2009 BFRL Project Description

Project Title: Fire Resistance Design and Rehabilitation of Structures

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BFRL Program: Measurement Science for Structural Performance Under Multi-Hazards

Objective: To develop a performance-based approach to evaluate fire behavior of steel and concrete structures by incorporating knowledge concerning fire loads, material response, and overall structural response to elevated temperatures. The project aims to deliver validated and improved tools, guidance, and pre-standards for the fire resistance design and rehabilitation of steel and concrete structures.

Problem:

What is the problem? Fire costs U.S. economy approximately $270B/year (Ref: Hall, NFPA, 2008). Yet, current building design practice does not consider fire as a design condition for structures. Rather, required fire ratings of building components and assemblies derived from standard fire endurance tests, such as ASTM E-119, are specified in current building codes. Currently, there are no science-based, accepted measurement tools to evaluate the fire performance of entire structures, including connections, under realistic fire scenarios. The state of the art in measurement science to predict structural performance to failure under extreme loading conditions such as in an uncontrollable fire is lacking. This can lead to significant safety concerns. Thus, there is an urgent and critical need to develop and implement improved standards, methodologies, and tools that explicitly consider realistic building fire loads, both in the design of new structures and in the rehabilitation of existing structures. As a result of its recent investigation of the collapse of the WTC towers and WTC 7, NIST has recommended the development of performance-based standards and code provisions, as an alternative to current prescriptive design methods, to enable the design and rehabilitation of structures to resist real building fire conditions, and the development of tools, guidelines, and test methods necessary to evaluate the fire performance of the structure as a whole system. A key recommendation resulting from the investigation of WTC 7 was that careful consideration should be given to the possibility that certain design features (e.g., long span floor systems, connections that cannot accommodate thermal effects, etc.) that may adversely affect the performance of the structural system under fire conditions.

Why is it hard to solve? Analysis of structural systems under fire conditions involves the prediction of performance of the entire structural system at, or near, its limit state of collapse as

an uncontrolled fire is considered an extreme (though not improbable) event. Development of accurate models to predict complex structural system behavior resulting from the effects of thermal expansion and diminished mechanical properties at elevated temperatures requires the availability of robust computational models, validated against large-scale tests under real fire exposures. At the present time, experimental data on the behavior of connections, members, and systems under realistic building fire conditions are lacking. In addition, detailed modeling of a complete structural system to failure imposes large computational demands. Reduced models of key structural components such as connections that capture the predominant behaviors and failure modes at elevated temperatures are needed for cost effective assessment of structural response to fire and resistance to collapse in an uncontrolled fire. Development and validation of such models pose a challenge.

How is it solved today, and by whom? Currently, the practice for assuring the fire resistance of structures is based on a Standard Fire Resistance Test (ASTM E 119) that has changed little since it was introduced in 1917. This standard does not account for realistic fires, actual loading, or structural system performance. The uses of such prescriptive practices, which are inconsistent with respect to risk, stifle innovation and increase the eventual cost. The move toward use of calculation methods (not really the performance-based design approach) is presently being initiated by a few industry groups (e.g., ICC, NFPA, SFPE, AISC, ACI, AISI, ASCE etc.) and universities (e.g., Purdue, Princeton, Lehigh, Michigan State University, Stanford). ICC and NFPA have recently identified 8 fire scenarios and introduced performance-based design approaches. Organizations such as AISC, ACI, and ASCE are now taking active positions in developing performance-based approaches.

Why NIST? This project supports the BFRL mission to promote U.S. innovation and industrial competitiveness by anticipating and meeting the measurement science, standards, and technology needs of the U.S. building and fire safety industries in ways that enhance economic security and improve the quality of life. Furthermore, this project is part of the BFRL Program addressing Measurement Science for Structural Performance Under Extreme Loads and supports BFRL core competency – performance, reliability, and resilience of structures and communities under extreme loads. Further, NIST has gained significant experience in structural response to fire (both analytical and experimental), through the investigation of the fire-induced collapse of WTC 1, WTC 2, and WTC 7, and through interactions between the structures and fire communities.

Approach:

What is the new technical idea? The technical approach calls for the development of a *unified* performance-based methodology to evaluate the fire behavior of building-type structures by incorporating knowledge concerning fire load, material response, and overall structural response to elevated temperatures. This approach will, for the first time, consider fire as a design condition in the building design process. The building layout (compartmentation, geometry), windows (ventilation), materials of construction, passive and active fire protection systems, and amount and location of combustibles will be included in the proposed approach. Recent technical advances have provided the ability to (1) predict the development and propagation of building fires, influenced by the building characteristics noted above, using application of fire science, and (2) predict structural system performance at elevated temperatures. Additionally,

this project will take a *risk and reliability-based approach* to the prediction and specification of the fire hazard, structural fire loads, the resulting reduction of structural resistance, and calculation of structural response. Such a comprehensive model-based approach to structural fire safety enables sensitivity studies to be conducted to establish the most important factors affecting the fire performance of the entire structure, to understand the behavior of different types of structural systems exposed to the same fire, and to evaluate the effectiveness of alternate rehabilitation, design, and fire protection strategies.

Why can we succeed now? The recent WTC (towers and 7) investigation focused national attention on the importance of understanding structural performance in fire and identified gaps and shortcomings in current prescriptive approach. Performance-based approaches have been successfully applied and adopted in seismic design. There is now strong demand from the private sector to fill the science and technology gaps that exist in our ability to predict the realistic behavior of structures under fire. In recent years, analytical capabilities have advanced considerably in areas such as Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), and parallel processing. Current design practice is more sophisticated today and hence the proposed approach, which relies on these computational capabilities, has good prospects for success.

What is the research plan? Recommendations from a national workshop, organized by NIST and held in October 2002, formed the basis for a coordinated national plan for problem-focused research on structural fire resistance design and rehabilitation of structures. NIST's role will be to develop a unified performance-based methodology to evaluate the fire behavior of building structures by incorporating knowledge concerning fire load, material response, and overall structural response to elevated temperatures. The methodology will require the establishment of specific performance objectives and metrics, the development of acceptance criteria, the development of validated predictive tools, the conduct (as necessary) of full- and reduced-scale experiments of structural components and systems in realistic fire conditions, and the development of technical guidance for the implementation of a comprehensive fire safety design approach.

Specifically the project plans to deliver the following products:

1. "Best Practices Guidance" document. This document aims to integrate information on current practice in fire resistance engineering with current best knowledge in fire risk assessment and characterization, material properties at elevated temperatures, and thermal and structural response calculation methods.

2. Simplified and comprehensive design approaches and the framework for a decision tool to select the level of design approach.

3. Report on performance of structural systems in fire, including factors that affect building performance, comparisons of system and component approaches, and modified design approaches based on analyses of the structural performance of selected typical building types in realistic fires.

4. Design guidelines at two levels e.g., simplified procedure for typical designs and comprehensive procedure for specialized designs.

5. Rehabilitation guidance including assessment tools and design guidelines involving both simplified and comprehensive procedures.
6. Analytical tools for predicting structural fire performance at two levels e.g., simplified tools for typical design issues and comprehensive analysis tools for more complex or unusual designs.
7. Pre-standards for steel and concrete buildings for design/rehabilitation tools and practices.

The project will be based on a combination of existing knowledge, the results of analytical sensitivity studies, and laboratory and field measurements. As needed, scaled experiments will be performed to measure the performance of selected structural components and connections, to develop material constitutive properties, and to characterize the performance of fire-protective coatings when exposed to fire.

Recent Results:

- WTC 7: Modeled steel and composite concrete structure, including connection behavior, under fire effects. Constructed models of multi-floor structure as well as substructure to determine member and system performance under fire exposure through collapse. Used ANSYS, ABAQUS, and LS-DYNA as appropriate to conduct the various analyses (2007, 2008).
- WTC 7: Completed investigative work to identify probable collapse sequence. Completed the documentation of the WTC 7 investigation (NIST NCSTAR 1-9, Chapters 1, 2, 8, 12, 13, 14 and 15) (2008). (Output)
- Completed draft "Best Practices Guidance" document for Structural Fire Resistance Design of Concrete and Steel Buildings (Product 1) (2008). (Output)
- Completed pilot study of 3-D visualization of computer results for fire dynamics simulation, transient heat transfer, and nonlinear structural response (2008).
- Provided technical support for a code change proposal (proposed by the Ad-Hoc Committee on Terrorism Resistant Buildings) recommending building burnout without collapse (2007). (Output)
- Submitted recommended changes to ASTM E119 standard through ASTM Committee E 05 (2007 and 2008). (Output)
- Established partnership with Michigan State University (2007) and the Indian Institute of Technology, Delhi (2008) to augment the research program on fire-structure interaction.
- Initiated modeling studies of steel and concrete structures (2007).

Standards and Codes: The following expected project outcomes when accomplished in FY 2013, will relate directly to standards and codes:

- Pre-standard for evaluating structural fire resistance of existing buildings.

- Pre-standard for performance-based design of structures for fire.
- Rehabilitation guidelines for performance-based design of existing structures for fire.
- Pre-standard for performance-based rehabilitation of structures for fire.

BFRL staff participation in the standards and codes committees directly related to the scope of the project includes:

- John Gross
  - AISC Committee on Specifications (TC3 - Loads, Analysis and Systems, TC 8 – Structural Design for Fire Conditions).
  - ISO TC92/SC4 – Fire Safety/Fire Safety Engineering (ISO TC92/SC4/WG12)
- Therese McAllister
  - ASCE 7 Standard Committee (Subcommittees on General Requirements for Structural Stability and on Load Combinations).