Designing Reinforced Concrete Structures for Fire Performance

Research recommends the development of a standardized natural fire model for burnout-resistance design

by Tricia G. Ladely and Veronica Nehasil

Concrete's excellent performance against fire is one reason it is widely used for building design. The noncombustible nature of concrete helps to contain the fire and limit the extent of the damage. Building codes that use standard time-temperature exposure data prescribe minimum requirements to ensure structural integrity for a suitable time for occupants to evacuate. Although reinforced concrete structures typically survive fires, there is potential for collapse during the cooling phase or later. The current design, using fire resistance to standard time-temperature exposure, does not cover the integrity of a structure during or after the fire. One example of an unexpected failure is the collapse of the 13-story Delft University of Technology Faculty of Architecture Building in the Netherlands in 2008, approximately 7 hours after the start of the fire.[1]

There is a growing interest from the fire community for additional knowledge on the stability of structures exposed to natural fires. Beyond standardized fire ratings, the objective is to design a fire-resilient built environment. There is an expectation for structures to be designed for evacuation and entry by firefighters and other first responders, as well as to improve current models used to determine if a structure can be repaired or if it should be demolished.

Proposed Study

A proposal to study the behavior and design of reinforced concrete structures under natural fires was submitted to the ACI Foundation's Concrete Research Council (CRC) by Thomas Gernay, Principal Investigator (PI), and Patrick Bamonte, Co-PI, during the 2019 Annual Request for Proposals. The objective was to develop a design method for reinforced concrete structural members subjected to fire that would achieve resistance to "full burnout" under real fires. Changing or replacing current fire-resistance requirements was not a research goal. However, the data and work were intended to complement the existing fire-resistance rating. "We know quite a lot about concrete behavior under the standard fire exposure that we use to qualify fire-resistance ratings for structural concrete—but we don't know too much about what's happening when there is a real fire, for example, in an office or apartment, where the structure has been heated for a while and then the fire starts to die off," said Gernay. Achieving the goal of using fire-resistance ratings along with burnout-resistance ratings would unlock the ability to model the potential for delayed structural failure as well as provide new tools for performance-based fire design.

Definitions

Fire resistance (R): the property of a material or assembly to withstand fire or provide protection from it. As applied to elements of buildings, it is characterized by the ability to confine a fire or, when exposed to fire, to continue to perform a given structural function, or both.

Fire-resistance rating: a legal term defined in building codes, usually based on fire endurance; fire-resistance ratings are assigned by building codes for various types of construction and occupancies and are usually given in half-hour or hourly increments.

Burnout resistance: the longest fire that a structural member can survive until full burnout.

Full burnout: the end of a fire event, defined as the time at which the structure has cooled down back to ambient; this can occur hours after the gas temperature inside the building has cooled down.

Endorsement and Industry Support

Joint ACI-TMS Committee 216, Fire Resistance and Fire Protection of Structures, chaired by Kevin Mueller, endorsed the proposal for the following reasons: developing a burnout-resistance rating method for reinforced concrete members would improve the current code provisions, and it would allow better comparison between concrete and other structural building materials regarding fire safety and the resilience of the built environment. The proposal had strong industry support from the CERIB Fire Testing Centre in France, including an offer to perform full-scale fire tests to help validate theoretical calculations. Kerakoll Group in Italy also endorsed the research and confirmed that the current concern in structural fire engineering was the gap in knowledge on the behavior of concrete structures exposed to natural fires. Acquiring such knowledge would help engineers evaluate if structures can be reoccupied after a fire and whether they can be repaired.

Project Summary

Title: Behavior and Design of Concrete Structures under Natural Fire

Principal Investigator: Thomas Gernay, PhD, Assistant Professor, Johns Hopkins University

Co-Principal Investigator: Patrick Bamonte, PhD, Associate Professor, Politecnico di Milano

Endorsed by: Joint ACI-TMS Committee 216, Fire Resistance and Fire Protection of Structures; CERIB Fire Testing Centre; and Kerakoll Group

Funded by: ACI Foundation

About the Research: The current design strategy for fire resistance of concrete structures is based on standard time-temperature exposure (such as ASTM E119), which evenly increases the heat in a concrete member until failure. The objective of this research was to quantify the ability of concrete members to survive until full burnout under real fire exposures, generating a new "burnout resistance" rating. A design method was provided to evaluate this rating.

The research was divided into four main tasks: 1) experimental testing of material specimens to characterize well-identified thermal-mechanical properties under cooling; 2) selection of realistic yet simple design fire scenarios that include the decay phases; 3) numerical parametric analyses to quantify the thermomechanical response of typical concrete members under the design fire scenarios; and 4) derivation of simple design methods to assess the burnout-resistance ratings of concrete members.

The key conclusions and results are as follows:

- The thermal and mechanical properties of concrete are not reversible during cooling;
- A standardized natural fire model is necessary to support the development of a simple method for burnout-resistance design;
- Evaluating the burnout resistance of a concrete member requires performing a thermal-mechanical analysis of the member throughout the fire history. Thermal analysis alone is not enough; and
- The creation of three design methods for determining burnout resistance.

Stakeholders: Thomas Gernay (PI), Johns Hopkins University; Patrick Bamonte (Co-PI), Politecnico di Milano; Fabienne Robert, Deputy Head of CERIB Fire Testing Centre and Industry Champion for the project; Kevin Mueller, Joint ACI-TMS Committee 216, Fire Resistance and Fire Protection of Structures; Kerakoll Group; and the ACI Foundation.

Supporting Innovation

In North America, fire resistance is determined by the ASTM E119-20[2] test method, which is incorporated into various building code provisions, such as ACI/TMS-216.1-14(19), "Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies,"[3] and ASCE/SEI/SFPE 29-05, "Standard Calculation Methods for Structural Fire Protection."[4] Gathering data and developing a design method for burnout-resistance ratings would offer structures increased life safety and improved resilience to fire.

"At the material level, what we wanted to do was to measure the concrete strengths during the cooling. So, we heated the samples, cooled them down, and during cooling, we measured the strengths. We also measured the strengths on some of the samples when the concrete was back to ambient temperature," Gernay stated. This new experimental data can now be used to assess the response of concrete throughout the fire history and in the residual state. For structural members, the project confirmed the accuracy of the current design for fire resistance. Testing to determine burnout resistance is new. "There isn't really any established standard or protocol, so we looked at the literature; but to my knowledge, it was the first time [testing like this] was done," said Gernay.

Full-scale fire testing is expensive and time-consuming. Using computer-based modeling for fire performance would greatly benefit the industry. The CRC quickly noticed this benefit when the proposal and experimental plan were judged. Supporting work to develop and validate computer-based modeling techniques for heat transfer and structural behavior of reinforced concrete benefits concrete design and provides a more accurate method of comparing building systems and material-to-material comparisons.

Benefits of Collaboration

With multiple contributors, the project provided work to two academic institutions, a master's and a doctoral candidate, and also provided an opportunity for technical collaboration between North America and Europe. The ACI Foundation's requirement to have at least one ACI technical committee endorse the project along with an advisory team comprising numerous stakeholders was helpful. "We find that [projects] have much better impact and go better when there's a team discussing things. Not when researchers do [work] in a vacuum," said Gernay. "We were fortunate to have a team with deep expertise and to work in a great collaborative environment. The help and support from the Industry Champions, the ACI Foundation, and Kevin Mueller and ACI Committee 216 were instrumental in the success of this project. Also, the opportunity to conduct full-scale experiments was a great validation for our numerical work."

The researchers hope this new knowledge of a concrete structure's behavior during cooling phases will lead to future collaborations, such as incorporation into the ACI 562 code on the "Assessment, Repair, and Rehabilitation of Existing Concrete Structures." This knowledge will benefit concrete structures and could be extended to other materials. "We are talking about concrete here; however, protected steel and timber can also fail during cooling. So, in terms of research, we've been applying similar methodologies to other materials. We are working on this research axis of understanding material and structural behavior during cooling, risk of delayed collapse, and providing design tools for burnout," Gernay said.

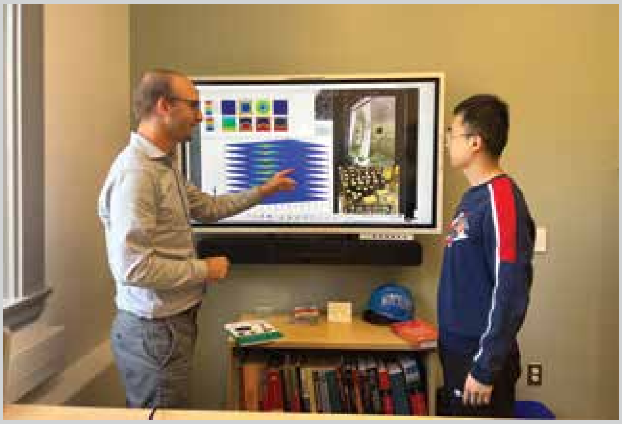
Gernay was well-equipped for this project as his award-winning doctoral thesis was on modeling concrete behavior at elevated temperatures.[5] By developing the finite element code used for the material model, he laid a strong foundation for current-day structural fire models. The data gathered in this study were added to the SAFIR computer program that models the behavior of building structures subjected to fire, thus contributing to ongoing research around the world.

Conclusions

This research generated new knowledge on the effects of cooling phases on the load-bearing capacity of concrete members in a fire. "The main takeaway, maybe we knew, but we quantified it, and we studied it, is that a structure can still collapse during the cooling phase or even in the hours thereafter," Gernay stated. Creating a standardized natural fire model to develop a "simple method" for burnout resistance will be necessary. Thermal analysis alone is not enough to determine resistance to full burnout; this requires thermal-mechanical analysis of concrete members throughout the fire history. The work contributed to the creation of a new design method for determining burnout resistance. Future work will

Supporting Valuable Research

The ACI Foundation was pleased to support the work of Gernay and Bamonte as well as the research needs of Joint ACI-TMS Committee 216. "We are extremely grateful to the ACI Foundation for this support," Gernay said. "This type of research, in close collaboration with the industry and standard technical committees, is not always easy to fund, but, we think, it can be really impactful to advance fire safety and resilience." The project aligned with CRC's objective to seek concrete research projects that further the knowledge and sustainability of concrete materials, construction, and structures in coordination with ACI technical committees. Support of the ACI Foundation by our volunteers with their time and expertise, along with our generous donors, helps us achieve our mission to invest in ideas, research, and people to create the future of the concrete industry.



PI Thomas Gernay (left) discussing a numerical model with a student

Co-PI Patrick Bamonte working at the Politecnico di Milano laboratory

study additional concrete mixtures and structural systems to further improve the accuracy of predicted behavior in natural fires as well as provide a straightforward method to evaluate the burnout resistance of concrete members. These research results will not only have a positive impact on safety for first responders but will also benefit structural engineers who design reinforced concrete structures for fire performance. In the future, designers and building owners can discuss the performance objective of a concrete structure regarding fire and design the structure to meet those performance objectives. Additional project details are available in "Behavior and Design of Concrete Structures under Natural Fire" and "Numerical Analysis of the Effects of Fire with Cooling Phase on Reinforced Concrete Members," at **www.acifoundation.org/research/research**.

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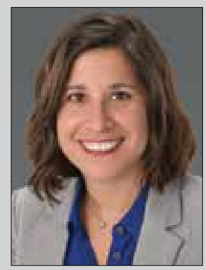
Selected for reader interest by the editors.



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