BRIDGES: THE NEXT GENERATION OF EXPERIMENTAL RESEARCH IN STRUCTURAL FIRES

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Abstract

Bridge fires, while not common, can have an enormous economic impact and can adversely affect the community served by the bridge, diminishing community resilience. Regulatory approaches that have been successful for buildings may not be applicable to bridges. And, while provisions addressing the protection of the structural elements of a bridge from high temperatures exist, little guidance is available to the bridge engineer to apply such provisions. This paper looks at these issues as well as a few examples of recent bridge fires, and attempts to make the case for the need to conduct large-scale experiments on bridges and bridge components under realistic fire conditions. Such tests can provide the technical basis for a performance-based approach to the design of bridges to resist fires. A new structural fire test facility, under construction at the National Institute of Standards and Technology, will enable the evaluation of the performance of large-scale bridge structures subjected to realistic fires. The capabilities of the National Fire Research Laboratory are presented along with its technical specifications.

Introduction

"Among the public safeguards that have been found necessary where buildings are built in proximity to each other are those pertaining to fire. Such regulations are founded on the long community experience that has been had with fires" [Ingberg, 1929]. Ingberg's comment addresses, of course, the objectives of minimizing life and property loss due to building fires. If, however, one were to extend his tenet to include transportation systems, one would need to add the objectives of minimizing economic impact and increasing community resilience. Highways are critical lifeline systems enabling commerce and the transportation of people and goods within and among communities. Failure of a single bridge can have a significant economic impact in terms of direct costs and lost productivity due to traffic disruptions and detours.

Regulations intended to reduce the risk of damage or collapse and minimize economic impact by protecting bridge structures from high-temperature exposure do exist [NFPA, 2011], but guidance in their application is limited. A performance-based design

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approach for fire holds promise for bridge structures, but the technical basis for predicting analytically the performance of a bridge structure exposed to fire, including complex nonlinear behavior, is lacking. To date, there have been no fire tests on the performance of bridge structures to provide the required technical basis and analytical model validation.

Recent Bridge Fires

Garlock *et al.* [2011] have shown, through a literature review and case studies, that bridge fires can lead to significant structural damage, partial or complete collapse, as well as costly detours in traffic flow. Garlock *et al.* go on to report on the frequency of bridge fires and notes that a 2008 New York Department of Transportation national survey found that, of the 1746 bridge failures reported (the majority resulting from flooding or collision), 52 were due to fire and 19 due to earthquake; in other words, bridges were almost three times more likely to collapse due to fire than to earthquakes.

In this paper two recent examples which led to significant cost of repair and disruption are highlighted: the McArthur Maze fire which involved the collapse of a section of an overpass onto the roadway below, and the fire on the Mezcala (Mexico) cable-stayed bridge that involved the failure of one stay and damage to a second.

McArthur Maze Fire – Steel Plate Girder Failure

Early on the morning of April 29, 2007, a tanker truck carrying nearly 3400 L (9000 gallons) of gasoline overturned on the I-80/880 interchange in Oakland, California and burst into flames [Bulwa and Firmrite, 2007]. The accident occurred at 3:41 A.M. and just over 20 minutes later, at 4:02 A.M., the elevated roadway collapsed (see Figure 1). "As the fire progressed, the bolted connections in the collapsed girder began to weaken due to heat and were placed under increasing load from the weakening of the remainder of the bridge" [Kodur, *et al.*, 2010].

Figure 1 - Collapse of the McArthur Overpass
Photograph by Robert Campbell (used with permission)

Mezcala Bridge Fire – Stay Cable Failure

In March of 2007, a traffic accident involving two school buses and a truck transporting coconuts caused a fire on the Mezcala Bridge, a cable-stayed bridge in Mexico, that resulted in failure of one stay and damage to a second [Zoli and Steinhouse, 2007]. It is reported that flammability of the exterior corrosion protection system on the bridge cables added to the thermal loading on the cables.

Structural Fire Resistance Regulations – A Historical Perspective

A historical look at the development of regulatory approaches to fire resistance of buildings provides the context for discussion regarding the challenges faced in determining the fire resistance of bridges.

Building Fires

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" [Lewis, 1994]. Thus, regulations to limit the spread of fire dates back over 200 years.

The U.S. grew rapidly with population centers in Philadelphia, New York, Boston, Chicago and San Francisco. Along with this growth came devastating fires that affected all of these burgeoning cities. The Great Chicago Fire of 1871, in which over 17,000 buildings were destroyed, marked a significant turning point in building practice whereby the fire resistance of a building began to be considered explicitly. "Although the early knowledge of the requirements for fire protection resulted from a study of the behavior of structures in fires and from examination of fire-damaged buildings, the development of skeleton-type construction made the necessity for fire endurance testing apparent" [Shoub, 1961]. New York City was the first American city to introduce a standard fire test method in the 1899 New York Building Code [Babrauskas and Williamson, 1978]. But it was the Great Baltimore Fire of 1904 that prompted the American Society for Testing and Materials (ASTM) to organize a national effort to standardize fire resistance testing; "A Standard Test for Fire-Proof Floor Construction" was issued just three years later in 1907. ASTM continued its work and in 1917 Committee C-5 issued a report that proposed a standard test method notable for two aspects, "the provision that structures be classified by their attained fire resistance" [Shoub, 1961], and the notion that "a furnace does not heat up instantaneously; for reproducible results, this initial heating should be quantified" [Babrauskas and Williamson, 1978]. The furnace time-temperature curve introduced by Committee C-5 remains unchanged to this day in the ASTM Standard E 119, *Standard Test Methods for Fire Tests of Building Construction and Materials* [ASTM, 2011], the standard commonly used in the United States for establishing fire resistance ratings.

It was Simon Ingberg of the National Bureau of Standards, now the National Institute of Standards and Technology(NIST), who introduced the fire "severity" concept suggesting that "all fires of the same severity have approximately the same effect on a structure" [Babrauskas and Williamson, 1978]. "Ingberg's work on fire severity and fire resistance was adopted by national standards and model building codes…and his classification of building types [fireproof, incombustible, exterior-protected and wood] remains the basis for requirements for fire resistance of building components…" [Evans *et al.*, 2001]. Fire resistance ratings for buildings, as established by ASTM E 119, are intended to ensure the that a fire will not spread beyond the compartment of origin.

One significant addition to building codes in the United States has been the provision that "an approved automatic sprinkler system…shall be allowed to be substituted for 1-hour fire-resistance-rated construction" [ICC, 2006]. This provision, known as the "sprinkler tradeoff" provision, recognizes the effectiveness of automatic sprinklers in suppressing a fire in its early stages, thereby preventing the fire from becoming a threat to the building or its occupants.

Bridge Fires

Consideration for the need for fire protection for bridges is more recent. And, as noted in the introduction, the impact of a bridge fire extends beyond life safety and replacement cost to the broader impact on the community served by the bridge.

The National Fire Protection Association (NFPA) *Standard for Road Tunnels, Bridges, and other Limited Access Highways* [NFPA, 2011] contains provisions for the consideration of fire. Quoting directly from Chapter 6:

> **6.3.1** …all primary structural elements shall be protected in accordance with this standard in order to:
> (1) Maintain life safety
> (2) Mitigate structural damage and prevent progressive structural collapse
> (3) Minimize economic impact
>
> **6.3.2** Critical structural members shall be protected from collision and high temperature exposure that can result in dangerous weakening or complete collapse of the bridge or elevated highway.

However, as pointed out by Garlock *et al.* [2011], "…current bridge design codes and standards offer limited information concerning the fire hazard."

A Case for Structural Fire Testing of Bridges

From the above discussion, one can identify three regulatory approaches to fire resistance for buildings: (1) construction restrictions (e.g., zoning and occupancy restrictions), (2) limiting the spread of fire beyond the compartment of origin (e.g., fire resistance rating requirements), and (3) active fire suppression (e.g., sprinklers). It is not at all clear, however, that any of these regulatory strategies would be effective in reducing the hazard from fire for bridges and elevated highway structures.

Additionally, results of tests on building components and assemblies are generally not applicable to bridge structures. For example, building fires are generally considered to be confined to a compartment, while bridges are likely to be exposed to plume fires. The combustible materials in a building (e.g., wood, paper, upholstery) are likely to have different burning characteristics than those affecting a bridge which may involve petroleum products (hydrocarbons). Finally, structural elements of a building are often different from elements found in bridges (e.g., steel plate girders or box sections, pre-stressed concrete beams, suspension cables, etc.). No systematic study has been conducted to date to quantify the effects of damaging hydrocarbon pool fires on the wide variety of bridge forms in use today. Such a study is required to fully understand the behavior and modes of failure exhibited by the various structural forms when exposed to extreme temperatures.

By treating fire as a design condition in the design and analysis of bridges, one can implement a performance-based design approach. Performance-based design generally involves the calculation of the structural response of a bridge to the effects of a postulated fire, developed through consideration of possible fire scenarios. One of the main obstacles for moving towards performance-based fire safety design is the lack of knowledge about bridge fire response. Numerical models are needed as well as design tools, but these models and tools need to be validated with experiments since the bridge response under high thermal loads is complex and nonlinear.

To conduct such experiments requires a facility with the capability to:

- Conduct tests on real-scale structural systems and components
- Apply controlled loads to test structures to simulate true service conditions
- Create realistic fires that grow, spread and decay
- Characterize the fires in real time
- Measure the response of structural systems and components to the point of incipient collapse.

Until now, no laboratory in the world has possessed this combination of capabilities.

The National Fire Research Laboratory (NFRL)

The National Institute of Standards and Technology (NIST) is adding a new, unique facility that will serve as a center of excellence for fire performance of structures ranging in size from small components to large systems (see Figure 2). The laboratory, called the National Fire Research Laboratory (NFRL), will be led, managed and operated as a collaborative facility through a public-private partnership between NIST and industry, academia, and other government agencies.

The work of the laboratory will be focused on the NIST Engineering Laboratory mission: to promote US innovation and industrial competitiveness in areas of national priority by anticipating and meeting the measurement science and standards needs for technology-intensive manufacturing and construction in ways that enhance economic prosperity and improve the quality of life.

Figure 2 - Rendering of the new NIST facility for large-scale structural fire research

Scientists and engineers from industry, academia, and government agencies will work side-by-side with NIST researchers to address significant technical problems and fill critical knowledge gaps, and international scientists and engineers will be welcome to partner with NIST in areas of mutual interest. Projects may be funded by industry and government on a cost-shared basis.

The additional capabilities will allow NIST to:

- Test the performance of large-scale structures, including bridge components, subjected to realistic fires and structural loading under 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 fire resistance performance of structures.
- Enable performance-based standards for fire resistance design of structures and foster innovations in design and construction.

The NFRL is adding 1990 m^2 (21,400 sq ft) laboratory space to its existing Large Fire Laboratory (Building 205) (see Figure 3) and installing an environmental control system (ECS) to supplement the existing ECS to accommodate fires up to 20 MW heat release rate.

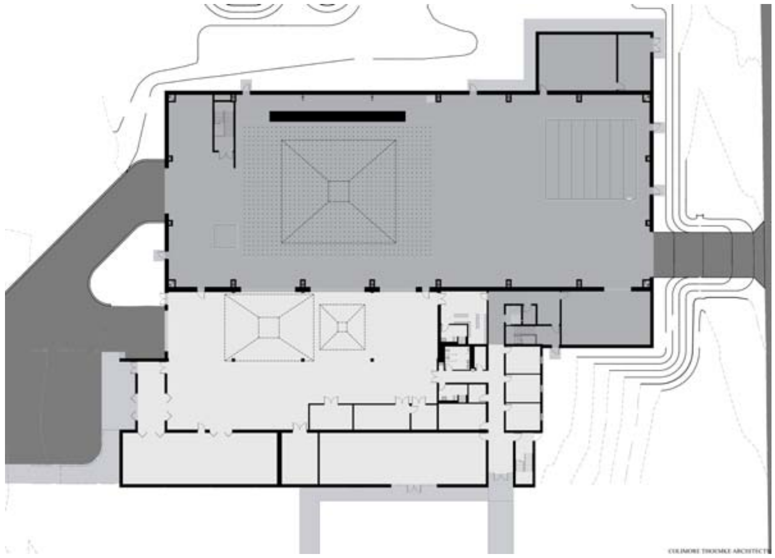

Figure 3 -Floor Plan of the National Fire Research Laboratory Expansion

The new laboratory space will accommodate structural systems or components 9 m (30 ft) high and roughly 12 m (40 ft) by 18 m (60 ft) in plan. Gravity loading will be applied using hydraulic actuators or fixed loads. Fully involved building fires, fueled by gas or liquid fuel, wood cribs, or actual building contents, will be employed to simulate building fire conditions. Characteristics of the fire (heat release rate) will be measured accurately using calorimetry.

The test area will consist of a 18.3 m × 27.4 m (60 ft × 90 ft) strong floor with anchor points on a 0.61 m × 0.61 m (2 ft × 2 ft) grid. The floor will be supported on a nine-cell reinforced concrete box girder providing a basement below the strong floor with a ceiling height of 2.7 m (9 ft). To one side of the strong floor will be a 9.1 m (30 ft) high × 18.3 m (60 ft) wide concrete strong wall with anchor points on the same grid as the strong floor. The strong wall will act to stabilize a test specimen to prevent uncontrolled failure, provide lateral restraint, or to laterally load a structure to simulate earthquake damage. A 13.7 m × 15.2 m (45 ft × 50 ft) hood, centered above the strong floor, will capture and remove smoke and hot gases.

The size of the test area was selected to enable the testing of large-scale structural systems or components; including bridge girders, cable systems, piers, etc.; under realistic hydrocarbon fires and controlled loading comprised of self-weight and vehicles. Technical specifications for the NFRL expansion are given in Appendix A.

Summary

In summary, the following points have been made:

- Fire represents a significant hazard in bridges
- Consequences of a bridge fire include:
    - structural damage, partial or complete collapse necessitating repair or replacement
    - disruption to traffic flow during repair or replacement
    - economic loss and adverse impact on community resilience
- The 100-plus year history of fire resistance regulations for building structures offers little guidance for bridge and transportation structures
- Current bridge design codes and standards offer limited information concerning the fire hazard
- Fire hazard can be overcome by addressing fire explicitly in the design and analysis of bridges
- Identification of failure modes and validation of advanced numerical models requires well controlled full-scale experiments
- The National Institute of Standards and Technology's new, unique fire/structure test facility, the National Fire Research Laboratory, will enable the evaluation of the performance of large-scale bridge components subjected to realistic fires.

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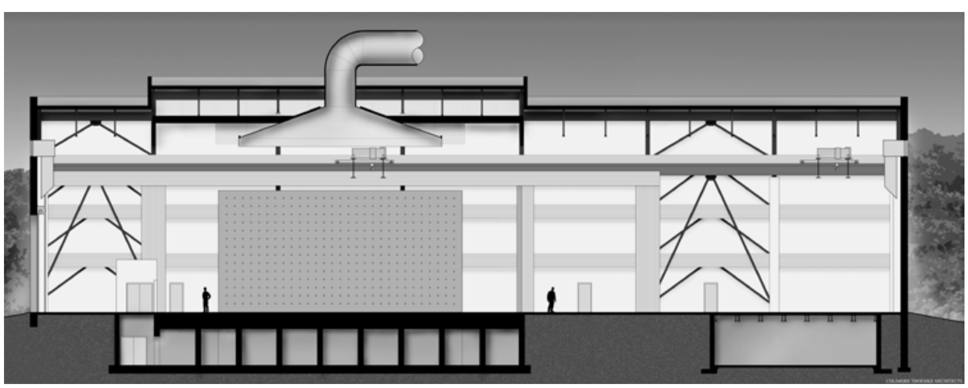
Appendix A - Technical Specifications



Strong Floor

- 18.3 m × 27.4 m (60 ft × 90 ft) post-tensioned floor with full basement
- 9 cell RC box girder with 406 mm (16 in) thick shear walls at 3.0 m (10 ft) o.c.
- Basement ceiling height: 2.7 m (9 ft)

- Floor thickness: 1.07 m (3 ft-6 in) with 152 mm (6 in) sacrificial top surface
- 1218 anchor points on 0.61 m × 0.61 m (2 ft × 2 ft) grid (sleeves or anchors)
- Load per anchor point: 445 kN (100 kip) up or down
- Shear capacity per anchor point: 222 kN (50 kip) (at top of slab)
- Moment capacity per anchor point: 136 kN·m (100 ft kip) (at c.g. of strong floor)

Strong Wall
- 9.1 m high × 18.3 m wide (30 ft high × 60 ft wide)
- 1.2 m (4 ft) deep post-tensioned concrete wall
- 420 anchor points on 0.61 × 0.61 m (2 ft × 2 ft) grid
- Horizontal load: 146 kN/m (10 kip/ft) at 9.14 m (30 ft)

ECS Hood and Pollution Control System
- 13.7 m × 15.2 m (45 ft × 50 ft) steel hood
- Height above floor: 12.5 m (41 ft) (excluding skirts)
- ECS maximum sustained capacity: 20 MW
- ECS maximum flow rate: 5100 m^3/min (180,000 ft^3/min)

Cranes
- Two 20-ton bridge cranes (sharing single set of rails)
- Height of rails above floor: 11.2 m (36 ft-8 in)
- Clearance, bottom of bridge-to-floor: 9.8 m (32 ft)

Configurable Hydraulic Loading System
- Hydraulic Power Unit 340 L/min (90 gal/min)
- Actuators (double acting) 762 mm (30 in) stroke w/ servo valve, load cell and swivels
  - Eight 240 kN (55 kip) Tension, 365 kN (80 kip) Compression
  - Two 445 kN (100 kip) Tension, 650 kN (145 kip) Compression
  - Two 956 kN (215 kip) Tension, 1470 kN (330 kip) Compression
- Four hydraulic service manifolds
- Controller