Steel Structures Research Update

Structural Fire Engineering

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INTRODUCTION

Across the United States, researchers are making exciting discoveries and advances in structural fire engineering. Eleven of the leading scholars in the field are featured. Brief research highlights are organized by the topic areas of behavior and design of steel and composite structures for fire, fire following earthquakes, and performance-based fire engineering. For each individual, related steel and fire research is also noted. Meanwhile, due to timing and circumstances, there are structural fire engineering researchers who do not appear in this article. You may find some of their structural steel research in past articles or perhaps a future research update.

BEHAVIOR AND DESIGN OF STEEL AND COMPOSITE STRUCTURES FOR FIRE

Dr. Lisa Choe, Dr. Venkatesh Kodur, Dr. M.Z. Naser, Dr. Erica Fischer, and Dr. Amit Varma are contributing in various ways to the behavior and design of steel and composite structures for fire. A two-story steel framed building specimen is used for fire tests of full-scale composite floor assemblies. System behavior and onset of collapse are investigated in a numerical study of braced frame buildings. Machine learning is used for autonomous evaluation of fire resistance. Validated modeling techniques are used to study fire and fire following earthquake behavior of steel moment-resisting frames. Comprehensive design procedures are developed for a new concrete-filled steel plate shear wall system.

Fire Resistance of a Full-Scale Composite Floor Assembly

Under way at the National Institute of Standards and Technology (NIST) is a series of four compartment fire experiments on a full-scale two-story steel-framed building with composite floor slabs. Research structural engineer Dr. Lisa Choe is leading the team: Matthew Hoehler (associate project leader), Matthew Bundy, Brian Story, Anthony Chakalis, Philip Deardorff, Selvarajah Ramesh, Xu Dai, and William Grosshandler. Team members Choe, Ramesh, Dai, Hoehler, and Bundy won the Best Paper Award at the 11th International Conference on Structures in Fire (SiF2020) for their paper, "Experimental Study on Fire Resistance of a Full-Scale Composite Floor Assembly in a Two-Story Steel Framed Building" (Choe et al., 2020b). Dr. Choe's honors also include the Department of Commerce Gold Medal in 2019, a group award for development of unique measurement capabilities for research at NIST's National Fire Research Laboratory (NFRL).

The research seeks to fill gaps in knowledge in the behavior of steel-concrete composite floors and beams with simple shear connections subjected to fire. Previous studies were limited with regard to beam span, boundary conditions for the concrete on metal deck slabs, and other details for the composite system (Choe et al. 2020a). Four 42-ft partially composite beam specimens were explored in the first phase of the work. Type of shear connection (welded-bolted double angle or shear tab) and slab continuity over the girder were the main parameters. The double angles had greater rotational ductility than the shear tabs in fire but could fail due to axial restraints in the cooling phase. The shear tabs were sensitive to the slab continuity in both the heating and cooling phases (Choe et al. 2020a). In the second phase, 20-ft × 30-ft composite floor assemblies are exposed to natural gas-fueled compartment fires simulating standard fire environments [Figure 1(a)]. Gravity loads are applied by frames connected to hydraulic actuators in the basement; adjacent bays are loaded with water-filled drums [Figure 1(b)]. Test variables include area and type of steel reinforcement in composite floor slabs; fire protection on exposed beams; and thermal restraints provided by the adjacent bays, such as bay beam framing, beam-end connections, and slab continuity. In the first experiment, the fire test compartment represented an edge bay on the first floor of the building. Prescriptive details of the floor specimen complied with a 2-hr fire resistance rating. Connections were shear tabs, and the minimum shrinkage reinforcement was used in the floor slab. The reinforcement ruptured before any membrane action could be developed, leading to integrity failure of the floor slab prior to the specified rating period (Choe et al., 2020b). Slab reinforcement and fire performance of composite floor systems were explored further with the second test in 2021 (Choe et al., 2021).

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Design and Construction of Fire-Resistant Structures

Dr. Venkatesh Kodur contributes practical structural fire engineering tools and strategies founded on comprehensive numerical simulations and case studies. Dr. Kodur, University Distinguished Professor in Civil and Environmental Engineering at Michigan State University, also serves as the Director of the Centre on Structural Fire Engineering and Diagnostics. Dr. Kodur's research includes mitigation of fire-induced collapse of steel framed structures, utilizing comprehensive numerical models, and incorporating the development of temperature-induced strength degradation and instability in critical structural members with the progression of horizontal and vertical fire spread in different compartments and stories. One example is a simplified approach for evaluating shear degradation in fire-exposed steel and composite beams (Kodur and Naser, 2018). Fire safety of steel and composite bridges is another focus area; a specific aim is to develop practical tools for identifying vulnerable bridges and developing mitigation strategies. Honors include a 2018 Literati Award for Best Research Paper, "Effect of Local Instability on Fire Response of Steel Girders" (Kodur and Naser, 2017) and a 2019 Outstanding Paper Award at the 6th International Conference on Applications in Structural Fire Engineering, Singapore, for "Evaluating Fire Resistance of Composite Box Bridge Girders" (Zhang and Kodur, 2019). Dr. Kodur has also co-authored a textbook, *Structural Fire Engineering*. This comprehensive book explains codes and standards; high-temperature material properties; and behavior and strategies for enhancing fire resistance of steel, concrete, composite, and timber structures (Kodur and Naser, 2020).

The work on steel and composite structures includes system-level response of braced frame structures in fire scenarios (Venkatachari and Kodur, 2020). This work sought to fill knowledge gaps with respect to system behavior and the onset of collapse (Figure 2). The literature shows that "limited attention is given to the effect of parameters such as realistic loading, restraint and fire exposure scenarios which can significantly influence the onset of instability in the structure" (Venkatachari and Kodur, 2020). The analysis of a 10-story braced frame building was conducted for different fire scenarios. The likelihood of collapse was examined for parameters including fire location, temperature and duration of the fire exposure, and number of compartments with fire exposure. Additional details can be found in Venkatachari and Kodur (2020).

Autonomous Evaluation of Concrete-Filled Tube Columns

Performance of structures under extreme conditions, artificial intelligence, and smart materials and structures are core interests for Dr. M.Z. Naser, an Assistant Professor in Civil Engineering at Clemson University. Investigation into temperature-induced moment-shear interaction (Naser and Kodur, 2020) and performance evaluation of concrete-filled tubes through machine learning (Naser et al., 2021) are just some of Dr. Naser's recent works. Honors include the 2018 Literati Award for Best Research Paper with Dr. Kodur. Dr. Naser has published extensively in structural fire engineering and machine learning, with a focus on "intelligent tools that can accurately evaluate fire resistance and identify damage mechanisms in structures" and an eye toward "technologies to realize autonomous and self-diagnosing structures that can facilitate safe post-fire inspections and timely repairs" (Naser, 2020). His publications include the *Structural Fire Engineering* textbook co-authored with Dr. Kodur (Kodur and Naser, 2020) and the *Handbook of Cognitive and Autonomous Systems for Fire Resilient Infrastructures* (Naser and Corbett, 2022).

Briefly highlighted here is Dr. Naser's work on the structural response evaluation of concrete-filled tube (CFT) columns using machine learning (Naser et al., 2021). Dr. Naser and collaborators noted the benefits of CFTs for building design and construction, including strength, ductility, and

Fig. 1. (a) Compartment fires with natural gas burners and (b) floor loading.

inherent fire resistance. They also noted that the adoption of high-strength materials might be inhibited by the range of applicability of current code provisions and supporting test data. The researchers used artificial intelligence (AI) to analyze a database of 3103 CFT columns tested under different loading conditions and with a range of material and geometric properties. Circular and square or rectangular cross sections, with a maximum outside dimension of 40 in., had been tested under concentric and eccentric loading. The research team used genetic algorithms (GA) and gene expression programming (GEP) to develop models capable of predicting the CFT column load capacities. "These algorithms incorporate a supervised learning process that mimics the natural selection process (i.e., Darwinian evolution) to express hidden relations between a number of factors … The main advantage of these approaches over traditional soft computing techniques is their capability to produce predictive expressions without relying on past formula or relationship" (Naser et al. 2021). As shown in the measured versus predicted capacity graphs in Figure 3, the predictions were generally better than those obtained using AISC 360 (AISC, 2016), Eurocode 4 (CEN, 2009), and AS 2327 (ASI, 2017). Additional details of this study can be found in Naser et al. (2021).

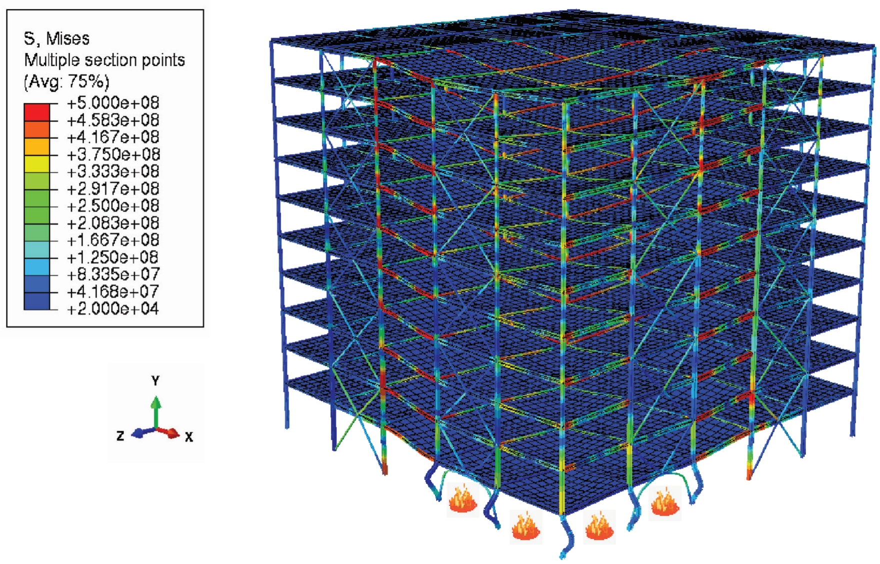
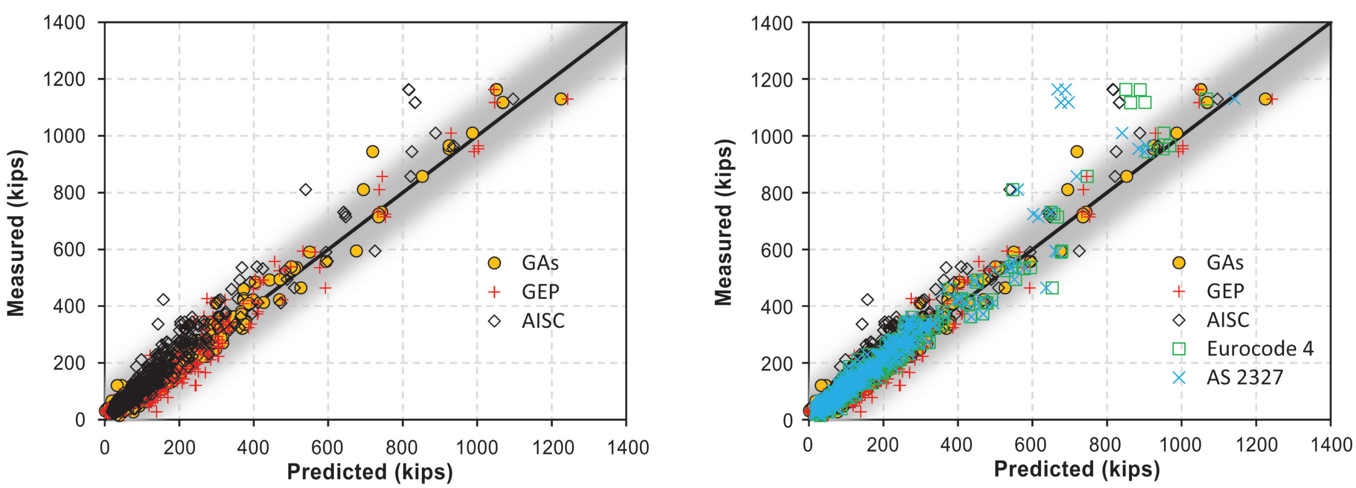


Fig. 2. Deformed configuration of the building at the onset of fire-induced progressive collapse (time = 154 min).



(a) AISC 360

(b) AISC 360, Eurocode 4, and AS 2327

Fig. 3. Measured versus predicted capacities for circular CFT columns under eccentric loading; genetic algorithms (GA) and genetic expression programming (GEP) predictions.

Development of Fire Modeling Capabilities in OpenSees

Simulating the behavior of steel and composite structures in fire, educating the next generation of structural engineers, and designing simple connections for fire conditions are three primary themes for Dr. Erica Fischer. Dr. Fischer is an Assistant Professor in the School of Civil and Construction Engineering at Oregon State University. Recognized locally and nationally for research and teaching excellence, Dr. Fischer's awards include AISC's Terry Peshia Early Career Faculty Award (2021). The American Society of Civil Engineers (ASCE) honored Dr. Fischer with the 2019 Collingwood Prize for her paper, "Experimental Evaluation of Single-Bolted Lap Joints at Elevated Temperatures" (Fischer and Varma, 2018). Her more recent work on connections includes advanced connection modeling, leading a working group within one of AISC's technical committees to synthesize numerical and experimental data on connection performance in fires and developing design provisions for connections exposed to various fire conditions. Dr. Fischer also led a collaborative research review on the fire behavior of steel simple connections, identifying gaps in knowledge and inconsistencies in testing methodologies and reporting of results (Fischer et al., 2021). Education on structural fire engineering extends past Dr. Fischer's classroom and to development of teaching modules with the support of AISC and the Structural Engineering Institute (SEI). The scope ranges from prescriptive fire protection design to structural fire engineering, and the modules are designed to be integrated into courses across civil engineering undergraduate curricula.

Simulation of fire performance of steel-frame buildings is a theme area with multiple facets. Dr. Fischer's research includes simulation of post-earthquake fire behavior of industrial facilities, benchmarking of structural fire engineering modeling to large-scale experimental tests, and development of OpenSees capabilities to simulate steel gravity framing systems in fire. Some work to date includes use of validated OpenSees modeling techniques to investigate fire and fire following earthquake behavior of a three-story, three-bay moment-resisting frame (Maddalozzo and Fischer, 2020). Five validation studies were used to test component and system behavior, considering temperature, forces, and displacements. Parameters for the fire and fire following earthquake investigations included locations of the compartment fire and the fuel load (Figure 4). Additional details can be found in Maddalozzo and Fischer (2020).

SpeedCore—Concrete-Filled Composite Steel Plate Shear Wall (CF-CPSW) Core

Dr. Amit Varma is well known for research on the behavior and analysis of steel and composite structures under fire loading and the development of design provisions for fire and collapse resistance. Dr. Varma is the Karl H. Kettelhut Professor in the Lyles School of Civil Engineering at

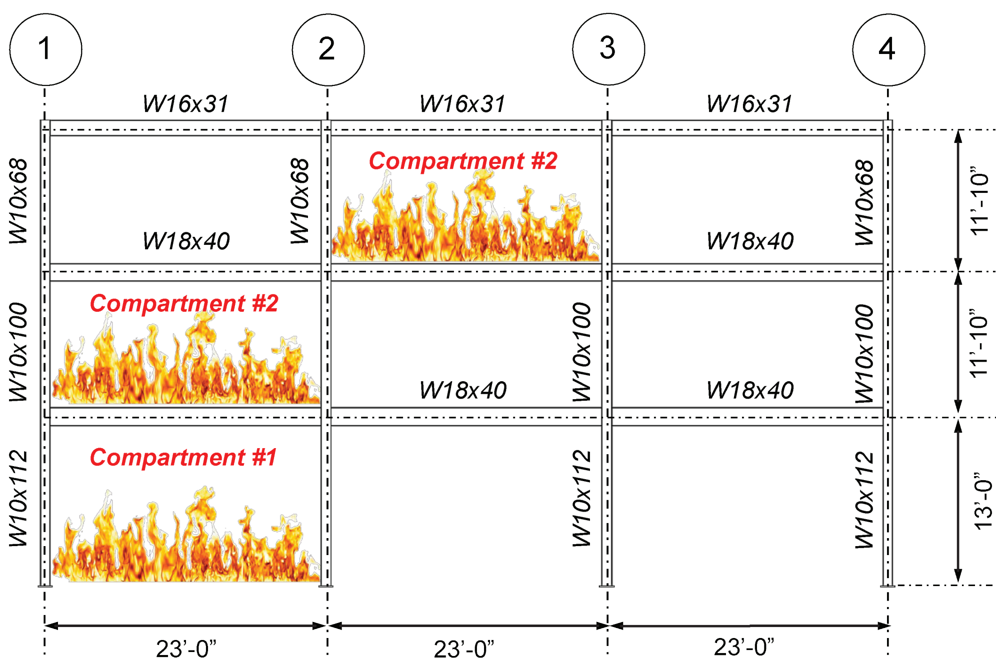


Fig. 4. Locations of compartment fires for moment-resisting frame study.

Purdue University and the Director of the Bowen Laboratory for Large-Scale Civil Engineering Research. While seeking to fill knowledge gaps in the fundamental behavior of structural steel components and assemblies, Dr. Varma pioneered an innovative method for realistic structural fire tests without the traditional gas furnace. Replication of this unique test method at several structural engineering laboratories across the world is just one indicator of Dr. Varma's global impact in this field. His research group has produced numerous works advancing the state of the art in behavior, analysis, and design for fire. Their achievements include publications on the fire behavior of steel and composite columns, composite floor assemblies, composite beams, and steel connections (e.g., Hong and Varma, 2010; Wellman et al., 2011; Selden et al., 2016; Fischer and Varma, 2018). Dr. Varma's group has also developed and benchmarked detailed 3D nonlinear finite element models for predicting the observed experimental behavior of steel connections and of steel and composite columns, floor assemblies, and beams (e.g., Agarwal and Varma, 2011; Selden and Varma, 2016; Choe et al., 2017; Fischer and Varma, 2017). The benchmarked modeling approaches have been used to investigate the fire behavior, resistance, and overall collapse of 3D steel and composite building structures (e.g., Agarwal and Varma, 2014; Agarwal et al., 2014; Fischer et al., 2019). The work has also been extended to evaluation of multi-hazard behavior and design of steel building structures under post-earthquake fire loading (e.g., Bhardwaj et al., 2019; Alasiri et al., 2020).

Dr. Varma's most recent accolades recognize his achievements in developing SpeedCore, a concrete-filled steel plate shear wall system with cost, safety, and construction schedule benefits, among others. An increased speed of construction is partly because no fireproofing is required for SpeedCore walls at least 18 in. thick (AISC, 2021). Dr. Varma's selections for 2017 and 2020 AISC Special Achievement Awards and the 2021 AISC T.R. Higgins Lectureship Award were based on his collection of work on the composite shear walls. More information about this hybrid core system, how it is designed and built, and how it works in fire can be found at AISC's SpeedCore webpage (AISC, 2021). Those looking for more information on the structural fire engineering and design of SpeedCore walls can view a series of recorded presentations on the "SpeedCore-Fire-Research" YouTube playlist (Figure 5; Varma, 2021). Computer programs to analyze and design SpeedCore walls for fire are available through an online repository (Varma and Anvari, 2020).

FIRE FOLLOWING EARTHQUAKES

Dr. Rachel Chicchi, Dr. Hussam Mahmoud, and Dr. Maria Garlock are advancing methods for fire following earthquake (FFE) evaluations. Three-dimensional nonlinear finite element building models explicitly include details of the gravity framing system and are used to compare different seismic damage–fire scenarios. A hybrid simulation framework incorporates thermal loads and seismic damage in the physical substructure. The seismic performance of nonstructural components (e.g., sprinklers) is incorporated into post-earthquake fire evaluations of steel frames.

Fig. 5. Screenshot of video presentation on SpeedCore fire resistance experiments (Varma, 2021).

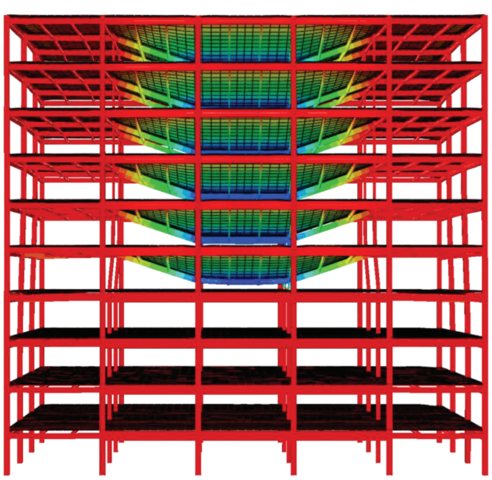
Post-Earthquake Fire Assessment

Post-earthquake fire assessment, critical temperature, simple methods of analysis for fire-resistant design, and connections are among Dr. Rachel Chicchi's topics of study. Dr. Chicchi is an Assistant Professor in the University of Cincinnati's Civil and Architectural Engineering and Construction Management department. She has collaborated with Dr. Fischer and Dr. Choe on a research review for fire behavior of simple shear connections (Fischer et al., 2021). Analysis of single-angle connections by her research group will address one of the knowledge gaps identified in the review. Work continues on simple methods of analysis to determine demands on the structure at elevated temperatures (Chicchi and Varma, 2021). One extension of the work is incorporation of local buckling for wide-flange columns into the simple equations. Another is an investigation into the applicability of the column flexural buckling equation for high-strength steel. In a separate study, important parameters affecting the critical temperatures of axially loaded wide-flange columns were identified and a closed-form equation proposed (Sauca et al., 2021). Meanwhile, post-earthquake fire assessment has evolved past an initial research review (Chicchi and Varma, 2017) into detailed studies and methods (e.g., Chicchi and Varma, 2018).

Dr. Chicchi's post-earthquake fire research includes methods for post-earthquake fire assessment of steel moment frame buildings (Alasiri et al. 2020). A detailed numerical methodology has been proposed and illustrated with a 10-story perimeter steel moment frame building case study. The nonlinear finite element model of the 3D building structure explicitly included the gravity framing system, including connections and composite slabs. "The model accounted for various limit states and failure modes resulting from inelastic deformations, local and global instability, and connection damage/failure at elevated temperatures, while incorporating the effects of temperature on steel and concrete material properties" (Alasiri et al., 2020). Buildings with different levels of seismic damage were subjected to various fire scenarios. Shown in Figure 6 is a fifth-story interior compartment fire and plots of the vertical deformation and temperature versus time for the failed interior gravity column. The researchers discovered that the seismic and fire behaviors were largely decoupled; the gravity columns were the most critical components in the post-earthquake fire. Additional details and design recommendations can be found in Alasiri et al. (2020).

Multi-Hazard Simulation and Testing

A primary research thrust for Dr. Hussam Mahmoud is the assessment and development of resilient and sustainable structural systems subjected to multiple hazards such as fire, blasts, earthquakes, and/or wind loading. Dr. Mahmoud is the George T. Abell Professor of Infrastructure in the Department of Civil Engineering at Colorado State University. He is also Director of the Structural Laboratory at Colorado State. Among his numerous recognitions and honors is the 2017 Terry Peshia Early Career Faculty Award from AISC. Dr. Mahmoud's contributions include new structural systems as well as new performance-based design and life-cycle analysis frameworks. Methods proposed include an approach for assessing steel column response under fire loads considering with various boundary conditions and temperature profiles (Memari and Mahmoud, 2018a). Also considered are factors such as second-order effects and



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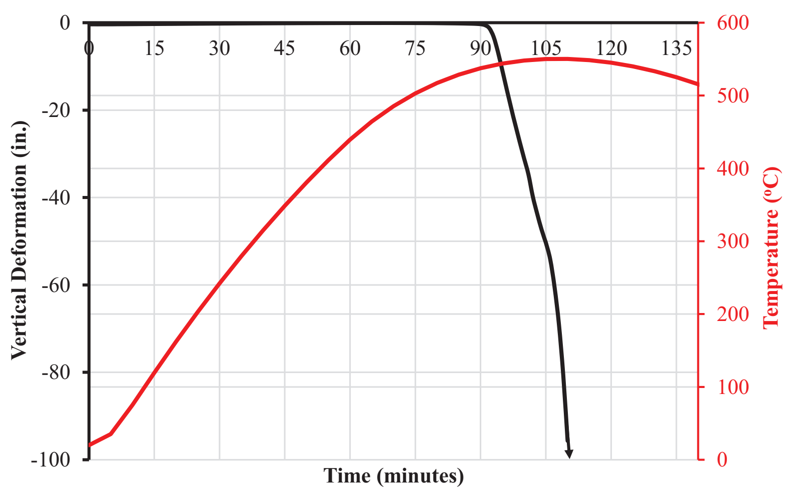


(b)

Fig. 6. (a) Response of building to fifth-story interior compartment fire and (b) vertical deformation and temperature versus time for failed interior gravity column.

residual stresses. A proposed framework for performance-based analysis of fires following earthquakes incorporates uncertainties associated with fire hazard, gravity loads, passive fire protection, and earthquake intensity (Memari and Mahmoud, 2018b).

A hybrid simulation framework was developed and illustrated with a test of a small-scale specimen (Memari et al., 2020). The four-story special concentrically braced frame (SCBF) building was 5 ft × 5 ft in plan, with four bays in each direction. A first story column was the physical test specimen, the substructure model. The rest of the planar frame was the numerical integration model (Figure 7). Leaning columns in the model represented the gravity frames. The framework was first tested using a numerical substructure-numerical integration model. For the physical substructure model, a small fire furnace with four radiative heaters and a self-reacting steel frame was used for thermal loads, and residual interstory drifts were used to represent different seismic damage levels in the frame. The level of residual interstory drift proved to be a significant factor in the fire performance of the column. Additional details and commentary on future studies can be found in Memari et al. (2020).

Community Level Studies and Nonstructural Components

From steel connections for fire to community resilience to the Creative Art of Structural and Civil Engineering (CASCE, https://casce.princeton.edu/), Dr. Maria Garlock is advancing structural engineering design and the education of future engineers. Dr. Garlock is a Professor of Civil and Environmental Engineering at Princeton University. She also serves as the program director of the Architecture and Engineering Program, is the Head of Forbes College at Princeton University, and is Associated Faculty in both the School of Architecture and the Program in Latin American Studies. Of her many accolades, perhaps the most notable in structural steel is the 2016 T.R. Higgins Lectureship Award for her steel structure-fire interaction research (Garlock, 2016). Other awards include the Bronze Award for the Advancement of Arc Welded Design, Engineering and Fabrication, given by The James Lincoln Arc Welding Foundation (2003) and a first-place poster in the category of Steel Structures, Composite Structures, and Connections in the 5th International Conference for Structures in Fire in East Lansing, Michigan, in 2010. The poster, co-authored with former student Spencer Quiel, was titled "Stress-Based Equations for Predicting the Buckling Capacity of Steel Plates Exposed to Fire" (Quiel and Garlock, 2010).

Dr. Garlock notes that her research on fire has evolved into fire following earthquake (FFE) community-level studies, specifically considering deep-basin seismic effects such as those found in Seattle. A paper on FFE scenario studies in Seattle is forthcoming (Coar et al. 2021). Not published, but in preparation, is a paper that examines the effects of different earthquake types on passive and active fire protection systems, and consequential structural-fire interaction performance. Meanwhile, an archetype nine-story steel moment-resisting frame (MRF) structure is modeled using OpenSees finite element analysis software and subjected to a suite of basin (Seattle) and non-basin (Los Angeles) earthquake records as developed by the University of Washington M9 Project (Frankel et al., 2018). The resulting peak floor accelerations and interstory drift

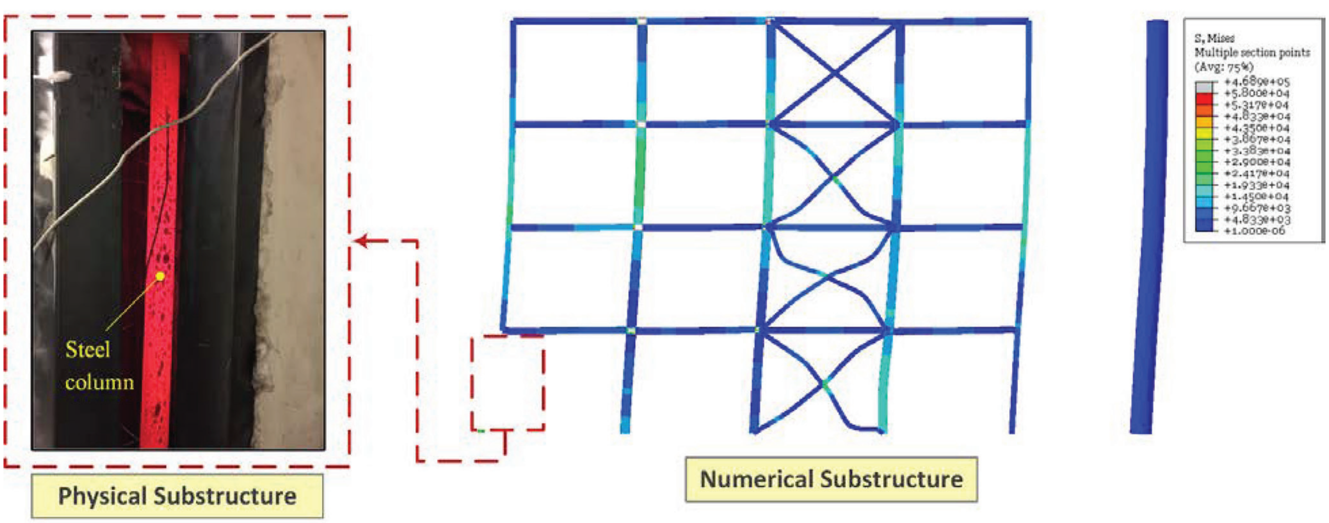


Fig. 7. Physical and numerical substructure, residual damage state.

ratios are used as intensity measures for existing component fragility curves of the active (sprinkler) and passive (compartment divider) fire protection systems (Pali et al., 2018; Soroushian et al., 2014). The seismic performance of these nonstructural components modifies the single-structure fire spread model based on the University of Delaware Disaster Research Center (Lee and Davidson 2010a, 2010b; Li and Davidson, 2013). The results of the fire spread model are used to apply time-dependent thermal loads to the seismically damaged OpenSees finite element structural model for structural performance evaluation of the steel frame (Figure 8).

PERFORMANCE-BASED FIRE ENGINEERING (PBFE)

Dr. Spencer Quiel, Dr. Negar Elhami-Khorasani, and Dr. Thomas Gernay are improving simulations for performance-based fire engineering (PBFE). A coordinated computational-experimental investigation supports a framework for realistic models of composite floor systems with different fire ratings. A cost-effective hybrid simulation incorporates realistic boundary conditions and system as well as element level response. Experimental characterization of advanced high-strength steels tests the range of applicability of current provisions.

Performance-Based Design of Passive Fire Protection for Floor Systems

Dr. Spencer Quiel is known for his research on buildings subjected to extreme loads such as fire, blast, and progressive collapse. Dr. Quiel is an Associate Professor in Civil and Environmental Engineering at Lehigh University. His experience in analysis and design of structures to resist extreme loads includes four years at Hinman Consulting Engineers. As a Department of Homeland Security Graduate Fellow, Dr. Quiel also spent two months of his doctoral studies at the Building and Fire Research Laboratory (BFRL) at the National Institute of Standards and Technology (NIST). Dr. Quiel was the 2016 recipient of AISC's Milek Fellowship for his research on "Performance-Based Design of Passive Fire Protection for Floor Systems in Steel-Framed Buildings."

For the Milek Fellowship, Dr. Quiel's research group is building a framework for performance-based design and analysis of steel-concrete composite floor systems to resist fire. The development of this framework for steel-framed buildings, motivated by the lack of design and analysis guidance, is founded on a coordinated computational-experimental investigation. Methods for quantifying realistic restraint of floor systems and modeling tools are being produced. The laboratory experiments include five large-scale structural-fire tests of partially restrained, partially

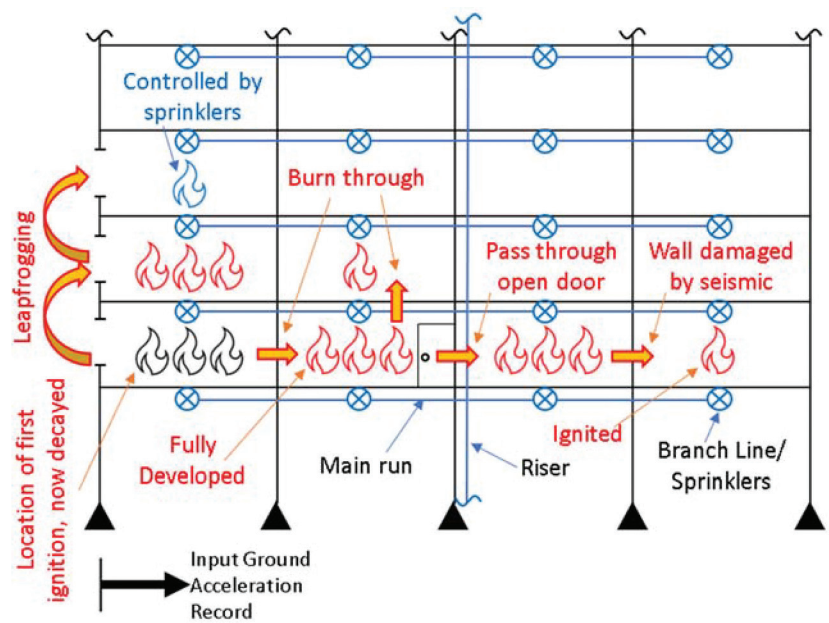


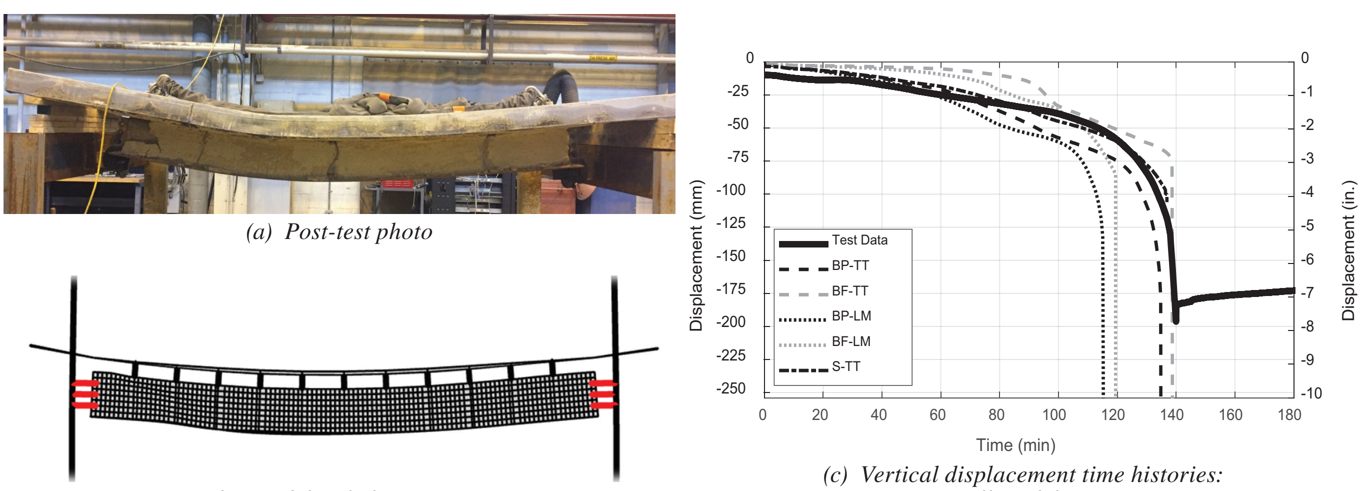
Fig. 8. Fire spread model for structural performance evaluation of steel frame.

composite steel floor beam assemblies and a number of small-scale, spray-applied fire resistive material (SFRM) tests. Parameters for the large-scale tests included passive fire protection (i.e., unprotected, coated with SFRM) and level of axial restraint (Kordosky et al. 2020). The experimental results have been used for validation of "thermal and structural analysis methods of varying complexity to capture the flexural response and failure of the fire-exposed composite floor beam specimens. The goal of this modeling effort is to develop accurate, conservative predictions of fire-induced mechanics and limit states at reduced computational cost, thus increasing the accessibility of these methods to practicing engineers" (Drury et al., 2020). A major outcome of the research will be tools for translating fire resistance ratings into realistic models of composite floor systems for performance-based design of steel buildings. Results have been promising, as demonstrated by comparisons of the final deflected shapes of the modeled and tested floor beam assemblies (Figure 9). Additional details of the experiments and modeling efforts can be found in Kordosky et al. (2020) and Drury et al. (2020).

Methods and Models to Advance Performance-Based Fire Engineering

Fire and elevated temperatures on steel structures is a primary focus for Dr. Negar Elhami-Khorasani, whose research encompasses resilient communities, performance-based design, reliability, and multi-hazard analysis. Dr. Elhami-Khorasani is an Assistant Professor in the Department of Civil, Structural and Environmental Engineering at the University at Buffalo. In Dr. Elhami-Khorasani's portfolio of work are topics such as parametric studies for performance-based fire design of composite floor systems and fire fragility functions for steel frame buildings (Elhami-Khorasani et al., 2019; Gernay et al., 2018). More recent research includes "Probabilistic Models for Temperature Dependent Strength of Steel and Concrete" and "Developing Real-Time Hybrid Simulation to Capture Column Buckling in a Steel Frame under Fire" (Qureshi et al., 2020a, 2020b). Qureshi et al. (2020b) received the best student paper award at the International Structures in Fire Conference in 2020. Dr. Elhami-Khorasani was also honored in 2020 with AISC's Terry Peshia Early Career Faculty Award, recognizing her structural steel research, teaching, technical service, and community outreach.

Dr. Elhami-Khorasani seeks to advance performance-based fire engineering (PBFE) through the development of methods and models for explicit evaluation of reliability and fire safety. Probabilistic material models for steel and concrete incorporate uncertainties in material behavior at elevated temperatures (Qureshi et al. 2020a). Qureshi et al. (2020a) also studied the influence of model choice on structural failure assessment of steel and concrete columns exposed to fire. This work was in collaboration with Dr. Thomas Gernay from Johns Hopkins University, Dr. Ruben Van Coile from Ghent University in Belgium, and Dr. Danny Hopkin from Olsson Fire & Risk and the University of Sheffield in the UK. Meanwhile, Dr. Elhami-Khorasani's work on real-time hybrid simulation provides a cost-effective method for obtaining realistic element-level response of the physical substructure by properly incorporating system-level response and interfacing boundary conditions during the fire event through a numerical substructure (Qureshi et al., 2020b). The proposed method was successfully applied to a benchmark study of a large-scale moment frame with buckling of one tube column subjected



(a) Post-test photo

(b) Model at failure: S-TT

(c) Vertical displacement time histories: Test vs. all model iterations

Fig. 9. Results of testing and modeling for a protected W12×26 *composite beam.*

to fire and subsequent frame collapse (Figure 10). "The real-time hybrid fire simulation is able to capture the dynamic behavior at the time of column failure, for which the obtained result is also applicable to progressive collapse applications in general" (Qureshi, 2021).

Characterization of New Steels at Elevated Temperatures

Risk-based methodologies, numerical modeling, and characterization of materials at elevated temperatures form the core of Dr. Thomas Gernay's contributions to performance-based fire engineering (PBFE). Dr. Gernay is an Assistant Professor in the Department of Civil and Systems Engineering at Johns Hopkins University. The founder and principal investigator for Johns Hopkins' Multi-Hazard Resilient Structures research group, Dr. Gernay actively develops SAFIR, a nonlinear finite element software for modeling the behavior of structures in fire, and conducts research on topics ranging from properties of advanced high-strength steels at elevated temperatures (Yan et al., 2020, 2021a, 2021b) to behavior of cold-formed steel structures during and after fire exposure (Batista Abreu et al., 2020, 2021). Dr. Gernay's research portfolio also includes fire fragility functions, probabilistic material models, and performance-based fire design and tensile membrane action in composite structures (Qureshi et al., 2020a; Gernay et al., 2018; Gernay and Khorasani, 2020).

Dr. Gernay's experimental materials characterization at elevated temperatures continues to strengthen computer simulation capabilities, especially with respect to behavior of new steels. This includes steels more commonly found in the automotive industry. Yan et al. (2020) investigated advanced high-strength steels (AHSS), taking the recent demand for high-performance steels in the major projects such One World Trade Center as a harbinger of the adoption of "next-generation" materials for economy, safety, and construction efficiency. Dual-phase (DP) and martensitic (MS) steels were tested at elevated temperatures and under steady-state (66 specimens) and transient-state conditions (22 specimens). Steady-state tests began with heating to a target temperature and then loading until fracture. Transient-state conditions involved loading to target stress levels and then heating at a constant rate. Several materials and a half a dozen different grades of steel were evaluated for strength, ductility, and stress-strain behavior under temperatures ranging from ambient to 1290°F. Figure 11 shows the test set-up and a set of AHSS specimens after the steady-state tests. "With increasing temperature, the specimens became softer and showed more ductile failures, with increasing fracture strain and clear necking phenomena" (Yan et al., 2020). Retention factors and predictive models were developed for the different materials. At elevated temperatures, the tested AHSS showed larger reductions in properties than their lower-grade counterparts. Revisions are needed to expand the applicability of current provisions to AHSS. Additional details can be found in Yan et al. (2020).

SUMMARY

Structural fire engineering researchers are making advances in the broad topic areas of behavior and design of steel and composite structures for fire, fire following earthquakes, and performance-based fire engineering. Specific topics include behavior of full-scale composite floor assemblies in fire, system behavior and onset of collapse of braced frame buildings, and machine learning for autonomous evaluation of fire resistance. Comprehensive design procedures are developed for composite core wall systems. Hybrid simulation frameworks incorporate thermal loads,

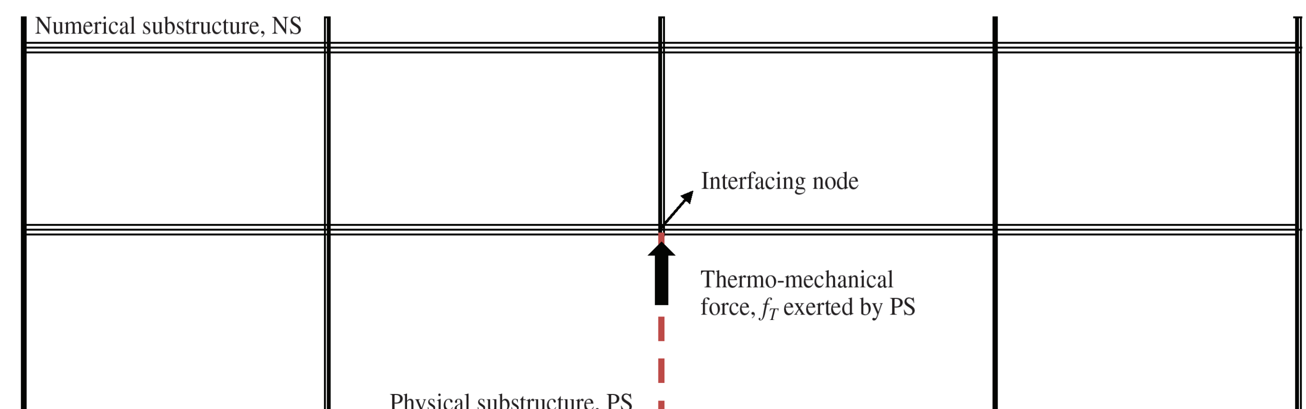


Fig. 10. Substructuring configuration for the benchmark study.

seismic damage, and realistic boundary conditions. Validated modeling techniques are being used to study fire and fire following earthquake behavior of steel frames; realistic models of composite floor systems are developed, and different seismic damage–fire scenarios are explored. Materials characterization expands modeling capabilities to new steels. The seismic performance of nonstructural components (e.g., sprinklers) is incorporated into post-earthquake fire evaluations of steel frames, and fire following earthquake is investigated at a community level.

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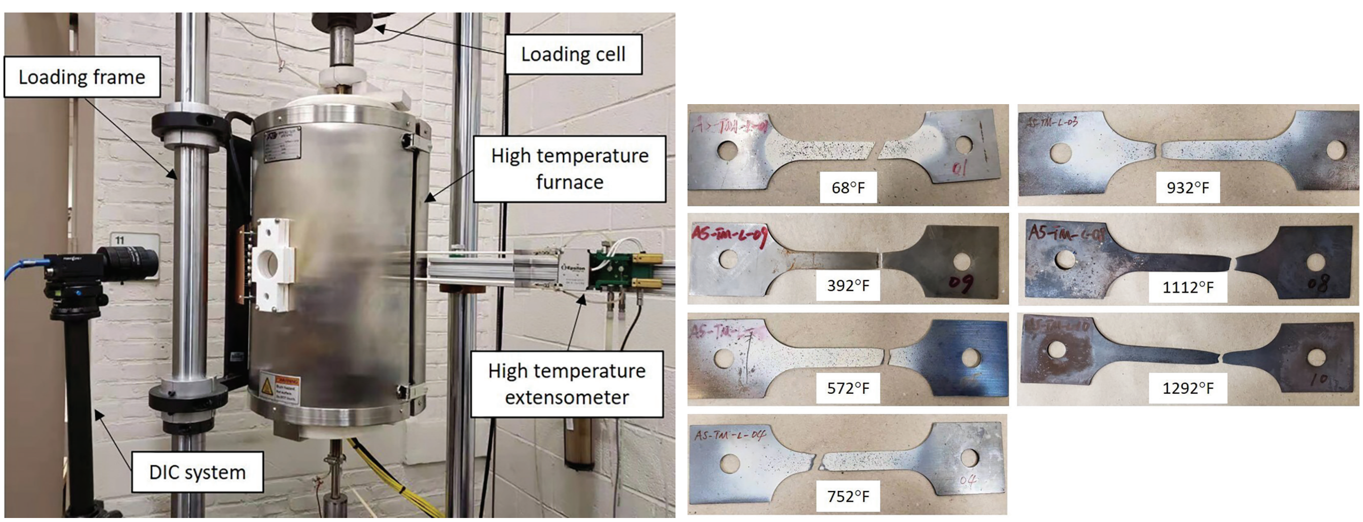

(a) (b)

Fig. 11. (a) Test set-up and (b) a set of AHSS specimens after testing.

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