)*	October 2007	SAN DIEGO	197,990	1,650	2
4	OLD *(HUMAN)*	October 2003	SAN BERNARDINO	91,281	1,003	6
5	JONES *(UNDETERMINED)*	October 1999	SHASTA	26,200	954	1
6	PAINT *(ARSON)*	June 1990	SANTA BARBARA	4,900	641	1
7	FOUNTAIN *(ARSON)*	August 1992	SHASTA	63,960	636	0
8	SAYRE *(UNDER INVESTIGATION)*	November 2008	LOS ANGELES	11,262	634	0
9	CITY OF BERKELEY *(POWERLINES)*	September 1923	ALAMEDA	130	584	0
10	HARRIS *(UNDER INVESTIGATION)*	October 2007	SAN DIEGO	90,440	548	6
11	BEL AIR *(UNDETERMINED)*	November 1961	LOS ANGELES	6,090	484	0
12	LAGUNA FIRE *(ARSON)*	October 1993	ORANGE	14,437	441	0
13	LAGUNA *(POWERLINES)*	September 1970	SAN DIEGO	175,425	382	5
14	HUMBOLDT *(ARSON)*	June 2008	BUTTE	23,344	351	0
15	PANORAMA *(ARSON)*	November 1980	SAN BERNARDINO	23,600	325	4
16	TOPANGA *(ARSON)*	November 1993	LOS ANGELES	18,000	323	3
17	49ER *(BURNING DEBRIS)*	September 1988	NEVADA	33,700	312	0
18	ANGORA (HUMAN)	June 2007	EL DORADO	3,100	309	0
19	SIMI *(UNDER INVESTIGATION)*	October 2003	VENTURA	108,204	300	0
20	SLIDE *(UNDER INVESTIGATION)*	October 2007	SAN BERNARDINO	12,759	272	0

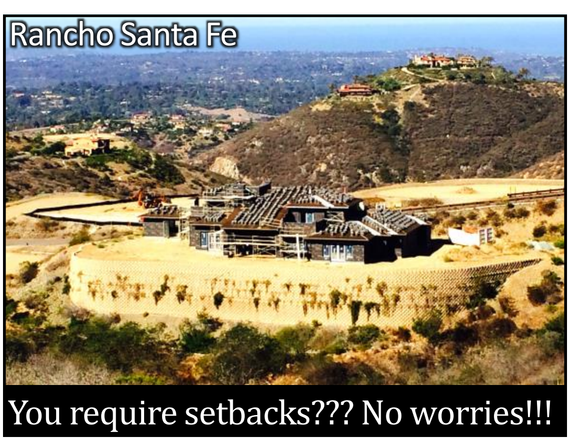
Note that this list does not include fire jurisdiction. These are the Top 20 within California, regardless of whether they were state, federal, or local responsibility. Also note that "structures" is meant to include all loss - homes and outbuildings, etc.

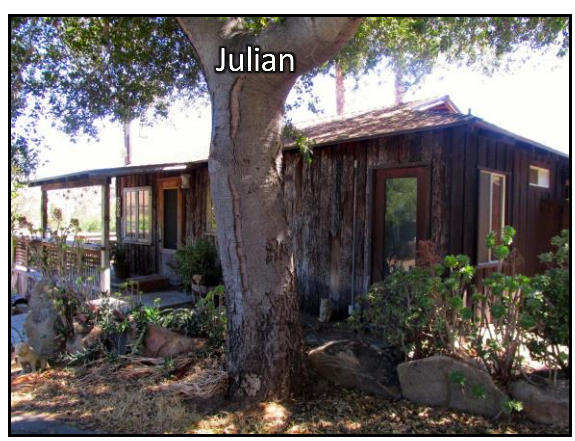
1/12/2009





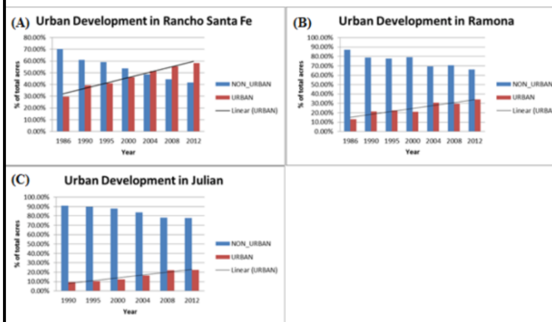
Study Site	Population	Average Income (USD)	Average House Value (USD)	WUI type
Rancho Santa Fe	3117	$180,612	$1,139,911	Interface
Ramona	20,292	$60,033	$485,597	Interface
Julian	1,502	$65,781	$510,138	Intermix





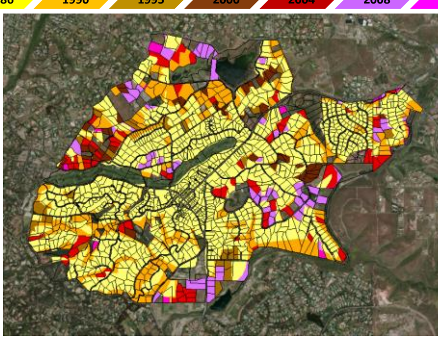
You can't tell me what to do!!!

All Communities are Indeed Expanding



We know exactly where that expansion is happening

Pre 1986 | 1986-1990 | 1990-1995 | 1995-2000 | 2000-2004 | 2004-2008 | 2008-2012



Which helps us look at risk through time

Defensible Space Contributes to Risk

"Good" Defensible Space

- No vegetation on roof
- 5 ft zone - minimal vegetation
- 30 ft zone – Some vegetation, mostly clear
- 100 ft zone- some sparse trees

"Bad" Defensible Space

- Lots of vegetation on roof
- 5 ft zone – over 75% veg cover
- 30 ft zone – over 75% veg cover
- 100 ft zone- Lots of connecting vegetation close to home

Remote Sensing of Defensible Space (via NAIP Imagery)

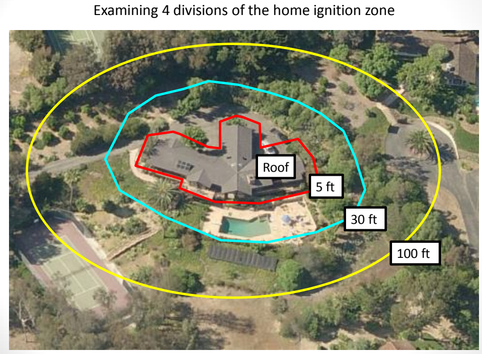
Accuracy	
Tree	92%
Grass	84%
Urban	67%

Accuracy: The likelihood that the resulting polygon depicts the correct feature on the ground.

ESRI supervised image classification

Remote Sensing of Defensible Space

Examining 4 divisions of the home ignition zone

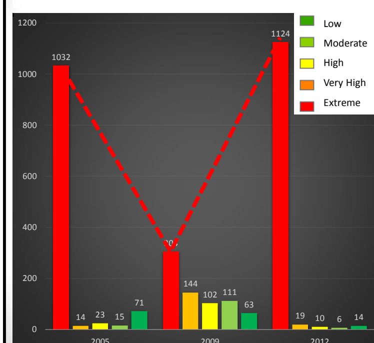


Results: Defensible Space 2005

Results: Defensible Space 2009

Results: Defensible Space 2012

Results: Defensible Space

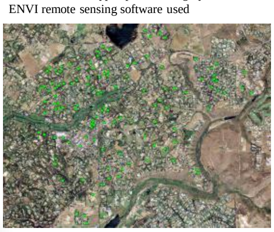


- Overall poor defensible space
  - May be a product of our category breaks
- Improvements in defensible space after 2007 fire
  - Quickly went back to poor

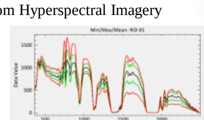
Remote Sensing of Wood Roofs (via AVARIS Imagery)

Wood shingle roofing detected from Hyperspectral Imagery

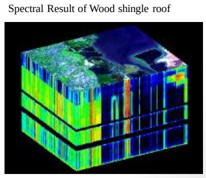
NASA AVARIS Hyperspectral Imagery
ENVI remote sensing software used



125 Roof-types detected out of 2089 Homes in RSF study site.
6% of homes in Rancho Santa Fe

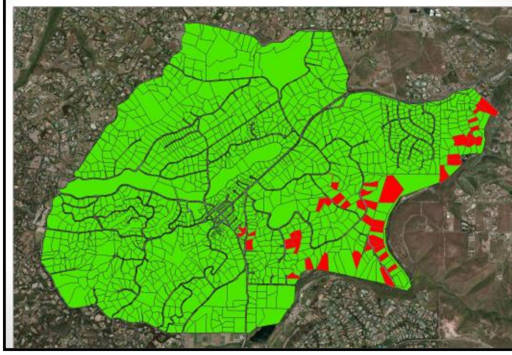


Spectral Result of Wood shingle roof



Wood Shake Roofs 2014

Homes that Burned in 2007

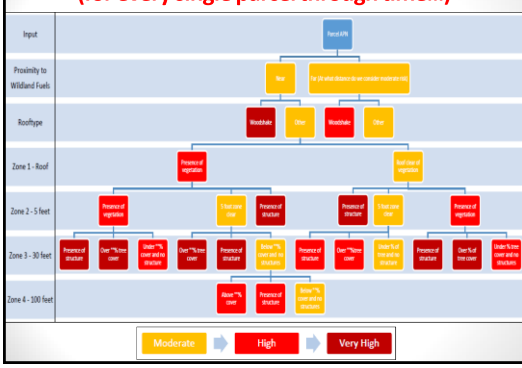


Next Steps: Developing a Risk Model
(for every single parcel through time…)

Risk = Hazard – Implemented Mitigation

- **Hazard factors**
  - Vegetation and Topography
  - Weather (and subsequent Fuel Moisture)
  - Fire History
  - Fire Hazard Severity Zone
- **Implemented Mitigation**
  - Distance to undeveloped vegetation
  - Housing density
  - Roof type
  - Defensible Space Compliance
  - Response times of fire engines

Next Steps: Developing a Risk Model
(for every single parcel through time…)



Preliminary Results (Rancho Santa Fe)

- **Lower risk in newer developments (not so sure in other study sites)**
  - Greater construction standards and setbacks
  - Less accumulation of "stuff"
  - Golf courses that act as fuel break
- **Defensible space improved after 2007 fire then regressed**
  - Higher density communities have lower defensible space compliance.
  - Poor defensible space in "low" income communities due to lack of maintenance.
  - Poor defensible space in high income communities is mostly due to exotic landscaping used for privacy
- **Many wood roofs in interior, which a single ember could ignite**
  - Remember the asset-rich…
  - 2007 Witch Fire "helped"

Cal Poly Fire Student Final Exam

US-Japan Workshop 2015.03.16

Estimation of Loss due to Anticipated Post-earthquake Fires in the Tokyo Metropolitan Area

Keisuke HIMOTO (BRI)
Keichi SUZUKI (Shimizu)

Background

- 2011 Tohoku Earthquake and Tsunami
  - Pacific coast of eastern Japan struck by tsunamis
  - More than 20,000 fatalities including missing persons


* Kyodo

Impact of the Tohoku Event

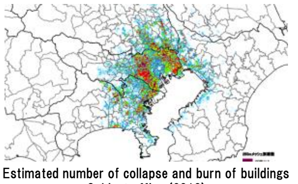
- Revision of disaster mitigation plans
- Loss estimation by anticipated earthquakes
  - Nankai-trough earthquake (M9.0-9.1)
  - Southern Tokyo Metropolitan Area earthquake (M7.3)


* Asahi 2012.08.29

3

Loss Caused by Post-earthquake Fires

- Fire spread in urban area
  - Past experience … Kanto (1926), Kobe (1995)
  - Densely-built urban areas do exist in wide range
- Blind spot of "Loss Estimation"


Estimated number of collapse and burn of buildings
Cabinet office (2013)


4

Mid-rise and High-rise Buildings?

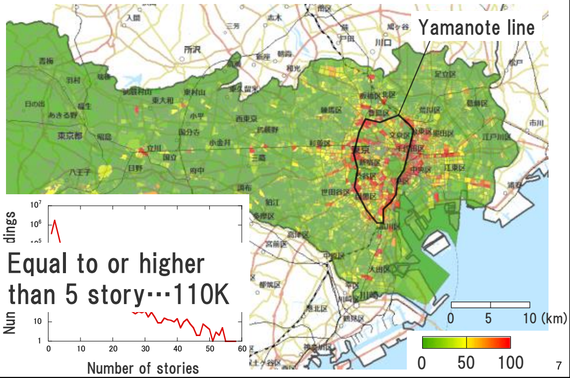
- Potential risk
  - Large number of occupants
  - Relatively few vertical route (evacuation + firefighting)

High-rise Building Fires

- Misfortunes of others?
  - Low frequency of occurrence in Japan
  - Strict fire safety requirement


Madrid (2005) Beijing (2009) Shanghai (2010) Seoul (2015)

Number of High-rise Buildings in Tokyo



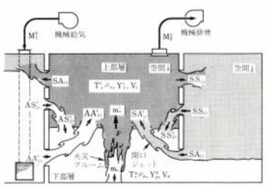
7

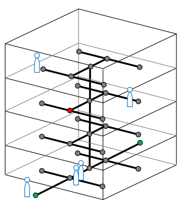
An Issue of Earthquake

- Failure of prerequisites
  - Damage on structure and equipment which maintain fire safety of the building at ordinary times
  - Reduced ability of fire service on a wide area disaster

Risk Assessment of a Building

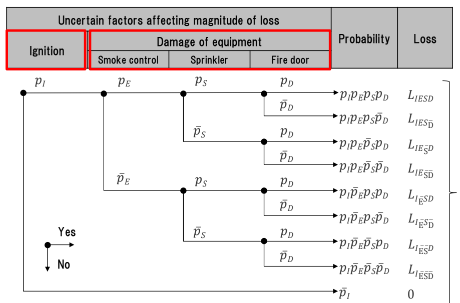
- Coupled simulation of fire and evacuation
  - Two-layer zone model for fire behavior inside a damaged building
  - Network model for evacuation behavior of occupants





9

Incorporating the Earthquake Effect



$$R = \sum_{i=1}^{N} p_i L_i$$

10

Questionnaire Survey by JAFSE

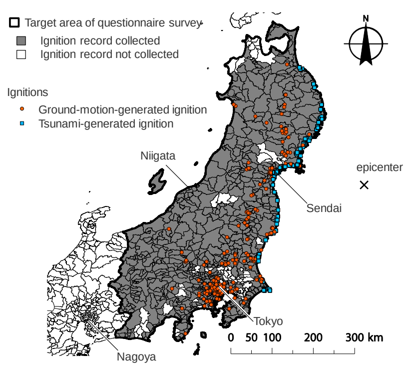
Subject	All fire services in 17 prefectures of eastern Japan Retrieval rate : 86.9% (258/297) by end of 2012
Items	Detailed information of all ignitions (incl. 0 ignition) occurred within 1 month following the earthquake - effect of tsunami inundation - estimated occurrence date and time - report time to fire service - estimated cause - type of fire (building, vehicle, forest, etc.) - consequent losses (area burnt, number of houses burnt, etc.) - firefighting activity

⇩

191 ground-motion-generated ignitions
163 tsunami-generated ignitions

11

Questionnaire Survey by JAFSE



12

Application of GLM

Area characteristics \ Seismic indices	CR	JMA	PGA	PGV	PGD	AR (0.5s)	AR (1.0s)	AR (1.5s)	AR (2.0s)	SI
Population	✓	✓	✓	✓	✓	✓	-	✓	✓	✓
No. of households	-	-	-	-	-	-	✓	-	-	-
No. of establishments (total)	-	-	-	-	-	-	-	-	-	-
No. of establishments (primary industry)	✓	-	-	-	✓	-	-	✓	✓	-
No. of establishments (secondary industry)	-	-	-	-	-	-	-	-	-	-
No. of establishments (tertiary industry)	-	-	-	-	-	-	-	-	-	-
No. of workers (total)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
No. of workers (primary industry)	-	-	-	-	-	-	-	-	-	-
No. of workers (secondary industry)	-	-	-	-	-	-	-	-	-	-
No. of workers (tertiary industry)	-	-	-	-	-	-	-	-	-	-
Area of administration (km^2)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Area of DID (km^2)	-	-	✓	-	✓	-	-	-	-	-
Area of zoning (total) (km^2)	✓	✓	✓	✓	✓	✓	✓	✓	-	✓
Area of zoning (residential) (km^2)	✓	-	-	-	-	-	-	-	-	-
Area of zoning (commercial) (km^2)	✓	-	✓	✓	✓	✓	-	✓	✓	✓
Area of zoning (industrial) (km^2)	-	-	-	-	✓	✓	-	✓	✓	✓
Area of farmland (km^2)	-	-	-	-	-	-	-	-	-	-
Area of forest land (km^2)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Residual deviance	*	451.4	485.9	458.6	466.4	456.7	454.0	454.4	464.1	451.6
AIC	*	714.9	753.3	724.0	737.9	724.2	717.5	723.9	731.6	719.1
ΔAIC	*	0.0	+38.4	+9.1	+23.0	+9.3	+2.6	+9.0	+16.7	+4.2

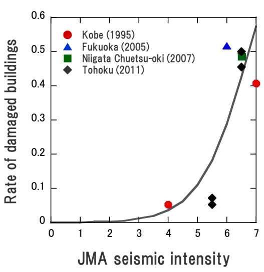
Number of Ignition

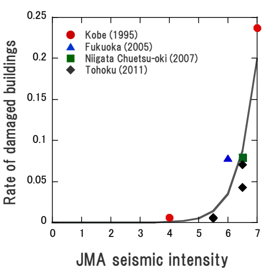
Poisson Model

$$p(N_i \mid \mu_i) = \frac{\mu_i^{N_i} \exp(-\mu_i)}{N_i!} \quad \text{where} \quad \ln \mu_i = \mathbf{x}^T \boldsymbol{\beta}$$

Covariates	Coefficient β	Std. error	Z value
Intercept	-7.908	6.433×10^{-1}	-12.291*
JMA seismic intensity	1.134	1.205×10^{-1}	9.414*
Population	1.834×10^{-6}	6.481×10^{-7}	2.830*
No. of workers (total)	3.818×10^{-6}	3.495×10^{-7}	10.924*
Area of administration (km^2)	2.562×10^{-3}	1.084×10^{-3}	2.364*
Area of zoning (total) (km^2)	1.204×10^{-2}	5.245×10^{-3}	2.296*
Area of forest land (km^2)	-2.085×10^{-3}	1.367×10^{-3}	-1.525

Existing Surveys





Fragility Model for Equipment

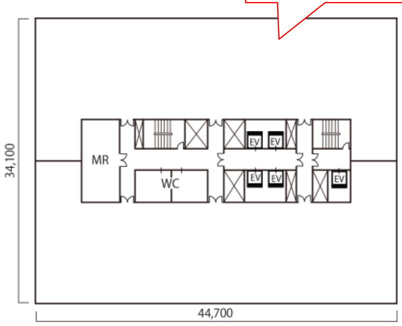
Logistic Regression Model

$$p = \frac{\exp(B_0 + B_1 x)}{1 + \exp(B_0 + B_1 x)}$$

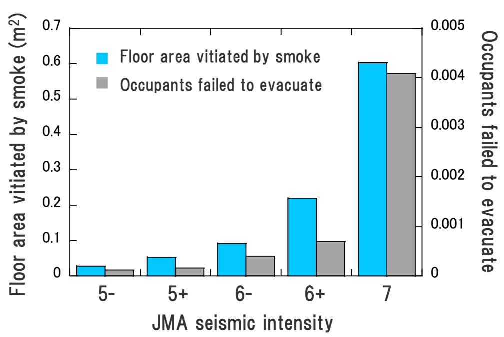
Name	B_0	B_1	x
Sprinkler system	-8.126	1.204	JMA seismic intensity
Indoor firefighting equipment	-14.855	1.924	
Fire alarm	-9.690	1.216	
Fire door	-11.327	1.537	
Smoke control system	-2.531	-0.00138	

Case Study

Location : Chiyoda, Tokyo
Use : Office
Number of story : 10
Area of each floor : 1,490m²

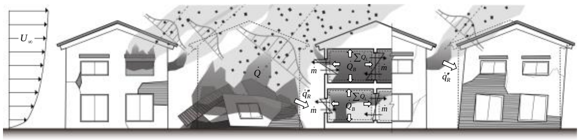


Risk of Post-earthquake Fires



Loss Estimation for Entire Tokyo

- Fire spread in urban area
  - Fire inside building: extended one-Layer zone model
  - Building-to-building fire spread:
    - Heat transfer from compartment gas and fire plume
    - Spotting of firebrands



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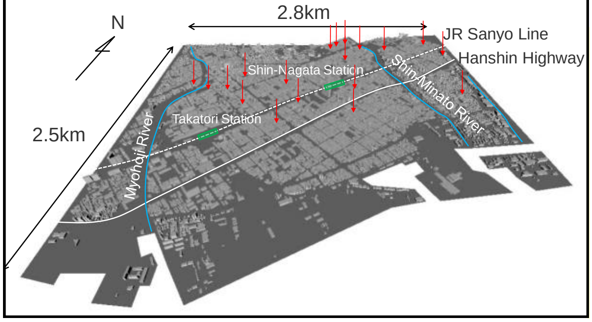
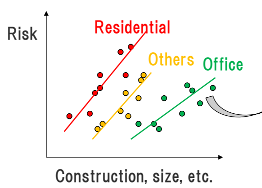
Loss Estimation for Entire Tokyo

- Fire spread in urban area



Loss Estimation for Entire Tokyo

- Fires inside buildings
  - Floor plans not available for entire Tokyo
  - Assume each floor as a control volume?
- Correlation – Building property vs. Risk



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Preliminary Results

	ID	A	B	C	D	E
Building property	Use	Office				
	No. stories	10	8	10	6	7
	No. rooms for each floor	5	4	6	4	3
	No. staircases	2	1	2	2	1
	Area for each floor [m^2]	1,490	290	1,030	2,030	130
	No. occupants	1,490	232	1,030	1,218	91
Risk	Smoke vitiated area [m^2]	0.219	0.412	0.378	0.475	0.067
	Occupants failed to evacuate	$0.7*10^{-3}$	$3.1*10^{-3}$	≒0	$3.2*10^{-3}$	≒0

＊Results with JMA seismic intensity at 6plus

22

Conclusions

- Post-earthquake fire in a building
  - Coupled simulation of fire and evacuation
  - Case study for a building
- Future works
  - Improvement of the model
    - Fires in multiple rooms
    - Probabilistic model for uncertain factors
  - Loss estimation for entire Tokyo

23

Laboratory of Urban Risk Mitigation Management
Nagoya University

Questionnaire Survey about the Great East-Japan Earthquake and its Application

○ Nagoya University U HIROI
Building Research Institute Tatsuya IWAMI
Kobe University Akihiko HOKUGO

2015.03.16

Introduction ; We have two purposes

The purpose of our study is…

•First : To investigate the detail of earthquake fire in the Great East Japan Earthquake by questionnaire survey (and make database)

•Second : To propose a method for predicting " how many tsunami-fires will occur " using by this database.

Purpose (1) Investigation

Methods of Investigation

- We (Japan Association for Fire Science and Engineering [JAFSE]) asked all the Fire Headquarters in Eastern Japan. This is large-scale questionnaire survey and some hearing researches.
  - The questionnaire collection rate was 87% (answers from 258 Fire Headquarters)
- We can find 2703 fires(include unrelated to Earthquake or Tsunami) during one month, from March 11 to April 11, 2011.

3

We make "Earthquake Fire Database"

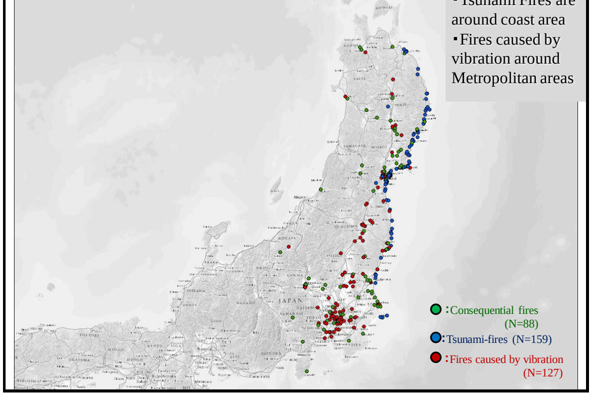
Cause classification code	Description	Cause classification detail code	Detailed description	Tsunami -fire	Fire caused by vibration	Consequential fire	Earthquake fire	Count
0	Irrelevant	-	Judged to be irrelevant to the Earthquake or tsunami					1560
1	Fire which occurred in a tsunami-flooded area	100	The cause is other than codes from 101 to 110 and is not clear.	○			○	2
		101	Fire on March 11 (not caused by earthquake vibration)	○			○	89
		102	Fire caused by electricity on or after March 12	○			○	15
		103	Vehicle fire or the fire the cause of which is a vehicle on or after March 12	○			○	23
		105	Ordinary fire that is irrelevant to the Earthquake					6
		106	Fire caused not by a vehicle or electricity but by tsunami or a tsunami-related factor on or after March 12	○			○	22
		107	Indirect fire or fire during recovery operations			○	○	2
		108	Fire caused by electricity conduction in a tsunami-flooded area	○			○	3
		109	Fire caused by a candle in a tsunami-flooded area			○	○	2
		110	Fire caused by earthquake vibration in a tsunami-flooded area		○		○	4
2	Fire directly related to an	200	Fire related to an earthquake. However, the real cause is not clear.			○	○	1
		201	Fire caused by the Great East-Japan Earthquake on March 11 (excluding the fire that is classified as 203 or 204)		○		○	99
		202	Fire caused not by the Great East-Japan Earthquake, but by another earthquake		○		○	17
						○	○	22
						○	○	12
					○		○	7
						○	○	20
				○			○	5
						○	○	29
								410
								27
								207
								119
Total				159	127	88	374	2703

We judged "374 fires are earthquake fire" in all 2703 Fires

And propose 3 pattern earthquake fire
1. Tsunami-fire (cause by Tsunami)
2. Fire caused by vibration
3. Consequential fire (caused by a factor unrelated to main shock's vibration or tsunami but we think earthquake fire. Ex : candles turn over by aftershocks)

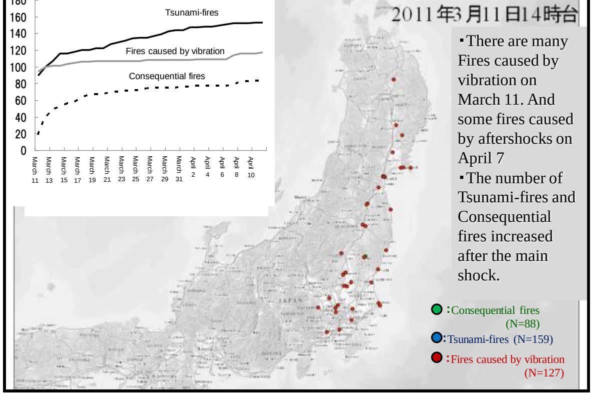
4

Geographical distribution of earthquake fires



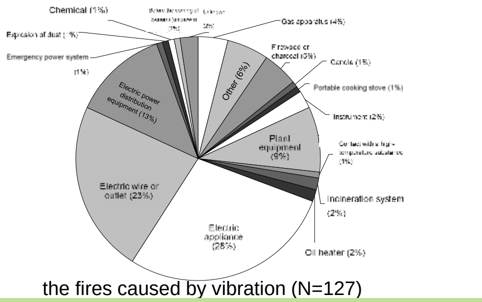
・Tsunami Fires are around coast area
・Fires caused by vibration around Metropolitan areas

Movie(3/11-3/21)



・There are many Fires caused by vibration on March 11. And some fires caused by aftershocks on April 7
・The number of Tsunami-fires and Consequential fires increased after the main shock.

Causes of The Fires (1)

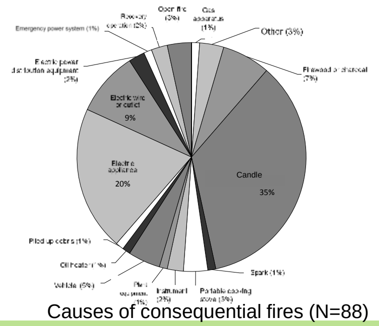


the fires caused by vibration (N=127)

- The percentage of the fires caused by electricity is 64%
- Some fires were caused by gas apparatus or oil heater during the vibration of the Great East-Japan Earthquake. (But these fires are fewer than the Great Hanshin-Awaji Earthquake 1995)

7

Causes of The Fires (2)



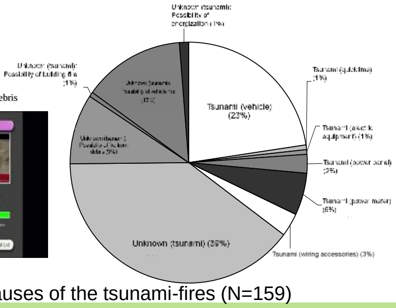
Causes of consequential fires (N=88)

- In many cases, electricity was the cause of consequential fires.
- However, candles were also main causes of the fires; actually 31 fires (35.2%) were caused by candles.(In many of the 31 cases, candles were used for lighting during a Wide-Area Blackout and turned over by an aftershock)

8

Causes of The Fires (3)

Tsunami-Fire occurred by scattered debris

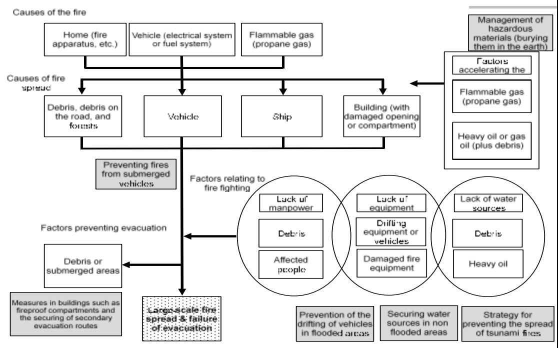


Causes of the tsunami-fires (N=159)

- Many tsunami-fires are "Unknown" causes, however many tsunami-fires were caused (or suspected to be caused) by vehicles.
- Some tsunami-fires were caused by electrical systems of buildings or by scattered debris.
- This movie focused on tsunami-fire occurred by scattered debris (Natori).

9

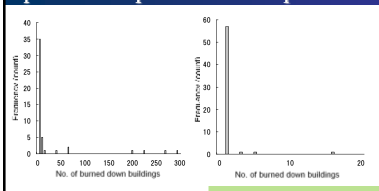
Mechanisms of tsunami-fires(estimated by the research)



mechanisms of tsunami-fires (white)
and measures for preventing the fires (gray)

10

Spread of 3 patterns earthquake-fires



the average number of buildings burned down in each fire is
(1)25.9 buildings per fire in tsunami-fires
(2)1.4 buildings per fire in fires caused by vibration, and
(3)1.7 buildings per fire in consequential fires.

Damage quantity of tsunami-fires is serious than other patterns.
The reasons may be that in the tsunami-flooded areas firefighting was difficult due to some reasons (for example, debris or flood prevented fire crews to reach burning buildings)

11

Purpose (2) how many tsunami-fires will occur?

- We think Poison-Regression formula

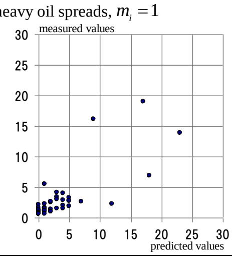
the number of tsunami-fires in area i is μ_i
(tsunami-fires into vehicle fires is $\mu_{1,i}$, the other is $\mu_{2,i}$)
I think the occurrence of vehicle fires corresponds to Poisson distribution
the No. of submerged buildings is n_i, the rate of the use of propane gas is l_i,
the No. of vehicles per house is e_i
In addition, suppose that fires other than vehicle fires are affected by the spread or non-spread of heavy oil. When heavy oil spreads, $m_i = 1$
$\mu_{1,i}$ and $\mu_{2,i}$ is

$$\ln \mu_{1,i} = a_1 e_i n_i + d$$
$$\mu_{2,i} = n_i (a_2 + b m_i) + c l_i$$

presume the coefficient by using the data
on our questionnaire survey
in 63 tsunami-flooded cities.

coefficient of multiple determination

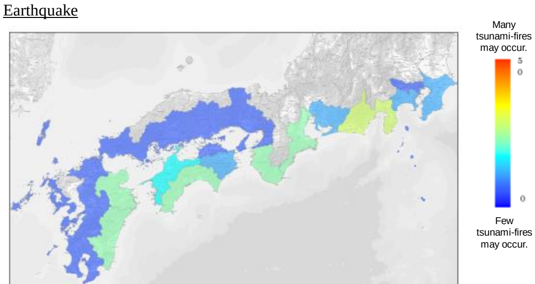
$R^2 = 0.627$



12

For example : Nankai Trough Great Earthquake(1)

We calculated the number of tsunami-fires caused by the Nankai Trough Great Earthquake

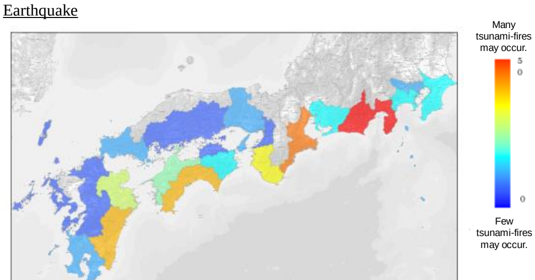


93 tsunami fires without heavy oil spills
270 tsunami fires with heavy oil spills in many places

13

For example : Nankai Trough Great Earthquake(2)

We calculated the number of tsunami-fires caused by the Nankai Trough Great Earthquake



93 tsunami fires without heavy oil spills
270 tsunami fires with heavy oil spills in many places

14

Conclusions

【Purpose(1)】

•Investigate the detail and make database of earthquake fires caused by the Great East-Japan Earthquake. We can find 374 earthquake fires.

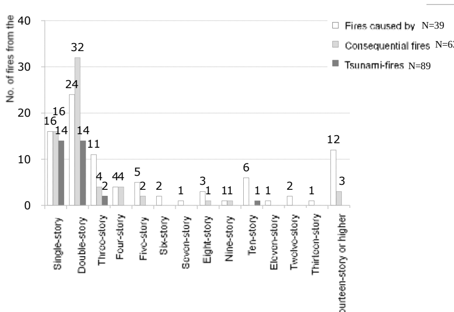
【Purpose(2)】

•Propose the formula for predicting the Number of tsunami-fires.

•This achievement enables the examination of the effect of measures against tsunami-fires, such as measures against heavy oil leakage, in various areas. Also, the achievement enables the relative understanding of the degrees of tsunami-fire risks.

15

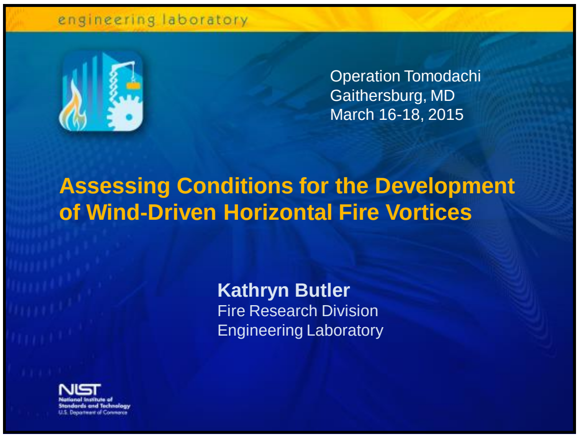
Aboveground floors of the buildings



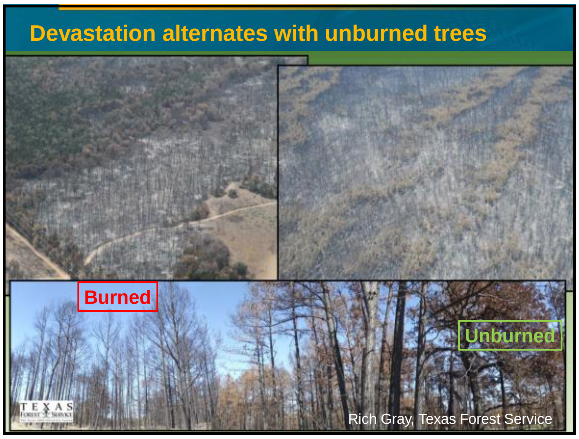
Aboveground floors of the buildings from which earthquake-fires broke out

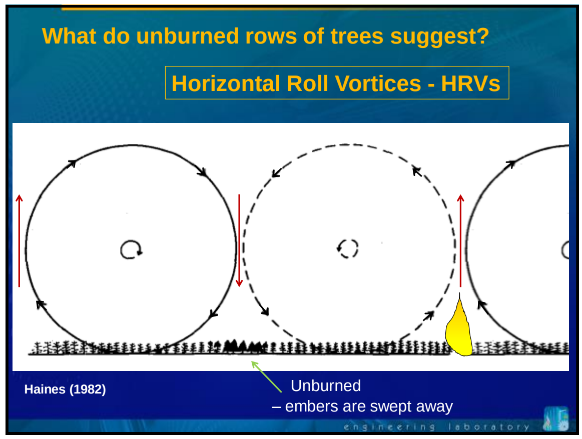
・higher buildings also became the origins of the earthquake-fires.
・Many of Fire caused by vibration occur in building on more than four-story (43%).

17

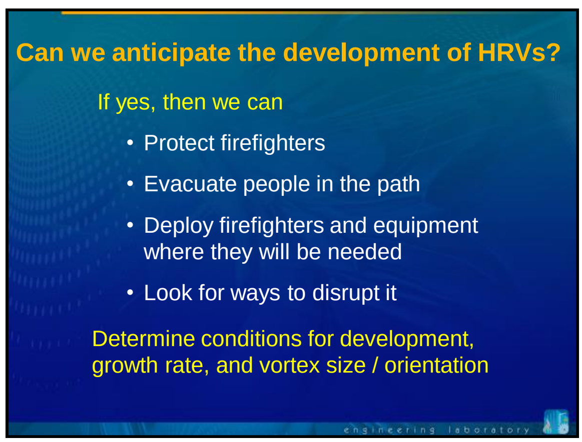

engineering laboratory
Operation Tomodachi
Gaithersburg, MD
March 16-18, 2015
Assessing Conditions for the Development of Wind-Driven Horizontal Fire Vortices
Kathryn Butler
Fire Research Division
Engineering Laboratory
NIST


Extreme Fire Behavior
Puts Lives and Communities at Risk
Bastrop Complex Fire – September 2011


Devastation alternates with unburned trees
Burned
Unburned
Rich Gray, Texas Forest Service


What do unburned rows of trees suggest?
Horizontal Roll Vortices - HRVs
Haines (1982)
Unburned
– embers are swept away
engineering laboratory


Smoke streets in Australia
Chris Hadfield – tweeted from orbit 9 Jan 2013 3:12 pm
engineering laboratory


Can we anticipate the development of HRVs?
If yes, then we can
• Protect firefighters
• Evacuate people in the path
• Deploy firefighters and equipment where they will be needed
• Look for ways to disrupt it
Determine conditions for development, growth rate, and vortex size / orientation
engineering laboratory

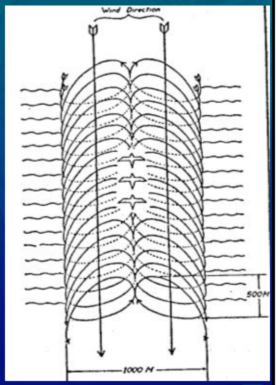
To be able to respond to the situation, need rapid calculation

– No time to collect detailed input data
– Computational Fluid Dynamics (CFD) is not an option

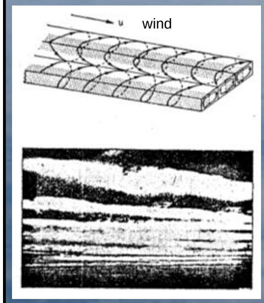
We know that horizontal vortices oriented with the wind are common

Longitudinal roll convection cell used by soaring gulls

Woodcock (1941)



HRVs may be indicated by cloud streets



Kuo (1941)

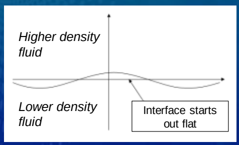
Tradition! Linear Instability Theory

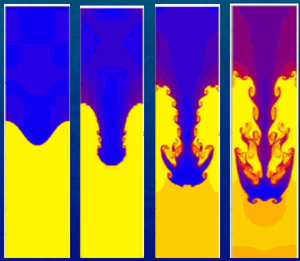
Given a mean state (velocity, density, temperature, etc.), find small perturbations that grow exponentially:

$$v = \tilde{v}\,(x, y, z)\; e^{\sigma t}$$

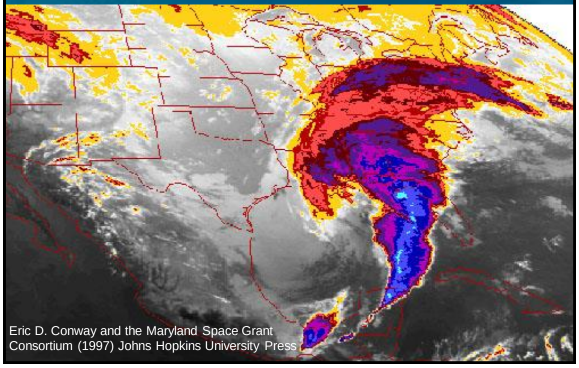
The perturbation that grows the fastest ($\sigma_{max} > 0$) wins.

This works well for some problems …





…but not so well for others



Eric D. Conway and the Maryland Space Grant Consortium (1997) Johns Hopkins University Press

Optimal perturbation theory

Modes of a non-normal matrix are not orthogonal. This means a sum of modes can grow before it decays.

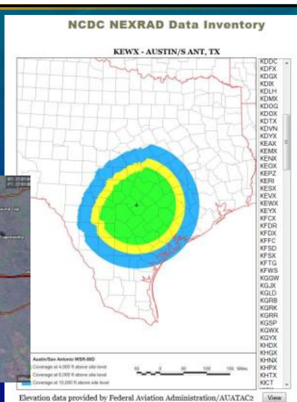
Exponential growth: $v = \tilde{v}\,(x,y,z)\ e^{\sigma t}$

Transient growth: $v\ =\ \sum_j\ \tilde{v}_j\,(x,y,z)\ e^{\sigma_j t}$

Which perturbations gain the most energy by time t?

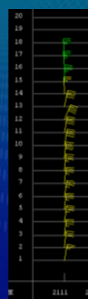
NCDC NEXRAD Weather Archive

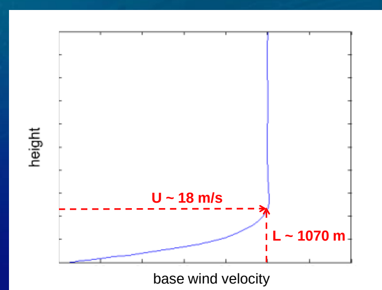
KEWX covered Bastrop, TX fire



Bastrop Wind Profile

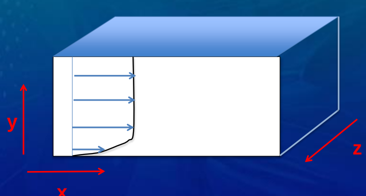
Strong, steady wind over flat terrain





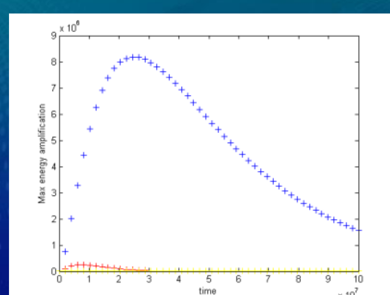
Maximum Energy Growth on Bastrop Wind Profile

Look for periodic perturbations that gain energy from the mean flow: Linear matrix calculation

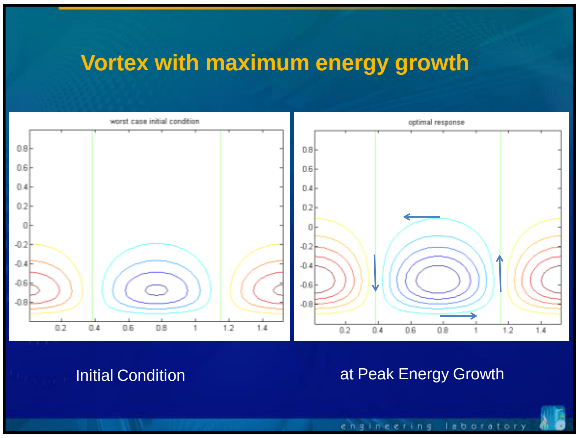


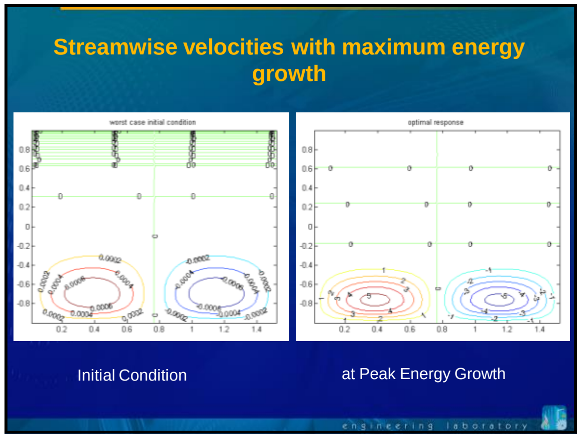
$$v\ =\ \tilde{v}(y)\,\exp[i(\alpha x + \beta z) + \sigma t]$$

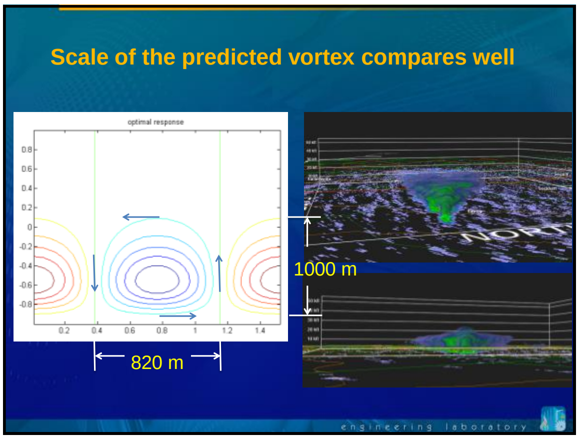
Maximum energy growth on Bastrop wind profile

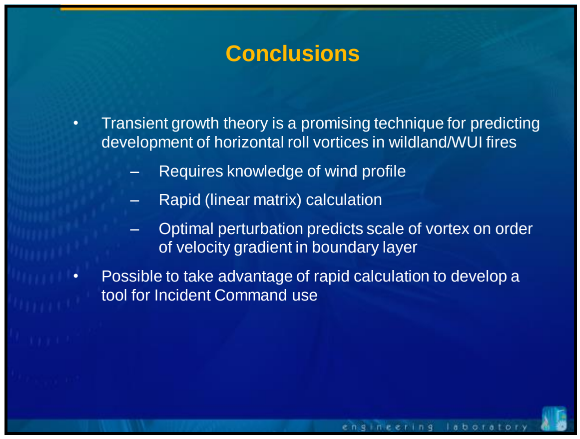


Maximum energy growth factor = $\boxed{8.2 \times 10^6}$


Vortex with maximum energy growth
worst case initial condition
optimal response
Initial Condition
at Peak Energy Growth
engineering laboratory


Streamwise velocities with maximum energy growth
worst case initial condition
optimal response
Initial Condition
at Peak Energy Growth
engineering laboratory


Scale of the predicted vortex compares well
optimal response
1000 m
820 m
engineering laboratory


Conclusions
• Transient growth theory is a promising technique for predicting development of horizontal roll vortices in wildland/WUI fires
– Requires knowledge of wind profile
– Rapid (linear matrix) calculation
– Optimal perturbation predicts scale of vortex on order of velocity gradient in boundary layer
• Possible to take advantage of rapid calculation to develop a tool for Incident Command use
engineering laboratory

UNIVERSITY OF MARYLAND
Department of Fire Protection Engineering

Modeling Wildland Fire Propagation:

Physical Processes and Real Time Data-Driven Modeling

Arnaud Trouvé
Professor
Fire Protection Engineering

Michael J. Gollner
Assistant Professor
Fire Protection Engineering

(USFS) Mark Finney, Sara McAllister, Jack Cohen, Jason Forthofer. (UK) Kozo Saito, Nelson Akafua

(UCSD) Ilkay Altintas, Raymond deCallafon, Larry Smarr, (UMD) Evan Ellicott, Kayo Ide

A. JAMES CLARK SCHOOL *of* ENGINEERING • UNIVERSITY *of* MARYLAND

Modeling Fire Propagation is Key

- **Operational Firefighting**
  - Suppression Planning
  - Evacuation
  - Real or near real-time

- **Predictive Modeling**
  - Operationally – prescribed fire selections
  - Risk Mapping

- **These tools are based on Rothermel's Semi-empirical equation**
  - *Correlations to observed phenomena*
  - *Laboratory and prescribed fire experiment – based*

$$ROS_{surface} = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \epsilon Q_{ig}}$$

Rothermel & Colleauges
Missoula, MT Wind Tunnel

Problems

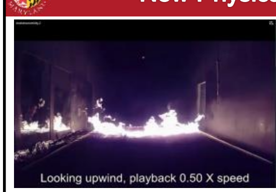
- Rothermel Spread Equation – Basis for all US Systems
  - **Not because it's right, but because its' useful**
- While used as predictive tool, predictions often inaccurate and unreliable
- **Problems**
  - Fires do not spread in one dimension (head ROS)
  - ROS is not typically steady
  - Fires and the atmosphere interact
  - Fuels are inhomogeneous and hard to characterize
  - Extreme Fire Behavior

Wildland Fire Spread is non-Steady

- Spread through discrete fuels can not be treated as continuous
- Spanwise structures develop at leading edge and propagate
- Intermittent heating of fuels
  - Non-steady and non-uniform heating causes fluctuating spread rate

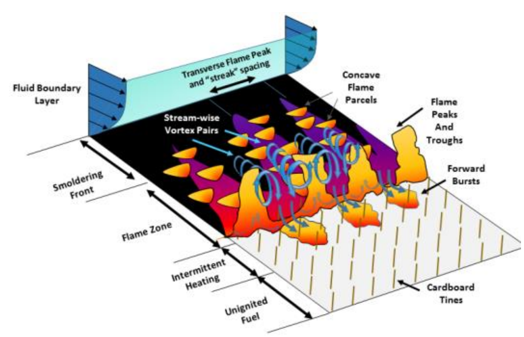
Video complements Mark Finney, USFS Missoula Fire Lab

New Physical Phenomena

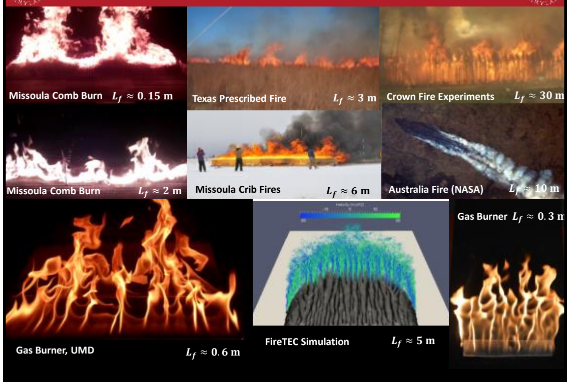


Top videos: Mark Finney, USFS Missoula Fire Lab, Bottom: Daniel Gorham, UMD student

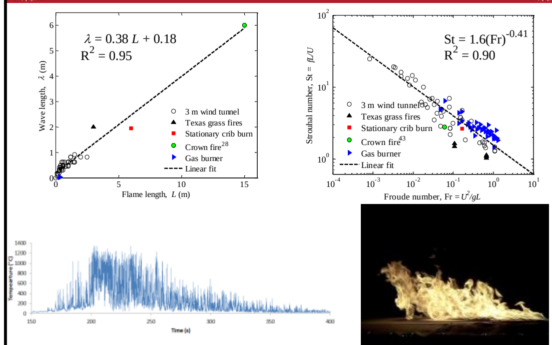
Experimental Observations



Streak or Peak Spacing



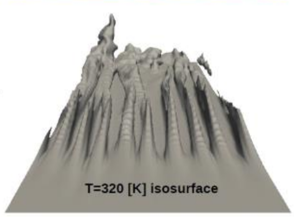
Scaling Results



LES Simulations

- New better case
  - U=0.5 m/s
  - Tplate=400 [K]
  - To = 300 [K]
  - Plate Length = 2 [m]

NEW: Smaller streaks combine to give bigger structures



Data-Driven Fire Modeling

- Develop predictive fire modeling capabilities
  - Reduce fire modeling uncertainties by integrating fire modeling and fire sensing technologies
    - Take advantage of progress made in sensor technology and ubiquity of sensor networks
  - A well-established approach in many areas of science (*e.g.*, weather and climate modeling applications)
    - Data assimilation
  - Application to: detection of incipient fires; post-event forensic investigations; real-time incident management operations
    - Real-time wildland fire spread monitoring

Data-Driven Fire Modeling

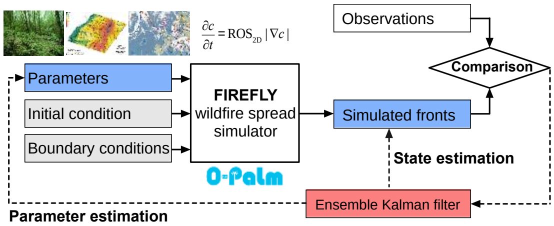
- M. Rochoux, S. Ricci, A. Trouvé
- M. Gollner, A. Trouvé (*http://wifire.ucsd.edu*)
- E. Ellicott, K. Ide, M. Gollner, A. Trouvé

Data-Driven Fire Modeling

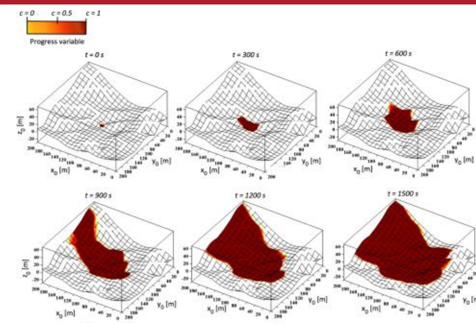
- Sensor-driven simulations of wildfire spread
  - Regional-scale modeling (10 m < L < 10 km)
    - Description of fire dynamics through the rate of spread (ROS)
    - Assumed known conditions (fuel, topography, wind & moisture)
  - Forward model
    - Model description of ROS (Rothermel)
    - Level-set-based solver for the fire front propagation equation (FireFly)
  - Assumed real-time observations of fire perimeter
    - High spatial resolution (10 m); high temporal resolution (10 minutes)
  - Inverse model
    - Ensemble Kalman filter (EnKF): statistical description of fire spread

Data-Driven Fire Modeling

- Data assimilation
  - Inverse model: find best estimate of the system state/parameters at present/future times given observations made at earlier times



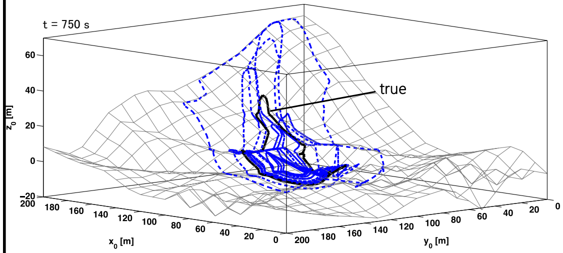
Data-Driven Fire Modeling



Growth of the burnt area over1500 s, simulated with FireFly over a complex terrain topography; moderate horizontal wind conditions (0.75 m s^{-1}, 315°)

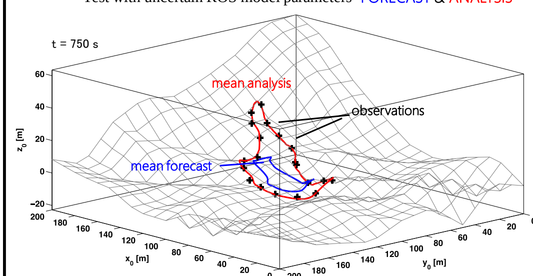
Data-Driven Fire Modeling

- Verification test (state estimation algorithm)
  - Test with uncertain ROS model parameters FORECAST



Data-Driven Fire Modeling

- Verification test (state estimation algorithm)
  - Test with uncertain ROS model parameters FORECAST & ANALYSIS



Data-Driven Fire Modeling

- Data-driven fire modeling
  - A promising novel approach to forecast wildfire spread
    - Reduce fire modeling uncertainties by integrating fire modeling and fire sensing technologies
    - Take advantage in progress made in sensor technology and ubiquity of sensor networks
  - EnKF-FIREFLY
    - Capable of correcting inaccurate predictions of the fire front position and of providing an optimized forecast of the wildfire behavior
  - Extension to large-scale fire events
    - Application to FireFlux experiment (Clements *et al.*, 2007)
    - Coupling with FARSITE

Acknowledgements

- **UMD Students**: Daniel Gorham (MS), Salman Verma (PhD), Ajay Singh (PhD), Wei Tang (PhD) and Colin Miller (PhD) and Raquel Hakes (BS)
- **US Forest Service, Missoula Fire Science Laboratory**: Dr. Mark Finney, Dr. Sara McAllister, Jack Cohen, Jason Forthofer
- **University of Kentucky**: Prof. Kozo Saito, Dr. Nelson Akafu, Brittany Adam (PhD), Justin English (MS)
- **University of California, San Diego**: Dr. Ilkay Altintas, Jessica Block, Prof. Larry Smarr, Prof. Raymond deCallafon
- **Funding**: USDA Forest Service, National Science Foundation and Minta Martin Foundation at the University of Maryland

Overview of NRIFD Fire Research

Sayaka Suzuki, Ph.D.
National Research Institute of Fire and Disaster, Japan

Hello

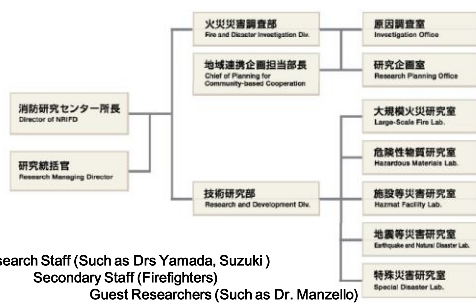
March 16 2015
Operation Tomodachi Fire Research

Brief History of NRIFD

- NRIFD was inaugurated in 1948 with the aim of protecting people and their properties from disasters
- As of April 1st 2001, it moved to be an independent executive agency
- As of April 1st, 2006, it became a part of the Fire and Disaster Management Agency, under Ministry of Internal Affairs and Communications

Operation Tomodachi Fire Research

Organization Chart



Research Staff (Such as Drs Yamada, Suzuki)
Secondary Staff (Firefighters)
Guest Researchers (Such as Dr. Manzello)

Operation Tomodachi Fire Research

Projects (5 years)

- Research and development for the safety of firefighters 〈2011 - 2015〉
- Research about improving the safety of hazmat and hazmat facilities 〈2011 - 2015〉
- Research and development of information technology for assisting fire-fighting and disaster prevention activity **against large scale disaster** 〈2011 - 2015〉
- Research on ensuring safety against diversified fire 〈2011 - 2015〉
- Research on and development of firefighting robots as a response against disaster 〈2014 -〉

New projects will start FY16!

Operation Tomodachi Fire Research

Safety of firefighters

monitoring as a precursor of secondary disaster at the site of a landslide

firefighter personal protective equipment

Vehicle and reconnaissance technique for fire brigade operations in a tsunami-affected area

Operation Tomodachi Fire Research

Safety of hazmat and hazmat facilities

Damage of oil storage tanks caused by tsunami

Extinguishants that are good for the environment

Operation Tomodachi Fire Research

Information technology

System for **earthquake damage estimation**

Simulation system for estimation of **fire spread with breakout simultaneous-with earthquake**

Research and development of a supporting system for initial response **to flood disaster**

Operation Tomodachi Fire Research

Ensuring safety against diversified fire

Fire risk of photovoltaic power system

Study on Fire whirl

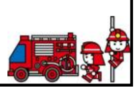
Ignition mechanism by Firebrand

Operation Tomodachi Fire Research

Firefighting robots as a response

Reconnaissance robot for firefighting

Establishing UAV application situation analysis by the fire brigade on--site



Operation Tomodachi Fire Research

With Firefighters…

Fire Cause Investigation

Hotel Fire (2012)

Care home fire(2013)

Technical support for fire investigations by local fire departments

Conference

sharing the technic of fire investigation with local fire department

Research Topic (Fire fighters from Tokyo Fire Department)

- Study on burning behavior in urban fire after earthquake – experiments with wood crib under wind -
- Study of on-site analytical techniques for chemical disaster - Analytical techniques for liquid and solid samples -

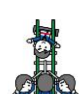
Operation Tomodachi Fire Research

Development of Evaluation Methods for Firebrand Ignitions

Sayaka Suzuki, Ph.D.
National Research Institute of Fire and Disaster, Japan

Samuel L. Manzello, Ph.D.
National Institute of Standards and Technology, USA

March 16 2015
Operation Tomodachi Fire Research

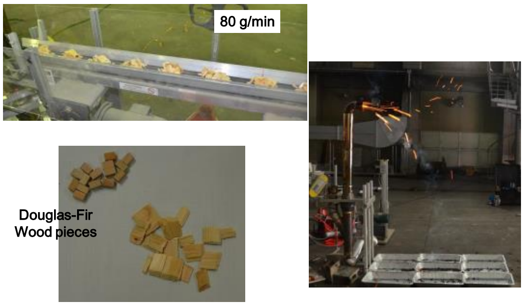


Collaboration NIST/NRIFD/BRI

- Full scale experiments in BRI
  - Important to evaluate individual components' vulnerability (weak points) to firebrand showers
  - Too big to be standard test methods
- New experimental capability developed in NRIFD
  - As new standard test methods for building components
  - Reproduce full-scale test results

Operation Tomodachi Fire Research

New Food for Dragon



Japanese Cypress Wood Chip

Operation Tomodachi Fire Research

Firebrands from different materials

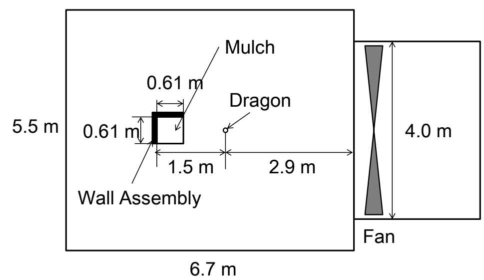
Operation Tomodachi Fire Research

Bench-Scale Test Set-Up

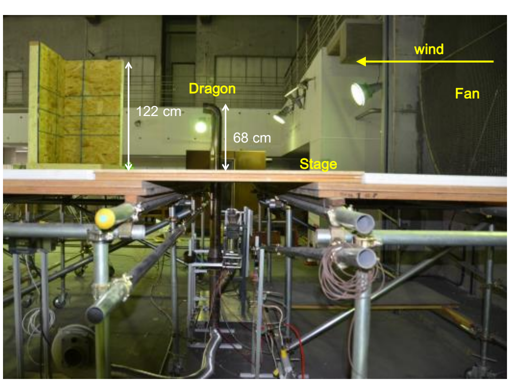
- Continuous Feed Baby Dragon was coupled with 4.0 m fan in fire extinguishing lab, NRIFD
- Feeding rate of Wood pieces – 80g/min
- Wind velocity (fan) - 6m/s
  - 10 % uncertainly 2 m x 2 m cross-section
- Wind velocity from Dragon's mouth – 5m/s
- Re-produced full-scale experiments- settings are based on full-scale experiments
  - Mulch was placed along re-entrant wall assembly (OSB and Studs)

Operation Tomodachi Fire Research

Layout (Top view)

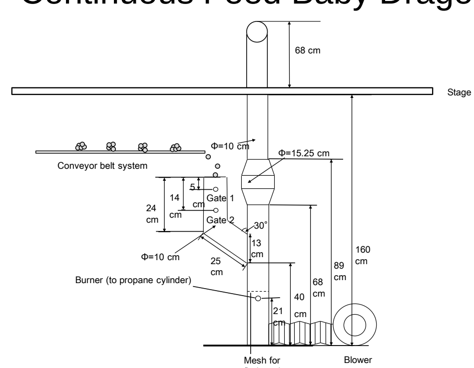


Operation Tomodachi Fire Research



Operation Tomodachi Fire Research

Continuous Feed Baby Dragon



Results (Front)

NRIFD

BRI

Mulch was ignited by firebrands
SI was observed first and transited to FI

Operation Tomodachi Fire Research

Results (Back)

NRIFD

BRI

Ignited (Flaming) mulch ignited wall assembly
Fire penetrated through OSB

Operation Tomodachi Fire Research

Summary

- Added the ability to produce different size/mass firebrands
- Bigger and lighter firebrands produced
- New experimental capability developed in NRIFD
- Reproduced same results as full-scale experiments in BRI
- More experiments & analysis in the future

Operation Tomodachi Fire Research

Acknowledgements

- This work (and travel here) was partly supported by JSPS Grant-in-Aid for Young Researchers (B) Grant Number 26750128.
- Special thanks to Dr. Shinohara, NRIFD

USDA United States Department of Agriculture Forest Service

Forest Service Research & Development
Rocky Mountain Research Station
Fire, Fuel, and Smoke Science Program

The effect of wind on the burning rate

Sara McAllister and Mark Finney
USDA Forest Service
RMRS – Missoula Fire Sciences Laboratory

Operation Tomodachi
March 16, 2015

Burning rate and residence time

- Will shed light on
  - Flame zone depth and fireline intensity
    - Governs fluid dynamics and heat transfer of flame
  - Fire spread rate
  - Residence time for "shot clock"
    - If $t_{res} < t_{ig}$, fire won't spread
  - Residence time for fire effects
- Current methods
  - Residence time = 8d (in)
    - Anderson 1969

Wood cribs?

- Wildland fuels not predictably arranged
- Fundamental understanding of burning rate
  - Wildland fuels = individual fuels separated by some distance
    - Litter layer → small and homogeneous
    - Trees and shrubs → larger and heterogeneous
- Same physical processes govern burning of cribs and wildland fuels
  - Ex: diffusion, convection and radiation, etc

Crib burning rate background

- 2 regimes – Gross 1962
  - open or loosely-packed
    - burning rate is more closely approximated by the free burning rate of the individual sticks
    - governed by heat and mass transfer processes near the surfaces
    - burning rate a function of the stick dimensions
    - independent of the "porosity" of the crib
  - closed or densely-packed
    - burning rate is limited by availability of oxidizer within the fuel bed
    - burning rate increases with the inter-stick spacing or the "porosity" of the crib.
- Critical spacing distance between crib and support platform of ½" (1.27 cm) – Block 1971
- First theoretical model of burning rate – Block 1971

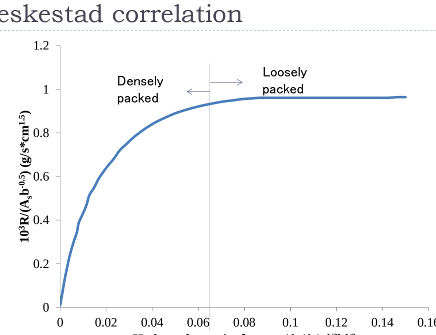
Crib burning rate background

- Heskestad (1973) re-correlated data from Gross (1962) and Block (1971)
  - Better fit than Gross (within ±20%)
  - More practical than Block
- Heskestad (1973) correlation

$$\frac{R}{A_s b^{-1/2}} = f\left[\left(\frac{A_v}{A_s}\right) s^{1/2} b^{1/2}\right]$$

  - R is the burning rate (g/s),
  - A_s is the exposed surface area of the sticks (cm²),
  - b is the stick thickness (cm),
  - A_v is the area of the vertical shafts in the crib (cm²)
  - s is the spacing between sticks (cm).

Heskestad correlation



Crib burning rate background

- Limitations
  - Based on experiments by Gross (1962) and Block (1971)
  - Geometries fairly limited
    - Gross only tested cubic cribs with l/b = 10
    - Block tested up to l/b = 20
  - Seemingly endless possible ways to build a crib with a given porosity
  - Wildland fuels aren't cubic!
- Our previous work: explored the burning rate of cribs with a wide variety of layouts and geometries to determine whether Heskestad relation and Block's critical spacing distance hold.

Crib-platform spacing

0 cm

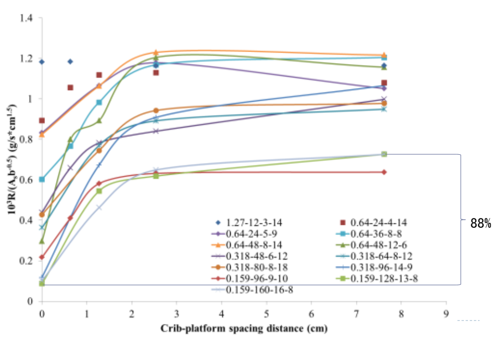
1.27 cm

2.54 cm

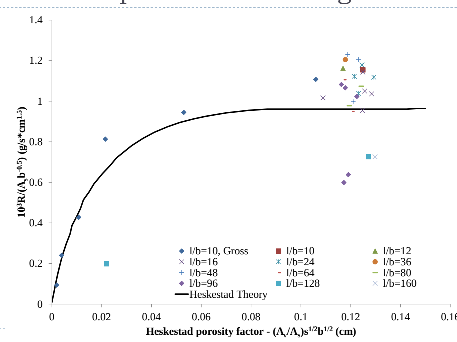
7.62 cm

0.64-48-12-6

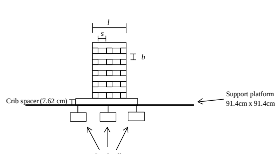
Crib-platform spacing



Heskestad plot – max burning rate



Experiment description



- Missoula Fire Lab's wind tunnel
- Ponderosa pine sticks, thicknesses 0.6 cm and 1.3 cm
- Conditioned at 35° C and 3% RH for 1-3+ days, equilibrium MC ~1%.
- 2 steel spacers of 7.6 cm (3 in)
- Dunked in isopropyl alcohol and allowed to drain. The total mass of fuel used was 10% or less of the crib weight.

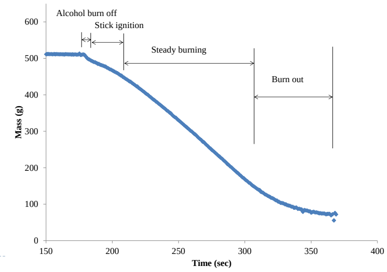
Effect of wind – testing schedule

- Preliminary tests
- Wind speeds of 0, 0.24, 0.37, and 0.70 m/s
- 3 replicates

Shorthand (b–l/b–n–N)	Stick thickness (b) [cm]	Stick length (l) [cm]	l/b [ ]	Number of sticks per layer (n) [ ]	Number of layers (N) [ ]	Porosity (φ) [cm]
1.27–10–2–25	1.27	12.7	10	2	25	0.120
1.27–10–7–10	1.27	12.7	10	7	10	0.004
1.27–16–6–14	1.27	20.32	16	6	14	0.039
1.27–20–4–21	1.27	25.4	20	4	21	0.120
0.64–40–10–10	0.64	25.4	40	10	10	0.072
0.64–40–14–15	0.64	25.4	40	14	15	0.021
0.64–96–20–9	0.64	60.96	96	20	9	0.116

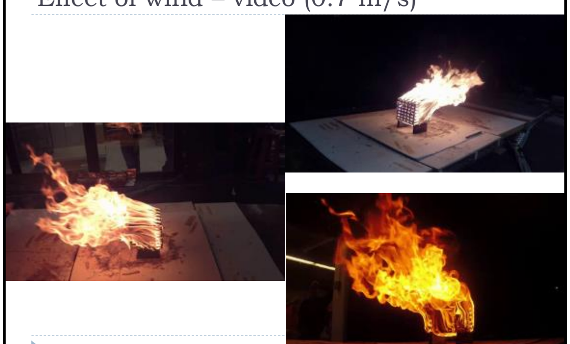
Data reduction

- Data recorded at 10 Hz
- The liquid fuel was observed to easily burn off before the steady state burning of the crib was achieved.

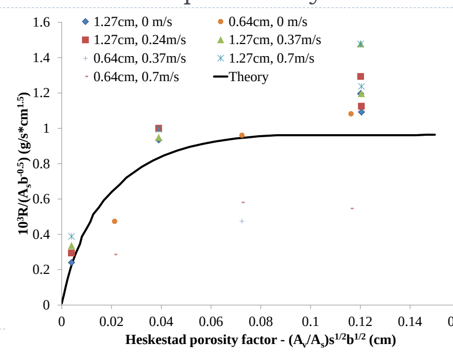


Effect of wind – video (0 m/s)

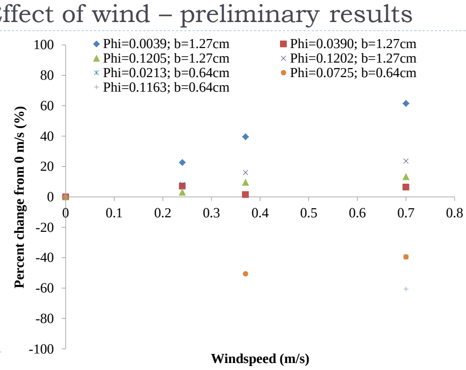
Effect of wind – video (0.7 m/s)



Effect of wind – preliminary results



Effect of wind – preliminary results



Summary

- Understanding burning rate of cribs may help understand wildland fire spread
- Preliminary work found that Heskestad correlation holds for wide variety of crib layouts, as long as ample spacing below is provided (at least 2.5 cm)
  - Very thin sticks (0.16 cm) still burned below correlation
- Wanted to know if forced ventilation has an effect
  - Cool visual changes in the flames
  - Effect of wind dependent on stick thickness
    - Thick sticks: very dramatic increase in burning rate for densely-packed cribs (60%+); Some minimal increase (~10%) in burning rate for transitional and loosely-packed cribs
    - Thin sticks: burning rate decreased with wind

Future work

- Investigate thinnest sticks (no wind) further
  - Do all porosities fall below correlation?
- More tests with wind!
  - Both thicker and thinner sticks?
- Connect cribs back to wildland fuel structures
  - Platform spacing → surface fuels vs. crown fuels
  - Effect of l/b → needle litter vs. slash (flame zone)

Questions?

- Work funded by the National Fire Decision Support Center

USDA United States Department of Agriculture
Forest Service

Forest Service Research & Development
Rocky Mountain Research Station
Fire, Fuel, and Smoke Science Program

Feasibility of Limiting Oxygen Index (LOI) as Material Flammability Classification

*Yuji NAKAMURA (Toyohashi Univ. Tech., Japan)
Koki KIZAWA, Shohei MIZUGUCHI (Hokkaido Univ., Japan)
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Kaoru WAKATSUKI (Shinshu U./NRIFD, Japan)

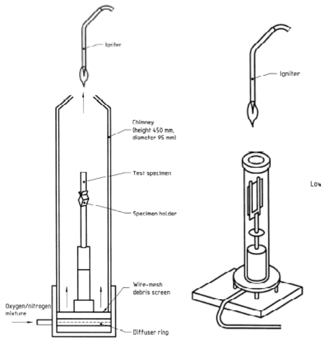
This work is a part of work on JEM 3rd, ISS Utilization Space Experiment International Project: FLARE

Fire-retardant material: Hard-to-Burn

http://www.apexglobal.eu/rescue-blanket/

Many plastic-based products around …

ISO4589-2: Protocol for plastic flammability test



Limiting Oxygen Index (LOI)

Definition:
Minimum O2 required to continuous burning (spread)

Low LOI: high fire-risk
High-LOI: low fire-risk

Protocol regulated by ISO4589-2
(standard sample size: 100 mm x 10 mm x 4 mm)

- ✓ One-time, 5 sec exposure of LPG flame is adopted
- ✓ If it does not ignite, LPG flame should be away
- ✓ 30 sec is maximum operation time to apply exposure.
- ✓ 180 s or 50 mm burning: fail
- ✓ If not ignited within 30 sec ignition operation, the material is "pass"

Reports from Wharton (1981, F&M): ASTM D2863-77

sample size for plate: 160 mm x 50 mm x XXX mm

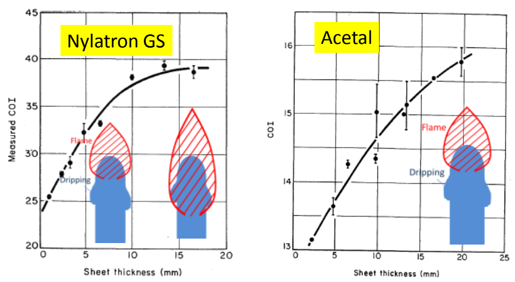
Specimen: Perspex

Type of Perspex	Form of test sample	Rod diameter (mm)	Sheet thickness (mm)	(COI) 30 °C	(COI) 50 °C	(COI) 70 °C	(COI) 80 °C	(COI) 90 °C
Clear	Round rod	2	—	17.2	16.7	16.2	—	15.9
		3	—	17.4	16.8	16.5	—	15.5
		5	—	—	16.3	—	—	—
		6.2	—	17.1	16.4	16.1	—	—
		6.35	—	—	16.5	—	—	—
		9.5	—	—	16.6	—	—	—
		10	—	17.6	16.6	15.4	—	15.0
		13	—	17.2	16.7	15.6	—	15.5
		15	—	17.2	16.7	16.0	—	15.0
Opal 040	Sheet	—	2.58	16.2	15.3	14.7	14.2	—
		—	3.08	16.3	15.4	14.9	14.2	—
		—	4.12	16.3	15.3	14.8	14.1	—

NO clear dependency is found in the thickness

Reports from Wharton (1981, F&M): ASTM D2863-77

sample size for plate: 160 mm x 50 mm x XXX mm



What is *NOT* sure about….

① Why the thickness of the test specimen is 4 mm for plate materials?

② Why 30 sec is maximum for flame exposure? (who decided?)

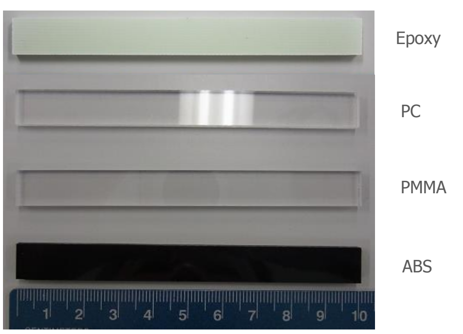
③ Dripping is the all matter? (what happens if we do not have any gravity drag?)

④ Can we use LOI as measure of material screening used in space?

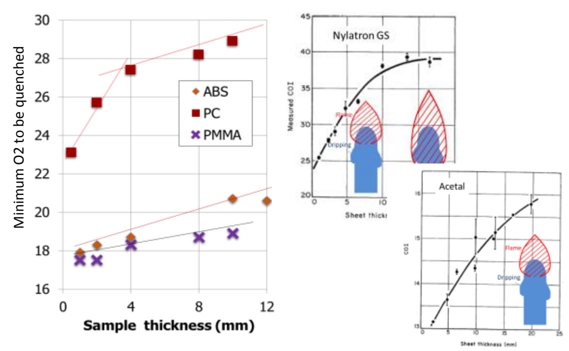
➔ we do not know much about how LOI is given in physical sense.

Tested sample (*not followed by* ISO4589-2)

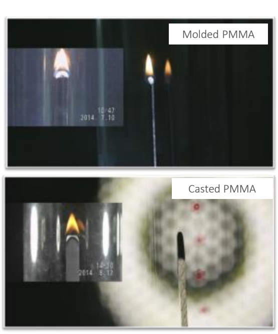
(*variable* sample size: 100 mm x 10 mm x 0.5~12 mm)

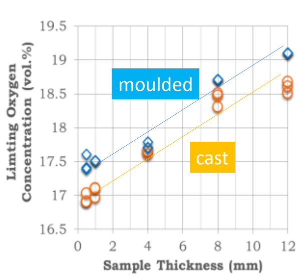


Effect of sample thickness on extinction limit

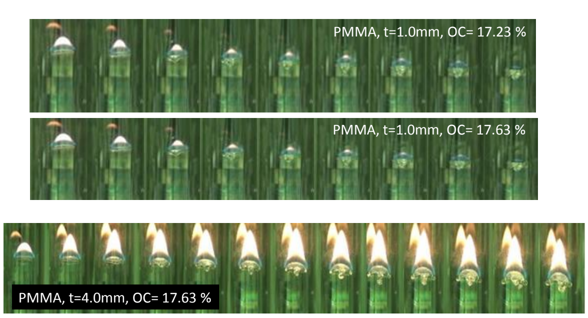


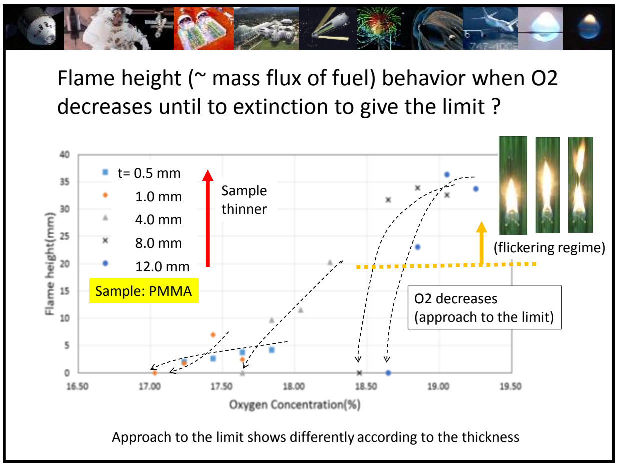
Can dripping increase the limit?; *Yes*!

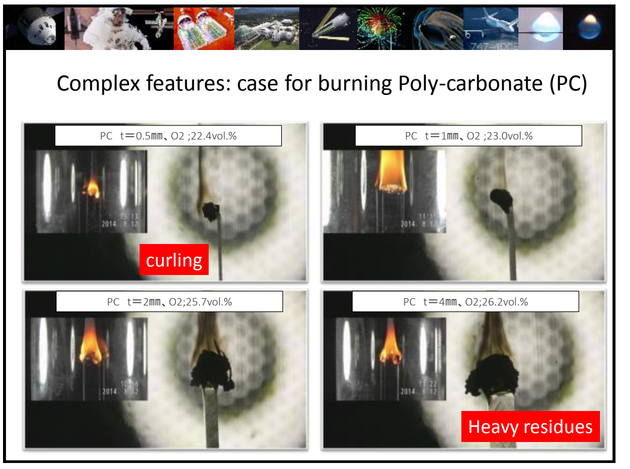


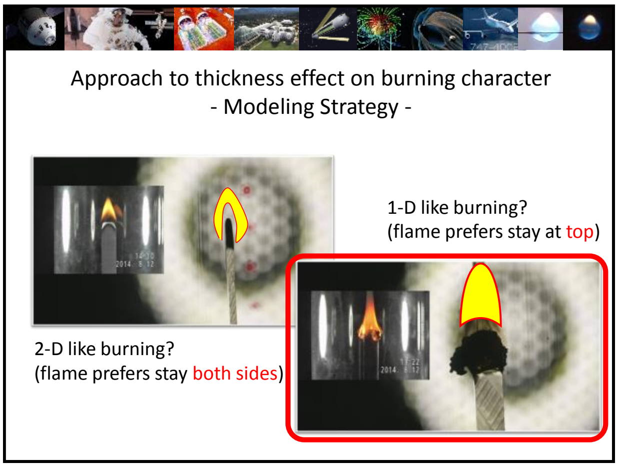


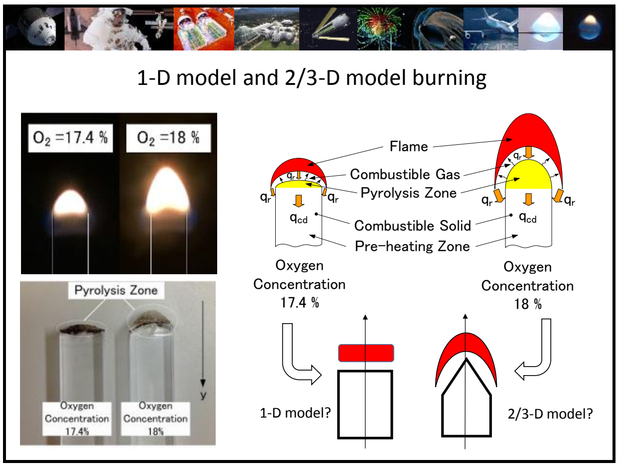
Flame size near the limiting condition

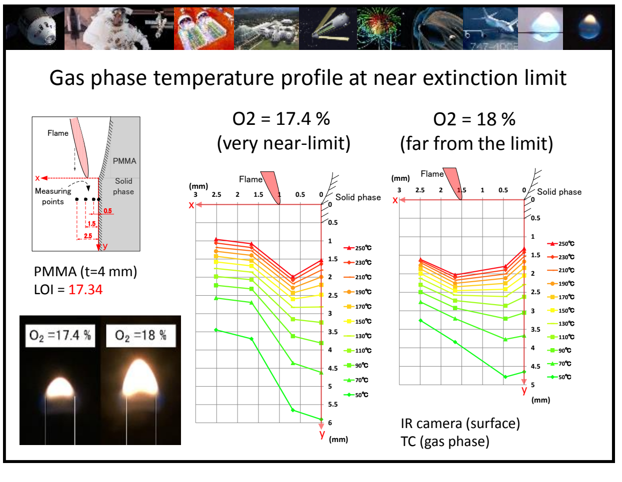


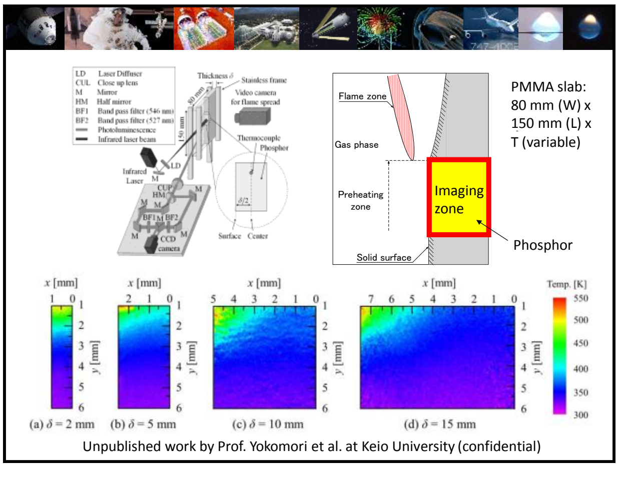

Flame height (~ mass flux of fuel) behavior when O2 decreases until to extinction to give the limit ?
t= 0.5 mm
1.0 mm
4.0 mm
8.0 mm
12.0 mm
Sample: PMMA
Sample thinner
(flickering regime)
O2 decreases (approach to the limit)
Flame height(mm)
Oxygen Concentration(%)
Approach to the limit shows differently according to the thickness

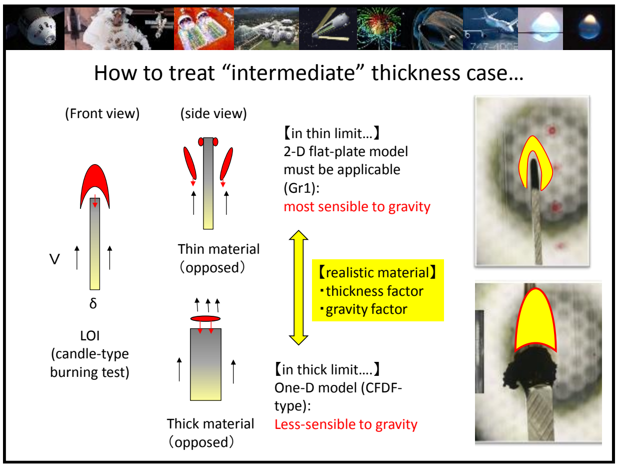

Complex features: case for burning Poly-carbonate (PC)
PC t=0.5mm、O2 ;22.4vol.%
PC t=1mm、O2 ;23.0vol.%
curling
PC t=2mm、O2;25.7vol.%
PC t=4mm、O2;26.2vol.%
Heavy residues

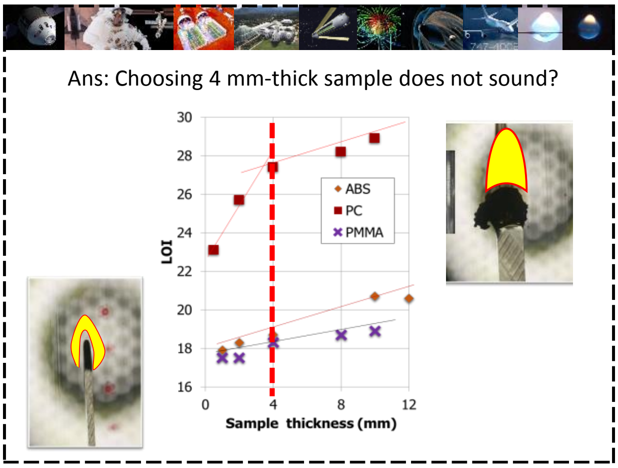

Approach to thickness effect on burning character
- Modeling Strategy -
1-D like burning?
(flame prefers stay at top)
2-D like burning?
(flame prefers stay both sides)

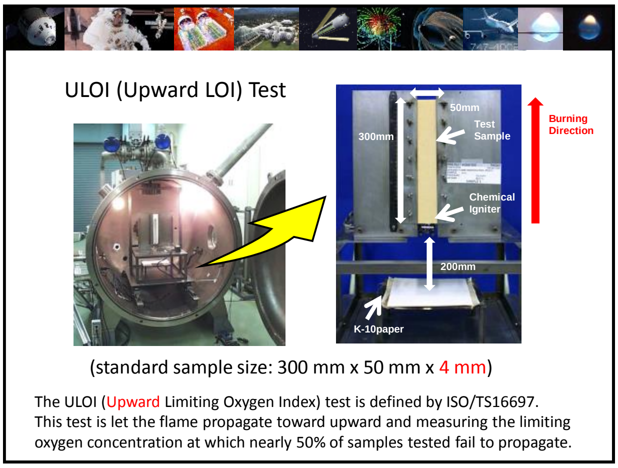

1-D model and 2/3-D model burning
O2 =17.4 %
O2 =18 %
Pyrolysis Zone
Oxygen Concentration 17.4%
Oxygen Concentration 18%
Flame
Combustible Gas
Pyrolysis Zone
Combustible Solid
Pre-heating Zone
Oxygen Concentration 17.4 %
Oxygen Concentration 18 %
1-D model?
2/3-D model?

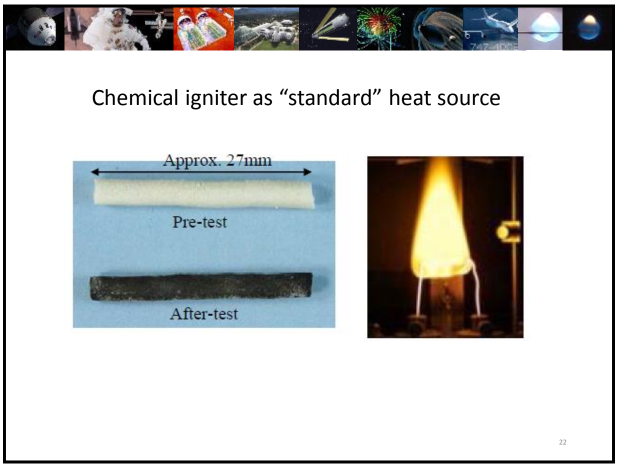

Gas phase temperature profile at near extinction limit
O2 = 17.4 %
(very near-limit)
O2 = 18 %
(far from the limit)
Flame
PMMA
Solid phase
Measuring points
PMMA (t=4 mm)
LOI = 17.34
O2 =17.4 %
O2 =18 %
IR camera (surface)
TC (gas phase)

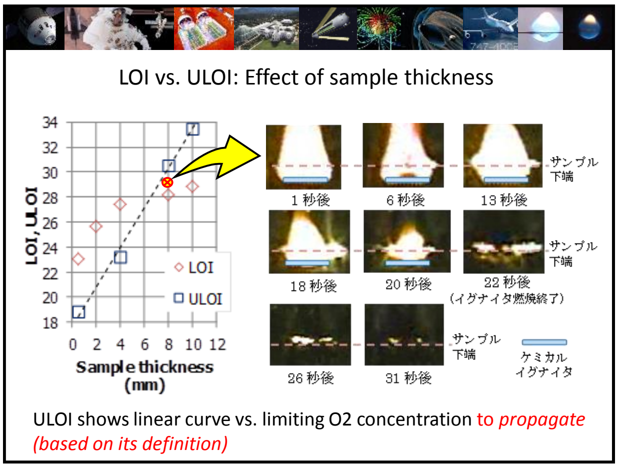

PMMA slab:
80 mm (W) x
150 mm (L) x
T (variable)
Flame zone
Gas phase
Preheating zone
Imaging zone
Solid surface
Phosphor
(a) δ = 2 mm
(b) δ = 5 mm
(c) δ = 10 mm
(d) δ = 15 mm
Temp. [K]
Unpublished work by Prof. Yokomori et al. at Keio University (confidential)

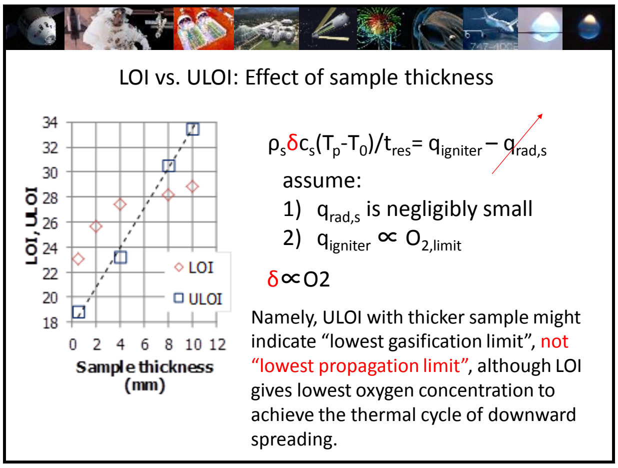

How to treat “intermediate” thickness case…
(Front view)
(side view)
V
δ
LOI
(candle-type burning test)
Thin material (opposed)
Thick material (opposed)
【in thin limit…】
2-D flat-plate model must be applicable (Gr1):
most sensible to gravity
【realistic material】
・thickness factor
・gravity factor
【in thick limit….】
One-D model (CFDF-type):
Less-sensible to gravity


Ans: Choosing 4 mm-thick sample does not sound?
LOI
30
28
26
24
22
20
18
16
0
4
8
12
Sample thickness (mm)
ABS
PC
PMMA


ULOI (Upward LOI) Test
50mm
300mm
Test Sample
Chemical Igniter
200mm
K-10paper
Burning Direction
(standard sample size: 300 mm x 50 mm x 4 mm)
The ULOI (Upward Limiting Oxygen Index) test is defined by ISO/TS16697.
This test is let the flame propagate toward upward and measuring the limiting oxygen concentration at which nearly 50% of samples tested fail to propagate.


Chemical igniter as “standard” heat source
Approx. 27mm
Pre-test
After-test


LOI vs. ULOI: Effect of sample thickness
LOI, ULOI
34
32
30
28
26
24
22
20
18
0 2 4 6 8 10 12
Sample thickness (mm)
LOI
ULOI
1 秒後
6 秒後
13 秒後
サンプル下端
18 秒後
20 秒後
22 秒後
（イグナイタ燃焼終了）
サンプル下端
26 秒後
31 秒後
サンプル下端
ケミカルイグナイタ
ULOI shows linear curve vs. limiting O2 concentration to propagate (based on its definition)


LOI vs. ULOI: Effect of sample thickness
LOI, ULOI
34
32
30
28
26
24
22
20
18
0 2 4 6 8 10 12
Sample thickness (mm)
LOI
ULOI
$\rho_s \delta c_s (T_p - T_0)/t_{res} = q_{igniter} - \cancel{q_{rad,s}}$
assume:
1) $q_{rad,s}$ is negligibly small
2) $q_{igniter} \propto O_{2,limit}$
$\delta \propto O2$
Namely, ULOI with thicker sample might indicate “lowest gasification limit”, not “lowest propagation limit”, although LOI gives lowest oxygen concentration to achieve the thermal cycle of downward spreading.

Remarks

① Why the thickness of the test specimen is 4 mm for plate materials? ... Not Sure Yet

② Why 30 sec is maximum for flame exposure? (who decided?) .... Too Short to Catch the (Real) Limit

③ Dripping is the all matter? (what happens if we do not have any gravity drag?) .... It Does Affect A Lot

④ Can we use LOI as measure of material screening used in space? .... Not Sure; Many Physics Uncovered (Needs simplification)

Thank you for your kind attention!

Fire-Structure Interaction:

What is the Problem?

The Problem of (Structural) Fire Safety Design in Japan

Kenichi IKEDA

Professor Dr.
Center for Fire Science and Technology
Tokyo University of Science

17th March 2015

Structural fire safety design became active from middle of 1980's to 2000 in Japan.

Many developments of constructional technologies were made and various new fire resistive building construction members, like the concrete filled steel tube column without fire protection, became in practical use.

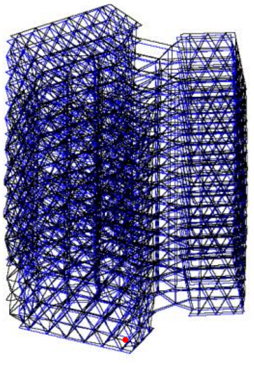
At the same time, several **structural fire safety design methods** were also developed, one method named **fire-resistance verification methods** was issued as a Notification No. 1433 of the Ministry of Construction May 31st, 2000.

Evaluation methods of the fire resistance of building members

Evaluation Method and Concept		Evaluation criteria: Stability of frame	Stability of Members	Strength of Materials
Frame level	Evaluate the stability of the frame directly and guarantee.	Frame does not collapse at fire	Failure of partial members are allowed unless the stability of the frame is guaranteed	—
Member level	Evaluate the stability ↓ Guarantee the stability of the frame	—	All members does not failure at fire	Failure of partial material components are allowed unless the stability of the members is guaranteed
Material level	Evaluate the strength of all materials of members ↓ Guarantee the stability of members at fire ↓ Guarantee the stability of frame at fire	—	—	All materials of all members does not lose required adequate strength

Design example of structural fire safety design by **frame Level**

Deformation of frame at fire



During these fifteen years, we made remarkable developments in the structural fire safety design field toward next stage.

But **many problems** which must be solved were left.

These problems are classified into
a matter of **social system** such as regulations and
a matter of **engineering** such as evaluating method of fire resistive performance.

As for a matter of **social system**,

The codes itself are **not perfect**.
The codes are **not practicable enough** for designers.

It takes much procedure time. 4mouths.

Simple and economical prescriptive code **remains parallel**.

The produced performance based code focuses on only specified or limited performances of building constructions. The necessary **other performances** which were implied before tacitly were omitted.

Lastly, the administration did not make improvement action for it at all.

As for a matter of **engineering**,
The new type constructions were applied to real buildings used **without sufficient research, development and engineering verifications**.

Designer pursuit economical results too much **without accounting real performances.**

Now, designers and administrations are making effort for improving these undesirable conditions.

Conclusions

1. **Performance** based code must be **economical** comparing to prescriptive codes. Unless it doesn't work.

2. **Designer** must be responsible for their design.

3. **Government** must understand the real conditions or status and **swing into** action.

Thanks

Fire-Structure Interaction: U.S. Perspective

Operation Tomodachi – Fire Research
NIST, Gaithersburg MD

March 17, 2015

John L. Gross, Ph.D., P.E., F.ASCE

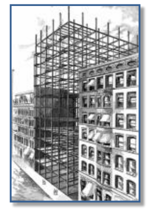
Assoc. Director for Structures Research
National Fire Research Laboratory

1

The beginning…

In 1791, just four years after the U.S. Constitution was signed, President George Washington issued the first regulations limiting building heights in the nation's new capitol of Washington D.C., "concerned as much about structural and fire safety as about urban design" [1].

Early knowledge of the requirements for fire protection resulted from examination of fire-damaged buildings, but the development of skeleton-type construction made the necessity for fire endurance testing apparent.[2] Shown here is the first metal-frame "skyscraper," the 12-story Home Insurance Building, built in the mid-1880s



1 Lewis, R. (1994). "Testing the Upper Limits of D.C. Building Height Act," *The Washington Post*, Saturday, April 23, Washington, D.C.

2 Shoub, H. (1961). "Early History of Fire Endurance Testing in the United States," Special Technical Publication No. 301, ASTM, Conshohocken, PA

2

The Equitable Building, 1891

The Equitable building "…is to be a modern office-building, absolutely fireproof…" (*The American Architect and Building News*, March 28, 1891)

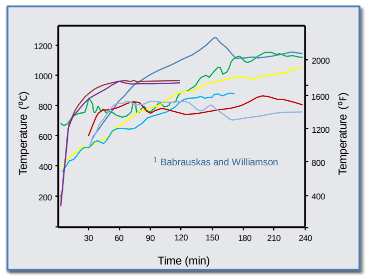
The tests shall consist of four kinds as follows:

A. – A Still Load, increased until each arch breaks down;
B. – Shocks, repeated until the arch is destroyed;
C. – Fire-and-Water, alternating until the arch is destroyed;
D. – Continuous Fire of high heat, until the arch is destroyed"

3

Furnace Temperatures for Floor Tests[1]

Many tests of floor systems were conducted, but it was clear that there was no agreement on either the exposing furnace conditions or acceptance criteria.



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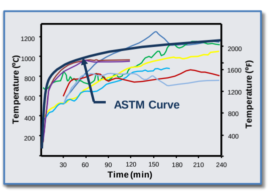
The genesis of the standard fire test

Largely as a result of the Baltimore fire of 1904, ASTM organized Committee P in 1905 to develop a standard fire test procedure, principally for floor systems.



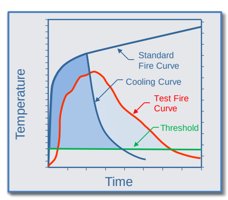
The primary feature of the standard fire test was the establishment of the time-temperature relationship shown here. The test, however, did not establish acceptance criteria.

5

Fire Research at NBS

Fire research began at NBS in 1914, led by Simon Ingberg

This work led to Ingberg's equal-area fire-severity hypothesis



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Ingberg's "fire severity" as a function of the fuel load

Fire Load		Assumed Combustible Load		Equivalent Fire Duration
(lb/ft²)	(kg/m²)	(Btu/ft²)	MJ/m²	
10	48.8	80,000	907.9	1 h 00 min
15	73.2	120,000	1361.9	1 h 30 min
20	97.6	160,000	1815.8	2 h 00 min
30	146.5	240,000	2723.7	3 h 00 min
40	195.3	320,000	3631.7	4 h 30 min
50	244.1	380,000	4312.6	6 h 00 min
60	292.9	432,000	4902.7	7 h 30 min

S.H. Ingberg, "Fire-Resistance Requirements in Building Codes," Quarterly of the National Fire Protection Association, Boston, October, 1929

7

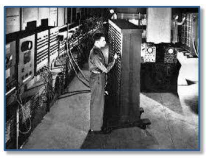
The required fire resistance is NOT a function of:

- Type of structural system
  - Redundancy
- Connections
  - Moment connections
  - Shear connections
    - Web connections
    - Seat connections
- Building/framing layout
  - Framing (spans)
  - Factors that affect the development and spread of fires

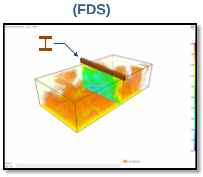
8

The advent of the electronic digital computer…

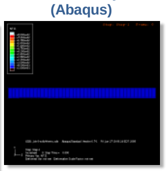
…heralded the development of computational fluid dynamics, transient heat transfer, and nonlinear structural mechanics



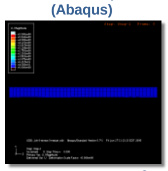
Fire Simulation (FDS)



Thermal Analysis (Abaqus)



Structural Response (Abaqus)



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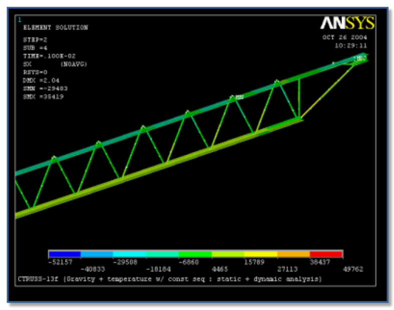
Current Capabilities in Fire-Structure Interaction



10

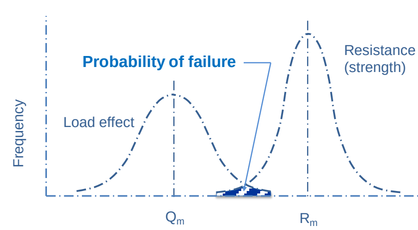
Concepts in a fire design[1]

Model of the structure \ Fire model	Generalized fire curves	Zone Models	CFD models
Component	Traditional	X	X
Assembly	X	Fire Safety Engineering	
System	X		

1 J. Maljaars, TNO, Delft, the Netherlands

11

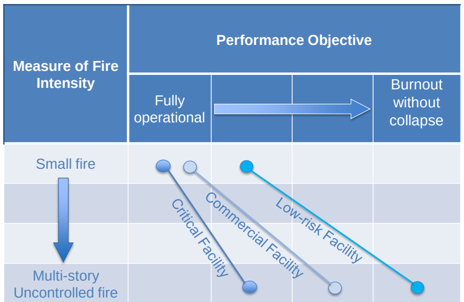
Reliability-based design



Probability density functions for load effect, Q, and resistance, R

12

Performance-based structural design for fire:



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Performance-based structural design for fire

A performance-based approach to structural design for fire…

- holds great promise to reduce the effects of fire on the built environment by:
  - allowing multiple performance objectives, and
  - explicitly considering fire as a design condition

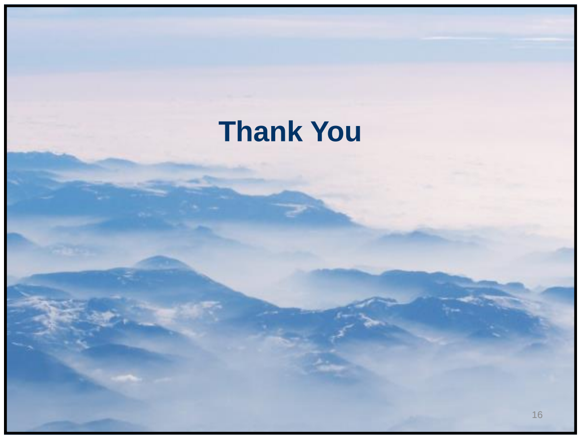
…thus leading to the clear potential to improve life safety, property protection, business continuity, and community resilience.

14

Vision of the future:

- A revolutionary transformation from the current prescriptive codes to new performance-based design standards
- Increased public safety with requisite technical justification
- Increased innovation and marketplace competition for new products, designs, and services
- Cost savings based on a rational and risk-consistent approach to design and use of materials

15



SIMPSON GUMPERTZ & HEGER
Engineering of Structures and Building Enclosures

U.S. Standards that Support Structural Fire Engineering Practice

Kevin LaMalva, P.E.
Operation Tomodachi - Fire Research
NIST (Gaithersburg, MD)
17 March 2015

www.sgh.com

Overview

- Structural Fire Engineering
  - Developing infrastructure for **standardized practice** in the U.S.
    - PBD process
    - Calculation methods
    - Performance expectations


Design


Review

2

Design Problem

- Uncontrolled building fire is an extraordinary event
- Heating of structural systems causes thermal load effects
- Critical that adequate strength/stability is maintained:
  - Occupant life safety
  - Other performance objectives (e.g., limitation of damage)



3

Design Philosophies

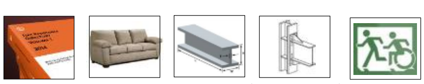
- Structural performance: *Capacity* > *Demand*

	Demand		***Capacity***
	Heating	Induced Forces	Structural Endurance
Prescriptive Method	Measured	Indeterminate*	Indeterminate*
Structural Fire Engineering	Calculated	Calculated	Calculated

* *Recognized by designers since the 1980s or perhaps earlier (Pettersson 1975, Law 1981)*

4

Design Variables

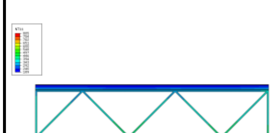
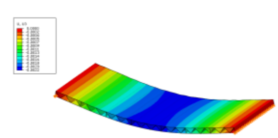


	Insulation	Fuel Load Control	Structural Design	Structural Detailing	Other Mitigation
Prescriptive Method					
Structural Fire Engineering					

5

SFE Design Process

- Estimation of fuel loads (FPE)
- Evaluation of structural design fire exposures (FPE)
- Evaluation of thermal response of the structure (FPE)
- Evaluation of fire effects on the structural response (SE)

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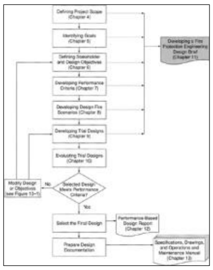
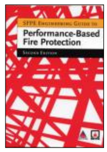
PBD Process

- **SFPE Guide**
  - *Performance-Based Fire Protection* (2000)





Design

Review

Fuel Loads

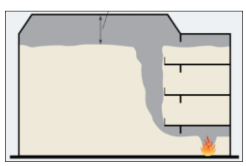
- **NFPA 557**
  - *Standard for Determination of Fire Loads for Use in Structural Fire Protection Design* (2012)

Fuel load in a conference room

Fuel load in an atrium

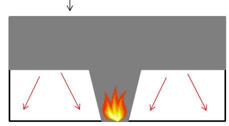
Structural Design Fire Exposures

- **SFPE Standard**
  - *Design Fire Scenarios* (Under Development)
- More comprehensive than NFPA 101 and NFPA 5000

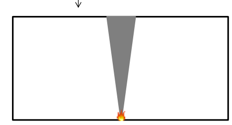


Structural Design Fire Exposures

- **SFPE S.01**
  - *Engineering Standard on Calculating Fire Exposures to Structures* (2011)
- Enclosed vs. Local Exposure



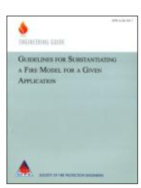
Fire in a conference room

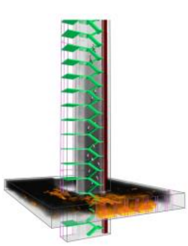


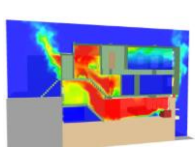
Fire within an atrium

Structural Design Fire Exposures

- **SFPE G.06**
  - *Guideline for Substantiating a Fire Model for a Given Application* (2011)

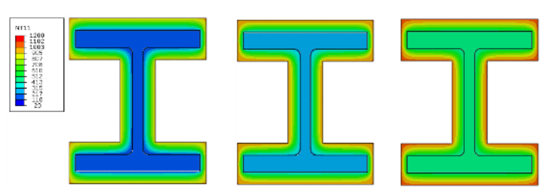






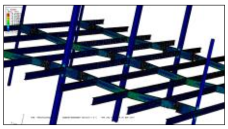
Thermal Response

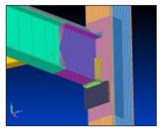
- **SFPE S.02**
  - *Standard on the Prediction of Thermal Response of Structural and Fire Resistive Assemblies* (2015)



Structural Response

- **ASCE/SEI 7 Appendix E**
  - *Performance-Based Design Procedures for Fire Effects on Structures* (2016)
- ***1st time fire considered as an explicit structural load in a U.S. standard***





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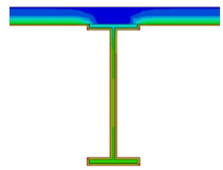
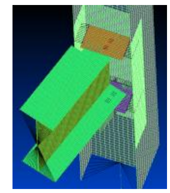
Structural Response

- **ASCE/SEI Guideline**
  - *Structural Fire Engineering* (Under Development)
- Best practices
- Detailed guidance and design examples





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Mandatory Performance Objectives

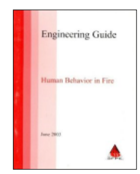
- <u>Fulfill Life Safety Function of Occupant Egress Features</u>
  - *Structural system shall allow occupants to travel safely to refuge areas or exit the building to a public way:*

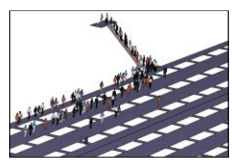
ASET vs. RSET
  - *Structural support of building egress routes shall be maintained for period of time necessary to ensure a safe and complete evacuation of occupants.*
  - *Structural support of building refuge areas shall be maintained throughout the heating and cooling of the structure.*

15

Mandatory Performance Objectives

- **SFPE Guide**
  - *Human Behavior in Fire* (2003)
- Egress Time Prediction (RSET)





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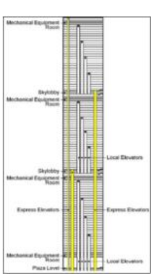
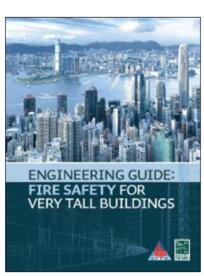
Mandatory Performance Objectives

- **SFPE/ICC Guide**
  - *Fire Safety for Very Tall Buildings* (2013)





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Discretionary Performance Objectives

AHJ ⟷ Designer

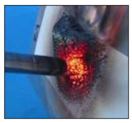
Design Brief

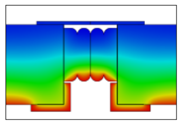
- <u>Provide Additional Structural Robustness</u>
  - Limitation of structural damage
    - Reduced recovery time, building resiliency, etc.
  - Structural support of fire barriers
    - Limit fire and smoke spread
  - Support of ingress routes for first responders
    - Satisfaction of mandatory performance objectives enhances safety

18

Areas Lacking Guidance

- Substantiation of structural-fire models
- Thermal properties of proprietary materials
- Mechanical integrity of non-structural FR assemblies





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Look Forward to Your Questions (Today or Anytime)?

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20

Development of Fire-Resistant Wooden Structure

Kouta Nishimura
(Kajima corporation)

Introduction

→Talk about a fire resistant wooden structural member

Background

Recently in Japan, the use of wood
(→a natural resource that can be reproduced)
has attracted the attention

↓

The use of wood has
・environmental advantages such as reducing CO_2
・effectively utilizing forest resources
・encouraging the growth of the domestic forestry industry

Background

Country	% of forest	Country	% of forest
Finland	73.9	Canada	33.6
Japan	68.2	USA	33.1
Sweden	66.9	France	28.3
Brazil	57.2	Australia	21.3
Russia	47.9	China	21.2
Italy	33.9	United Kingdom	11.8

Japan is eminently a large forest country →25,000,000ha
↓
Decrease in demand for wood、lack of management of the forest
↓
The present conditions aren't well kept

Background

Japanese government decided to make a policy(2010.10)
「Public buildings will be required to become wooden structure. But, buildings which are difficult to construct using wooden structure, are required to use a wooden interior material」
↓
This policy will enhance wood demand for the building industry while performing environmental measures
↓
Japanese government's aim
→Increase the self sufficiency ratio of the wood supply to more than 50% by 2020

Background

Wooden construction buildings → weak against the fire
↓
Required to have a fireproof performance like a building made of concrete or steel
↓
They must have a fireproof performance during a fire and fire extinguishing activities
↓
Especially in most urban areas of Japan, buildings of more than 2 stories or 100㎡ of total floor space are required to be "a fireproof buildings"

Background

Fire resistant wooden structural members are required for

・Structural performance

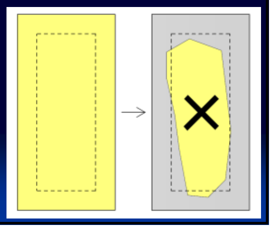
→Deformation volume and deformation velocity

・Fireproof performance

→A load sustaining part isn't carbonized during a fire and fire extinguishing activities

→It is difficult to satisfy this standard by「MOESHIRO」design

→adding an extra thickness for the carbonized layer to the load sustaining part



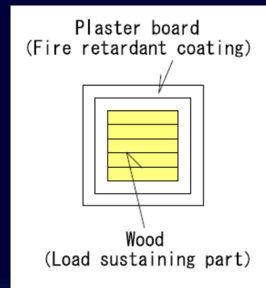
Background

99% of fire resistant wooden structures in Japan are coated with plaster board

→ It's a wooden structure, but we can't see the wood

↓

Our research group developed a new fire resistant wooden structural member

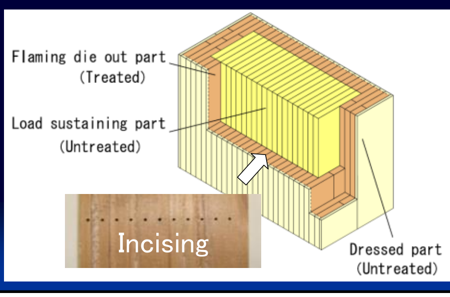


Fire resistant wood (FR wood)

The major characteristics of this member

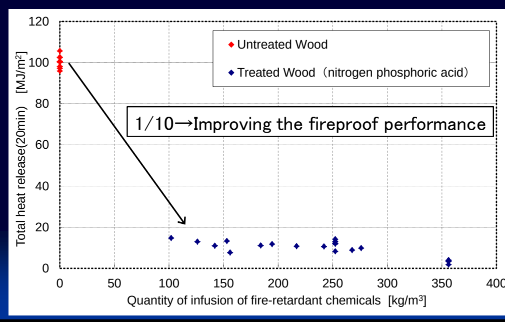
① Infusion of fire-retardant chemicals

② Incising processing



Infusion of fire-retardant chemicals

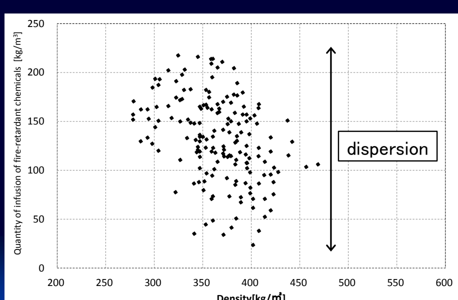
The total heat release is controlled to 1/10 by infusion of fire-retardant chemicals



Infusion of fire-retardant chemicals

There is the dispersion of the quantity of chemical infusion

→If we use it, a weak point occurs in the member



Incising processing

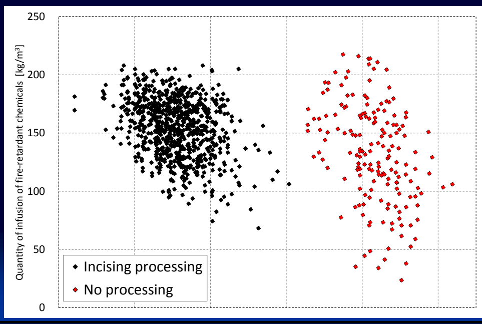
Incising processing is making a hole of about 1mm diameter

It is done before the infusion of fire-retardant chemicals

→ Equalize the dispersion of chemical infusion

Incising processing

It is clear that the dispersion of the quantity of chemical infusion with incising processing improved

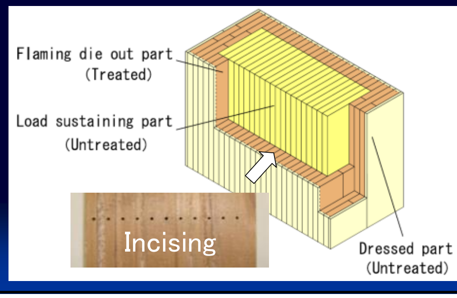


Fire resistant wood (FR wood)

A flaming die out part has been created these two processing

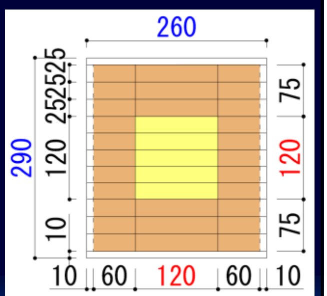
→It placed around a load sustaining part

→This member can ensure enough a fireproof performance

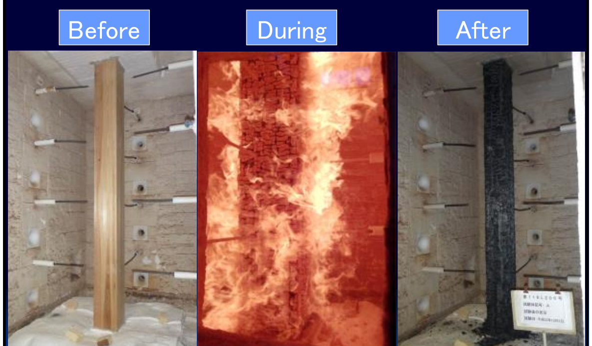


Outline of the specimen

- Member : column
- Kind of wood : cedar
- Length : 3300mm (heating area : 3000mm)
- Average of the quantity of infusion chemicals : 165kg/m³
- Quantity of incising : 1600holes/m²

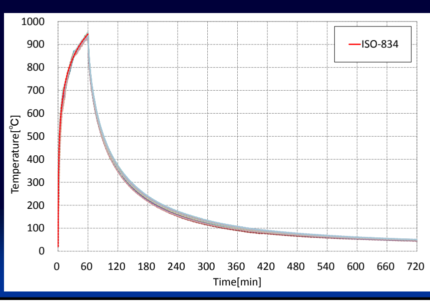


Result of fire test (situation)



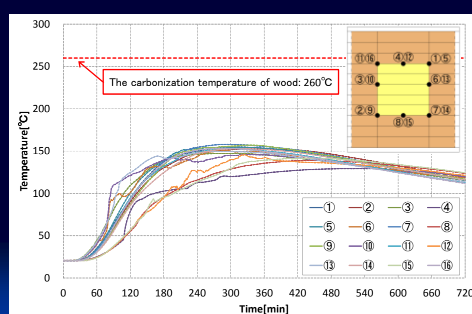
Result of fire test (heating)

After heating for 1 hour according to ISO-834, Specimen is left for 11 hours without fire fighters using the water →During this time, it takes a constant load



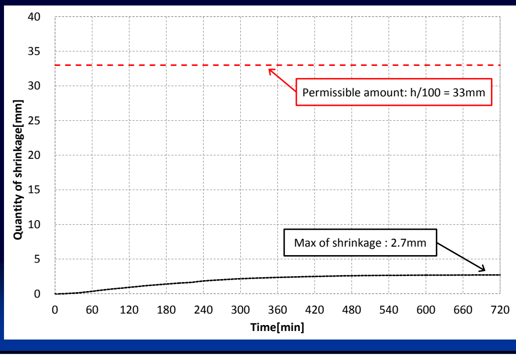
Result of fire test (temperature)

The maximum temperature of a load sustaining part is about 150℃ and did not reach 260 ℃



Result of fire test (deformation)

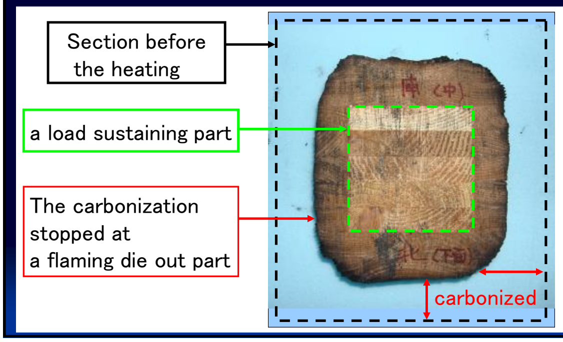
The quantity of shrinkage was very small



Result of fire test (carbonization)

A load sustaining part has survived well without being carbonized

→ It can be confirmed that it has a fireproof performance



Result of fire test

We confirmed a fireproof performance of other members

Conclusion

・Our research group developed the "Fire Resistant Wood" which can ensure enough a fireproof performance by "infusion of fire-retardant chemicals" and "incising processing"

・As a result of the fire test, the maximum temperature of a load sustaining part is about 150℃ and it didn't reach 260 ℃ (the carbonization temperature of wood)

・The carbonization stopped at the flaming-die-out part and a load sustaining part has survived well without being carbonized

Application example in Tokyo

Address
31-11, sekiguchi 2-chome,
Bunkyou-ku, Tokyo 〒112-0014

END

Thank you for your attention !

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Research Priorities for Structure-Fire Interaction – the CIB and NIST Perspectives

Jiann Yang, Matthew Bundy, John Gross, Fahim Sadek, and Anthony Hamins

Operation Tomodachi – Fire Research, March 16-18, 2015

NIST National Institute of Standards and Technology U.S. Department of Commerce

CIB in Brief (www.cibworld.nl)

- CIB is the acronym of the abbreviated French (former) name: "Conseil International du Bâtiment" (International Council for Building).
- In 1998, the abbreviation has been kept but the full name changed into: International Council for Research and Innovation in Building and Construction
- CIB was established in 1953 as an Association whose objectives were to stimulate and facilitate international cooperation and information exchange between governmental research institutes in the building and construction sector, with an emphasis on those institutes engaged in technical fields of research.
- CIB has since developed into a world wide network of over 5000 experts from about 500 member organizations with a research, university, industry or government background, who collectively are active in all aspects of research and innovation for building and construction.

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Genesis

- In October 2011, CIB Leadership decided to commission a series of international R & D roadmap documents
  - Fire resistance of structures being one of them
  - The published roadmap will form an international basis to advance performance-based engineering design of structures.
- NIST tasked to lead effort
  - Coordinated with CIB W14 (Fire) and FORUM (International Forum of Fire Research Directors) to plan and organize the Roadmap Workshop
  - Commissioned 3 White Papers to facilitate discussions at Workshop and to form framework for roadmap

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Roadmap Focus

- To identify research and development needs for large-scale experiments on fire resistance of structures to support performance-based engineering and structure-fire model validation;
- To prioritize those needs in order of importance to performance-based engineering;
- To phase the needed research in terms of a timeline, i.e. near term (less than 3 years), medium term (3 to 6 years) and long term;
- To identify the most appropriate international laboratory facilities available to address each need;
- To identify the potential collaborators and sponsors for each need;
- To identify the primary means to transfer the results from each series of tests to industry through specific national and international standards, predictive tools for use in practice, and comprehensive research reports; and
- To identify the means for the coalition of international partners to review progress and exchange information on a regular basis.

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The 3 White Papers:

- Concrete structures (http://dx.doi.org/10.6028/NIST.GCR.15-983)
  - Prof. Luke Bisby (U. Edinburgh, UK)
  - Dr. Hossein Mostafaei (FM Global, US / formerly NRC-Canada)
  - Dr. Pierre Pimienta (CSTB, France)
- Steel structures (http://dx.doi.org/10.6028/NIST.GCR.15-984)
  - Prof. Maria Garlock (Princeton U., US)
  - Dr. Joël Kruppa (Ismans Engineering School, France)
  - Prof. Guo-Qiang Li (Tongji University, China)
  - Dr. Bin Zhao (CTICM, France)
- Timber structures (http://dx.doi.org/10.6028/NIST.GCR.15-985)
  - Prof. Andrew Buchanan (U. Auckland, New Zealand)
  - Dr. Birgit Östman (SP Wood Technology, Sweden)
  - Dr. Andrea Frangi (ETH Zurich, Switzerland)

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The White Papers

- To provide comprehensive reviews of the current state-of-the-art on research, technology, testing, and best practices in performance-based design (PBD) engineering for concrete, steel, and timber structural systems, and suggested areas where considerable gaps in knowledge exist.
- To facilitate discussions at the Workshop and to form framework for the Roadmap

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The Workshop (May 21-22, 2014 @ NIST):

- Participants
  - 54 from 11 countries (Asia, North America, Europe, Oceania)
  - Academia, Authority Having Jurisdiction (AHJ), industries, governments, professional associations, SDOs
- Format
  - Plenary – white paper presentations
  - Break-out – brainstorming & discussion, categorization, prioritization, development strategies, and implementation plans (moderated by workshop facilitators)
  - Summary

Workshop Output:

- International efforts to support the PBD research agenda
  - Testing and test-beds
  - Societal and regulatory
  - Modeling and simulations
  - Material properties and system performance
- Implementation plans
  - Major tasks and milestones
  - Performance targets and reviews
  - Technology transfer
  - Roles and responsibilities of stakeholders
  - Potential collaborators
  - Dependency

Workshop Output:

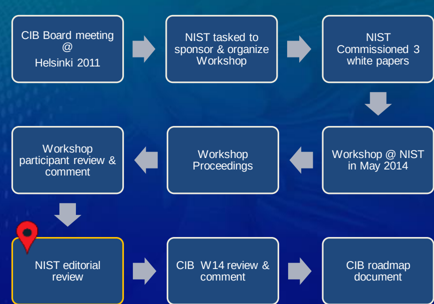
- Implementation plans (concrete)
  - Fire as a load
  - High-temperature strain and deflection measurements
  - Stakeholder education and code development
  - Multi-scale conditions and testing of concrete elements and samples
  - Societal awareness of fire issues
- Implementation plans (steel)
  - 3-D Full-scale tests on structural systems
  - Material properties for steel construction
  - Applicable fire scenarios
  - Simulation with connection models

Workshop Output:

- Implementation plans (timber)
  - Predict the reliability of fire compartmentation
  - Specific acceptable performance criteria
  - Development of structural models for timber fire resistance
  - Calculating the strength of structural timber exposed to fire
  - Compartment burnout encapsulation
  - Reliability-based analysis of fire testing
  - Design fires based on use and occupancy

	NIST GCR 02-843-1	NIST IR 6890 (2002)	NIST IR 7133 (2004)	NIST SP 1061 (2006)	NIST GCR 07-910	NIST GCR 07-915	NIST GCR 12-958	NIST/CIB Roadmap Workshop
Needs for test facilities	X	X						X
Advanced instrumentation	X	X			X	X	X	X
Test fires / fire scenarios	X			X		X		X
Material constitutive models and properties	X	X	X	X		X	X	X
Numerical models (Fire-Structure)		X		X			X	X
Full-scale data (connections, sub-assemblies, systems)	X	X	X	X		X	X	X
Model validation	X	X	X	X		X	X	X
Improvement of ASTM E119	X				X	X		
Development of design tools	X	X	X		X	X		X
Development of research Plans led to PBD	X	X	X	X	X		X	X
Outreach and education								X

Where are we in the process?



CIB Research Roadmap Structure

- Conceptual framework
  - *What are the issues?*
- State of the art
  - *Where are we today?*
- Future scenario
  - *Where do we want to be in the future?*
- Development strategy
  - *What is needed to get us there?*
- Research & development contribution
  - *How can R & D contribute to development strategy?*
- Research & development agenda
  - *What will be the relevant areas of science & technology development and their priorities?*

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Acknowledgments

- Ms. Stéphanie Vallerent (CSTB, FORUM member)
- Dr. Alec Lei (ABRI, FORUM member)
- Prof. George Hadjisophocleous (Carleton U., CIB W14 Chair)
- The White Paper Teams
- The NIST NFRL Team
- The Energetics Team (Workshop facilitators)

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Thank you!

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Multiphysics Simulation of Fire-Structure Interaction

Ann E. Jeffers and Paul A. Beata
Department of Civil and Environmental Engineering
University of Michigan
Ann Arbor, MI USA

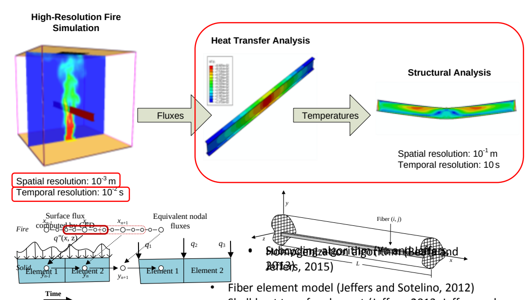
Overview

- Motivation
- Simulation framework for coupling fire dynamics model to thermo-structural model
- Application: Plate exposed to localized fire
- Results
- Conclusions

Motivation

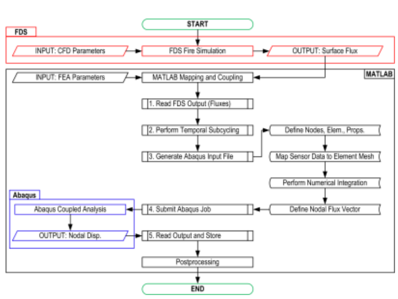
- Current CFD codes do not take into account the structural performance
- Current structural models do not take into account spatial variations in boundary conditions associated with real fires
- As a result, we may be missing important effects at the fire-structure interface

Simulation Framework



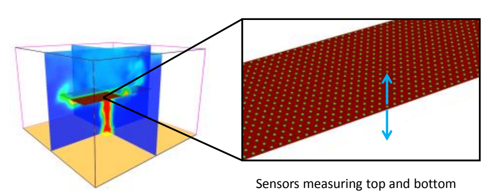
- Fiber element model (Jeffers and Sotelino, 2012)
- Shell heat transfer element (Jeffers, 2013; Jeffers and Beata, 2014; Jeffers, 2014)

Software Framework



Output from FDS

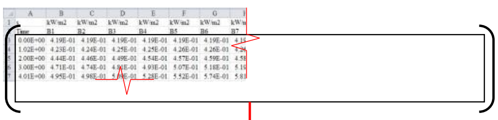
Sensor data from FDS stored in [firename]_devc.csv:



Sensors measuring top and bottom incident surface flux

Output from FDS

Sensor data from FDS stored in [firename]_devc.csv:



[{ TIME }, { B1 } . . . { Bn }, { T1 } . . . { Tn }]

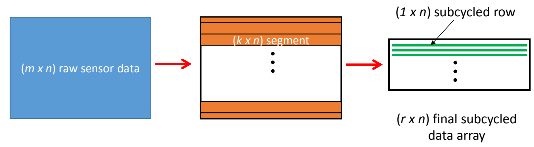
TIME array with *m* entries; one for each of the *m*-steps of the FDS fire *(m x 1)*

Bi arrays with *m* entries; total of *n* sensors on (B)ottom surface *(m x n)*

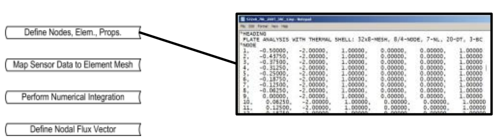
Ti arrays with *m* entries; total of *n* sensors on (T)op surface *(mxn)*

Subcycling

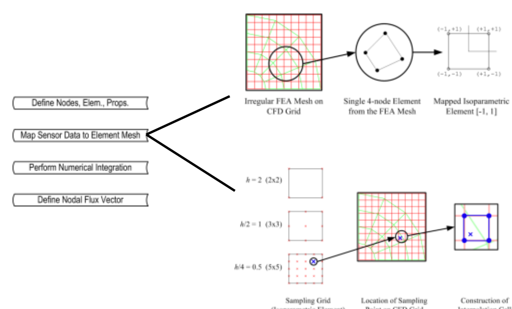
Subcycling is performed to reduce the *m* x *n* sensor data to *r* x *n* array, where *r* is the number of time steps in the thermo-structural simulation



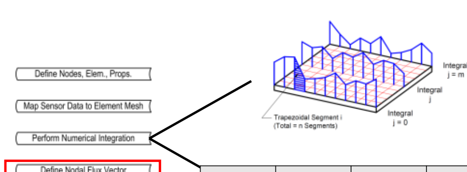
ABAQUS Input File



Equivalent Nodal Heat Fluxes

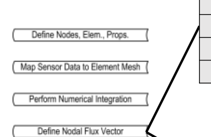


Equivalent Nodal Heat Fluxes



Trap.	Romberg	Romberg	Romberg
T(h)			
T(h/2)	R_{22}		
T(h/4)	R_{32}	R_{33}	
T(h/8)	R_{42}	R_{43}	R_{44}

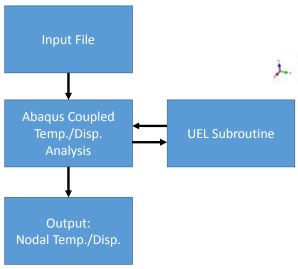
Equivalent Nodal Heat Fluxes



Trap.	Romberg	Romberg	Romberg
T(h)			
T(h/2)	R_{22}		
T(h/4)	R_{32}	R_{33}	
T(h/8)	R_{42}	R_{43}	R_{44}

```
204, U501, 20.0
*DLOAD
204, U1001,          2.0260089484
*DLOAD
204, U1002,          2.2379219037
*DLOAD
204, U1003,          2.1459705589
*DLOAD
204, U1004,          1.9454110823
*DLOAD
205, U201, 25.0
*DLOAD
```

ABAQUS Analysis



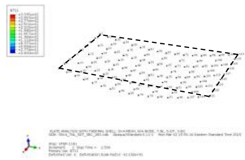
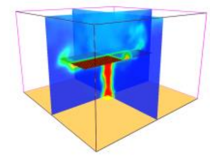


Plate Exposed to Localized Fire

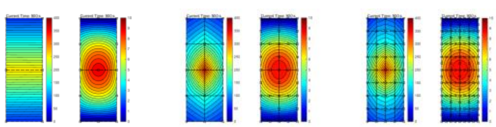


2m x 1m Plate (5-cm thick)
Conductivity: 2.0
Specific Heat: 1000
Density: 2000

Elastic Modulus: 2E10
Poisson's Ratio: 0.2
Coeff. Thermal Expansion: 1E-5

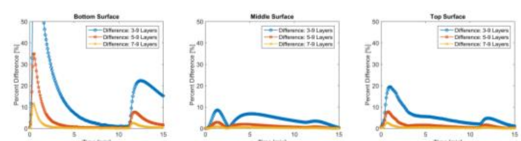
0.5 MW Fire
15 min Duration
1.0 m Separation

Thermo-Structural Response



Number of Layers

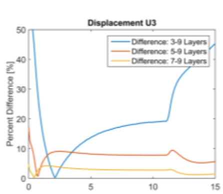
Convergence (Temperature)



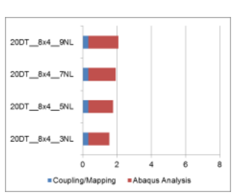
	Percent Difference		
Temperature	3 Layers	5 Layers	7 Layers
Bottom	17.02	3.80	1.02
Middle	4.17	1.07	0.30
Top	5.65	1.51	0.42

Number of Layers

Convergence (Displacement)

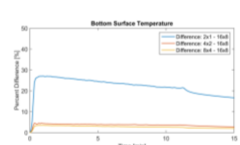


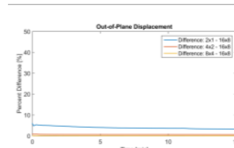
Computing time



	Percent Difference		
Displacement	3 Layers	5 Layers	7 Layers
Translation U3	21.62	7.60	2.71

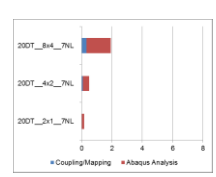
Number of Elements





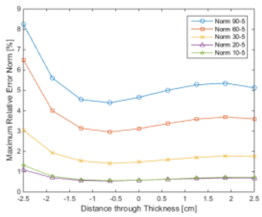
Temp. (Bot. Surf.)	% Difference
2x1	22.18
4x2	3.60
8x4	2.69

Displacement U3	% Difference
2x1	3.93
4x2	0.68
8x4	0.12

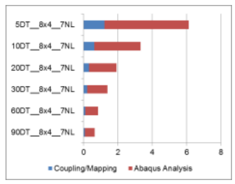


Time Step

Convergence



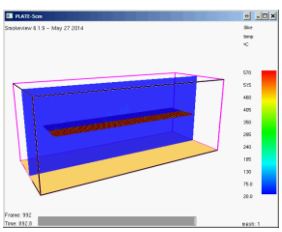
Computing Time

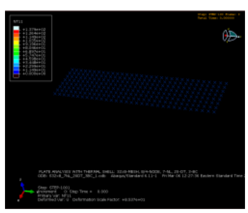


Conclusions

- A simulation framework for the multiphysics simulation of structures in fire has been developed
- The framework focuses on the extreme case of a fire impinging on a structure and is applicable to cases in which the structure is at a distance to the fire source
- The framework has been demonstrated to be highly efficient, allowing structural performance to be included in CFD simulations at practically no cost

Future Work





Acknowledgments

This work was performed in collaboration with Jim Lua and others at Global Engineering and Materials. The project was sponsored by the Office of Naval Research under contract N00014-13-C-0373.

ONR

GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

TAKENAKA

Thermal Elongation of Steel Beams Constrained by RC Slab and Adjacent Frames

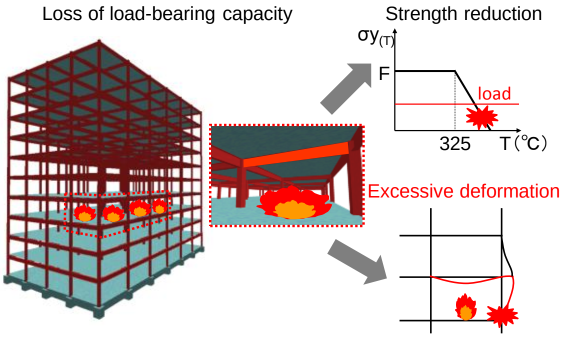
Tomohito OKAZAKI[1] and Mamoru KOHNO[2]

[1]Takenaka Corporation
[2]Tokyo University of Science

1

Collapse risk of a building in fire

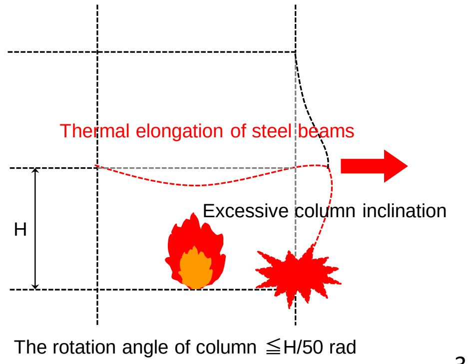
TAKENAKA



2

Thermal deformation of a building

TAKENAKA



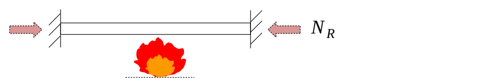
The rotation angle of column ≦H/50 rad

3

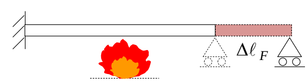
Fundamental theory

TAKENAKA

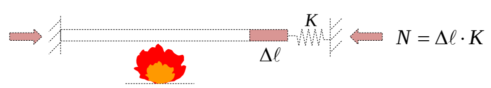
Ends of a beam are fixed



End of a beam is free



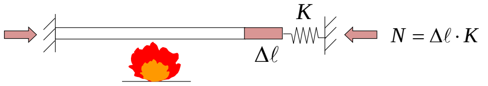
End of a beam is constrained by a spring



4

Theoretical formula

TAKENAKA



Compressive strain

$$\Delta\ell = \underbrace{\ell\alpha T}_{\text{Thermal strain}} - \overbrace{\frac{\ell\sigma}{E}}^{\text{Compressive strain}} = \frac{A\sigma}{K}$$

$$\sigma = \frac{\ell\alpha T}{\left(\dfrac{\ell}{E} + \dfrac{A}{K}\right)} = \frac{E\alpha T}{\left(1 + \dfrac{EA}{K\ell}\right)}$$

Thermal strain

$$\boxed{\Delta\ell = \ell\alpha T\left(1 - \frac{1}{1 + \dfrac{AE}{K\ell}}\right)}$$

5

Boundary conditions in an actual building

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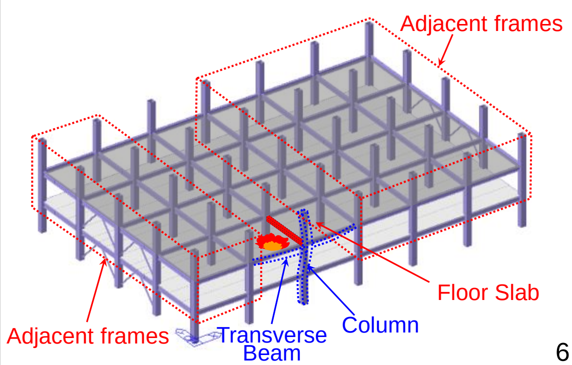
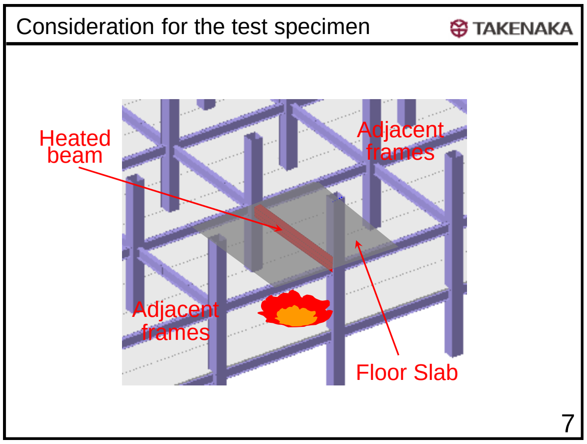
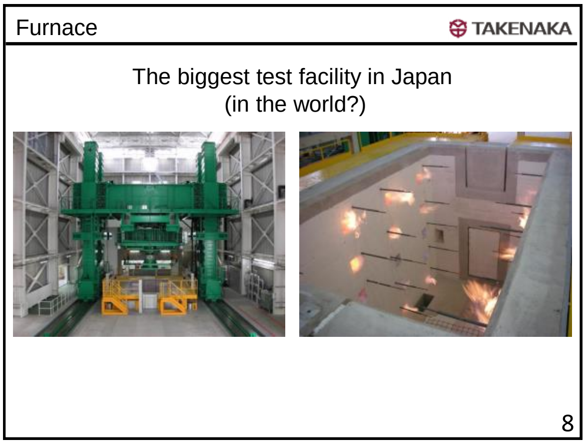
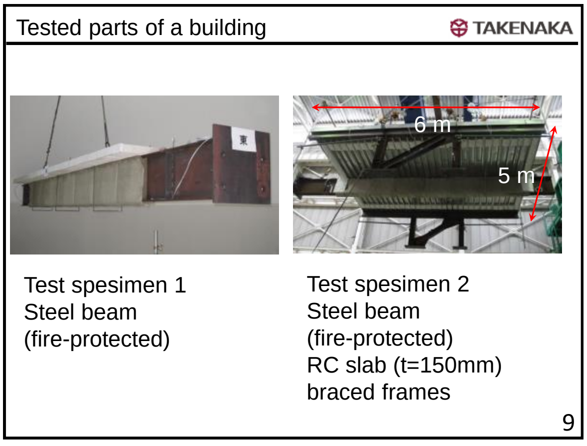
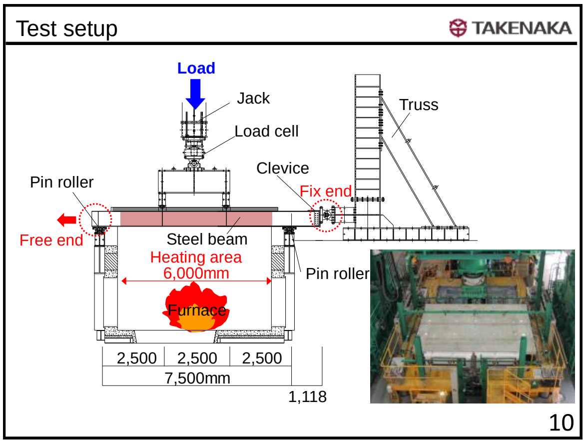


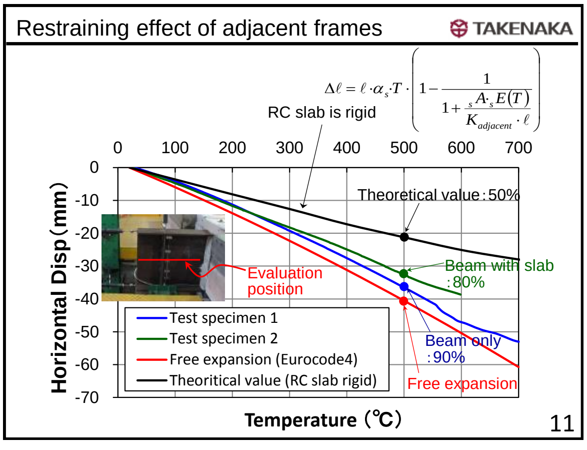
6

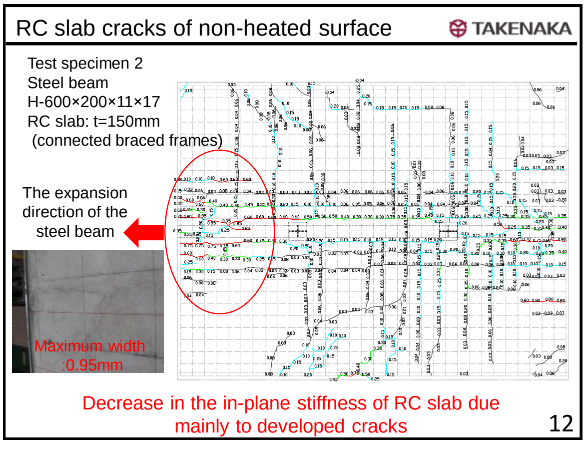

Consideration for the test specimen
TAKENAKA
Heated beam
Adjacent frames
Adjacent frames
Floor Slab
7


Furnace
TAKENAKA
The biggest test facility in Japan
(in the world?)
8


Tested parts of a building
TAKENAKA
6 m
5 m
Test spesimen 1
Steel beam
(fire-protected)
Test spesimen 2
Steel beam
(fire-protected)
RC slab (t=150mm)
braced frames
9


Test setup
TAKENAKA
Load
Jack
Load cell
Truss
Clevice
Pin roller
Fix end
Free end
Steel beam
Heating area
6,000mm
Furnace
Pin roller
2,500
2,500
2,500
7,500mm
1,118
10


Restraining effect of adjacent frames
TAKENAKA
$\Delta\ell = \ell \cdot \alpha_s \cdot T \cdot \left(1 - \frac{1}{1 + \frac{{}_sA \cdot {}_sE(T)}{K_{adjacent} \cdot \ell}}\right)$
RC slab is rigid
Theoretical value : 50%
Beam with slab : 80%
Evaluation position
Beam only : 90%
Free expansion
Test specimen 1
Test specimen 2
Free expansion (Eurocode4)
Theoritical value (RC slab rigid)
Horizontal Disp (mm)
Temperature (℃)
0
100
200
300
400
500
600
700
0
-10
-20
-30
-40
-50
-60
-70
11


RC slab cracks of non-heated surface
TAKENAKA
Test specimen 2
Steel beam
H-600×200×11×17
RC slab: t=150mm
(connected braced frames)
The expansion direction of the steel beam
Maximum width :0.95mm
Decrease in the in-plane stiffness of RC slab due mainly to developed cracks
12

Objective of study

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Decrease in the in-plane stiffness of RC slab due mainly to developed cracks

↓

Quantification of the stiffness reduction of typical RC slabs

↓

Test specimens were composed of steel beams and RC slabs

13

Specification of test frames

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Specimen	Size of beam	Fire resistance hour
H400-1	H-400 × 200 × 8 × 13	1 hour
H400-2		2 hour
H600-1	H-600 × 200 × 11 × 17	1 hour
H600-2		2 hour

Thick of RC slab: 150mm

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Test setup

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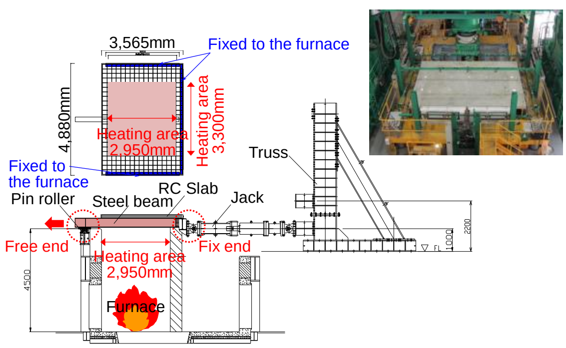


15

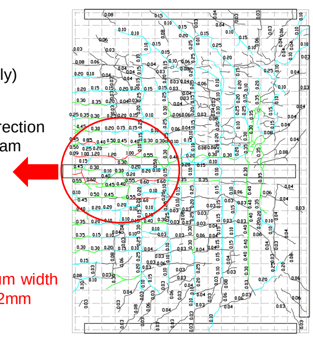
RC slab cracks of non-heated surface

TAKENAKA

Test specimen H600-2
Steel beam
H-600×200×11×17
RC slab: t=150mm
(3 sides was connected rigidly)

The expansion direction of the steel beam

Maximum width :1.2mm



Similar crack pattern of all tested specimens

16

Stiffness of RC slab

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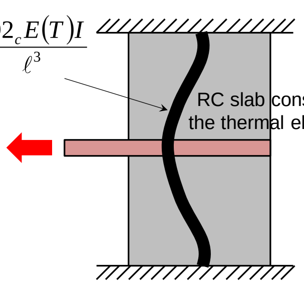
$$K_{slab} = \frac{192{}_{c}E(T)I}{\ell^{3}}$$



17

Evaluated in plane stiffness of RC slabs

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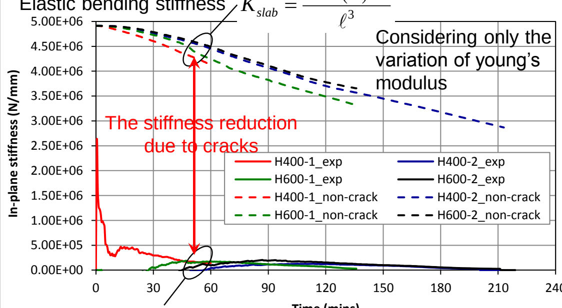
Elastic bending stiffness, $K_{slab} = \dfrac{3 \cdot E(T) \cdot I}{\ell^{3}}$



Obtained from test results

18

Stiffness reduction ratio

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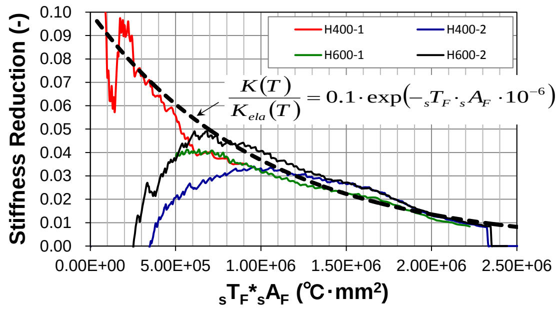

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Evaluation formula for elongation

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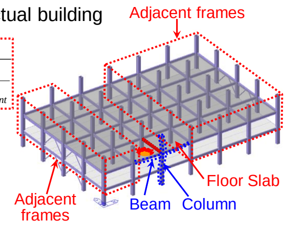
Total suppressive effect of a actual building

$$K_{total} = \boxed{K_{column} + K_{beam}} + \boxed{\frac{1}{\frac{1}{K_{slab}} + \frac{1}{K_{adjacent}}}}$$



$$\frac{K_{slab}}{K_{slab\_RT}} = 0.1 \times \exp(-{}_sT_F \cdot {}_sA_F \times 10^{-6})$$

Coefficient of thermal expansion : $_s\alpha$

$$\Delta\ell / \ell = -2.416 \times 10^{-4} + 1.2 \times 10^{-5} \times {}_sT + 0.4 \times 10^{-8} \times {}_sT^2 \qquad (20℃ \leq {}_sT \leq 750℃)$$

$$\Delta\ell = \ell \cdot {}_s\alpha \cdot {}_sT$$

$${}_s\alpha = \frac{(-2.416 \times 10^{-4} + 1.2 \times 10^{-5} \times {}_sT + 0.4 \times 10^{-8} \times {}_sT^2)}{{}_sT}$$

20

Evaluation formula

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Fundamental formula

$$\Delta\ell = \ell \cdot \alpha \cdot T \left(1 - \frac{1}{1 + \frac{A \cdot E}{K \cdot \ell}}\right)$$

Suggested evaluation formula

$$\Delta\ell = \ell \cdot {}_s\alpha \cdot {}_sT \left(1 - \frac{1}{1 + \frac{\sum A \cdot {}_sE(T)}{K_{total} \cdot \ell}}\right)$$

Scope of application

$(20℃ \leq {}_sT \leq 750℃)$

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Comparison of the thermal elongations

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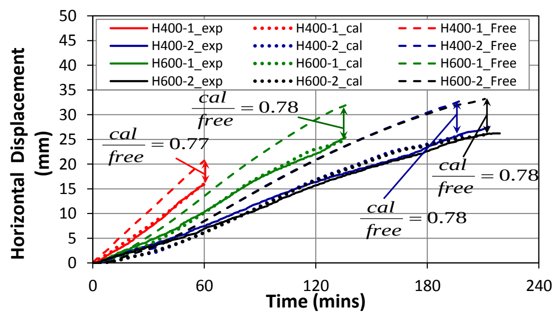

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Conclusion

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1. The reduction effect of RC slabs on thermal elongation was around 20% of that provided in Eurocode 4.
2. The in-plane stiffness reduction of typical RC slabs was quantified and the following evaluation equation was suggested.

$$\frac{K_{slab}}{K_{slab\_RT}} = 0.1 \times \exp(-{}_sT_F \cdot {}_sA_F \times 10^{-6})$$

3. The thermal elongation of steel beams can be predicted accurately by the presented simple theoretical formula for the performance based fire engineering.

$$\Delta\ell = \ell \cdot {}_s\alpha \cdot {}_sT \left(1 - \frac{1}{1 + \frac{\sum {}_sA \cdot {}_sE(T)}{K_{total} \cdot \ell}}\right)$$

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TAKENAKA

Thank you for your kind attention.

Behavior and Design of Composite Beams Subjected to Fire

Amit H. Varma, Kristi Selden, Erica Fischer

Operation: Tomodachi
NIST, Gaithersburg, MD
May 2015

Acknowledgements

This research was funded by:

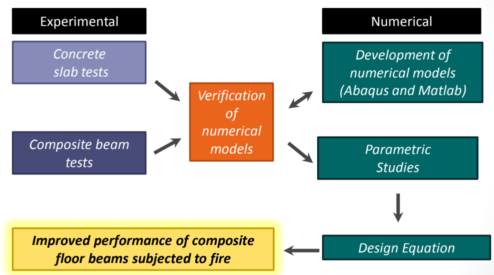
The National Science Foundation
Grant No. CMMI-0758461

Any opinions, findings, and conclusions or recommendations are those of the authors only and do not necessarily reflect the views of the sponsors.

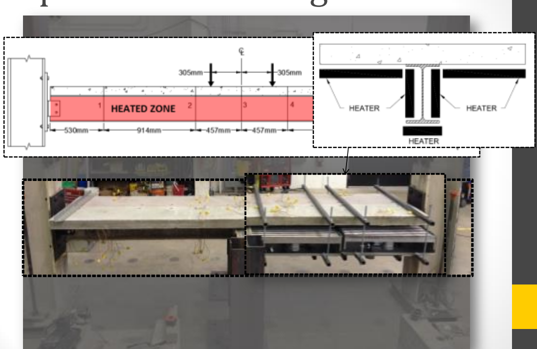
Research Objectives

- How do composite beam systems designed according to U.S. codes and standards behave when subjected to the combination of thermal and structural loading in the event of fire?
- How can structural engineers be better equipped to account for fire in the design of composite beams?

Research Approach

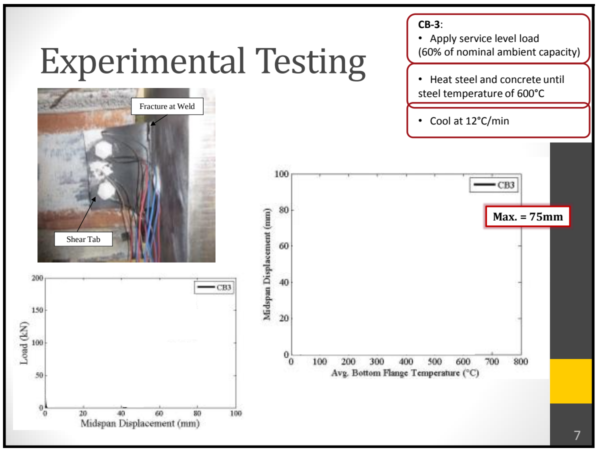


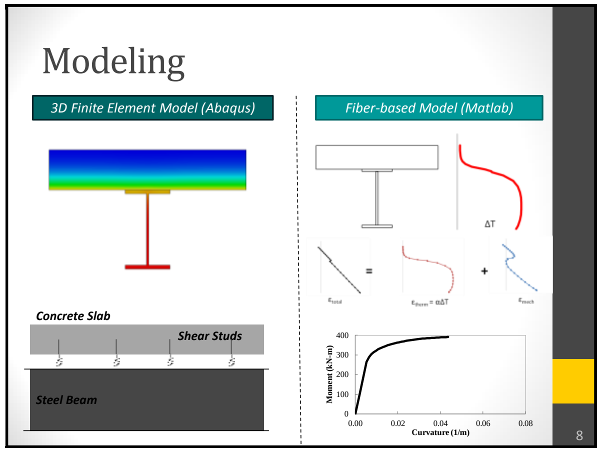
Experimental Testing

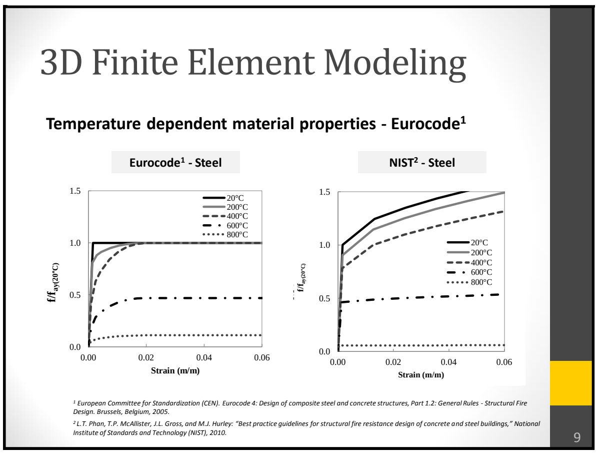


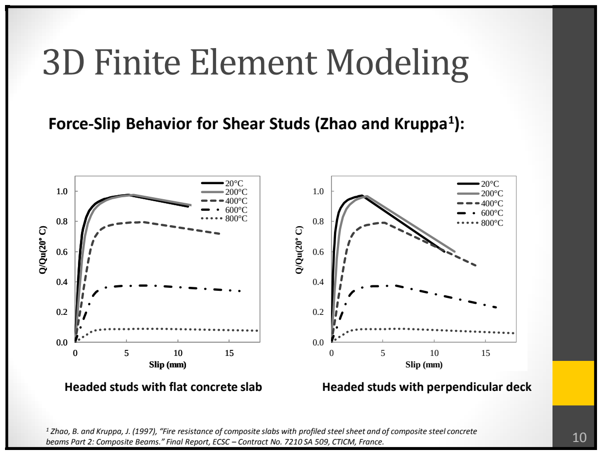
Experimental Testing

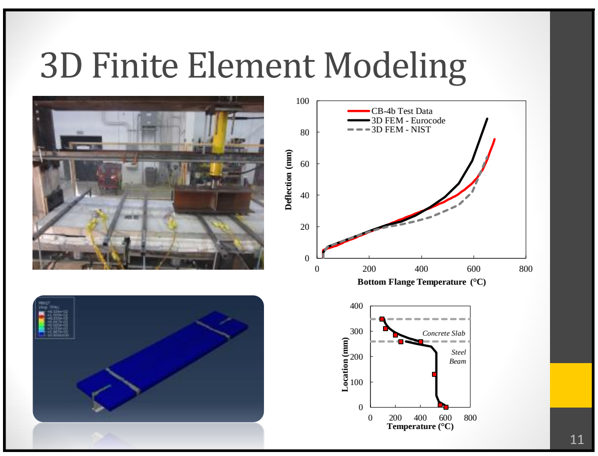
Specimen	Connection	Testing Protocol	Max. Steel Temperature
CB-A	Shear Tab	(1) Load to failure at ambient	N/A
CB-1	Double-angle, all-bolted	(1) Heat to 550°C (2) Cool (3) Load to failure at ambient	550°C
CB-2	Double-angle all-bolted	(1) Heat to 500°C (2) Load to failure	500°C
CB-3	Shear Tab	(1) Load to 156kN (35kip) (2) Heat to 600°C (3) Cool	600°C
CB-4	Shear Tab	(1) Load to 111kN (25kip) (2) Heat to 700°C (3) Cool	700°C

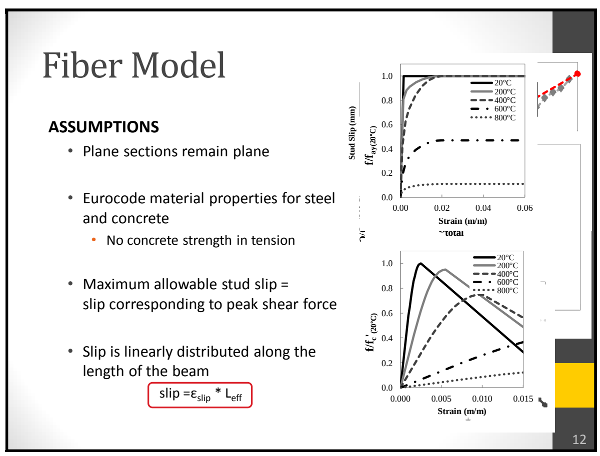

Experimental Testing
CB-3:
• Apply service level load (60% of nominal ambient capacity)
• Heat steel and concrete until steel temperature of 600°C
• Cool at 12°C/min
Fracture at Weld
Shear Tab
CB3
Load (kN)
Midspan Displacement (mm)
Max. = 75mm
Midspan Displacement (mm)
Avg. Bottom Flange Temperature (°C)
7


Modeling
3D Finite Element Model (Abaqus)
Fiber-based Model (Matlab)
Concrete Slab
Shear Studs
Steel Beam
ΔT
Moment (kN-m)
Curvature (1/m)
8


3D Finite Element Modeling
Temperature dependent material properties - Eurocode[1]
Eurocode[1] - Steel
NIST[2] - Steel
20°C
200°C
400°C
600°C
800°C
Strain (m/m)
[1] European Committee for Standardization (CEN). Eurocode 4: Design of composite steel and concrete structures, Part 1.2: General Rules - Structural Fire Design. Brussels, Belgium, 2005.
[2] L.T. Phan, T.P. McAllister, J.L. Gross, and M.J. Hurley: "Best practice guidelines for structural fire resistance design of concrete and steel buildings," National Institute of Standards and Technology (NIST), 2010.
9


3D Finite Element Modeling
Force-Slip Behavior for Shear Studs (Zhao and Kruppa[1]):
Slip (mm)
Headed studs with flat concrete slab
Headed studs with perpendicular deck
[1] Zhao, B. and Kruppa, J. (1997), "Fire resistance of composite slabs with profiled steel sheet and of composite steel concrete beams Part 2: Composite Beams." Final Report, ECSC – Contract No. 7210 SA 509, CTICM, France.
10

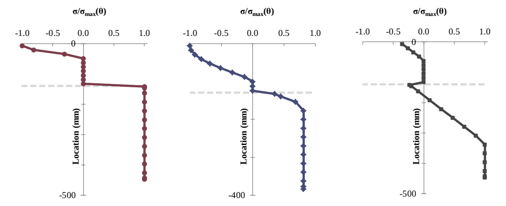

3D Finite Element Modeling
CB-4b Test Data
3D FEM - Eurocode
3D FEM - NIST
Deflection (mm)
Bottom Flange Temperature (°C)
Location (mm)
Concrete Slab
Steel Beam
Temperature (°C)
11


Fiber Model
ASSUMPTIONS
• Plane sections remain plane
• Eurocode material properties for steel and concrete
• No concrete strength in tension
• Maximum allowable stud slip = slip corresponding to peak shear force
• Slip is linearly distributed along the length of the beam
slip = $\varepsilon_{slip} * L_{eff}$
Strain (m/m)
12

Fiber Model

FAILURE MODES

Full Yielding of Steel Beam	Concrete Crushing	Stud Fracture



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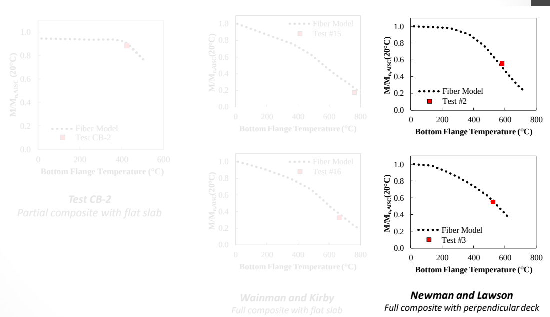
Fiber Model

BENCHMARKED EXAMPLES



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Parametric Study

GOAL

Determine how the flexural capacity changes with:

- Percentage composite action
- Deck type and orientation
- Thermal gradient
- Cross-section geometry
- Beam length

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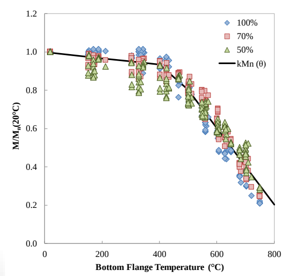
Design Equation

Flat Slab

$M_n(\theta) = k_{Mn}(\theta)^* M_{n,AISC}$



Bottom Flange Temperature (°C)	Flat Slab $k_{Mn}(\theta)$
20	1.00
100	0.98
200	0.97
300	0.95
400	0.93
500	0.80
600	0.60
700	0.40
800	0.20

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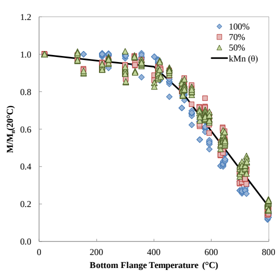
Design Equation

Perpendicular Deck

$M_n(\theta) = k_{Mn}(\theta)^* M_{n,AISC}$



Bottom Flange Temperature (°C)	Perpendicular Deck $k_{Mn}(\theta)$
20	1.00
100	0.98
200	0.97
300	0.95
400	0.93
500	0.79
600	0.59
700	0.39
800	0.18
900	0.09

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Conclusions

(6.) Parametric study conducted to investigate influence of geometry, level of composite action, and thermal gradient

- There is a complex inter-relationship between stud slip capacity, beam length, and level of composite action.

- Temp... was dev... design moment capacity
- Based upon steel beam bottom flange temperature
- Simple method that does not require extensive thermal and structural analysis

composite beam approaches that of an equivalent fully composite beam.

(5.) Fiber model is capable of predicting elevated temperature moment capacity and failure mode of composite beam cross-section

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Recommendations for Future Work

1) **Experimental testing with steel profiled deck**

2) **Experimental investigations focusing on long beams with low levels of composite action at high temperatures**

3) **Behavior of connections during both heating and cooling**
   - Experimental testing
   - Incorporate into modeling

4) **Post-heating capacity: material properties and behavior of structural members and systems**

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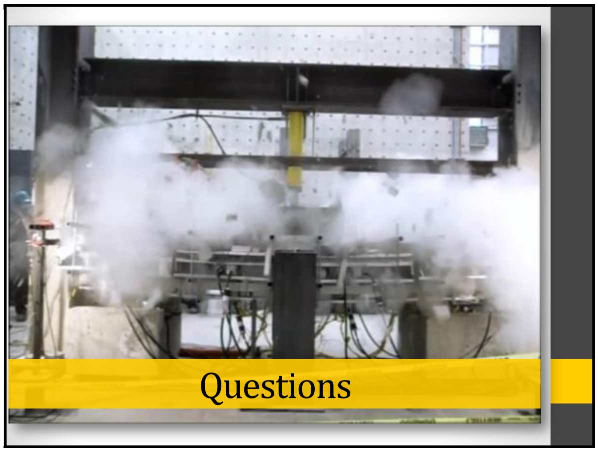


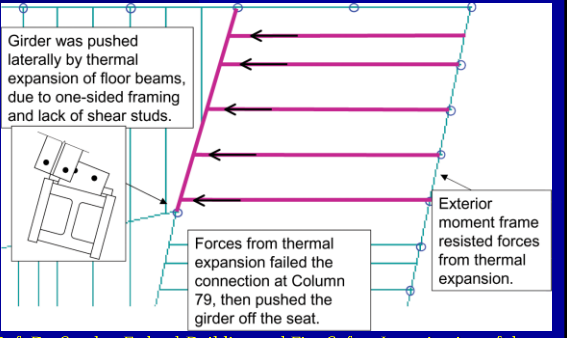
March 16-18, 2015 NIST
Operational Tomodachi Fire Research Meeting

A Simple Model for Fire Resistance of Steel Beams under Non-Uniform Temperature

Takeo Hirashima

Division of Architecture and Urban Science,
Graduate School of Engineering,
Chiba University, Japan

Thermal Response of WTC 7 in Fire



Ref. Dr. Sunder, Federal Building and Fire Safety Investigation of the World Trade Center Disaster, Slide 33, NIST 2008

Performance Based Design of Structures in Fire

Knowledge of the structural fire behaviour

Behavior of simple supported elements from standard fire resistance tests

/ Performance of fire protection
/ Resistance of the element in fire

⬇

Global behavior of a structural frame exposed to compartment fire

/ Thermal stress and deformation
/ Behaviour of the connection, *etc.*

Fire resistant design for steel structures in Japan

Design factors of Heating
Fire Room, protection, section,

Design factors of Mechanics
Span, Steel-grade, section, load

Thermal analysis
Thermal action
Heat transfer

Mechanical analysis
on the basis of
limit state design

Steel temp.(max.)

Critical temp.(load=resistance)

Steel temp. < Critical temp.

No

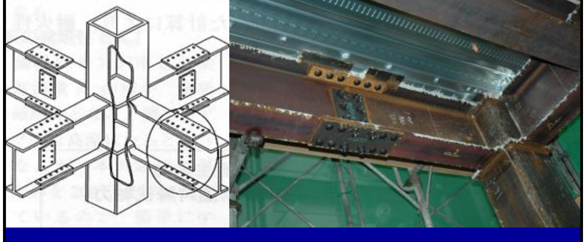
No

Yes

END

Ref. : Recommendation of Architect Institute of Japan

Moment-Resisting Beam-Splice Connections



BSC (Beam-Splice Connections) have:
/ larger resistance (than the connected beam).
/ larger heat capacity (than the other connections).

Agenda

Today's Theme:
The behaviour and simple modelling of Steel Beams with Beam-Splice Connections in Fire

1) Temp. Distribution of Steel Beams

2) Ductility of the Connection

3) Approximation for the Fire Resistance

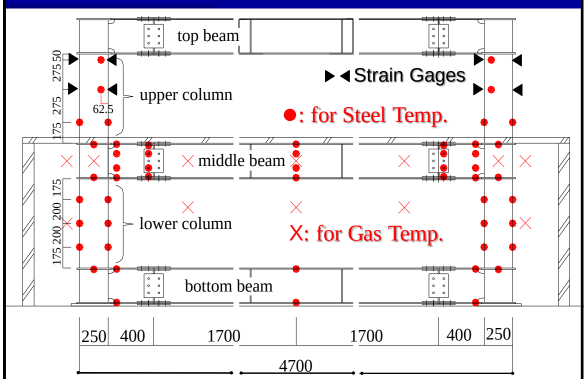
Topic 1

Temperature Distribution of Steel Beams

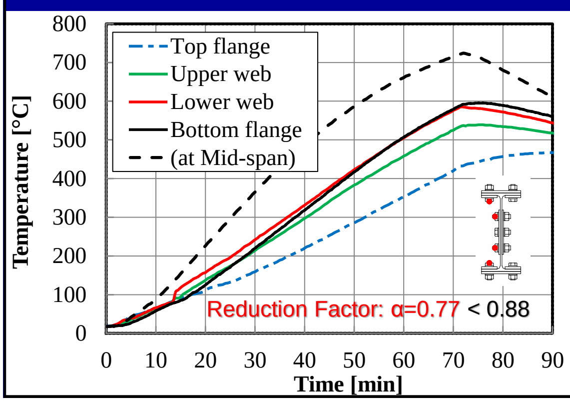
Ref.
Hirashima *et al*, An Experimental Investigation of Structural Fire Behaviour of a Rigid Steel Frame, 11th IAFSS Symposium, 2014

Fire Resistance Test of a Steel Rigid Frame

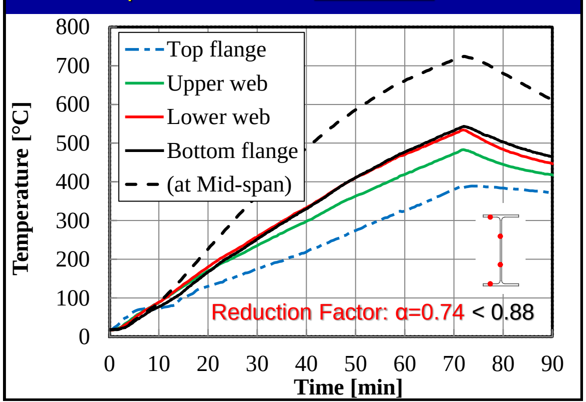
Arrangement of Thermocouples



Temperatures at the Beam-Splice Connection



Steel Temperatures at the Beam End



Summery 1

Temperature Distribution of Steel Beams

Temperature is considerably lower for beam ends than for mid-span of beam.

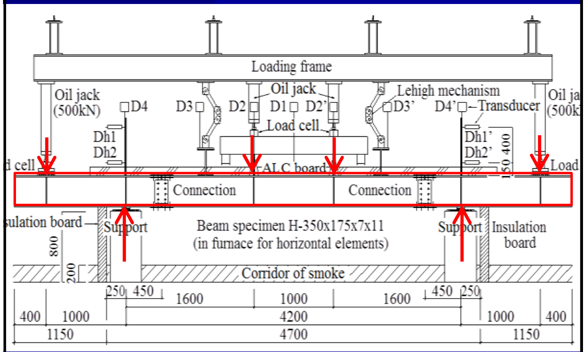
The temperature reduction factor of beam-splice connections is quite lower than the Eurocode's value.

Topic 2

Ductility of the Connection

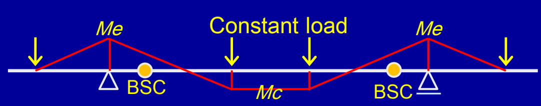
Ref.
Hirashima *et al*, The Behaviour of Steel Beams with Moment-Resisting Beam-Splice Connections in Fire, SiF 2012
Hirashima *et al*, Load-Deformation Behaviour of Bolted Double-Splice Friction Joint at Elevated Temperature, SiF 2014

Setup of the load-bearing fire tests

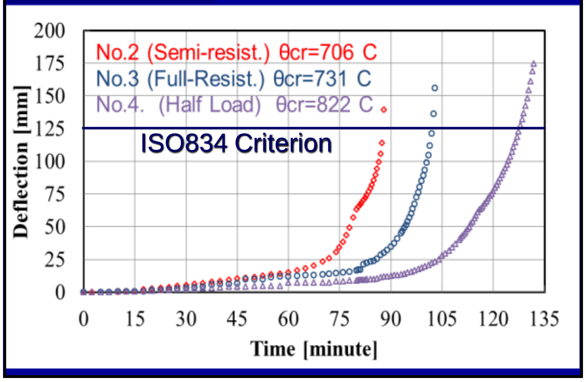


The test parameters

Specimen	Connections (BSC)	Constant load ratio
No. 2	Semi-resist. , 0.73	$\dfrac{Mc+Me}{2Mp}=0.48$
No. 3	Fully-resist.	
No. 4	$jMu/Mp=1.18$	0.24

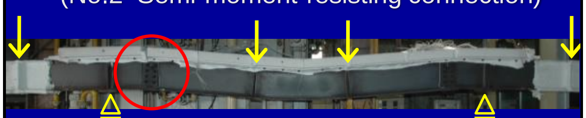


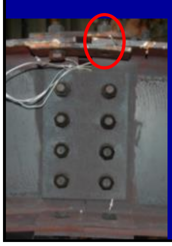
Deflection at the mid-span of beams



Deformation of the beam with BSC

(No.2 Semi-moment-resisting connection)



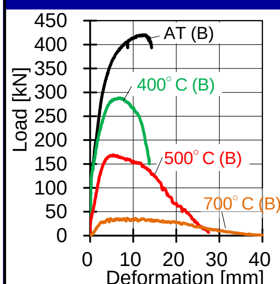


/ Bending deflection

/ Large rotation at the connections

/ Bolts failed (through the top-flange)
This Bolt Temp.≒500℃

Effect of temperature on the ductility



Thick-plate specimen (t=19 mm, e/d=2.5)

Brittle failure (AT)

Ductile failure (500˚C)

Summery 2

Ductility of the Connection

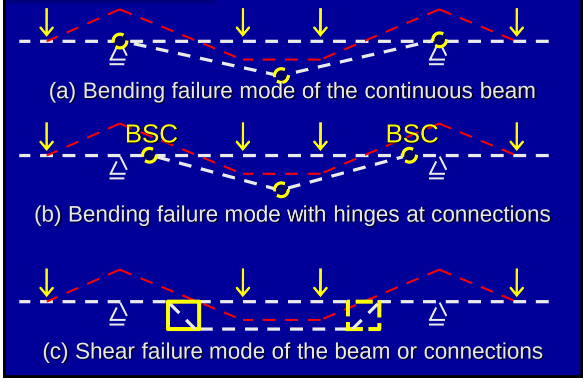
The beam-splice connection had load carrying capacity up to ISO 834 criterion.

The deformation capacity of the connections is considerably improved in case of the fire situation.

Topic 3

Approximation method for the Fire Resistance

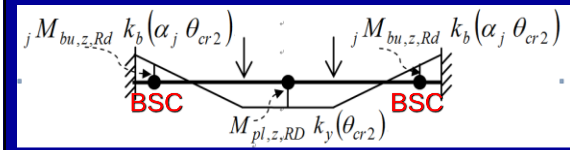
Simple plastic collapse model



Equation of the critical temperature

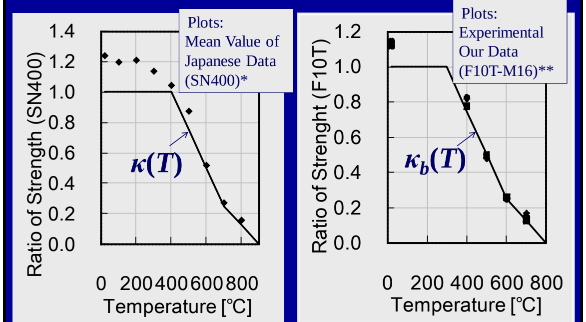
$$ {}_jM_{z,\,ft,\,Ed} = M_{pl,\,z,\,Rd}\,k_y(\theta_{cr2}) + {}_jM_{bu,\,z,\,Rd}\,k_b(\alpha_j\,\theta_{cr2}) $$

Effect = Resistance at elevated temperature



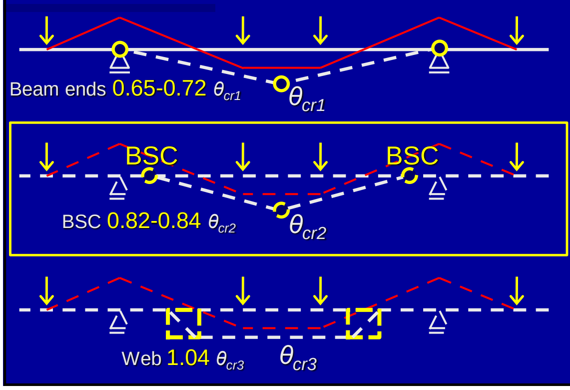
(b) Bending failure mode with hinges at connections

Strength reduction factors of steel and bolt



SN400 Steel (I-Beam) F10T Bolt (Joint)

Temperature reduction factors



Validity of the approximation method

Specimen	Test	Calculation
2. Semi-Resist.	706°C	681°C
3. Full-Resist.	731°C	731°C
4. Full-Resist. (Half Load)	822°C	826°C

The critical temperatures are the mean temperatures at the mid-span of the beams at the fire limit state.

Conclusions

1) The temperature reduction factor of beam-splice connections is quite lower than the Eurocode's value.
2) The ductility of the beam-splice connections is improved in case of the fire situation.
3) The critical temperature for the steel beam with BSC can be approximated on the basis of simple plastic collapse design method.

Thank you very much

for your kind attention.

Post-Earthquake Fire Performance of Buildings: Full-Scale Test Outcomes and Suggestions for Performance-Based Design

Brian Meacham, PhD, PE, FSFPE
WPI Department of Fire Protection Engineering

NIST Workshop: Operation Tomodachi
Gaithersburg, MD, 17 March 2015

BNCS Project

- Full-Scale Structural and Nonstructural Building System Performance during Earthquakes & Post-Earthquake Fire (http://bncs.ucsd.edu/index.html)
- US$5 Million academe/government/industry effort
- Reports on building design, seismic tests and outcomes, and link to documentary video on BNCS site, and fire report on WPI website (http://www.wpi.edu/academics/fpe/earthq90.htm)

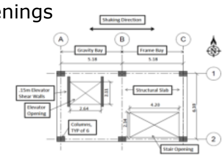
Test Site

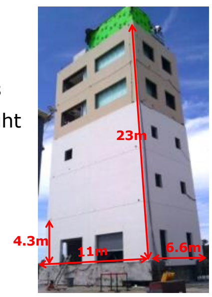
- Englekirk Structural Engineering Center, University of California, San Diego
  - High performance outdoor shake table (LHPOST)

- Movement EW direction
- Peak acceleration of 4.2g
- Peak velocity of 1.8 m/s

Building structure

- Design
  - 5-story reinforced concrete
  - Six 66 cm by 46 cm columns
  - 4.3m deck-to-deck floor height
  - 0.2 m floor slabs with 2 openings





Architectural Components

- Façades
  - Balloon framing for floors 1-3
    - Vertical Metal Studs
    - Gypsum boards (fire-rated gypsum X panels for interior)
    - Exterior Insulation finishing system (EIFS)
  - Precast concrete cladding panels floors 4-5
    - 2 Panels on each side
- Window openings but no glazing system
- Façades

Space use

Floor 1

Floor 2

Floor 3

Floor 4

Floor 5

Roof

Architectural Components

- Ceilings
  - Different type of ceiling system at each floor
- Partition walls
  - Different configurations at each floor

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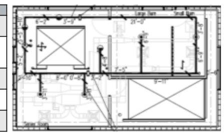
Fire Sprinkler System

- Charged wet pipe automatic sprinkler system
- Layout and components varied at each floor level

Level	Pipe	Sprinkler Head
Floor 1	3.8 cm (1 ½ in) Steel Schedule 10 main line 2.5 cm (1 in) Steel Schedule 40 branch line	4 Quick Response Pendent 3 Quick Response Upright
Floor 2	3.8 cm (1 ½ in) CPVC main line 2.5 cm (1 in) CPVC branch line	2 Quick Response Pendent 2 Quick Response Upright 2 Residential Concealed Pendent
Floor 3	3.8 cm (1 ½ in) Steel Schedule 10 main line 2.5 cm (1 in) Steel Schedule 40 branch line	4 Quick Response Pendent 3 Quick Response Upright
Floor 4	3.8 cm (1 ½ in) Steel Schedule 10 main line 2.5 cm (1 in) Steel Schedule 40 branch line	3 Quick Response Pendent 3 Quick Response Upright
Floor 5	3.8 cm (1 ½ in) Steel Schedule 10 main line 2.5 cm (1 in) Steel Schedule 40 branch line	4 Quick Response Pendent 3 Quick Response Upright



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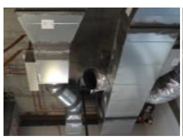
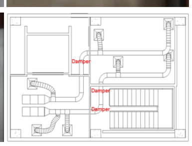
MEP Components

- HVAC ductwork
- Flexible Duct connections between ducts and diffusers
- Duct connections firestopped with fire caulk
- 3 fire and smoke dampers





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Egress Systems

- Fully functioning elevator
- Pre-fabricated metal stairs

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Burn Compartments

- Four compartments on Floor 3: Large Burn Room (LBR), Small Burn Room (SBR), Elevator Shaft (ES) and Elevator Lobby (EL)
- 1-hr fire rated drywall grid ceiling system Type-X gypsum tiles (only in LBR, SBR and EL)
- Interior walls: Type-X gypsum board on steel studs

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Additional Fire Protection Features

- Various fire protection systems installed on Floor 3

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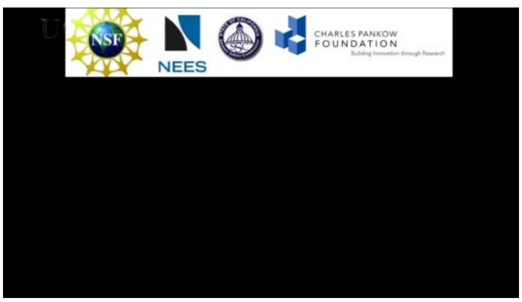
Ground Motion Tests (13)

Date	Name	Seismic Motion
April 16, 2012	BI-1: CNP 100	Canoga Park 1994 Northridge Earthquake
	BI-2: LAC 100	LA City Terrace 1994 Northridge Earthquake
April 17, 2012	BI-3: LAC 100	LA City Terrace 1994 Northridge Earthquake
	BI-4: SP 100	San Pedro 2010 Maule (Chile) Earthquake

Date	Name	Seismic Motion
May 7, 2012	FB-1: CNP 100	Canoga Park 1994 Northridge Earthquake
May 9, 2012	FB-2: LAC 100	LA City Terrace 1994 Northridge Earthquake
	FB-3: ICA 50	2007 Pisco (Peru) Earthquake
May 11, 2012	FB-4: ICA 100	2007 Pisco (Peru) Earthquake
May 15, 2012	FB-5: DEN 67	Pump Station #9 2002 Denali Earthquake
	FB-6: DEN 100	Pump Station #9 2002 Denali Earthquake

Ground Motion Tests

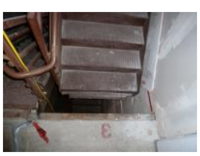
Ground Motion Tests

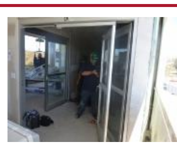


Contents / Potential Fuels



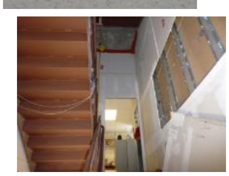
Access / Egress System






Structure / Compartmentation



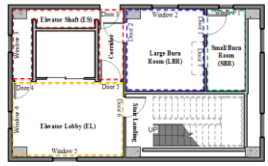


Fire Tests

- Fire Test Objectives
  - Assess fire and smoke spread in earthquake damaged building
  - Assess the performance of fire safety systems in post-earthquake fire conditions
  - Obtain temperature data for post-earthquake fire modeling studies
  - Develop a guidance for post-earthquake design fire scenarios

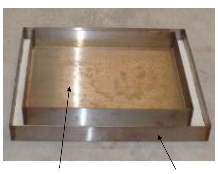
Fire Test Schedule

Date	Sequence
May 23, 2012	1. LBR-1
	2. SBR
May 24, 2012	3. LBR-2
	4. ES
May 25, 2012	5. EL-1
	6. EL-2

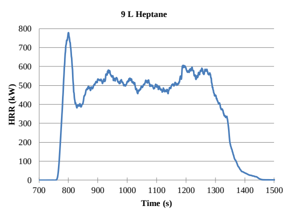


- Heptane as fire source
- Burn time < 15 minutes
- Peak HRR ranges 500 kW ~ 2MW
  - Multiple small pans for fuel spread conditions
  - By changing the number of pans

Heptane Pan Fire Design

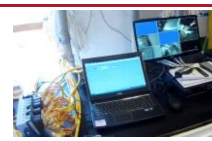


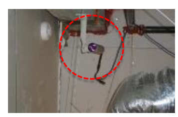
Heptane pan (0.6 m×0.4 m) Retention pan (water)



Fire Test Instrumentation

- DAQ system on Floor 2
- Thermocouples to obtain temperatures
- Video cameras to obtain visual data





Fire Test

LBR-2 fire and sprinkler activation

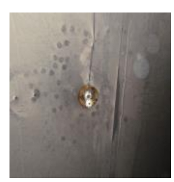
LBR-2 north exterior view

EL-1 fire and sprinkler activation

EL-1 south west exterior view

Sprinkler / Fire Door Performance

- Automatic sprinkler system and fire door were not damaged during motion tests
- These systems activated as expected during fire tests



Compartmentation Performance

- About 2.5 cm gap formed along joint between LBR and SBR partition wall
- Flame extension observed through the gap during LBR-2 fire test

Compartmentation Performance


Intumescing of fire stop

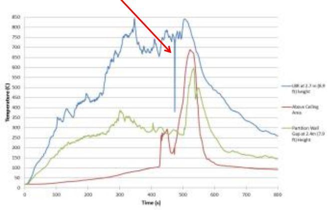
With the damage to the gypsum wall system due to ground motion, the fire was able to bring the system to failure much more quickly than any fire rating might suggest


Spalling of concrete slab


Failure of wall system

Compartmentation Performance

Failure of HVAC ducting allowing hot gases in space above ceiling (not fully fire rated system)

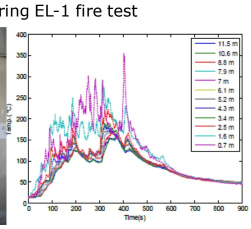


Compartmentation Performance

- EIFS installed as part of balloon framing façade
- Flame extension through window openings during LBR-2, EL-1 and EL-2 fire tests burned the insulating material
- Significant smoke spread through balloon framing

Fire and Smoke Spread

- Fire and smoke spread through the elevator shaft observed during EL-1 and EL-2 fire test
- Temperatures in the range of 250 C and 300 C were recorded in the elevator shaft during EL-1 fire test



Structural Performance

- Structural damage occurred in joint areas on Floor 2 during the seismic tests
  - Beam-column connection steel rebars exposed with loss of concrete cover due to hinge motion

Summary

- Post-earthquake building fire performance / risk not well characterized and perhaps not well addressed in building design / retrofit
- Recent testing indicates some systems work well, while others do not, but more data needed
- A risk-informed approach to fire scenario development and performance assessment of earthquake prone buildings is needed

Acknowledgements

- Dr. Haejun PARK and Mr. Jin-Kyung KIM for their significant efforts on the fire-related test and instrumentation planning, data collection and analysis for this project, and Mr. A.J. Campenella for help on the test site

Acknowledgements

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  - California Seismic Safety Commission
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  - Englekirk Advisory Board
  - Federal Emergency Management Agency
  - National Science Foundation
  - Network for Earthquake Engineering Simulation
- Fire Test Facilitators
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Thank You!

bmeacham@wpi.edu

BNCS Project Site:
http://bncs.ucsd.edu/index.html

Experimental Study on Fire Resistance of Mid-rise Steel Construction Exposed to Post-earthquake Fire

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1

Introduction

Earthquakes happen often in Japan.

Building safety Inspection
- ➢Postearthquake Quick Inspection of Damaged Buildings
- ➢Certificate of Misfortune Disaster
- ➢Postearthquake Damage Evaluation

These are mainly on the point of structural safety.

What about fire safety ?
- just after earthquake ,
- to keep on using the building.

➡ Structure and compartmentation

NILIM : research project (FY2009-2011)

2

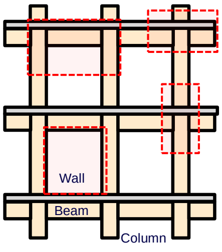
Introduction

- Steel structure : Damage of fire protective covering by earthquake is important.

  Cf. Reinforced concrete structure

Fire tests (4 series) to clarify fire performance supposing damage by earthquake.

- ☐ Column (Load bearing capacity)
- ☐ Beam (Load bearing capacity)
- ☐ Wall (Insulation and Integrity)
- ☐ Column-Beam-Wall



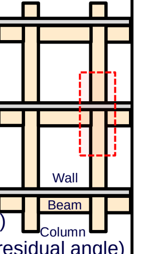
3

Fire Test : Column

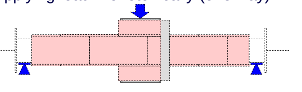
- ◆ Supposing 4m floor height
- ◆ Steel frame

  Column:Square Steel Box（500×500×25mm）

  Beam：H-steel（700×400×16×28mm）
- ◆ Fire protective covering (rating 2 hours fire-resistive construction)
  - ・Rockwool (45mm）
  - ・Fibre reinforced calcium silicate board (35mm)
  - ・High temperature insulation ceramic felt(40mm)
- ◆ Horizontal load: Story drift angle 1/100 (targeted residual angle)



Applying load monotonically (one way)



4

Fire Test : Column

- BRI Structure testing machine capable of 10 GN

5

Fire Test : Column

- Fibre reinforced calcium silicate board (35mm) 1.7 GN

- High temperature insulation ceramic felt(40mm) 1.8 GN
- Rockwool (45mm）2.1 GN

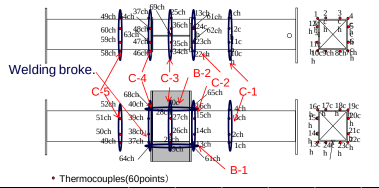
6

Fire Test : Column

·

7

Fire Test : Column



• Thermocouples(60points)

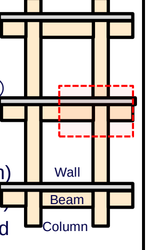
Column	Story drift angle	Time to 350 C of average temperature							Heating (min)
		C−1	C−2	C−3	C−4	C−5	B−1	B−2	
Felt(40mm)	0	168.5	219	191	167	159.5	167	165.5	240
	1/100	169.5	215.5	188	167.5	160	150	162	225
	Ratio	1.01	0.98	0.98	1.00	1.00	0.90	0.98	
Cal. Sil. Board (35mm)	0	166	231	213	222	215.5	212	217	260
	1/100	225	285.5	248.5	236.5	220.5	231	254	330
	Ratio	1.01	0.98	0.98	1.00	1.00	0.90	0.98	
Rockwool(45mm)	0	219.5	236	225.5	224	229.5	212.25	207	287
	1/100	219	241.75	209	193.25	210.5	199.75	203.25	265
	Ratio	1.00	1.02	0.93	0.86	0.92	0.94	0.98	

14% of fire resistance time shortened at the part fire protective covering broke for Rockwool.

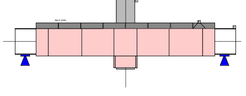
8

Fire Test : Beam

- Supposing 4m floor height
- Steel frame
  - Column:Square Steel Box（500×500×25mm）
  - Beam：H-steel（700×400×16×28mm）
- Fire protective covering (rating 2 hours fire-resistive construction)
  - ･Rockwool (45mm)
  - ･Fibre reinforced calcium silicate board (35mm)
- Horizontal load: Story drift angle 1/100 (targeted residual angle)



Applying load monotonically (one way)



9

Fire Test : Beam

- BRI Structure testing machine capable of 10 GN

10

Fire Test : Beam

Fibre reinforced calcium silicate board (35mm) 1.9 GN

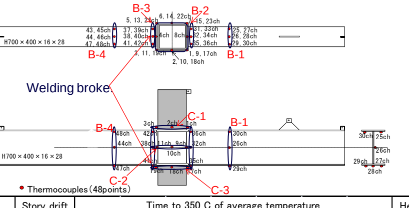
3mm wide crack

Rockwool (45mm) 1.8 GN

9mm wide crack (the maximum)

11

Fire Test : Beam



• Thermocouples (48points)

Beam	Story drift angle	Time to 350 C of average temperature							Heating (min)
		C−1	C−2	C−3	B−1	B−2	B−3	B−4	
Cal. Sil. Board (35mm)	0	–	268.75	241.25	173.25	245.75	249.75	181	288
	1/100	–	244.75	230.75	172.75	241.75	193.75	137.5	288
	Ratio	–	0.91	0.96	1.00	0.98	0.78	0.76	
Rockwool(45mm)	0	–	222.75	217.75	143.00	206.25	215.00	149.25	320
	1/100	–	241.5	220	145	205.5	211.5	149.5	227
	Ratio	–	1.08	1.01	1.01	1.00	0.98	1.00	

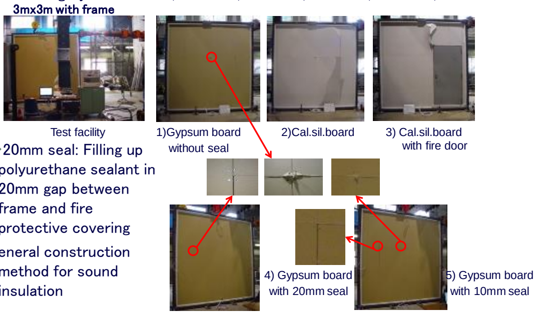
25% of fire resistance time shortened at the part where fire protective covering of fibre reinforced calcium silicate board broke.

12

Fire Test : Wall

- Horizontal load: Story drift angle 1/100 (targeted residual angle)
- Loading cycle：+-1／600, +-1／300, +-1／150, +-1／120, +-1／100, +-1／75

3mx3m with frame



Test facility

1)Gypsum board without seal

2)Cal.sil.board

3) Cal.sil.board with fire door

4) Gypsum board with 20mm seal

5) Gypsum board with 10mm seal

- 20mm seal: Filling up polyurethane sealant in 20mm gap between frame and fire protective covering

General construction method for sound insulation

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Fire Test : Wall

6) Gypsum board with 10mm seal with Story drift angle of 1/100

Fire protective covering		Story drift angle	Heating (min)	Fire resistance (min)	Ratio	Performance	Part
Gypsum board 12.5mm+12.5mm		0	74'00"	72'00"	1.0	Insulation	Center of wall
		1/100	65'00"	63'00"	0.875	Insulation	Center of wall
Cal.Sil.board 8mm+8mm		0	60'00"	60'00"	1.0	Insulation	Center of wall
		1/100	43'00"	27'30"	0.458	Insulation	Center of wall
Cal.Sil.board with fire door	Wall	0	75'00"	28'00"	1.0	Integrity	Upper frame
	Door		75'00"	53'00"	1.0	Integrity	Lower frame around door
	Wall	1/100	41'00"	20'00"	0.714	Integrity	Lower frame around door
	Door		41'00"	40'30"	0.764	Integrity	On the door
Gypsum board with 10mm seal 12.5mm+12.5mm		0	62'00"	41'30"	0.576	Integrity	Center of wall
		1/100	55'00"	53'50"	0.748	Integrity	Lower frame
Gypsum board with 20mm seal 12.5mm+12.5mm		0	66'00"	60'00"	0.833	Integrity	Center of wall
		1/100	54'00"	44'30"	0.618	Integrity	Center of wall

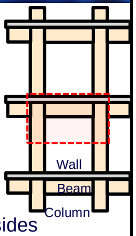
Gap between frame and fire protective covering occurred to fail the integrity.

Filling up polyurethane sealant seemed to decrease fire protective covering defect, but it did not contribute fire resistance time.

14

Fire Test : Column-Beam-Wall

- Supposing 4m floor height
- Steel frame
  - Column:Square Steel Box（300×300×12mm）
  - Beam：H-steel（294×200×8×12mm）
- Fire protective covering (rating 1 hour fire-resistive construction)
  - ・Calcium silicate board (15mm+Spacer 40mm)
- Wall : Gypsum board 12.5mm+12.5mm for both sides
  - Light gauge metal stud frame WS-65, WR-65 (0.8mm)
- Horizontal load: Story drift angle 1/100 (targeted residual angle)
- Loading cycle：+-1／600, +-1／300, +-1／150, +-1／120, +-1／100, +-1／75



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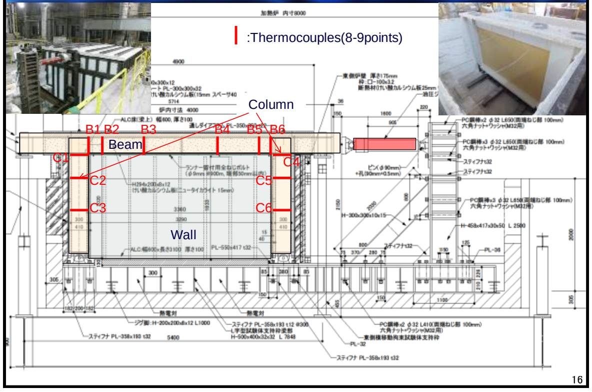
Fire Test : Column-Beam-Wall



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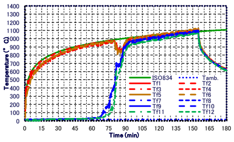
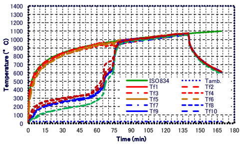
Fire Test : Column-Beam-Wall

Gap between wall and beam at 48 minutes after heating with story drift angle of 0

30mm Gap between wall and column before heating with story drift angle of 1/100





Compartmentation can not be expected with both story drift angle.

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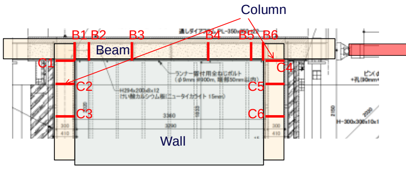
Fire Test : Column-Beam-Wall



Beam and Column	Story drift angle	Time to 350 C of average temperature												Heating (min)
		C-1	C-2	C-3	C-4	C-5	C-6	B-1	B-2	B-3	B-4	B-5	B-6	
Cal. Sil. Board (15mm)	0	100.5	103	99.75	102	102.3	113.8	91.75	92.5	96.25	104.8	101.3	104.8	155
	1/100	60	79.25	86.5	87	82	59.25	59.25	59.5	71.5	57.25	53	57.25	140
	Ratio	0.60	0.77	0.87	0.85	0.80	0.52	0.65	0.64	0.74	0.55	0.52	0.55	

40-50% of fire resistance time of beam and column shortened by wall with story drift angle of 1/100.

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Conclusion

- 14 % of fire resistance time of column without adjacent wall shortened at the part fire protective covering broke.
- 25% of fire resistance time shortened at the part where fire protective covering of fibre reinforced calcium silicate board of beam without adjacent wall broke.
- 40-50% of fire resistance time of beam and column shortened by adjacent wall intervention with story drift angle of 1/100.

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Nilim starts new research from April about post-earthquake fire for three years.

Thank you

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Observations from the May 13, 2008 Fire and Collapse of the Faculty of Architecture Building – Delft University of Technology

Michael D. Engelhardt
The University of Texas at Austin

Brian Meacham
Worchester Polytechnic Institute

Venkatesh Kodur
Michigan State University

1

Research Team

- University of Texas at Austin - Michael Engelhardt
  - Adam Kirk (now with Leslie E. Roberston)
- Worcester Polytechnic Institute - Brian Meacham
- Michigan State University - Venkatesh Kodur
- TNO
  - IJsbrand van Straalen
  - Johan Maljaars
- Efectis Netherlands
  - René de Feijter
  - Kees Both (now with Promat International, Belgium)
- Efectis France - Daniel Joyeux
- TU Delft Faculty of Architecture - Kees Van Weeren

Funding for US Team: National Science Foundation

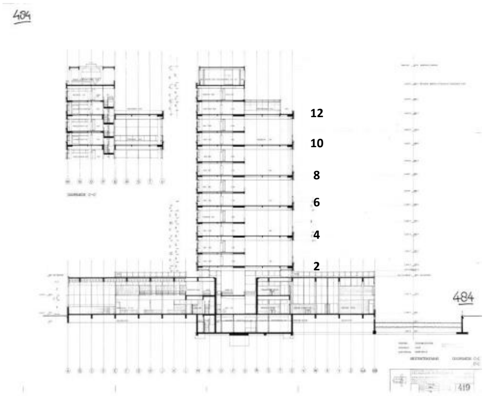
Objectives

- Collect information and data that will contribute to the investigation of the May 13, 2008 fire at the Faculty of Architecture Building at the Delft University of Technology.
- Conduct preliminary analysis of structural response.

Overview of "Faculty of Architecture" Building ("Bouwkunde")

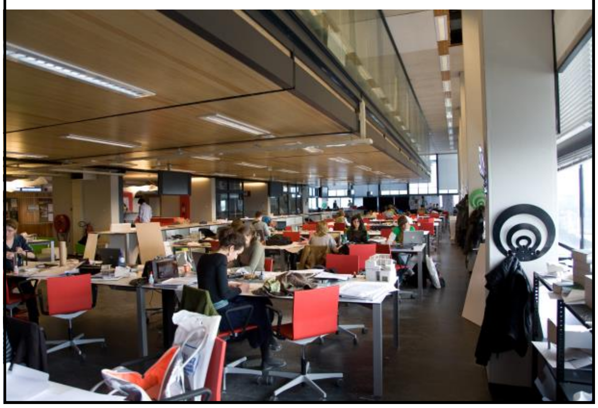
- Location: Delft University of Technology (TU Delft); Delft, Netherlands
- Constructed ~ 1970
- Building houses Architecture School (Faculty of Architecture) at TU Delft
- Building is ~ 14 stories in height; reinforced concrete construction
- Building destroyed by fire on May 13, 2008

The building just as it was completed | J.H. van den Broek (1898-1978)

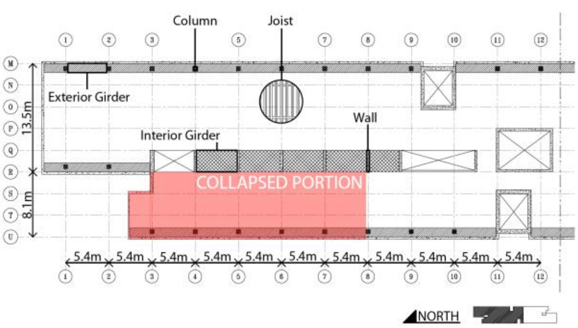


Building Fire Safety Systems

- No automatic sprinkler system
- Fire rated barriers
- Manual fire extinguishers and fire hoses
- Fire alarms
- Trained students and staff

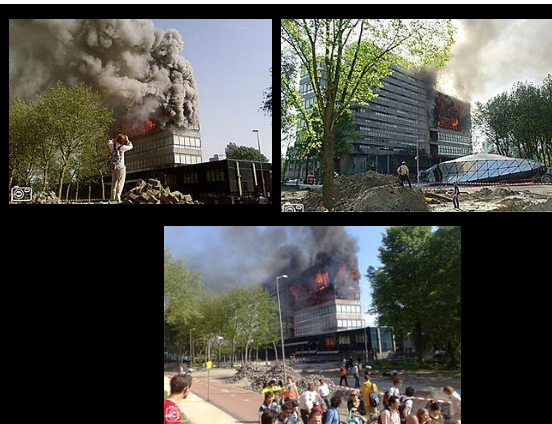


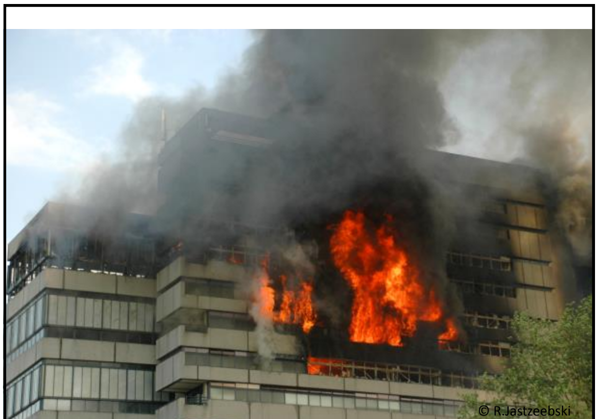
Building Structural System



<u>Fire on May 13, 2008</u>

- **Point of origin and cause:**
  - **6th Floor - Southwest Wing**
  - **Coffee vending machine malfunction due to water leak from above**
- **Fire initiation: ~ 9 am**
- **Fire spread vertically and horizontally from compartment of origin for next several hours**
- **Collapse of northwest wing of building ~ 4 pm**





Data Collection Effort

- More than 3000 photos of building before, during and after fire.
- Nearly complete set of original design drawings and calculations.
- Material data for first item burning and adjacent materials.
- Interviews with eye witnesses, fire fighters, and building staff.

Preliminary Investigation of Structural Response

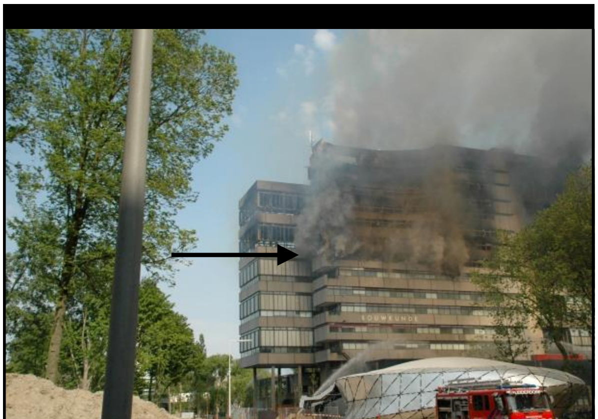
Objective: Develop initial simplified analysis of structural response to guide future detailed investigations.

Approach:

Detailed review and analysis of photographic evidence.

Detailed review of structural design drawings and calculations.

Simplified calculations of structural member response to fire.



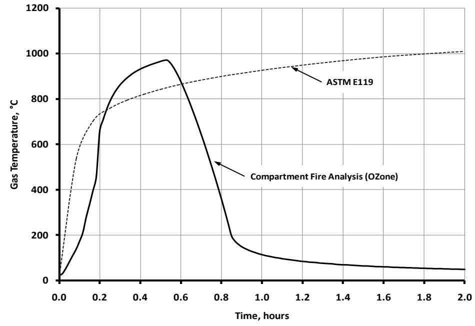
Approaches to Analysis of Structural Response to Fire

- Member Response
- System Level Response

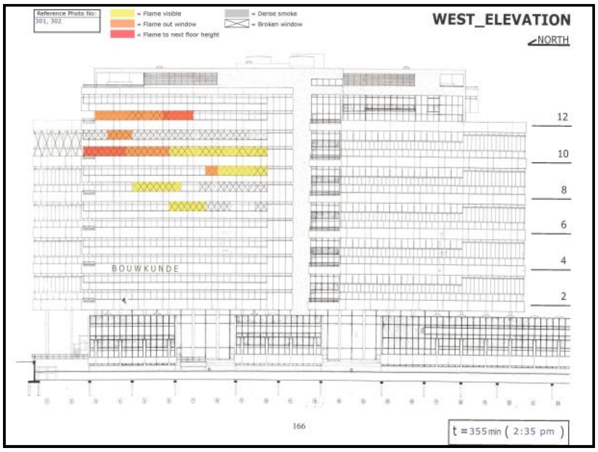
Approach to Member Level Response

- **Model Fire Environment**
- **Heat Transfer Analysis**
- **Structural Response Analysis**

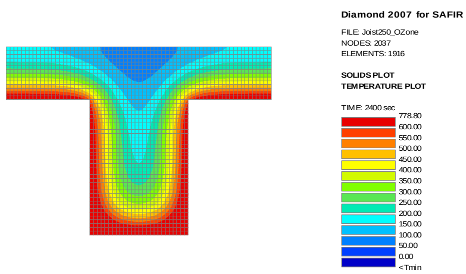
Modeling Fire Environment



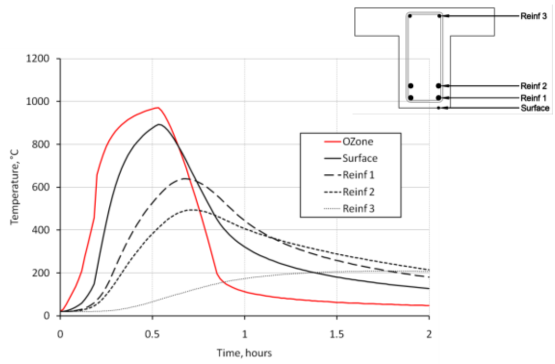
Compartment Fire Analysis

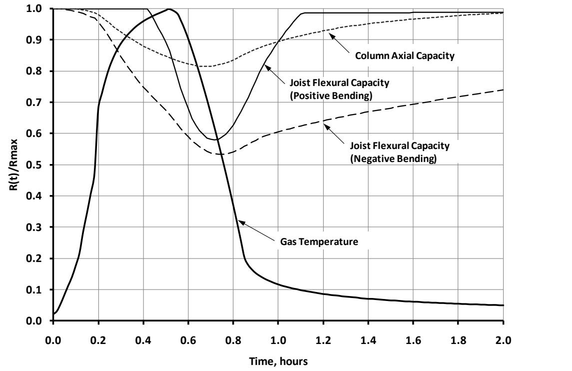


Heat Transfer Analysis



Heat Transfer Analysis – Reinforced Concrete Floor Joist – Faculty of Architecture Building, Delft – May 13, 2008 Fire
Time = 40 minutes

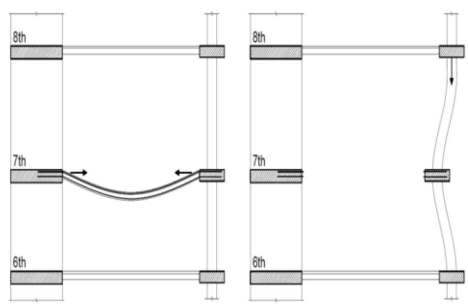




Normalized Cross-Sectional Capacity of Joist and Column during Fire Exposure

Effect of Spalling

Preliminary Collapse Hypothesis



Observations and Conclusions

- **Reinforced concrete buildings can collapse in fire.**
- **The presence of an automatic sprinkler system would likely have been very beneficial.**
- **Fire modeling for structural fire design requires better system-level tools.**
- **Predicting building structural response to fire requires system-level analysis.**
- **Spalling can have an important impact on the response of R/C structures to fire …… but is very difficult to predict and model.**

Observations and Conclusions

- **Understanding of structural response to fire can be greatly enhanced by studying actual fire events. More opportunities are needed.**

Structural Performance of Tunneling Shields in Fire

March 17, 2015

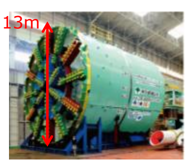
○Shigeaki BABA
Ken-ichi HORIGUCHI
Takamasa FUKUDA
Mitsuhiro SATO
(Taisei Corporation, Japan)

Contents

1.Outline of the Fire Performance in the Expressway Shinagawa Line Project

Outline of the Expressway Shinagawa Line Project

Shinagawa Line Route ground plan



Shield machine

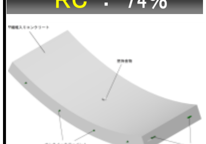
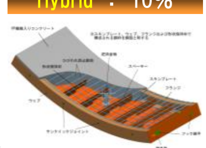
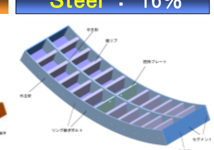
The shield tunnel inside

Outline of the Fire Proof Segment

- ◆ In the shield tunneling, there is the case that the secondary lining is omitted for the purpose of short duration and rationalization of construction.
- ◆ One of the major concerns of such shield segment is its fire resistance in this case because the shield segment is exposed to the high temperature of a fire.
- ◆ This "fire proof segment" is provided "fire proof band" which does not contribute to the strengths.
- ◆ This fire proof segment was applied in this project.

The percentage of the used segment

RC : 74%	Hybrid : 10%	Steel : 16%

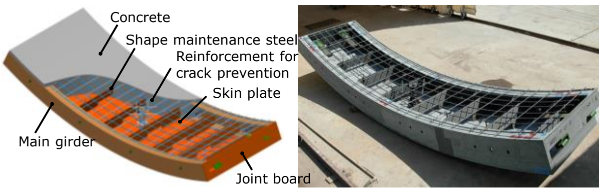




Cheap	Price	Expensive
Small	Strength	Large

- ◆ RC segment → The general part (stable foundation)
- ◆ Hybrid segment → Soft foundation and the heavy loading part
- ◆ Steel segment → Joint part in an entrance and exit

Outline of Hybrid Segment (HB segment)

- HB segment is a composite structure consisting of steel shell and concrete.
- Fire resistive performance is required.



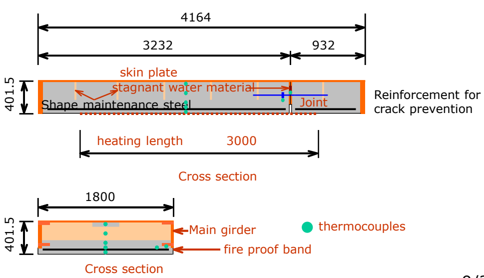
HB segment

the fire performance required in this project

- Don't cause remarkable degradation in fire
  - RABT Heating experiment
  - An explosive spalling of concrete doesn't occur.
  - The maximum temperatures of the steel and the rubber are within the target area.
- Possess the enough proof strength after fire
  - Load test using a specimen after heating experiment
  - The strength of the specimen after fire has to possess beyond the design strength.

Fire Resistance Test in Fire

- Concrete strength : 42 MPa
- Heating area : 3000mm x 1800 mm
- Height of specimen : 401.5mm
- Quantity of Polypropylene fiber : 0.2Vol% (1.82 kg/m^3)



Fire Resistance Test in Fire

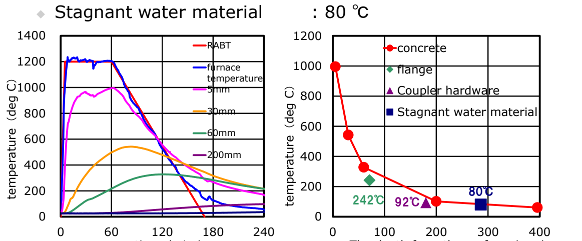
An explosion of concrete by heating has not found.

before heating after heating

RABT The test piece surface situation before and after heating.

Fire Resistance Test in Fire

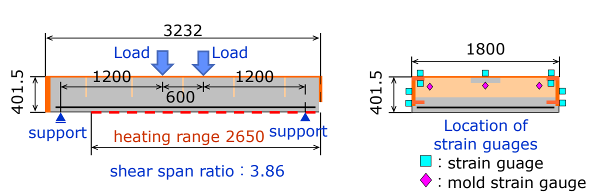
- Maximum Temperature Results
  - Concrete at 60mm : 350 ℃
  - Flange : 242 ℃
  - Coupler hardware : 92 ℃
  - Stagnant water material : 80 ℃



temperature in history Maximum temperature distribution

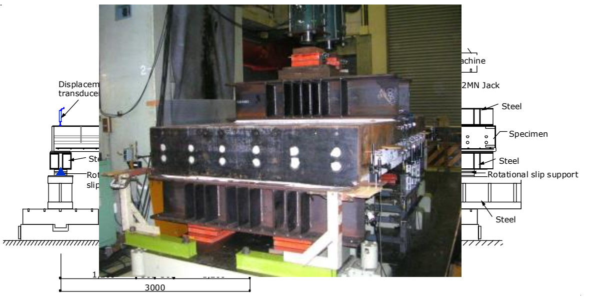
Structural Test after RABT Heating

- The specimen after fire was used.
- monotonously load for simple beam condition
- The span was 3m, shear span ratio is set as 3.86.
- The design strength value is 1257kN.



Structural test set-up after heating

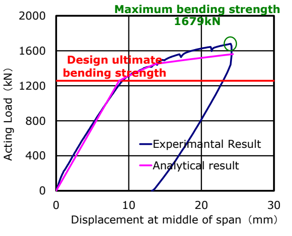
Structural Test after RABT Heating



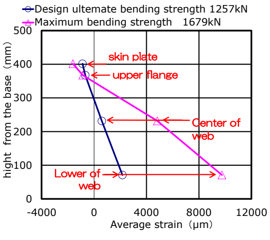
Structural test set-up after heating

Structural Test after RABT Heating

- This specimen possesses the enough proof strength to design strength.
- The bending strength of specimen after heating is investigated, and the comparison between the experimental test and numerical analysis showed that the numerical analysis was reliable to experimental result.



Load displacement relationship



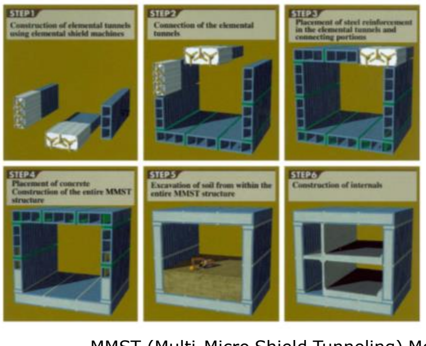
Strain distribution

Concluding Remarks

- A specimen for a full-scale shield segment was fabricated and fire-tested using the German RABT fire curve
- The specimen is made of high strength concrete mixed with organic fibers for the prevention of explosive spalling.
- Fire resistance test of shield segment was carried out, no spalling occurred and its internal and steel temperatures were clarified in this test.
- In addition, the bending strength of specimen after heating is investigated, and the comparison between the experimental test and numerical analysis showed that the numerical analysis was reliable to experimental result.

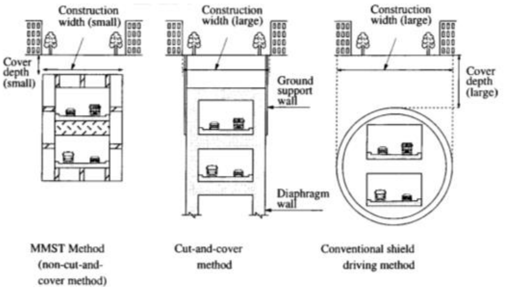
2.Outline of the Fire Performance in Multi-Micro Shield Tunneling (MMST) method

Outline of MMST Method



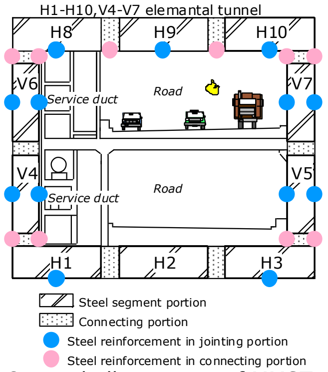
MMST (Multi-Micro Shield Tunneling) Method

Comparison of MMST method



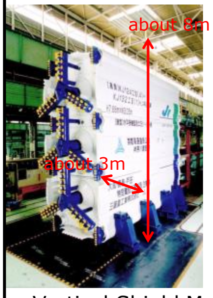
Comparison of MMST method with cut-and-cover and conventional shield tunneling methods

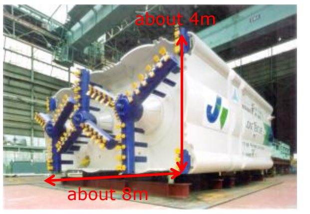
Outline of MMST Method



Outer shell structure of MMST

Shield machine of MMST



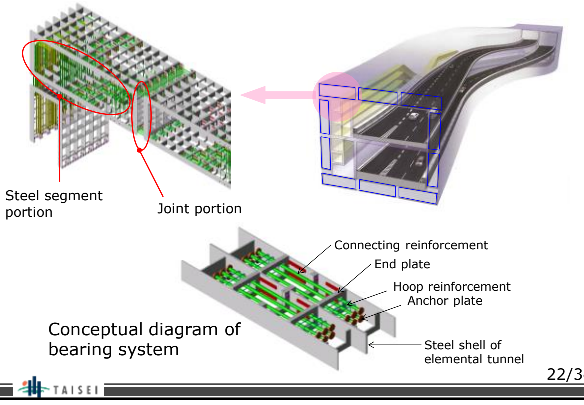


Vertical Shield Machines Horizontal Shield Machines

the fire performance required in MMST method

- Don't collapse joint in and after fire
  - An experiment using RABT Heating
  - Maintain the design load in fire.
  - The maximum load exceeds the structural strength under design after fire.
- Don't collapse MMST shell structure in and after fire
  - Finite element analysis carried out to understand maximum deformation and internal force.

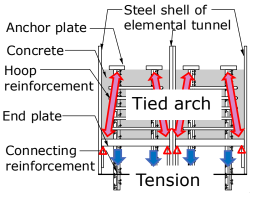
Fire Resistance Test of Joint Connection



Conceptual diagram of bearing system

Fire Resistance Test of Joint Connection

- Test set-up
  - Actual size model under load in fire
  - RABT curve



Structure of segment joints and connections

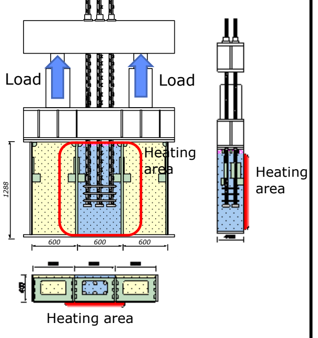
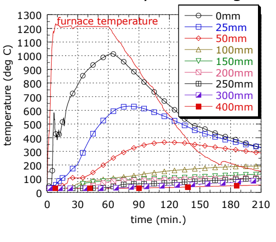


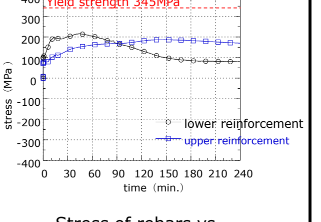
Figure of segment joint specimen

Fire Resistance Test of Joint Connection

- No explosive spalling of concrete
- Maximum temperatures at 40mm depth and at 70mm depth were 500 ℃ and 350℃, respectively.
- The maximum stress of connecting reinforcement in fire was less than yield strength.



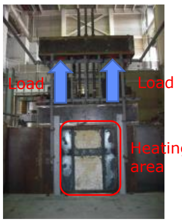
Internal temperature vs heating time



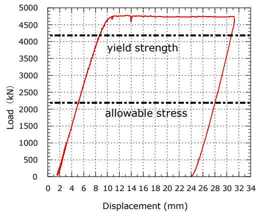
Stress of rebars vs heating time

Fire Resistance Test of Joint Connection

- Structural Test Results of Joint after RABT Heating
- Test set-up after heating
- Two 4000kN jacks were used and monotonous loading was applied.
- The specimen was not collapsed when the load reached the yield strength.



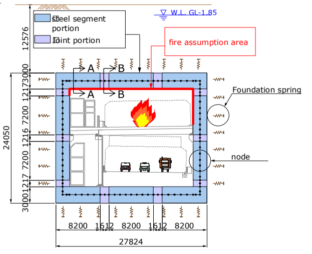
Structural test set-up after heating



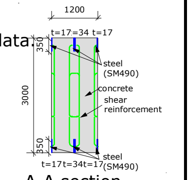
Relationship of vertical displacement and load

Finite Element Analysis of MMST shell structure

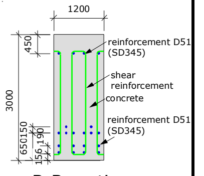
- Finite Element Analytical model
- This analysis was carried out using the test data.
- Support condition was modeled by the foundation spring of the tension cut.



Analytical model



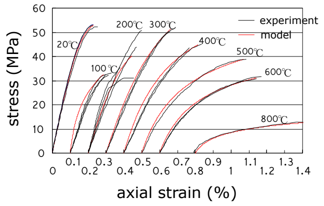
A-A section



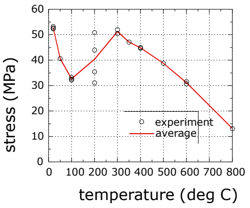
B-B section

Finite Element Analysis of MMST shell structure

- Calculation Model of Concrete using MMST method
- stress- strain relationship and compressive strength at elevated temperature



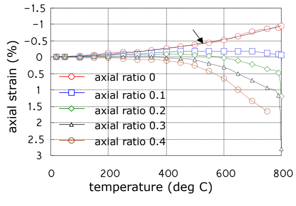
Relationship of concrete stress and strain at high temperature



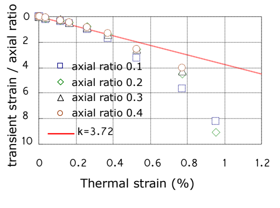
Compressive strength vs temperature

Finite Element Analysis of MMST shell structure

- Calculation Model of Concrete using MMST method
- Axial strain with temperature under load and model of transient strain



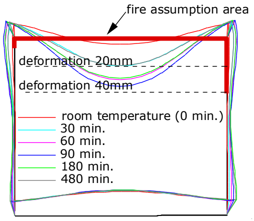
Axial strain under heating



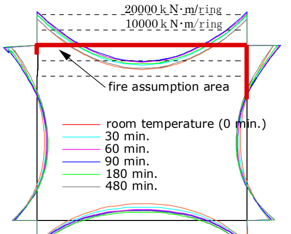
Model of transient strain

Finite Element Analysis of MMST shell structure

- Analytical results of outer shell structure MMST method
- MMST shell structure was not collapsed in fire.
- The maximum deformation is 38 mm in fire, 22 mm after fire.



Distribution of deformation



Distribution of bending moment

Concluding Remarks

- The fire performance of the MMST structure must be investigated and verified to ensure that it meets or exceeds the safety level specified by the German RABT fire curve.
- The shell's steel parts were subjected to a rapid-heating test to clarify the explosive fracturing conditions of the concrete used for the shell and the restraining effect of the incorporated organic fiber.

To meet fire safety requirements,

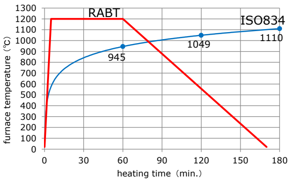
- The yield strengths of the segment joints and connections were evaluated using a full-scale shield segment model.
- An elasto-plastic thermal stress deformation analysis also was carried out using the test result data in order to confirm the structural safety of the MMST shell structure in a fire.

3. Outline of the Fireproof Testing Laboratory
in Taisei Technology Center

31/34

3.Outline of the Fireproof Testing Laboratory

- The effective heating capacity: 3m wide x 6m length x 4m height
- Thermal capability: ISO834,RABT,etc.
- Experimental target : column, girder, wall, shield segment, etc.



Multi-purpose heating furnace with 20MN load device

32/34

3.Outline of the Fireproof Testing Laboratory

The effective heating area: 1m x 1m
Thermal capability: ISO834,RABT,etc.

Small wall heating furnace

The burning possible area:5m x 5m

Burning laboratory equipment
(furniture calorie meter)

33/34

Thank you for your attention.

34/34

Validation Studies of Home Damaging and Ignitability Modeling of Vegetation Fire Radiant Exposure

Mark A. Dietenberger, Ph.D.
Charles R. Boardman
USDA, FS, Forest Products Laboratory
Madison, WI 53726 USA

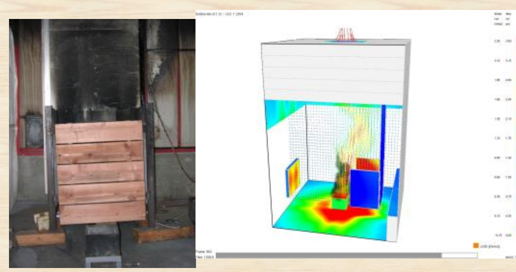
Outline

- Heat Damage & Ignition of Structures from Heterogeneous Fuel Burns
- Wall Mockups Heated Radiatively by Propane Burner under HRR Hood
- FDS Predictions versus Mockup Tests
- EcoSmart Damage/Ignitability Model versus Mockup Tests
- Wall Mockup Heated Radiatively by Litter Burn under HRR Hood

Selective Fuel Clearances to Mitigate Heat Damage and Ignition on Structures

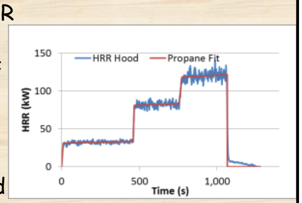
- Assume Homes Hardened Against Fire Brands, then Model Fuel Flame Threat
- Home Damage/Ignitability Model Implemented on EcoSmart Landscape
- Using FDS to Design Experiments, Calibrate Semi-Physical Models, and Predict Selective Fire Scenarios

Propane Burner with Vertical Walls under HRR Hood and FDS Results

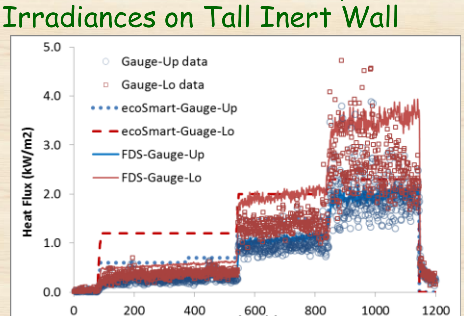


Propane Burner with Vertical Walls

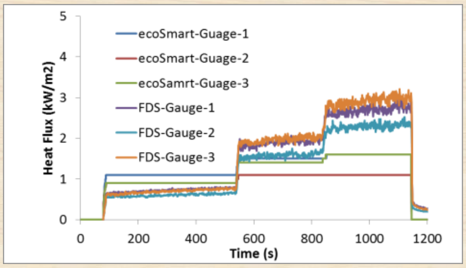
- 3 steps of propane HRR measured accurately
- Material properties of propane given in FDS
- Measure and predict surface irradiances
- ISO 9705 burner used



Model Versus Data of Propane Burn Irradiances on Tall Inert Wall



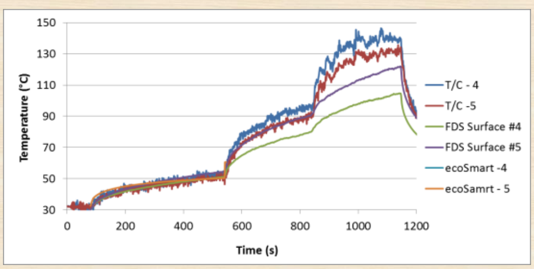
FDS Versus ecoSmart of Propane Burn Irradiances on Redwood Wall



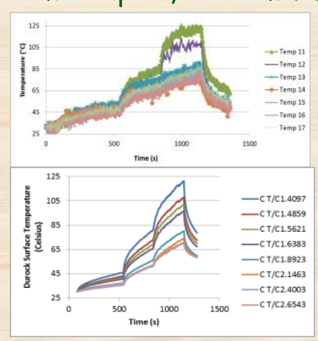
Temperature Response of Redwood Wall

- Redwood properties from Wood Handbook
- Measure and predict surface temperatures
- T/Cs at center and 4 corners
- Heat damaging sap flow around 120 degrees Celsius

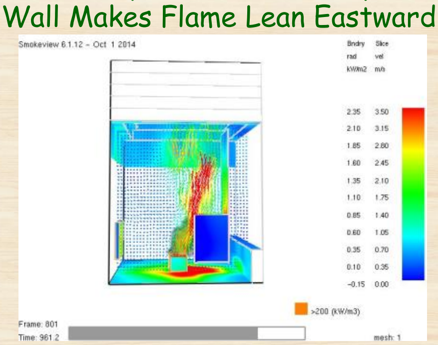
Temperature Response of Redwood Wall



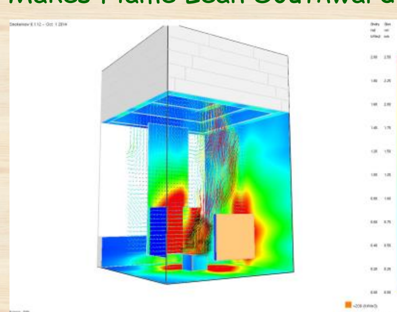
Temperature Response of Durock Wall: Top-Thermocouples, Bottom-FDS

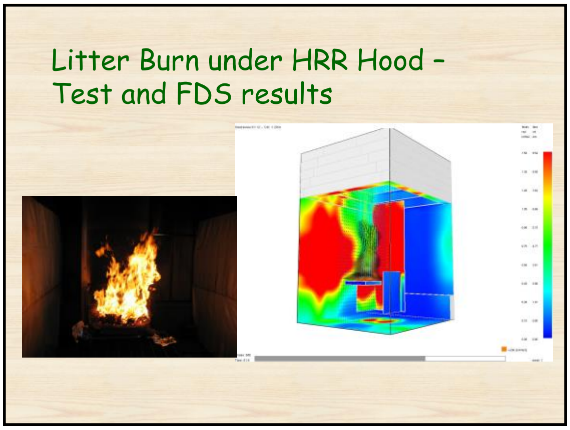


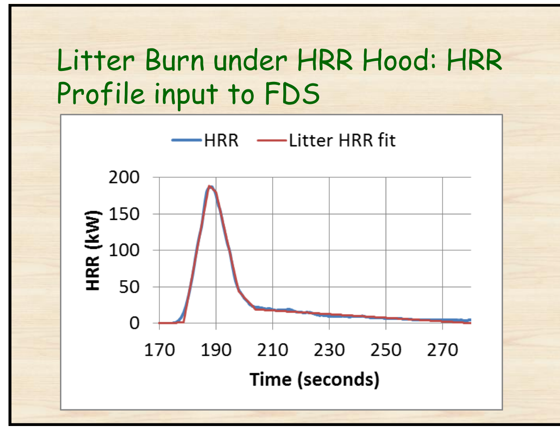
Sensitivity to Conditions: Open West Wall Makes Flame Lean Eastward

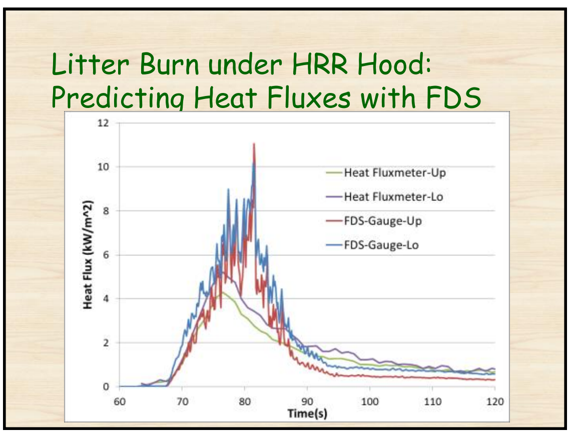


Sensitivity to Conditions: Open North Wall Makes Flame Lean Southward




Litter Burn under HRR Hood –
Test and FDS results


Litter Burn under HRR Hood: HRR
Profile input to FDS
HRR
Litter HRR fit
HRR (kW)
200
150
100
50
0
170
190
210
230
250
270
Time (seconds)


Litter Burn under HRR Hood:
Predicting Heat Fluxes with FDS
Heat Flux (kW/m^2)
12
10
8
6
4
2
0
60
70
80
90
100
110
120
Time(s)
Heat Fluxmeter-Up
Heat Fluxmeter-Lo
FDS-Gauge-Up
FDS-Gauge-Lo


Questions ?
Thank You !
See web site
http://www.fpl.fs.fed.us for
additional publications

Experimental Study on the Generation of Fire Whirls

R. Dobashi, T. Okura, R. Nagaoka, T. Mogi
The University of Tokyo

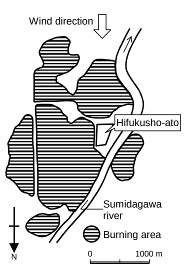
Background

Fire (Buoyant flow) → Interaction → Fire Whirl
Swirling flow → Interaction


Increase of flame height
↓
Increase of heat flux causing great damages.
It might play an important roll on WUI.

2/23

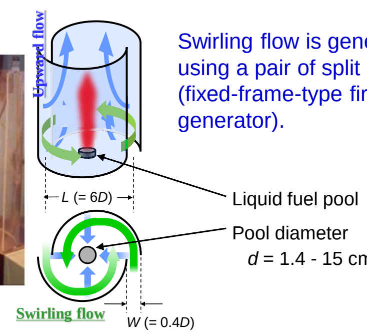
Hifukusho-ato fire whirls after Great-Kanto Earthquake (in 1923, Tokyo, JAPAN)



About 38,000 people were killed in less than 15 minutes.

3/23

Previous research 1/4

Swirling flow is generated by using a pair of split cylinders (fixed-frame-type fire whirl generator).

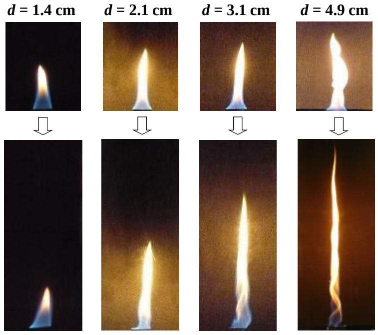
4/23

Previous research 2/4

d = 1.4 cm | d = 2.1 cm | d = 3.1 cm | d = 4.9 cm

Without swirling flow

With swirling flow



Fuel: Methanol

5/23

Previous research 3/4

For a laminar diffusion flame
Burke-Schumann Theory can be applied

$$\bar{u}_r \frac{\partial Z}{\partial \bar{r}} + \bar{u}_z \frac{\partial Z}{\partial \bar{z}} = \frac{1}{Pe}\frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left(\bar{r}\frac{\partial Z}{\partial \bar{r}}\right)$$

$$\frac{h}{d} = \frac{Re}{16\ln\left[1/(1-Z_{st})\right]}$$

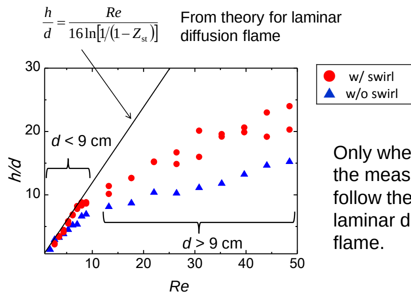
h : Flame height
Re (= $u_0 d/\nu$) : Reynolds number
u_0 : Fuel vapor velocity
d : Pool diameter
D : Diffusion coefficient
Z_{st} : Stoichiometric mixture fraction

h/*d* can be estimated for laminar diffusion flames (proportional to *Re*)

Journal of the Combustion Society of Japan ,Vol.51, No.155 (2009), pp.56-62 (in Japanese)
Proceedings of the Combustion Institute, 33 (2011), pp.2425–2432

6/23

Previous research 4/4

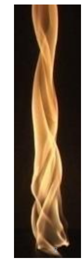


Only when d < 9 cm, the measured data follow the Eq. for laminar diffusion flame.

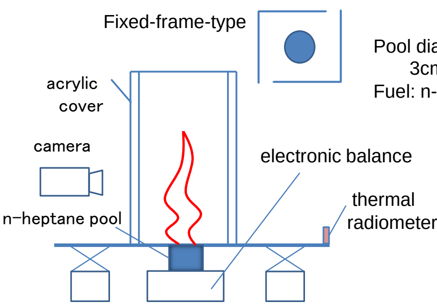
7/23

Objectives of this study

- Experiments have been performed on fire whirls of up to 20 cm pool
- The flame-height, fuel consumption rate, radiation intensity have been measured
- Discuss the mechanisms of fire whirl



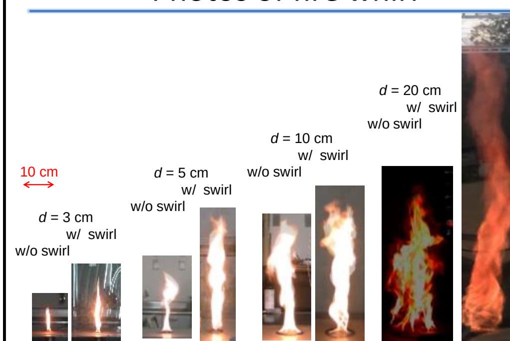
Experimental setting



Pool diameter:
3cm – 20 cm
Fuel: n-Heptane

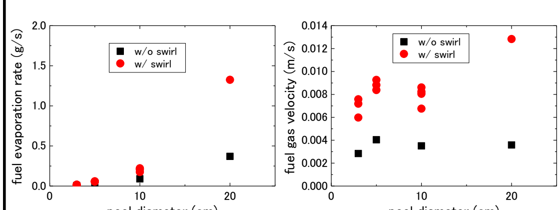
9/23

Photos of fire whirl



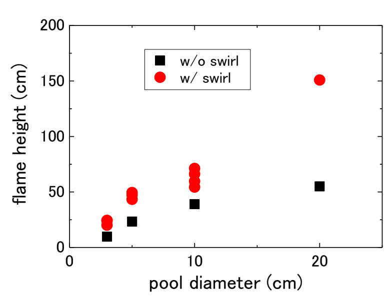
10/23

Fuel evaporation rate



11/23

Flame height



12/23

Regression rate and h/d with pool diameter

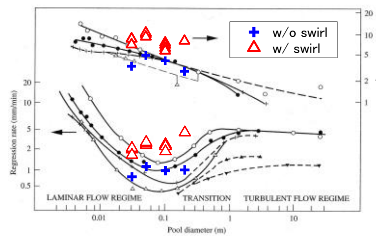


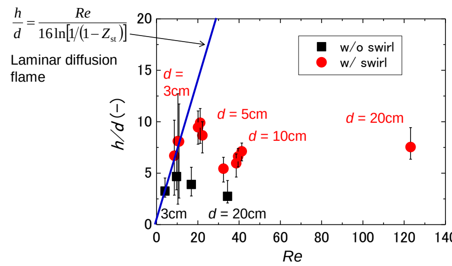
Figure 5.1 Regression rates and flame heights for liquid pool fires with diameters in the range 3.7×10^{-3} to 22.9 m. ○, Gasoline; ●, tractor kerosene; △, solar oil; +, diesel oil; ▲, petroleum oil; ▼, mazut oil (Blinov and Khudiakov, 1957, 1961; Hottel, 1959). By permission)

Swirl makes *h/d* larger

Swirl enhances regression rate to the value of large pool diameter

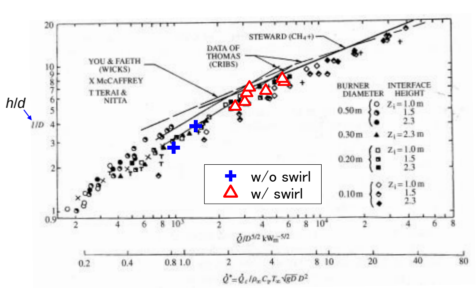
D. Drysdale, An Introduction to Fire Dynamics (2nd Ed.), John Wiley &Sons (1998)

Relation between *Re* and h/d



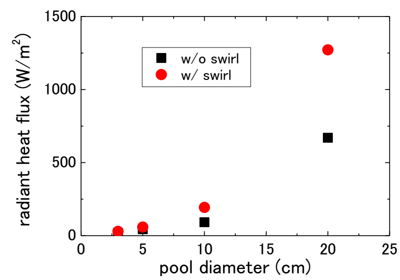
Pool flame will be diffusion control flame (Burke-Schumann theory) when $d < 5$ cm.
It will be buoyancy control flame when $d > 10$cm.

Relation between h/d and heat release rate parameter $\dot{Q}/d^{5/2}$

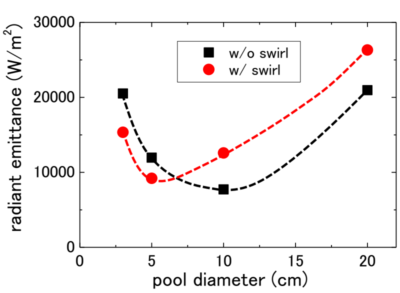


Measured data of d >10cm agree with the behavior of buoyancy control flame

Measured radiant heat flux



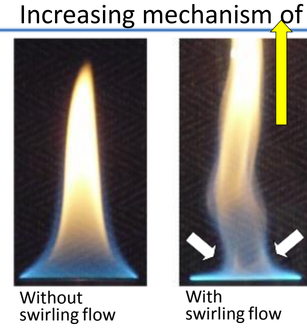
Radiant emittance



When d >10cm, swirl enhances radiant emittance

Discussion

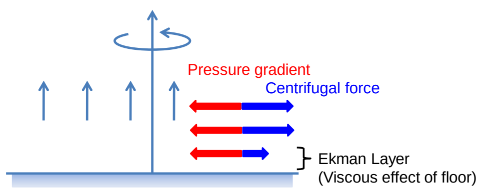
Increasing mechanism of flame height



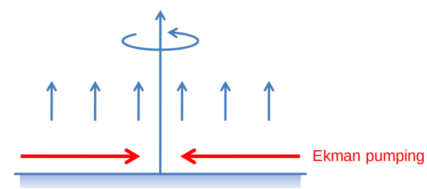
Swirling flow
⇩
Base part of the flame approaches to the liquid surface
⇩
Increase of the heat transfer to liquid fuel
⇩
Enhancement of the fuel evaporation
⇩
Increase of flame height *h*

Mechanism of flame approach ⇨ Viscous effect of floor (Ekman pumping)

Possible Influence of Ekman Layer

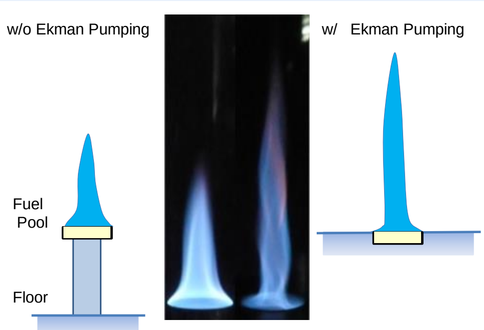


Possible Influence of Ekman Layer



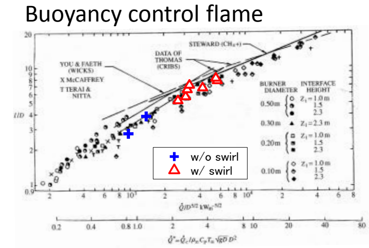
- Flame approach can be explained by radial inflow induced by viscous floor effect (Ekman layer).
- Ekman pumping may be playing an important role for the flame-height increase of fire whirl.

Experiment of the effect of floor



Discussion
Scaling effect on *h*/*d*

- $d < 5$ cm Laminar diffusion flame
- $d > 10$ cm Buoyancy control flame



- Slope is approximately 2/3

Summary

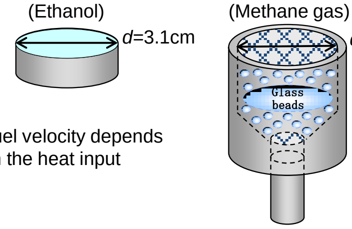
To understand the mechanism of fire whirl, experiments were performed on middle scale fuel pool (up to 20cm in diameter).

- h/d of fire whirl on larger pool ($d > 10$cm) doesn't follow the correlation of laminar diffusion flame, rather follows that of buoyancy control flame.
- The effect of Ekman pumping may increase the flame height of fire whirl.
- Radiant emittance was increased by swirling flow when pool is larger ($d > 10$cm).

Experiment under u_0 = constant

Liquid fuel pool
(Ethanol)

Gas burner
(Methane gas)



Fuel velocity depends on the heat input

Fuel velocity can be controlled constant

25

Experiment under u_0 = constant

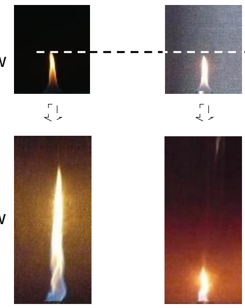
Liquid pool flame Gas burner flame

Without swirling flow

$\Gamma = 0$

With swirling flow

$\Gamma > 0$



Gas flow rate is controlled as the flame heights are equal

Flame height does not increase when u_0 = constant

26

Applying to practical accidents

Scale

a few cm — a few m — a few hundreds m

This study	Real scale accident
Laminar flame	Effects of turbulence Other scale effects Smoke generation Fluctuation et.

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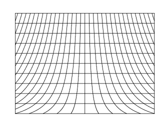
Appendix

Burke-Schumann Analysis

$$\bar{u}_r\left(Fr,\frac{\Gamma}{\nu}\right)\frac{\partial Z}{\partial \bar{r}}+\bar{u}_z\left(Fr,\frac{\Gamma}{\nu}\right)\frac{\partial Z}{\partial \bar{z}}=\frac{1}{Re}\frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left(\bar{r}\frac{\partial Z}{\partial \bar{r}}\right)$$

$$\bar{u}_i = u_i/u_0$$
$$\bar{r} = r/D$$
$$\bar{z} = z/D$$
Z : mixture fraction



Coordinate transformation

Analytical solution

$$\frac{H}{D}=\frac{Re}{16\ln\left[1/\left(1-Z_{st}\right)\right]}$$

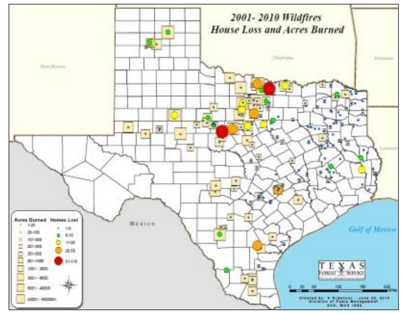
28

Characterization of Wildland Fire Fuel Burning and Ember Generation

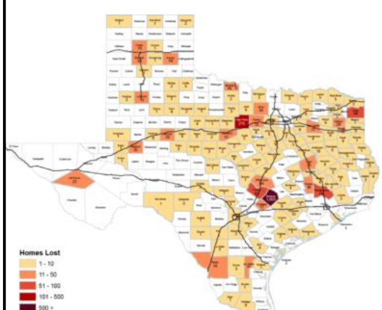
O.A. Ezekoye
Department of Mechanical Engineering
The University of Texas at Austin

Kris Overholt, Jan Michael Cabrera, Andrew Kurzawski, Craig Weinschenk, Matthew Koopersmith, Karen Ridenour, & Rich Gray

Rural Community Wildland Fire Problem



2011 Was Bad



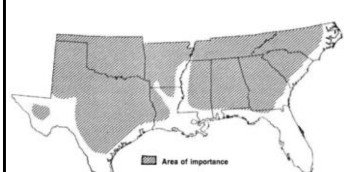
- Wet 2010 followed by 2011 drought
- 31,453 fires
- 4,011,709 acres

Grassland Fire Risk

Cross Plains, TX
Texas Forest Service Case Study
Gray et al (2007)

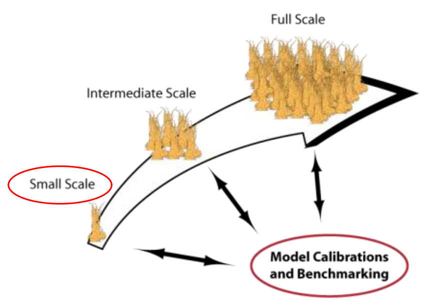
Issues in Ember Attack of Attic Spaces

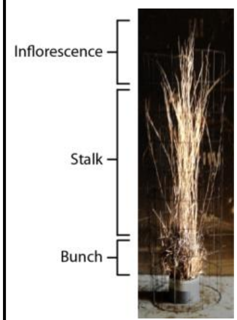
Prairie Grasses
Little Bluestem



Ubiquitous throughout US

Relevant to Texas grassland fires

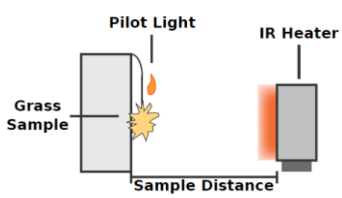




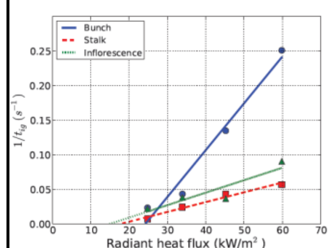
Average specimen height 1.5 m

Simple Ignition Measurement

Measure time to ignition
Calculate critical heat Flux



Ignition Properties



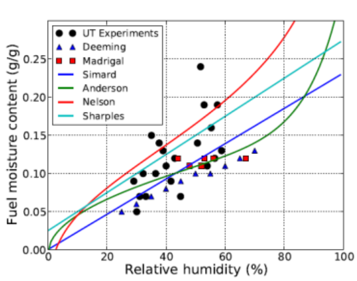
Critical heat fluxes
Bunch: 24 (kW/m^2)
Stalk: 18 (kW/m^2)
Inflorescence: 15 (kW/m^2)

Typical cellulose: 15 (kW/m^2)

Thermally thick vs thin

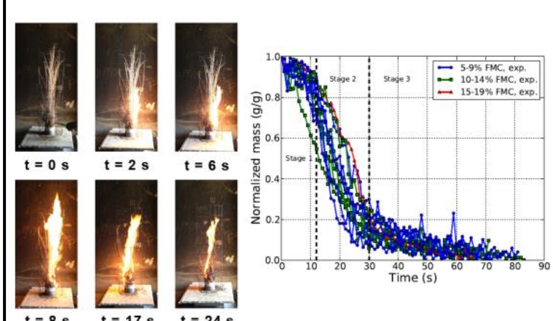
Inflorescence morphologically similar to stalk

Moisture Content

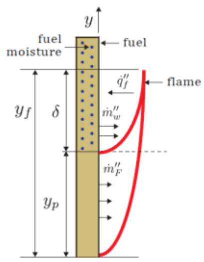


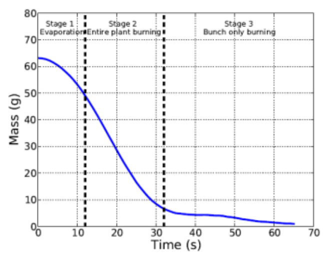
Surprisingly poor prediction of fuel moisture content with RH

Single Plant Burning Process



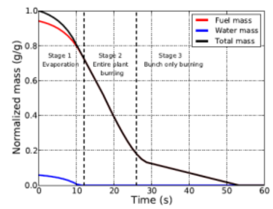
Simple Flame Spread Model?

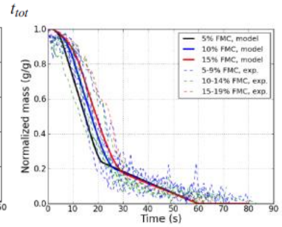




Simple Model Predictions

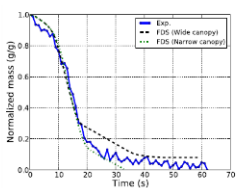
$$\frac{dy_p}{dt} = \frac{y_f - y_p}{t_{tot}}$$



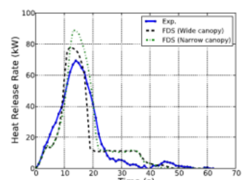


$$t_{tot} = (\rho_w c_p \Delta T_{PC} + \rho_F c_p \Delta T_{PC} + \rho_w h_{fg} + \rho_F c_p \Delta T_{IGN}) \frac{1}{\dot{q}'' A'''}$$

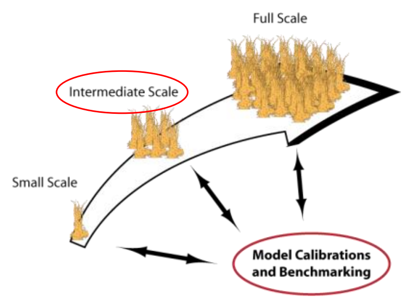
Single Plant WFDS Simulation



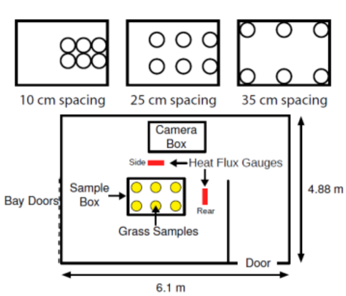
WFDS wide and narrow canopy



Two configurations: with and without metal holder
Burning rate from tests used to limit WFDS burning rate



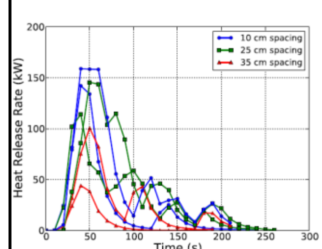
Multiple Plant Burns



Center to center plant spacing to represent actual levels of fuel loading

Measurements
Gas temperatures
Heat fluxes
Char fraction

Experimentally Derived HRR



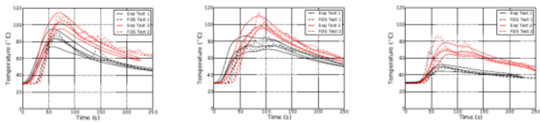
Gas temperatures used to invert for HRR

Average heat of combustion from tests was 16.4 kJ/g

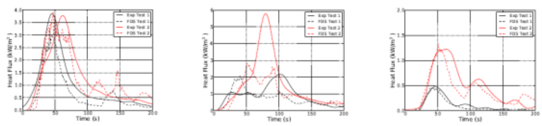
Heat of combustion for similar grasses 16.3 to 18.5 kJ/g

Average char fraction 12%

Temperatures and Heat Flux



10 cm spacing | 25 cm spacing | 35 cm spacing

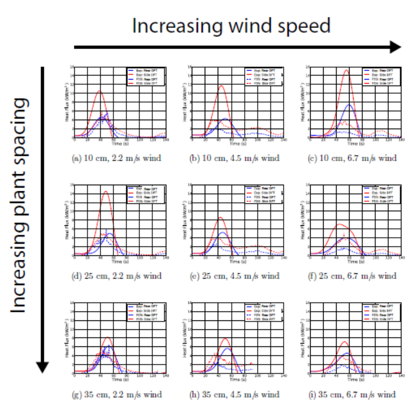


Plant Burns with Wind

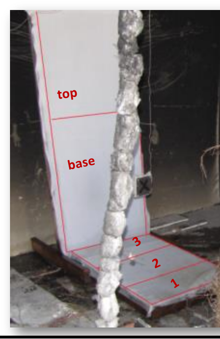
Top: 2.2 m/s

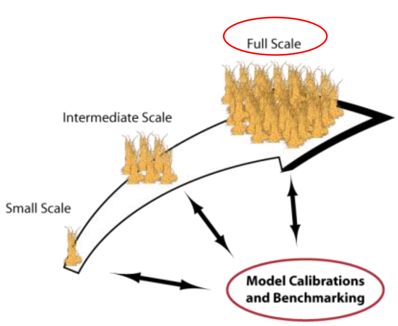
Middle: 4.5 m/s

Bottom: 6.7 m/s



Ember Collection

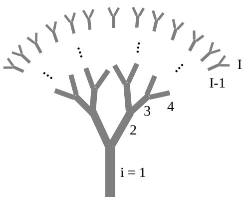




Prescribed burn at Camp Swift near Bastrop, TX on Feb 16, 2011

Conducted by the Texas Forest Service
Instrumented field of primarily little bluestem grass

Ember Production
Fractal Plant/Tree Model



$$\frac{m_{i+1}}{m_i}=\frac{\rho_s V_{i+1}}{\rho_s V_i}=\frac{\rho_s\left[n_{i+1}\left(\frac{\pi}{4}D_{i+1}{}^2\right)L_{i+1}\right]}{\rho_s\left[n_i\left(\frac{\pi}{4}D_i{}^2\right)L_i\right]}$$

$$=\frac{\rho_s\left[n_{i+1}\left(\frac{\pi}{4}D_{i+1}{}^2\right)AD_{i+1}\right]}{\rho_s\left[n_i\left(\frac{\pi}{4}D_i{}^2\right)AD_i\right]}=\left(\frac{n_{i+1}}{n_i}\right)\left(\frac{D_{i+1}}{D_i}\right)^3$$

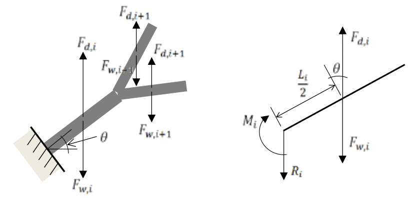
$$\frac{m_{i+1}}{m_i}=2\left(2^{-\frac{1}{2}}\right)^3=2^{-\frac{1}{2}}\approx 0.71$$

Fractal model for branching vegetation wildland fuel packet

Mandelbrot, 1977

Barr and Ezekoye, 2014
Collin et al, 2011

Aerodynamic Loading and Fracture



Critical Breakage Diameter

maximum flexural stress, σ, in the cylindrical branch subjected to M_i is

$$\sigma=\frac{32M_i}{\pi D_i{}^3}\qquad \sigma=\frac{8L^2\cos\theta}{\pi D^2}\left[\rho_a U^2 C_d-\frac{\pi}{2}\rho_s D g\right]$$

$$\frac{\pi\sigma}{8A^2\cos\theta}\left(\frac{D}{D_o}\right)^2+\frac{\pi}{2}\rho_s g D_o\left(\frac{D}{D_o}\right)-\rho_a U^2 C_d=0$$

If the critical flexural stress for the material is σ_{cr}, then the critical diameter for fracture, D_{cr}, at which the critical stress is achieved can be determined from

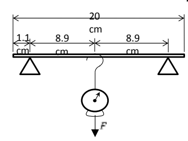
$\sigma_w=2\rho_s g D_o A^2\cos\theta$ as the characteristic stress associated with weight

$\sigma_d=\frac{8}{\pi}\rho_a U^2 C_d A^2\cos\theta$ as the characteristic stress associated with drag

$$\frac{D_{cr}}{D_o}=\sqrt{\left(\frac{\sigma_w}{\sigma_{cr}}\right)^2+\left(\frac{\sigma_d}{\sigma_{cr}}\right)}-\left(\frac{\sigma_w}{\sigma_{cr}}\right)$$

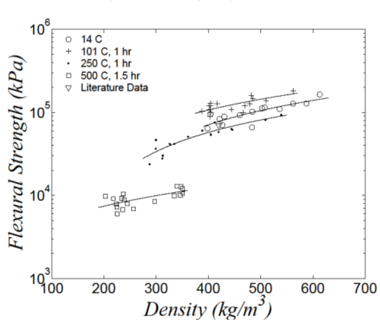
What is σ_{cr}?

Mechanical Testing
yellow poplar



Treatment	Mass Fraction Lost	$\frac{D_{avg}}{D_{o,avg}}$	$\frac{L}{L_o}$	$\frac{V}{V_o}$	$\frac{\rho}{\rho_o}$	$\frac{\sigma}{\sigma_o}$	$\partial\sigma_{cr}/\partial\rho_s$ (kPa-m^3/kg)
14 ˚C	0.00	1.00	1.00	1.00	1.00	1.00	342
101˚C, 1 hr	0.061	0.99	1.00	0.97	0.97	1.21	372
250˚C, 1 hr	0.32	0.92	1.00	0.85	0.81	0.52	236
500˚C, 1.5 hr	0.78	0.67	0.86	0.39	0.57	0.091	25.2

Strength vs. Density
(yellow poplar)



Pyrolysis and Oxidation Effects

Pyrolysis of wood is often modeled as a two step process.

The first step is the pyrolysis of hemicellulose and lignin around 520 K.

The second step is the pyrolysis of cellulose around 620 K.

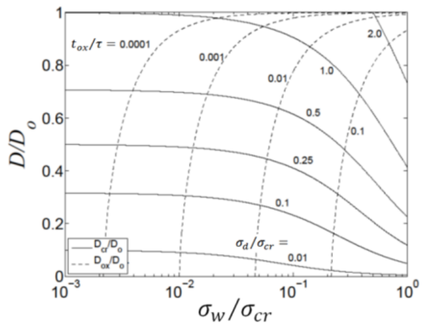
Surface oxidation takes place at yet higher temperatures.

$$\frac{D_{ox}}{D_o}=\left[1-\frac{t_{ox}}{\tau}\left(\frac{\sigma_w}{\sigma_{cr}}\right)^{-3/2}\right]^{2/3}$$

$$\tau=\left[3C\frac{\rho_a}{\rho_s}\ln(1+B)\left(\frac{U}{\nu}\right)^{1/2}Pr^{1/3}\alpha_a\left(\frac{2\rho_s g A^2\cos\theta}{\sigma_{cr}}\right)^{3/2}\right]^{-1}$$

When $\frac{D_{ox}}{D_o}=\frac{D_{cr}}{D_o}$ breakage occurs.

Breakage Map



Brand Lofting Model

Based on Woycheese et al

$$\boldsymbol{F}_w = -mg\hat{\boldsymbol{k}}$$

$$\boldsymbol{F}_d = \frac{1}{2}\rho_a DLC_d|\boldsymbol{W}|^2\frac{\boldsymbol{W}}{|\boldsymbol{W}|}$$

$$\frac{d}{dt}(m\boldsymbol{V}) = \boldsymbol{F}_d + \boldsymbol{F}_w$$

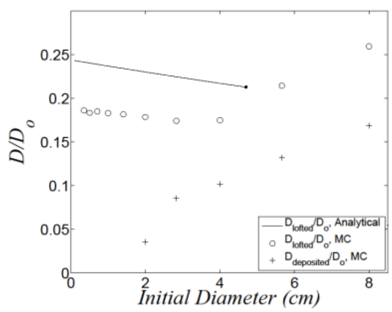
$$\frac{dV_x}{dt} = \frac{2}{\pi}\left(\frac{\rho_a}{\rho_s}\right)\frac{C_d}{D}|\boldsymbol{W}|W_x - \frac{2V_x}{D}\frac{dD}{dt}$$

$$\frac{dV_z}{dt} = \frac{2}{\pi}\left(\frac{\rho_a}{\rho_s}\right)\frac{C_d}{D}|\boldsymbol{W}|W_z - \frac{2V_z}{D}\frac{dD}{dt} - g$$

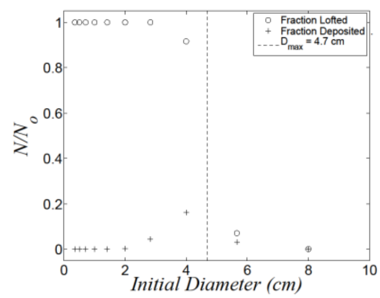
$$\frac{dD}{dt} = -2C\alpha_a\frac{\rho_a}{\rho_s}ln(1+B)\left(\frac{|\boldsymbol{W}|}{\nu_a}\right)^m Pr^{1/3}D^{m-1}$$

Biscuit Fire, 2002 (Southern Oregon)
http://www.uwec.edu/jolhm/EH3/Group9/wildfirebiscuitfire.htm

Lofted and Deposited Diameters



Fraction Lofted and Deposited



Monte Carlo simulations with uniformly distributed parameters in orientation, density, plume time.

Conclusions

- Experiments were performed to calculate physical properties and measure the flame spread rate of little bluestem grass.
- The physical properties were compared to those found in literature.
- Models captured the mass loss and heat release rates but not the breakage that occurs as plants burn.
- A model for ember generation was developed.
- Experiments were conducted to parameterize the model.
- With further work, the model might be useful for inferring ember properties in actual fire scenarios.

Operation Tomodachi – Fire Research
National Institute of Standards and Technology (NIST)
Gaithersburg, Maryland, USA
18/03/2015

HIROSAKI UNIVERSITY

Fire Extinguishment by Using Ice Capsule Filled with Liquid Nitrogen

Miho Ishidoya, Hiroyuki Torikai*, Akihiko Ito
Hirosaki University, JAPAN

Research of Fire Extinguishment

We are proposing to use an extinguishing capsule for firefighting.

The capsule is a spherical hollow Ice made by ourselves.

Liquid nitrogen is used as an extinguishing agent.

Back ground

The Great Hanshin-Awaji earthquake

The Great East Japan earthquake

○ There were two huge earthquakes in japan during the past 20 years.

- The Great Hanshin-Awaji earthquake (1995)
- The Great East Japan earthquake (2011)

○ Multiple fires always broke out simultaneously in wide area. （Post earthquake fire）

Problems of Firefighting after the occurrence of a huge earthquake

The Great East Japan earthquake

○Infrastructure (roads, water source for firefighting and etc.) was violently destroyed due to the impact of the earthquake and also tsunami.

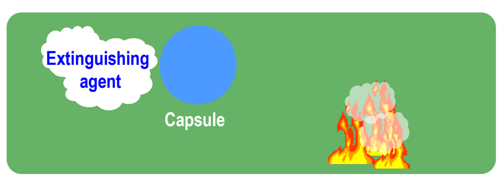
○ Fire engines and also survivors could not approach to the fire area due to the damaged road or tsunami debris.

○ In that emergency situation, conventional extinguishing tools, such as a fire extinguisher, could not be useful because of their limited effective range.

For mitigation and minimization of the post-earthquake fire damage, there is the necessity to develop new firefighting method.

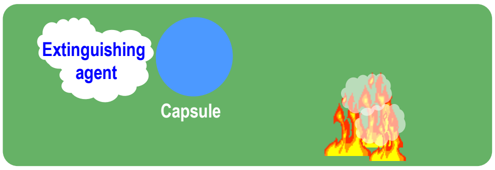
It is desirable that the method can deliver extinguishing agents over a long distance (more than several tens of meters).

Capsule extinguishing method



1. When extinguishing agent is packed in a capsule, it can be easily transported through the surrounding air without reduction of its concentration.
2. When the capsule breaks in burning area, the extinguishing agent can be directly supplied to the flame.

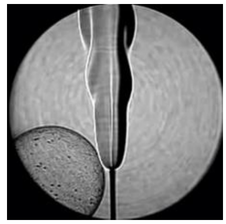
Capsule extinguishing method



○ The method would be possible to increase the effective range and the extinguishing effectiveness of the extinguishing agents and decrease the amount of the extinguishing agents needed to blow fire off.

Various capsules

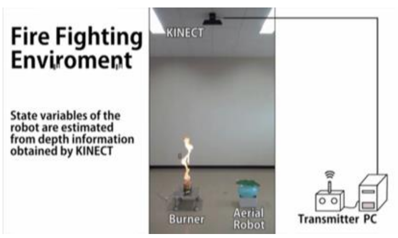
○Soap bubble



○Rubber balloon

In our previous studies, soap bubbles and rubber balloons filled with gaseous extinguishing agents have been used as an extinguishing capsule.

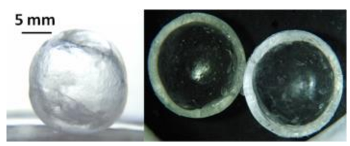
Rubber balloon ＋ Quad rotor helicopter (Aerial firefighting robot)



○Prof. Yasushi Iwatani, Hirosaki University

The control system of the helicopter consists of a depth sensor, a computer and a transmitter. The computer processes the image data from the depth sensor fixed at the ceiling, and the control signals are generated at 30 fps. The signals are passed through the transmitter to the helicopter.

Spherical Ice Capsule



Outer diameter: 20 mm
Wall thickness: 2 mm

○ A hard shell capsule can be shot at high speed with a pressure gas gun.

Pepper ball gun

PepperBall Technologies, Inc., TAC 700 Launcher
(This is non-lethal weapon)

(from YouTube)

○ The effective range of a pressure gun, such as a paint ball gun, is usually around 20 - 30 m.

○ When the pepper ball impacts on a wall, the pepper powder is released around the target area because the pepper ball has a large amount of momentum.

Extinguishing agent

- In this study, liquid nitrogen is used as an extinguishing agent.
- This is not an ordinary extinguishing agent.
- However, liquid nitrogen has several good aspects for fire extinguishment.

Feature of Liquid Nitrogen

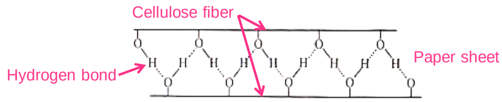
	Liquid nitrogen	Water
Boiling point [K] at 0.1MPa	77	373
Latent heat [kJ/kg]	200	2257
Volume expansion rate at 373.15K, 0.1MPa	700 times	1700 times

- The boiling temperature of liquid nitrogen is much lower than that of water.
  ⇒It is very difficult to transport liquid nitrogen from its application location to fire source under the atmospheric condition.
- Liquid nitrogen has a lower value of latent heat than water.
  ⇒Liquid nitrogen absorbs less amount of heat than water from burning area.
- Liquid nitrogen boils and evaporates much faster than water.
  ⇒Liquid nitrogen will be better to be used for indirect extinguishing method.
  ⇒Fire is not extinguished directly by liquid nitrogen, but by the vaporized liquid nitrogen that is, nitrogen gas.

Advantage of use of liquid nitrogen

Camera: SONY HDR-PJ630,
Recording frame rate : 30fps
Playback speed: ×3

The cellulose fibers in a paper sheet are attached together by hydrogen bond. When water soaks into the paper sheet, water molecules separate the hydrogen bonds. As a result, the shape of the paper is deformed.



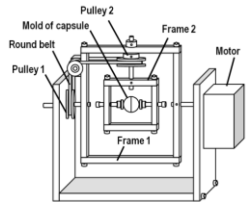
＊Liquid nitrogen has no influence to paper sheet.

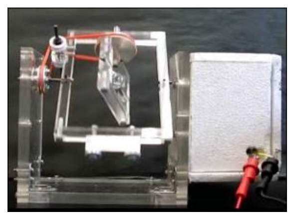
Objectives

In order to clarify the fundamental extinguishing characteristics of the ice capsule filled with liquid nitrogen, the blowoff experiments of a methane-air jet diffusion flame have been performed.

- The capsule extinguishing method could be used as a mitigation measure to the post-earthquake fire
- Liquid nitrogen vaporizes rapidly under atmospheric condition. Therefore, it is difficult to delivery liquid nitrogen over a long distance.
  ⇒The effectiveness of the use of the capsule for fire extinguishment can be proved easily by using liquid nitrogen.

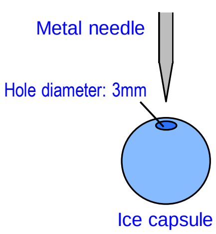
Forming method of ice capsule





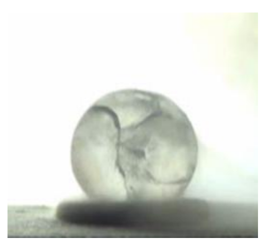
- The molding machine with semi-randomized two-axis motion was used to make the ice capsule.
- The mold of the ice capsule consisted of two acrylic hemispherical bowls.
- When the machine at the rotating rate of about 72 rpm was placed in a freezer at about -10 ℃, it took approximately 35 minutes to form one ice capsule.

Filling liquid nitrogen into capsule



(1) The Inlet hole of liquid nitrogen was made with metal needle.
(2) The capsule was immersed into liquid nitrogen.
(3) The capsule was filled up with liquid nitrogen in one minute.
(4) The volume of the filled liquid nitrogen was 2 cm^3.

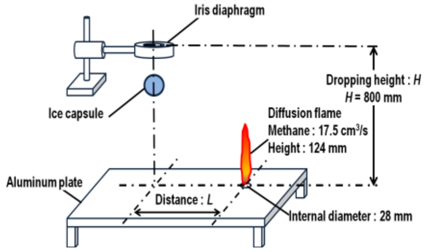
Evaporation of liquid nitrogen in a capsule



Camera: CASIO FX-E1,
Recording frame rate : 30 fps

- When the capsule filled with liquid nitrogen is put in a room, the liquid nitrogen evaporates in the ice capsule.

Experimental setup for blowoff experiments



- The ice capsule is dropped freely from the height of 800 mm and impacts on the aluminum plate.
- Impact velocity of ice capsule filled with liquid nitrogen was 4.5 m/s.
- Distance, L, between the burner center and impact point was varied.
- The extinguishing probability was computed as the ratio of the number of successful extinguishments to the number of total experiments of 10.

Experimental results

Extinguishing process

After the capsule crushes, liquid nitrogen spreads in the radial direction along the aluminum plate surface.

When the liquid nitrogen passes through the base region of the flame, the flame lifts off from the burner due to local extinction caused by the reduction of oxygen concentration.

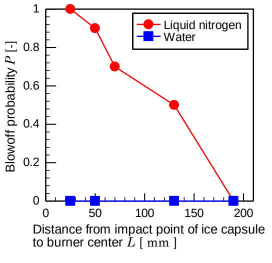
Finally, the flame is blown off to the downstream, and then the flame extinguishment is achieved.

Extinguishing process (Bird's eyes view)

Camera: NAC Memrecam HX-3
Recording frame rate : 10000 fps

- Droplets of liquid nitrogen are generated at the impact.
- The droplets travel smoothly on the plate due to the Leidenfrost effect.
- The white fog is formed due to the condensation of water vapor in the air, which is cooled by passing of liquid nitrogen or mixing with low temperature liquid nitrogen vapor.
- The liquid nitrogen vapor is considered to reduce the oxygen concentration in the flame zone, and extinguish it perfectly.

Blowoff probability



The blowoff probability decreases as the distance between the impact point and the flame increases. The probability shows non-zero less than 200 mm.

For comparison, ice capsule filled with water is used. The extinguishing probability always shows zero.

- In this blowoff experiments, the extinguishing distance of the ice capsule is not large and limited less than 200 mm.
- Liquid nitrogen shows the higher extinguishing effectiveness than water.

Summary

○ Fire extinguishing method using ice capsule filled with liquid nitrogen has been proposed .

○The hard shell capsule, such as the ice capsule, is though to be useful for a long range firefighting.

○The rapid vaporization of liquid nitrogen after it is released from the crushed ice capsule can be considered to be the key factor to achieving the fire extinguishment in this method.

Future work

We are planning to perform the extinguishing experiment using a gas gun.

- The impact velocity of the ice capsule increases more, the diameter of the produced liquid nitrogen droplets will become smaller.
- The smaller droplets are vaporized faster and the larger amount of the nitrogen gas will be produced at once.
- This is considered to be effective for this extinguishing method, and we will be able to get the higher extinguishing effectiveness by using gas gun.

Thank you for your kind attention.

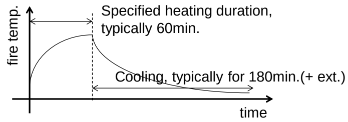
A Practical Computer Code for Prediction of Thermal Response of Timber Structural Elements during Heating and Post Heating Self-Burning Period

Kazunori HARADA, Yukiko Chatani

Dept. of Architecture & Architectural Engineering, Kyoto University

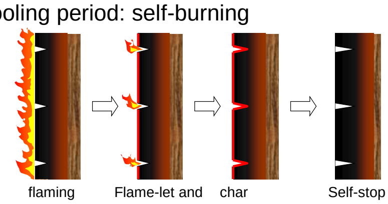
background

- Fire resistance requirement
  - Building shall not collapse during complete process of fires foreseeable to take place inside
  - In practice: specified hours of heating followed by cooling down to normal temperature



background

- Timer elements
  - Heating period: Charred layer forms, acting as an insulation to inner core
  - Cooling period: self-burning



objective

- Prediction of:
  - charring during fire (heating)
  - self-burning during post fire (cooling)
- Develop a simple computer code for prediction
  - Heat conduction, decomposition of volatile components, char oxidation
  - for use in design of timber elements

Model

- Governing equations:
  - Heat conduction, 2-dim., transient

$$\rho c\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}(\lambda_x\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(\lambda_y\frac{\partial T}{\partial y})+Q_{evap}+Q_{decomp}+Q_{glow}$$

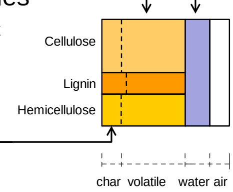
heat absorption by evaporation of water

heat absorption by decomposition of volatile components

Heat generation by char oxidation (glowing combustion)

Model – material

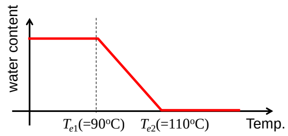
- Evaporation of water
  - Endothermic, 90-100ºC
- Decomposition of volatiles
  - Endothermic, 250-360ºC
- Char oxidation
  - Exothermic, 400-1000ºC



Model – material - water

- Evaporation of water
  - Assuming constant evaporation per temperature rise

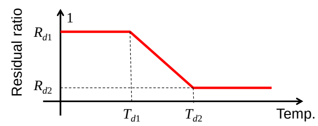
$$Q_{evap} = -L_v \rho_0 \left(-\frac{\partial w}{\partial t}\right) \approx -L_v \rho_0 \frac{w_0}{T_{e2} - T_{e1}} \frac{\partial T}{\partial t} \quad \text{[W/m}^3\text{]}$$



Model – material - volatiles

- decomposition of volatile components
  - Assume heat transfer control (Thermally programmed decomposition)

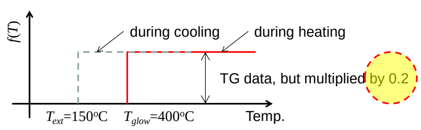
$$Q_{decomp} = -L_d \rho_0 \left(-\frac{\partial R}{\partial t}\right) \approx -L_d \rho_0 \left(\frac{R_{d1} - R_{d2}}{T_{d2} - T_{d1}}\right) \frac{\partial T}{\partial t} \quad \text{[W/m}^3\text{]}$$



Model – material - char

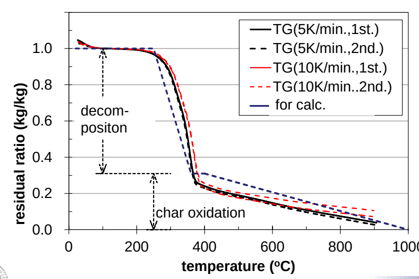
- Char oxidation
  - Reaction rate, starting temperature were determined by TG test data
  - stopping temperatures

$$Q_{glow} = \Delta H \rho_0 \left(-\frac{\partial R}{\partial t}\right) = \Delta H \rho_0 f(T)$$



Model – material - parameters

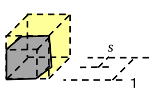
- Reaction temp. – T.G. data

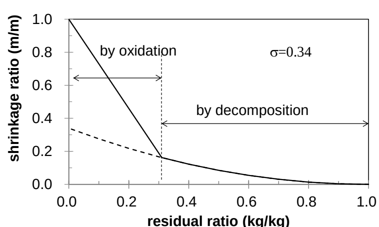


Model - shrinkage

- Shrinkage ratio

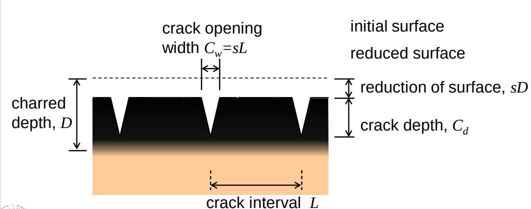
$$s = \sigma(1 - R)^2$$



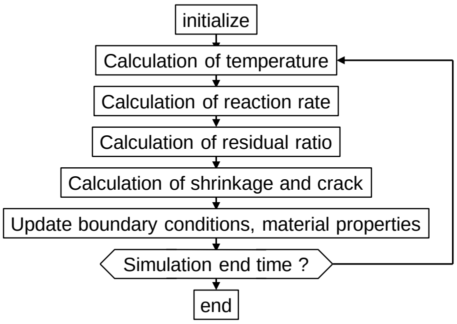


Model - shrinkage

- Crack pattern
  - W/D ratio, C_w/C_d = 3.15
  - crack interval, L = laminar width



Calculation flow



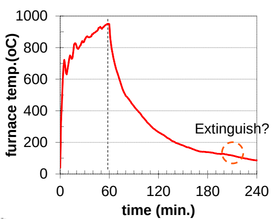
Experiment

- Glue laminated timber, larch wood
- A wall slab of 22mm x 4 laminars

Density : 480kg/m^3
Water cont.: 14%-wt.

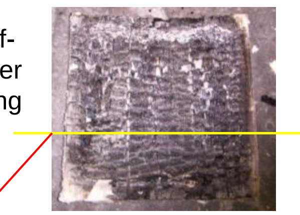
Experiment

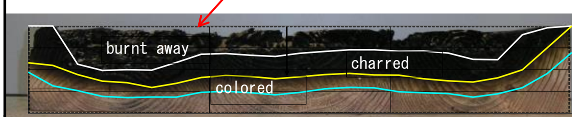
- Small-scale gas furnace
- Heating temp.: ISO 834 (60 min.) + cooling



Experiment

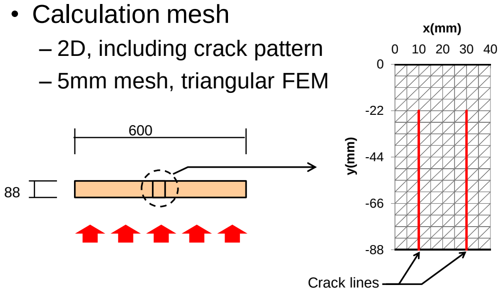
- Specimen is self-extinguished after 3 hours of cooling





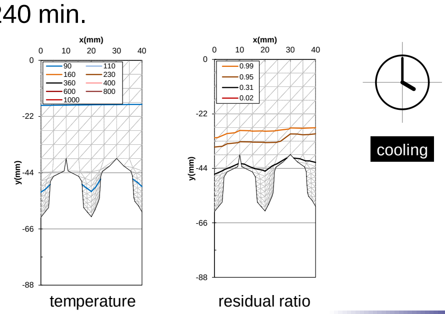
Calculation - settings

- Calculation mesh
  - 2D, including crack pattern
  - 5mm mesh, triangular FEM



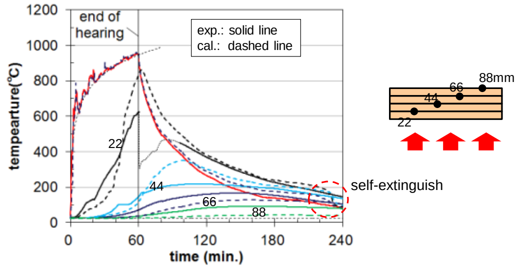
Results - profile

- 240 min.



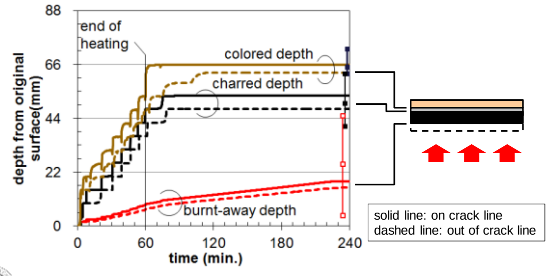
Results - temperature

- Comparison with experiment



Results – deterioration depth

- Comparison with experiment



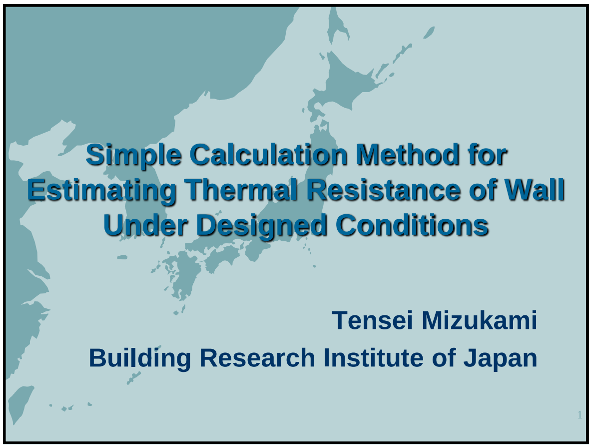
conclusions

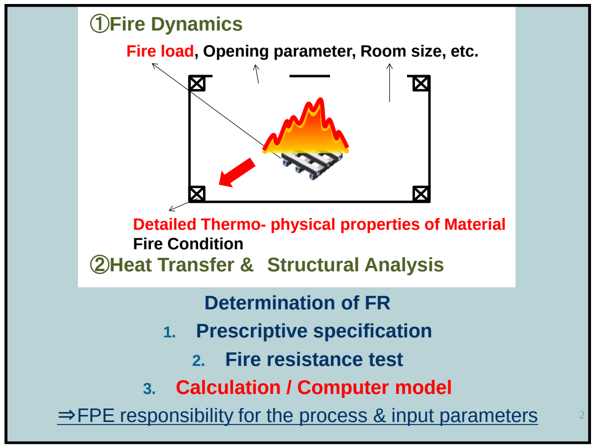
- A simple model for thermal response of timber element is being developed.
- Comparison with experiment is fair after adjustment of char oxidation rate.
- As a research, rational formula for char oxidation is needed considering thickness of char layer

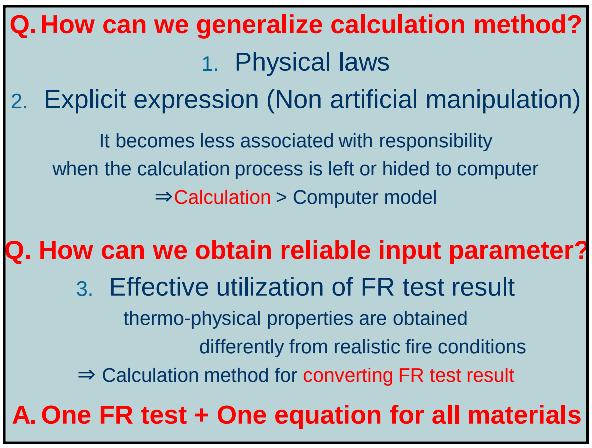
Validation study

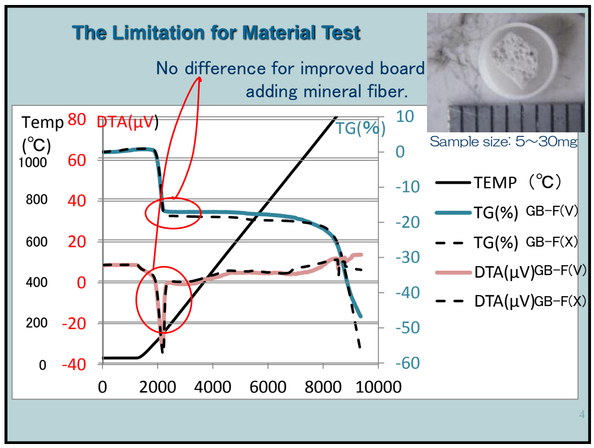
- The Code is being developed by voluntary work from interested bodies.
- First step validation study has been done (2012-13fy)

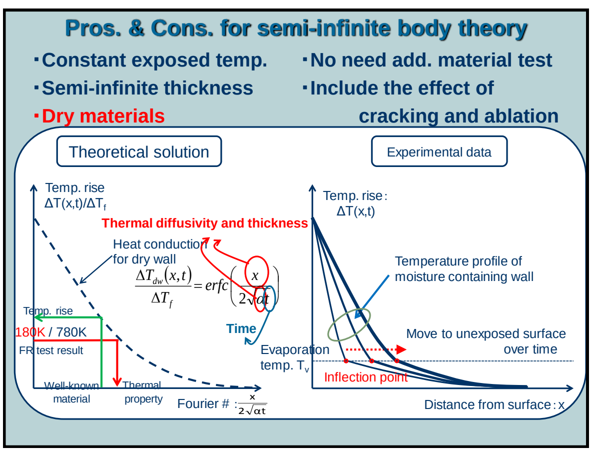
Preliminary reporting meeting March, 2014, Building Performance Standardization Association

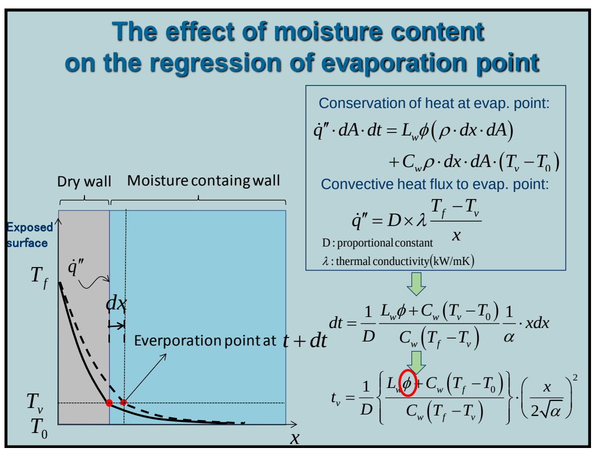

Simple Calculation Method for Estimating Thermal Resistance of Wall Under Designed Conditions
Tensei Mizukami
Building Research Institute of Japan
1

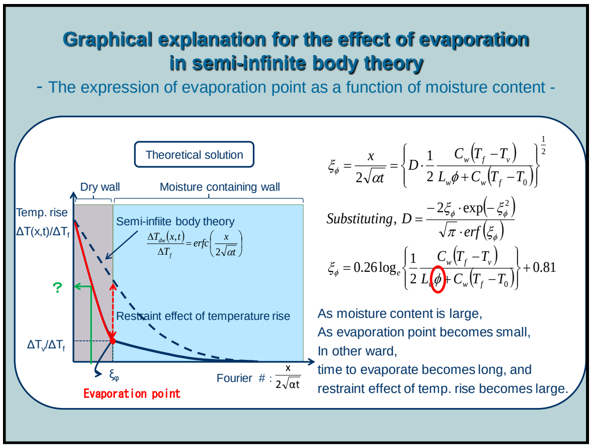

①Fire Dynamics
Fire load, Opening parameter, Room size, etc.
Detailed Thermo- physical properties of Material
Fire Condition
②Heat Transfer & Structural Analysis
Determination of FR
1. Prescriptive specification
2. Fire resistance test
3. Calculation / Computer model
⇒FPE responsibility for the process & input parameters
2

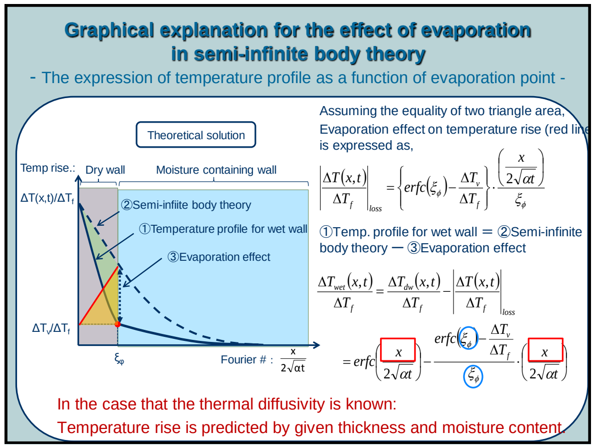

Q. How can we generalize calculation method?
1. Physical laws
2. Explicit expression (Non artificial manipulation)
It becomes less associated with responsibility
when the calculation process is left or hided to computer
⇒Calculation > Computer model
Q. How can we obtain reliable input parameter?
3. Effective utilization of FR test result
thermo-physical properties are obtained
differently from realistic fire conditions
⇒ Calculation method for converting FR test result
A. One FR test + One equation for all materials

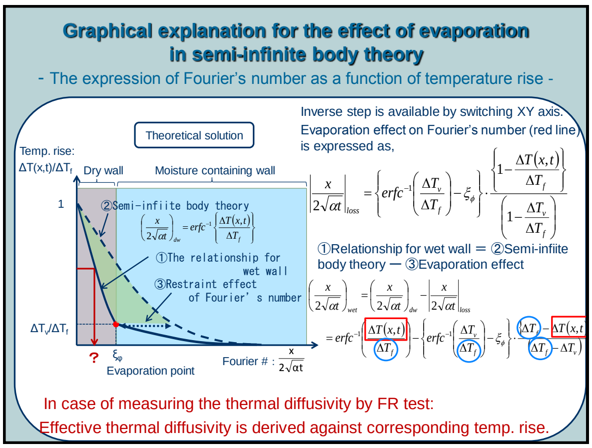

The Limitation for Material Test
No difference for improved board
adding mineral fiber.
Sample size: 5~30mg
Temp (℃)
DTA(μV)
TG(%)
TEMP (℃)
TG(%) GB-F(V)
TG(%) GB-F(X)
DTA(μV)GB-F(V)
DTA(μV)GB-F(X)
0 2000 4000 6000 8000 10000
4

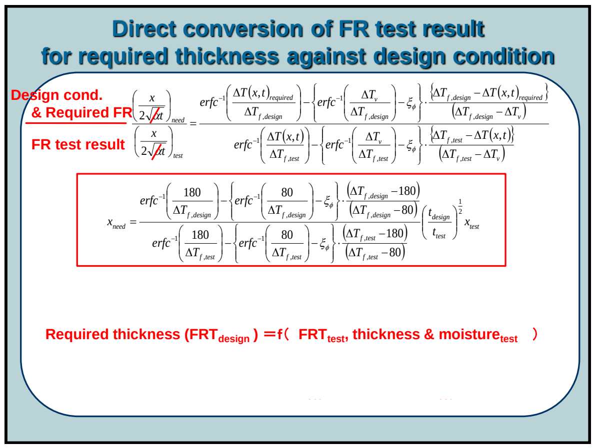

Pros. & Cons. for semi-infinite body theory
･Constant exposed temp.
･Semi-infinite thickness
･Dry materials
･No need add. material test
･Include the effect of cracking and ablation
Theoretical solution
Experimental data
Temp. rise ΔT(x,t)/ΔT_f
Thermal diffusivity and thickness
Heat conduction for dry wall
$\frac{\Delta T_{dw}(x,t)}{\Delta T_f} = erfc\left(\frac{x}{2\sqrt{\alpha t}}\right)$
Time
Temp. rise
180K / 780K
FR test result
Well-known material
Thermal property
Fourier # : $\frac{x}{2\sqrt{\alpha t}}$
Temp. rise: ΔT(x,t)
Temperature profile of moisture containing wall
Move to unexposed surface over time
Evaporation temp. T_v
Inflection point
Distance from surface : x

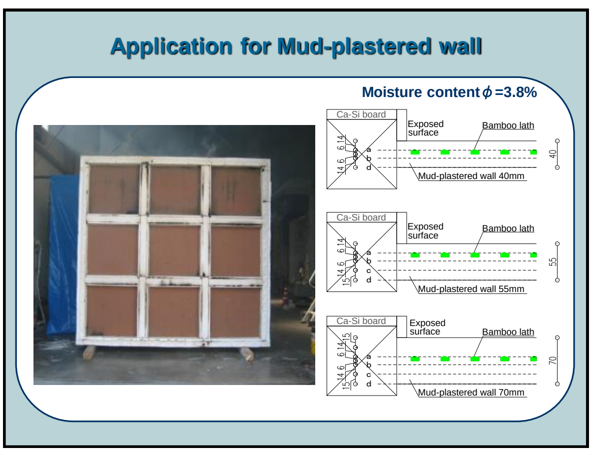

The effect of moisture content on the regression of evaporation point
Conservation of heat at evap. point:
$\dot{q}'' \cdot dA \cdot dt = L_w \phi (\rho \cdot dx \cdot dA) + C_w \rho \cdot dx \cdot dA \cdot (T_v - T_0)$
Convective heat flux to evap. point:
$\dot{q}'' = D \times \lambda \frac{T_f - T_v}{x}$
D : proportional constant
λ : thermal conductivity(kW/mK)
$dt = \frac{1}{D} \frac{L_w \phi + C_w (T_v - T_0)}{C_w (T_f - T_v)} \frac{1}{\alpha} \cdot x dx$
$t_v = \frac{1}{D} \left\{ \frac{L_w \phi + C_w (T_v - T_0)}{C_w (T_f - T_v)} \right\} \cdot \left(\frac{x}{2\sqrt{\alpha}} \right)^2$
Dry wall
Moisture containg wall
Exposed surface
T_f
$\dot{q}''$
dx
Everporation point at $t + dt$
T_v
T_0
x

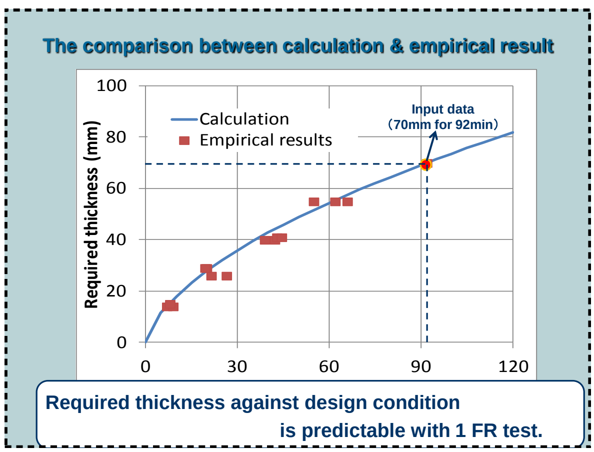

Graphical explanation for the effect of evaporation
in semi-infinite body theory
- The expression of evaporation point as a function of moisture content -
Theoretical solution
Dry wall
Moisture containing wall
Temp. rise
ΔT(x,t)/ΔTf
Semi-infiite body theory
?
Restraint effect of temperature rise
ΔTv/ΔTf
ξφ
Evaporation point
Fourier #
As moisture content is large,
As evaporation point becomes small,
In other ward,
time to evaporate becomes long, and
restraint effect of temp. rise becomes large.


Graphical explanation for the effect of evaporation
in semi-infinite body theory
- The expression of temperature profile as a function of evaporation point -
Theoretical solution
Temp rise.:
ΔT(x,t)/ΔTf
Dry wall
Moisture containing wall
②Semi-infiite body theory
①Temperature profile for wet wall
③Evaporation effect
ΔTv/ΔTf
ξφ
Fourier #
Assuming the equality of two triangle area,
Evaporation effect on temperature rise (red line)
is expressed as,
①Temp. profile for wet wall = ②Semi-infinite body theory − ③Evaporation effect
In the case that the thermal diffusivity is known:
Temperature rise is predicted by given thickness and moisture content.


Graphical explanation for the effect of evaporation
in semi-infinite body theory
- The expression of Fourier's number as a function of temperature rise -
Theoretical solution
Temp. rise:
ΔT(x,t)/ΔTf
Dry wall
Moisture containing wall
②Semi-infiite body theory
①The relationship for wet wall
③Restraint effect of Fourier's number
ΔTv/ΔTf
?
ξφ
Evaporation point
Fourier #
Inverse step is available by switching XY axis.
Evaporation effect on Fourier's number (red line)
is expressed as,
①Relationship for wet wall = ②Semi-infiite body theory − ③Evaporation effect
In case of measuring the thermal diffusivity by FR test:
Effective thermal diffusivity is derived against corresponding temp. rise.

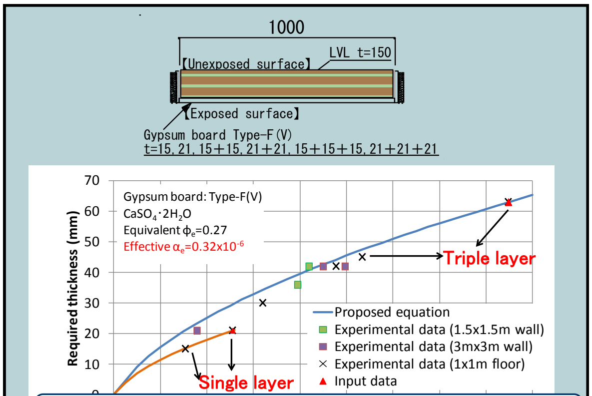

Direct conversion of FR test result
for required thickness against design condition
Design cond.
& Required FR
FR test result
Required thickness (FRTdesign) =f(FRTtest, thickness & moisturetest)


Application for Mud-plastered wall
Moisture content φ=3.8%
Ca-Si board
Exposed surface
Bamboo lath
Mud-plastered wall 40mm
Mud-plastered wall 55mm
Mud-plastered wall 70mm


The comparison between calculation & empirical result
Required thickness (mm)
Calculation
Empirical results
Input data
(70mm for 92min)
Required thickness against design condition
is predictable with 1 FR test.

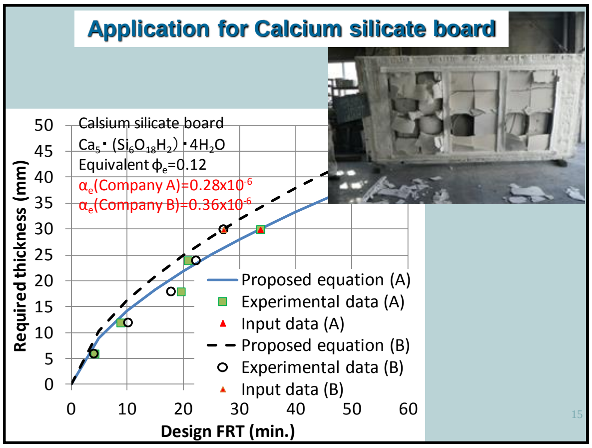
Application for Gypsum board

Experimental data	Thickness (mm)	FR time (min)
1.5x1.5m wall	36	78.875
	42	83.75
3x3m wall	21	35.625
	42	99.25
	42	89.85
1x1m floor	15	30.75
	21	51
	30	64
	42	95.5
	45	106.75
	63	169.5



For the design purpose, Interpolation is conservative.

Application for Calcium silicate board



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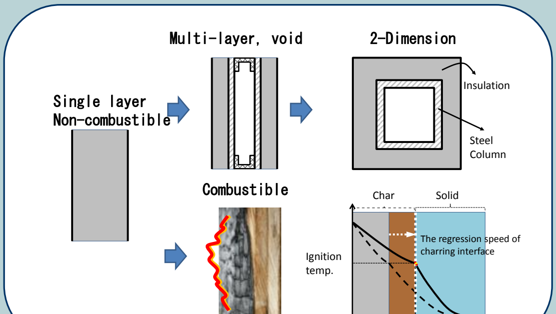
Conclusion

- Semi-infinite body theory is developed for moisture containing wall in the form of equation.
- Direct conversion equation is proposed and validated.
- The key point is…
  - Thermal property is summarized in single term.
  - The theory is applied for FR test to derive it as temperature dependent effective value.
- In result,
  - The expression is simple with no empirical / modification coefficient caused by different heating or boundary condition. (No artificial manipulation)
  - The input data is obtained by FR test which is achieved consensus.
  - And no additional cost for existing results

Future work

Application for multi-layer, void and combustible materials.



Fire Resistance of Timber Panel Structures

Dr. Jun-ichi Suzuki
National Institute for Land and Infrastructure Management (NILIM),
Ministry of Land, Infrastructure, Transport and Tourism (MLIT), Japan

Dr. Tensei Mizukami
Building Research Institute, Japan

Dr. Shiro Nakajima
Building Research Institute, Japan

Contents

Background and Objectives

- The Act for Promotion of Use of Wood in Public Buildings(2010)
  - Establish environmentally friendly and sustainable Society
  - Encourage use of timber materials in building fields
  - Require research activities and review of the building regulations related to timber constructions
- Objectives
  - Clarify fire resistance of timber panel construction
  - Develop design method for timber panel structures
    - Heavy Timber construction : Cross Laminated Timber (CLT) panels
      Laminate Veneer Lumber (LVL) panels

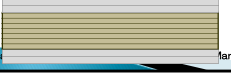
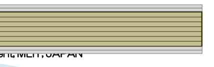

CLT panel construction


GLT panel construction

LVL panel Construction

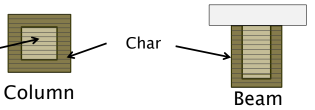
Requirements and Design methods for timber structures

- Required function and performance in fire
  - Load bearing wall and Floor
    - Prevent structural collapse : Load bearing capacity
    - Prevent fire spread : Insulation and Integrity
- Design methods: Encapsulation, reduced section design
  - Encapsulation design
    - Complete Encapsulation : no-charring of timber elements
      - 1h fire resistance: Type X Gypsum boards, 42mm thick on both sides
    - Limited Encapsulation
      - 1h quasi-fire resistance: Gypsum boards, 25mm thick on both sides

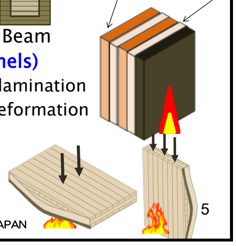
1 hour Fire resistance

1 hour quasi-Fire resistance


Design methods for timber structures

- Reduced Cross-Section design/ Charring design
  - Columns and Beams: Charring rate approx. 0.75 mm/min



- Wall and Floor panels (LVL, CLT panels)
  - Charring behavior: charring rate, delamination
  - Collapse behavior: Buckling, large deformation
  - Fire resistance tests
    - Several types of Timber panels
    - Loaded wall and floor panels



Experiments of Timber panel structure

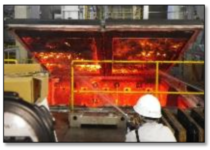
- Fire resistance test of LVL and CLT panels
  - Heating test of timber panels (ISO834)
    - Objective: Charring behavior
    - Experimental Parameters
      - Tree Species: Japanese cedar, Larch
      - Thickness of laminar: 12mm to 30mm
      - Types of Adhesive:
        - Resorcinol-formaldehyde resin (RF)
        - Aqueous polymer-isocyanate-based resin (API)
      - Panel Type: LVL, CLT
      - Element Type
        Wall (Vertical element)
        Floor (Horizontal element)


Wall

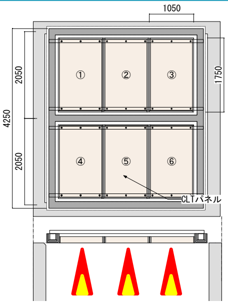
Wall (after fire test)

Heating test of timber panels (Specimens)

Horizontal panels

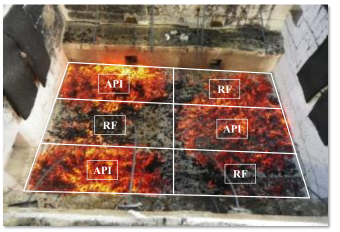


Burning Panels(just after test)

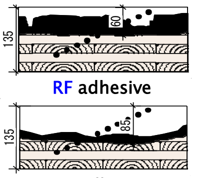


Setup(Horizontal Furnace)

Heating test of timber panels(furnace)



Delamination of charred layer



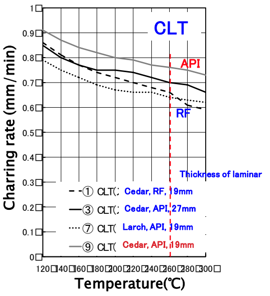
RF adhesive

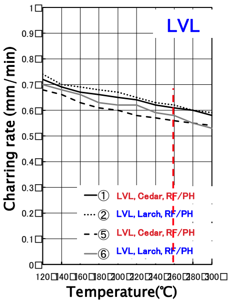
API adhesive

Charring of CLT panel

- Stickability of charred layers RF > API

Charring rate of vertical panels





Charring rates of CLT panels :0.65 to 0.75 mm/min
LVL panels : 0.6 mm/min

Experiments of Timber panel structure

- **Fire resistance test of Loaded panels**
- Objective: Collapse behavior
  - Experimental Parameters
    - Axial Load Ratio: 1/2 to 1/8
    - Panel Type: LVL(150mm)
      CLT(150mm, 210mm)
  - Experimental Setup
    - Simple Support (pin)
    - Centrally loaded condition
    - One-sided heating

Wall Specimen (CLT-150)

List of Wall Specimens and condition

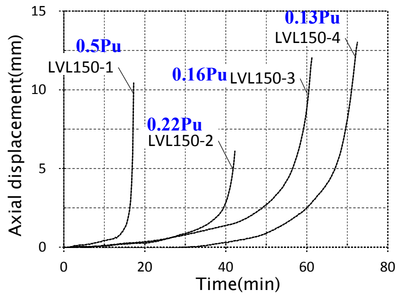
Symbol	Dimension (Thickness x width x Length)	Number of longitudinal plank	E (kN/mm²)	Buckling length (mm)	Cross-sectional area (mm2)	Applied load (kN)	Failure time (min)
CLT150-A	500, 150	3	4.58	2150	75000	Pu=934	0
CLT150-1		3	4.53			(1/3)Pu=312	23.75
CLT150-2		3	4.50			(1/4)Pu=234	63.0
CLT150-3		3	4.67			(1/6)Pu=156	55.25
CLT150-4	(150×500×4300)	3	4.64				66.75
CLT210-A		4	4.15	3300	105000	Pu=1523	0
CLT210-1	500, 210	4	4.27			(1/3)Pu=507.6	22.25
CLT210-2		4	4.28			(1/4)Pu=380.7	50.5
CLT210-3		4	4.27			(1/6)Pu=253.8	68.5
CLT210-4	(210×500×3300)	4	4.20			(1/8)Pu=190.4	79
LVL-0	500, 150	–	6.6	3300	75000	Pcr=963	0
LVL150-1		–				P=451	17.25
LVL150-2		–				P=212	43.5
LVL150-3		–				(1/6)Pcr=161	61.25
LVL150-4	(150×500×3300)	–				(1/8)Pcr=121	72.5

Test Specimen (LVL panel wall)

Before fire test

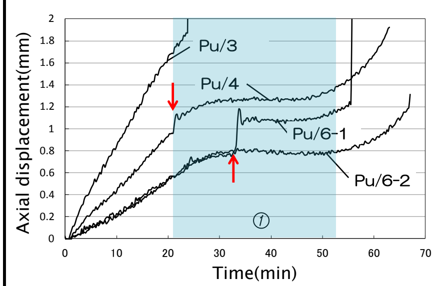
After fire test

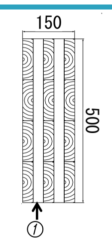
Results　Axial displacement of LVL panel wall



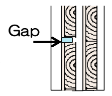
Steady increase of axial displacement before buckling

Results　Axial displacement of CLT panel

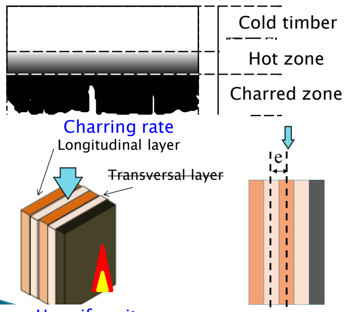




- Difference of behavior between LVL and CLT panel
- Rapid increase in axial disp. caused by discontinuity of transversal plank (gap between planks)

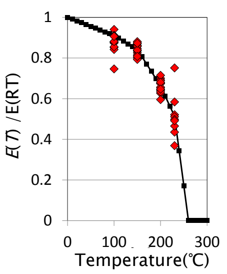


Prediction of buckling strength of walls in fire



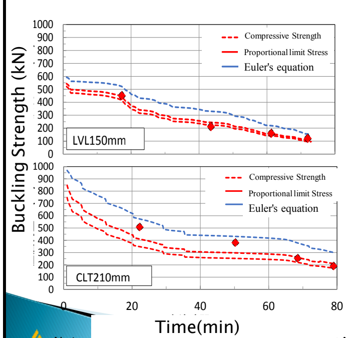
Ununiformity of cross section

Eccentricity



Degradation of $E(T)$

Prediction of buckling strength of walls in fire



Prediction of buckling strength

- Euler's equation
  Centrally loaded condition
- Secant equation

$$P_{cr} = \frac{\sigma_y A}{1 + \frac{ec}{i^2}\sec\left(\frac{\pi}{2}\sqrt{\frac{P_{cr}}{P_E}}\right)}$$

- Material Strength
  - Compressive strength
  - Proportional limit stress
- Transversal layer in CLT panel would braces.

Conclusion

- A series of fire testing of timber panel structure was conducted to develop the reduced design method.
- Charging rates of timber panels mainly depend on Adhesive type.
- Stickabiliy of RF adhesive is greater than API adhesive.
- Residual strength of timber panel structures in fire is predictable using Secant Equation with the influence of charring.

Thank you for your kind attention.

An approach for ascertaining residual capacity of reinforced concrete beams exposed to fire

Venkatesh K. R. Kodur [a] and Ankit Agrawal[a]

[a]Department of Civil and Environmental Engineering, Michigan State University, USA

Operation Tomodachi –Fire Research Meeting

NIST, Gaithersburg

March, 2015

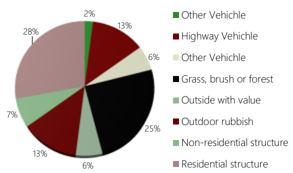
Outline

- **Introduction**
- **Background and Motivation**
- **Previous Studies on Post-Fire Residual Strength Evaluation**
- **Approach for Evaluating Post-Fire Residual Capacity**
  - **Critical Parameters**
  - **Case Study**
- **Conclusions**

2

The Fire Problem in Recent Years

Reported fire incidents by major property class in 2012 [NFPA]



- An estimated **1,375,000** fires
- Killed **2,855** civilians (non-fire fighters)
- An estimated **$12.4 billion dollars** in damage

In **2007-11**, an estimated **15,400 high-rise** structure fires were reported per year accounting for **3%** of the reported structure fires reported **[NFPA]**

Major fire-related high rise building collapses (partial or complete) over the last decade

- **TU Delft, Faculty of Architecture building, Netherlands (May, 2008)**
- **Windsor Tower, Madrid (February, 2005)**
- World Trade Center, New York (2001)

3

Background and Motivation

Concrete construction finds **widespread application** in **modern day infrastructure.**

- **Good Fire Resistance**
  - Exhibit **good passive fire resistance**
  - Better **active fire protection systems** and **fire-fighting strategies**
  - **Complete collapse** due to fire alone is rare
- **Uncertainty in Post-Fire Response**
  - Fire induced **damage** is **highly variable**
  - **Degradation** may **not be too apparent** in short fires

Need to ascertain residual capacity through **rational engineering** approaches prior to **re-occupation** and for subsequent **retrofitting**.

Trump Tower, Chicago

Winsdor Tower, Madrid after fire (February, 2005)

4

Previous Studies on Post-ire Residual Strength Evaluation

Approaches to **evaluate residual capacity** of **fire exposed RC beams** in the past:

Hsu and Lin (2006), Kodur et al. (2010), Bai and Wang (2011)

- **General Procedure**
  - **Simplified sectional analysis**
  - **Temperatures** using **finite difference** approaches or **empirical equations**
  - **Residual capacity** calculated based on **reduced strength of reinforcement** and **damaged concrete area**
- **Drawbacks**
  - No consideration for initial **load levels** or **boundary conditions** of the member
  - **Strain hardening** in reinforcing steel at high temperatures not accounted for
  - **Tension stiffening effect** in concrete at high temperatures is ignored
  - Cannot predict **residual deformations** in RC beams exposed to fire

$$\lambda = 1{\cdot}45\left(t_h + \frac{t_c}{2}\right)^{0{\cdot}2}\left(0{\cdot}4 + 0{\cdot}03\frac{H}{B}\right) - 5a$$

Non-dimensional parameter for section dimensions and fire characteristics

$$T_{smax} = \lambda T_{fmax}$$

Maximum rebar temperature based on peak fire temperature

$$M_u = A_s f_{yT}\left(d^* - \frac{A_s f_{yT}}{1{\cdot}7 b^* f'_c}\right)$$

Residual Moment Capacity for singly reinforced section

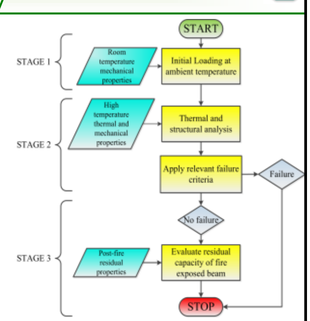
Simplified approach by Kodur et al. (2010)

5

Approach for evaluating post-fire residual capacity

A **three stage approach** is proposed:

- **STAGE 1**
  - Apply loads to simulate realistic loading conditions at room temperature
- **STAGE 2**
  - Conduct a sequentially coupled thermal stress analysis to evaluate response during fire event
- **STAGE 3**
  - If the beam survives fire exposure, trace residual response via incremental loading to failure with residual deformations from Stage 2 as initial state



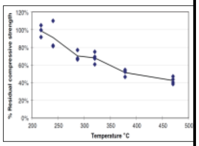
Flow chart describing the three stages involved in residual capacity analysis.

6

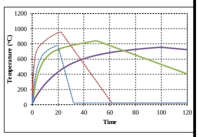
Critical Parameters influencing Post-fire Residual Capacity

The post fire residual capacity of RC beams depends on:

- **Structural parameters**
  - Load Level
  - Boundary Conditions
- **Fire exposure scenario**
  - Duration of Heating and Cooling phases
  - Peak Fire Temperature
- **Material characteristics**
  - Thermal and mechanical properties during fire exposure
  - Degradation in mechanical properties of concrete after fire exposure
  - Recovery in mechanical properties of concrete after fire exposure



Residual compressive strength of concrete as per Nassif (2005)



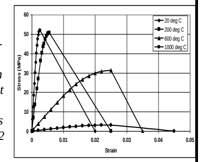
Parametric fire exposures as per Eurocode 1 for different compartment conditions

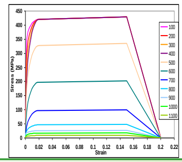
Properties of Constituent Materials

The properties of constituent materials play a crucial role :

- **Stage 1**
  - Room temperature mechanical properties of concrete and steel reinforcement are utilized
- **Stage 2**
  - Thermal conductivity and specific heat of concrete and reinforcing steel
  - Modulus of elasticity, yield strength, ultimate strength and strain at ultimate strength are also a function of temperature
- **Stage 3**
  - After cooling down of the beam, the post fire residual properties of reinforcing steel and concrete are utilized

Typical stress-strain curves for concrete in compression at elevated temperature as per Eurocode 2





Typical stress-strain curves for reinforcing steel at elevated temperature as per Eurocode 2

Failure Criteria

Different failure criteria are to be considered at each stage of the analysis depending on the relevant failure limit state:

- **Stage 1**
  - Strength limit state generally governs
  - Corresponds to the point at which flexural or shear capacity is exceeded
- **Stage 2**
  - Strength limit state corresponding to exceedance of flexural or shear capacity
  - Deflection increases significantly at high temperature
  - Deflection or rate of deflection limit state is to be applied as a reliable performance index
- **Stage 3**
  - After cooling down, the properties of reinforcing steel recover
  - Strength limit state generally governs

- **Thermal Limit State** (ASTM E119)
  - Limit of unexposed temperature
    - Average of 9 points = 140°C or at any point = 180°C
  - Limit of rebar temperature: 593°C
- **Strength Limit State** (ASTM E119)
  - Moment or shear capacity exceeds external loads
- **Deflection Limit State** (BS 476)
  - Maximum deflection limit: L/20
  - Rate of deflection limit: $L^2/9000d$(mm/min) or L/30

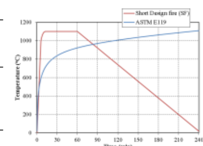
Failure limit states

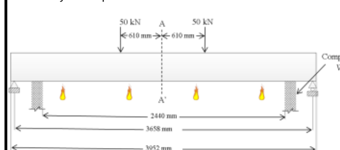
Case Study

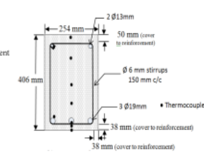
Two concrete beams tested under fire exposure by **Dwaikat and Kodur (2009)** were selected for residual capacity analysis.

Beam designation	Support Condition	Fire exposure	Concrete type	Initial Load (kN)	Fire resistance (min)	Extent of spalling
B1	Simply supported	ASTM E119*	NSC	50	180	Minor
B2	Axially restrained	SF	NSC	50	No Failure	Minor

Summary of test parameters and results used for model validation

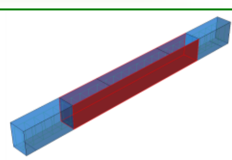






Analysis Procedure

- **Uncoupled Heat Transfer Analysis**
  - **Temperature** at each node considered as **only degree of freedom**
  - **Temperature** in **rebar** considered to be the **same as** that of **concrete** at that location
  - A combination of **convection** [$q = h(\theta - \theta_0)$] and **radiation** [$q = \sigma\mathcal{E}((\theta - \theta_Z)^4 - (\theta_0 - \theta_Z)^4)$] boundary conditions
- **Sequentially Coupled Thermo-mechanical Analysis**
  - Temperatures calculated from thermal analysis applied as nodal loads in structural model
  - Thermal stress analysis
  - Fire induced degradation



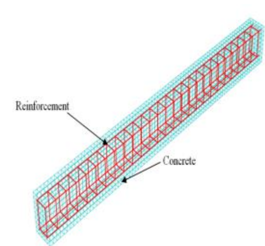
Three sided fire exposure through surface based interactions

Loading and boundary conditions

Finite Element Model

The three stage approach is implemented using the commercial FEA package **ABAQUS**

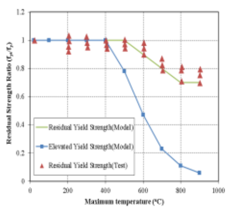
- **Discretization**
  - **Concrete** discretized using **8 node linear brick elements** (DC3D8 heat transfer elements or C3D8R stress elements with Reduced Integration)
  - **Reinforcement** discretized using **2 node link elements** (DC1D2 heat transfer element or T3D2 truss element)
  - **Perfect bond** assumed between reinforcement and concrete and implemented through **tie constraint**



Discretized view of the selected beam for numerical simulation

Material Properties for Analysis

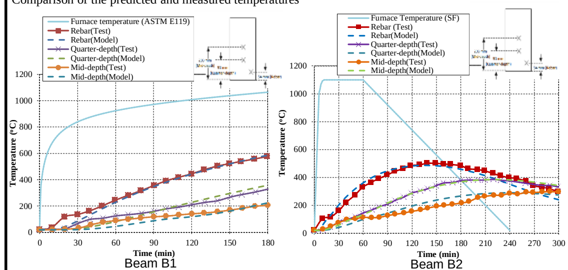
- **Stage 1**
  - Typical uniaxial stress-strain relationships for concrete and steel at room temperature are adopted
- **Stage 2**
  - Temperature dependent thermal and mechanical properties
  - Eurocode 2 and 3 provisions
- **Stage 3**
  - Residual uniaxial compressive and tensile strength of concrete after assumed to be 10% less than the strength attained at the maximum temperature
  - The residual stress-strain relationship for reinforcing steel is calculated using degradation observed by Neves et al. (1996)



Normalized residual strength and yield strength of reinforcing steel with temperature

Results and Discussion: Thermal Analysis

Comparison of the predicted and measured temperatures

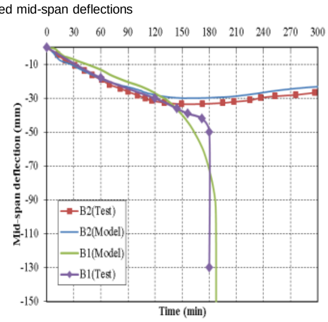


- **Key Observations**
  - Temperatures in beam B1 rise steadily for entire duration of fire exposure
  - Temperatures in beam B2 attain peak value during cooling phase of fire and decay subsequently, with peak rebar temperatures below 500°C

Results and Discussion: Structural Analysis

Comparison of the predicted and measured mid-span deflections

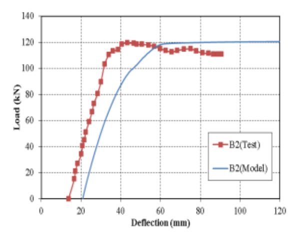
- **Key Observations**
  - Mid-span deflections increase during early phases of fire exposure
  - Beam B1 fails at about 180 minuets due to excessive deflection and there is no residual strength left for stage 3 analysis
  - For beam B2, due to cooling phase, temperatures experienced are relatively lower and a recovery in deflections is observed during decay phase of fire



Results and Discussion: Residual Analysis

Comparison of the predicted and measured load-deflection response for residual strength test of beam B2

- **Key Observations**
  - The predicted load deflection response by the finite element model is very similar to the measured response during the test
  - Predictions by the model predict a greater degradation in capacity than cross sectional analysis
  - Significant residual capacity is retained after fire exposure



Beam designation	Fire exposure	Maximum rebar temperature: °C		Residual deformation: mm		Residual load carrying capacity: kN (% Reduction)		
		Measured	Model	Measured	Model	Measured	Model	Simplified Approach*
B2	SF	493	489	13.7	20.9	119.5 (NA)	120.8 (16)	82.7 (11)

* Simplified approach proposed by Kodur et al. [2]

Conclusions

A general approach for evaluating residual capacity of fire exposed RC beams was developed. Based on the results of analysis the following conclusions can be drawn:

- **Three stages of analysis** are required **for evaluating the residual strength**
- The finite element computer software ABAQUS, can successfully be applied for evaluating the response of fire exposed reinforced concrete structural members
- **Incorporating temperature dependent strain hardening properties of steel** reinforcement and **tension stiffening properties of concrete** leads to **more realistic predictions** of **residual capacity** than simplified cross sectional analysis
- **Reinforced concrete beams retain significant residual flexural capacity** after exposure to design fire scenarios wherein the **peak temperatures experienced by rebars** remain **below 500°C**.

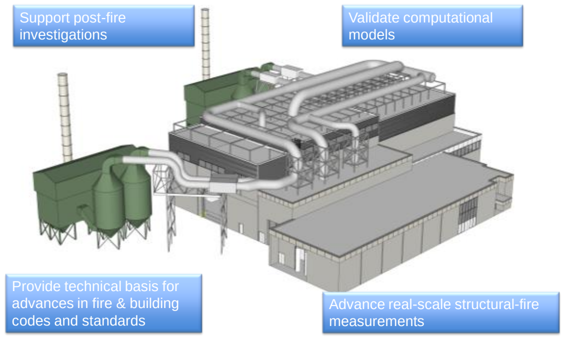
Thank You for your time …

Structural Fire Measurement Capabilities at the NIST National Fire Research Laboratory

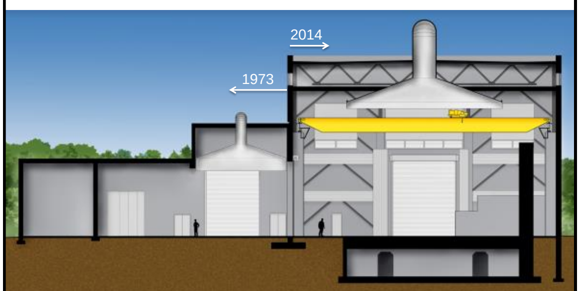
Operation Tomodachi – Fire Research
NIST, Gaithersburg MD
March 18th , 2015

Matthew Bundy, NFRL Director of Operations

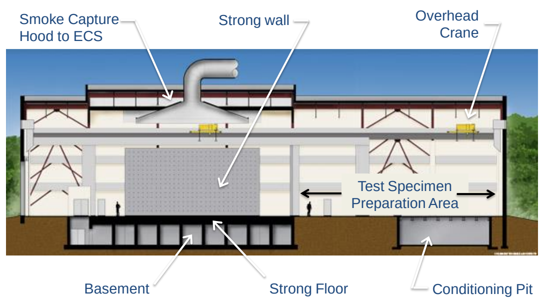
The National Fire Research Laboratory (NFRL) is a unique facility dedicated to understanding fire behavior and the structural response to fire.



The New Structural Fire Lab at NIST



Major Features of the NFRL Expansion



Basis of Design for NFRL

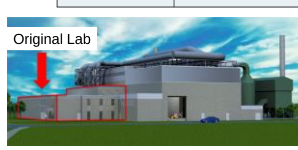
NFRL Expansion Design Objectives*

- Conduct tests on **real-scale** structural systems and components
- Apply **controlled loads** to the test structure to simulate true service conditions
- Measure response of the **structural system** and components up to incipient local or global collapse.
- Create **realistic fires** that grow, spread and decay
- Characterize the fires **in real time**

*Basis of Design considered key findings of 2003 SFPE Roadmapping Workshop and several Stakeholder Workshops between 2004 and 2008.

Summary of Capabilities

Specification	Original Laboratory	New Expansion
Total Floor Area	1000 m²	2000 m²
Fire Capacity	1 MW (small hood) 3 MW (medium hood) 10 MW (large hood)	20 MW
Strong Floor/Strong Wall	None	18 m x 27 m x 1.2 m thick strong floor and 18 m x 9 m x 1.2 m thick strong wall
Structural Loading	None	Hydraulic loading system, 240 kN-960 kN actuators; 760 mm stroke



Example of a10 MW Fire

Research Focus

- Develop metrology to quantify high temperature strains and displacements throughout a structure (beyond point measurements)
- Measure the performance of real-scale structures under realistic fire and structural loading in controlled laboratory conditions.
- Develop an experimental database on the performance of large-scale structural connections, components, subassemblies and systems under realistic fire and loading.
- Validate physics-based models to predict the fire performance of structures.
- Provide the technical basis for performance-based standards, foster innovation, and enhance safety of buildings, infrastructure, emergency responders, and the public at large.

Fire Measurement Development

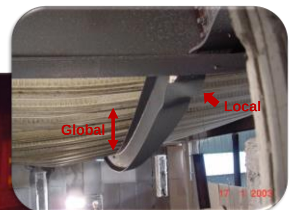
Accurate and reliable measurements are needed to quantify:

- Structural Forces
- Displacement
- Strain
- Temperature (Gas and Surface)
- Fire Heat Release Rate
- Heat Flux
- Fire Growth and Spread

Displacement and strain

Need repeatable, accurate and versatile measurement methods that will work in a hostile environment

- Essential for experimental control & model validation
- Engineering & technology barriers



Source: http://www.dec.uc.pt/~lborges/cardington/after/index39.htm

This problem has not been solved…
(mechanical and optical techniques have been used successfully in some situations)

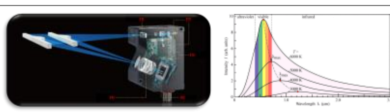
Source: http://www.steelconstruction.info/Fire_testing

Displacement and strain

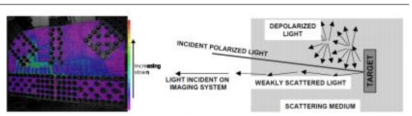
Candidate technologies for "deep dive" (low & high tech)

Mechanical (point)

Laser (point/line)



Optical (surface)

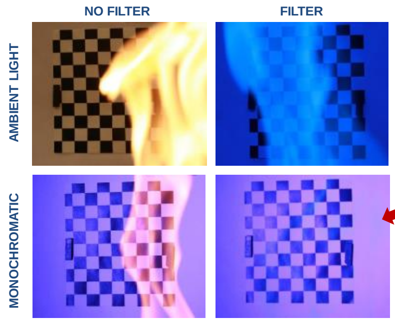


Displacement and strain

Full-scale experimental validation with real fire

Displacement and strain

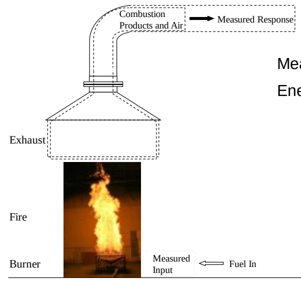
First results with optical systems are promising…



Flame no longer obstructing target pattern

Fire Calorimetry Measurement

The rate of heat released by a burning material a the primary measurement of the NFRL.



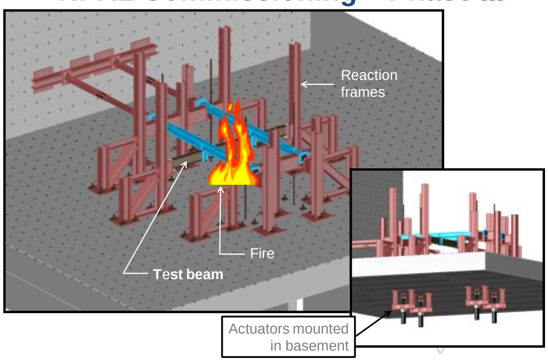
$$HRR = (\Delta H_C)_{Mass\_O2}(\dot{m}^o_{O2} - \dot{m}_{O2})$$

Measurement Validation:

Energy In = Energy Out

- Input: metered flow of natural gas (traceable to primary flow standard and gas composition standards)
- Verify 100% complete combustion
- Measured response: heat released (oxygen consumption calorimetry)

NFRL Commissioning – Phase III



Thank You!

Please join us for the Lab Tour

engineering laboratory

Experimental Design of Large-scale Composite Floor System Subjected to Fire

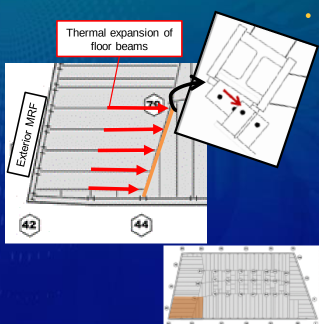
March 18, 2015

John Gross, **Lisa Choe**, Fahim Sadek

NIST National Institute of Standards and Technology U.S. Department of Commerce

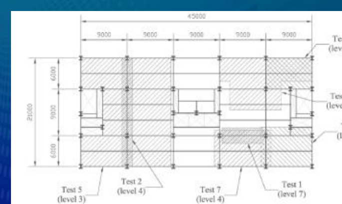
Contents

Fire-induced collapse of WTC 7 building



- Factors that led the failure of composite floor systems
  - Long floor beam spans,
  - Asymmetrical framing of floor beams,
  - Non-composite girders,
  - Connection type, especially the use of seated connections

Cardington test series



8 story steel framed building

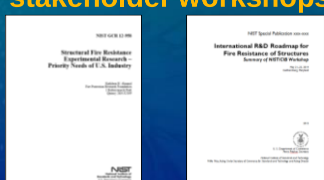
Regular floor plates

Symmetrical framing of floor beams

Fire protection on primary members & connections

- Steel temperature (secondary beams) exceeded 1000 °C
- Excellent performance due to both membrane/diaphragm effects of the reinforced composite slab with steel beams
- Connection failure observed during the cooling phase of fire

Recommendations from previous NIST stakeholder workshops



- Understanding the embedded safety factors in current prescriptive design method
- Conducting large-scale experiments to understand the system-level performance of engineered building structure
- Identifying realistic fire scenarios
- Generating a good test database for validation of analytical models

Experimental Design Objectives

- To provide the technical basis for performance-based standards for fire resistance design of **composite floor systems** and foster innovation in the building design and construction industry.
  - Apply realistic structural floor loads and fire under controlled laboratory conditions
  - Measure the true structural-fire performance of composite floor system
  - Develop an experimental database on structural performance of connections, components, subassemblies and systems under realistic fire conditions
  - Validate physics-based models to predict the fire performance of steel building system.

Test Variables for NFRL Composite Floor Tests

Structural
- Symmetry in framing
- Floor plate geometry
- Restraint provided by adjacent bay framing or floor (continuity)
- Types of connections

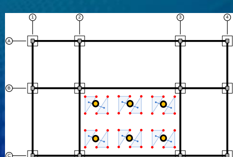
Fire
- Heat (fuel) source
- Heat release rate
- Extent of fire
- Fire-thermal boundary condition

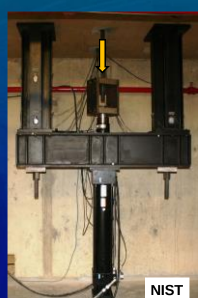
Fire-Structural Interaction

Proposed Test Matrix

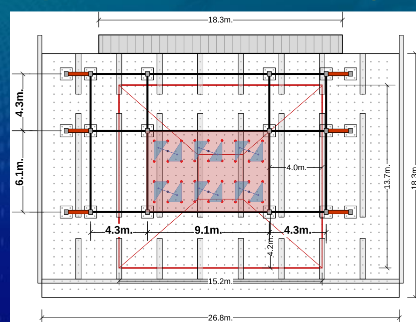
Test No	Fire Condition	Fireproofing	Framing	Floor plate	Bay location	Floors involved
1 (BASE STRUCTRE)	Fire 1	Code Required	Balanced	Regular	Edge	One
2	Fire 1	Engineered	Balanced	Regular	Edge	One
3	Fire 1	Engineered	Unbalanced	Regular	Edge	One
4	Fire 1	Engineered	Unbalanced	Irregular	Edge	One
5	Fire 2	Engineered	Balanced	Regular	Edge	One
6	Fire 1	Engineered	Balanced	Regular	Corner	One
7	Multi-floor	Engineered	Balanced	Regular	Edge	Two
8	Standard Fire	Code Required	Balanced	Regular	Edge	One

Design of Structural Loading System (Whiffletree system)





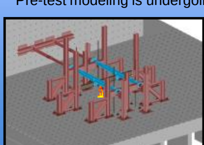
Proposed Test Frame Configuration



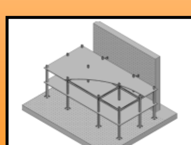
Plan view of two story gravity frame (H_{story}= 3.7 m)

Ongoing/Future Work

Commissioning Project
- Large-scale steel beam will be tested under structural and localized fire loading conditions.
- Fabrication of test assembly is undergoing.
- Pre-test modeling is undergoing.



NFRL Composite Floor Tests
- Preliminary design is complete.
- Plans are underway to solicit feedback on test configuration.
- Pre-test modeling will be performed.



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A Design Fire for Full-scale Steel Structure/Fire Experiments

March 18, 2015

Operation Tomodachi - Fire Research

William Grosshandler
Engineering Laboratory
National Institute of Standards and Technology

NIST National Institute of Standards and Technology U.S. Department of Commerce

OVERALL OBJECTIVE

- Determine response of a prototype steel-framed building subjected to a large fire that stresses a composite floor system, beams, and connections beyond point of failure (but not to collapse)

OUTPUT

- Experimental data on structural temperatures, deformations, and failure modes as function of time and position
- Replicate experiments with quantified uncertainties in measurements and boundary conditions
- Comparative numerical simulations of experiments (*a priori* and *a posteriori*)

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DETERMINING THERMAL LOAD

FACTORS CONSIDERED
- Bay geometry
- Fuel load (MJ/m^2)
- Ventilation
- Measurement constraints and repeatability

FIRE GROWTH OPTIONS
- Previous fire experiments: use as reference
- Standard fire curve: controlled temperature (T) vs time (t) relation, heat release rate (HRR) unspecified (e.g., ISO 834)
- Parametric fire curve(s): multiple options for controlled HRR vs time relation, T unspecified (e.g., EUR 26698 EN)
- Naturally-burning fire: HRR and T are unspecified; direct consequence of distribution of fuel, ventilation, and geometry

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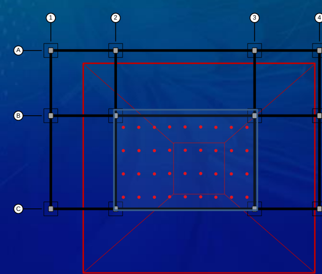
BAY GEOMETRY

OVERALL DIMENSIONS: 9.1 m x 6.1 m x 3.3 m high, with composite floor above and fire resistant (non-load bearing) walls



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FUEL LOAD

FROM PREVIOUS LOAD SURVEYS (e.g., EUR 26698 EN, table 1.4.2)

Shopping center	600 to 940 MJ/m^2
Standard office	420 to 660 MJ/m^2
Library	1500 to 2300 MJ/m^2

CHARACTERISTIC FIRE HEATING VALUES FOR VARIOUS CONTENTS (e.g., EUR 26698 EN, table 1.4.1)

Paper, cardboard, cotton, wood	17 to 20 MJ/kg
Plastics	20 to 40 MJ/kg
Diesel fuel, gasoline, n-heptane	45 MJ/kg
Natural gas	50 MJ/kg

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VENTILATION

OVER-VENTILATED FIRE: HRR within room controlled by available fuel; limited by air brought in by natural ventilation; produces less smoke.

UNDER-VENTILATED FIRE: HRR within room controlled by available air, smokier; excess fuel may feed fire external to room.

OPENINGS INTO ROOM DICTATE BOUNDARY BETWEEN TWO REGIMES: For wood crib fires with open areas in walls equal to A_{vent} and vent height equal to h,

$A_{vent}\sqrt{h} > 10\ m^{5/2}$ ➔ fuel controlled HRR (i.e., over-ventilated)

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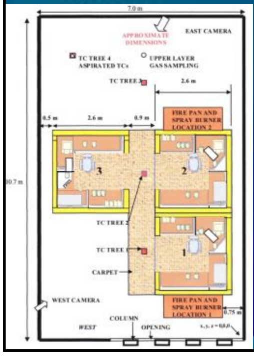
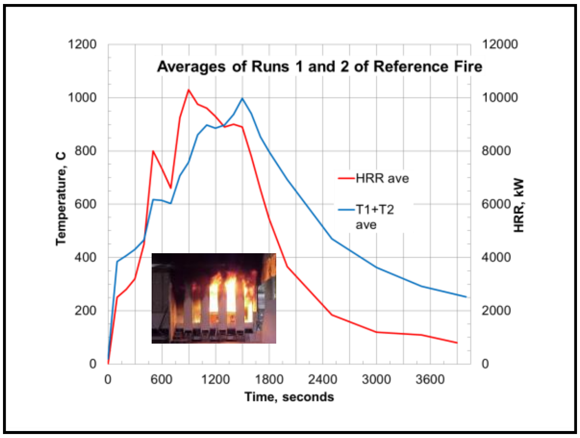
REFERENCE FIRE A

NIST (2005): Full-scale office fire



Parameter	value
room depth x width x height	10.7 m x 7 m x3.36
vent opening, height x width	2.12 m x 2.25 m
vent area	4.77 m^2
$A_{vent}\sqrt{h}$	6.9 m $^{5/2}$
fuel	3 work stations, 40 L of heptane (400 MJ/m^2)
duration	4000 s
Peak temperature	~1050 °C

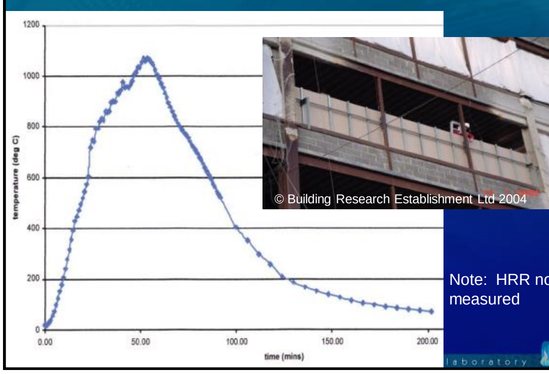


REFERENCE FIRE B

BRE Cardington (2003): Test 7 conducted in eight-story steel structure, part of European collaborative study.

Parameter	value
room depth x width x height	11 m x 7 m x 4.1 m
vent opening, height x width	1.27 m x 9.0 m
vent area	11.4 m^2
$A_{vent}\sqrt{h}$	12.9 $m^{5/2}$
fuel	Wood cribs, 720 MJ/m^2
duration	12,000 s (3.3 hr)

BRE Cardington Test 7



Note: HRR not measured

PROPOSED PARAMETRIC FIRE

BASED ON EUR 26698 EN, Fig. 1.4.4

Parameter	value
room depth x width x height	6.1 m x 9.1 m x 3.3 m
vent opening, height x width	2.12 m x 3.24 m
vent area	6.87 m^2
$A_{vent}\sqrt{h}$	10 $m^{5/2}$
Fuel*	Natural gas, 1250 MJ/m^2
duration	14,400 s (4 hr)
Peak temperature	~1050 °C

*Energy load might represent a combination office/library .

PROPOSED PARAMETRIC FIRE

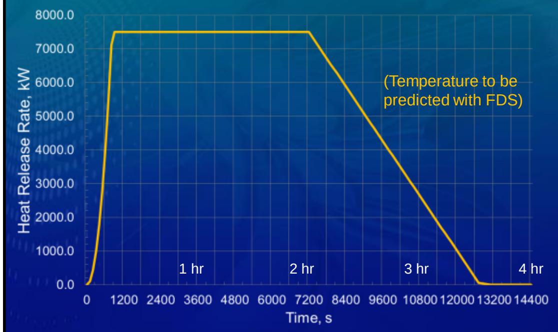
SECOND-ORDER GROWTH WITH TIME
- medium growth rate

PEAK HRR OF 7500 kW
- 40.5 kW/m^3 , same as in NIST Reference Fire A
- Peak reached at 900 s

MAINTAIN PEAK UNTIL 70% OF TOTAL ENERGY CONSUMED
- 48,600 MJ at 7200 s (2 hr)

LINEAR DECREASE UNTIL TOTAL ENERGY DEPLETED
- 69,400 MJ at 12,600 s (3.5 hr)

PROPOSED PARAMETRIC FIRE



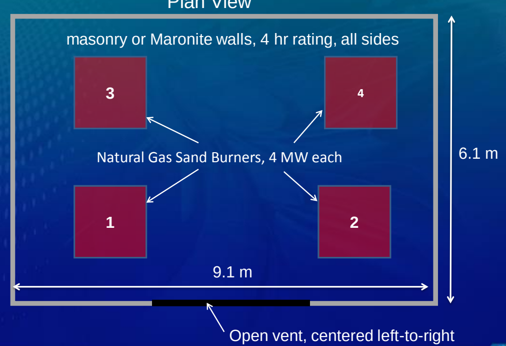
PROPOSED PARAMETRIC FIRE

WHY NATURAL GAS?

- Allows independent control of HRR during experiment
- Extensive experience with high accuracy flow rate measurements and independent means of HRR calculation
- Lowest sooting fuel, provides best chance for optical measurements of displacement
- Best suited for FDS simulation
- Provides baseline for comparison to future solid fuel fires

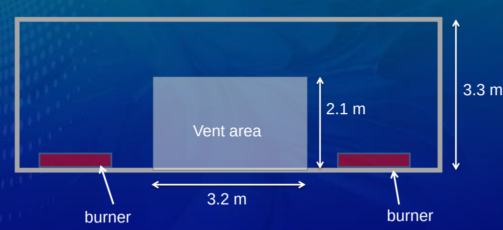
EXPERIMENTAL BAY WITH SAND BURNERS

Plan View

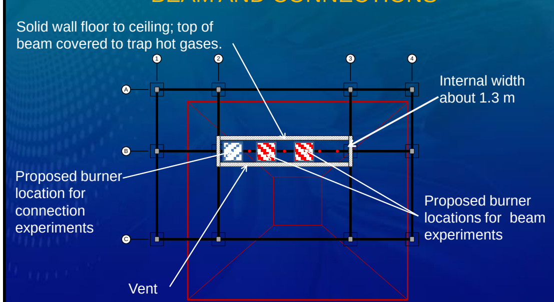


EXPERIMENTAL BAY WITH SAND BURNERS

Elevation



ISOLATED FIRES UNDER RESTRAINED BEAM AND CONNECTIONS



PROPOSED FIRE EVALUATION SEQUENCE

BURNERS
- Construct and evaluate control system and sustained heat output

NUMERICAL SIMULATION OF THERMAL ENVIRONMENT
- FDS calculations to check impact of various burner and vent strategies on upper layer temperatures

ENCLOSURES
- Conduct short duration burns in enclosure to determine relation between upper layer gas temperature and HRR
- Compare with FDS

EXPECTED OUTCOME

- Indication of how steel structures with composite floors of the type evaluated might behave in a beyond-design fire condition (i.e., beyond the fire resistance rating required by current building codes)
- Not a representation of a specific “Design Fire Scenario” in the sense associated with Performance-Based Design
- Identification of weaknesses in experimental and numerical procedures on which continued research may be necessary

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THANK YOU

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Appendix4 Posters Provided

Determination of Design Fire Load for Structural Fire Safety Design of Building in the Compartment Subdivided by Non-fire Rating Partitions

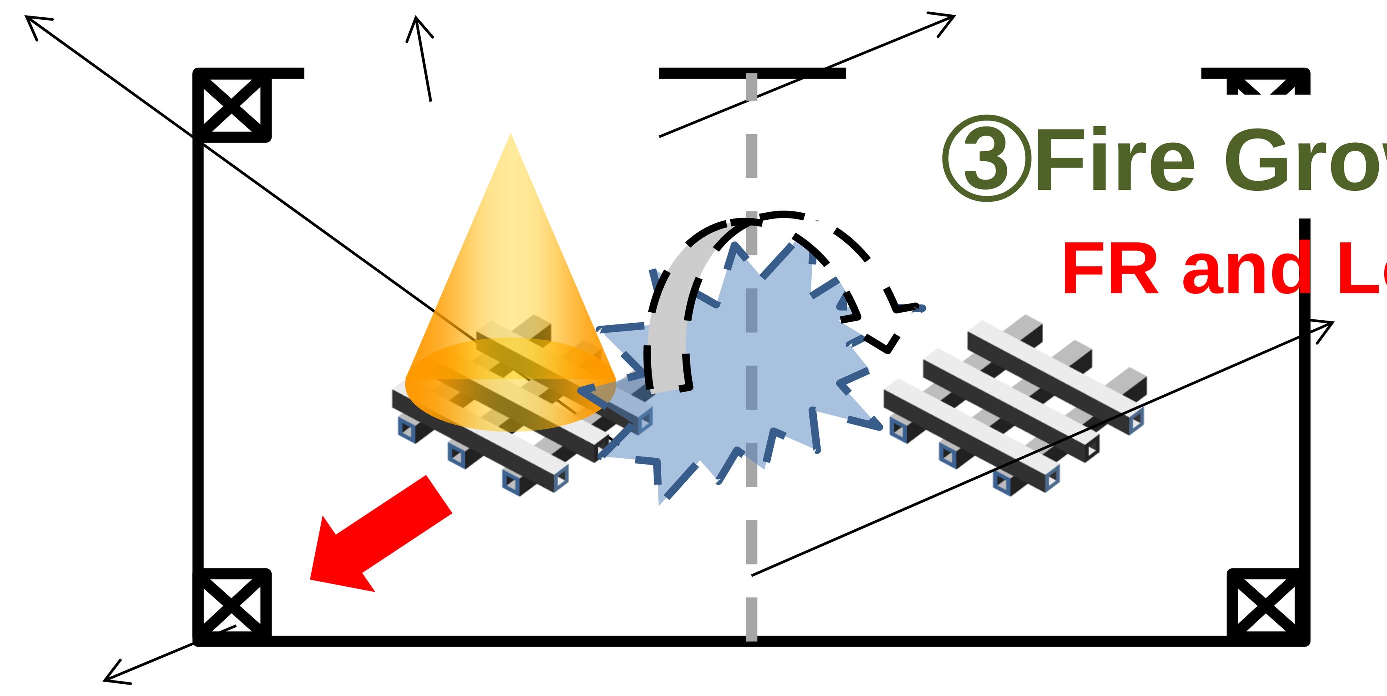
T. Mizukami. Building Research Institute, mizukami@kenken.go.jp

Achieved Integrated Framework by Introducing Probabilistic Risk-based approach

The Flow of P-b FSD

①Fire Dynamics

Fire load, Opening parameter, Room size



③Fire Growth Scenario?

FR and Location of partition, Fire load

Detailed Thermo- physical properties of Material

Fire Condition

②Structural Analysis

Limitation in the use of Computational tools

【Solution】Direct Conversion Eqn. for FR test results

Treatment for Uncertainties in Crossover Field

【Deterministic Approach】

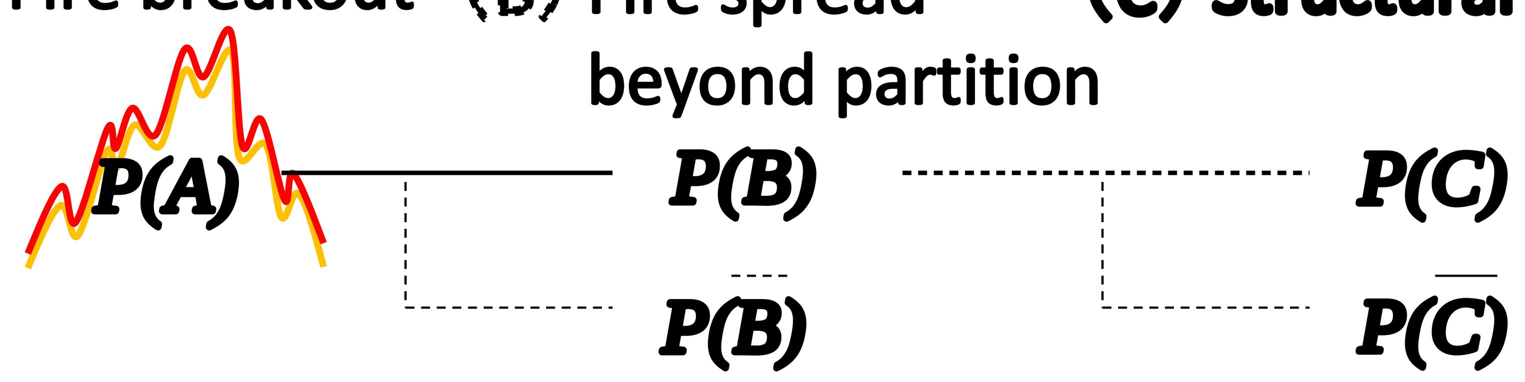
worst case scenario / high safety margin

⇒The more evaluation region is integrated, the more safety margin is integrated.

【Probabilistic Risk-based approach】

An existence of the partition plays increment roll in P(C), but reduction roll in P(Ḃ), therefore, the overall effect seems to be balanced out.

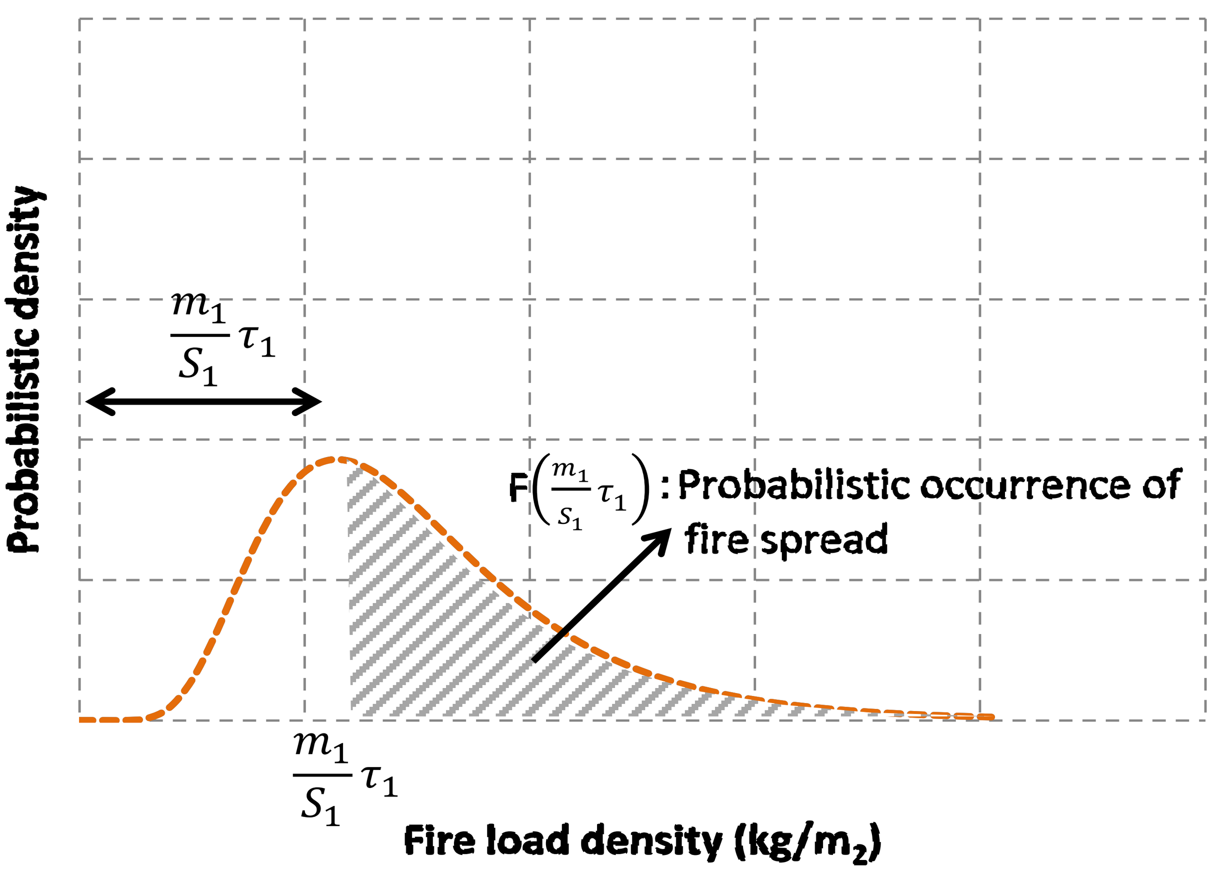
(A) Fire breakout (B) Fire spread beyond partition (C) Structural failure

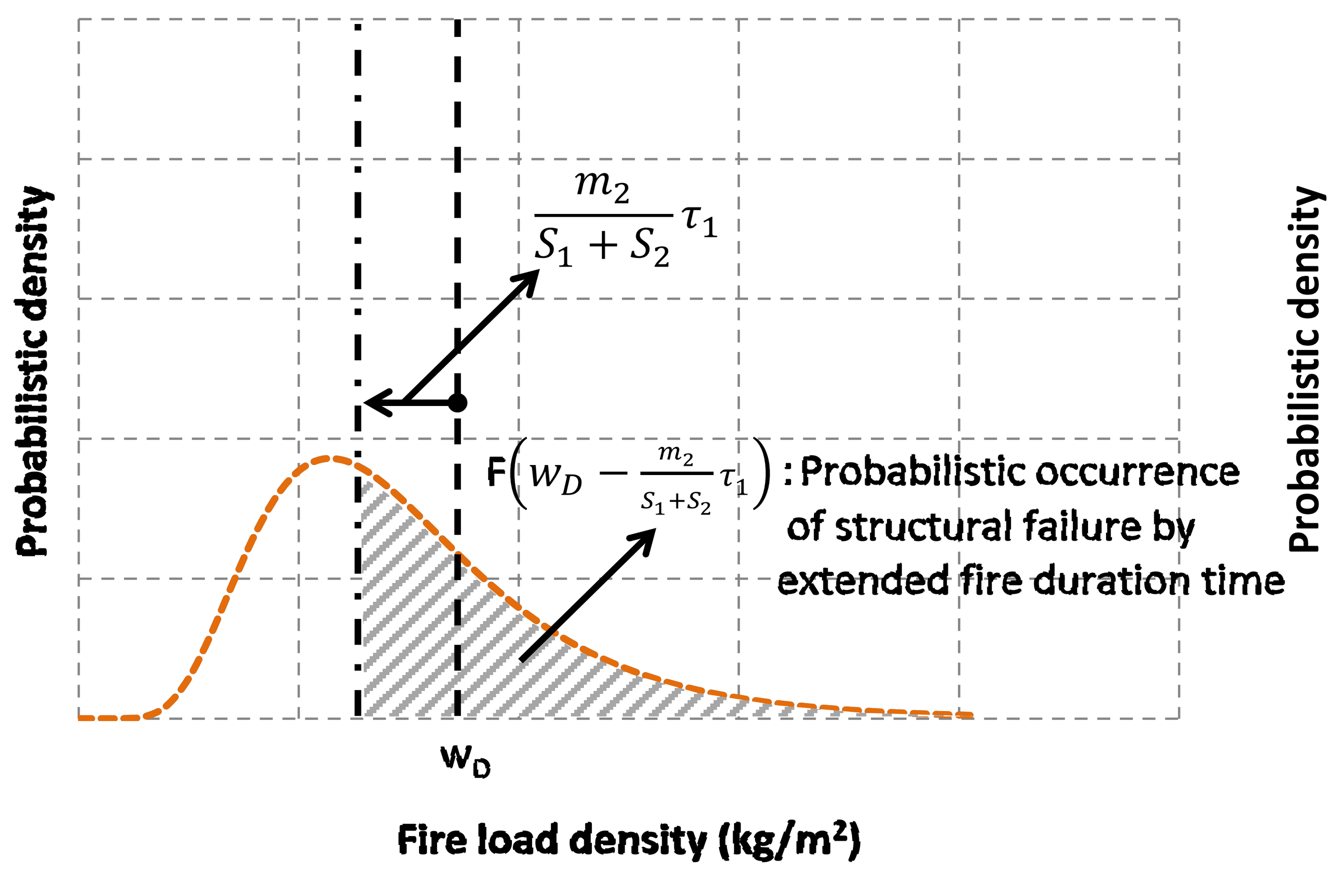


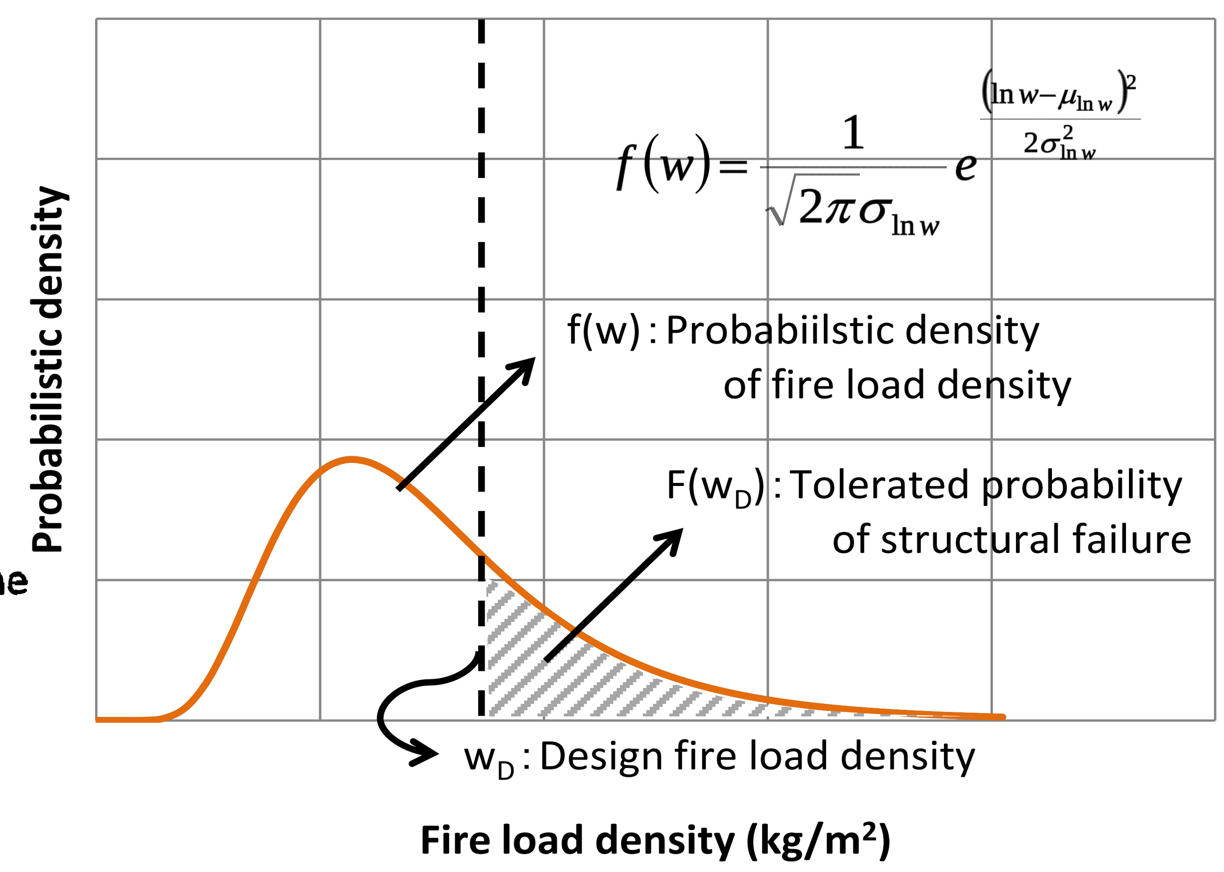
$$P_F S_1 \times P(B)P(C) \le P_F S \times P(w_D)$$

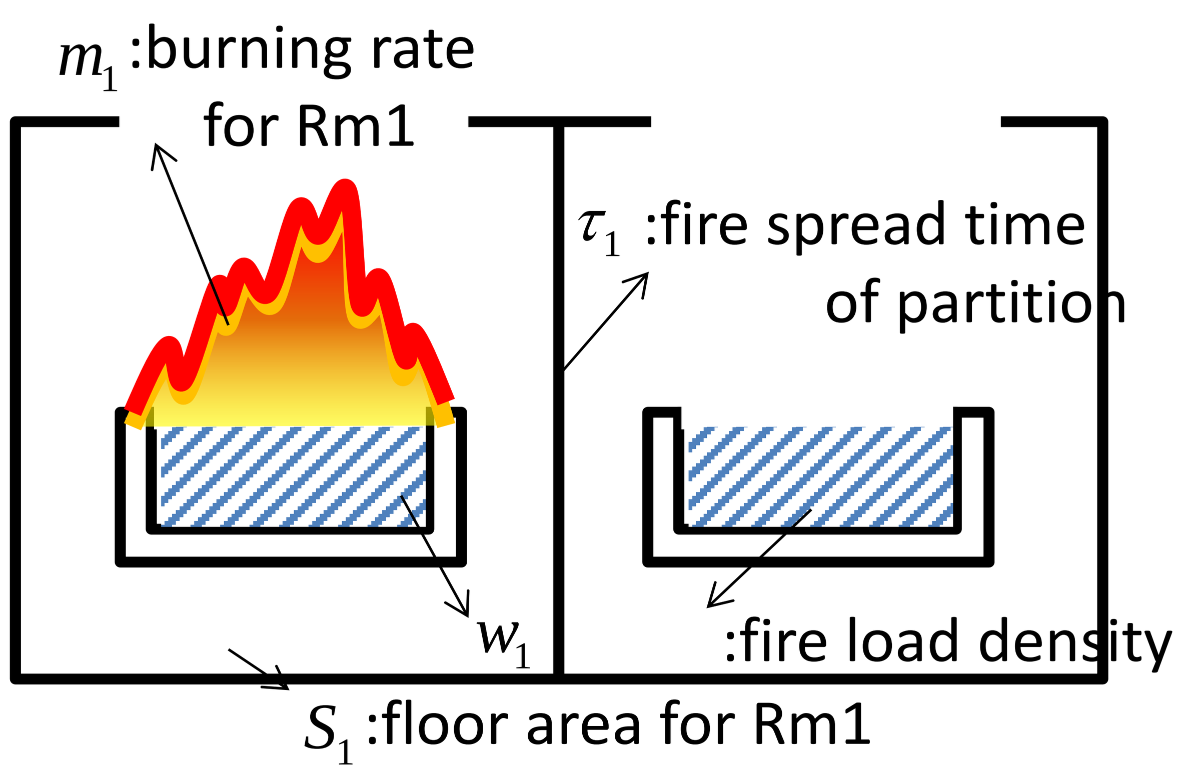
Quantification of Tolerability of Risk & Probability Occurrence of Each Event

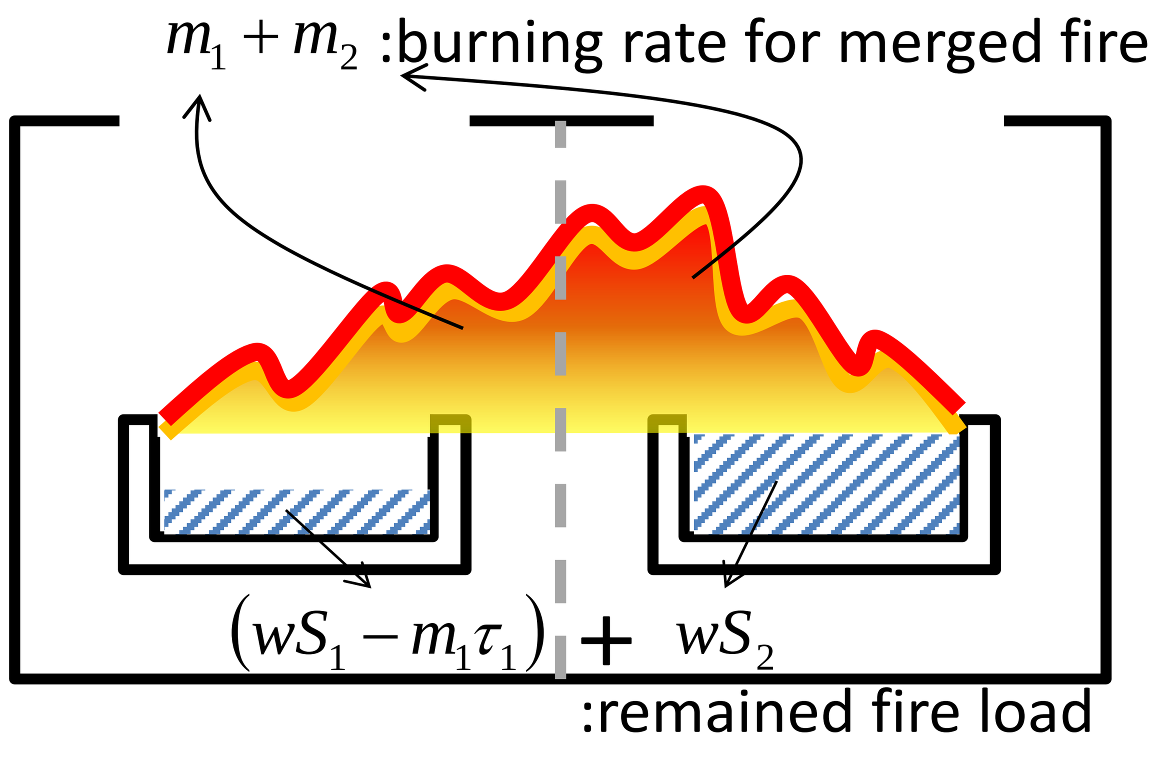
PO of Fire Spread ✖ PO of Structural Failure ≦ Tolerability of Risk



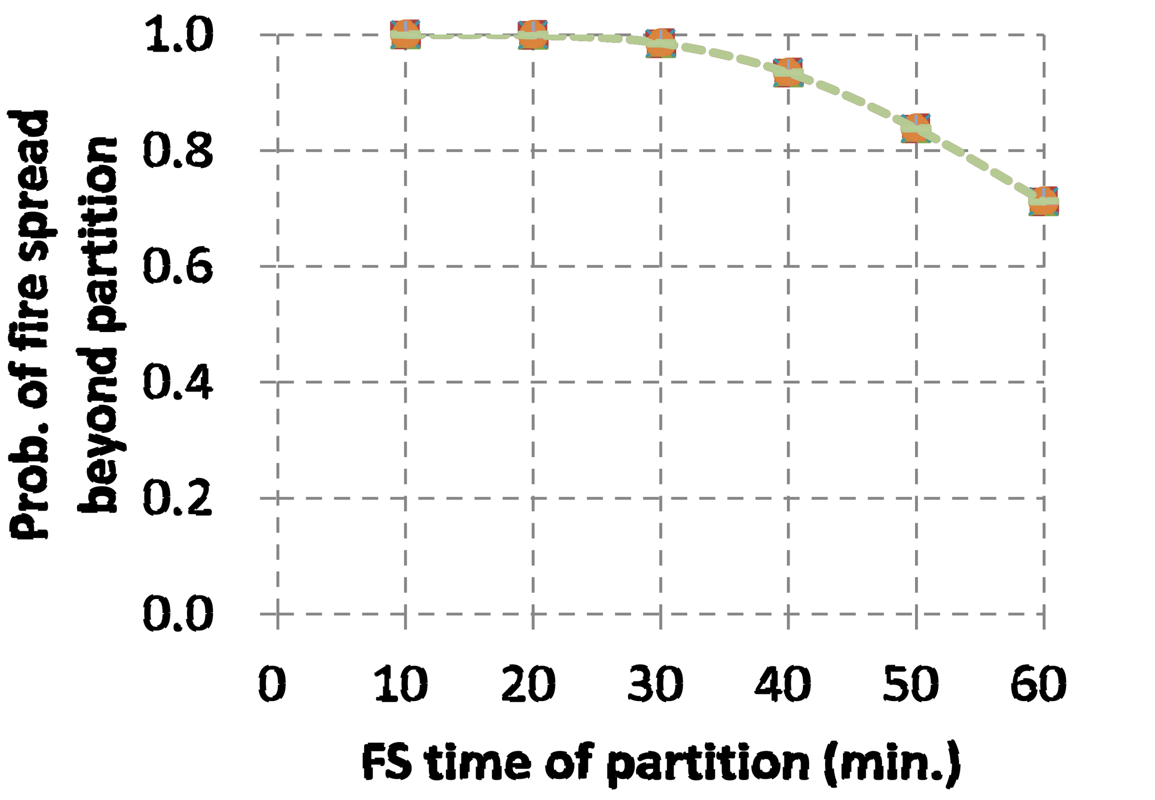


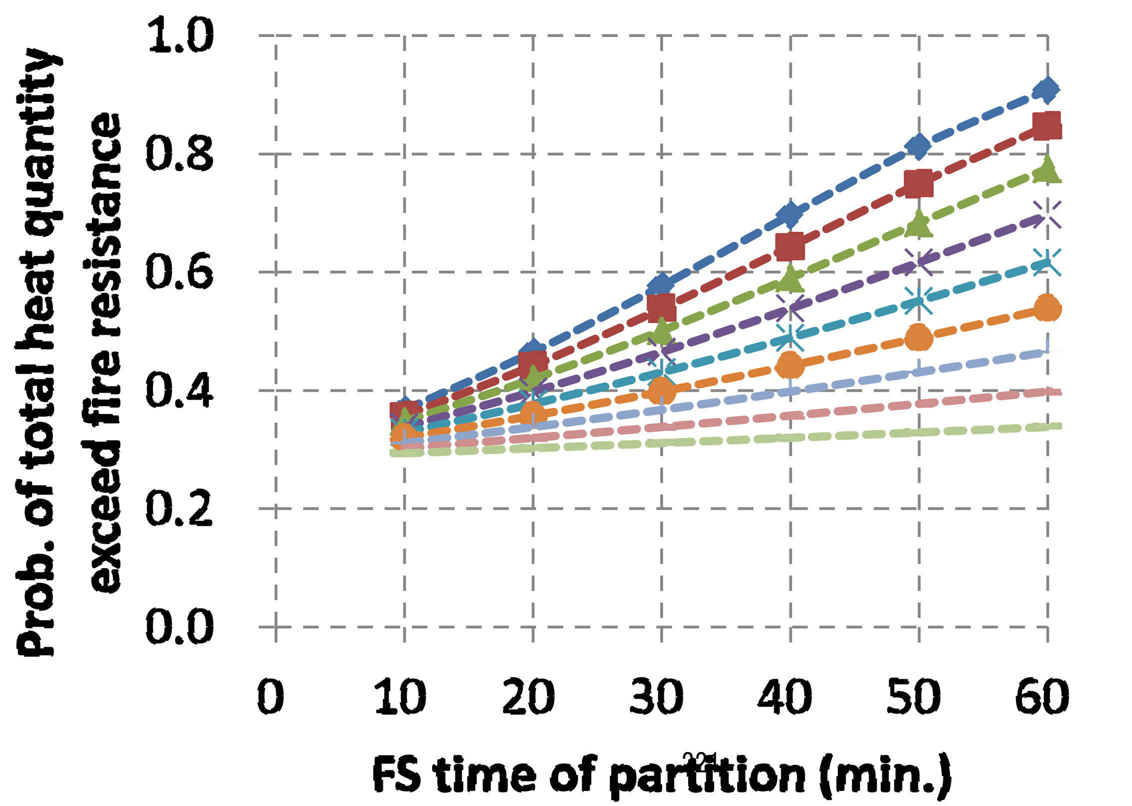


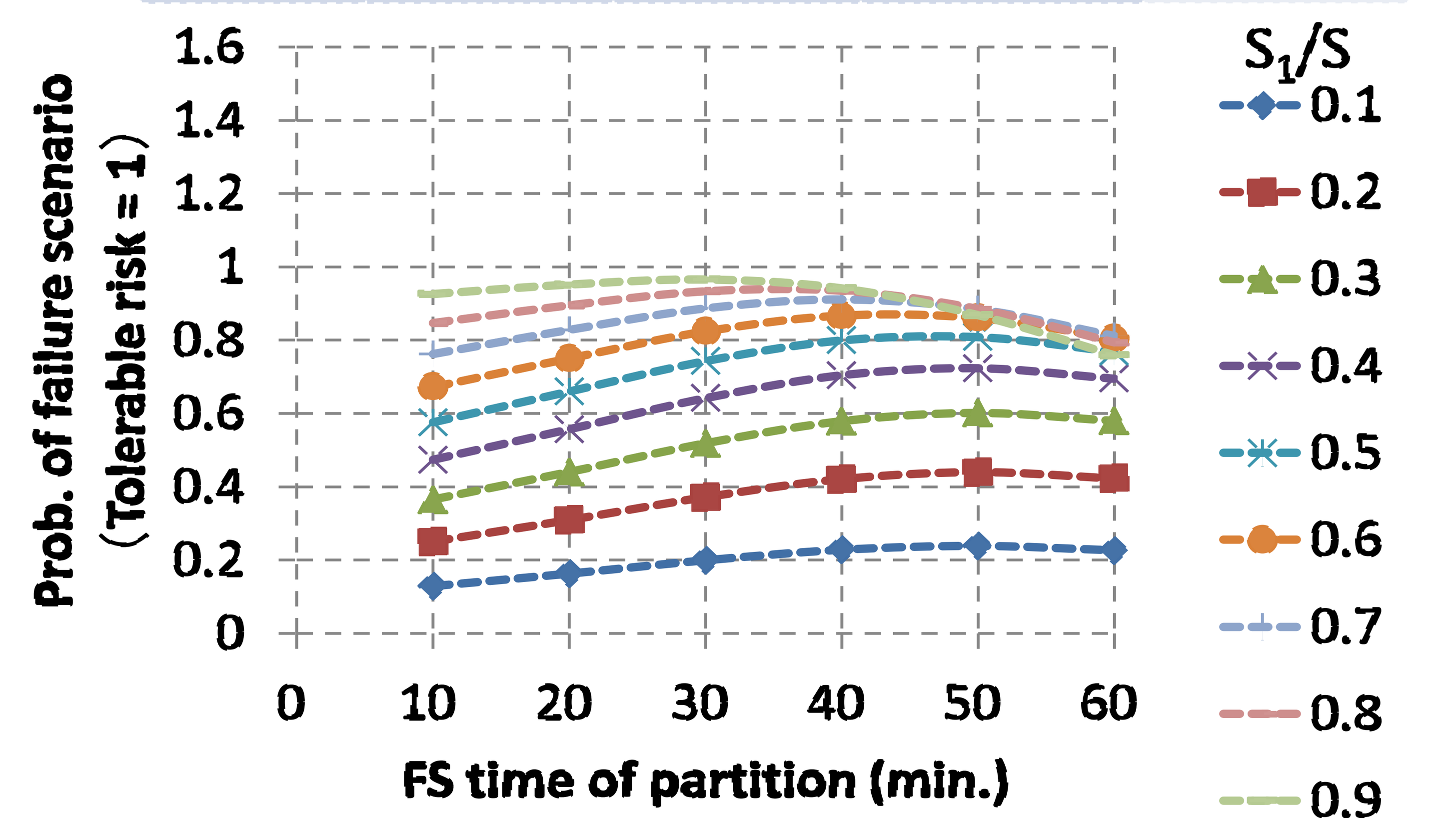




Survey data	Sample number	Average [kg/m²]	Standard [kg/m²]	Design Fire load [kg/m²]
1	10	17.1	7.6	
2	6	22.3	4.7	
3	5	45.3	4.6	
4	5	36.5	4.1	35
5	18	23.7	6.7	
6	11	46.7	10.5	
Total	55	30.1	13.5	







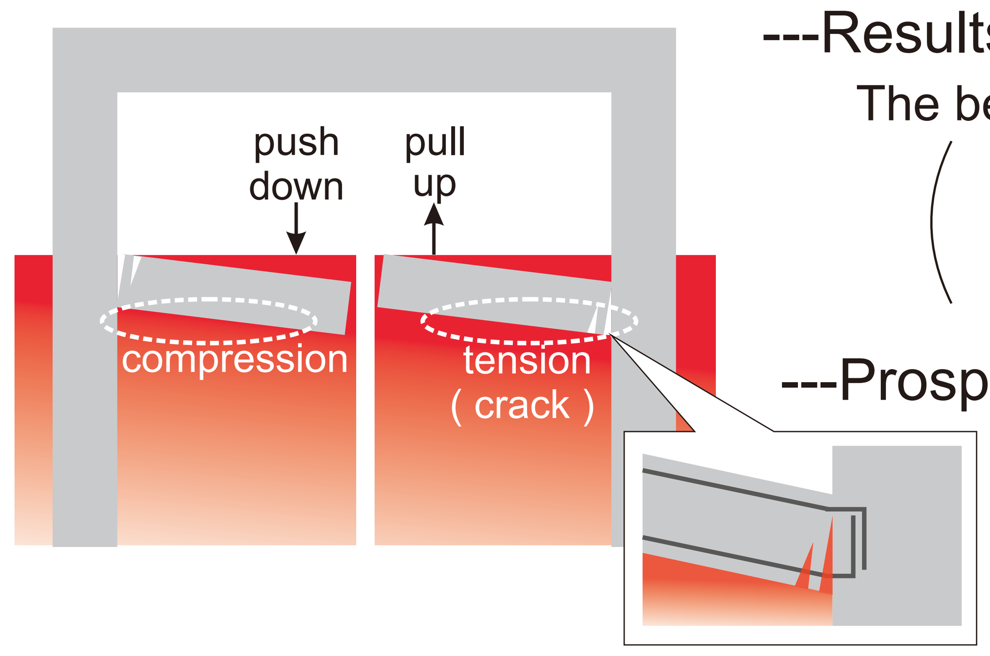
Experimental Study on Influence of Crack Width on Fire Resistance of Reinforced Concrete Members

AMIKURA Ayano, RAOUFFARD Mohammad M , and NISHIYAMA Minehiro
Kyoto University, Japan

National Institute of Standards and Technology
March 16th 2015

Background

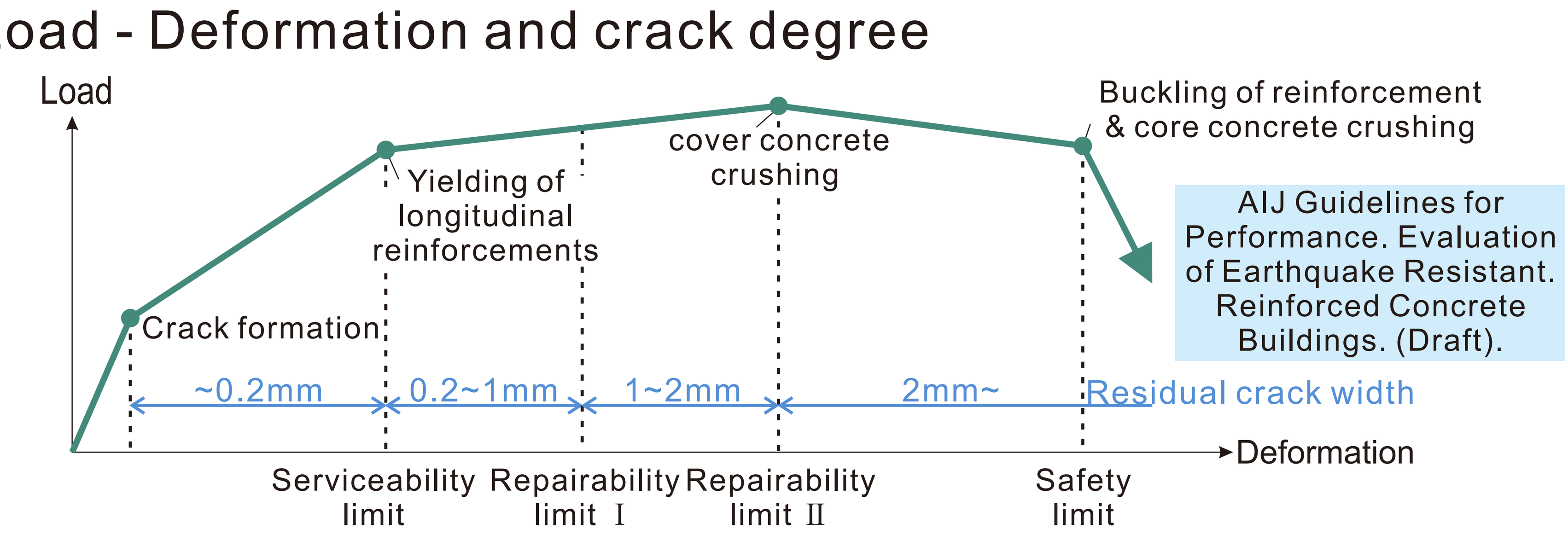
Fire test conducted in 2011



---Results—
The beam pulled up
higher temperature
(at the lower reinforcing bar)
larger deformation

---Prospects—
Reinforcing bars within concrete were exposed to fire directly at the cracks.

Load - Deformation and crack degree



Almost all large earthquakes would be followed by fire.
Fire resistance of damaged RC structure should be evaluated.

Experiments

Purpose

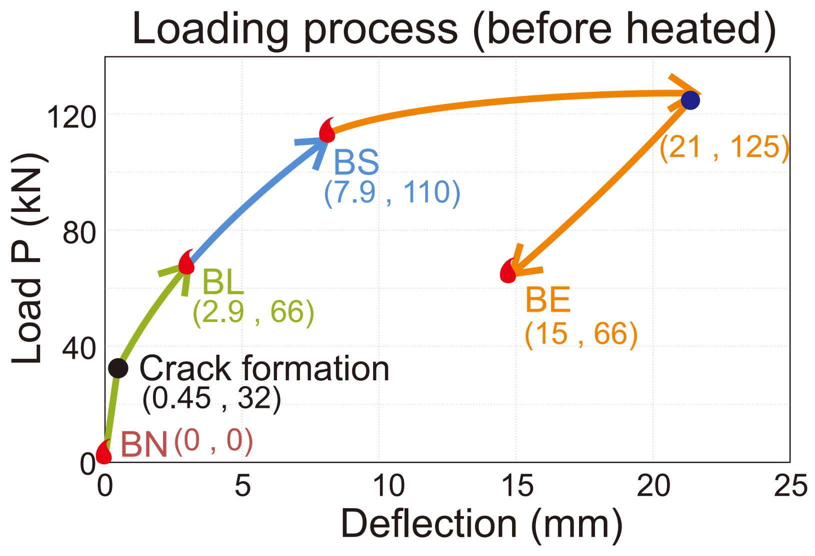
To investigate how cracks influence the rise in temperature and, therefore, load carrying capacity of reinforced concrete members in fire.

Parameter

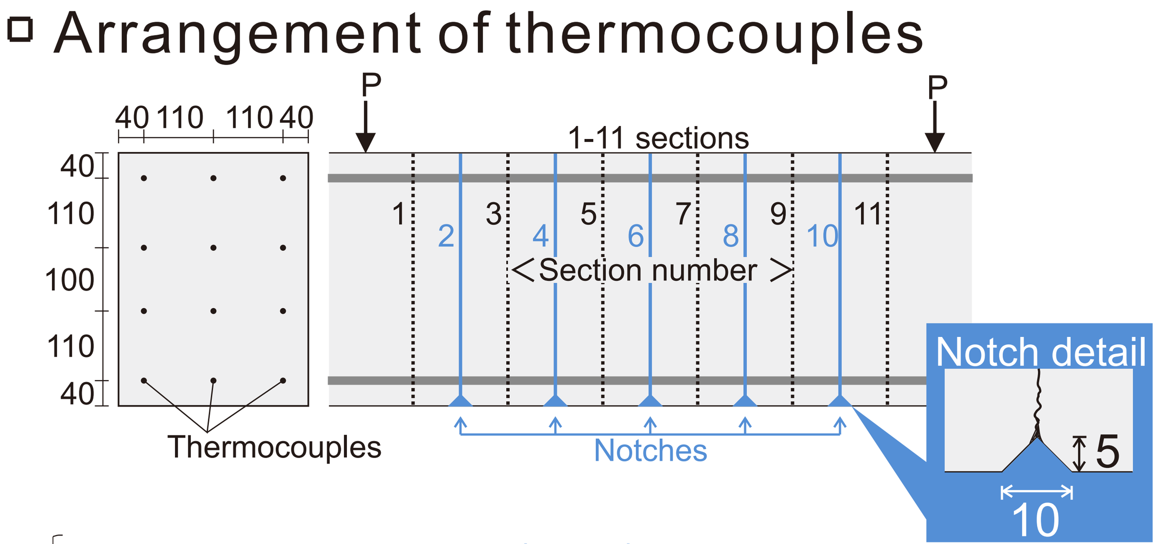
Crack width controlled by load

Specimen	load	P (kN)	Average crack width before heated (mm)
BN	None	0	0
BL	Service load	66	0.15
BS	Short-term load	110	0.3
BE	Exceeded load	125→66	1.29→1.17

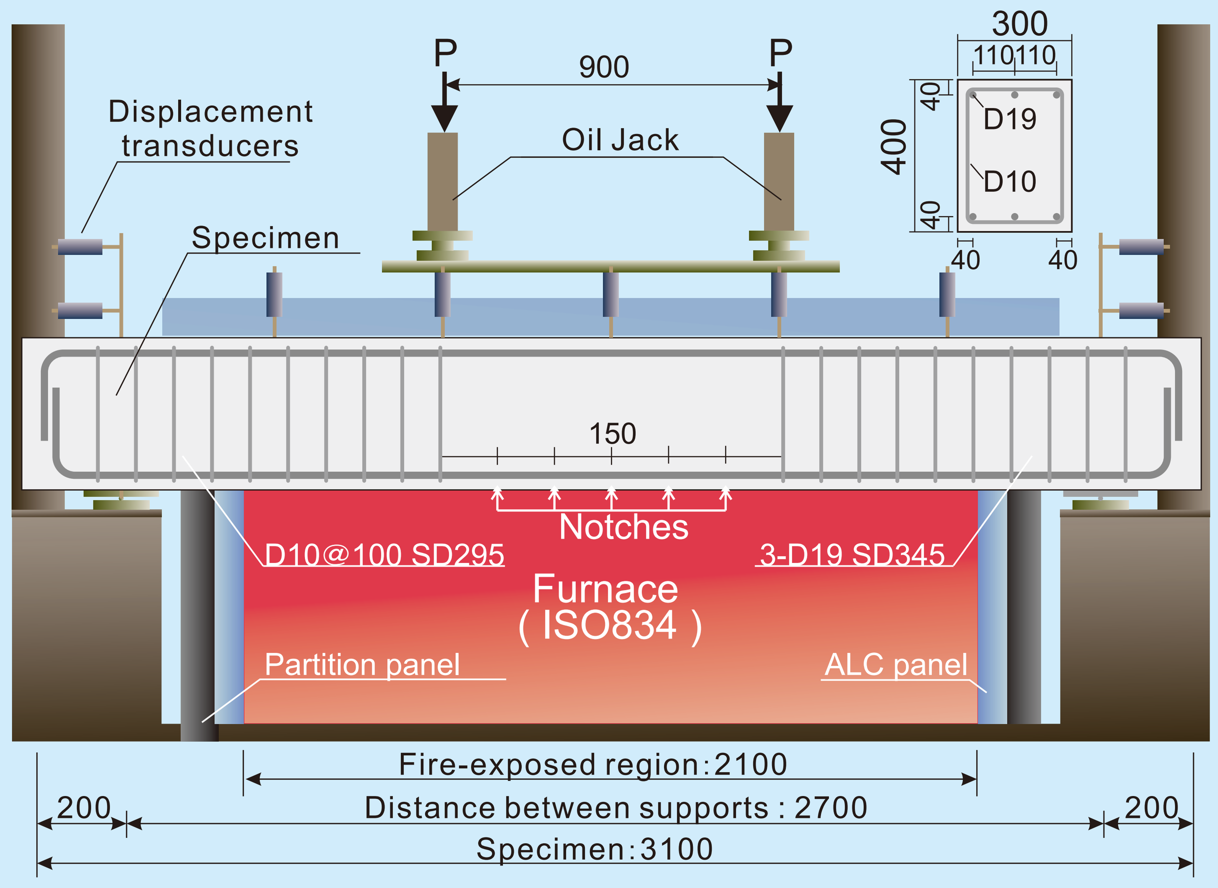
Loading process (before heated)



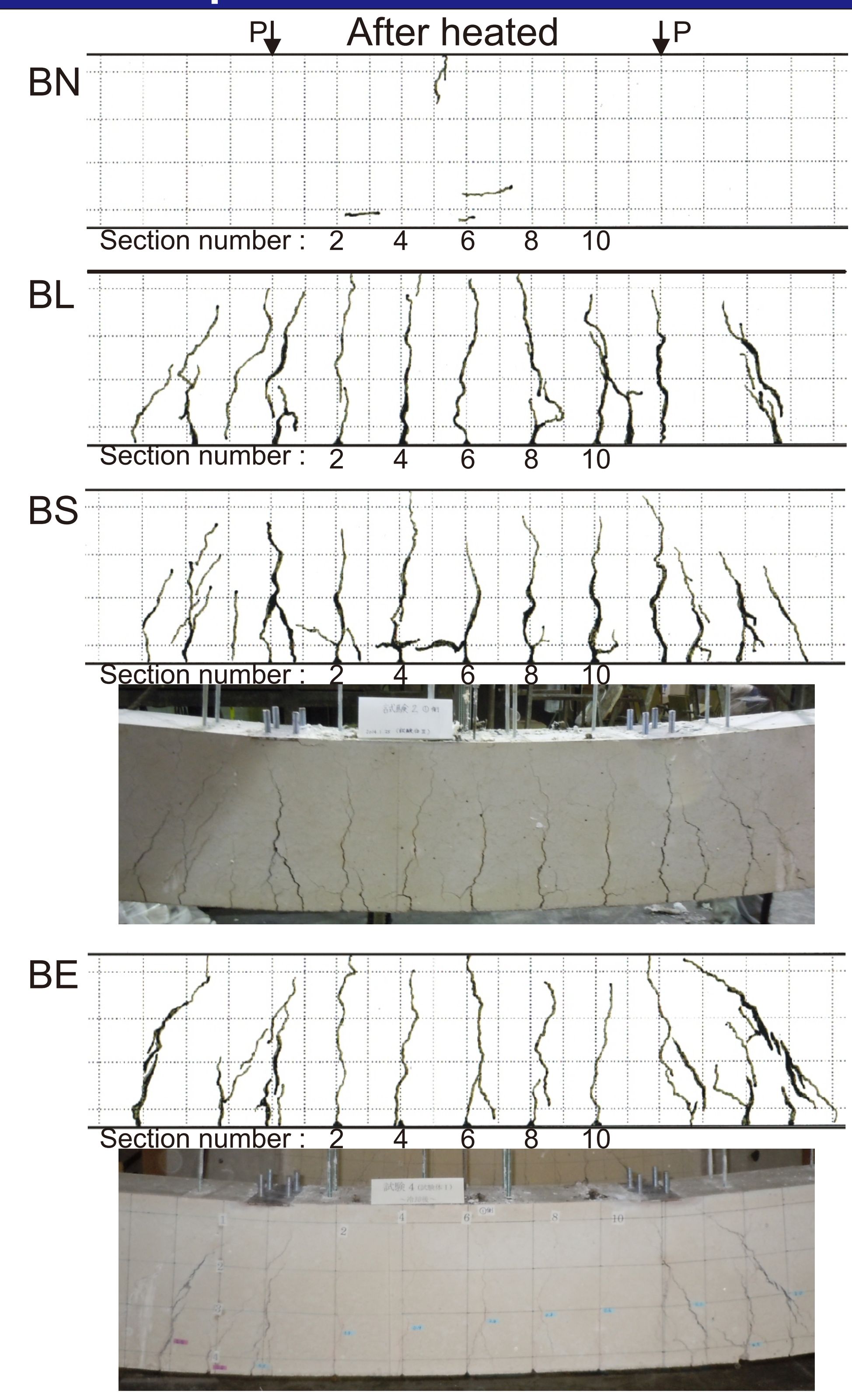
Arrangement of thermocouples



Even-number sections (solid) ...on the cracks
Odd-number sections (dotted)...between the cracks

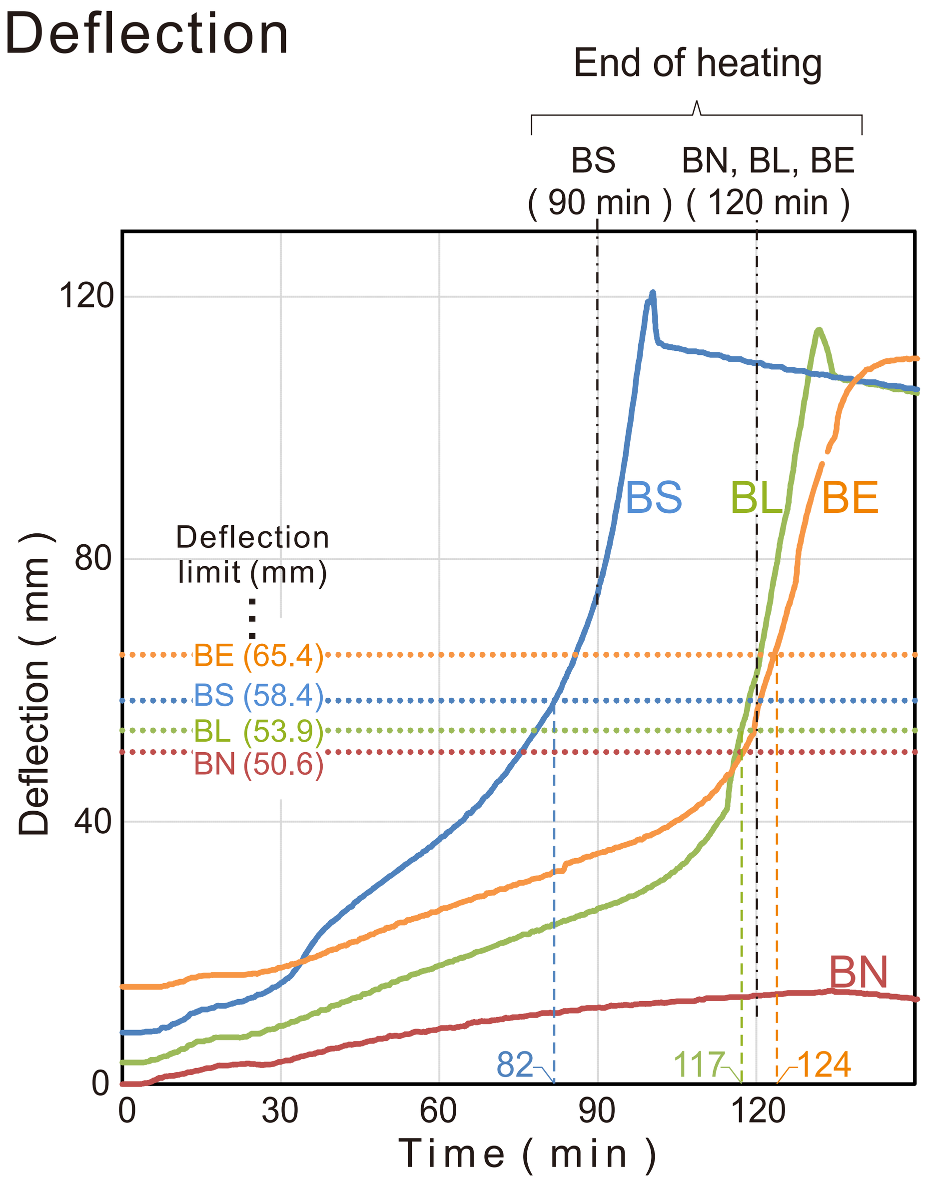


Crack patterns after heated



Results

Deflection

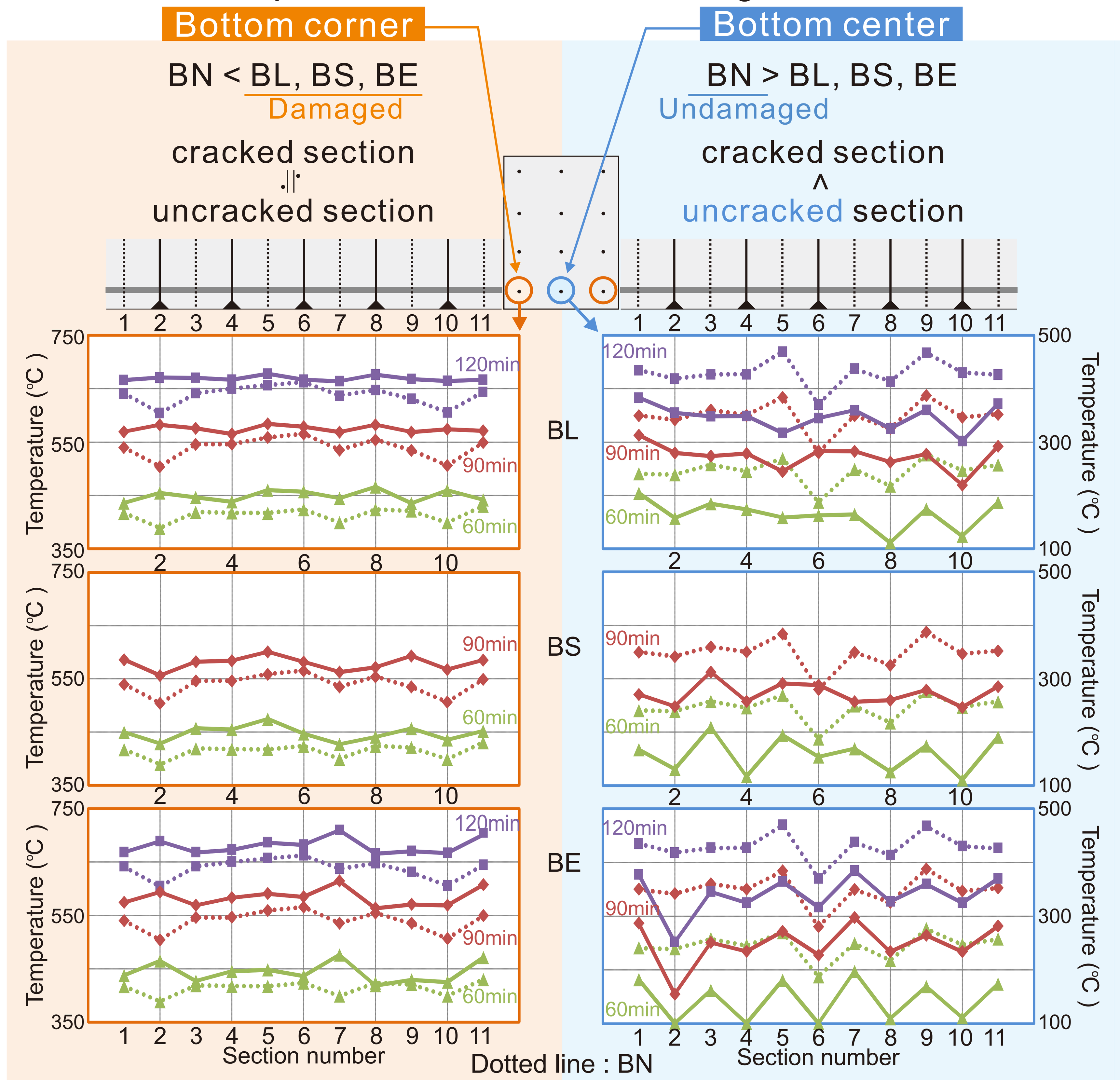


※Deflection limit δ

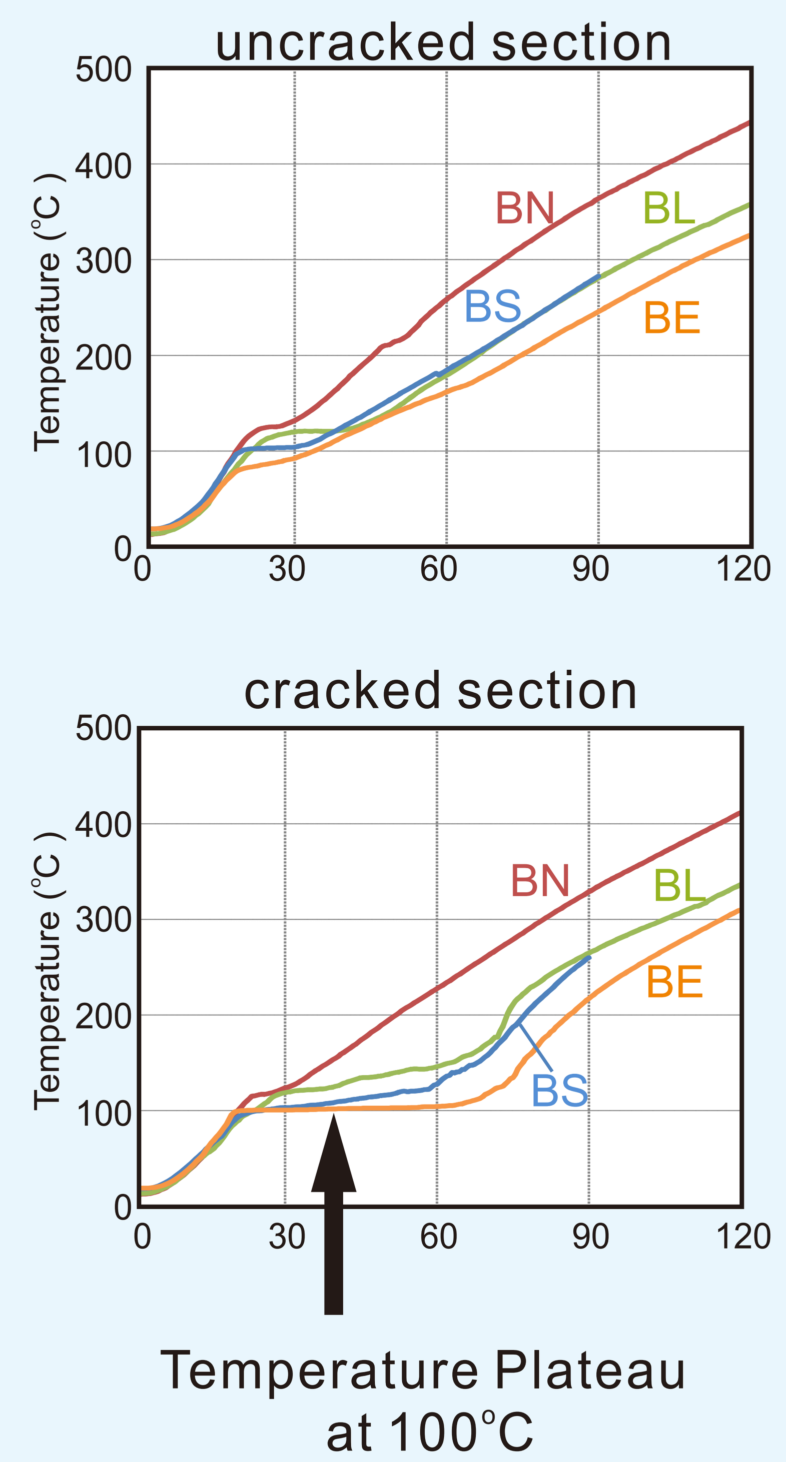
$$\delta = \frac{L^2}{400D} + \delta_i$$

δ : Deflection limit by ISO834
δ_i : Initial deflection due to loading
L : Distance between the supports
D : Beam depth

Internal temperature distribution along the axis



Temperature-Time relation



This work was supported by JSPS KAKENHI Grant Number 23246101

Fire Resistance of Reinforced Concrete Frames Subjected to Service Loads

March 16th 2015, NIST

Dept. of Architecture and Architectural Engineering, Kyoto University
RAOUF-FARD M. Mahdi, NISHIYAMA Minehiro

Research introduction

Concrete, if appropriately designed, is a fire-resistant material. However, thermal/structural response of global RC structures to severe fires have rarely been investigated. A statically-indeterminate frame (Fig. 1) subjected to service loads was heated to collapse. The failure mode of the frame was investigated.

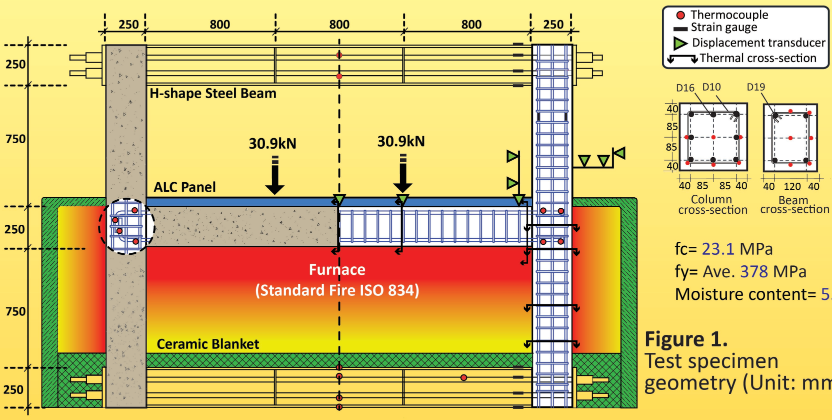


Figure 1. Test specimen geometry (Unit: mm)

Research results

Experimental Work

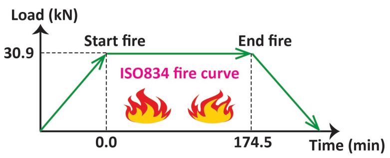


Figure 2. Loading and heating process

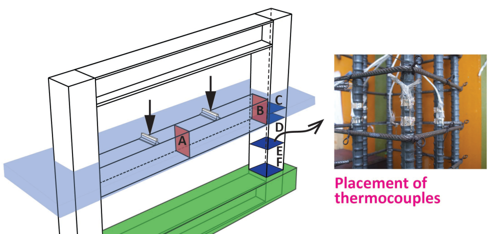


Figure 3. Thermal cross-section arrangement

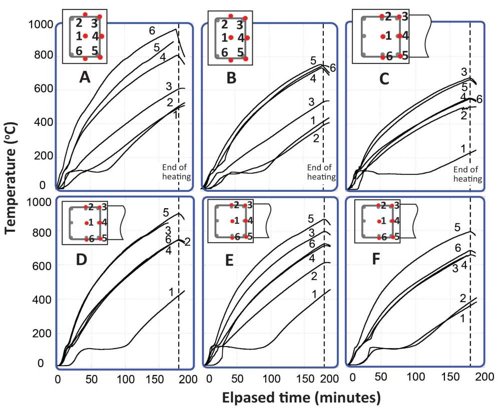


Figure 4. Internal temperature distribution

Column-beam joints absorbed less heat (Approx. 250°C) than beam mid-span and bottom columns at the end of fire test.

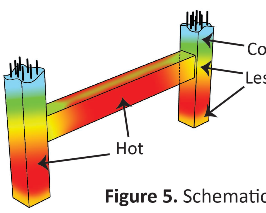


Figure 5. Schematic thermal gradient

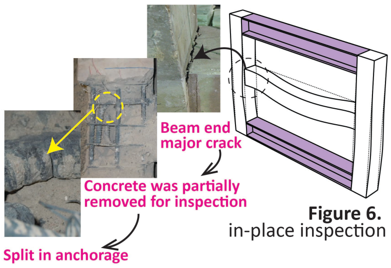


Figure 6. in-place inspection

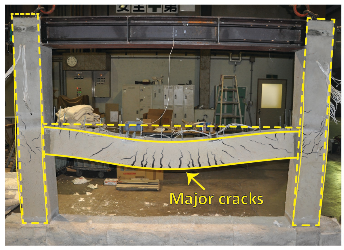


Figure 7. Crack pattern

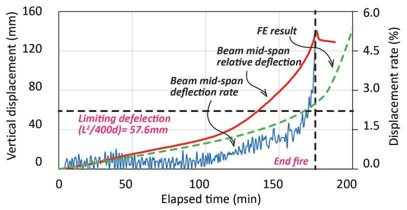


Figure 8. Relative deflection and deflection rate of beam mid-span

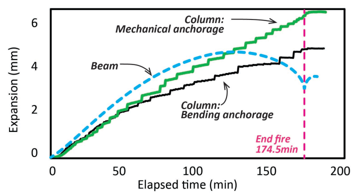


Figure 9. Axial expansion

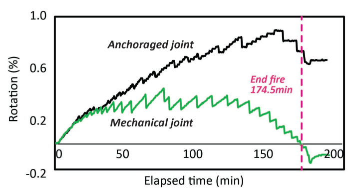
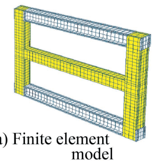


Figure 10. Measured rotation at top column bottom end

Finite Element Analysis

- *FE program: FINAL
- *Concrete: 8-node element
- *H-shape steel beam: 4-node element
- *Reinforcement: Truss element
- *No bond element
- *Concrete & Steel temperature-dependant factors: AIJ guidelines
- *Materials' thermal properties: EN1-2



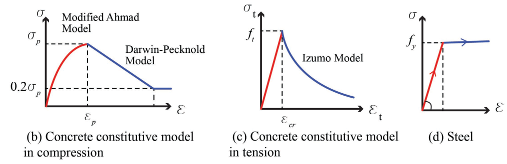


Figure 11. FE model and material constitutive models

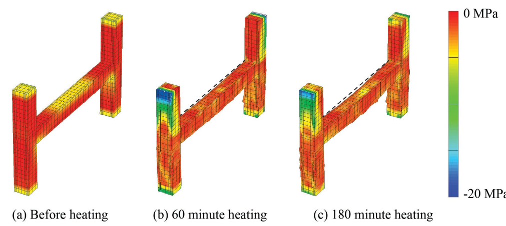


Figure 12. Minimum principal stress distribution

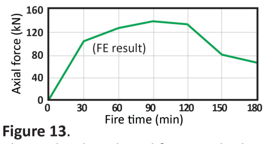


Figure 13.
Thermal-induced axial force in the beam

Structural Response & Failure Mechanism

(Up to 60min)

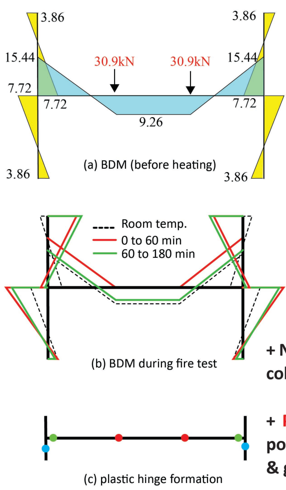
Beam:
*The BDM shifted upward (due to the thermally-induced negative bending moment)

Column:
*The lower column resisted very large moments (due to the large deformation of the beam)
*The bending moments in the upper column changed sign.

(Between 60 to 180min)

Beam:
*The BDM shifted downward (almost to its initial place)

Column:
*The bending moments in the column slightly decreased.



+ No shear failure was seen in the lower columns (blue dots in Fig 14.c)

+ Plastic hinges formed at the loading point and beam ends successively (red & green dots in Fig 14.c, respectively)

Figure 14.
Bending moment redistrbution during fire test and plastic hinge formation

This research work was financially supported by JSPS KAKENHI, Grant Number 23246101

A Study on the Effect of the Opening Pattern of the Rooms on the Severity of a Fully developed Fire

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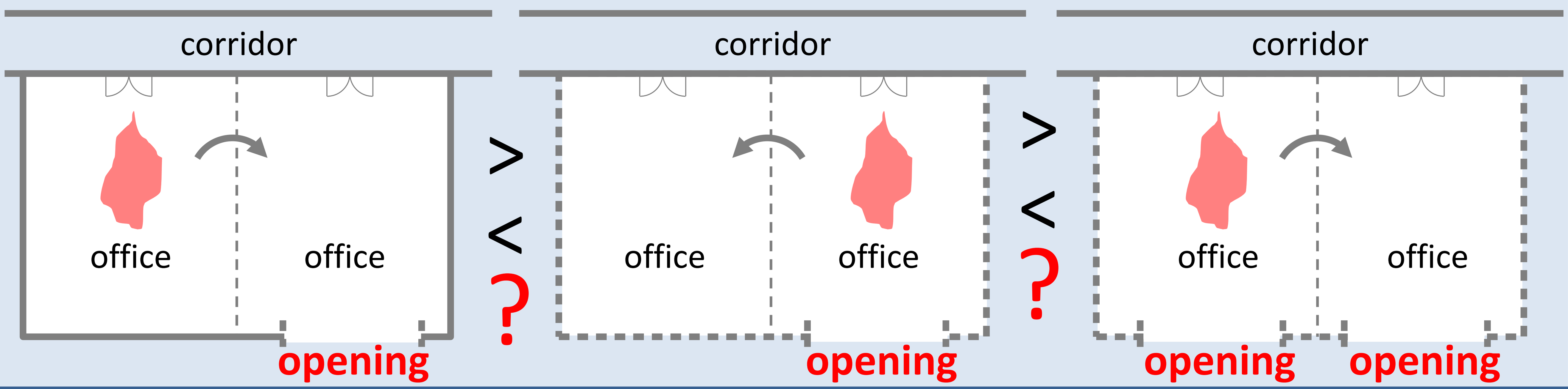
MOTIVATION

How to select the most severe fire scenario for structural elements ?



METHOD

Multi-room fire spread model

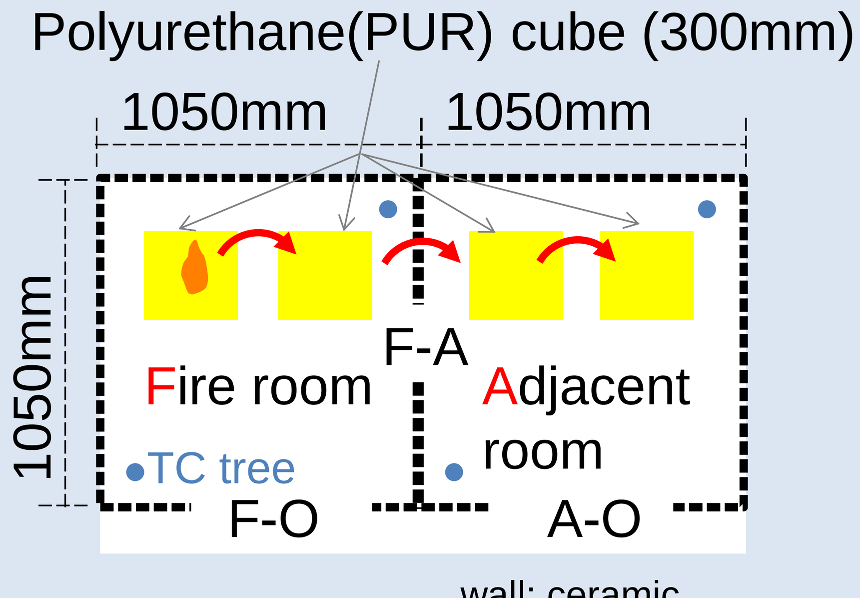
Experiment (Main Theme)

Validation of the model

Parameter study

EXPERIMENTAL SETUP & CONDITION

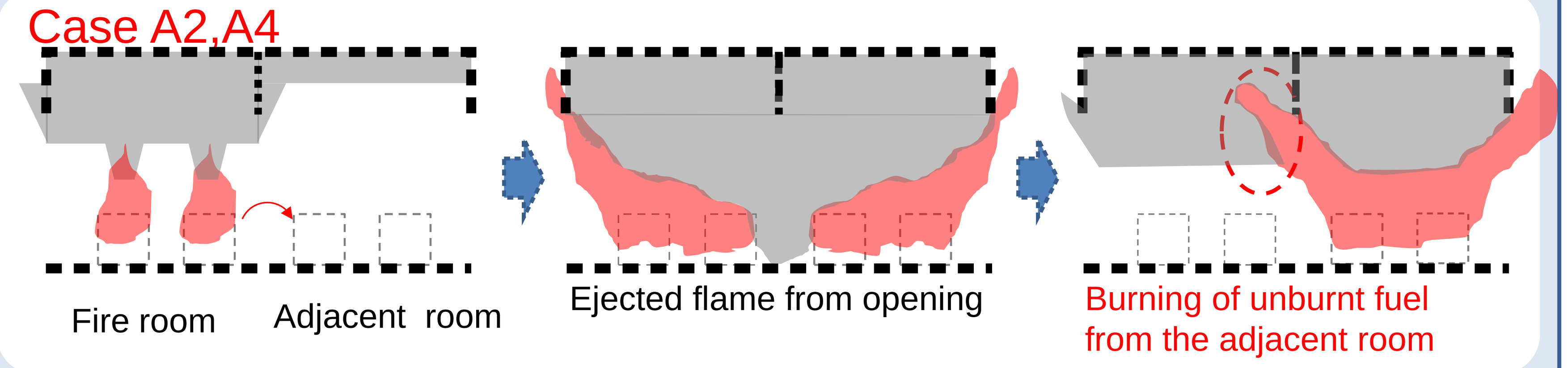
- Model scale experiments with two rooms
- Varying opening pattern
- Measurement:
  MLR of each PUR cube, compartment temperatures

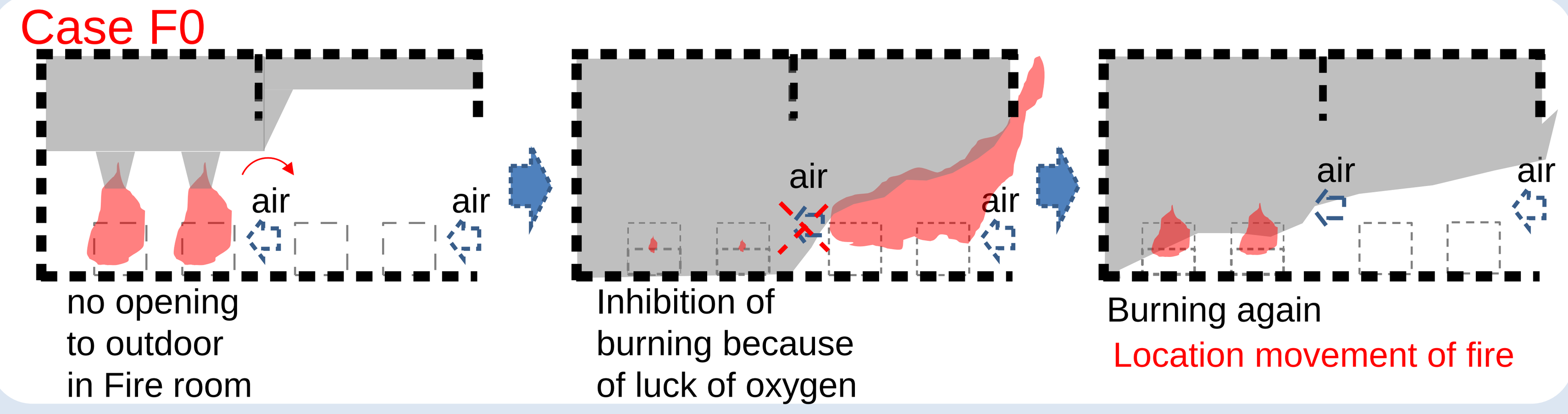


case		Opening (W*H) [m] F-O	A-O	F-A
Series A	A0	0.4*0.5	Close	0.2*0.5
	A2		0.2*0.5	
	A4 (F4)		0.4*0.5	
	A8		0.8*0.5	
Series F	F0	Close	0.4*0.5	
	F2	0.2*0.5		
	F8	0.8*0.5		

EXPERIMENTAL RESULTS

Two key phenomena observed in multi-room fire spread scenario





Series A

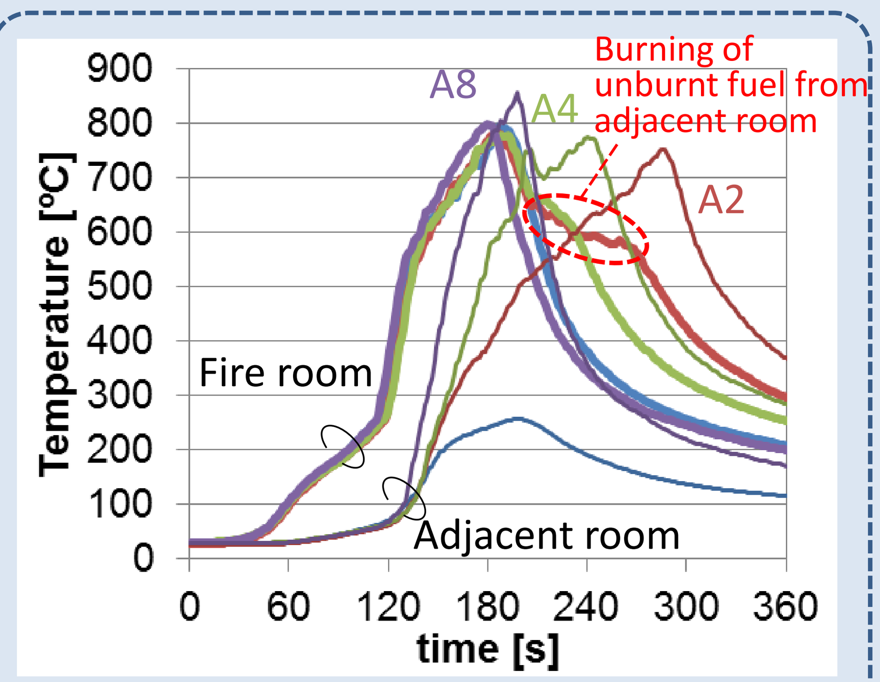


Fig.1 Compartment temperature

Series F

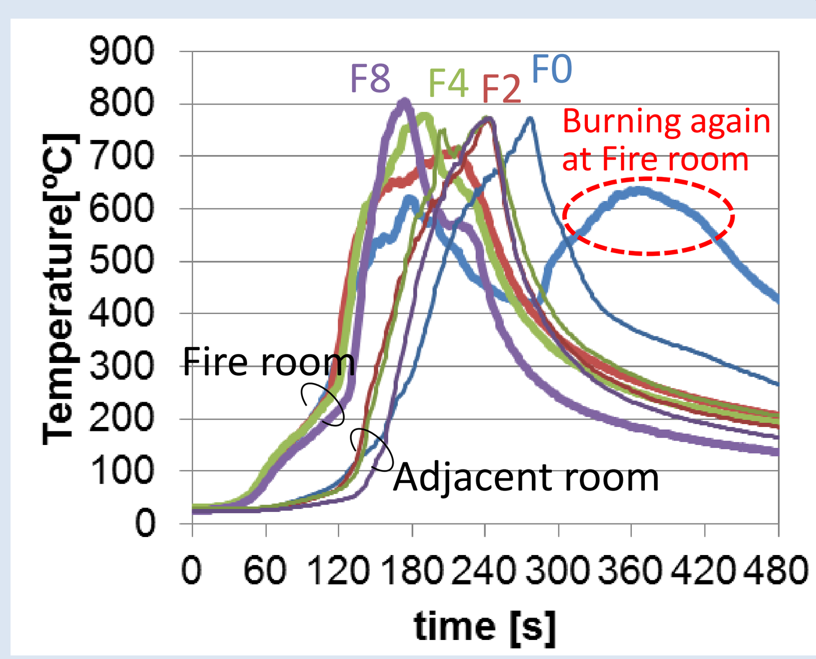


Fig.2 Compartment temperature

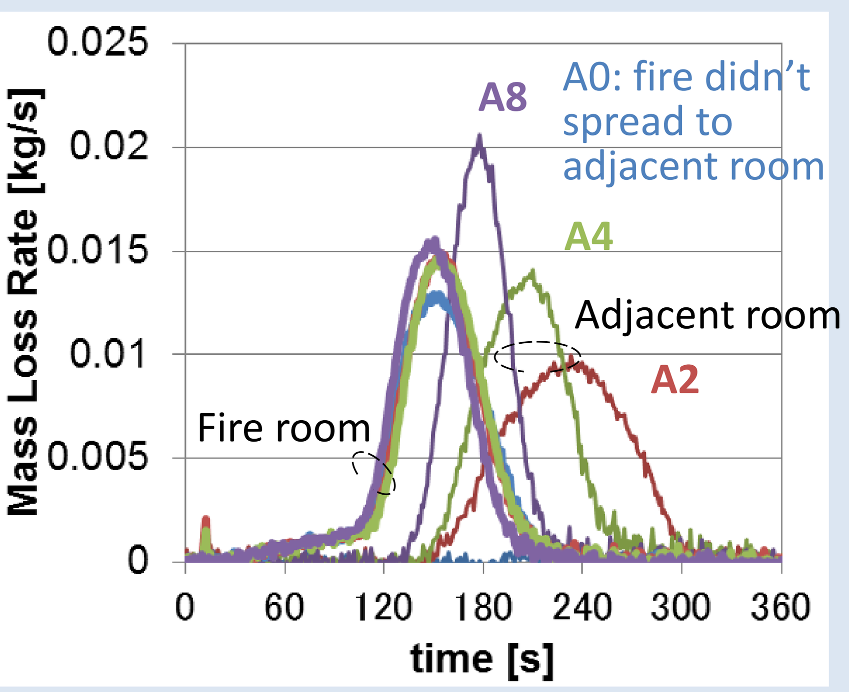


Fig.3 Mass loss rate

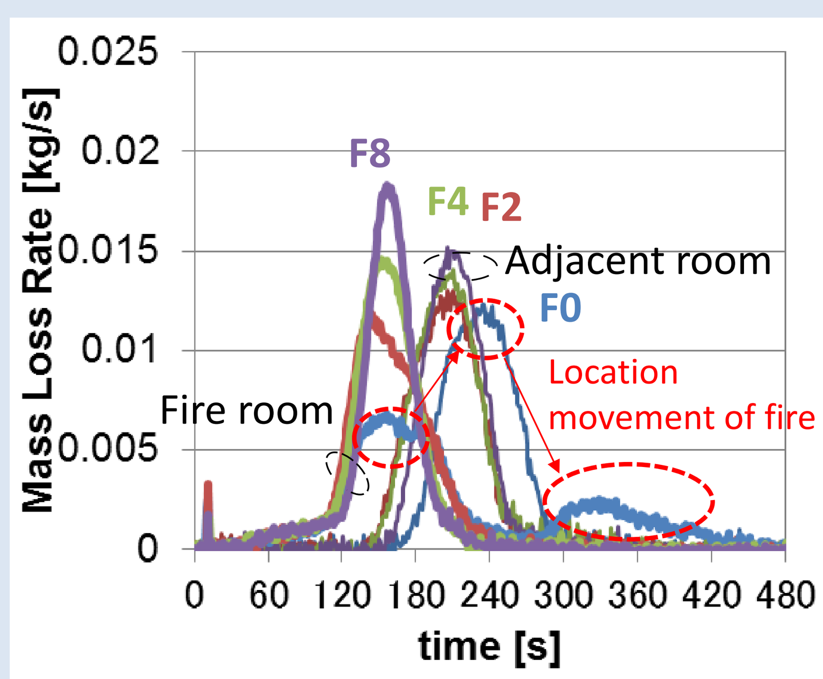


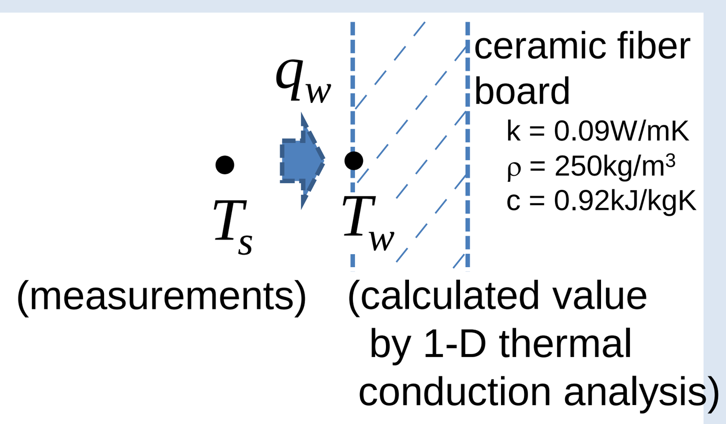
Fig.4 Mass loss rate

DISCUSSION

- Energy based method (absorbed energy in wall) is used for calculating fire severity.

$$E = \int q_w dt = \int \{h_c(T_s - T_w) + \sigma(T_s^4 - T_w^4)\} dt$$

h_c: thermal convection coefficient (=0.023kW/m²K)
σ : stefan-Boltzmann constant



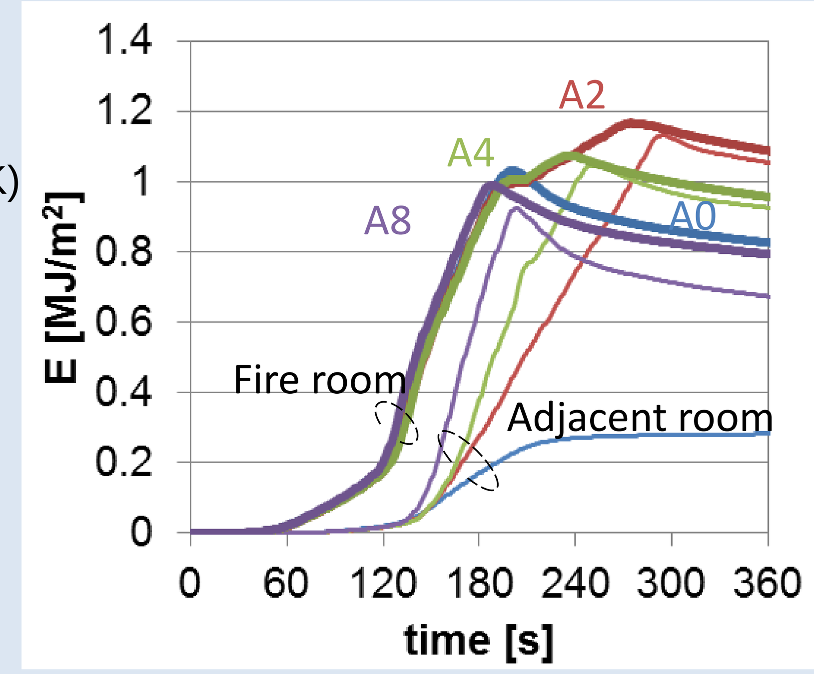


Fig.5 Energy absorbed in wall

- Severity of fire increase with a decrease in $A\sqrt{H}/A_t$ (Fig.6).
- Severity of fire room increase with a decrease in the ratio of the opening factor* of the room to sum of opening factor* (Fig.7).

*opening factor calculated from the size of the opening to outdoor

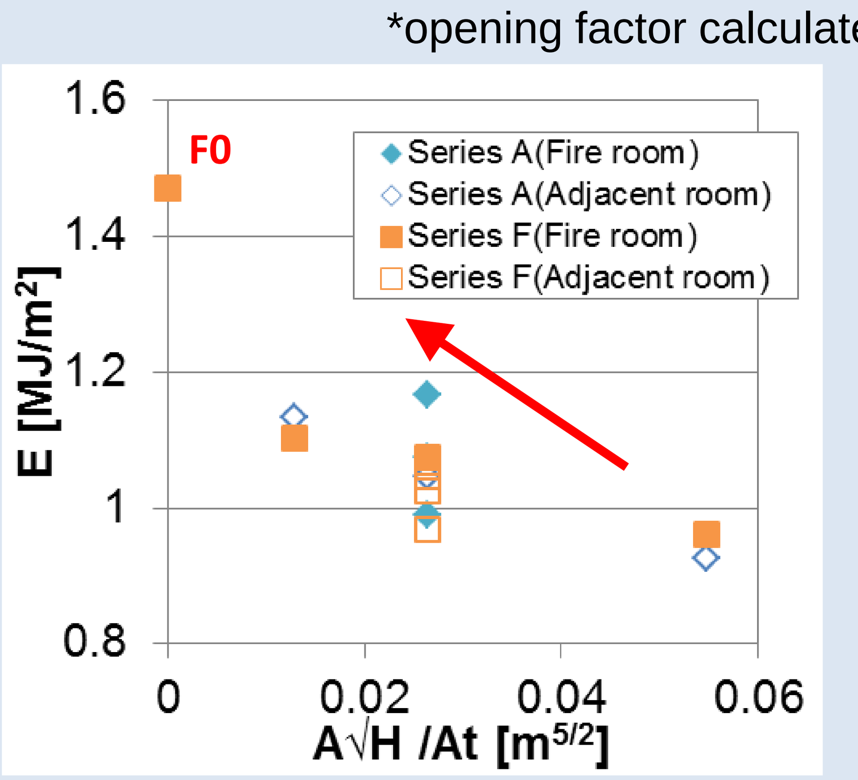


Fig.6 Total amount of energy absorbed in wall

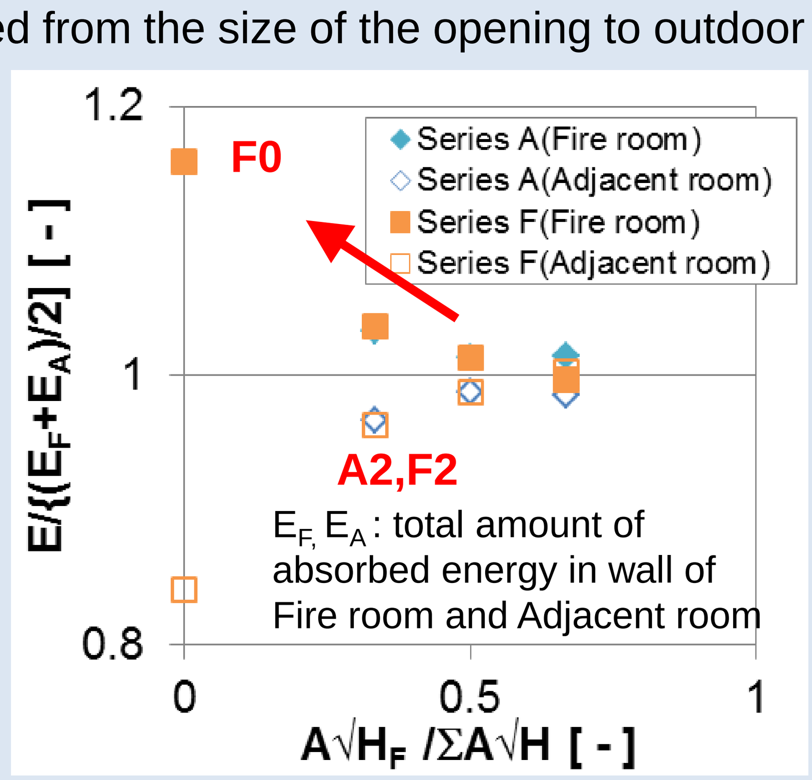


Fig.7 Severity of fire in a room normalized by average severity

CONCLUSION

- Burning of unburnt fuel from adjacent room and the location movement of fire were observed because of the luck of oxygen in the compartment.
- Uneven distribution of openings affects the severity in multi-room fire spread scenario, especially when there is not any opening in the room ignited at first.

TAKENAKA

Influence of Water Content on Load-Induced Thermal Strain of High-Strength Concrete

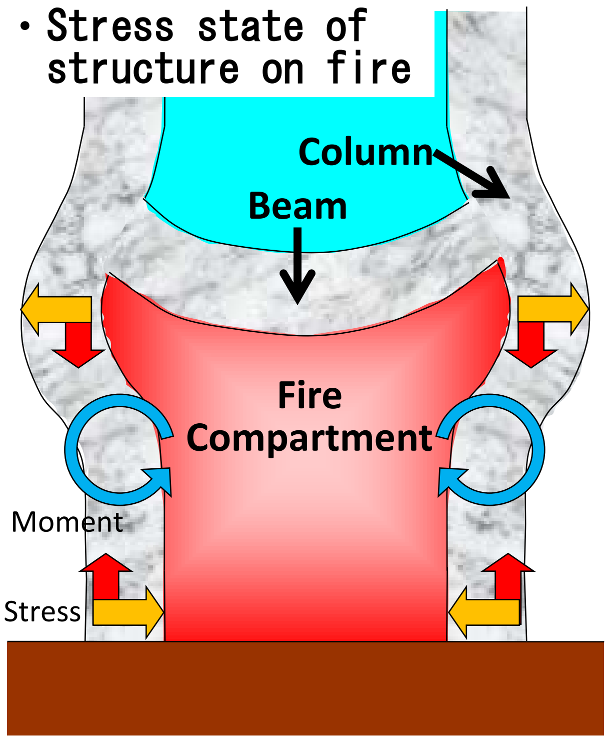
H. Yamashita (JTCCM) , T. Yoshida , T. Hirashima (Chiba Univ.)

・Introduction

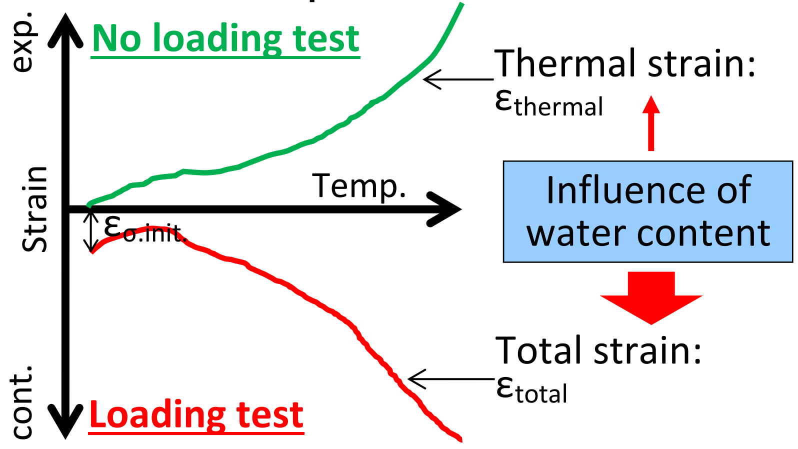
In investigating the fire safety of a structure subjected to fire, a deformation analysis of the structure should be performed because the complicated stress state might induce an unexpected behavior. For the analysis of RC structures, formulation of total strain is needed. It is reported that the total strain is affected considerably by the water content of concrete.

The objective of the present study is to consider the effect of evaporable water and W/B on the LITS of high-strength concrete.

・Stress state of structure on fire



・Strain of concrete at elevated temperature



<u>LITS Model</u>:

$$\varepsilon_{total} = \varepsilon_{thermal} + \varepsilon_{\sigma.init.} + \text{LITS}$$

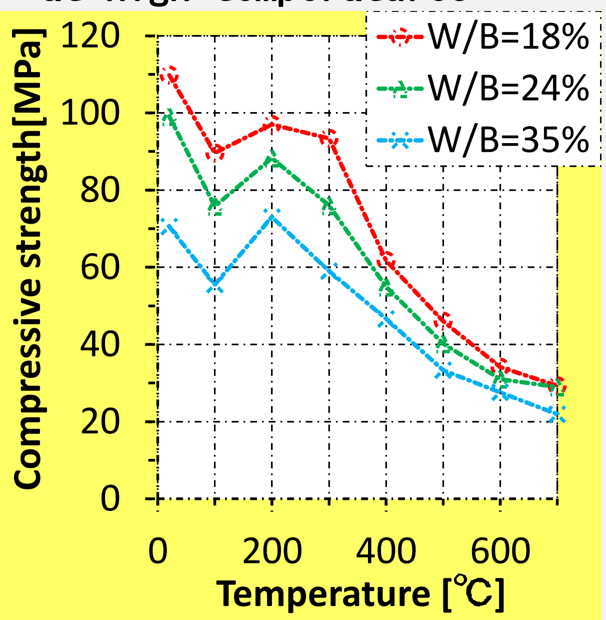
Elastic·Plastic strain, Drying shrinkage,etc.

・Specimens

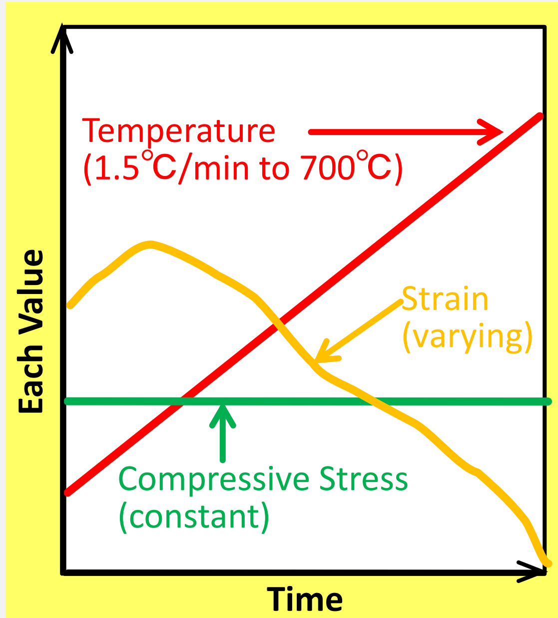
Thermocouples are embeded at 5 points.

- Size: ϕ75 X150 mm
- W/B:18,24,35 %
- Aggregate: Quartzite
- Moist Cond.: <u>Air Dried</u> at Room Temp. or <u>Oven Dried</u> at 105℃

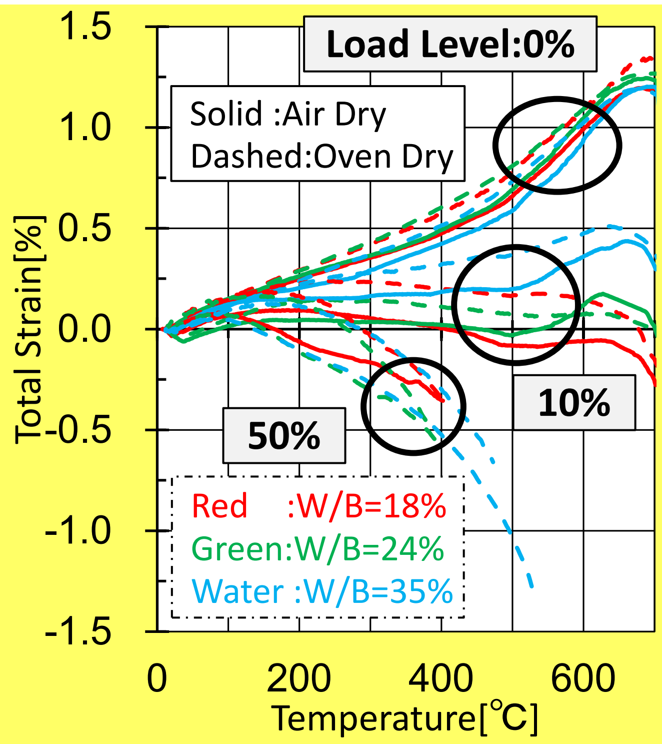
・Compressive strength at high temperatures



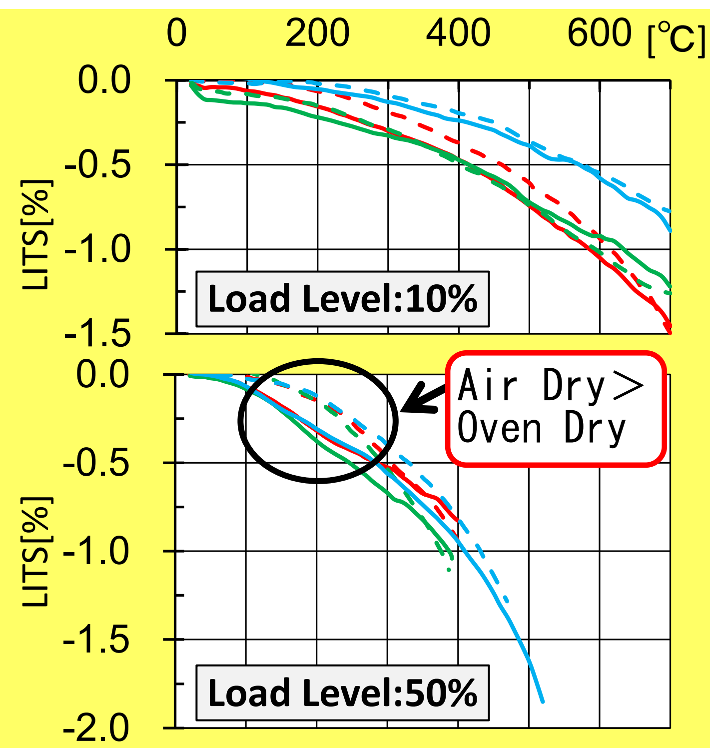
・Specimen condition on the test



・Results of $\varepsilon_{thermal}$ & ε_{total}



・Results of LITS



・Conclusions

1) LITS were larger for the oven-dried specimens than for the air-dried specimens below 200° C. When the stress level was increased, this effect was greater.

2) The influence of W/B in the present study was unsettled.

In the future, we should analyze the results of the present study and consider the strain model that can evaluate the effect of water adequately.

Cut-cell Immersed Boundary Method for Conservative Treatment of Complex Geometries in Fire Dynamics Simulator

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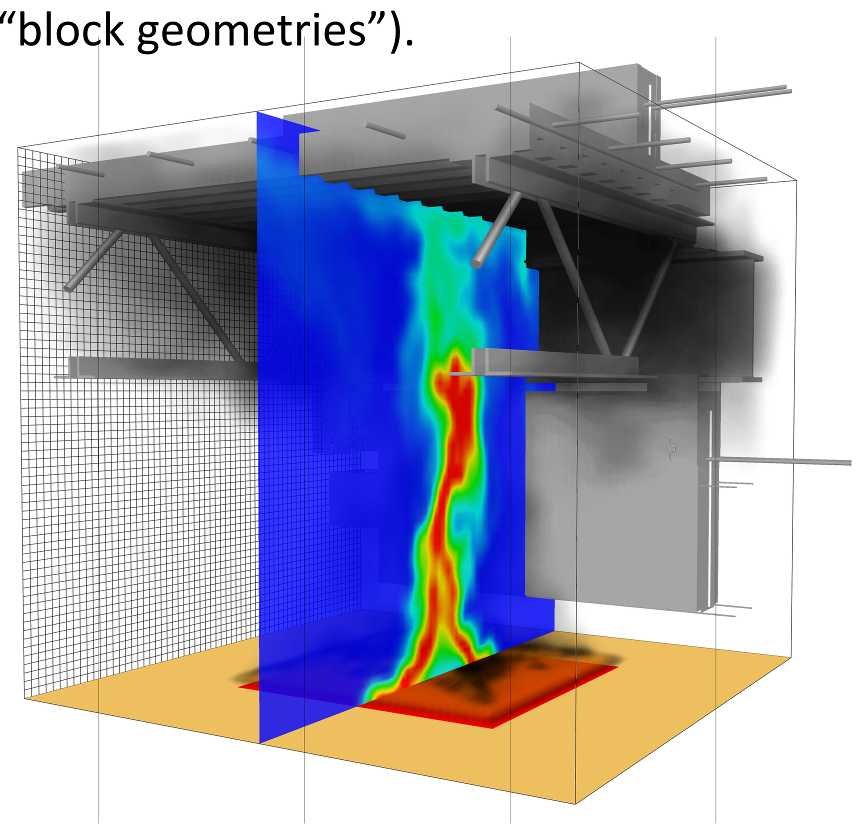
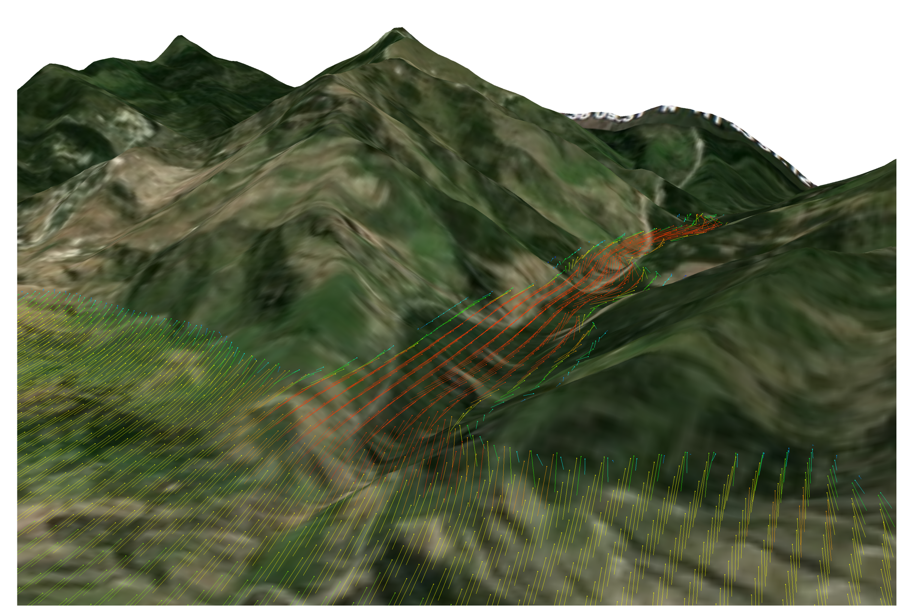
[a]Fire Research Division, Engineering Laboratory, National Institute of Standards and Technology
[b]Department of Mechanical and Aerospace Engineering, The George Washington University

Motivation and Objectives

Simulating flows around complex solid objects is necessary for (1) performance-based design of fire protection systems, (2) fire-structure interaction problems, and (3) predicting winds and pollutant transport in complex terrain and urban canopies. Improvements in geometric accuracy will translate into safer buildings at lower cost. Accurate estimation of transient fire load on structural members, which may displace and deform under realistic fire scenarios, requires well-characterized boundary layer and radiation heat transfer models. Predicting wind fields over complex terrain also requires special boundary layer treatment for momentum; in particular, wind field models cannot tolerate spurious (non-physical) pressure waves. In general, the requisite accuracy for these problems cannot be achieved with rectilinear grids ("block geometries").



Fire-Structure Interaction: 12 MW fire load on a steel/concrete floor connection assembly[5].

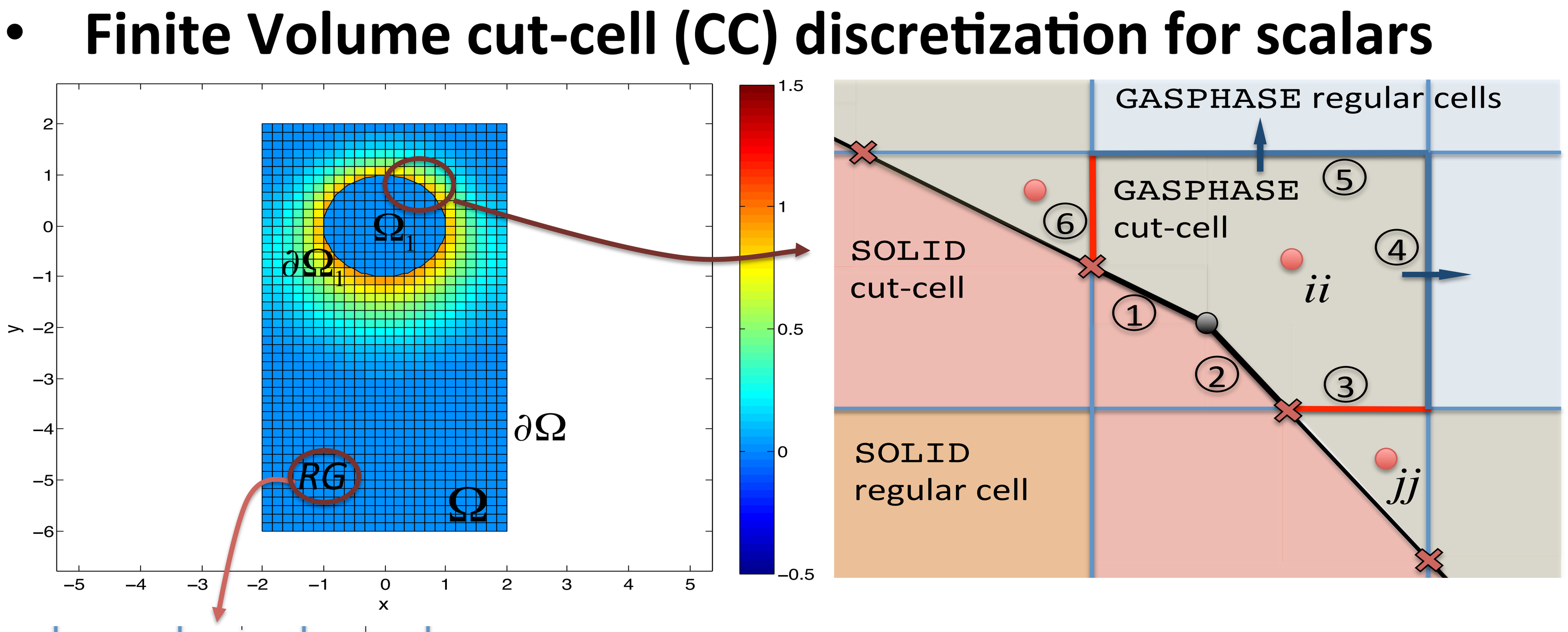


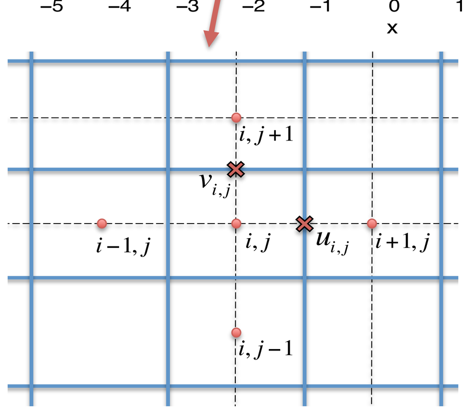
Velocity vectors (35 m/s [78 mph] max [red]) for a wind field in Mill Creek Canyon, Utah[6]. 4 km x 4 km horizontal domain, 1 km vertical. 40 m grid resolution on a single mesh.

Objective: Develop an efficient, conservative numerical scheme for treatment of complex geometry within FDS. The basic capability for velocity reconstruction around arbitrarily shaped solids in fire simulations is implemented in FDS[1,2] using a direct-forcing Immersed Boundary Method (IBM)[3]. IBM itself does not enforce exactly the no penetration condition, violating the conservation of chemical species in the gas-phase regions, and leading to erroneous simulation results. To address this issue, a novel hybrid cut-cell (CC) immersed boundary method (IBM) is proposed.

Methodologies

- **Finite Volume cut-cell (CC) discretization for scalars**





Scalar Transport:

$$\frac{\partial \rho\phi}{\partial t} + \nabla\cdot(\rho\phi\mathbf{u}) = -\nabla\cdot(-\rho D_\phi \nabla\phi) + f_\phi \quad \text{on} \quad \Omega,\ t\in\Re_+$$

+ BCs on domain and immersed boundaries.

- Divide the domain on $ii \rightarrow (i,j)\in\Im$ cells.

$$\int_{\Omega_{ii}} \frac{\partial\rho\phi}{\partial t} d\Omega + \int_{\Omega_{ii}} \nabla\cdot(\rho\phi\mathbf{u}) d\Omega = -\int_{\Omega_{ii}} \nabla\cdot(-\rho D_\phi\nabla\phi) d\Omega + \int_{\Omega_{ii}} f_\phi d\Omega$$

- Define as unknown the cell average of $\phi(\mathbf{x},t)$. Use divergence theorem on advective and diffusive terms. Gather ϕ_{ii} into $\{\phi\}$, and assemble to global

$$[M]\{\dot{\phi}\} + [A_{adv}]\{\phi\} = -[A_{diff}]\{\phi\} + \{\mathbf{f}_\phi\} + \{\mathbf{f}_{BC}\}$$

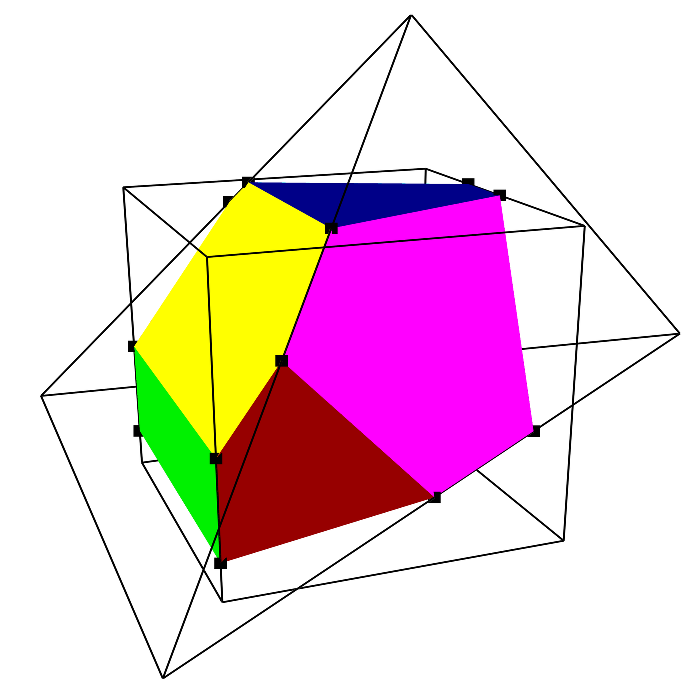
- FV Discretization is *natural* to cut-cells: i.e. CC discretization of diffusive term

$$\int_{\Omega_{ii}} \nabla\cdot(-\rho D_\phi\nabla\phi)\, d\Omega = \int_{\partial\Omega_{ii}} (-\rho D_\phi\nabla\phi)\cdot\hat{\mathbf{n}}_{ii}\, d\partial\Omega = \sum_{k=1}^{nfc=6} (-\rho D_\phi\nabla\phi)_k \cdot\hat{\mathbf{n}}_{ii,k} A_k$$

where the 6 cut-cell faces are treated individually:

- k=4,5 regular GASPHASE faces.
- k=3,6 GASPHASE cut-faces.
- k=1,2 INBOUNDARY cut-faces.

- **Computational Geometry in FDS**

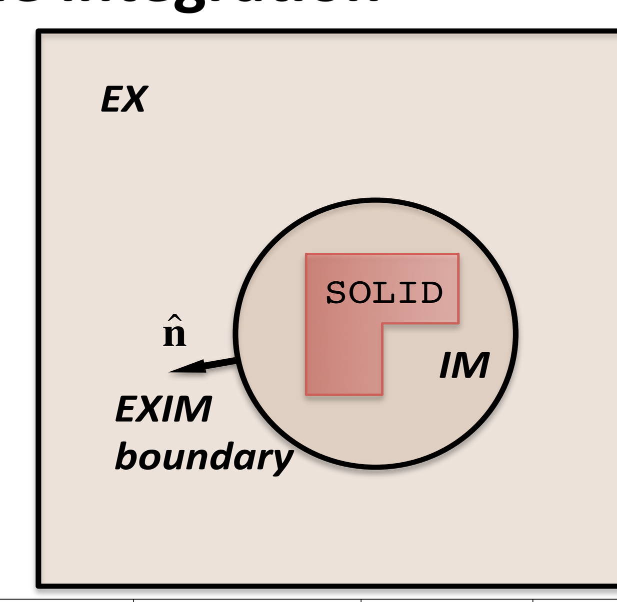


Problem: Determine the volume of a tetrahedron/box intersection region and the area of the bounding faces

Qualitative graphical verification using OpenGL

1. Draw a tetrahedron clipped outside of the box
2. Draw a box clipped outside of the tetrahedron
3. Compute the intersection vertices and compare
4. Compute intersection volume and face areas

- **Small cut-cells: Explicit Implicit time integration[4]**



Overcomes the CFL condition on a sub region of the domain where the scalar is evolved implicitly. Known $\{\phi\}^n$ divided in $\{\phi_{EX}\}^n$ and $\{\phi_{IM}\}^n$

1. From $\{\phi\}^n$ define fluxes $\left([\rho\phi\mathbf{u} - \rho D_\phi\nabla\phi]\cdot\hat{\mathbf{n}}\right)^n$ at *EXIM* boundary.

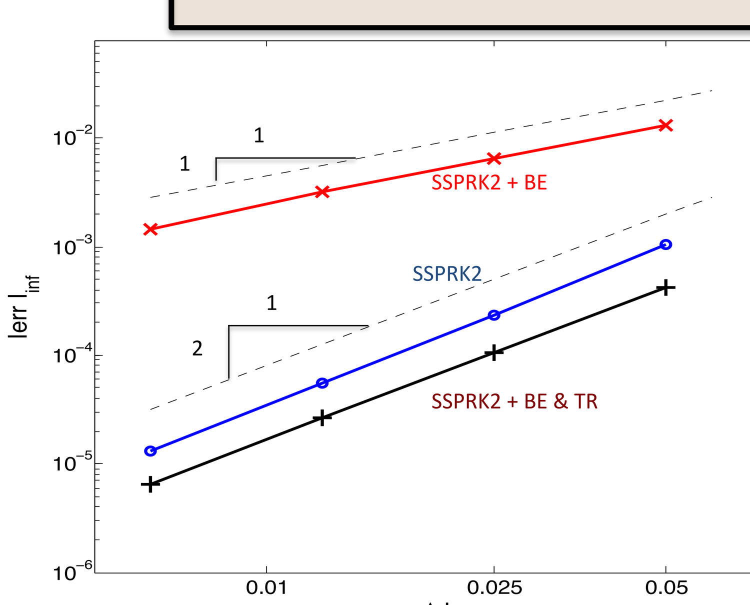
2. Integrate *EX* explicitly, i.e. Forward Euler:

$$\{\phi_{EX}\}^n \rightarrow \{\phi_{EX}\}^{n+1}$$

3. Integrate *IM* implicitly, i.e. Backward Euler (BE), using *EXIM* fluxes as boundary condition: $\{\phi_{IM}\}^n \rightarrow \{\phi_{IM}\}^{n+1}$

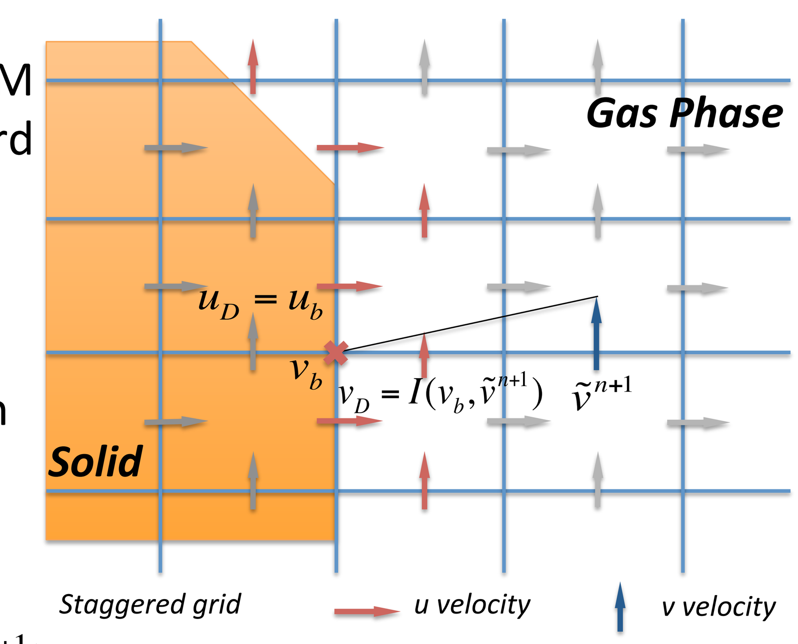
Step 1 ensures conservation, steps 2 and 3 can be done in parallel.

We combine the SSPRK2 integrator in FDS with BE, or with BE + Trapezoidal Rule (TR) on the 2[nd] RK2 stage.



Infinity Error for EXIMSSPRK2 at T=0.5, heat equation with Gaussian initial condition.

- **CC+IBM Method**



Combine CC for scalars with direct forcing IBM for momentum equations: i.e. for Forward Euler Fractional Step

$$\frac{\mathbf{u}^{n+1} - \mathbf{u}^n}{\Delta t} = -(\mathbf{F} + \nabla H)^n$$

Given a desired velocity $\mathbf{u}_D$ at time t_{n+1}, in forcing points

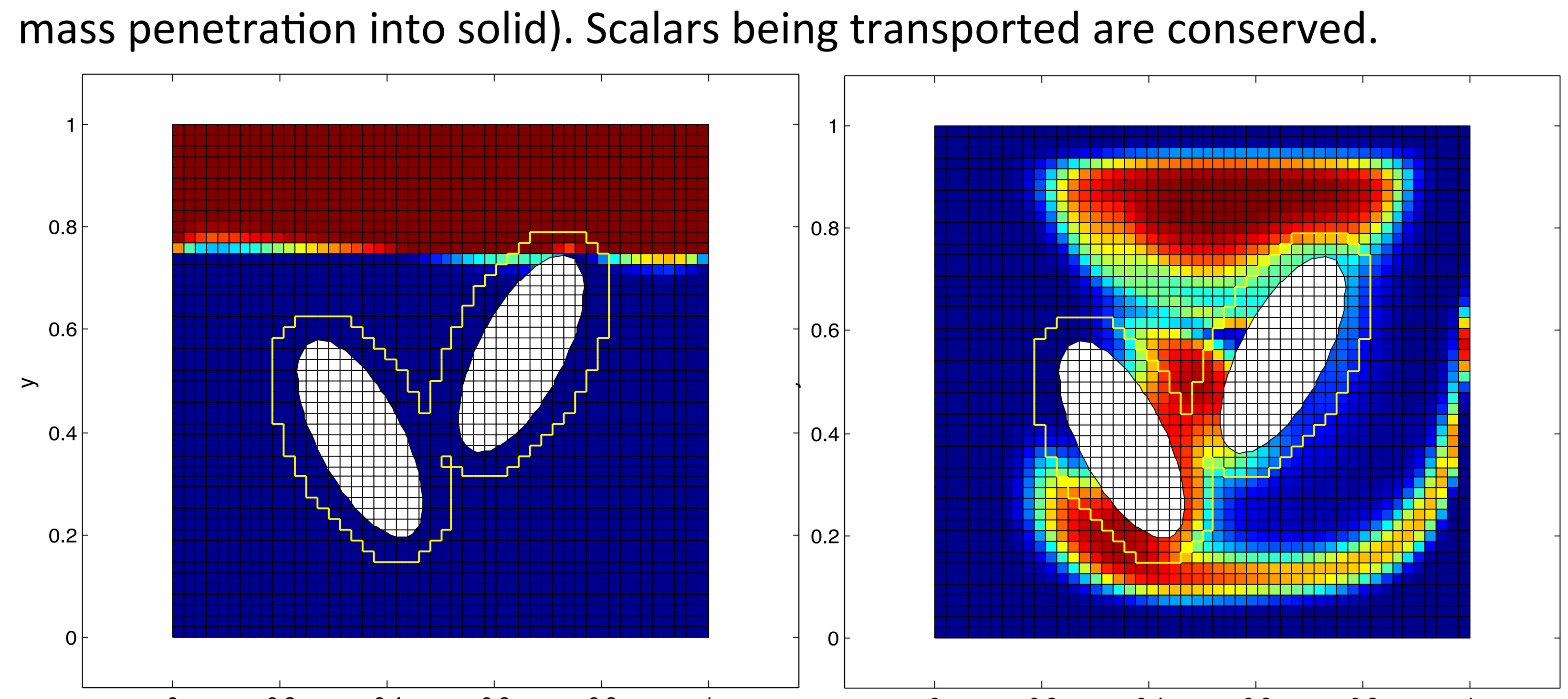
$$\mathbf{F}^n = \mathbf{F}_{IB} = -\frac{\mathbf{u}_D - \mathbf{u}^n}{\Delta t} - \nabla H^{n-1}$$

$\mathbf{u}_D$ obtained from interpolation $I(\mathbf{u}_b, \tilde{\mathbf{u}}^{n+1})$ + flux matching (if using discrete divergence equivalence between GASPHASE cut-cell and underlying structured cell). Then

$$\Delta H^n = -\left[\nabla\cdot\mathbf{F}^n + \frac{\partial}{\partial t}(\nabla\cdot\mathbf{u})\right] \quad \text{Poisson}$$

$$\mathbf{u}^{n+1} = \mathbf{u}^n - \Delta t(\mathbf{F} + \nabla H)^n \quad \text{Correction}$$

Boundary conditions on the Bernoulli integral H^n are defined consistently (no mass penetration into solid). Scalars being transported are conserved.



Scalar Advection on Lid driven cavity at Re=100 with two immersed ellipses. Scalar integral during computation varies on < 10^{-14}. Grid 48x48, t=0.25 , 7.5. Blue to red, scalar varies from 0 to 1. Yellow segments: EXIM scalar time integration boundary.

[1] K. McGrattan et al. Fire Dynamics Simulator, Technical Reference Guide, NIST, Gaithersburg, MD. Sixth Ed., Sept. (2013).
[2] G.P. Forney. Smokeview, A Tool for Visualizing FDS Data Vol. II, NIST, Gaithersburg, MD. Sixth Ed., May (2013).
[3] E. A. Fadlun et al. J. Comput. Phys. 161, pp. 35-60 (2000).
[4] S. May, M. Berger. Proc. Finite Vol. Cmplx App. VII, pp. 393-400 (2014).
[5] https://3dwarehouse.sketchup.com/
[6] https://www.google.com/earth/

High Temperature Performance of Firefighting Protective Equipment

Firefighting Technology Group
National Institute of Standards and Technology, Gaithersburg, MD

National Institute of Standards and Technology
U.S. Department of Commerce

Motivation

Current test methods and standards do not fully characterize the performance of firefighter equipment in high temperature, rough duty environments. Representative test methods will characterize the performance of fire fighter equipment under the extreme environments in which firefighters operate.

The three major areas of study include:

- performance of firefighter electronic equipment in rough-duty fire fighting environments
- performance of firefighter self-contained breathing apparatus (SCBA)
- performance of firefighter protective clothing

Firefighter Electronic Equipment

Investigating performance issues with portable radios that may be vulnerable to elevated temperatures encountered during firefighting activities. Exposure, which falls into four categories, is characterized by the time duration and temperature:

Table : Thermal Classes for Equipment Exposure

Thermal Class	Time Duration (min)	Temperature (°C/°F)
Class I	25	100/212
Class II	15	160/320
Class III	5	260/500
Class IV	< 1	$> 260/500$

During exposure tests, measurements are taken of temperature, airflow velocity, and heat flux in the test section of the apparatus. Typically 2 to 3 replicates of each test are performed.

Figure : Class III Exposure of two radios (one inside/one outside a turnout gear pocket) (l) and microphone - speaker attachments (r).

This work is being used to inform the NFPA technical committee in charge of developing/maintaing the 1802 standard on portable radio equipment.

Firefighter Self-Contained Breathing Apparatus

SCBAs have been examined in the convective flow loop exposing the equipment to temperatures up to 260°C/500°F and the radiant environment with heat fluxes up to 15 kW/m^2.

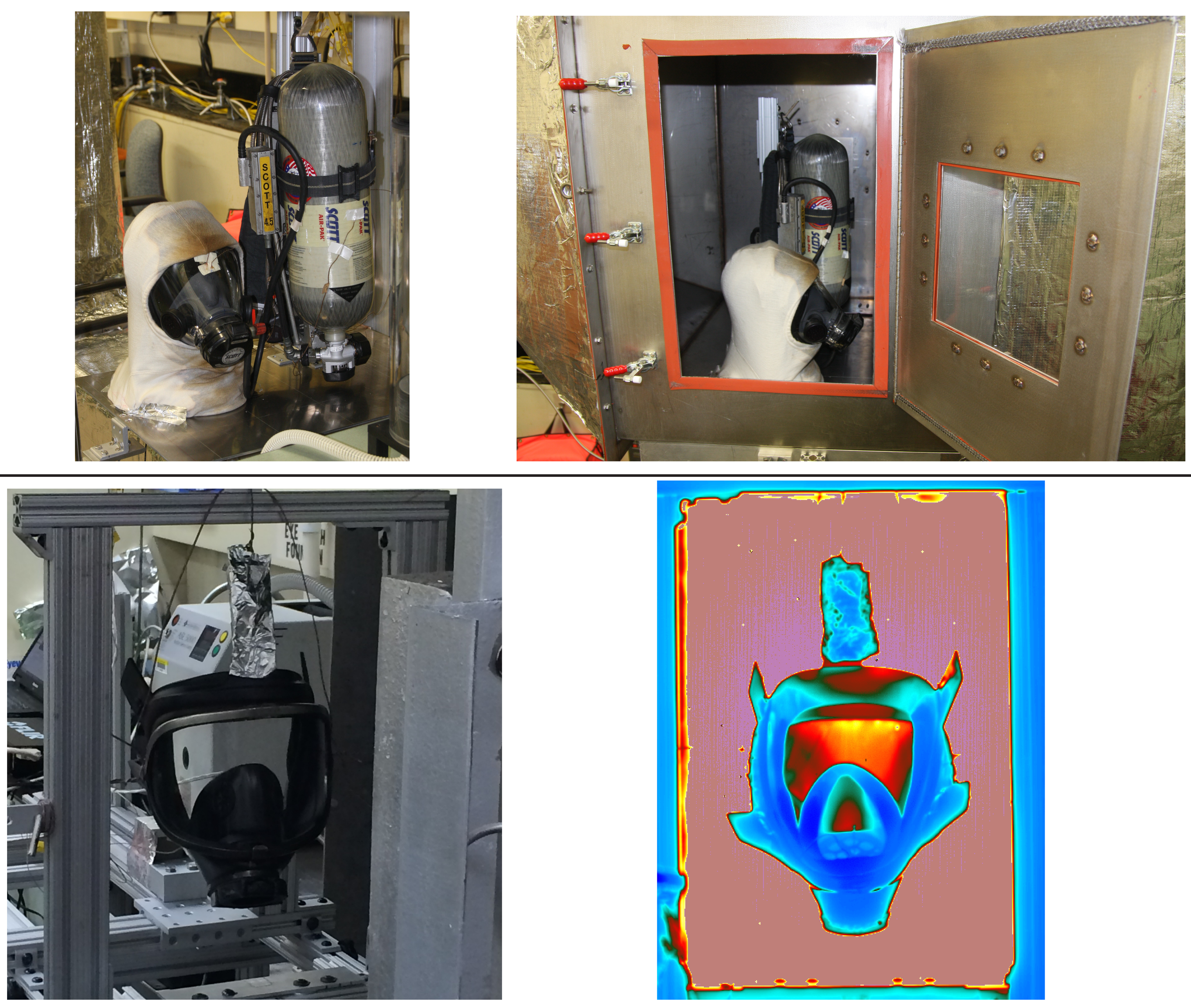


Figure : Flow loop exposing an SCBA tank and mounted face piece (top) and a pre-test image and during test IR image of the inside of a face piece after exposure to 15 kW/m^2 radiant heat flux (bottom).

Work focused on SCBA face piece exposures has led to improvements to the NFPA 1981 standard.

Research Resources

- Floor Radiant Panel (x2)
- Radiant Panel (x2)
- Cone Calorimeter
- Large Scale Test Facility
- Flow Loop
- Plunge Test Apparatus
- Thermal Protective Performance Apparatus
- Radiant Protective Performance Apparatus
- Heated Mannequin
- Breathing Mannequin
- Breathing Machine (x2)
- FLIR SC8000 HD IR Camera

Firefighter Protective Clothing

Four turnout coats were exposed to radiative heat fluxes of 1.5, 2, 3, 5, and 10 kW/m^2 in the radiant heat panel lab for times of 5 and 10 minutes. Tests included thermocouple measurements as well as HD and IR video on each side of the coats:

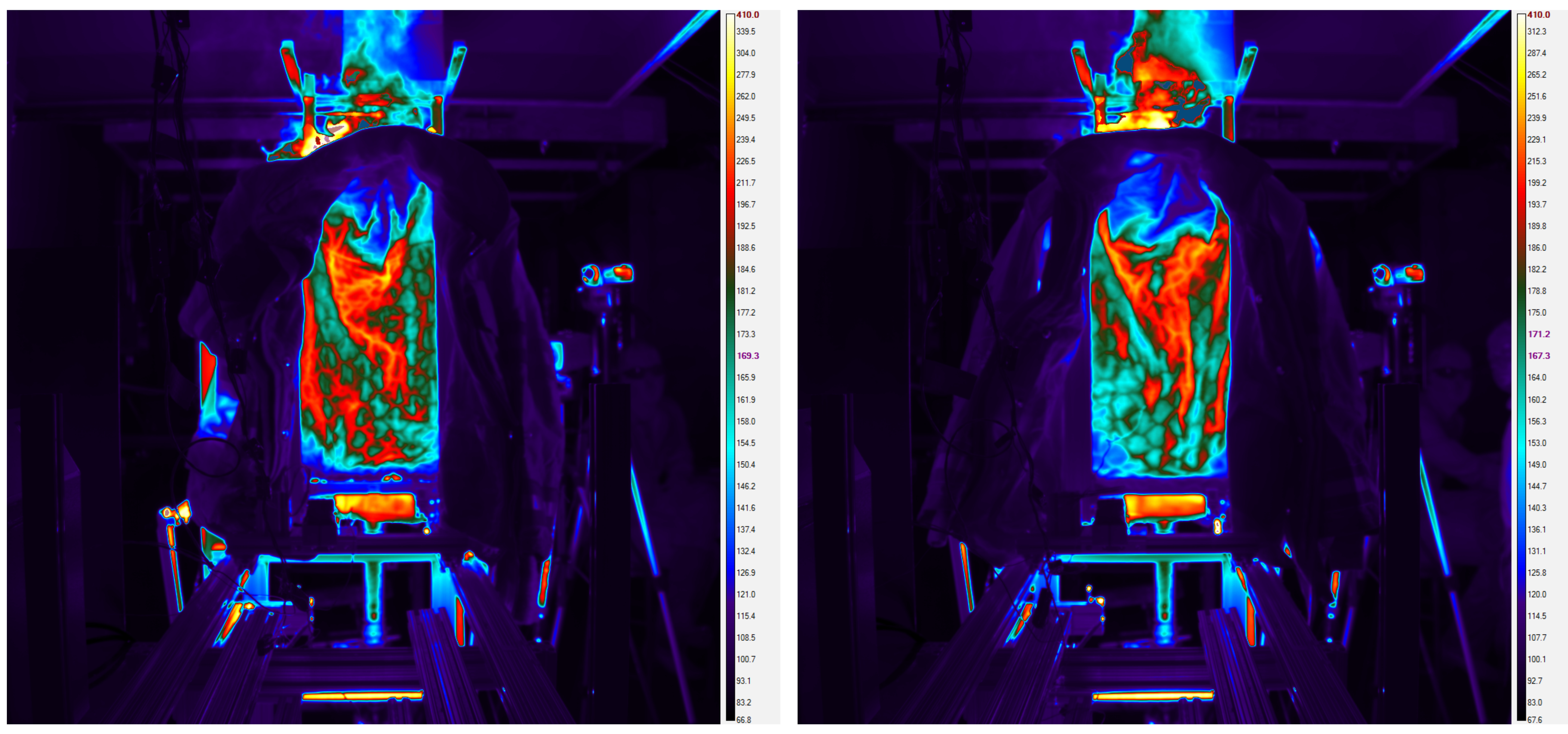


Figure : Two turnout coats exposed to 10 kW/m^2 of radiant energy for $<$ 5 minutes. Image produced using FLIR IR camera.

In addition to bench scale laboratory testing, firefighter protective clothing and helmets are also tested as part of full scale experiments. In these tests, a leather helmet and high temperature thermoplastic helmet were exposed to high-temperature gases in a flow path during both gas burner tests and "real" fuel tests in which the fire room flashed over. The helmets were instrumented with thermocouples to measure the interior and exterior surface temperatures as was the chin strap buckle.

Figure : Two firefighter helmets (leather(l) high temperature thermoplastic (r)) along with a standard hardhat were placed in the flow path in a two-story full scale fire test in Delaware County, PA.

Four inch samples of turnout gear (outer shell, moisture barrier, and thermal liner) were set 1 m off the ground and exposed to high temperature exhaust gases of room and contents fire. The gear was instrumented to measure the exposed (exterior) temperature and the temperature that a firefighter would feel against his/her work shirt. The elevation was set to be that of a typical crouched firefighter.

Figure : Turnout gear samples placed in the flow path of a two-story full scale fire experiment in Delaware County, PA. The sample (l) was instrumented to record temperature on interior and exterior of the sample. Three samples were placed in the potential flow path (r).

Acknowledgements

This research was performed with assistance from the Department of Homeland Security.

National Research Institute of Fire and Disaster

Fire and Disaster Management Agency, Government of Japan

4-35-3 Jindaiji-Higashimachi, Chofu, Tokyo, 182-8508, Japan

The NRIFD is the unique institute in Japan engaged in comprehensive research on firefighting and disaster prevention. Continues in the tradition of its predecessor, the Fire Research Institute (FRI) established in 1948, and builds upon results already achieved. Our basic mission is the same as that of the Fire Research Institute when it was established, i.e., to provide scientific and engineering support to assist firefighters in their work and respond to society's demand for safety and security.

Building Fire

Personal Protection

Oil Tank Protection

Firefighting Foam

Rescue Robot

Fire Investigation

Mission

1. Continuous implementation of research and development into fire and disaster prevention based on the long-term vision.
2. The implementation of and support for investigations into the causes of fires and accidents involving the leakage of hazardous materials.
3. Professional support for fire-fighting activities in the event of large-scale or extraordinary disasters.
4. Establishing and maintaining cooperation with people related to science and technology in the field of fire fighting.

Research Staff : 26 (as of 2015 Feb.)

Research Facilities in Campus

Large Fire Experiments Building

Experimental area
24 x 24 x 20 m (W x D x H)
Exhaust capacity
45,000 m^3/h x 4

Steel-made explosion proof vessel

Fire Extinguishing Research Building

Experimental area 1
25 × 25 × 22 m (W × D × H)
Exhaust capacity
90,000 m^3/h x 1,

Experimental area 2
14 × 14 × 12 m (W × D × H)
Exhaust capacity
30,000 m^3/h x 1

X-ray CT scan

Please visit http://nrifd.fdma.go.jp/english/index.html for more information

US-JP Workshop: Operation Tomodachi 2015 March 16th NIST, Gaithersburg, MD, USA

Center for Fire Science and Technology, Tokyo University of Science (TUS), Japan

Tokyo University of Science (TUS) has long been at the forefront of fire science. TUS established the Center for Fire Science and Technology (CFSaT) in 1981 and hasn't looked back since. Today, the CFSaT carries on research to help reduce the damage and impact of fires. The CFSaT cooperates with other leading institutions—academic and otherwise—working in areas of fire safety research, education and engineering worldwide. Today, the CFSaT carries on this tradition of research at the Fire Research and Test Laboratory, which was established in March 2005 and boasts world-class facilities and equipment.

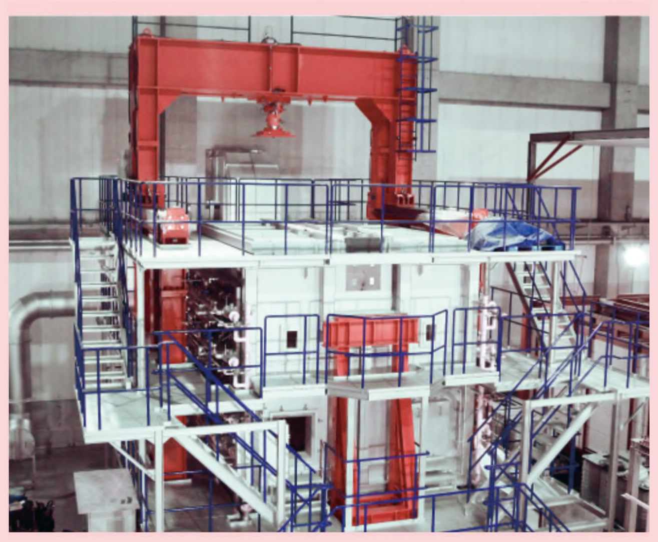

Exterior view

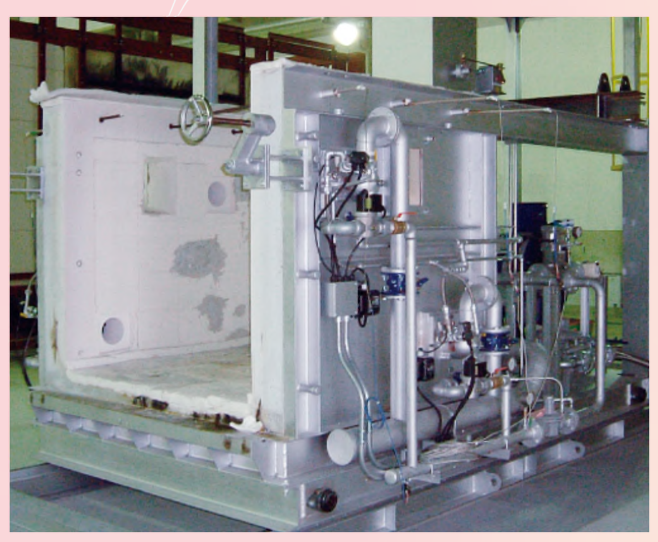

Interior view

Fire Research and Test Laboratory at CFSaT

The Fire Research and Test Laboratory at CFSaT is located on the Noda campus. It's total area is approximately 1900 m^2 with a ceiling height of 18 m. The Full-Scale Fire Test Hall is a large-scale laboratory which is available for full-scale experiments that vary depending on such parameters as fire resistance of structural members and materials, burning behavior of combustible materials, and smoke movement. In order to provide education and research based on practice and theory at the Center. The Full-Scale Fire Test Hall is also equipped with essential tools for fire research such as smoke chamber for measurement of heat release rate and furnaces for fire resistance test. The Small Test Laboratories are comprised of a multi-purpose experiment room, a cone calorimeter testing room, temperature and humidity controlled rooms, a library, an observation room, a conference room and others.

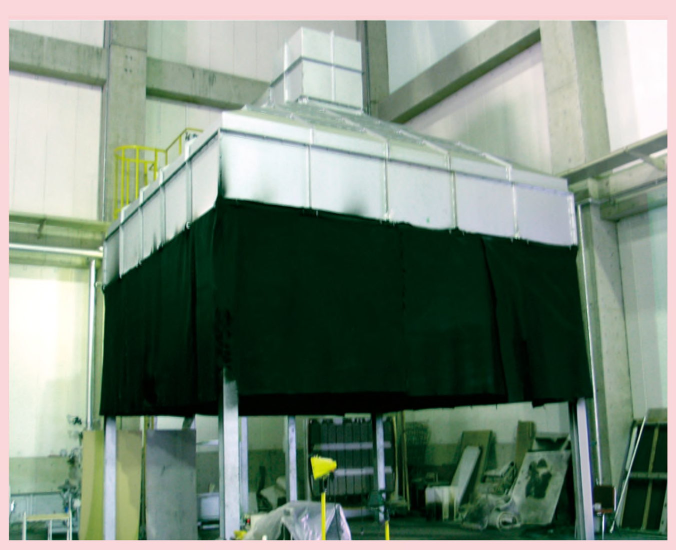

Structural Fire Resistance Furnace for Walls


Multiple Full-scale Structural Fire Resistance Furnace


Structural Fire Resistance Furnace (Medium scale)

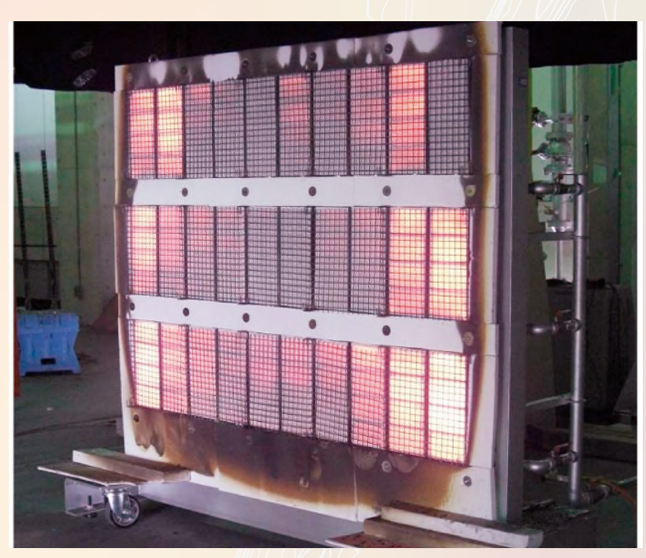

Secondary Combustion Furnace


Cone Calorimeter

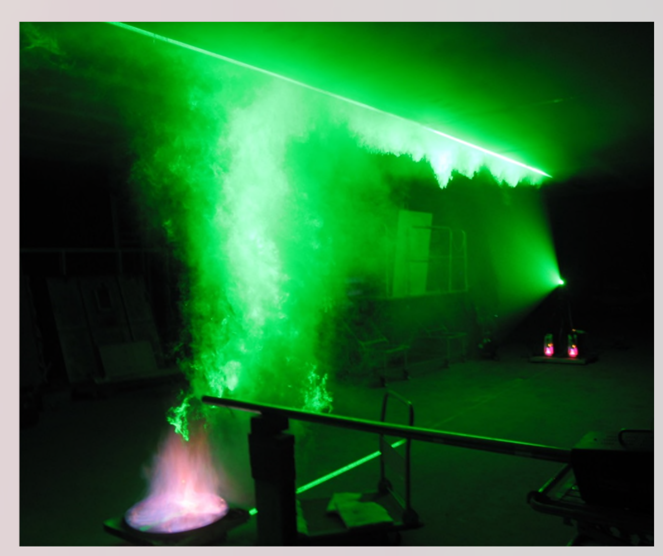

Calorimetry Hood (5 m x 5m)


Full-Scale Compartment for Fire Experiment (with Sprinkler system)


Room Corner Testing Unit


ICAL Testing Unit


FT-IR Gas Analyzer with Smoke Density Chamber


PIV System

Joint Usage / Research Center

The CFSaT is currently working to promote collaborate researches as a Joint Usage / Research Center recognized by Japanese Government since 2009. A major feature of Joint use and joint research is that benefits are realized for both parties. It is expected that excellent researchresults can be promoted by actively engaging in information exchange regarding shared problems where both researchers have "equal standing." In particular, if it is possible to conduct exchange between various fields, doing so is expected to be highly effective, and may even lead to the discovery of research seeds. Furthermore, by utilizing the advanced research facilities and equipment for fire science at this center, high-level results are expected that are continuous, extensible, and fruitful.

Experiments on Suppression Performance of Sprinkler System Against Different Fuels

Masaki Noaki, Yoshifumi Ohmiya

1 Background and Purpose

Burning suppression effect by sprinkler

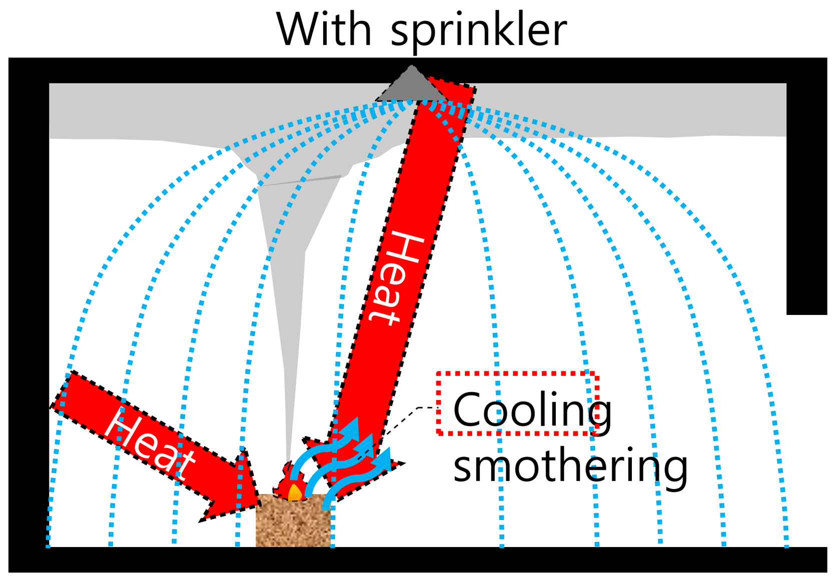
① Cooling

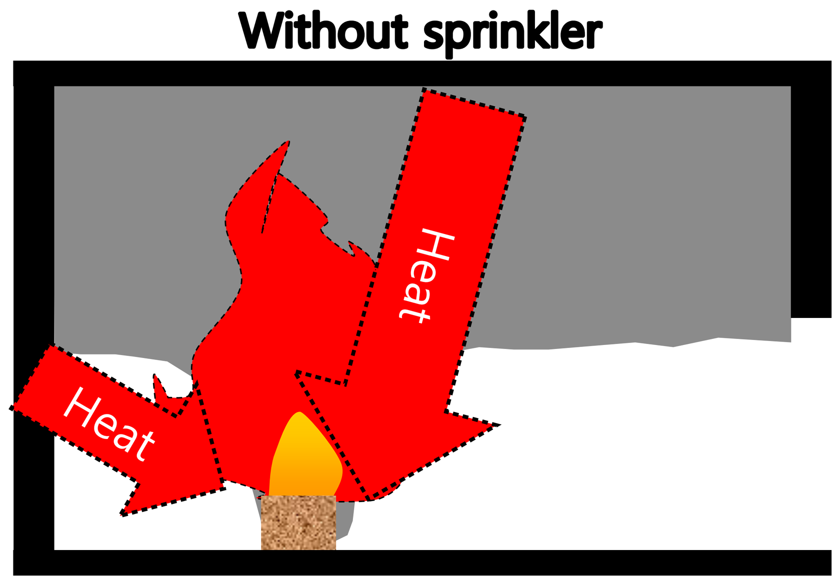
② Decrement of temperature of smoke layer and walls

⇒ Decrement of incident heat of combustibles

③ Smothering

And so on…



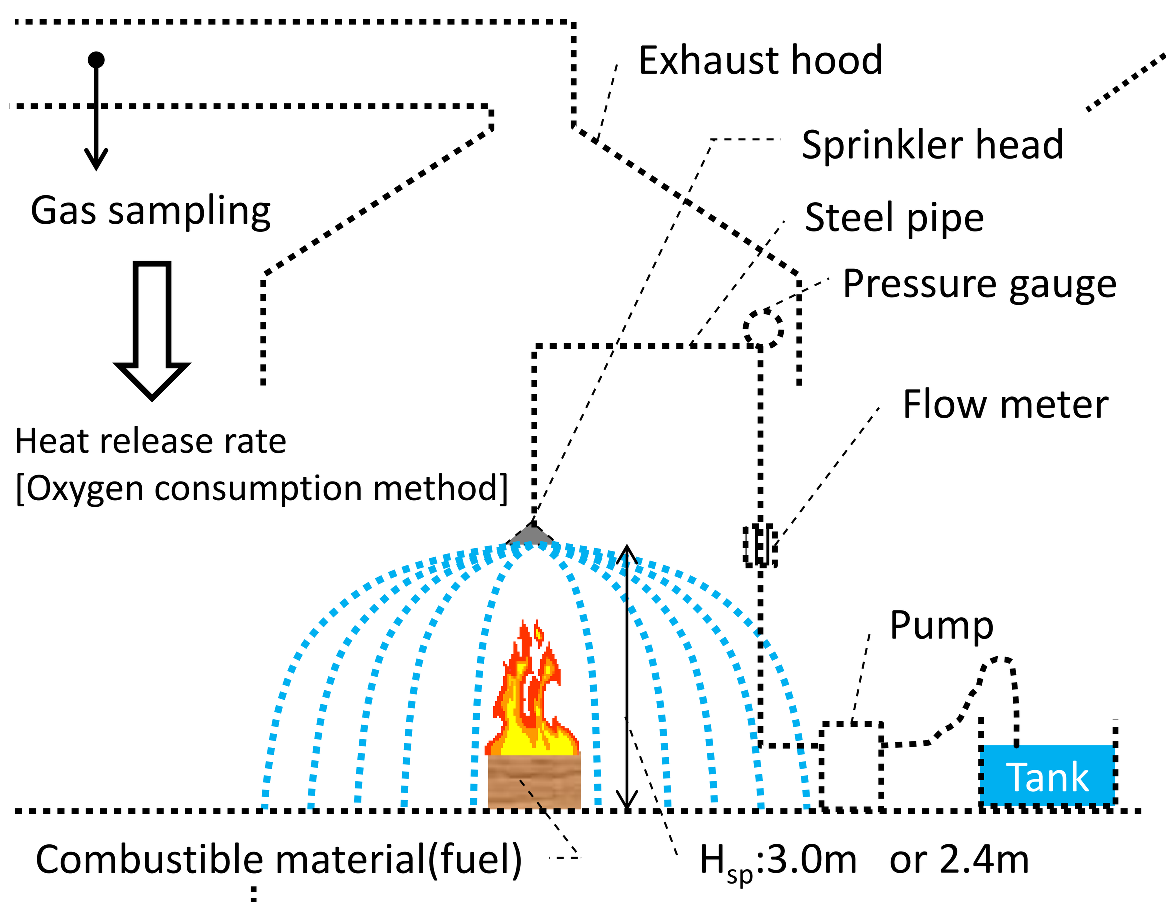


Purpose of this study

Collection of quantitative knowledge about influence of "①Cooling" on suppression performance on heat release rate by sprinkler.

2 Experiment overview

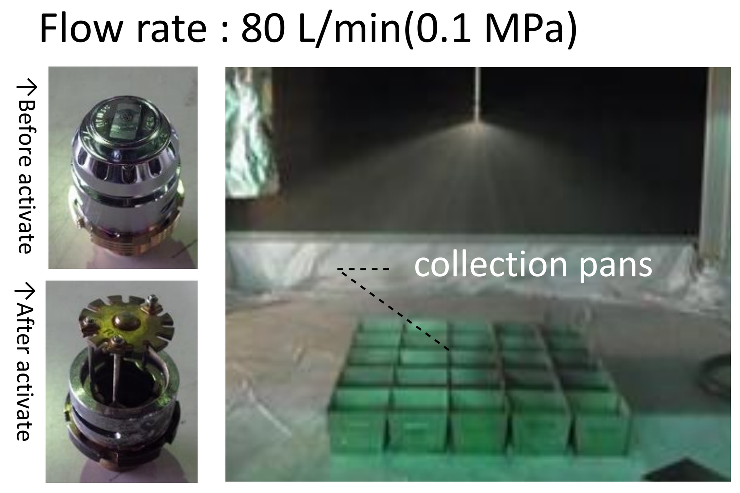
a series of free burning experiments using or not sprinkler system were carried out. and heat release rate of combustible materials were measured.



Manufacturer : Senju Sprinkler Co.

Model number : VQR

Flow rate : 80 L/min(0.1 MPa)



Water spray density [g/s/m²]

52.8	41.7	36.1	41.7	38.9
36.1	25.0	25.0	27.8	38.9
25.0	22.2	19.4	25.0	44.4
36.1	25.0	27.8	22.2	33.3
44.4	38.9	38.9	33.3	33.3

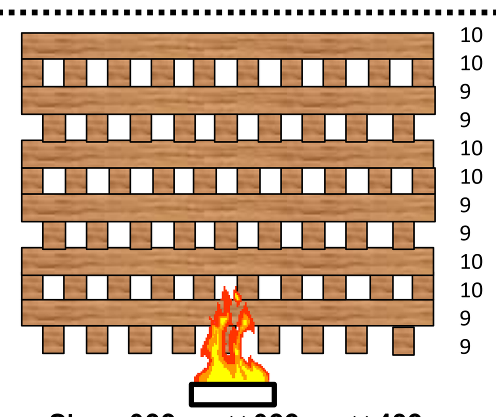
H_{sp}=3.0m
mean value : 33.3

52.8	61.1	38.9	50.0	58.3
27.8	27.8	25.0	33.3	50.0
25.0	16.7	22.2	30.6	52.8
36.1	22.2	22.2	30.6	55.6
44.4	36.1	50.0	47.2	47.2

H_{sp}=2.4m
mean value : 38.5

Ignition source : Ignition agent
95mm × 95mm × 2mmthick

Sofa

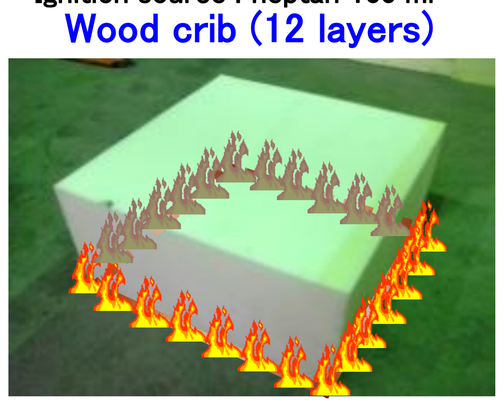


Size : 900mm × 900mm × 480mm
Ignition source : heptan 100 ml

Wood crib (12 layers)

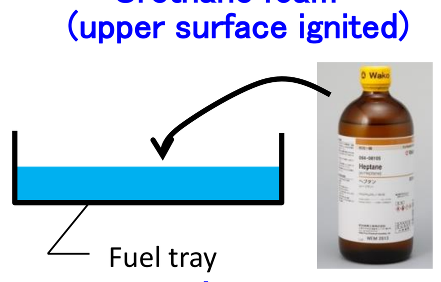
Ignition source : gas lighter

Urethane foam (upper surface ignited)



Hemp cord impregnated methanol

Urethane foam (bottom periphery ignited)



n–heptan

The reason of choice these materials

To prevent the surround (ex.wall) temperature from raising, combustible materials which maximum heat release rate was about 1000 - 1500 kW when sprinkler system didn't activated were selected. But n-heptan is exception.

Parameters of experiments
- Kind of materials
- Distance between sprinkle and fuel
- Sprinkler activation time

↑ Experimental conditions

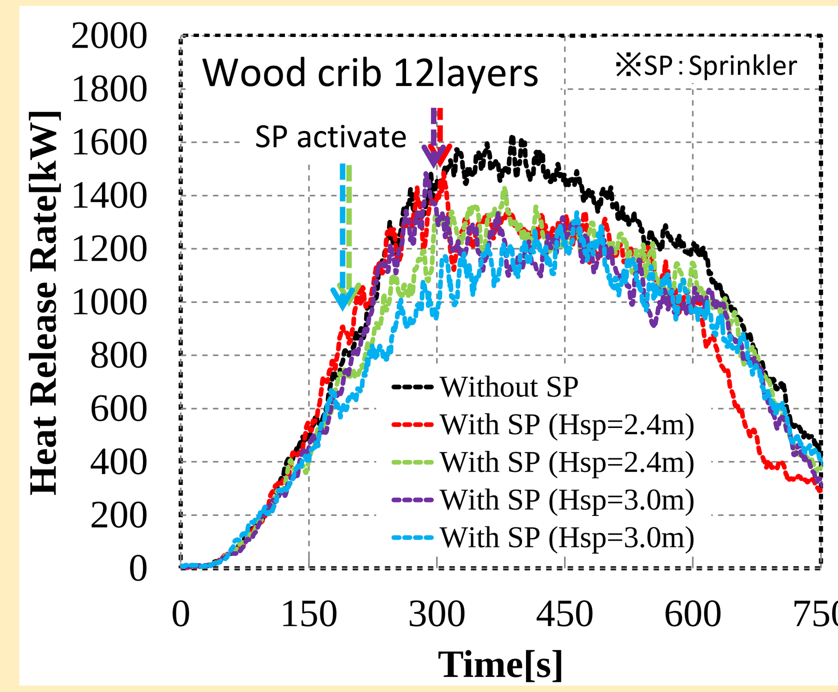
combustible materials	Size [mm] (Length × Width × Height)	Surface area [m²]	Mass [kg]	Density [kg/m²]	Height of sprinkler H_{sp} [m]	Sprinkler activation time*4 [s]
n–heptan	500 × 500	0.25	4.1(6ℓ)	684*3	–	without Sprinkler
n–heptan	800 × 800	0.64	10.9(16ℓ)	684*3	–	without Sprinkler
n–heptan	500 × 500	0.25	4.1(6ℓ)	684*3	2.4	HRR peak (1min after ignition)
n–heptan	800 × 800	0.64	10.9(16ℓ)	684*3	2.4	HRR peak (1min after ignition)
n–heptan	500 × 500	0.25	4.1(6ℓ)	684*3	3.0	HRR peak (1min after ignition)
n–heptan	800 × 800	0.64	10.9(16ℓ)	684*3	3.0	HRR peak (1min after ignition)
Wood crib (12layers)	900 × 900 × 480	12.9	48.4	393.5	–	without Sprinkler
Wood crib (12layers)	900 × 900 × 480	12.9	46.5	378.0	2.4	HRR peak (4.5min after ignition)
Wood crib (12layers)	900 × 900 × 480	12.9	48.3	392.7	3.0	HRR peak (4.5min after ignition)
Wood crib (12layers)	900 × 900 × 480	12.9	47.2	383.7	2.4	HRR peak × 1/2 (2.5min after ignition)
Wood crib (12layers)	900 × 900 × 480	12.9	48.1	391.1	3.0	HRR peak × 1/2 (2.5min after ignition)
Urethane foam (upper)*1	1000 × 1000 × 500	1.0	8.1	16.2	–	without Sprinkler
Urethane foam (upper)*1	1000 × 1000 × 500	1.0	8.0	16.0	2.4	HRR peak (3min after ignition)
Urethane foam (upper)*1	1000 × 1000 × 500	1.0	7.9	15.8	3.0	HRR peak (3min after ignition)
Urethane foam (bottom)*2	1000 × 1000 × 500	5.0	8.2	16.4	–	without Sprinkler
Urethane foam (bottom)*2	1000 × 1000 × 500	5.0	8.1	16.2	3.0	HRR peak (1.5min after ignition)
Sofa	690 × 1200 × 710	2.8	19.9	68.6	–	without Sprinkler
Sofa	690 × 1200 × 710	2.8	19.7	67.9	2.4	HRR peak (3.5min after ignition)
Sofa	690 × 1200 × 710	2.8	19.5	67.2	3.0	HRR peak (3.5min after ignition)

*1 "upper" means that urethane foam was ignited at center of upper surface.
*2 "bottom" means that urethane foam was ignited at bottom periphery.
*3 literature data
*4 "HRR peak" means that sprinkler was activated at the time which heat release rate of combustible without sprinkler reach maximal value.

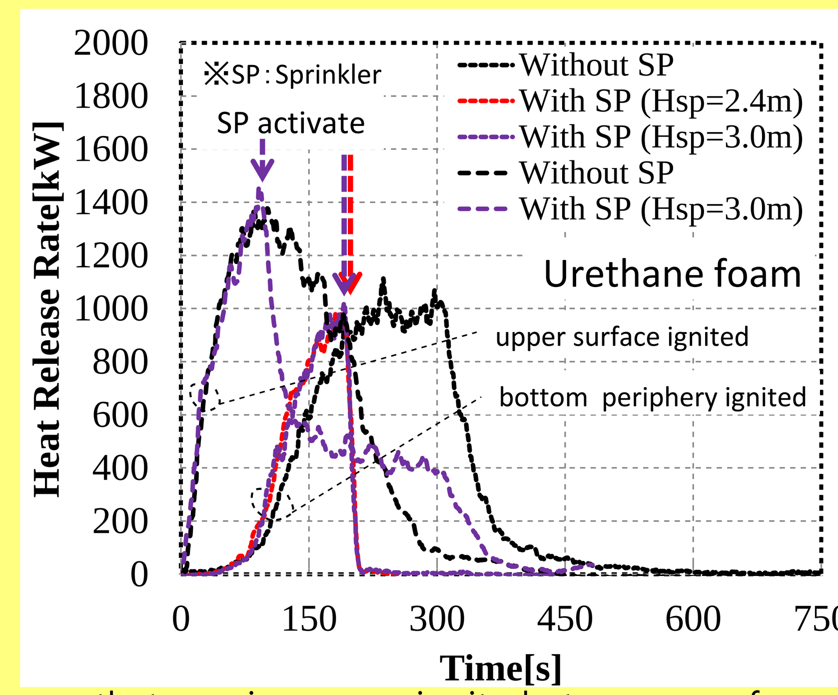
3 Experimental Results

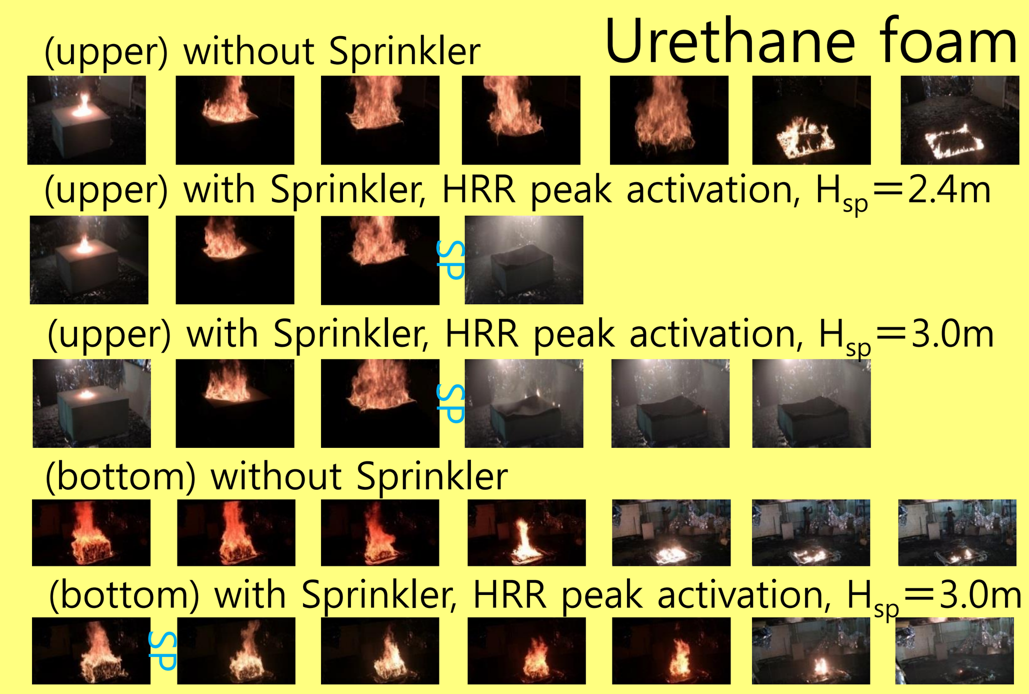
Heat release rate

Photographs every 1min from ignition

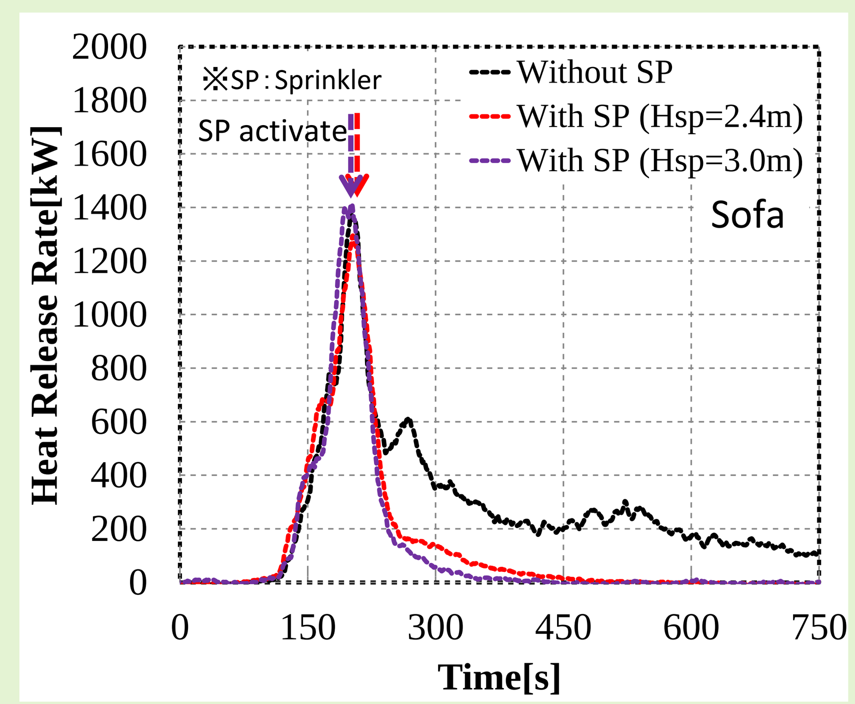


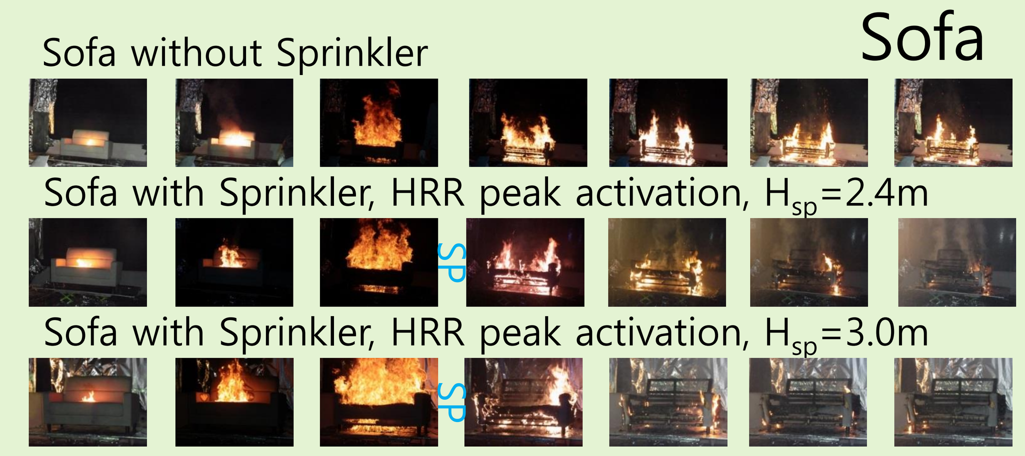
Though maximum heat release rate was about 1500kW on condition that sprinkler was not activated, the maximum heat release rate was about 1200kW-1300kW on condition that sprinkler was activated. The distance between fuel surface and sprinkler and the sprinkler activation time didn't have much influence on heat release rate. In case of HRR peak × 1/2 activation, burning area and heat release rate continued increasing after sprinkler activation.



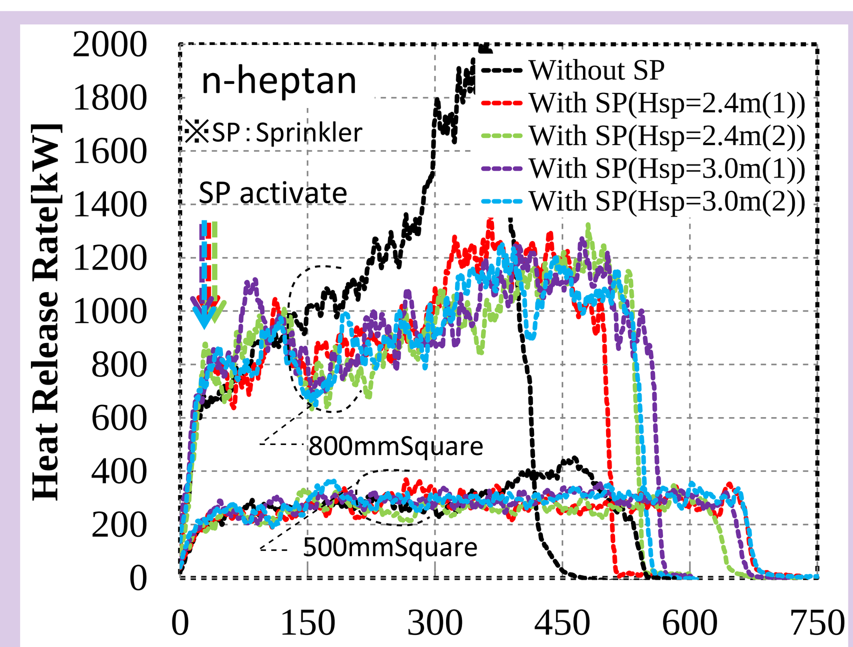


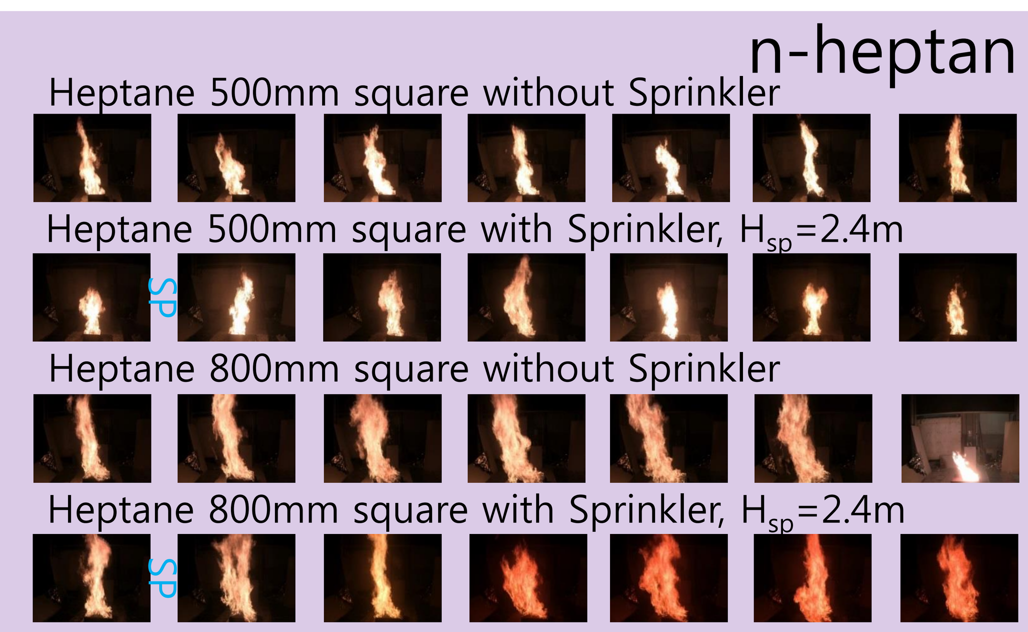
In case that specimen was ignited at upper surface, although maximum heat release rate without sprinkler was about 1000kW, heat release rate became 0kW after sprinkler activated. About 15-30s after sprinkler, the fuel was almost extinguished. On the other hand, in case of bottom periphery ignition, maximum heat release rate without sprinkler was about 1400kW. The heat release rate under sprinkler activation fluctuates between 400 – 600 kW. In this case, specimen continued to burn after sprinkler activation.





In case that sprinkler was not activated, maximum heat release rate without sprinkler was about 1400kW and finally burnt out. In case that sprinkler was activated, heat release rate with sprinkler activating condition was 200 – 400 kW lower than one without sprinkler. Although the specimen continues to burn, the frame of sofa was not burnt out.





※ Photos of H_{sp}=3.0m's cases were omitted because H_{sp}=3.0m cases and H_{sp}=2.4m cases were very similar.

In case that 800mm square set as fuel tray, although heat release rate without sprinkler continued increasing with progress of the time, heat release rate under sprinkler activation fluctuated 1000 – 1200 kW. As for this reason, it is supposed that sprinkler cools the fuel tray, and suppressed boiling of n-heptan. In experiments using 500mm square tray, heat release rate were almost the same time-history even sprinkler was activated or not. They were about 300 kW. From these results, it is supposed that sprinkler didn't have much influence on heat transfer to specimen from flame.

4 Summary

■**The quantitative knowledge about influence of "①Cooling" on suppression performance on heat release rate by sprinkler were collected.**

■**With the case except urethane foam(upper), fuel continued to burn after sprinkler activation.**

■**Even if distance between fuel surface and sprinkler was the same condition, heat release rate under sprinkler activation differs according to a kind of fuel.**

Summary of experimental results

combustible materials	Size [mm] (Length × Width × Height)	Maximum HRR without SP※1 [kW]	Representative HRR with SP※2	remarks column
n–heptan	500 × 500	300	300	
n–heptan	800 × 800	2000	1000–1200	
Sofa	690 × 1200 × 710	1400	200–400kW decrease than the time history of heat release rate without sprinkler.	specimen continued to burn after sprinkler activation.

combustible materials	Size [mm] (Length × Width × Height)	Maximum HRR without SP※1 [kW]	Representative HRR with SP※2	remarks column
Wood crib (12layers)	900 × 900 × 480	1500	1200–1300	In the case of HRR peak × 1/2 activation, burning area and heat release rate continued increasing after sprinkler activation.
Urethane foam (upper)*1	1000 × 1000 × 500	1000	0 (extinguished)	About 15–30s after sprinkler, specimen was almost extinguished.
Urethane foam (bottom)*2	1000 × 1000 × 500	1400	400–600	specimen continued to burn after sprinkler activation.

※1 The maximum heat release rate under the condition without sprinkler.
※2 The value of heat release rate after sprinkler activation when heat release rate was approximately steady.

Scale-model Experiment of Fire Whirl Behind an L-shaped Wall

Yuta Kawagoe[1], Kozo Sekimoto[2], Kazunori Kuwana[1]

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[2] *Institute of Research for Technology Development (IR4TD), University of Kentucky, USA*

Abstract

When a pool fire interacts with a spinning flow, a fire whirl is generated. The generation of a fire whirl tends to increase the fire damage mainly because of induced strong wind and increased flame height and burning rate. This paper studies the occurrence of a fire whirl behind an L-shaped wall. Under the presence of lateral wind, a fire whirl is generated by the interaction between a pool fire and the recirculation region behind the wall. A recently conducted large-scale experiment, in which the height of generated fire whirl exceeded 10 m, is reproduced using a scale model. The scale-model experiment uses a wind tunnel, and the range of wind velocity tested is determined from the wind condition of the large-scale experiment based on scaling analysis. It is found that there is a narrow range of wind velocity that generates intense fire whirl.

Large-scale experiment (wind velocity, 2 m/s)

Pool fire before the occurrence of fire whirl

Fire whirl

A fire whirl is created by burning heptane (pool diameter, 1.5 m) in the recirculation region behind an L-shaped wall (height, 9 m). Before fire whirl is created, the flame height is 2-3 m, while the flame height of the fire whirl exceeds 10 m.

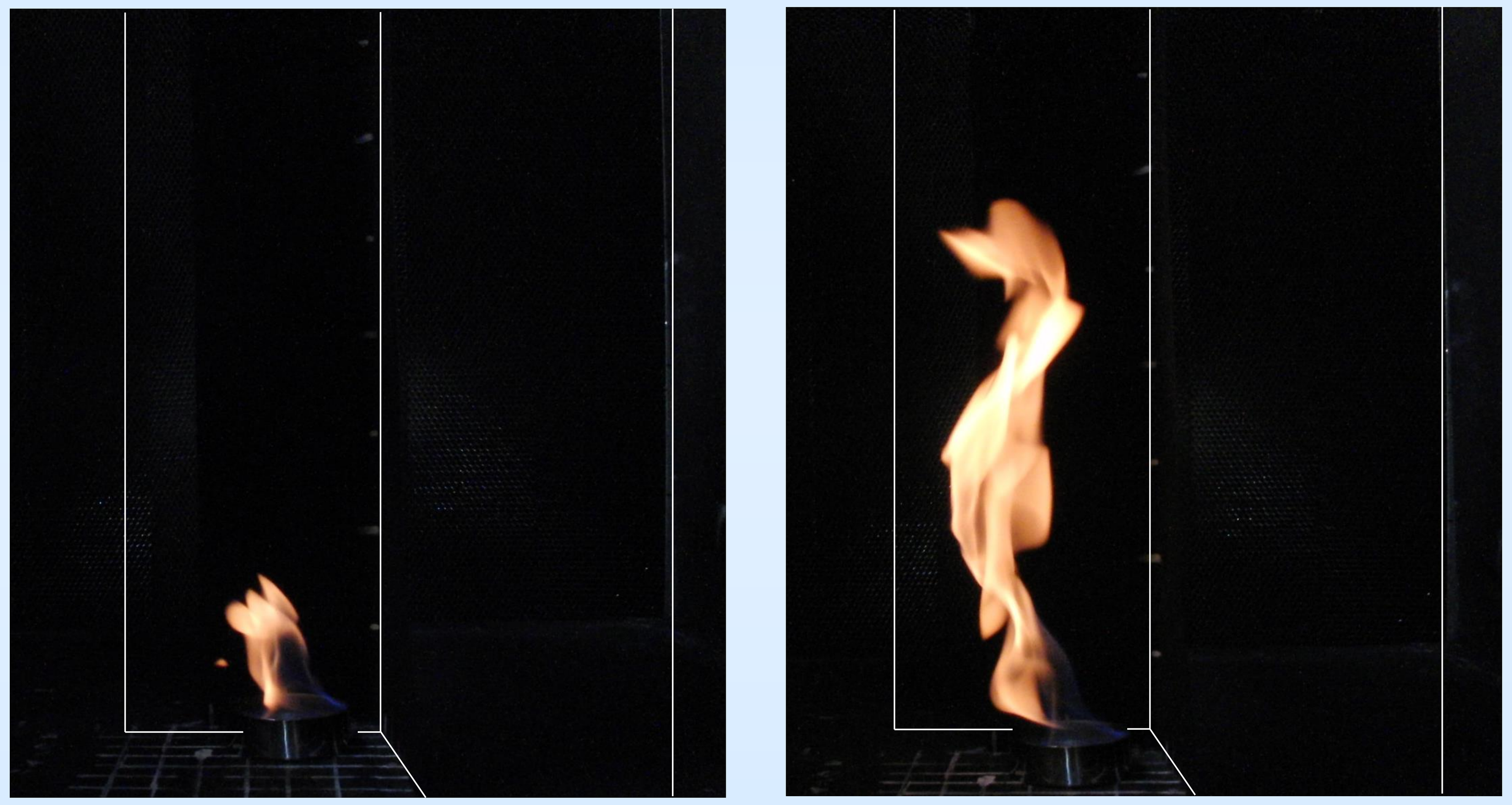
Scaling analysis

Froude number using flame height $$\frac{U^2}{gH} = \text{constant}$$

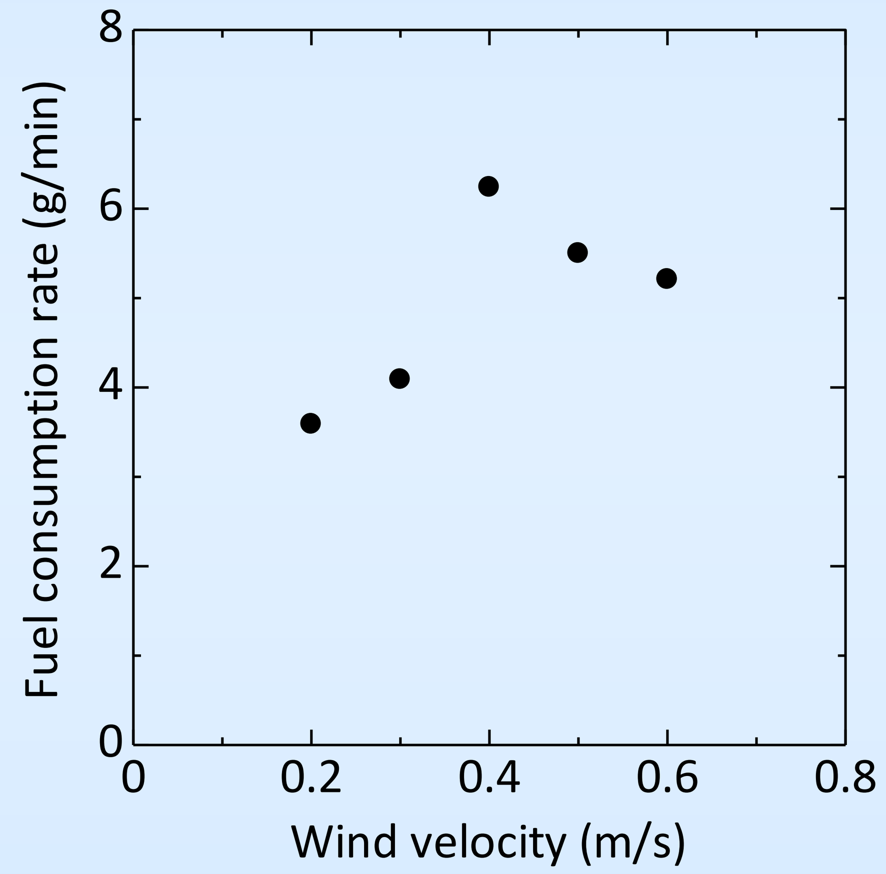
U: wind speed (m/s)
g: acceleration of gravity (m/s^2)
H: flame height (m)

	Large-scale experiment	Scale-model experiment	Mass fire
Flame height, H (m)	2-3	0.1-0.2	10-20
Wind velocity, U (m/s)	2	~0.5	~5

Scale-model experiment (wind velocity, 0.5 m/s)



Flame shapes before and after the occurrence of fire whirl



Measured fuel consumption rate

The large-scale experiment is reproduced by scale-model experiment. A wind tunnel is used, and the wind velocity is adjusted such that the Froude number of the scale-model experiment is close to that of the large-scale experiment. It is found that there is a narrow range of wind velocity that generates intense fire whirl.

Moving fire whirl along a line fire

Fire whirl observed in Brazil in 2010

Fire whirls reproduced by a scale-model experiment

Visualizing Outdoor Fire and Smoke Data

National Institute of Standards and Technology

Engineering Laboratory

Glenn P. Forney

What is Smokeview?

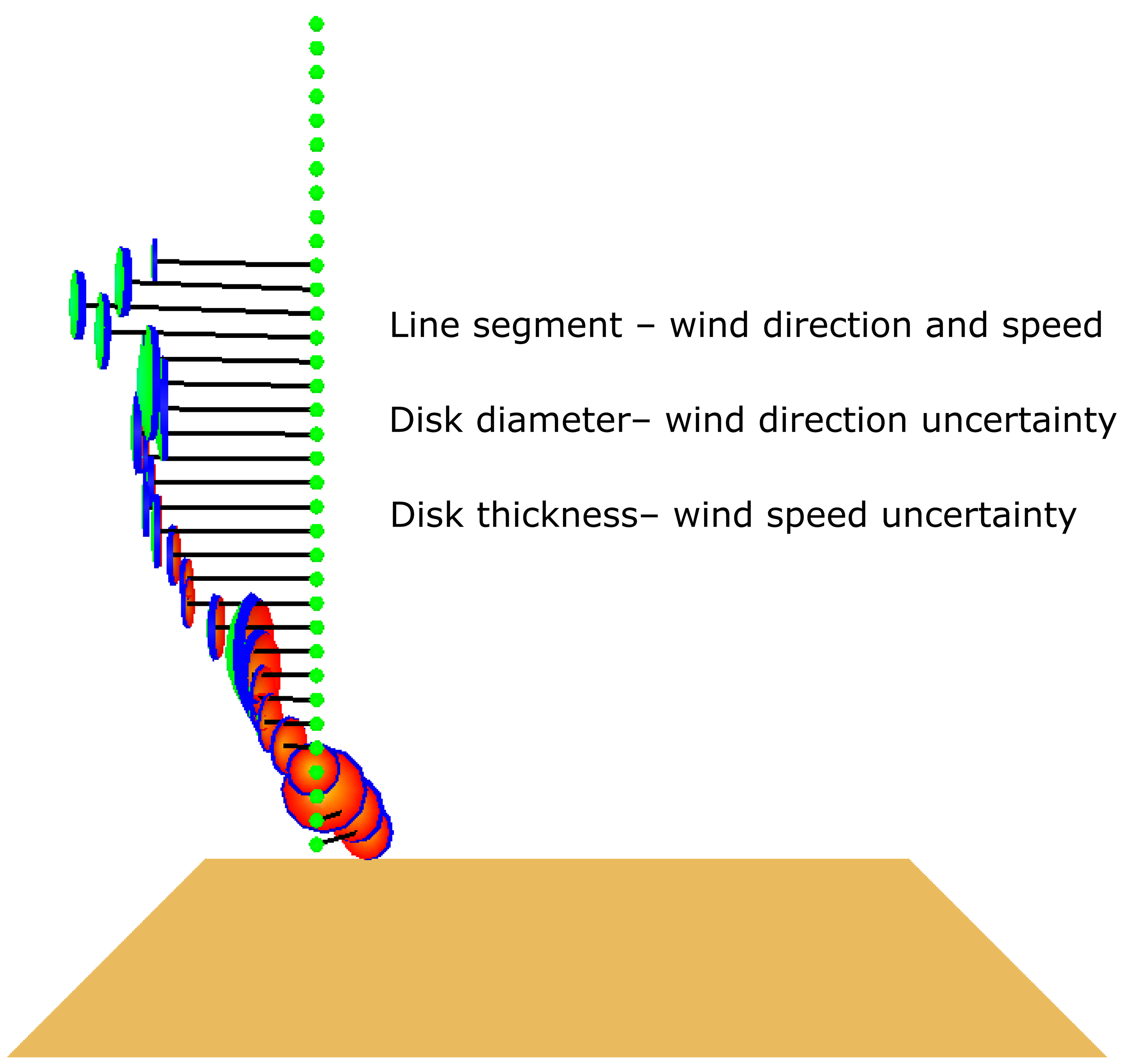
Making Visualization as Accurate as Computation

- **Smokeview** is a visualization tool developed by NIST for visualizing fire and smoke flow dynamics predicted by fire models such as FDS or CFAST.
- **FDS** solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires.
- **WFDS** a variation of FDS for models fire in the wildland urban interface

Obtaining Smokeview

- Download the installation program for Smokeview and FDS from **http://fire.nist.gov/fds** *(click on the "download" link)*
- Run the downloaded setup program.
- The setup program installs the Smokeview and FDS software, documentation and sample cases .

Visualizing Wind



Line segment – wind direction and speed

Disk diameter– wind direction uncertainty

Disk thickness– wind speed uncertainty

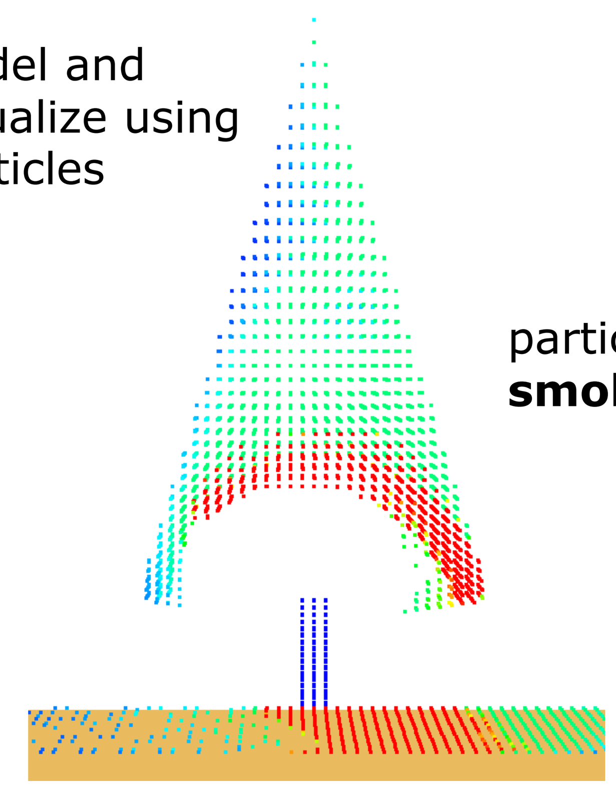
Techniques for Visualizing Fire and Smoke Flow

Providing Insight Not Numbers

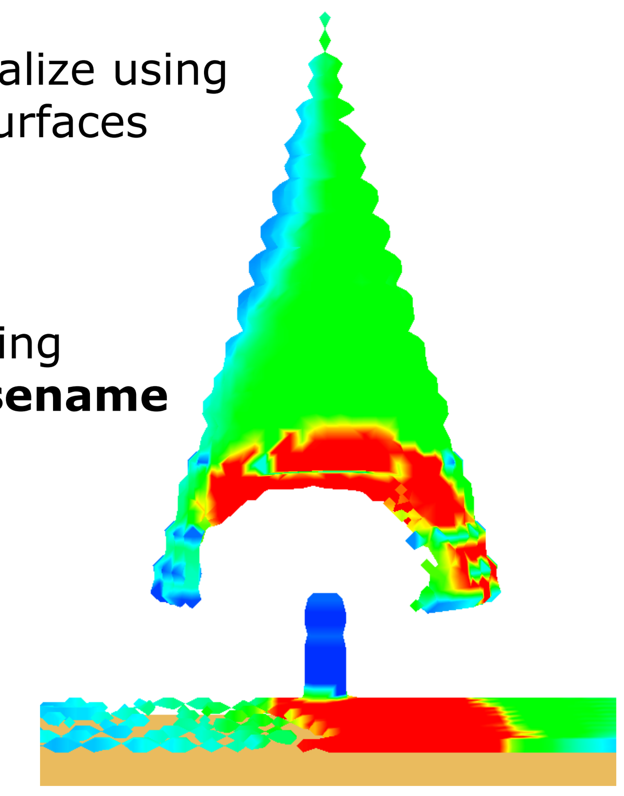
Model and visualize using particles

Visualize using isosurfaces

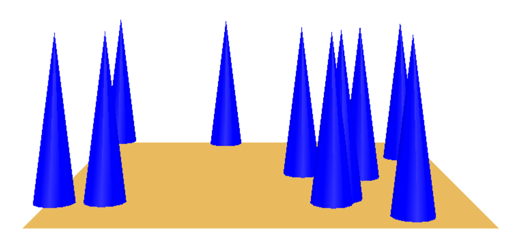
particles to isosurfaces using **smokezip –part2iso casename**

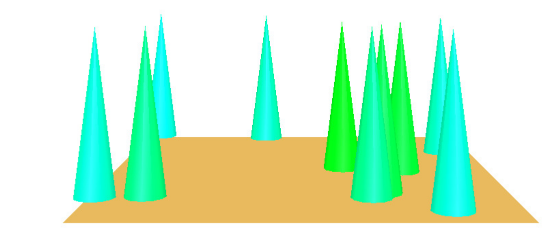


particles

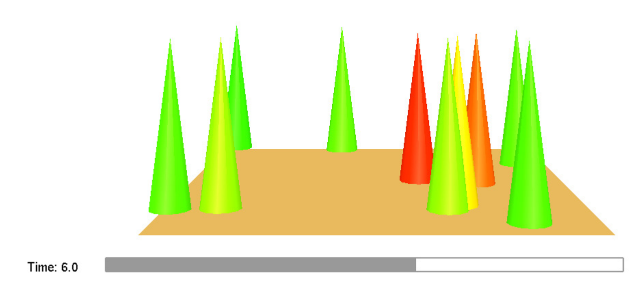


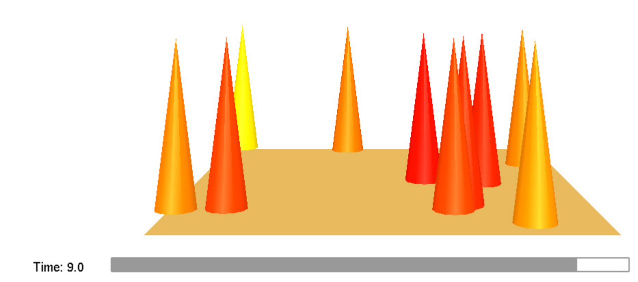
isosurface



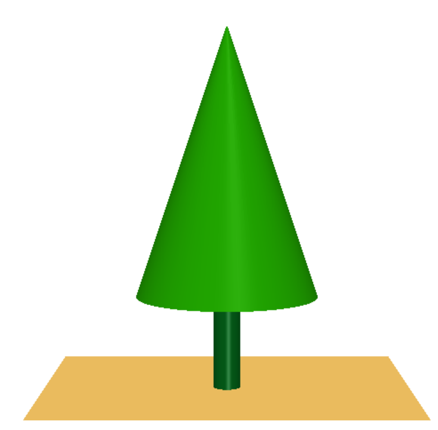


Visualize using objects colored by temperature

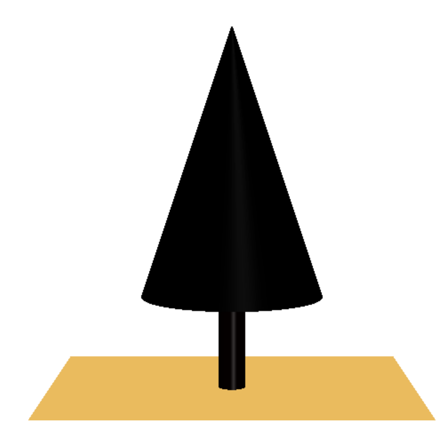




Visualize using objects representing states



original



charred, most of canopy present

charred, most of canopy burned away

charred, most of canopy and trunk burned away

A fast method for modeling and visualizing fire lines – levelsets

- fireline

- burned area

300 s

900 s

1500 s

This research was funded in part by the US Forest Service

For additional information:
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(301) 975-2313

Characterization of Fire Spread Along Fences

Rik Johnsson and Alex Maranghides

(rikj@nist.gov, 301-975-3083, alexm@nist.gov, 301-975-4886)

Fire Research Division, Engineering Laboratory, National Institute of Standards and Technology

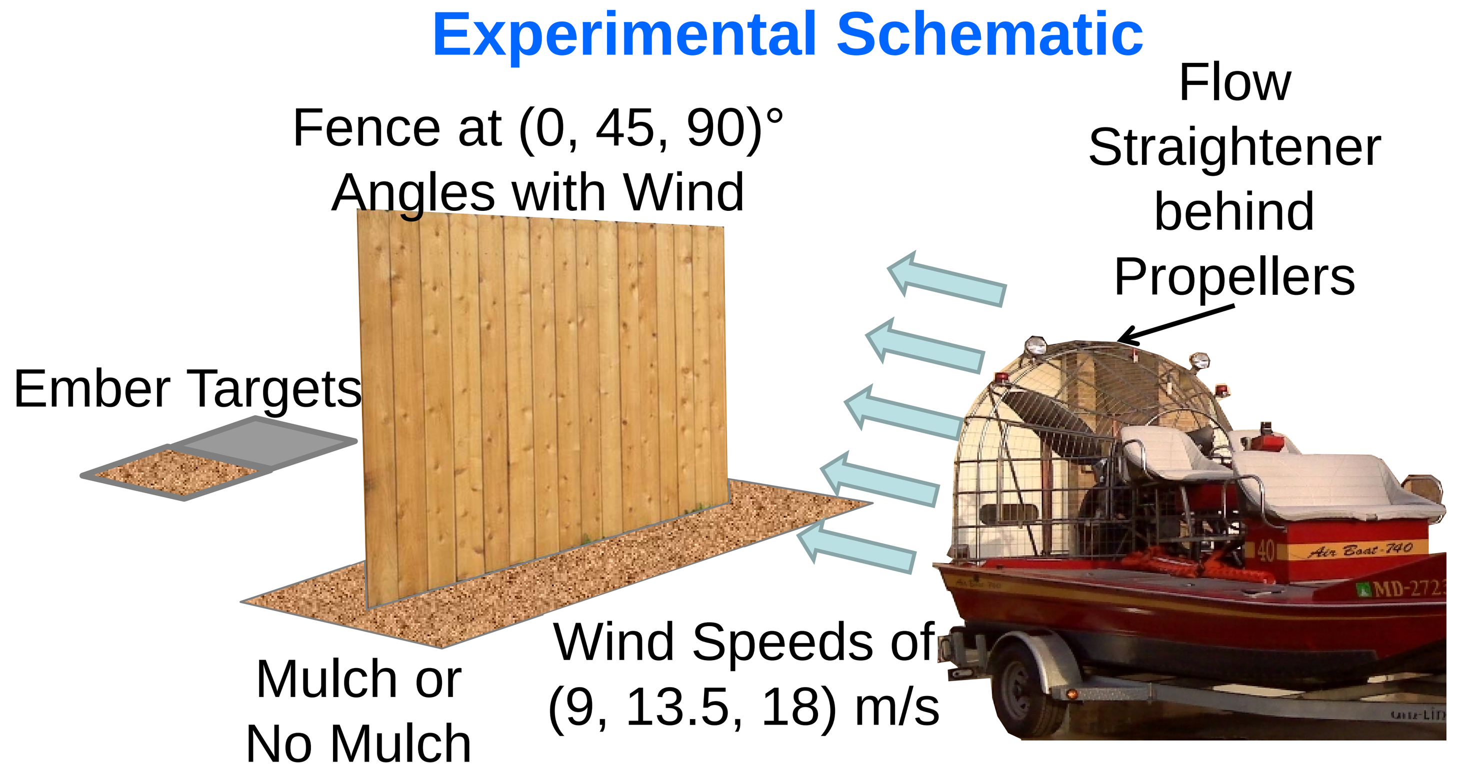
Background

During investigations following Wildland-Urban Interface (WUI) fires, fences along with adjoining structures have been discovered burned, and instances of fires spreading to structures along fences have been observed in California and Colorado WUI fire events. The role of fences and other exterior landscape features as conduits of fire spread to structures is of interest to the WUI fire research community so efforts to design new or harden existing structures and exterior features can be informed by technical knowledge. An experimental series focused on fences has been conducted, and others addressing woodpiles, landscape timbers, and plantings are planned.

Objectives

- To observe the burning behavior of wind-driven privacy-fence fires.
- To understand the rate of fire spread along privacy fences as related to wind speed and wind direction.
- To determine the impact of fence material type, preservative, and ground cover on the fire spread rate.
- To ascertain whether a burning fence produces significant embers capable of igniting downwind combustibles.
- To determine the feasibility of utilizing an airboat for reproducible, controlled outdoor fire experiments.

Experimental Schematic



Parameters Explored

	Conditions		
Parameters	**1**	**2**	**3**
Type of Material	Western Redcedar	California Redwood	Vinyl
Preservative	No	Yes	
Mulch	Yes	No	
Mesh	Yes	No	
Angle (°)	0	45	90
Wind Speed (m/s)	9	13.5	18

Test 15 photos showing progression of the fire: ignition (UL), initial wind-blown fire (UR), spread to half of the fence (BR), and spread to the full fence (BR).

Summary of Results and Conclusions

- Fire can spread along privacy fences as fast as 1.44 m/min.
- Fastest fire spread occurred with winds in line with the fence.
- Fastest fire spread occurred with moderately high winds (~13.5 m/s) while higher winds caused complex competition between sustained spread and extinguishment.
- The presence of a combustible ground cover beneath the fence was significant. In these tests, fire did not spread without mulch.
- Cedar and redwood fire spread rate differences were not significant.
- Fire spread rate differences due to preservative were not significant, but burning behavior differences were observed.
- Vinyl fence fires can vary qualitatively from wood fires due to structural differences and heated material behavior differences.
- Downwind mulch targets were susceptible to fence ember ignition.

Experimental Set-Up

- A survey of S. California and N. Texas fence companies found privacy fences were the most common type (top styles varied). Cedar, redwood, and vinyl were the most common materials.
- Fence dimensions were 2.4 m (8 ft) long by 1.8 m (6 ft) tall with three 2x4 horizontal stringers.
- Board dimensions were 14 cm (5.5 in) wide and 19 mm (3/4 in) thick.
- Fences were supported by 3 or 4 steel angle "feet" and cables.
- The flow straightener was two stacked 1.2 m x 2.4 m (4 ft x 8 ft) framed sections of 19 mm (¾ in) cell aluminum honeycomb of 11 cm thickness. It was angled downward ≈9° for most tests.
- Two walls were constructed to confine the wind flow: 2.4 m (8 ft) high, 4.8 m (16 ft) long, and 3.0 m (10 ft) apart.
- The wind source was a 16 ft Alumitech Airboat with a 375 hp GM-360 V-8.
- A 1.1 m x 3.0 m mulch pan was located under the fence. Mulch depth was 5 cm. A 2.5 cm (1 in) chicken-wire mesh was sometimes used to hold the mulch down.
- Water and mulch ember targets, each 46 cm x 66 cm, were placed at 3 m (10 ft) intervals downwind from the trailing edge of the fence along the centerline of the wind corridor.
- Fires were ignited with a propane burner 30 cm (1 ft) from the leading end of the fence.
- Instrumentation:
  - 6 bidirectional probes for wind velocity
  - 6 thermocouples for fire spread tracking
  - 3 heat flux gauges at trailing end of fence
  - 4 HD video cameras

Test Descriptions and Results

Test No.	Type of Material	Mulch (Y/N)	Mesh (Y/N)	Wind Angle (°)	Wind Speed (m/s)	Comments	Spread Rate (m/min)	No. Targets Ignited
18	Cedar	Y	N	90	0	Ambient wind only	No spread	0
1	Cedar	Y	N	90	9	Flow not angled	0.07	0
17	Cedar	Y	N	90	9		No spread	0
5	Cedar	Y	N	45	9	Ignited front	1.16	0
6	Cedar	Y	N	45	9	Ignited back	1.1	0
7	Cedar	Y	N	45	13.5	Ignited front	0.57	2
8	Cedar	Y	Y	45	13.5	Ignited front	0.28	2
4	Cedar	N	N	0	18, 13.5, 9	Tried multiple speeds	No spread	0
2	Cedar	Y	N	0	9	Flow angled near end	0.08	0
3	Cedar	Y	N	0	9	Angled flow this test forward	0.44	0
9	Cedar	Y	Y	0	13.5		1.32	4
14	Cedar	Y	Y	0	13.5		0.47	2
15	Cedar	Y	Y	0	13.5		0.67	3
13	Cedar+	Y	Y	0	13.5	+2 coats wood preservative	0.61	3
11	Redwood	Y	Y	0	13.5		1.15	4
12	Redwood+	Y	Y	0	13.5	+2 coats wood preservative	1.44	2
16	Vinyl	Y	Y	0	13.5		0.54	0
10	Cedar	Y	Y	0	18		1.01	3

A view of the overall setup showing the airboat, angled flow straightener, and corridor.

Acknowledgements

The authors thank Montgomery County Fire and Rescue Training Academy for space and support for the experiments, Sandy Spring VFD and Chief George Brown for their airboat, Marco Fernandez for setting up and running these large experiments, and the NFRL staff for assistance.

Highway 31 Fire – A Study of a Residential Community Attacked by Wildfire in the Night

David Evans* and L Ray Scott

Home Safety Foundation

Summary

Highway 31 Fire – A Study of a Residential Community Attacked by Wildfire in the Night

Of the U.S. housing stock, 32-percent are located in the Wildland-Urban Interface that covers one-tenth of all the land in the U.S. with housing. Housing developers are establishing new communities built on land cleared from forest. Historically these areas have experienced repeated wildfire. Now, new communities consisting of closely spaced, light-weight construction homes are subject to threat. Americans have become accustomed to major fires in the western U.S. threatening and destroying homes. Such events have been less frequent in the eastern U.S.

This poster presents facts gathered from an on-scene study of the 2009 Highway 31 Fire that spread in the night from wildland pine forests to the Barefoot Resort, a newly established retirement community in South Carolina. Fire spread was predominately by flying brands igniting spot fires simultaneously throughout the residential community. Use of long pine needle mulch throughout the community provided many locations that were easily ignited by brands and readily burned with high intensity.

The South Carolina Forestry Commission's Highway 31 fire after action report[1] named it the worst WUI fire in South Carolina's history. Extreme fire weather combined with highly volatile fuels created a powerful and unpredictable force of nature which at its peak consumed 1,100 acres an hour. In total 19,130 acres burned causing $50 million in damage. In the Barefoot Resort Community 76 homes were destroyed, 97 homes were damaged and 2500 residents had to be emergency evacuated in the middle of the night.

As there were a large number of homes lost, the Home Safety Foundation pursued information about the wildland fire, its spread, community preparations, and the community evacuation through interviews with eye-witnesses -- firefighters and residents. This study illustrates the fire hazards faced by new residential communities built in areas that historically have experienced wildfires.

WUI Community Vulnerabilities

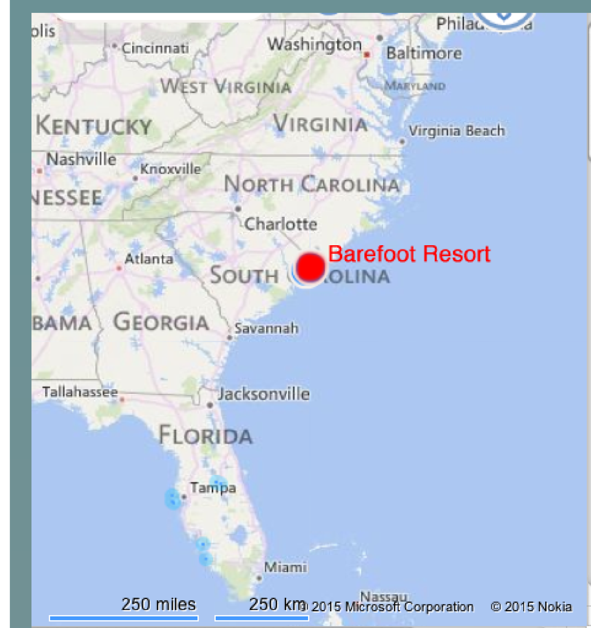
- An emergency notification system is needed to alert residents of threatening conditions and evacuation orders.
- High density narrowly separated houses constructed with unprotected combustible materials increase risk of house to house fire spread.
- Volatile mulch materials, like long pine needles, placed around building foundations, increase the risk of building ignition.
- Multiple simultaneous building ignitions can overwhelm Fire Departments, rendering firefighters unable to respond to all fires.

References

1 Jones, Darryl, Highway 31 Fire, April 22-May 20, 2009 After Action Report, South Carolina Forestry Commission, February 2010
2 www.bing.com/maps, Microsoft Corporation, 2015
3 Highway 31 Fire Task Force Briefing, May 21, 2009 from Chief Garry B. Alderman, Horry County, SC, Fire Rescue
4 www.mapquest.com
5 Photo credit David Evans, Home Safety Foundation
6 Photo credit Jerry Frejeolle, Barefoot Resort Resident

*Corresponding Author: David Evans, DEvans@SmartSafety.org

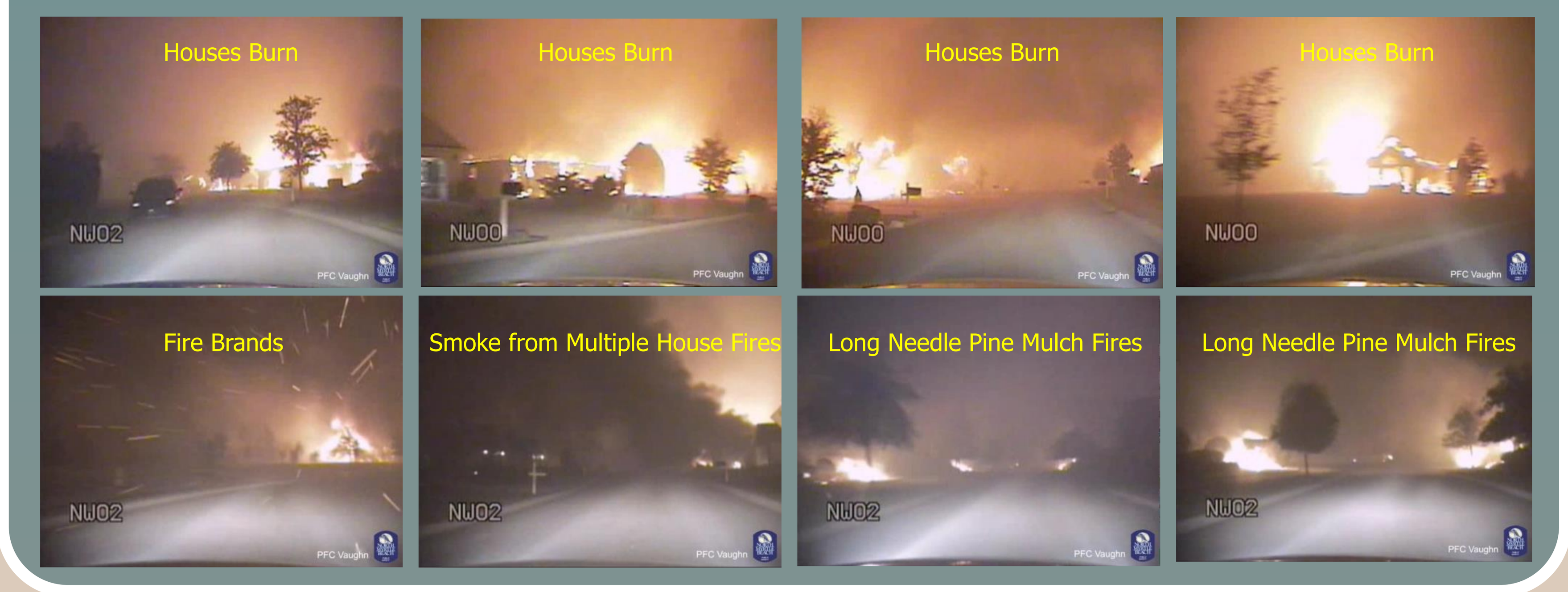
Fire Invades Barefoot Resort Retirement Community



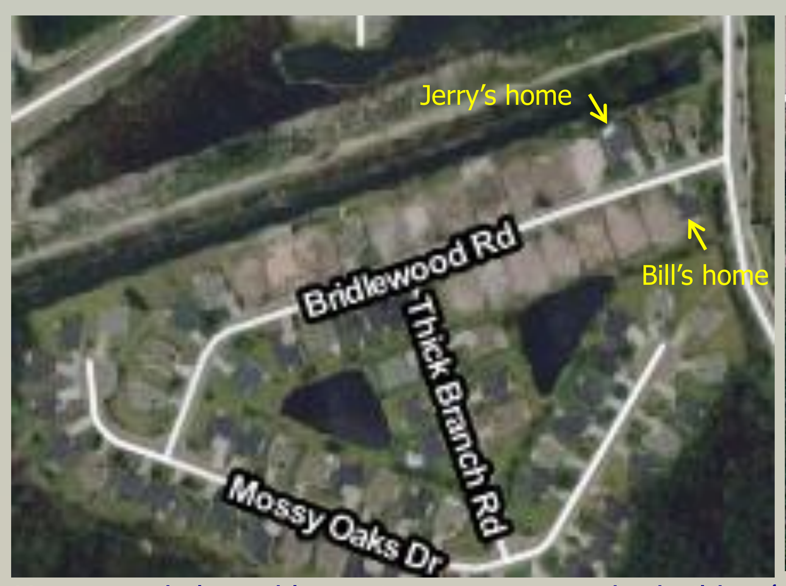
Fire Location:
Coastal South Carolina[2]

Photo from North Myrtle Beach police car dash camera[3] shows the wind-driven pine tree crown fires "jumping over" Highway 22, a four lane divided highway. A resident estimated that after the fire jumped the highway, it was 4 minutes until houses were burning in Barefoot Resort.

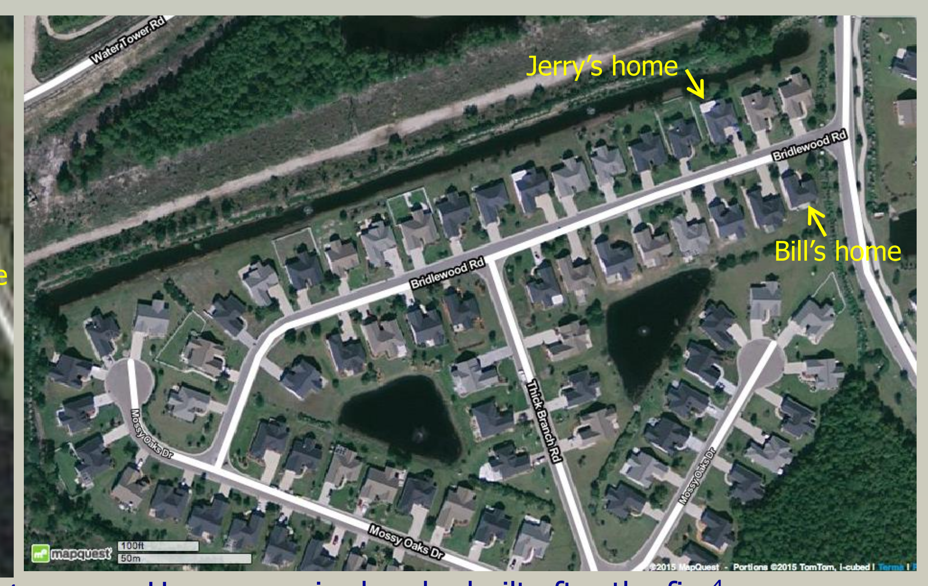
Police Car Dash Camera Video of Barefoot Resort Fire.[3]



Bridlewood Road Homes

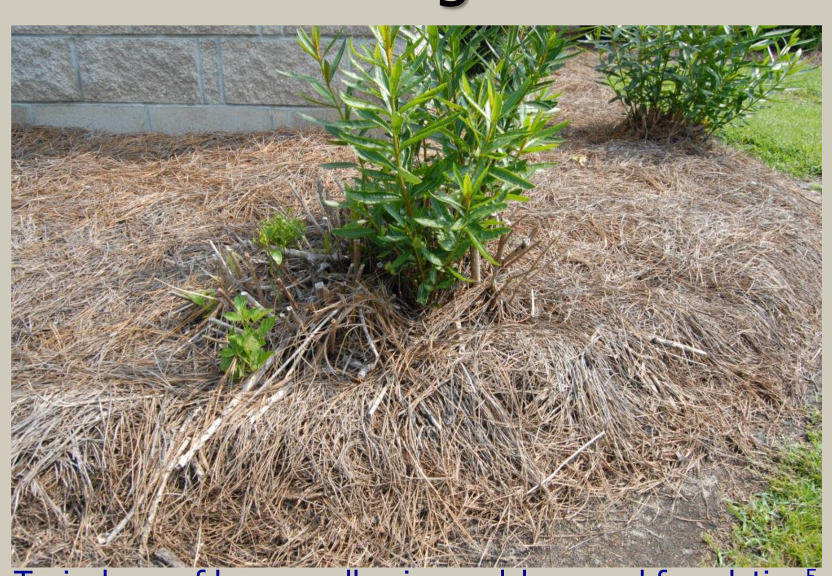


Homes and cleared lots prior to repairs and rebuilding[4]

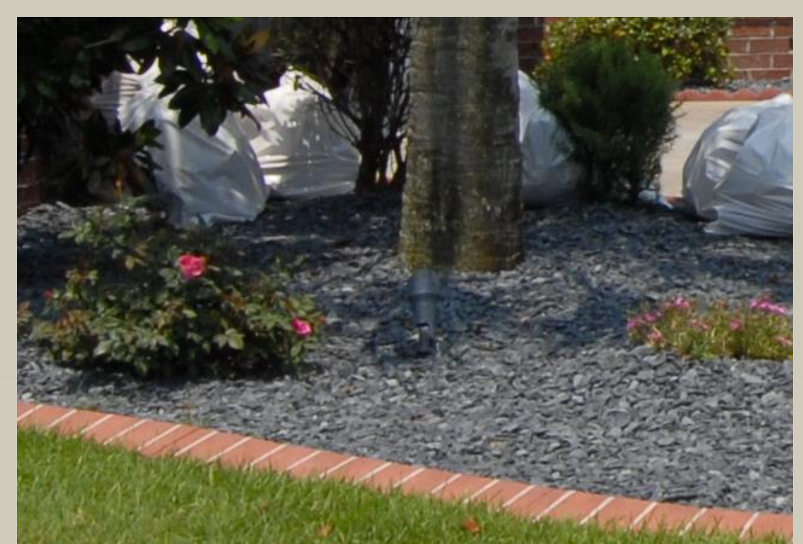


Homes repaired and rebuilt after the fire[4]

Long Needle Pine Mulch vs. Rocks



Typical use of long needle pine mulch around foundation[5]



Typical use of rock ground cover around foundation[5]

Eyewitness accounts of the fire

Ray Scott (right) interviews eyewitness Jerry Frejeolle[5]

Mr. Jerry Frejeolle lives at 5804 Bridlewood Road near the corner of the resort where the fire entered the community. Although the fire was far away from the resort, about 9:00 p.m. Jerry turned on his yard sprinkler system to wet down his lawn. After four hours of pre-wetting the grass surrounding his house, the fire entered the development. At 1:15 a.m., Jerry was awakened by what sounded like a propane tank exploding. His bedroom was lit by the red glow of the flames from the wildland fire and burning houses in the rear of his home. Jerry went outside and saw homes on fire 5 or 6 houses down the street from his house. The wind direction was at a 45 degree angle to Bridlewood Road. Dense smoke and brands were blowing across his street. He pounded on his next door neighbors' doors to alert them. One neighbor's home smoke detector was sounding. Jerry activated his yard sprinklers again. Then using a garden hose he began wetting his house's siding, roof, shrubs, and trees, thinking that if he could keep things wet he could save his house. Jerry defended his home with the garden hose for almost two hours as the houses continued to burn one after another on both sides of his street, the fires spreading toward his home. He estimated the time of fire spread from one house to the next was approximately 15 minutes with houses catching fire at their roofs. When the flames were just two houses from his, Jerry and his wife used a key they had been given to enter the home across the street and assist their elderly neighbor from her bed to their car. Jerry drove her to a nearby relative's house. When he tried to return he was stopped by Public Safety Officers and could not get back to his home.

Damage to siding on Jerry's home[6]

Jerry's house survived with some damage as did the two houses to the right of his. Seven houses to the left of his were destroyed. The house directly across the street from Jerry where the elderly neighbor lived was destroyed along with 6 adjacent houses to its right. Jerry saw no fire department intervention on his street.

Mr. Bill Flohr, a retired Fire Chief, lives at 5801 Bridlewood Road. Bill had advised Jerry to turn on his lawn sprinklers earlier that evening. Bill took precautions as well, storing outdoor furnishings and wetting down outside combustibles including the pine straw in his yard. Bill's wife gathered important personal items and documents and had them bagged and ready at the door should they need to evacuate. Bill noted the winds had diminished in the evening before the fire struck. At about 2:00 a.m., Bill woke up hearing a strong wind blowing. From the bathroom window he saw glowing embers hitting the glass then being blown upward toward the soffit of this house. Bill went outside and saw firebrands blowing around and hitting everywhere. He saw houses burning down his street and beds of mulch around houses were burning. Looking between houses he could see the tops of the trees in the nearby pine woods burning. Bill and his wife decided to leave. When they opened the garage door to back out both cars many embers had collected at the bottom of the door and were blown in the garage. He just closed the door and left. On his way out he passed a North Myrtle Beach fire truck on its way in and thought it was the first apparatus responding to the fire.

Side of Bill's home that faced a destroyed house after repairs[5]

Bill's house survived but sustained damage from the fire that destroyed the house next door belonging to the elderly lady rescued by Jerry. There was approximately a 10 foot separation between Bill's home and the destroyed house. In the narrow side yard setback Bill had installed a concrete sidewalk leading to the back yard with a foot wide strip of stone between the walk and the foundation of his house. Bill's house sustained $60,000 damage and fire did enter the structure through a vinyl bedroom window. Bill credits his home's survival to the efforts of firefighters and several things that provided firefighters time to set up a defense. Storing or wetting combustibles prevented some possible ignitions from flying brands. He also credits the felt paper used as a barrier during construction between the OSB (wood sheathing) and vinyl siding. Heat exposure had deformed and melted away the vinyl siding to expose the felt paper. The felt paper sustained visible heat damage but remained intact, protecting the OSB from ignition. OSB was protected even though fire exposure had transferred enough heat to melt plastic insecticide tubing and insulation on electrical wiring within the exterior wall.

Scale Modelling of Wildland Fires Using Stationary Fires

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Motivation

Wildland fire spread has been observed to be strongly influenced by convective heating and direct flame contact. Recent experiments have shown that buoyant instabilities contribute to convective heating and flow in large wildland fires, making the understanding of these instabilities important to accurately model wildland fire spread.

Phenomena and scaling

Fig.1 Side-view flame photographs

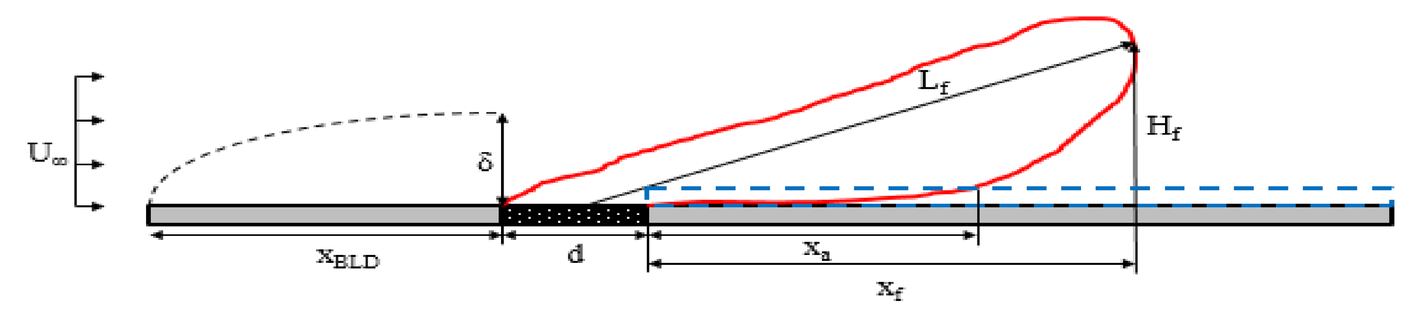

Fig.2 Flame geometrical parameters

Flame tilt phenomena were observed in wind-blown fires. Averaged flame shape can be obtained using the method shown above. In order to study the buoyant instability phenomena of the flame, parameters related with the flame geometry were calculated (flame length, flame tilt angle, flame attachment length). An understanding of mean flame geometry and stochastic pulsations is necessary to fully describe the preheating and ignition of fuel beds ahead of the flame front.

Results indicate that complex pulsing behavior exists; nevertheless, scaling over several orders of magnitude suggest large-scale coherent structures are present in the flow [1, 2]. Using peak frequencies measured, the stationary experiments follow a Strouhal-Froude scaling similar to flame pulsations in spreading laboratory, crown and prescribed fires [3]. Figures on the right show the method we used to obtain the flame pulsation frequency and one example of flame pulsation occurrence under different wind velocities with fire size = 5kW

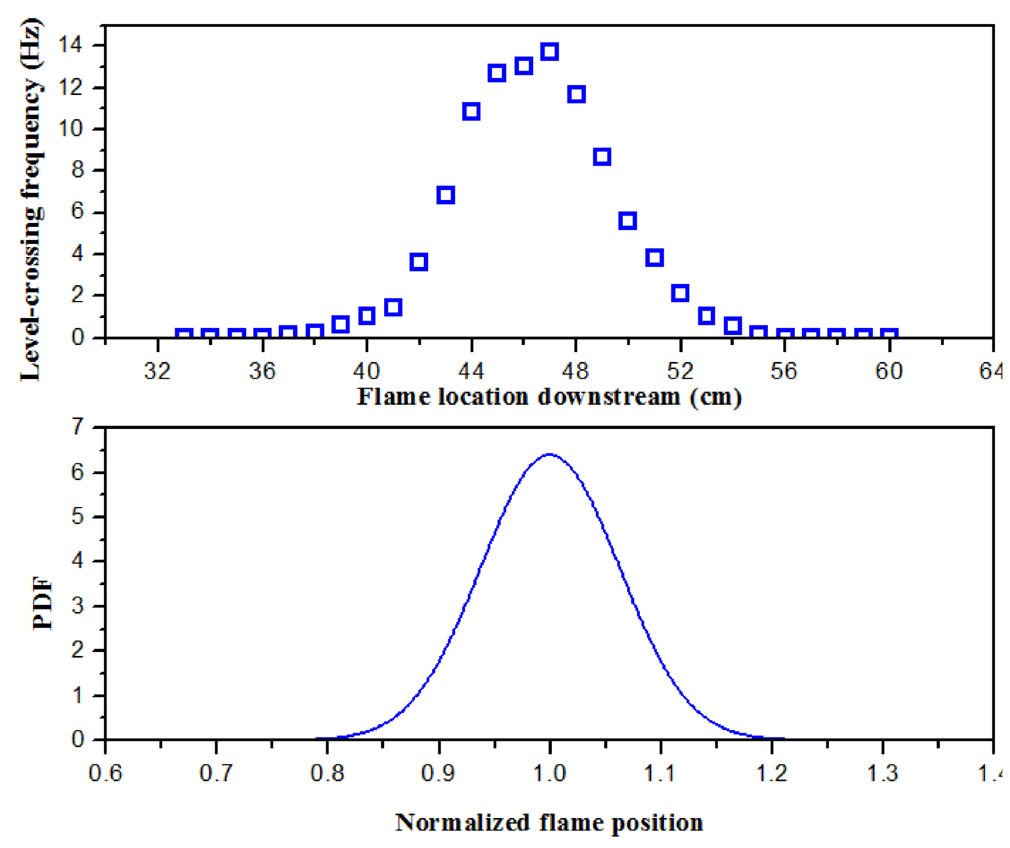

Fig.3 Typical level-crossing frequency and PDF of normalized flame positions. Probability Density Function of a normalized flame downstream generally follows a normal distribution

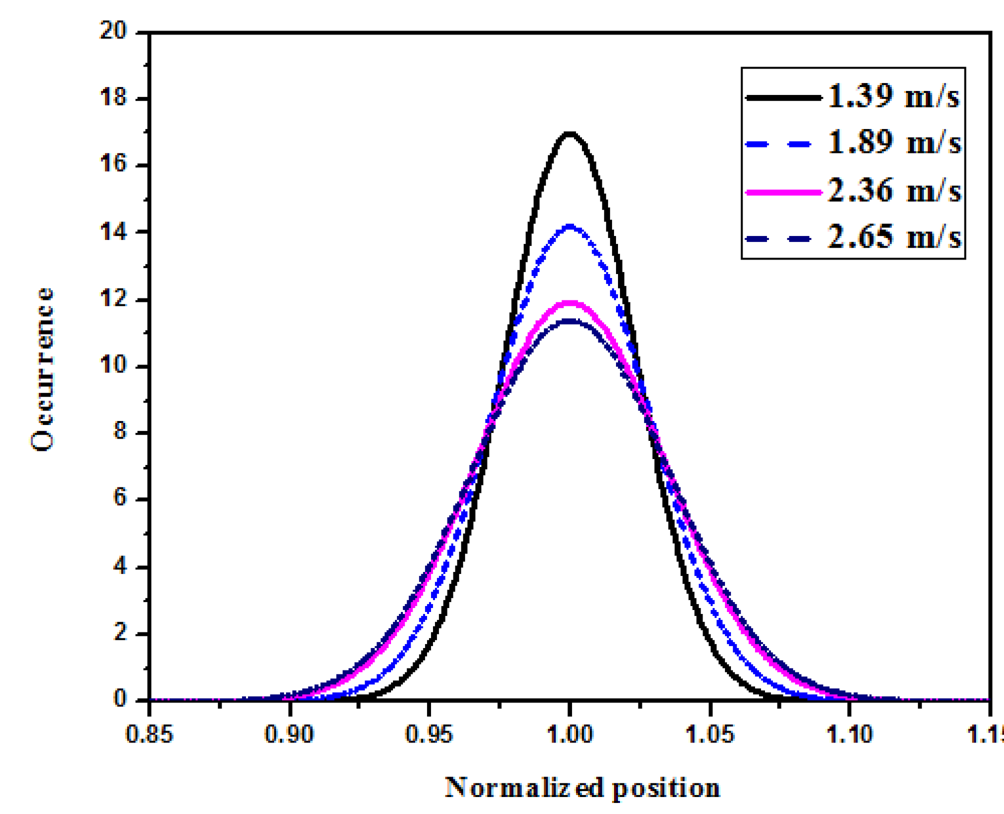

Fig.4 Flame pulsation occurrence under different wind velocities with fire size=5kW. Flame pulsation occurrence in the stream-wise direction was found to increase with increasing wind velocity.

Experimental Results

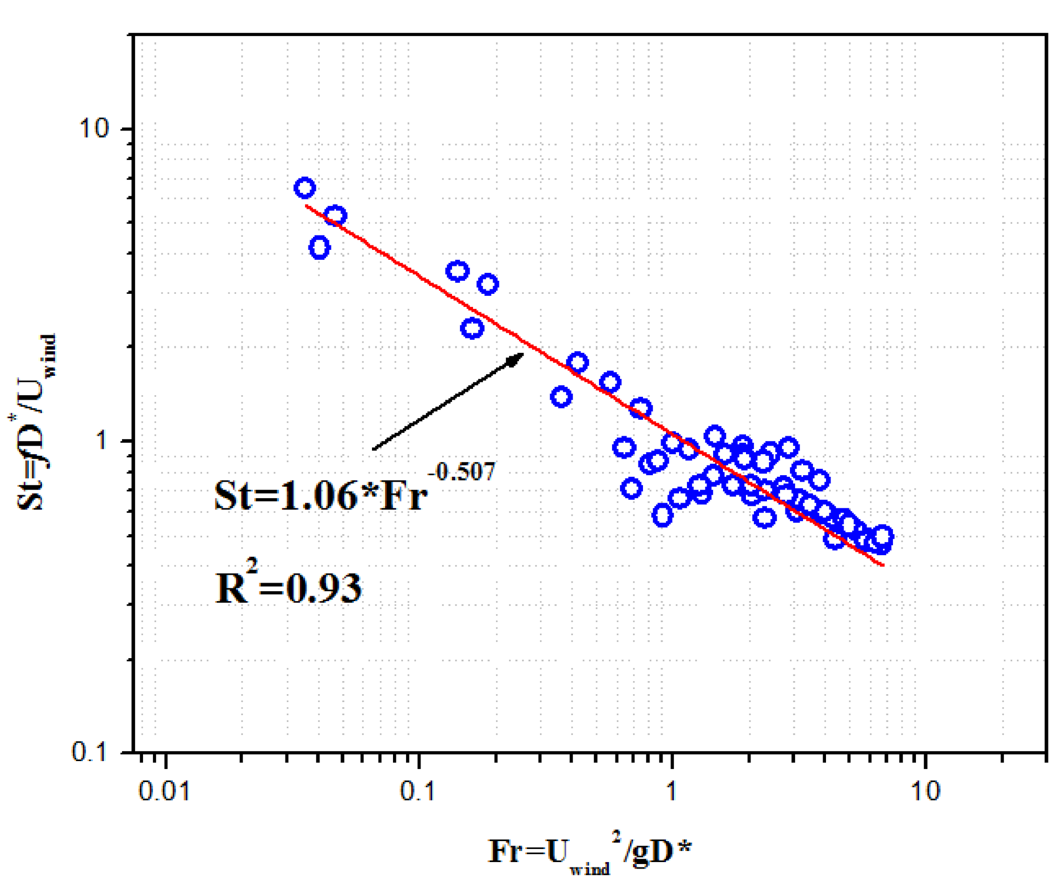

Fig.5 The scaling result of St-Fr using wind velocity and D* as the characteristics velocity and length scales.

$$D^* = \left(\frac{\dot{Q}}{\rho c_p T_\infty \sqrt{g}}\right)^{2/5}$$

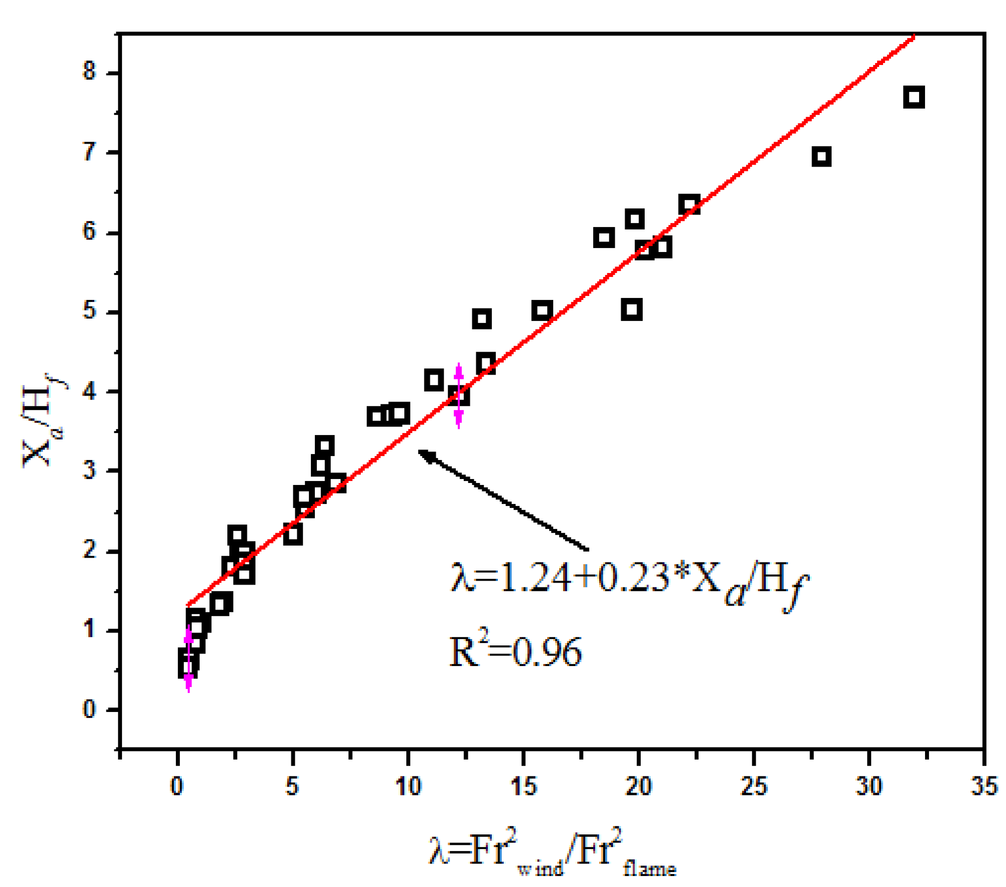

Fig.6 The Froude number competition, $Fr^2_{wind}=U^2_{wind}/gL$, $Fr^2_{flame}=U^2_{flame}/gD^*$. L is the burner length that facing the coming wind. X_a/H_f is the ratio of maximum frequency location over flame height.

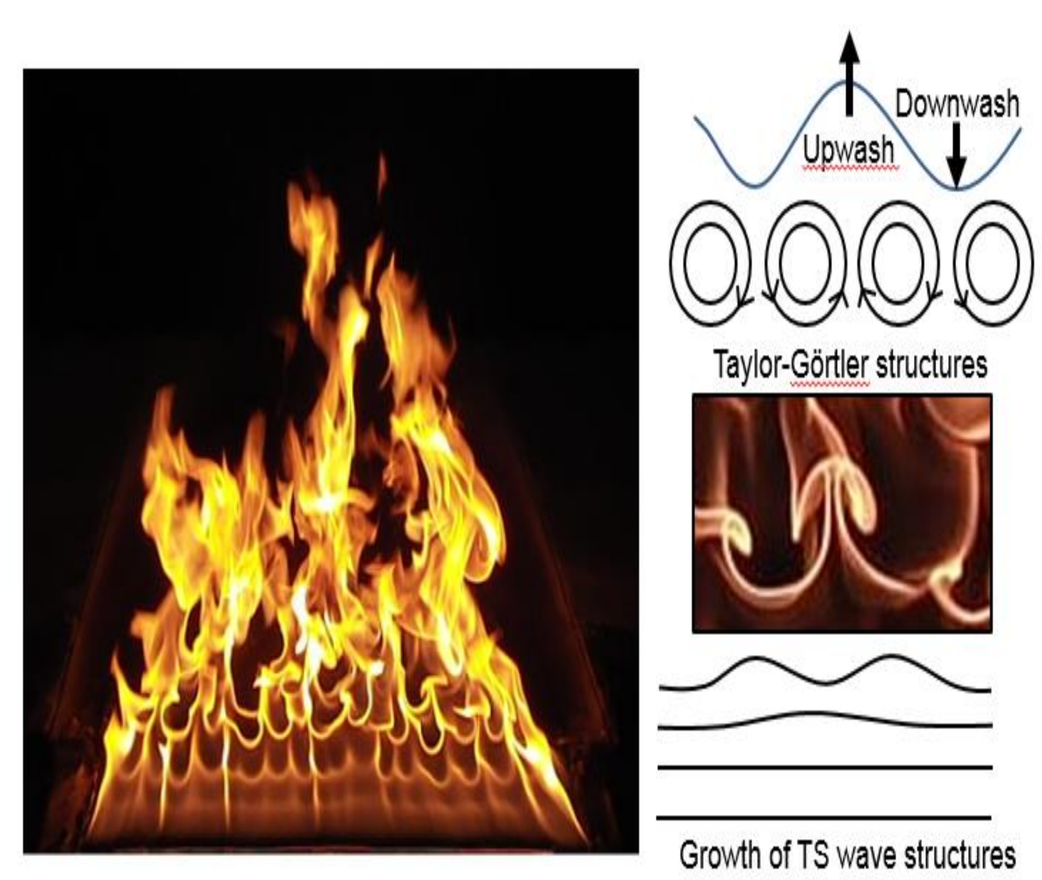

Fig.7 Flame streak phenomena at the burner base. Meanwhile, image processing of front-view images have exposed Görtler-like structures that create peaks and troughs in the flame front as well as span-wise waves similar to Tollmein Schlicting (TS) [4]

Future work

Our research team is currently investigating the relationship between observed behavior in small scale gas burners and the peak and trough structure observed in larger fires. Additional experiments and data analysis methods are being performed to further elucidate the mechanisms and intermittencies associated with flame pulsations.

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[2] Finney, M., Forthofer, J., Grenfell, I., *A Study of Flame Spread in Engineered Cardboard Fuel beds Part I: Correlations and Observation*, Seventh International Symposium on Scale Modeling

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A Simple Method of Burning and Surface Flame Spread of a Cubical-Shaped Polyurethane Foam Block

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[1]SHIMIZU Corporation, [2]Kyoto University, [3]Tokyo University of Science

1.Introduction

- Background

  Design heat release rate(HRR) is an important parameter.

Measurement by open calorimeter

Size dependence?

Simultaneous burning?

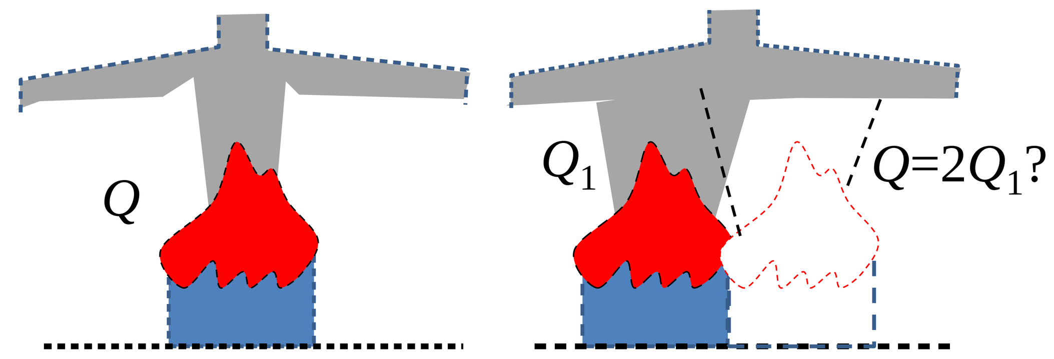

Fig.1 Measured HRR by open calorimeter

- Objective

  A simple prediction method of burning rate considering the three dimensional flame spread and burnt-out shape

2. A Model of Flame Spread and Burning

- Change of Burning area

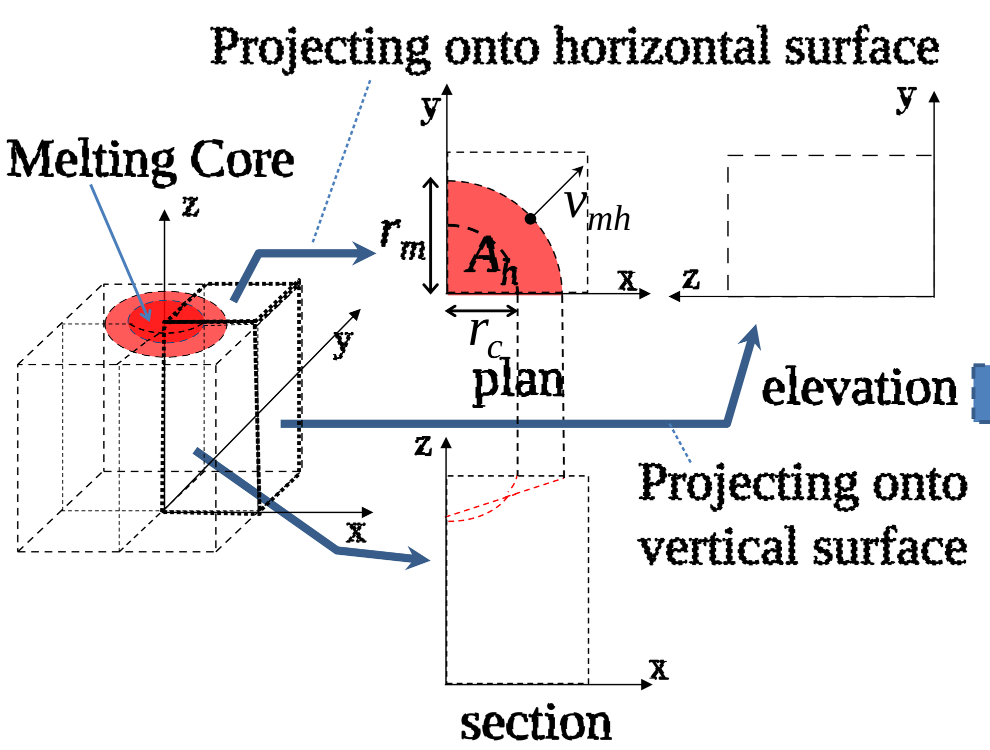

Fig.2 Flame spread over the top surface

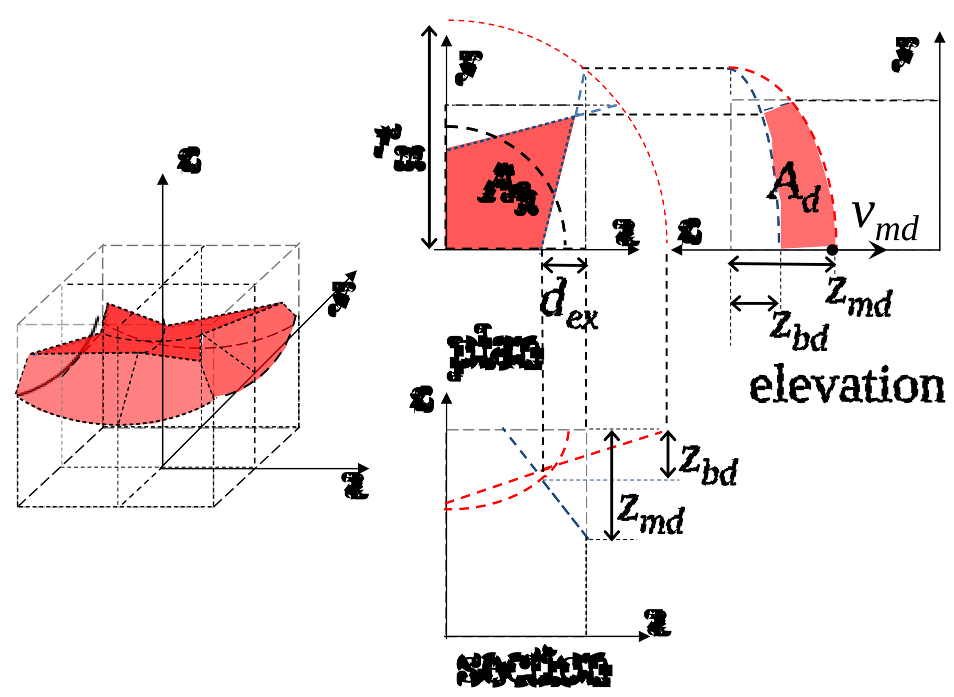

Fig.3 Flame spread over the vertical surface

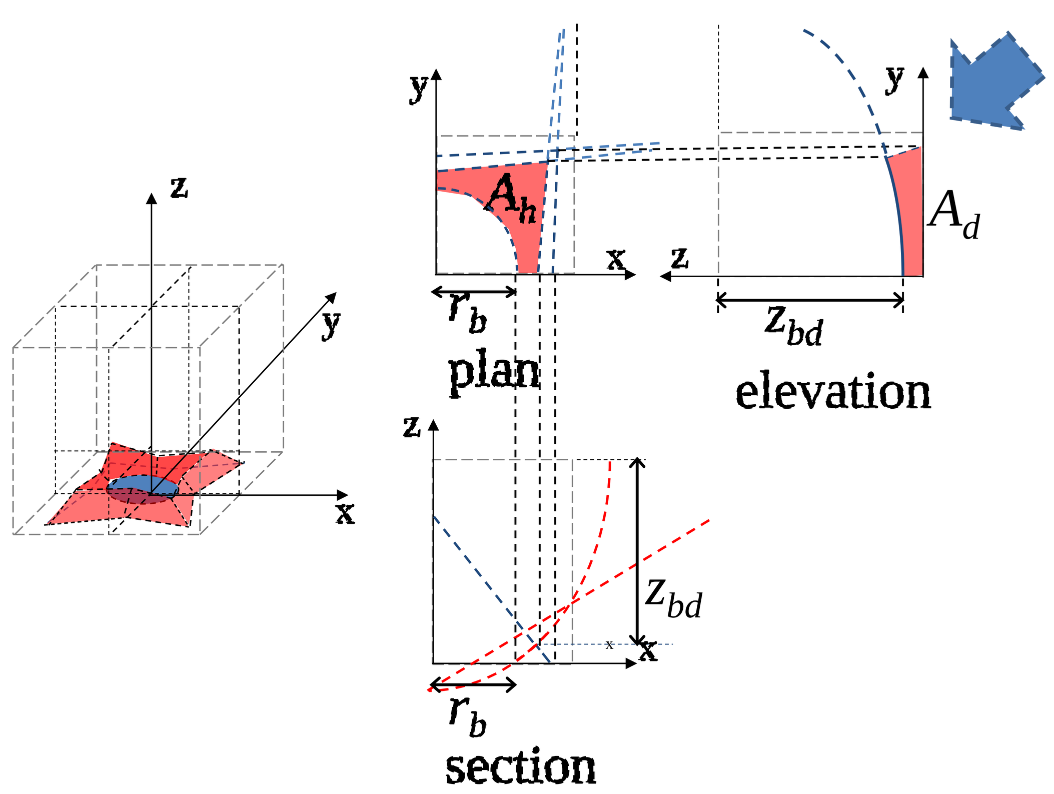

Fig.4 Burnt-out of bottom side

Nomenclature

- A_h : burning area on horizontal surface (m^2)
- A_d : burning area on vertical surface (m^2)
- c : specific heat (kJ/kg・K)
- d_{ex} : horizontal burnt-out depth from edge (m)
- ΔH : heat of combustion (kJ/kg)
- L_v : heat of vaporization (kJ/kg)
- q_0 : heat release rate per unit area(kW/m^2)
- q : heat flux(kW/m^2)
- r_b : burnt-out radius of bottom side(m)
- r_c : melting core radius (m)
- r_m : flame spread radius (m)
- T_m : melting temperature(K)
- T_0 : initial temperature(K)
- v_m : flame spread velocity (m/s)
- v_c : burnt-out spread velocity(m/s)
- z_{md} : flame spread height from the top surface (m)
- z_{bd} : burnt-out height from the top surface (m)

- Burning rate

$$q_h = \frac{q_{cf} - q_r}{c(T_m - T_0) + L_v} \Delta H$$

$$q_v = Const.$$

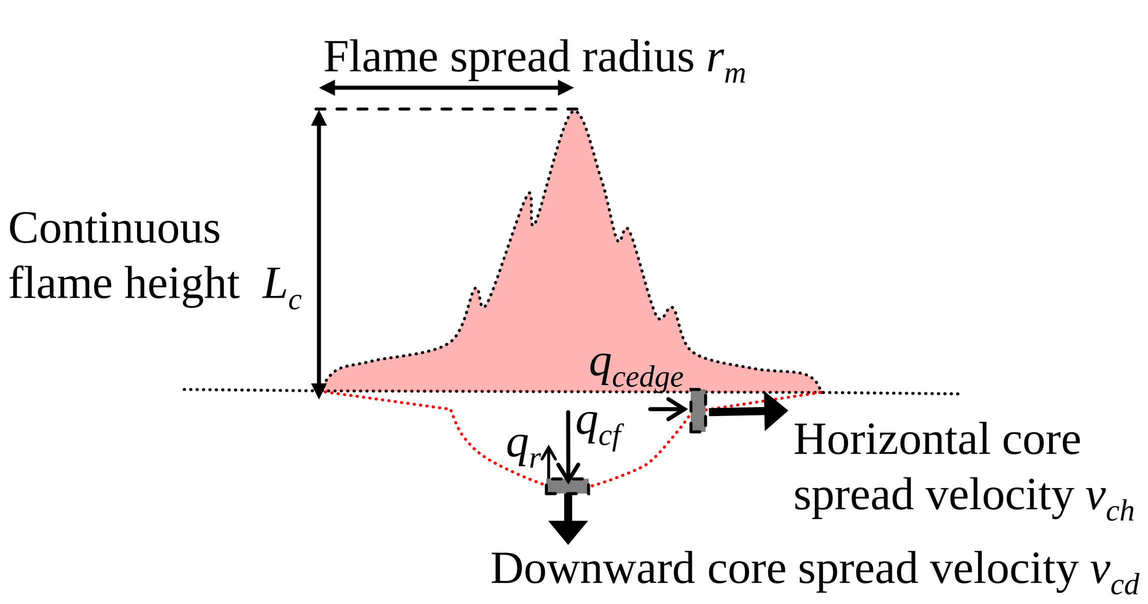

Fig.5 The Section of Melting Core

3.Experiments

- Specimen

  Material :flexible polyurethane foam

  Size :0.5m × 0.5m × 0.5m

  Density:15.6kg/m^3

  Heat of Combustion ΔH : 26,500kJ/kg

- Arrangement

  One block placed in an open space

  Ignition Point : center of top surface

- Measured

  HRR, position of flame spread front and burnout surfaces

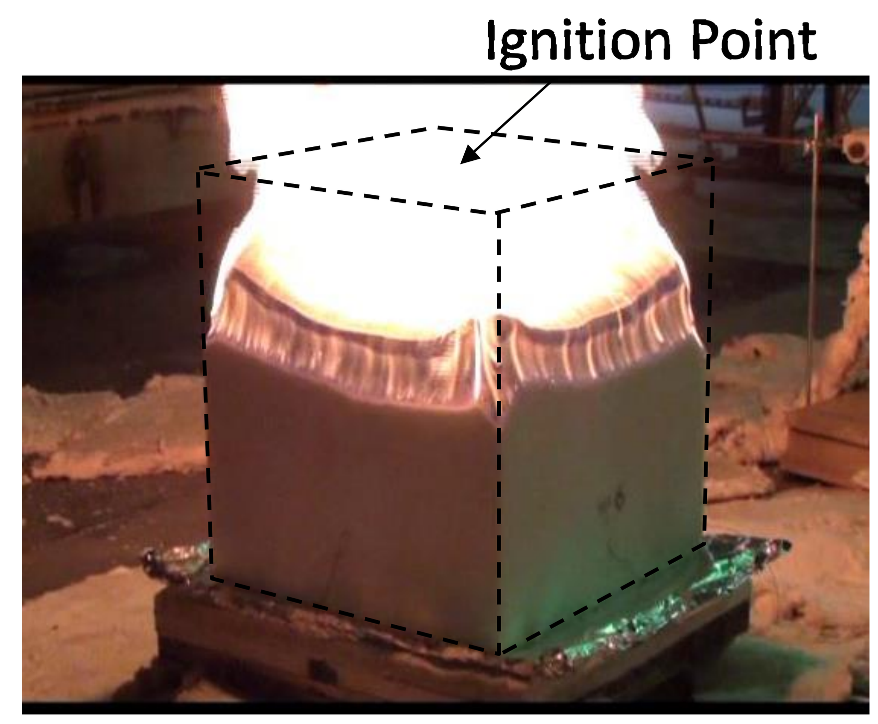

Fig.6 Burning behavior (210seconds)

4.Calculation Results

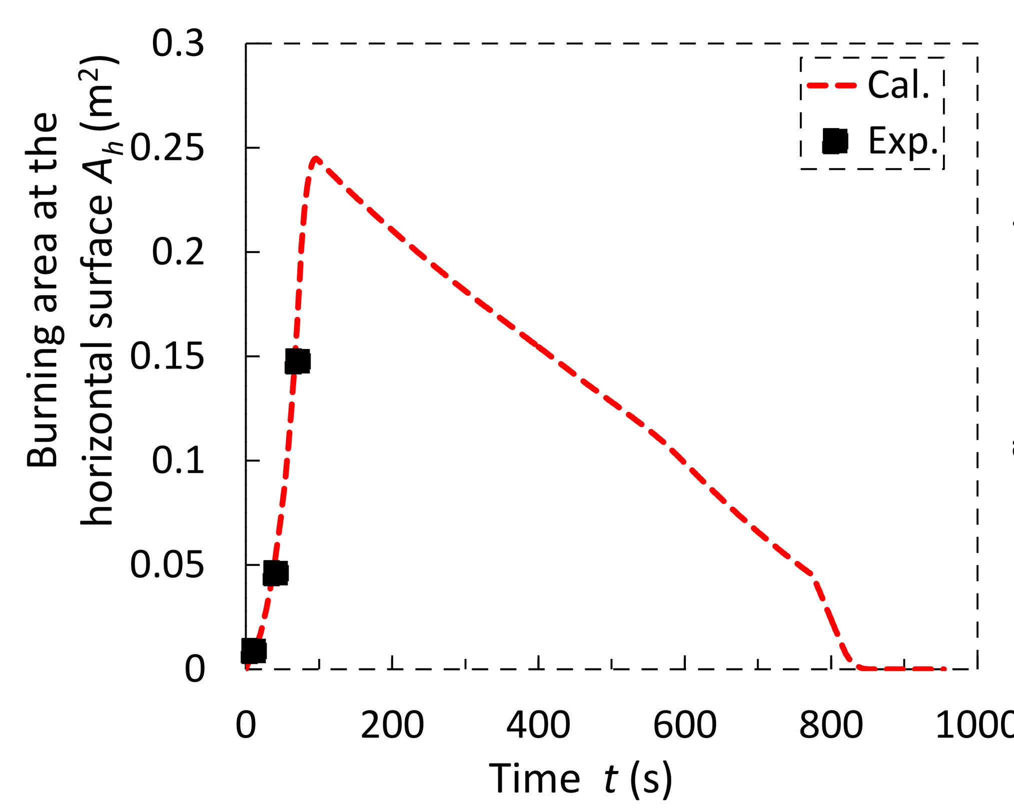

Fig.7 Comparison of calculated and measured burning area at the horizontal surface

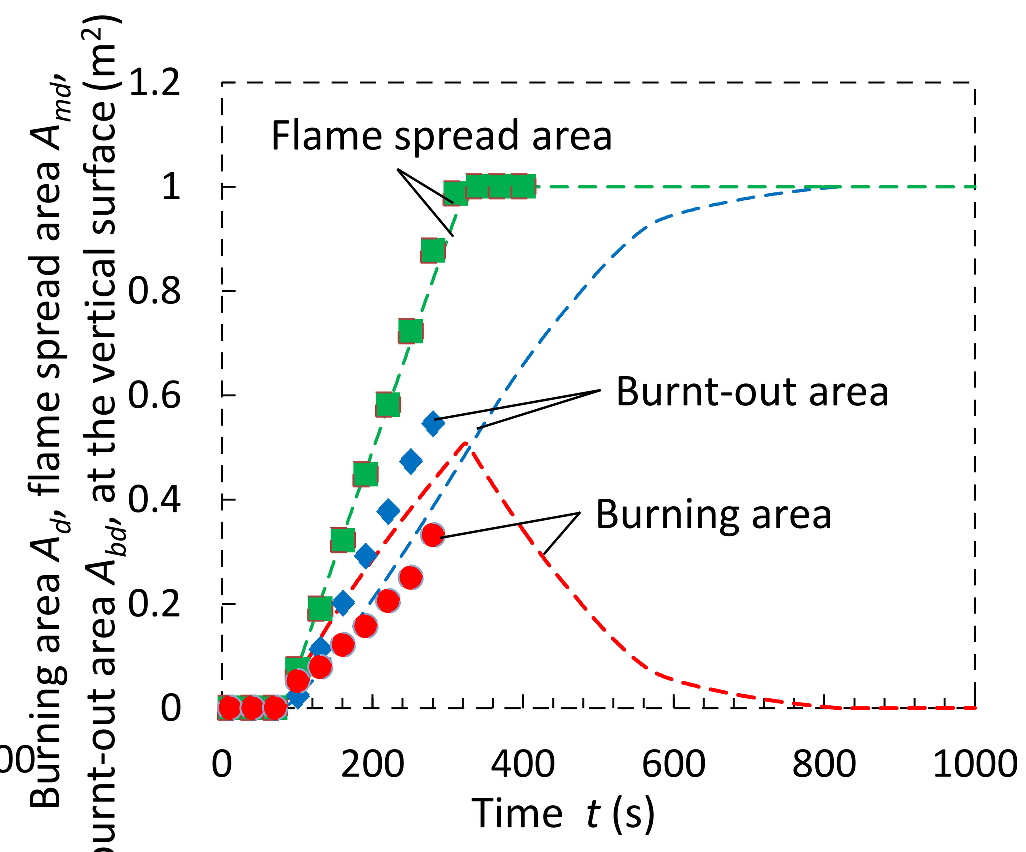

Fig.8 Comparison of calculated and measured burning area, flame spread area and burnt-out area at the vertical surface

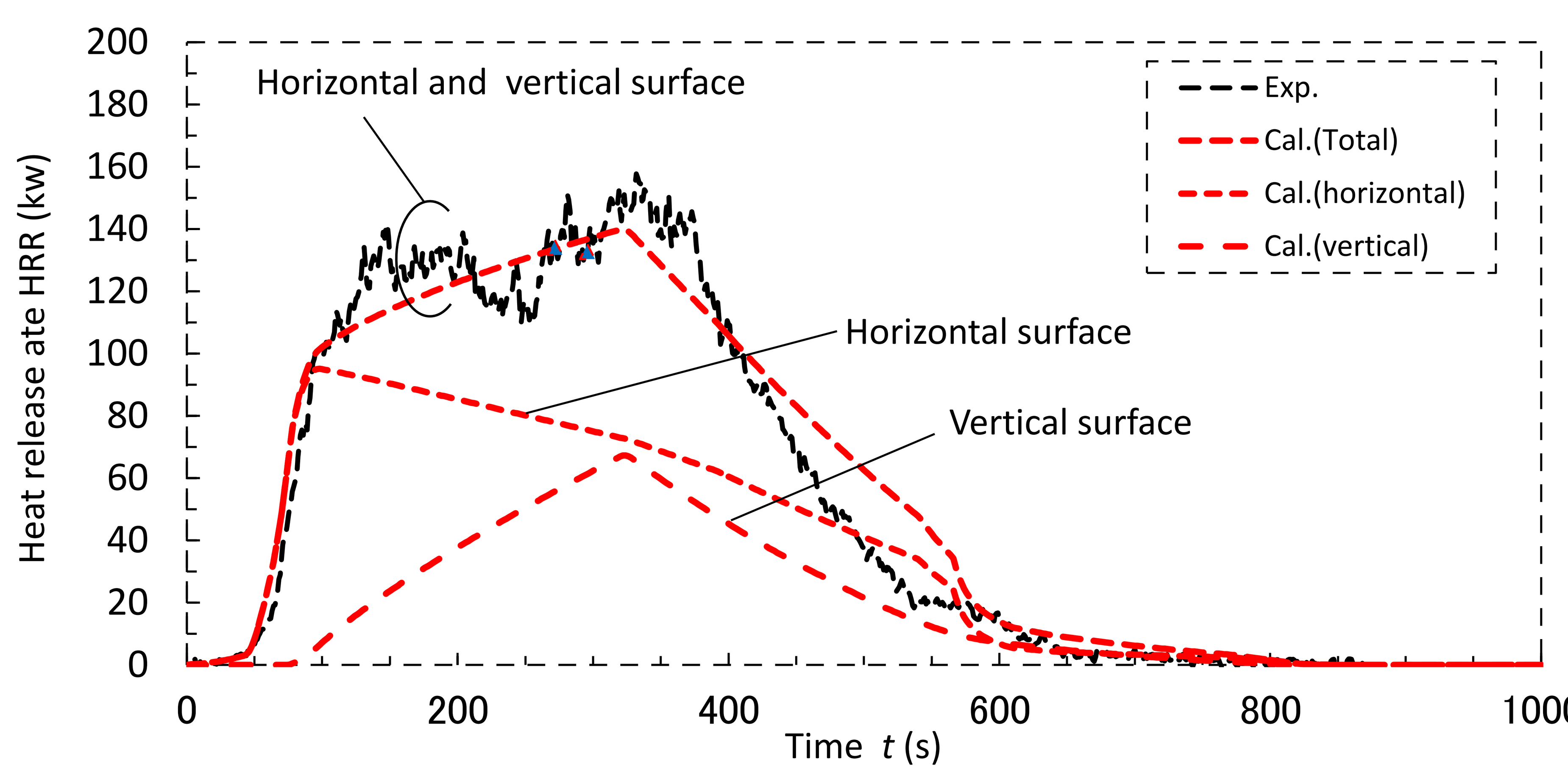

Fig.9 Comparison of calculated and measured HRR

5.Conclusions

- The simple model for calculation of burning rate of a polyurethane foam block considering the effect of size was proposed.
- The calculated HRR of a cubical-shaped polyurethane foam block is predicted well up to peak HRR.

Evaluating Effectiveness of Fire Blocking Barrier Fabrics used in Soft Furnishings

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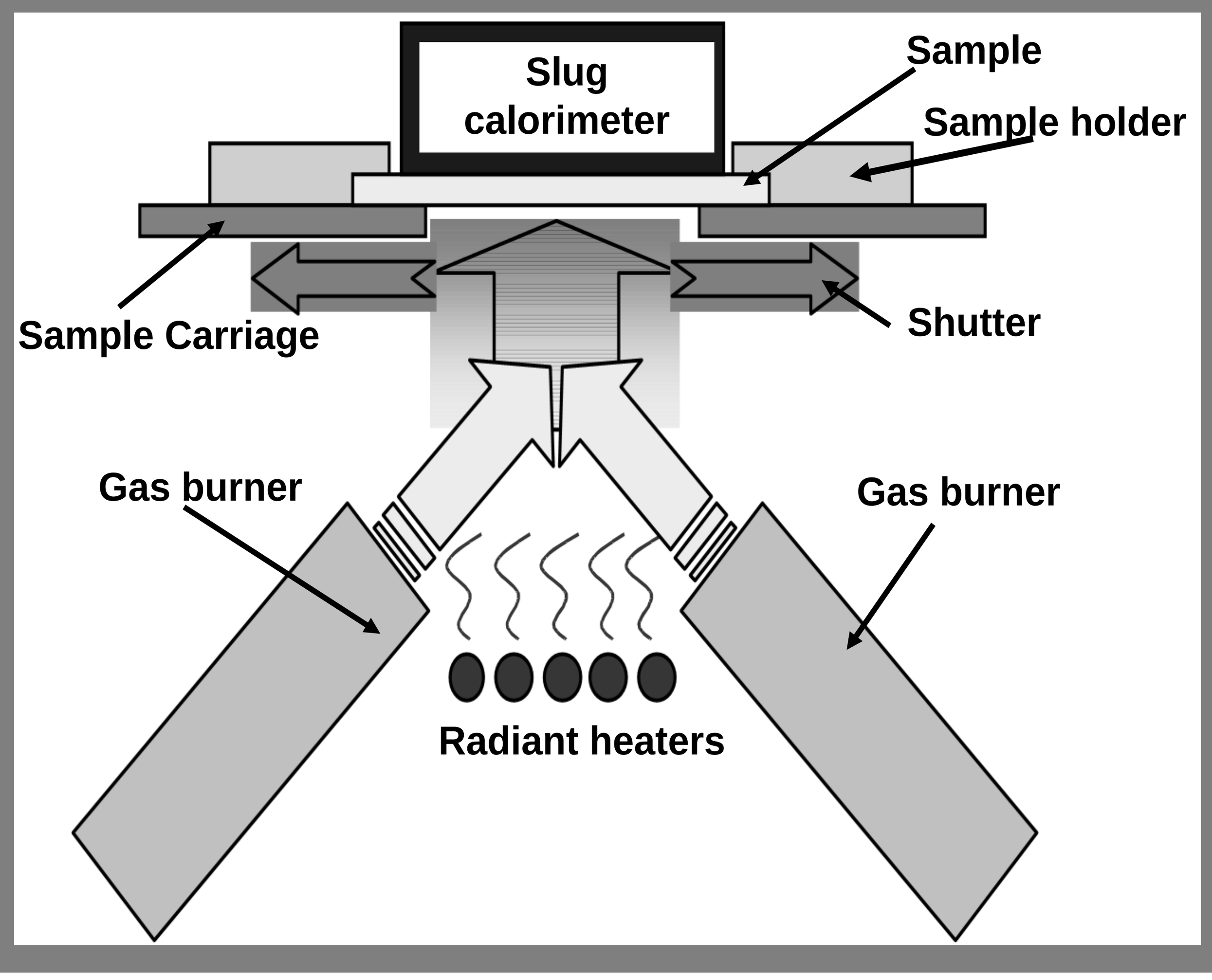
Operation Tomodachi - Fire Research at NIST – March 16-18, 2015

Thermal Protective Performance Test

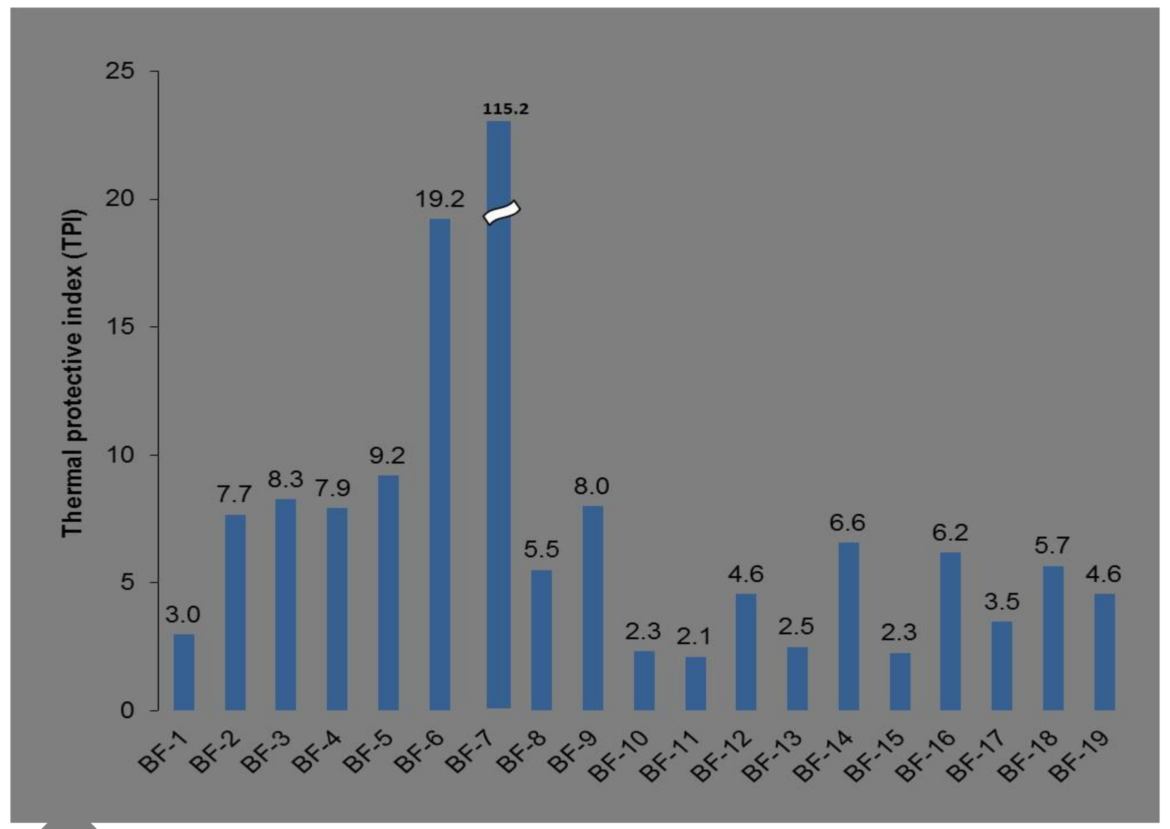


Abstract

In order to improve upholstered product fire safety, fire blocking barrier fabrics (BF) must protect the flexible polyurethane foam (FPUF) from both flaming ignition and smoldering ignition sources. The objective of this study was to quantify heat transfer characteristics and smoldering propensities of BFs used in soft furnishings.

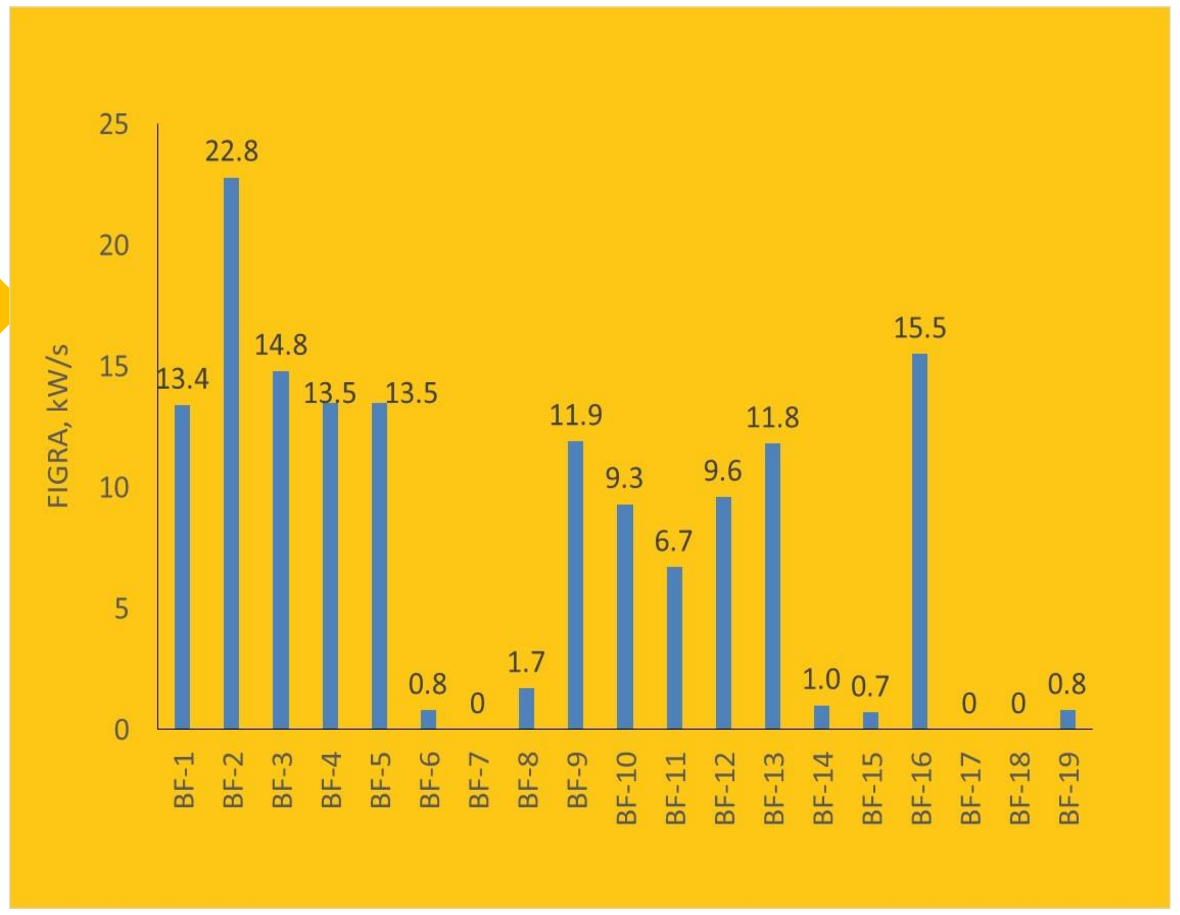
Major finding are:

- The higher the thermal protective index (TPI), the better is the thermal protection of a BF.
- FIGRA values distinguishes BFs containing inorganic fire resistant fibers (FIGRA < 2 kW/s), BFs with active flame retardants (FIGRA < 10 kW/s), and passive BFs (FIGRA > 10 kW/s).
- Mydrin test showed a clear distinction between active and passive BFs.
- Many BFs in combination with a cover fabric (CF) increase smoldering propensity.



Parameters	Performance Attributes
Heat transfer, J/m^2 Thermal Protective Index (TPI)	Thermal protection of cushioning components
Time to Ignition (TTI), s	Ignitability of BF under burning cover fabric/ticking
Peak Heat Release Rate (PHRR), kW/m^2	Maximum heat release to maintain positive feedback mechanism
Total Heat Released (THR), MJ/m^2	Flammable content of BF
Char	Protective property of BF after been consumed in fire
FIre Growth RAte (FIGRA), kW/s	Fire spread rate
Visible damage	Qualitative fire performance under end-use conditions
Charred Volume Fraction (CVF), %	Average volumetric rate of smoldering propagation

Cone Calorimetery



Mydrin test

CF/BF/Foam

BF/Foam

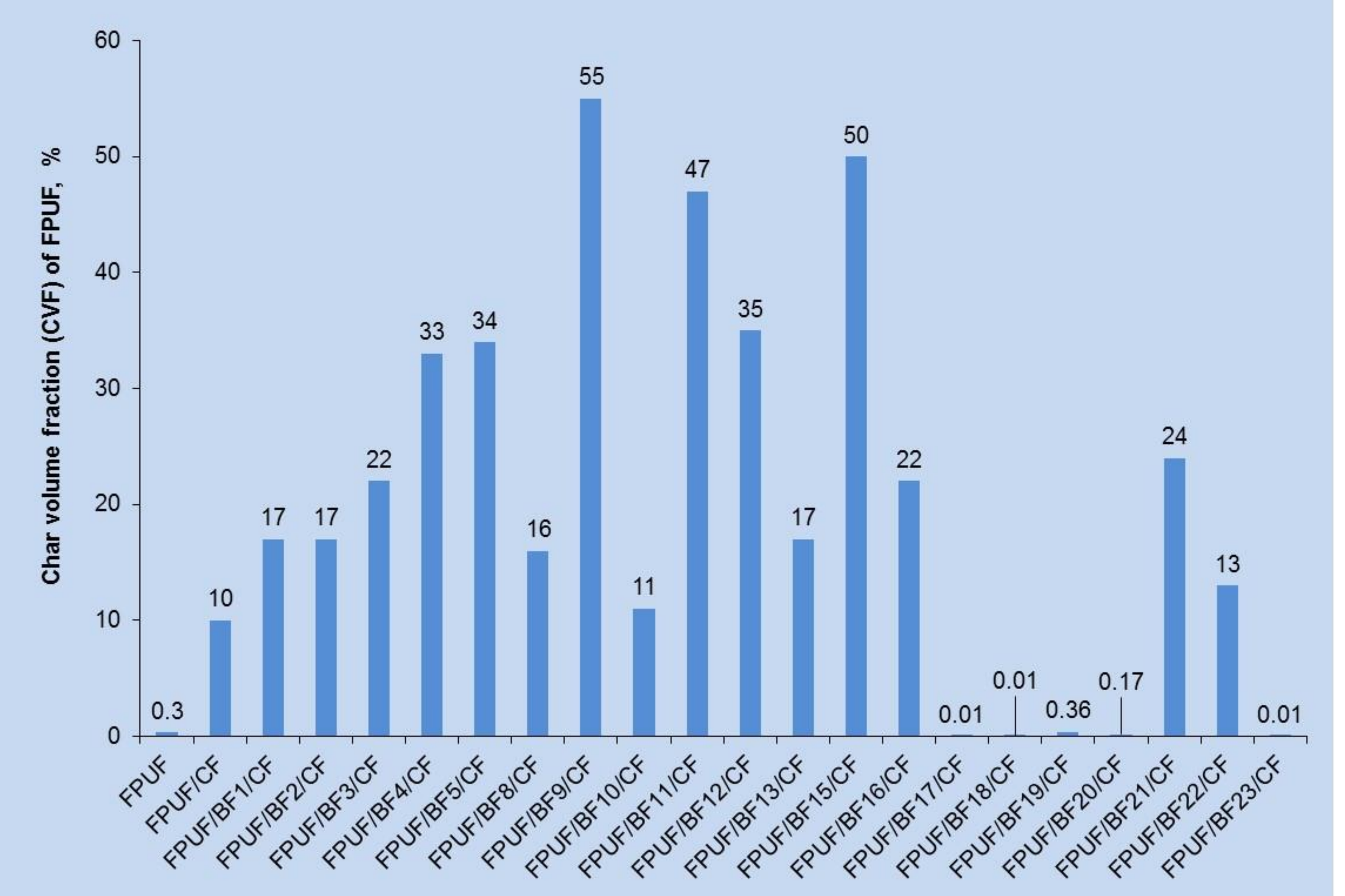
Foam

Smoldering Ignition test

16 CFR Part 1634 (proposed)

BF char

$$CVF(\%) = \frac{(Wt.\ of\ foam\ before\ test) - (Wt.\ of\ foam\ after\ test) \times 100}{(Wt.\ of\ foam\ before\ test)}$$



Identifying a Near-worst Case Scenario for Smoldering Upholstered Furniture

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Operation Tomodachi - Fire Research at NIST – March 16-18, 2015

Abstract

Smoldering poses a serious fire hazard. A large number of residential fire deaths can be attributed to smoldering materials, such as flexible polyurethane foams (FPUFs), commonly found in upholstered furniture and bedding [1].

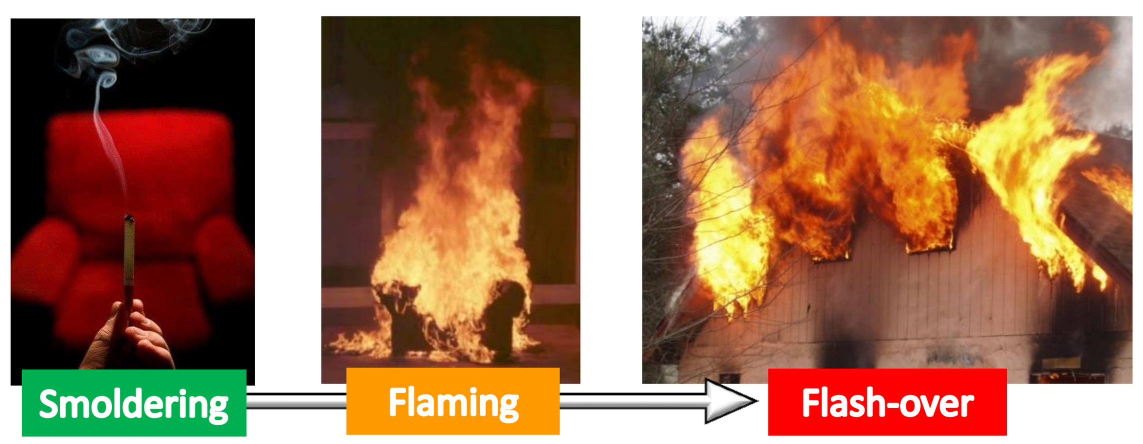

FIGURE 1. These images show a possible scenario where a weak smoldering ignition source (cigarette) leads to flash-over trough transition from smoldering to open flame.

Smoldering of residential upholstered furniture (RUF) is a complex problem that varies based on the properties of the components (e.g., FPUF, cover fabric, etc.), the layering sequence of the components and the construction of the product. It follows that the possible combinations are almost limitless and, thus, real-scale testing for assessing the smoldering propensity of RUF is not an economically viable solution [2].

Bench-scale tests are more economically feasible than real-scale tests but do not necessarily represent a realistic smoldering scenario. It would seem to be desirable to adopt a small-scale test offering a near-worst-case configuration so that variation from this scenario in actual furniture would most likely lead to less severe smoldering.

The bench scale tests that are currently used in the USA (here referred to as the "standard test") do not offer such a scenario [3]. In fact, they might severely underestimate smoldering propensity of household furniture where the buoyant airflow within the foam is not hindered.

Our findings

- **Our modified test has proven to be a more severe test than the standard test. It may offer a near-worst-case scenario, useful for identifying upholstery materials that are less likely to result in smoldering ignition in actual furniture independently of its configuration and/or geometry.**
- **Transition to flaming never occurred in the standard test but it has been observed in the modified test when the temperature of the crevice (HF) approached 600 °C.**
- **The geometry of the crevice plays a key role on smoldering. Crevice type 1 (see Figure 5) is used in our modified test and appears to be the most smoldering prone crevice configuration.**

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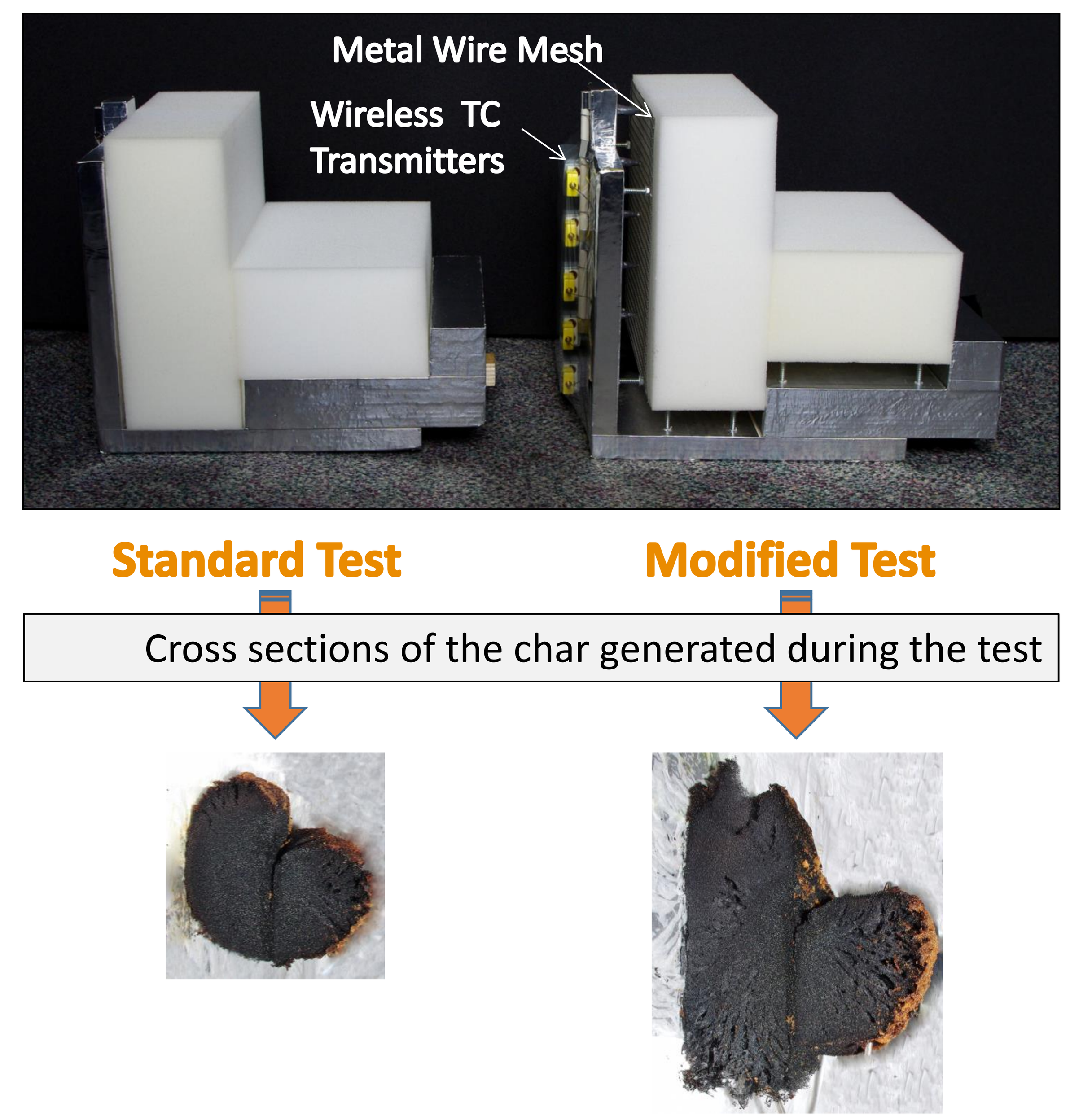

FIGURE 2. The smoldering test has been redesigned. The two top pictures show the modified and the standard test. The modified test allows for air flow by including a wire mesh to separate the foam pieces from the wooden frame and thus allow the mock-up to have better access to air. Wireless transmitters are used to monitor the foam temperature and mass loss in real time. The bottom pictures compare the cross sections of the charred foam produced in the two tests.

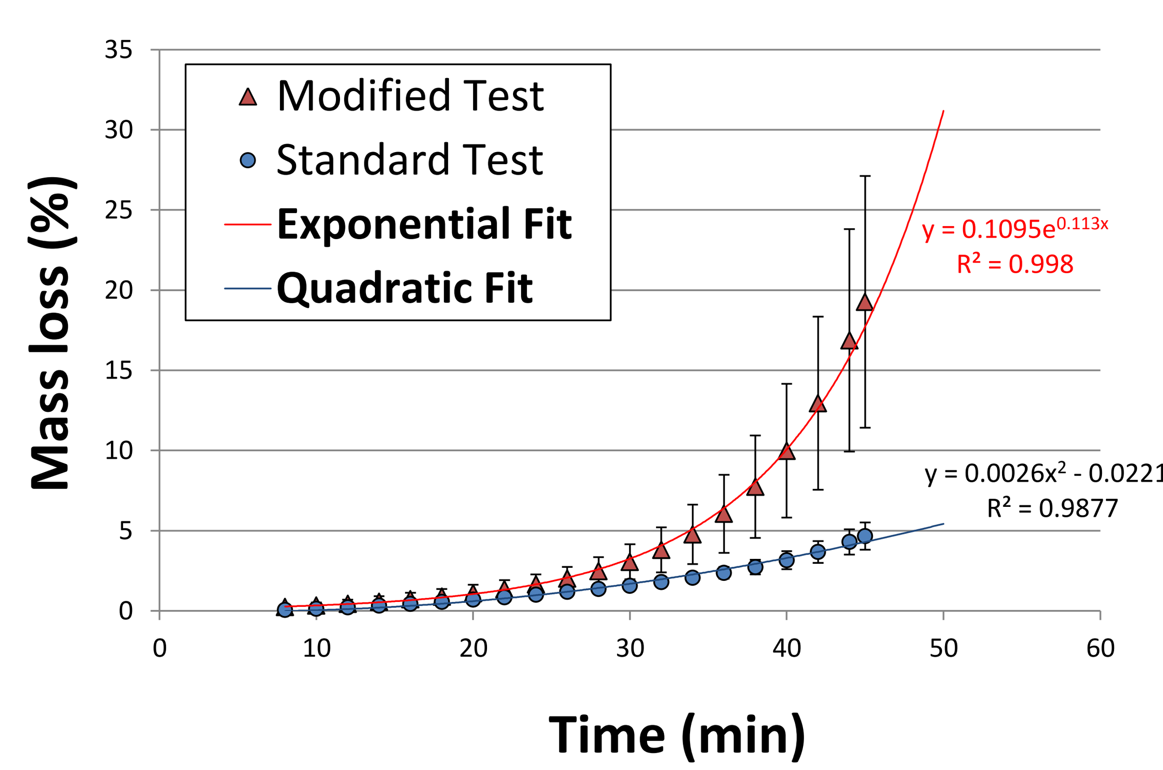

FIGURE 3. Mass loss vs. time for the standard test and modified test. There is a significant increase in mass loss in the modified test (exponential fit) as compared to the standard test (quadratic fit).

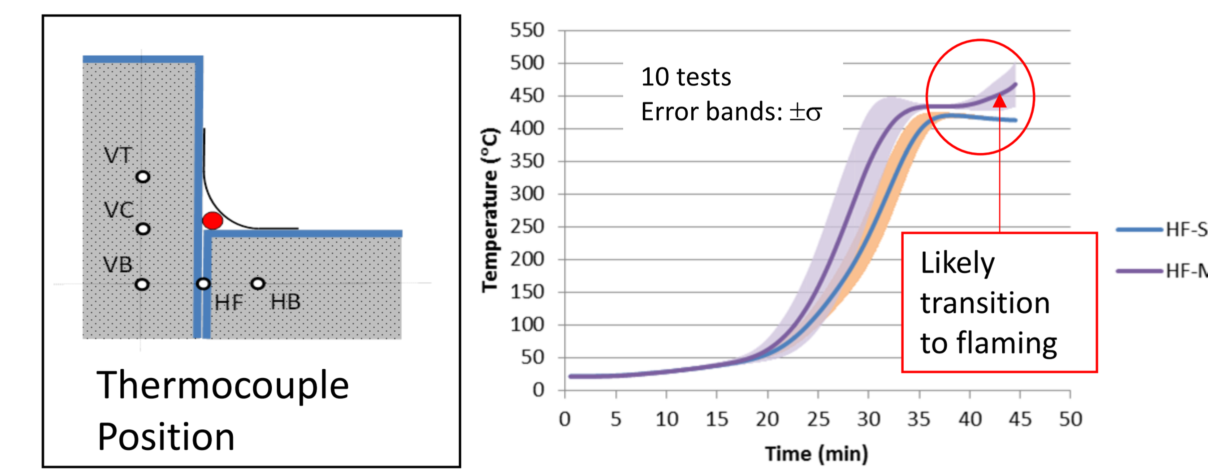

FIGURE 4. On the left: schematic drawing showing the location of the five thermocouples. On the right: profile temperature in the crevice (thermocouple HF) for the standard test (HF-SM) and the modified test (HF-MM). Transition to flaming was likely to occur in the modified test but it was never observed in the standard test.

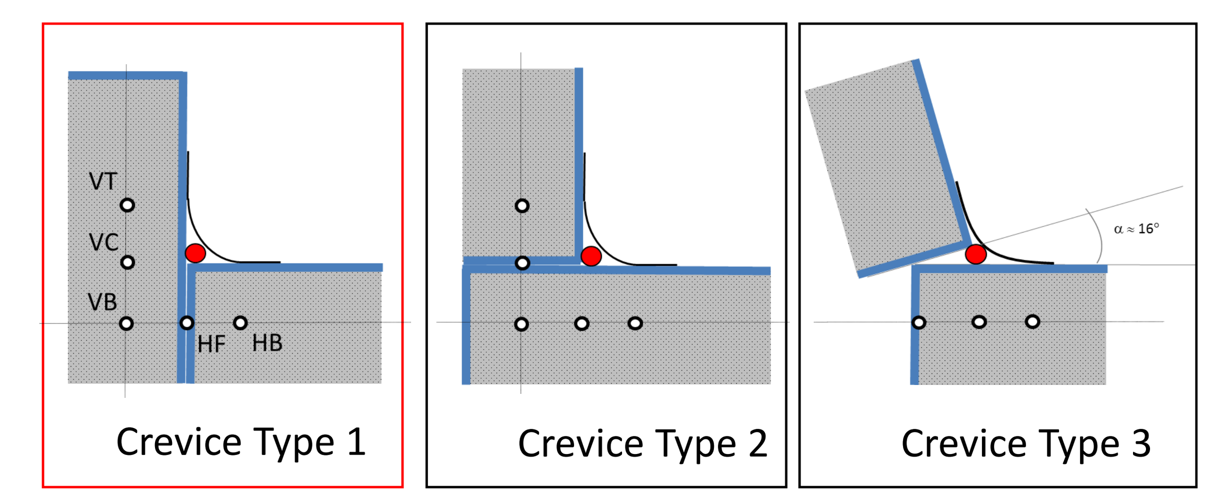

FIGURE 5. Crevice Type 1 is the most smoldering prone crevice configuration. It is the only crevice type that can induce sustained smoldering even in presence of polyester batting between the foam and the cover fabric (see Figure 6).

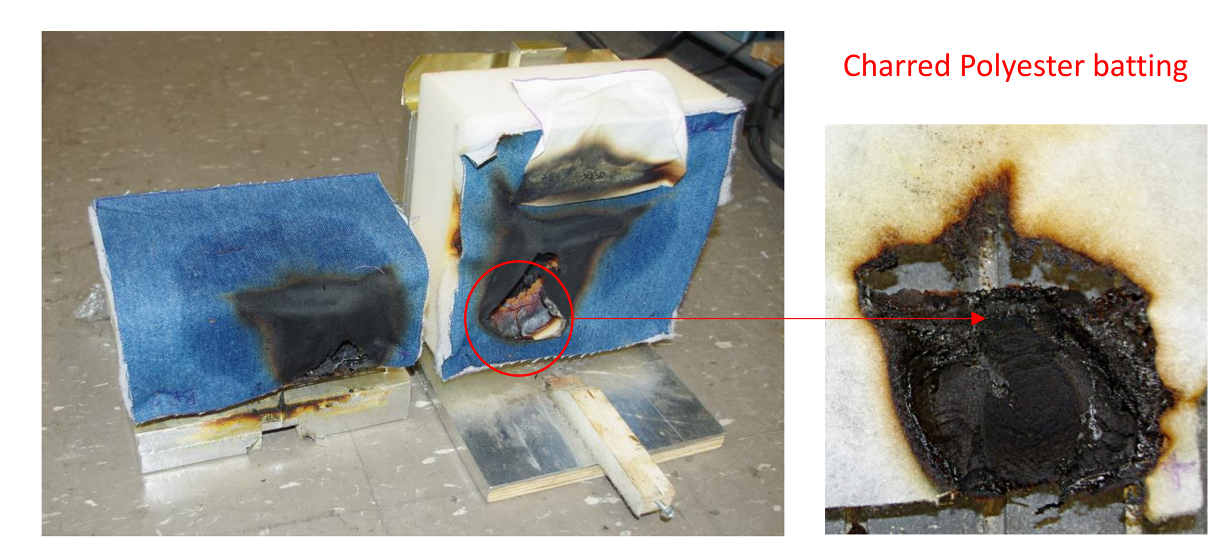

FIGURE 6. **Crevice Type 1** is the most severe crevice type. It is the only crevice type that can induce severe smoldering even in presence of polyester batting between a polyurethane foam and a cellulosic cover fabric (see Figure 6). The polyester batting generates a fibrous charred skin over a tarring polyurethane foam. As a consequence, the foam collapses and produces a large cavity in the crevice. Such a cavity promotes an increase in the convective flow and leads to a rapid increase in smoldering temperature with likely transition to flaming. This is a surprising result. In fact, polyester polymers are thermoplastics that are expected to melt without charring.

A Methodology for Estimation of Local Heat Fluxes in Steady Laminar Boundary Layer Diffusion Flames

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Motivation

Modeling the realistic burning behavior of condensed-phase fuels has remained out of reach, in part because of an inability to resolve complex interactions at the interface between gas-phase flames and condensed-phase fuels. The current research explores the dynamic relationship between combustible condensed fuel surface and gas-phase flames in both laminar and turbulent boundary layers.

Local mass burning rate technique

A methodology was developed earlier [1] that allowed for the estimation of local mass burning rates. The method has its basis in the Chilton-Colburn [2] extension to the Reynolds Analogy [3] that establishes a relationship between mass, momentum, and heat transfer in a boundary layer over a solid or liquid fuel surface.

$$\frac{\tau_s}{U_\infty \nu^{2/3}} \equiv \frac{h}{c_p \alpha^{2/3}} \equiv \frac{\dot{m}''}{D^{2/3}\ln(1+B)}$$

By extension of the Reynolds Analogy, it was hypothesized that the non-dimensional temperature gradient at the surface of a condensed fuel is related to the local mass burning rate through some constant of proportionality [1,4] and was given by,

$$\dot{m}''_f = \frac{C}{L}\left(\frac{\partial T^*}{\partial y^*}\right)_{y^*=0} = \frac{Bk_w}{c_p L}\left(\frac{\partial T^*}{\partial y^*}\right)_{y^*=0}$$

Experimental Facility and Instrumentation

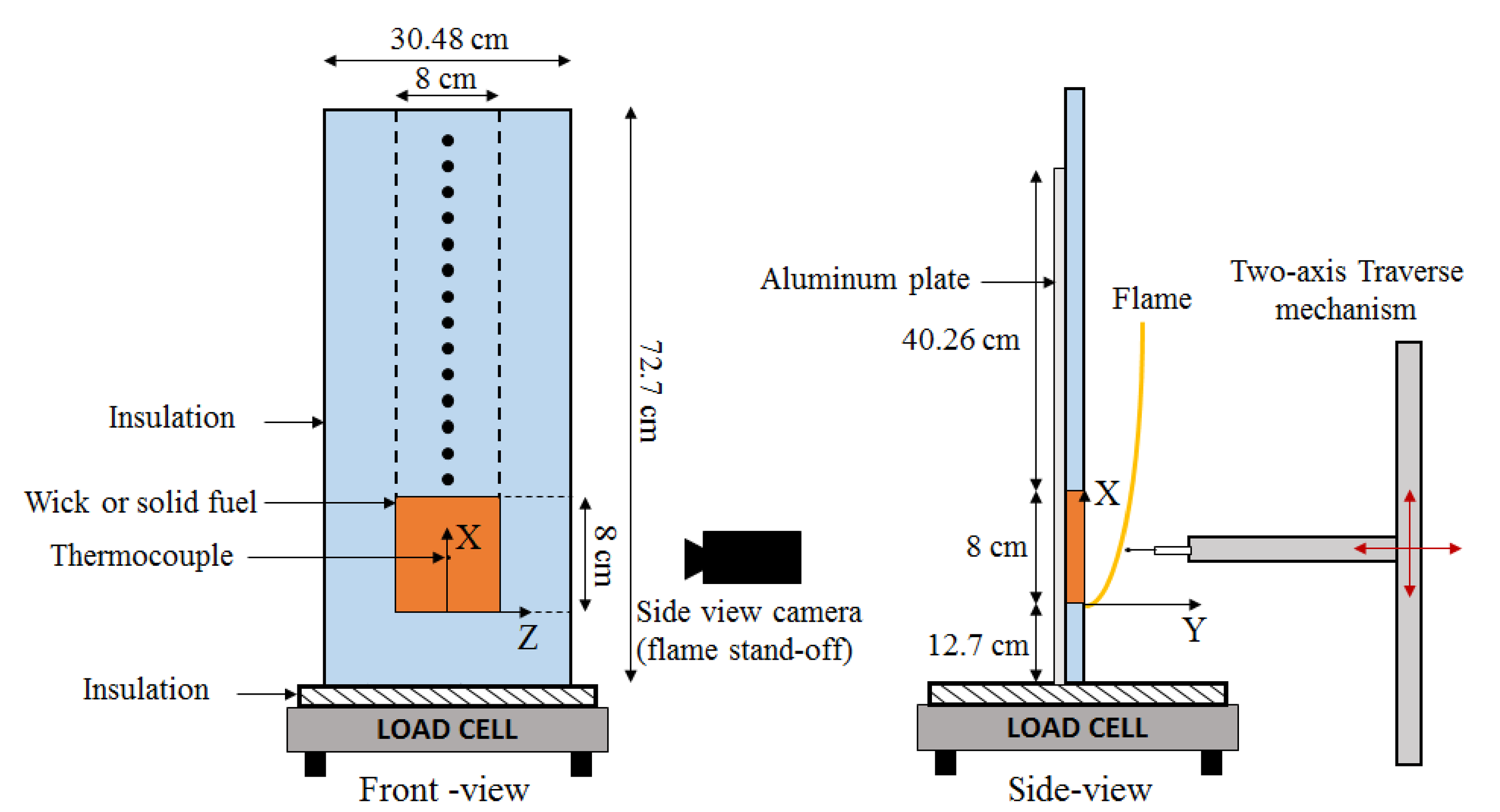

Fig. 1 Schematic diagram of the experimental set-up in a vertical configuration. The black dots above the wick represent the positions for wall heat flux measurements by a water-cooled heat flux gauge.

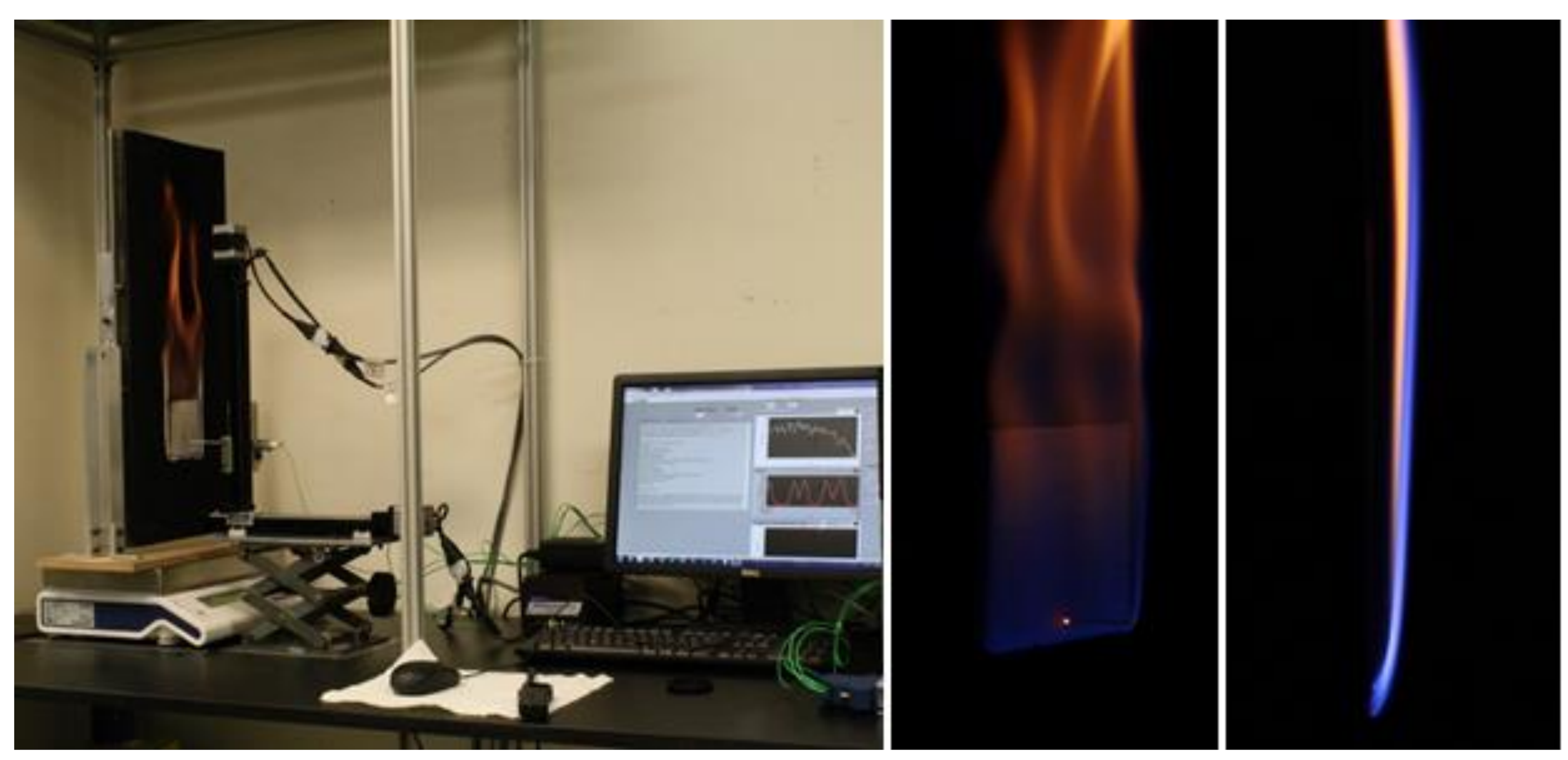

Fig. 2 (left) Photograph of the experimental set-up used to measure mass-loss rates and temperature profiles over a vertical, free-convection ethanol diffusion flame. (right) Front and side-view photograph of a vertical ethanol diffusion flame.

Experimental Results

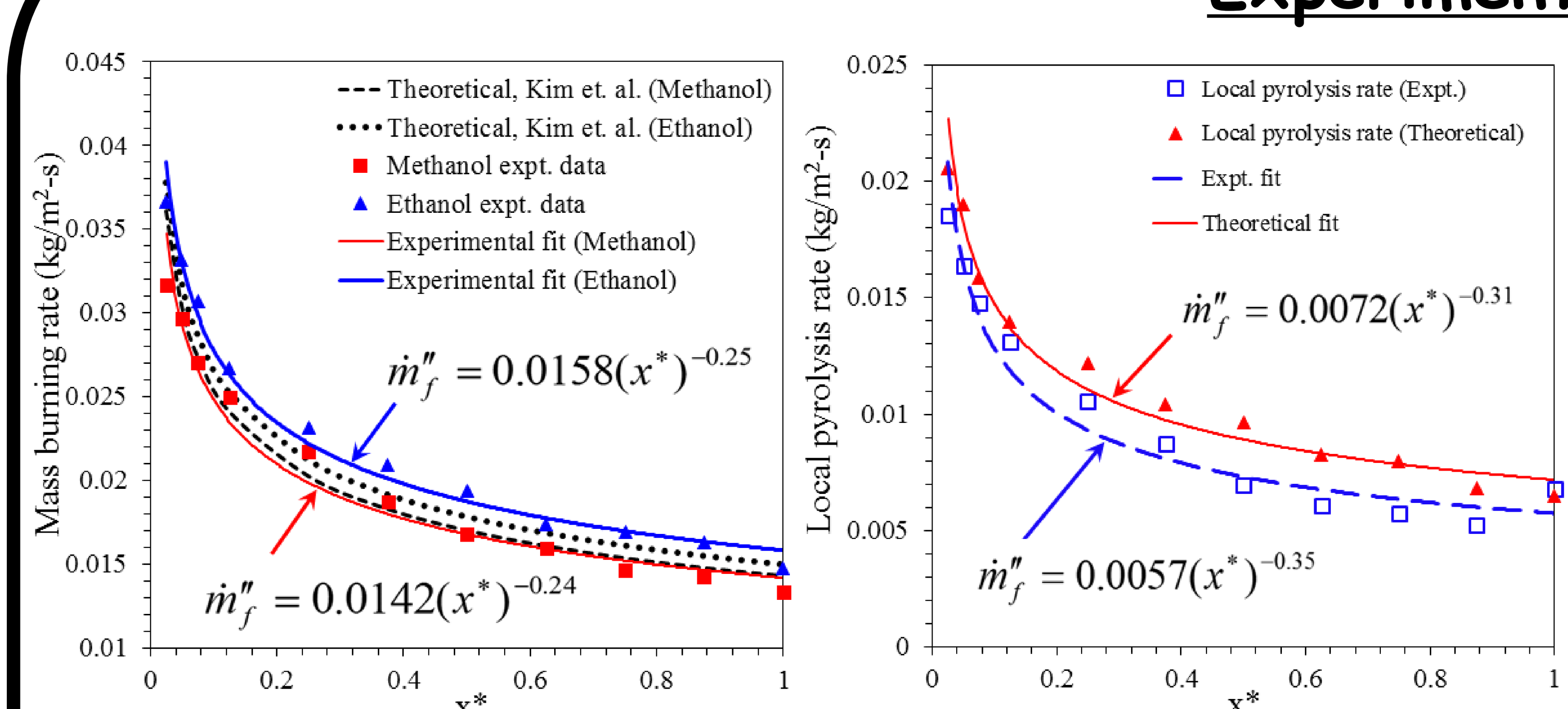

Fig. 3 Variation of the local mass burning rates at the methanol/ethanol condensed fuel surface (left) and PMMA surface (right) along its length.

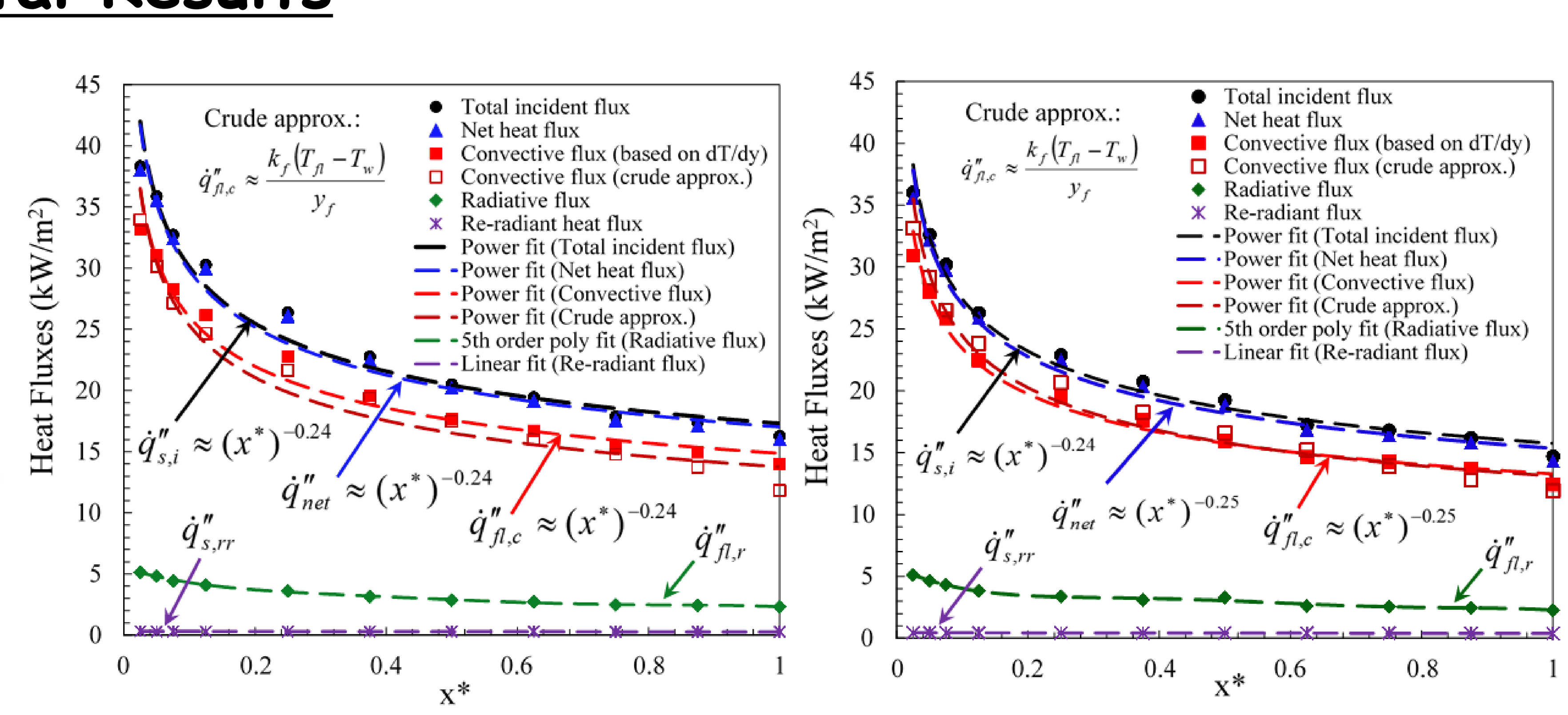

Fig. 4 Distribution of various components of heat flux in the pyrolysis zone for a methanol (left) and ethanol (right) diffusion flame.

Acknowledgments

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