Introducing a new structural-fire testing capability at NIST and large-scale structural-fire experiments

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National Fire Research Laboratory

Dedicated to research in fire science and safety for over 100 years, the National Institute of Standards and Technology (NIST) further expanded its fire testing capabilities to enable large-scale structural-fire experimentation. The National Fire Research Laboratory (NFRL), located on NIST campus in Gaithersburg, Maryland, offers approximately 3000 m^2 of laboratory space after completion of renovation and expansion in 2015. NIST initially built a 1000 m^2 laboratory in 1973 and added an Emissions Control System serving three exhaust hoods (1 MW, 3 MW, and 10 MW) for fire research. The recent construction of 2000 m^2 of new laboratory space added a heavily reinforced, post-tensioned concrete strong floor measuring 18.3 m by 27.4 m, and a strong wall measuring 9.1 m by 18.3 m. The existing (ECS) was expanded allowing for a test fire up to 20 MW using natural gas, liquid hydrocarbons, wood cribs, or actual building contents. These newly added features enable NIST to safely support and mechanically load structural specimens, ranging in size from small components to a two-story steel, concrete, or timber building with 2 bays by 3 bays in plan, and expose the structural test specimen to realistic fire conditions.

Figure 1 National Fire Research Laboratory at NIST

In addition, the NFRL has developed infrastructure not only to support high-quality measurements, but also to promote a safe environment for conducting experiments. A wide range of high throughput data acquisition tools are available to view, record and stream measurement results in real time with various

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scan rates including high definition video data. Oxygen depletion calorimetry can be used to measure the heat release rate of fires ranging from 20 kW to 20000 kW. Configurable hydraulic loading systems can simulate realistic structural loads on a test structure during a fire test. Other measurement systems support a wide range of data types, including but not limited to temperature, heat flux, strain, force and displacement, with well quantified uncertainty necessary for conducting structural-fire tests. To quantify the strains and displacements under open-flame fires, the development of various measurement techniques, including blue spectrum lasers, Digital Image Correlation (DIC), and fiber optic sensors, is also ongoing in collaboration with academic researchers. The NFRL is fully equipped with passive and active fire protection systems, including manual and automatic control of fire monitor and deluge systems. More detailed information regarding the measurement capabilities and technical specifications of the NFRL can be found in Bundy et al. (2016) and NFRL homepage (https://www.nist.gov/el/fire-research-division-73300/national-fire-research-laboratory-73306).

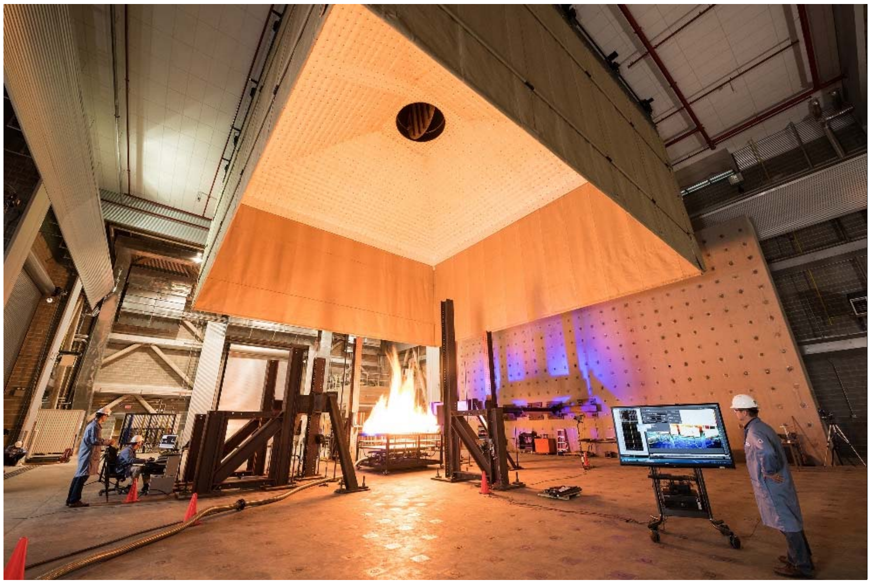

Figure 2 Newly expanded structural-fire test bay

NFRL Commissioning Project

To deliver a fully operational NFRL ready for real-scale structural-fire tests, NIST researchers recently completed open flame fire tests on 6.17 m long W16×26 structural steel beams. The main objective was to test, or shakedown, the newly-added structural-fire testing and measurement capabilities to insure the safe and effective execution of experiments. A secondary objective was to generate data that could be used for validation of analytical models (e.g., computational fluid dynamics models and finite-element models).

The test setup was erected under the 20 MW exhaust hood in the new high bay (Figure 3). The bases of supporting columns were fixed into strong floor by tensioning high-strength steel anchor rods. The W16x26 beam specimens were attached to the columns using one of two beam-to-column connection types. A purpose-built seated connection was used for simulating simply-supported boundary conditions so that rotational and axial displacements of the beam ends were unrestrained. A second type was an all-bolted double-angle connection, one of the common shear connection types used in steel frame buildings, that axially restrained thermal expansion at the beam ends.

During the test, the specimen midspan was exposed to an open flame fire (with the maximum heat release rate of 1.5 MW) using a 1 square-meter natural gas burner and, simultaneously, loaded using two hollow structural sections (HSS) loading beams bearing on the top flange of the specimen. The distance from the burner to the bottom surface of the beam was 1.1 meter. The ends of HSS loading beams were connected to actuators, mounted underneath the strong floor via high-strength steel rods (Figure 3). The HSS loading beams were protected from heating due to the fire by flowing water through them. The sequences and magnitudes of applied forces and fire were controlled using the data acquisition system.

Figure 3 NFRL commissioning test setup and structural loading system

Under combined structural loading and open flame fire conditions, the behavior of the W16x26 steel beam was more complicated than under room temperature conditions (Figure 4). The open flame fire heated the beam unevenly and the non-uniform temperature distribution resulted in a shift of the neutral axis since steel loses stiffness and strength when heated. At the same time, the beam exhibited thermal bowing due to the non-uniform temperature distribution. The combination of thermally induced effects with the applied structural loads can produce an unexpected failure mode. This makes the control of the mechanical loading at the point of instability or localized failure challenging.

The presence of restraint at beam ends, provided by structural connections to the framing members, can adversely affect the fire resistance of the beam specimen. The test results showed that the fire resistance of the steel beam specimen with double-angle bolted connections reached only 80 % of that of the unrestrained steel beam. As the temperature increased in the restrained steel beam, the restraint of thermal expansion introduced an axial force in the beam. The beam, originally designed for bending moment only at room temperature, was subjected to an axial force and the additional moment resulting from thermal bowing, called the second order effect. The magnitude of this thermally-induced force and moment will vary depending upon the stiffness of adjoined structures.

Figure 4 Failure of restrained steel beam exposed to localized fire

Upcoming Tests on Composite Floor Systems

In its failure investigation of the World Trade Center (WTC) buildings (NIST, 2012) , NIST showed that the collapse of a 47-story steel frame building, WTC 7, was initiated by cascading failure of composite floor systems on a number of floors. Uncontrolled (building contents) fires caused thermal expansion of floor beams which pushed primary girders off from their seated connections. With a loss of lateral support, some critical gravity columns buckled which eventually led to collapse of the entire building. Researchers have presumed a number of important factors that could have contributed to this fire-induced collapse, including long floor beam spans, asymmetrical framing of floor beams, non-composite girders, and connection type, especially the use of seated connections. As mentioned in Almand (2013), there are still “the many unanswered questions about composite floor system performance”. Hence, NIST has initiated a multi-year fire experimental project motivated by the need to generate experimental results which would be of “great practical import and a major impact on design methods” (Almand, 2013) for composite floor system under fire conditions.

Through several meetings and surveys with stakeholders from fire, structural engineering and standards communities, the specifics of the test frame configuration, structural test fires, and details of the test matrix were proposed (Manzello and Suzuki, 2015). The proposed test series will consist of two main parts: 12.8-m long steel-concrete composite beam tests and steel-concrete composite floor tests. Detailed structural design of test structures was performed in accordance with US National Specifications including ANSI/AISC 360 Specification for Structural Steel Buildings, ASCE 7 Standard for Minimum Design Loads for Buildings and Other Structures, and the International Building Code.

Figure 5 shows the test setup for composite beam tests. A total of four steel-concrete composite floor beams will be tested under a structurally significant fire. Three purpose-built natural gas burners each with a rating of 1.3 MW will be used to produce a fire to achieve the upper layer gas temperature of 1000 °C. A fire barrier wall will confine the fire below the test beam. Ventilation for inlet air and outgoing combustion products will be provided through 3 m^2 of open area distributed along the bottom portion of the wall. The composite beam specimens will be attached to the support columns with one of two connection types: a double-angle connection and a single-plate connection in accordance with the AISC steel construction manual. A uniform floor load, which achieves approximately 50 % of room-temperature capacity, will be simulated by applying six equally-spaced point loads along the centerline of the floor beam. The loads will be applied by three HSS beams, hydraulically loaded at their ends and controlled to maintain a constant load and to remain level throughout the test duration.

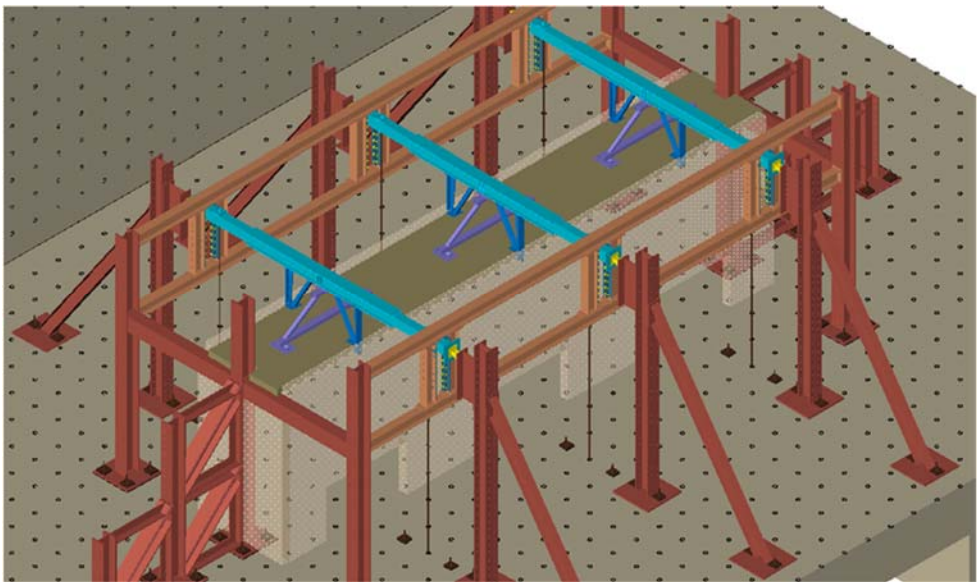

Figure 5 Schematic of long-span composite beam test setup

The experimental tests on real-scale floor systems will be followed by the completion of the long span beam tests mentioned above. Test variables being considered include: (1) fire conditions in terms of severity, duration and location, (2) fire protection scheme, (3) framing of floor beams, (4) geometry of floor plate, (5) restraints provided by adjacent bays and connections, and (6) multi-floor fires. The fire(s) designed for the series of experiments will be confined to the test bay, and the thermal load will simulate a fire in an over-loaded office setting, up to and beyond a flashover condition, followed by cool-down.

The test frame suggested for study is a two-story, two bays by three bays gravity frame with each story height equal to 3.3 m. The test bay (dark grey area shown in Figure 6) will be 6.1 m by 9.1 m. A plan showing the extent of the strong floor and strong wall, the footprint of the hood, and the plan view of the test structure is shown in Figure 6. Note that the steel frame illustrates the test bay configured as a corner bay (see dashed line in Figure 6). The test bay will be loaded hydraulically to simulate the gravity service load condition. For this series of composite floor tests, the columns will not play a role in floor failure; rather, the columns will be protected, so that they provide a reliable load path.

Various conventional and advanced measurement tools (thermal imaging, fiber optics technology, and digital image correlation) will be used to quantify the fire performance of each test structure. The measurement includes (1) the characteristics of test fire(s) using the heat release rate, gas temperatures, and radiation, (2) thermal response (temperatures and heat fluxes) of composite floor systems and fire barrier walls, and (3) structural responses (displacements, forces, and strains). The uncertainty analysis will be conducted to systematically measure and reduce the uncertainty in the fire, thermal and structural measurements carried out in this project.

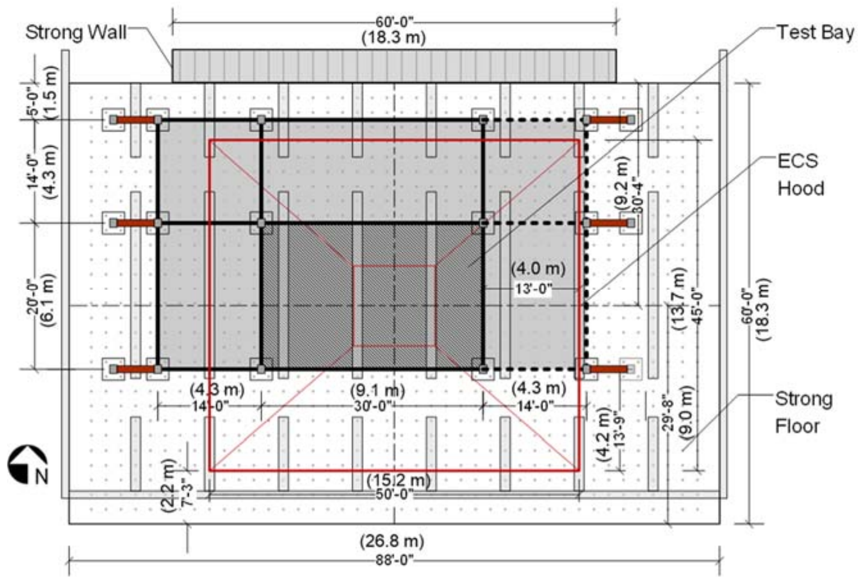

Figure 6 General plan view of test frame on the strong floor

Expected Outcomes

The tests planned at the NFRL represent a major advance in real-scale testing of steel-concrete composite floor systems under fire and structural loading. The proposed test plan captures a broad spectrum of geometric, design, and loading parameters relevant to modern steel construction practice. The temperature and structural response data, through heating and cooling phases, will be extremely valuable for validation of physics-based models for prediction of structural performance under fire. As such, this research will provide important steps forward for performance-based standards for fire resistant design of steel buildings.

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