Concepts for High Temperature Furnace Testing of Scaled Building Members and Connections under Axial Load

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Abstract:

Fire can have one of the most damaging and harmful exposure conditions on building components throughout their life-cycle. Recent developments in building materials and designs, such as new architectural trends in sustainable, green, and energy-efficient focused materials and components, have introduced new fire scenarios. Lack of adequate understanding of the behavior of new and emerging materials under fire and high temperature conditions can lead to unpredicted property damage or injury of building occupants. One objective of this paper is to review documented full-scale fire tests on building components and identify potential constraints and conditions that will yield suitable alternative testing options at the small scale. Reduced cost and time and safety considerations make fire testing of small-scale specimens a desired alternative to full-scale fire testing. In the current study, the use of a scaled-down model and full-scale, but small-size connections are considered for small-scale electric lab furnace as alternatives to conventional, full-scale fire testing. This elevated temperature testing approach allows developing a better understanding of the behavior of certain materials and connections when exposed to high temperature under structural load by more convenient and affordable means.

Keywords: *Scale-down model; experimental fire test; lab furnace; building components; envelope and connections; high temperature testing; fire safety.*

1. Introduction

Governing building fire codes generally address design and specification of fire safe related features focused on smoke detection and fire alarm installations in new buildings. However, new architectural trends focused on sustainable, green, and energy-efficient building systems and facilities may in many instances increase the risk of fire incidents because of the modern materials and building components underpinning these design trends. Fires in residential buildings (e.g., single-family dwellings and multi-family apartment buildings) remain a serious concern for governmental agencies (Mierley and Baker 1983, Istre et al. 2001, Karter 2013). This can be seen in an official report from The China Fire Services where they indicated that in a populous society, 39.7% of fire incidents occurred in residential buildings (Yung and Beck 1995, Wang and Fan 1997, Zhong et al. 2004, Xin and Huang 2013, Xin and Huang 2014).

In the past decade, developments in innovative building materials and components desirable for green and sustainable properties have been on the rise. As a result, an urgent need exists for better understanding of the behavior of these new materials and components under high temperature and direct fire exposure. One of the most critical aspects of building safety is thermal behavior of structural and non-structural components when exposed to fire or high temperature. Thermal performance investigations of certain materials used in a building often lead to selection of different strategies and options for fire safety systems (Lo et al. 2008) and to inspection and maintenance of old fire protection devices (Lo 1999). Harper (2004) states the importance of adequate understanding of the behavior of building components and materials under fire and high temperature in order to develop proper fire disaster prevention strategies. Generally, fire codes are considered as the best reference when selecting materials subjected to fire. However, developing fire code provisions for new materials for each new cycle is a lengthy process. In many cases, the outcome of experimental tests and feedback from users about new materials' probable shortcomings will be important for such provisions. This long process for issuance of new material fire code provisions along with competitive material and product market issues often necessitates conduction of fire or high temperature product performance certification testing. Therefore, interest has increased in carrying out experimental tests on new materials in fire research labs (Jatheeshan and Mahendran 2015, Le Dréau et al. 2015, Wang et al. 2015, Roszkowski and Sulik 2016). Nguyen et al. (2009) conducted a full-scale fire test on a concrete frame infilled brick wall to evaluate thermal performance of masonry. Their results indicate that a restrained brick wall in a frame buckles at high temperature. Gunalan et al. (2013) employed full-scale fire testing to explore weak points of light wall panels fabricated with cold-formed steel when exposed to fire. Pascual et al. (2015) used a full-scale fire test to determine thermal behavior of blind-bolted connections for hollow and concrete-filled steel tubular columns. The first formal record of a fire test of a full-scale steel structure occurred at the Building Research Establishment Cardington between 1995 and 1996 (Martin and Moore 1997). Cardington fire test is one of the biggest full-scale fire tests in the history of experimental study on fire. The Cardington test utilized seven, real-scale thermal tests at altered positions inside an eight-story steel structure.

Despite noteworthy outcomes from full-scale fire tests, the number of reported tests is limited. Fire testing history has shown that this type of experimental study is accompanied by high expenses, long lead times and fire hazards. Perhaps these are the most serious disadvantages of full-scale fire testing and are also the main reasons for the limited number of reported tests. In the present study, scaled-down specimens and isolated connection tests are proposed for effective, manageable, and affordable experimental tests. Scaled-down tests use scaling laws to infer full-scale fire test results by testing reduced-scale specimens in small-scale facilities. Figure 1 shows an overview of the proposed scaling method for planning small-scale fire tests. Alternatively, full-size connections with dimensions appropriate for the small-scale, lab furnace can be tested. For both approaches, the specimens can be studied under simultaneously application of elevated temperature and axial load profiles.

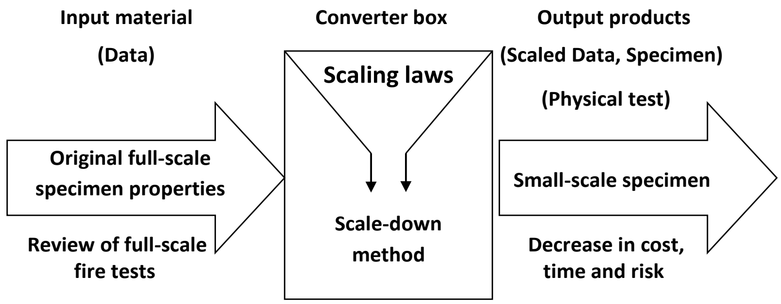

Figure 1. Overview of the proposed method for applying scaling laws in the planning of small-scale fire tests

2. Review of full-scale, furnace fire tests

A brief summary of relevant full-scale fire tests in the literature at this point is useful for framing the subsequent discussion of scaling methods applicable to small-scale fire testing. Nguyen et al. (2009) conducted a full-scale fire test on a 3 m high x 3 m wide unloaded infill wall constructed with 45 terra cotta, hollow blocks laid with conventional mortar. The block wall was confined inside a concrete frame and subjected to fire on one face, while out-of-plane horizontal displacements were measured at various locations on the unexposed face. Nguyen et al. found that the restrained brick wall could buckle when exposed to fire. Gunalan et al. (2013) conducted experimental fire testing to investigate thermal and structural performance of load-bearing cold-formed, steel stud wall systems with varied insulation schemes subjected to fire conditions. Eleven, full-scale specimens were tested in a test facility that used six, gas-fired burners mounted on a carriage with wheels. The burners applied heat to the specimen in a manner that would allow the specimen temperature to follow the AS 1530.4 standard fire curve during testing. Cold-formed steel stud wall systems with external insulation provided higher fire resistance ratings than conventional cavity insulated wall systems in these tests. Chen et al. (2012) used a modern, full-scale furnace to conduct fire tests on load-bearing, cold-formed steel stud walls sheathed with different types of fire-resistant wall board. Five, full-scale, cold-formed steel stud wall panels sheathed with double layers of three different fire-resistant panels on both sides, including fire-resistant gypsum plasterboard, magnesium board and calcium silicate board were exposed to loading and fire in a gas-fired furnace test facility following the ISO 834 standard time-temperature curve. The testing indicated that the fire performance of magnesium board was superior to that of the fire-resistant gypsum plasterboard and that the calcium silicate board exhibited undesirable explosive spalling. The steel studs experienced buckling in the middle third. Kodur and Mcgrath (2003) examined fire endurance of high strength concrete columns by full-scale test methods. Fire-resistance tests on six, reinforced concrete columns under service load were performed. Columns were heated in a gas-fired furnace custom-fabricated for fire testing loaded columns. Columns were subjected to a constant load, and the furnace temperature followed the ASTM E119 standard time-temperature curve. The steel framework of the furnace was external to the furnace chamber. Aggregate type, concrete strength, load intensity, and detailing and spacing of ties have were found to influence the fire-resistance of the tested columns. Conventional (large) column tie spacing led to extensive buckling of column bars and severe spalling of concrete and loss of concrete core. On the other hand, specimens with closer tie spacing showed significantly better performance due to the confinement effect of ties.

3. Scale-down Approach

Scaled-down testing apparatus offers an attractive alternative to full-scale fire testing facilities. The appeal of small-scale fire testing is that it is in general more manageable, economical and safer than full-scale testing. Scaling methods attempt to preserve correct relations between all main aspects, e.g., geometric proportions of a full-scale model during the conversion to small-scale as shown in Figure 1. Testing of a properly scaled model, can allow estimation of full-scale behavior.

Scaling laws are used to establish the full-scale to small-scale conversion formulas for parameters. For instance, the volume of a body varies with the cube of its length scale (l^3) and its surface area varies in terms of l^2. Hence, the ratio of surface area to volume of a smaller object is larger than that for a larger object of the same geometrical shape. There are two types of scaling laws applicable to this discussion. If all parts of an object scale in a similar geometric way with size, the scaling is termedisometric. In contrast, when different components of an object with different functionalities do not scale in a similar way; e.g., the shape of an object changes as its size changes, the scaling is termedallometric (Ghosh 2011).

When miniaturizing a full-scale specimen or component for fire testing, one must, for example, consider the possible consequences from the reduction of both volume and surface area. The rules of geometric scaling are well-known; e.g., perimeter (*P*), area (*A*) and volume (*V*) are defined with l, l^2 and l^3, respectively, where l is the length scale. Scale models often are represented in geometric scale terms, e.g., S_L (L referring to length); and in general, the scale of any quantity *i* is $S_i = i_p/i_m$ where i_p and i_m are the quantity value of the prototype, or item at full-scale, and the scale model, respectively. Physical Dimensions and scale factor relationships for various quantities considered in structural analysis and modelling are given in Table 1.

Table 1. Scale factors for prototype and scale models (Harris and Sabnis 1999)

Quantities	Scale factor	Dimensions
Stress	S_E	FL^{-2}
Modulus of elasticity	S_E	FL^{-2}
Specific weight	S_E/S_l	FL^{-3}
strain	1	-
Linear dimension	S_l	L
Linear displacement	S_l	L
Area	S_l^2	L^2
Moment of inertia	S_l^4	L^4
Concentrated load	$S_E.S_l^2$	F
Uniform distributed line load	$S_E.S_l$	FL^{-1}
Moment	$S_E.S_l^3$	FL
Shear force	$S_E.S_l^2$	F

3.1 Example for scale-down method

A simple example illustration of the scale-down method is the scale-down of a load case for a full-scale steel beam in order to fit within the size of small-scale laboratory test facilities. In this example, the full-size beam under load is 8000 mm long, has a solid rectangular cross section, roller and pin supports, and is subjected to a 200 kN, mid-beam point load (Figure 2a). The beam has a cross-sectional area, A = 400×500 = 2×10^5 mm^2, and a modulus of elasticity, E = 210 kN/mm^2. If in this example an assumption is made that a small lab can only test such beams with a maximum length of 2000 mm in this manner, scaled dimensions for fabrication of a small-scale specimen beam with a length of 2000 mm for test must be determined. In accordance with Table 1, the point load of 200 kN is scaled to 12.5 kN, and the cross-sectional area is scaled to 1.25×10^4 mm^2 as shown schematically in Figure 2b. Table 2 presents a brief comparison between geometry and loading quantities resulting from the scale-down method and the well-known beam equations for this example. The comparison suggests the feasibility in this example of straightforward scaling of full-scale testing to fit small-scale laboratory facilities.

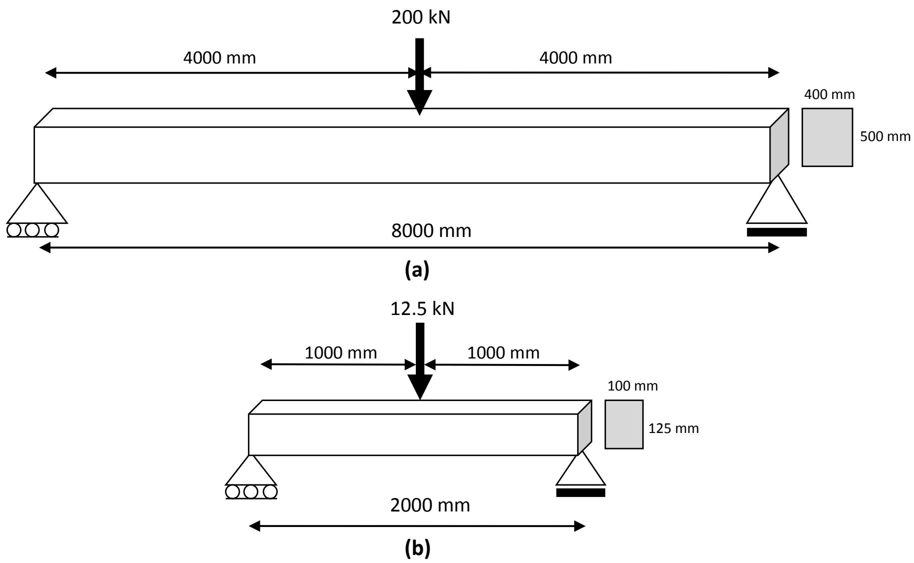

Figure 2. Sketch of: a) the prototype or full-scale beam, and b) the scaled-down beam (not to scale)

Table 2. Comparison between beam equations and scale-down method

Geometry and loading quantities	From Beam's Equations				From Scale-down method			
	Equation	Prototype model (p)	Scale-down model (m)	$\frac{m}{p}$	Recommanded Scale factor	SE	SI	Scale factor
Deflection (δ) at midpoint (mm)	$\frac{FL^3}{48EI}$	2.438	0.6095	0.25	S_l	1	0.25	0.25
Moment (M) at midpoint (kN.mm)	$\frac{FL}{4}$	400000	6250	0.015625	$S_E.S_l^3$	1	0.25	0.01563
Shear (V) at end (kN)	$\frac{F}{2}$	100	6.25	0.0625	$S_E.S_l^2$	1	0.25	0.0625
End Slope (θ)	$\frac{FL^2}{16EI}$	0.0009143	0.0009143	1	1	1	0.25	1

4. BCERL small-scale, high temperature test facility

The Building components and Enclosures Research Laboratory (BCERL) at Penn State has developed small-scale fire test facilities for conducting scaled-down tests under varied, time-temperature and load profiles. The MTS Systems 110-kip electrohydraulic load frame shown in Figure 3a. is being retrofitted with an electric furnace capable of applying the time temperature curve found in ASTM E119 standard (ASTM 2012) to the furnace control volume. The design intent was to have a customizable test facility for small-scale fire testing on a wide range of specimens. The load frame is capable of performing axial tensile, compression, and cyclic tests up to 0.5 Hz at the maximum actuator stroke of +/- 3 in. The tall, double-column load frame structure allows for a wide range of specimen lengths to be tested on this machine. The load frame is controlled by a MTS FlexTest 40 Controller.

Mechanical wedge grips with 67-kip capacity and liners for flat or round specimens and rated for a temperature range of -200˚F to 600˚F are used to hold the specimen or adapters to the specimen during tensile and cyclic tests in the load frame. When used in conjunction with the furnace, the grips are placed on the outside of the furnace allowing the specimen to run through the entire length of the furnace as shown schematically in Figure 3b. Placing the grips externally will ensure that the grips will not be subjected to the high temperatures of the furnace.

A high temperature (to 2900˚F) axial extensometer with ceramic rods designed to engage the specimen under test and chilled water cooling means is one technique used to measure test specimen strain within the furnace. This extensometer is configured with a gauge length of 2.0 inches and a +50% to -10% measuring range. The extensometer frame is mounted external to the furnace and passes through designated holes on the furnace. Type S thermocouples are one means used to monitor the temperature inside the furnace and at the surface or within the specimen. A custom, split tube furnace designed for steady-state and transient high temperature tests is shown in Figure 3. This split tube furnace has a 29 in. outside diameter and 40 in. outside height. The internal dimensions of the furnace are about 12 in. diameter by 30 in height. The end openings in the top and bottom of the furnace are adjustable to a maximum diameter of 12 in. to accommodate specimens with maximum width of 12 in. The end openings are made adjustable using stackable end plugs.

The furnace is capable of replicating the time-temperature curve in the ASTM E119 standard (ASTM 2012). Figure 4 shows this curve along with a number of other common time-temperature relationships used for fire testing at full-scale and small-scale. A significant capability in this furnace as compared to typical load frame furnaces is its ability to replicate the initial ramping that is seen within the first 10 minutes of the E119 curve. There are three independently-controlled zones in the furnace for improved control of the temperature uniformity or gradient within the furnace control volume.

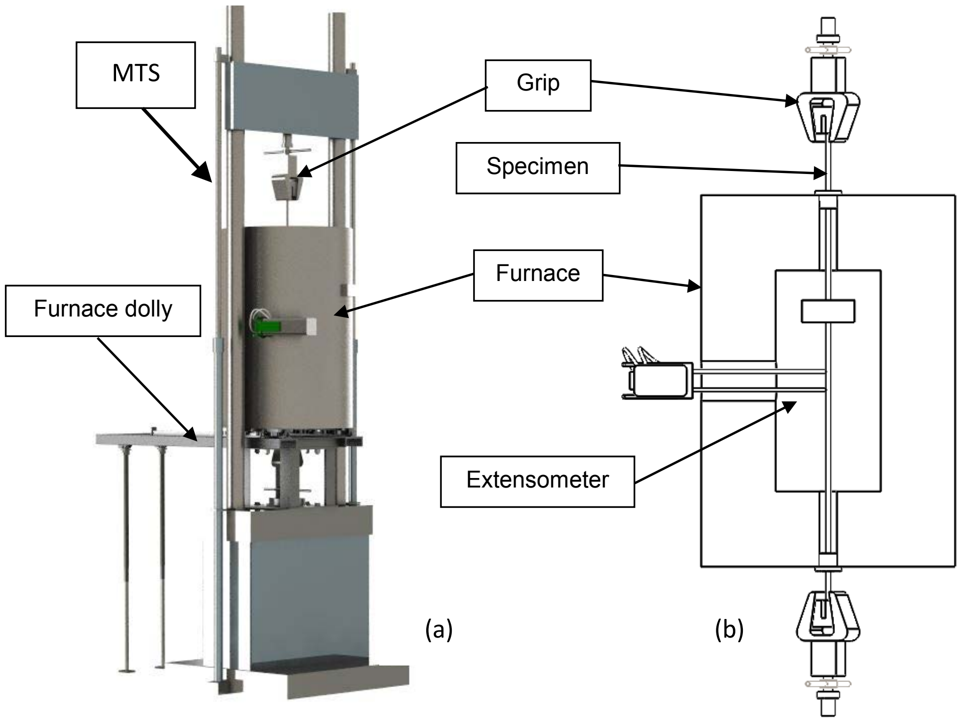

Figure 3. a) BCERL small-scale, high temperature test facility, b) 2D cross-section of furnace

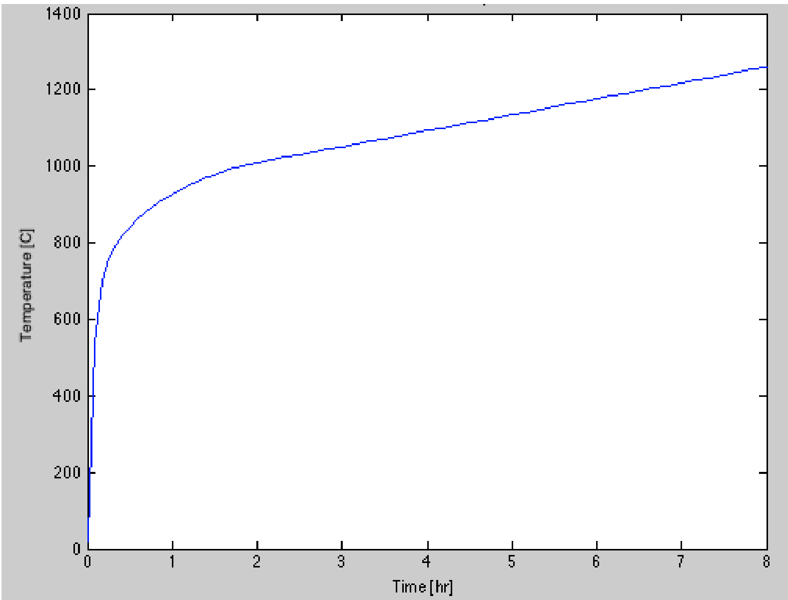

Figure 4. Typical time-temperature profiles used for full-scale and small-scale fire and elevated temperature testing (ASTM 2012)

For in-lab transportation of the furnace, the custom furnace dolly shown in Figure 3a has been designed and fabricated to fit with not only the MTS load frame, but two other custom load frames in BCERL to further increase the range of testing capabilities with the furnace. Linear slides have been mounted on the top side of the dolly to allow for 39 in. of travel across the length of the slide to allow the furnace to be pulled out of the load frame crosshead area between tests.

5. Projected small-scale fire test projects

In this section, scale-down techniques are presented for use of the BCERL small-scale, high temperature test facility to conduct small-scale tests with higher throughput and substantially reduced cost compared to typical full-scale testing. For conducting a full-scale fire test it is often necessary to fabricate an industrial furnace based on the actual size and loading of a member in buildings or with very large overall dimensions in order to accommodate a wide-range of full-scale fire tests. Typical components of the furnace compartment for a full-scale facility shown schematically in Figure 5 generally include: external structural framing, refractory walls, gas distribution and metering system, access doors and panels, load application system, environmental controls, specialized sensors and actuators, and a furnace data acquisition and control system. Existing dimensions and properties of the component(s) under test in a full-scale test help determine a logical relation between a scaled-down specimen that will fit the BCERL facilities and real-scale members. Fire testing on a scaled concrete column is one of the potential fire test projects that is expected to adapt well to the BCERL small-scale furnace. For instance, it is assumed that the real-scale circular concrete column with height H and cross-sectional area, πR^2 is exposed to fire and concentrated load *P* as depicted in Figure 5. With the aim of decreasing cost and increasing parametric variations to study, the use of scale-down techniques (Ghosh 2011) yield small-scale conversions of the real-scale column height and diameter to 0.2 H and 0.4R, in order to fit the testing inside the BCERL lab furnace as depicted schematically in Figure 6. The scaled concrete column also requires scaling of P based on the new specimen size. Fire tests on scaled-down concrete column specimens with variations in specimen size, cross-section and reinforcement under different loading profiles is considered to be a good match for the BCERL furnace.

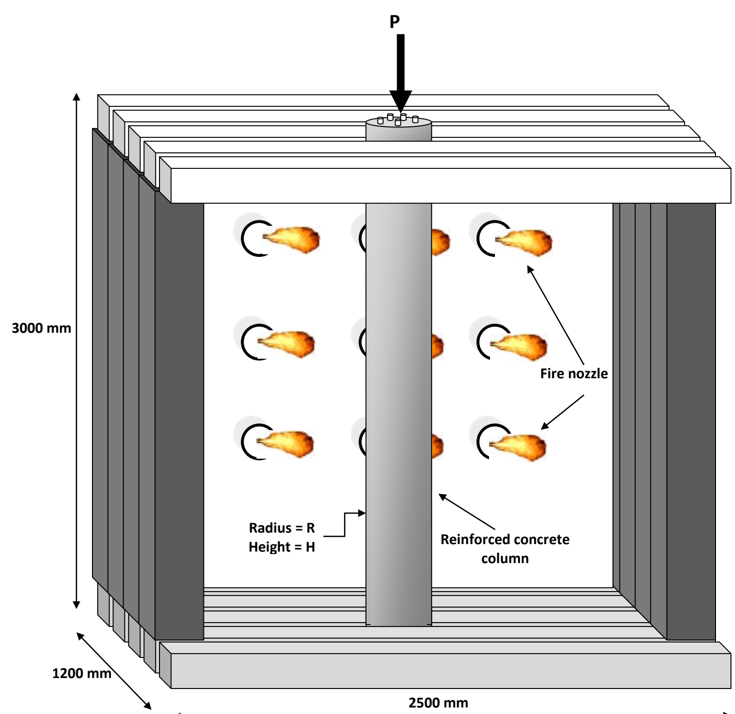

Figure 5. Schematic of a furnace and test setup for a full-scale fire test on a reinforced concrete column

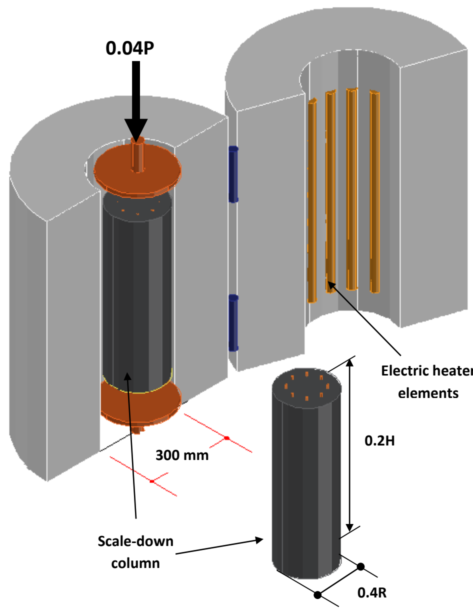

Figure 6. Scaled-down fire test of a real-scale concrete

Despite the widespread use of cold-formed steel in light-frame buildings, poor performance at high temperature is considered to be a serious weakness in many of cold-formed steel construction applications. Conducting scaled-down fire tests on cold-formed steel members and connections can lead to improvements in the thermal performance of cold-formed steel in construction. Figure 7 shows a shear connection that is widely used in cold-formed members as scaled-down to fit the BCERL furnace. Using a small-scale lab furnace, high temperature tests on cold-formed steel member connections and even connections of cold-formed steel to different materials will be of great value in the evaluation of potential failure modes of connections and fasteners and in the evaluation of concepts for mitigation of these failure modes.

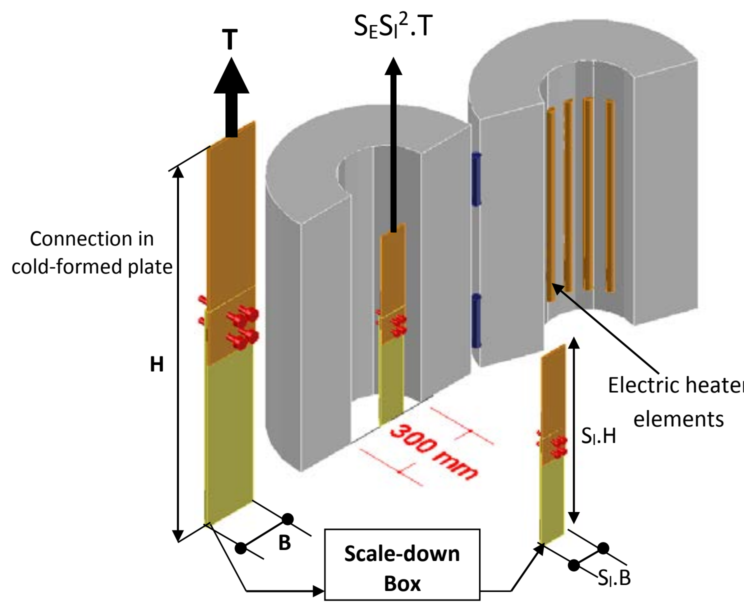

Figure 7. Fire tensile test of connection in cold-formed plates

After masonry walls are built, various types of anchors are used to attach other structural or nonstructural components to them. Masonry walls often reach high temperatures when exposed to direct flame or heat generated in surrounding spaces during fires. Hence, concern exists about the potential for failure of masonry anchorage. Figure 8 shows a standard masonry brick with a common masonry anchor detail scaled down to fit the BCERL furnace in order to subject the detail to high temperature tensile or shear testing. High temperature testing will help better understand shear and tensile capacities of masonry anchors (mechanical and chemical) and embedded or adhered fasteners at elevated temperature. In a similar fashion, anchorage and embedded fastener details for other wall and substrate materials can be scaled for testing in the BCERL furnace.

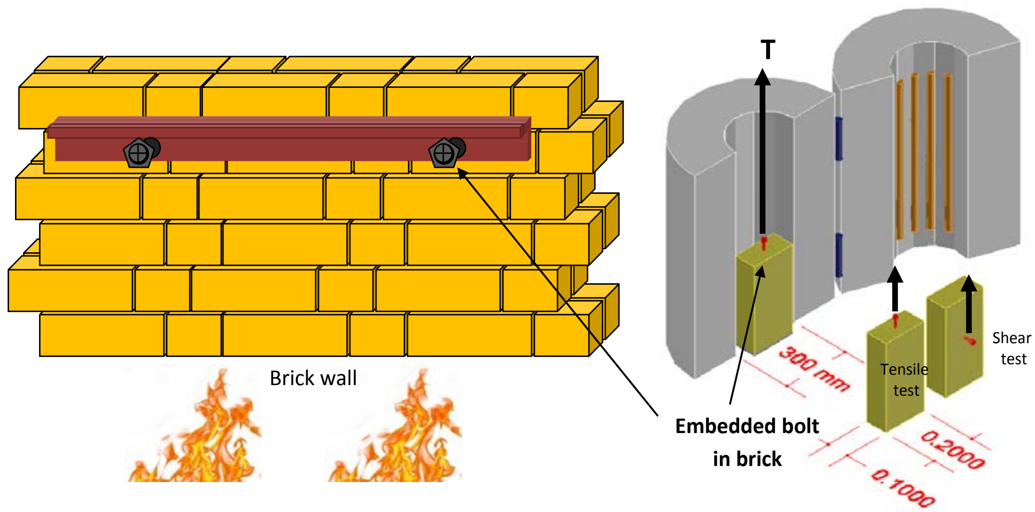

Figure 8. Fire tensile test of embedded bolt in brick

Fiberglass Reinforced Plastic (FRP) is often used to retrofit deteriorated concrete structures to satisfy new code requirements. In many cases, FRP is used in conjunction with concrete beams and columns to improve structural stability. However, FRP does not perform nearly as well at high temperatures as it does at ambient conditions. Two common methods of joining concrete members and FRP are FRP strip embedment in the concrete, or FRP attachment to the face of the member. Figure 9 shows two scaled-down FRP details fitted to the BCERL furnace in order to subject the details to high temperature tensile testing. In one detail, an FRP strip is embedded, and in the other an FRP strip is bonded to the face of a masonry element. Tensile loading will yield important information about rupture or pullout of the FRP strip in the first case, and bond failure in the second case.

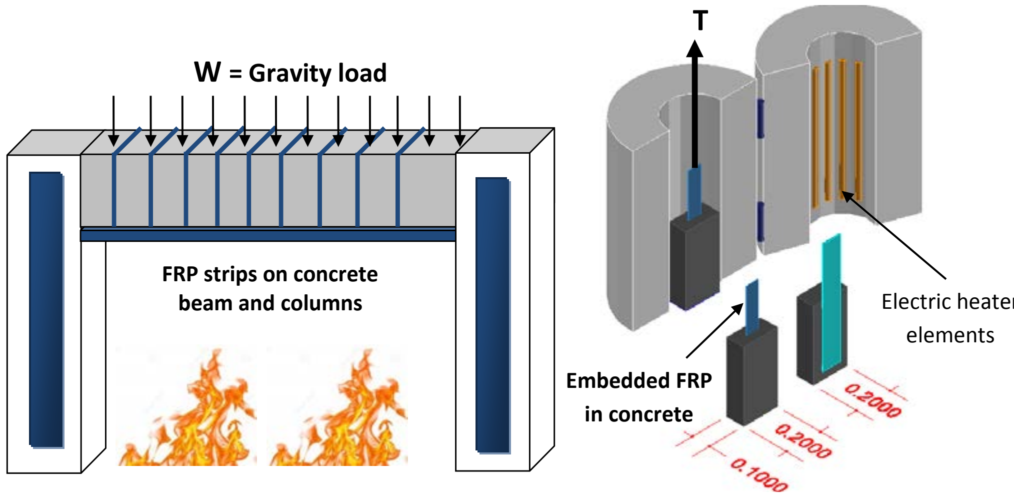

Figure 9. Fire test on the FRP strips in concrete members

6. Summary and Conclusion

A review of a number of full-scale fire tests on building components amenable to scaling down to fit testing in small-scale laboratory furnaces has identified many of the challenges and shortcomings inherent in full-scale fire testing, such as high cost, long lead times, low throughput, and safety issues. Examples of affordable scaled-down testing alternatives to these full-scale tests at small-scale have been suggested and described. Scale-down specimens and full-scale, but small dimension specimens able to fit in a relatively small laboratory furnace offer many opportunities to investigate high temperature testing of materials, components or connections using minimal space and existing facilities in research labs such as BCERL at Penn State. General design details for adapting a larger-than-typical laboratory furnace to an electrohydraulic load frame have been presented. Simultaneous high temperature and structural load testing of scaled-down specimens in smaller furnaces such as the BCERL lab furnace is expected to be of great value to construction material manufacturers, especially manufacturers of connection, anchorage and fasteners details products.

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