State-of-the-Art on Fire Resistance of Concrete Structures:
Structure-Fire Model Validation

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EXECUTIVE SUMMARY

This white paper presents the current, international, state-of-the-art large-scale experimental, modeling, and performance-based design (PBD) efforts related to structural fire resistance of concrete structures. The paper addresses these topics with emphasis on research and development needs for large-scale experiments on fire resistance of structures to support performance-based engineering and structure-fire model validation; prioritizing those needs; phasing the needs in terms of near, medium and long term; identifying the most appropriate international laboratory facilities and collaborators available to address each need; identifying possible means to transfer the results of research to industry; and identifying a means for the coalition of international partners to review progress and exchange information on a regular basis.

Any future research strategy in this area relies on demonstrating suitable drivers to promote the work; these may be driven either by safety or property protection concerns, or by economic, sustainability, or optimization goals. It will also be necessary for the international concrete construction, fire testing, research, and regulatory communities to work together and acknowledge the considerable unknowns regarding the performance of concrete structures in fire, as well as the serious limitations of current approaches to structural fire testing and design. The following key research needs are highlighted herein:

- Enhanced material thermal and constitutive models are needed as inputs to future computational modeling activities.
- A credible, repeatable, representative, and temporally and economically efficient test method for characterization of different concrete mixes' propensity for heat-induced spalling in fire is needed.
- Small-scale tests are needed on concrete and reinforced concrete structural elements to provide basic validation data for computational modeling.
- Spalling tests and associated modeling must be developed to account for and understand as many of the known spalling risk factors as possible. Numerical models for spalling need to be improved and validated.
- Large-scale structural tests are needed which sequentially ramp up the complexity of structural fire testing assemblies, eventually leading to whole structure testing. These tests should be planned to interrogate as many of the relevant thermal and structural issues as possible.
- Once computational modeling capability is developed and validated against an appropriate range of tests, parametric modeling studies should be undertaken to understand and interrogate the overall whole structure response for various types of concrete structures. Large-scale whole structure tests of 'exemplar' reinforced concrete buildings are needed to credibly validate and corroborate testing and modelling of materials, and small scale and large scale structural elements.
- Computational models and modeling tools must be carefully and sequentially validated for predicting whole structure response to fire.
- Tests and models are needed to allow engineers to quantify fire damage to concrete structures after different fire exposure levels. Such testing and modeling would support the development of intensity measures, damage indices, performance limits, and quantification of consequences of damage; these are needed in support of PBE of concrete structures for fire.

DISCLAIMER

The potential collaborators listed herein are given for the purposes of this review and are based on the information available in the literature and the specific knowledge of the authors. In no case does such identification imply recommendation or endorsement by the authors, nor does it imply that the collaborators identified are the only available for the stated purposes.

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1.0 INTRODUCTION

The U.S. National Institute of Standards and Technology (NIST) conducted a building and fire safety investigation of the World Trade Center (WTC) disaster of September 11, 2001; the Final Report included 30 recommendations that address (1) specific improvements to building standards, codes, and practices; (2) changes to, or the establishment of, evacuation and emergency response procedures; and, (3) research and other appropriate actions needed to help prevent future building failures. As part of NIST's plan to implement the report's recommendations regarding new methods for fire resistance design of structures, an international research and development (R&D) roadmap on the fire resistance of structures is being developed. NIST has commissioned three white papers to be used as the basis for technical discussions at an international workshop. This report is one of these three independent white papers on the current, international, state-of-the-art large-scale experimental, modeling, and performance-based design (PBD) efforts related to structural fire resistance of concrete structures. The paper addresses:

1. highlighting research and development needs for large-scale experiments on fire resistance of structures to support performance-based engineering and structure-fire model validation;
2. prioritizing the needs in order of importance to performance-based engineering;
3. phasing the needs in terms of near (< 3 yrs), medium (3-6 yrs) and long term (6-9 yrs);
4. identifying the most appropriate international laboratory facilities available to address each need;
5. identifying potential collaborators and sponsors for each need;
6. identifying means to transfer the results from each series of tests to industry through specific national and international standards, predictive tools for use in practice, and comprehensive research reports; and
7. identifying a means for coalition of international partners to review progress and exchange information.

2.0 CURRENT STATE-OF-THE-ART IN STRUCTURAL FIRE ENGINEERING FOR CONCRETE

In general, concrete structures have (historically) performed well in building fires [Bailey and Khoury 2011]. Because concrete is non-combustible and has a relatively low thermal conductivity, and provided that the concrete cover to the internal steel reinforcement remains in place during heating (i.e. there is no cover spalling), heat flow to the interior of a reinforced concrete element in fire occurs slowly. Concrete structures are therefore widely assumed to possess ‘inherent fire resistance’; this is typically ensured in design by prescribing minimum overall member dimensions and minimum concrete cover to the steel reinforcement. Historical evidence suggests that these simple, prescriptive approaches have provided an acceptable level of performance of concrete structures in building fires.

For a variety of technical and economic reasons (briefly discussed in Section 2.3.1) large-scale structural fire testing, computational analysis, and PDB of concrete structures for fire has received only a fraction of that given to steel-framed structures. The available research on concrete and concrete structures is summarized in this section.

It is noteworthy that a number of state-of-the-art reviews on structural fire engineering testing, analysis and design are available in the literature [e.g. British Steel 1999, Grosshandler 2002, Grosshandler 2003, Almand et al. 2004, Beyler et al. 2007, Kodur et al. 2007, Beitel and Iwankiw 2008, Kodur et al. 2011, Wald 2011, Vassart and Zhao 2011, Bisby et al. 2013]; none of these has focused exclusively concrete structures. A useful review of large scale structural fire testing was recently published by Bisby et al. [2013].

2.1 Full-Scale Experiments

2.1.1 Laboratory Settings

Since the mid 1900s, a large number of large-scale standard fire resistance tests have been performed on reinforced concrete structural elements in standard fire testing furnaces [e.g. ISO 1999, ASTM 2011]. Various prior research needs assessments have highlighted a large number of deficiencies associated with such tests and have identified a range of general structural fire engineering research needs which have yet to be properly addressed; some of these are discussed in Section 3.1.

In addition to standard furnace tests, a smaller number of ad-hoc, non-standard structural fire tests performed in laboratories have also been presented in the literature. Several authors have presented results from fire tests on concrete elements or assemblies using custom made or modified standard furnaces to study specific structural response issues or specific types of concrete structures which cannot be easily investigated using a standard ‘single element’ approach. For instance, Van Herberghen and Van Damme [1983] used a modified standard floor furnace to study the fire resistance of post-tensioned continuous (unrestrained) flat floor slabs with unbonded prestressing tendons in standard fire conditions; Kordina [1997] used a modified floor furnace to investigate the punching shear behavior of reinforced concrete flat slabs in standard fire conditions; Kelly and Purkiss [2008] used an oversized floor furnace to study the fire resistance of simply-supported, partly-restrained, long-span post-tensioned concrete slabs under standard fire exposure; Li-Tang et al. [2008] studied the structural fire behavior of model-scale, three-span continuous unbonded post-tensioned concrete slab strips in a custom built furnace subject to a standard fire; Zheng et al. [2010] performed a series of standard fire tests on two-span, continuous post-tensioned concrete slabs in a furnace with a central support built inside the heating chamber; and Annerel et al. [2011] used a modified standard floor furnace to perform punching shear tests on concrete slabs subjected to a standard fire. Several other examples are available in the literature however an exhaustive summary is avoided here.

Only one large-scale natural fire test of a 'real' multi-storey concrete building appears to have ever been performed. Bailey [2002] presents the results of a natural fire test on a full-scale, seven-storey cast in-place concrete building that was performed at the UK Building Research Establishment (BRE) Cardington test site. The full-scale building was a concrete frame three bays by four bays. It had two cores that incorporated cross bracing for lateral load support, and the floor slab was 250 mm thick. The main aim of the test was to investigate the behavior of a full-scale concrete building during a realistic compartment fire, under sustained design load. Bailey [2002] states that the test aimed to:

- investigate how the whole building resisted or accommodated large thermal expansions from the heated parts of the structure (lateral thermal expansion of the floor slab in particular);
- identify both beneficial and detrimental modes of whole building behavior that cannot be observed through standard furnace tests on isolated structural elements;
- investigate the effects of concrete spalling and its possible significance on whole building response; and
- compare test results and observations from large-scale fire tests with current methods of SFE design.

A fire compartment was built into an edge bay of the building with an area of 225 m^2 between the ground and first floor. One internal column was exposed to the fire and eight additional columns were partially exposed to the fire. The columns were made from high strength concrete (103 MPa cube strength), incorporating 2.7 kg/m of polypropylene (PP) fibers to prevent explosive spalling. The cover to the steel reinforcement was 20 mm. The structure was loaded using sand bags and the fire load was timber cribs with a load of 40 kg/m^2. Key observations and conclusions relevant to the current report were that [Bailey 2002]:

- gas temperatures were reduced early in the fire due to explosive spalling of the soffit of the floor slab; slab soffit spalling was extensive, reduced the severity of the fire throughout the test, and exposed the bottom reinforcing bars; spalling was explosive and probably exacerbated by high in-plane compressive stresses in the slab caused by lateral restraint to thermal expansion;
- vertical displacements toward the edge of the building were larger than the displacements near the center and showed no signs of a stabilizing plateau;
- the slab remained stable and supported the load 'by compressive membrane action at small slab vertical displacement'; such action can only occur at small displacements, and thus if the slab's vertical displacements were greater or lateral restraint surrounding the heated slab were less, 'it is difficult to see how the slab could have supported the static load' [Bailey 2002]; and
- thermal expansion of the floor slab resulted in lateral displacement of the external columns.

Two further large-scale non-standard structural fire tests were also performed at BRE to study the performance of hollowcore concrete slabs resting on steel beam flooring systems [Bailey and Lennon 2008]. These were performed after worrying results from tests and incidences of failures of hollowcore slabs during real building fires in Europe [Van Acker 2003, De Feijter and Breunese 2007]. The tests were intended to demonstrate that tying together and grouting of hollowcore slabs could prevent premature shear failure (this having been observed in smaller scale tests on hollowcore slabs).

The fire compartment was 7.0 m × 17.8 m in plan with a height of 3.6 m. Fifteen 1200 mm wide × 200 mm hollowcore slabs, with concrete compressive strength of 85 MPa and moisture content of 2.8% by mass, were placed in a single row to form the compartment roof. The slabs were loaded with sandbags and exposed to a natural fire using 32.5 kg/m^2 of wooden cribs; the intent being to follow the ISO 834 [ISO 1999] standard fire for the first 60 minutes. Observations and conclusions were that (Bailey and Lennon 2008):

- properly designed and detailed hollowcore floor systems behave well when subjected to severe fire scenarios, as well as during the *cooling phase* of the fire;
- edge units fractured during the cooling phase however this did not lead to loss of load bearing capacity;
- no significant spalling of the units was observed;
- different *end restraint conditions* did not affect the measured vertical displacement, however restraint conditions kept outer portions of the edge slab in place when it fractured along its length; and
- there was evidence of a lateral compressive strip forming at the ends of the units caused by restraint to thermal expansion; thus may have enhanced the flexural and shear capacity of the slabs.

Large-scale non-standard fire tests on unloaded and loaded concrete columns and unloaded post-tensioned concrete slabs in real fires have also been reported by Wong and Ng [2011] and CCAA [2010], however neither of these studies is particularly scientific or instructive. The CCAA tests in particular aimed (but largely failed) to assess the magnitude and extent of spalling for various types of Australian *aggregates* in a real fire, and to provide guidance on possible measures to limit its effects.

Ring et al. [2011] present limited results of four large-scale non-standard fire tests on 'frame-like' concrete structures performed to investigate redistribution of loading within reinforced concrete structures subjected to fire. These tests were designed to provide data for the development, assessment, and validation of numerical tools for predicting the structural response of concrete tunnels in fire. Triangular tubular frames were constructed on slope and loaded to simulate a soil overburden. Two of these frames incorporated PP fibers in their concrete mix. Oil burners were used to heat the atmosphere inside the tubes to 1200°C in nine minutes and remaining at 1200°C for three hours. These tests are not particularly helpful in studying the fire resistance of buildings; however, they do provide data for validation of computational models and they clearly demonstrate the benefits of PP fibers in preventing heat-induced spalling.

In general the available non-standard testing of concrete structures presented above shows that the behaviour of concrete in fire is considerably more complicated than would be assumed on the basis of the available prescriptive guidance, which typically prescribes only overall member dimensions and minimum concrete cover. This may present possible benefits and/or risks for concrete structures in fire. Whole building response has not been widely investigated for concrete buildings.

Some laboratories, such as BAM (Germany), NRC (Canada) and CERIB (France) are able to carry out Hybrid Fire Testing (HFT). HFT couples physical tests on part of a structure with real-time computational simulation of the rest of the structure [Mostafaei 2013]. HFT allows reproduction, in a more realistic way, of the boundary conditions and the applied external loads during a fire. However, HFT is not yet widely accepted or properly validated for whole frame reinforced concrete structures.

2.1.2 Real Buildings

Relatively few detailed technical analyses of the performance of real concrete buildings during and after real fires are available in the literature. A 2008 report by the Concrete Society [2008] on assessment, design and repair of fire damaged concrete structures provides summary information on a number of real fires that have been reported in concrete buildings by Ingham [2007], Berry [1991], Srinivasan et al. [2007], Sivagnanam [2002], Nene and Kavle [1992], Morales [1992], Smart [2006], Dilek [2005, 2007], Taerwe et al. [2006], Peker and Pekmezci [2003], Boam and Copper [1994], Cabrita Neves et al. [1997], and Calavera et al. [1992]. Consistent observations from these studies are that:

- real concrete buildings subjected to real fires generally perform well, and structural failure (i.e. local or global collapse) is rare;
- in many cases fire-damaged structures can be brought back into use by removal and replacement of damaged concrete and internal steel reinforcement;
- considerable structural damage and irrecoverable deformation is observed in concrete slabs and beams due to differential thermal gradients, thermal bowing, and discrete cracking in regions not explicitly designed for the stresses and deformations experienced under these thermal actions;
- cracking and spalling can be severe, particularly for modern concrete mixes and for elements with thin concrete webs (as in many precast concrete elements); widespread spalling of slab soffits was observed in many fires, although in general this did not lead to structural failure; and
- relaxation of prestressing tendons was observed in both bonded and unbounded post-tensioned construction; prestressing tendons are particularly sensitive to high temperature [Gales et al. 2011a, b].

Fletcher et al. [2006] discuss the performance of the Windsor Tower, a high rise building in Madrid, Spain, which was partly constructed from concrete and which experienced a severe fire resulting in major structural collapse in 2005. Due to the complexity and uncertainty of response of this structure, the only relevant conclusion from this report is that the steel portions of the structure suffered considerably more damage than those made from concrete. Reasons for this are not given, other than the typical 'inherent' fire resistance of concrete. Fletcher et al. [2006] also discuss the performance of the CESP Buildings in Sao Paolo, Brazil, during a fire in 1987. These were concrete frames with concrete ribbed slab floors and experienced a major fire exceeding two hours in duration. The concrete core of one of the buildings collapsed during the fire; attributed to lateral thermal expansion of the concrete floor beams resulting in secondary bending moments and lateral shears on columns that were not designed for such forces.

de Feijter and Breunese [2007] describe the aftermath of a severe fire in a multistory car park constructed partly from precast prestressed hollowcore concrete slabs which spanned from a central core to a load-bearing precast concrete façade. The structure was severely damaged during the fire and total structural collapse was a serious concern. Excessive crack formation was observed in the hollow core slabs, including horizontal cracks between the individual cores and vertical cracks from the cores to the slabs' bottom surfaces; these resulted in total separation of the bottom half of the hollowcore elements (along with the internal prestressed reinforcement) over a large portion of the structure. Spalling to a depth of several centimeters was widespread in both the slab soffit and the concrete façade elements, exposing steel reinforcement in many places. de Feijter and Breunese [2007] concluded that for concrete structural elements that are exposed to exterior environments it cannot be taken for granted that spalling will not occur during fire. They also concluded that differential thermal cracking is a particular concern for concrete structures un-reinforced with small amounts of internal reinforcement (e.g. precast elements prestressed only in the longitudinal direction) and that consideration should be given to the connection between structural elements, both to account for compressive stresses developed due to lateral restraint during heating, and for tensile stresses developed due to thermal contraction on cooling. It is clear based on the above that it is essential for structures to be considered not as separate parts, but rather as a connected whole.

A notable fire event in another concrete car park structure was the Gretzenbach fire, reported by Muttoni et al. [2005]. In this case, an underground cast-in-place concrete flat slab structure collapsed in punching shear during the cooling phase after a 'rather small and localized fire' [Annerel et al. 2013]. Full details of this collapse are not widely available, however a forensic structural fire analysis has been presented by Annerel et al. [2013]; this suggests the need for additional work on punching shear of concrete slabs in fire.

Gales et al. [2011a, 2011b] present detailed reviews of available test data and case studies of real fires in unbonded post tensioned (UPT) concrete buildings. They show that multiple case studies and much of the available furnace test data show that the response of real UPT buildings in fire is more complicated than suggested by the available prescriptive guidance, particularly with respect cover spalling and prestressed tendon rupture under localized heating. It is shown that concrete spalling of some form has occurred in all reported real fires in UPT buildings, and that in more than 65% of these cases tendons have ruptured as a result. Spalling has occurred in more than half of available furnace tests on UPT elements. Tendon rupture or release of prestress occurred in the majority of real fires, leading to both partial and progressive failure of UPT buildings. Tendon rupture has been observed in 33% of reported furnace tests, and is more likely in a real building than a furnace test; localized heating of tendons is particularly problematic and can lead rapidly to tendon rupture. Gales et al. [2011b] highlight two fundamental inadequacies of available test data for UPT structures in particular: (1) that the total anchor-to-anchor length of UPT tendons in standard furnace tests is always much shorter than in real UPT structures, and (2) standard furnace tests are designed to provide uniform heating, thus failing to simulate spatially non-uniform, travelling, and/or localized fires in real buildings. The result of both factors is that furnace tests cannot capture the conditions most likely to result in unbonded prestressing tendon rupture in fire.

2.1.3 Tunnels

Several dramatic fires in tunnels have occurred during the past two decades, including: the Channel tunnel (1996 and 2008), Mont Blanc (1999) and Frejus (2005) between France and Italy, Storebealt (1994) in Denmark, Tauern (1999) in Austria, and Gothard (2001) in Switzerland.

Very high temperatures were reached in all of these tunnel fires (probably more than 1000°C) and it is likely that these temperatures were reached during the first 15 min of the fires [Voeltzel and Dix 2004, Abraham and De Robert 2003]. Similarly, high levels of temperature and heating rate have been measured in tunnel fire tests such as the EUREKA 499 fire tests and the Memorial Tunnel Fire Test Program [Lönnemark and Ingason 2005]. High temperatures and heating rates often result in considerable spalling and damage to tunnel linings and structures. These have potentially serious consequences for the safety of users and of fire and rescue teams. Fire damage to tunnels also typically necessitates ime-consuming and costly refurbishment of the tunnel prior to re-opening. In addition to direct economic losses from repair activities, indirect economic losses associated with tunnel closure are often substantial. While spalling of concrete in fire has been known for more than a century and occurs frequently in building and fires, these more recent examples in tunnel fires have clearly highlighted a significant problem; spalling of modern concrete mixes.

Adequately addressing the spalling problem is now a primary requirement in any new tunnel design. Fire resistance tests on large-scale concrete elements are required in most tunneling projects. National authorities have introduced temperature versus time curves in various tunnel fire testing regulations. Three of the most commonly used curves in Europe (the RWS, HCinc and RABT fires) were designed to represent the maximum envelope for all possible fire events in road or rail tunnels. These curves reach 1200 to 1300°C in less than 10 minutes [World Road Association 1999, Taillefer et al. 2013].

Heat induced spalling phenomena remain relatively poorly understood from a fundamental perspective [Maluk 2014] and depend on a large number of factors, including the geometry of the concrete elements and the externally applied loads [Guerrieri and Fragomeni 2013, Jansson and Bostrom 2013, Carre et al. 2013]. Other factors influencing spalling are discussed in Section 2.2.3. So that laboratory tests provide results that are as representative as possible of the credible worst case fire situation large elements (close to full scale) are generally tested for compliance with anti-spalling design requirements. These are generally slabs or walls with sections larger than 4 m². The elements are typically mechanically loaded in an attempt to reproduce the externally applied in-service loads [Taillefer et al. 2009, Pimienta et al. 2010, Jansson and Bostrom 2013] despite the fact these loads are not well known in practice.

2.2 Structural Fire Modelling

2.2.1 Modelling Approaches

Experimental studies on the behavior of full-scale reinforced concrete structures in fire have shown that designers "*need to (better) understand the behaviour of entire structures in fire to ensure that premature collapse will not occur"* [Bailey 2002]. Performing full-scale structural fire tests is expensive, and historically they have been infeasible. A potentially cost-effective alternative approach to evaluate the behavior of entire concrete structures in fire is to employ *validated* computational modeling approaches.

Two main modeling approaches may be used for concrete structures in fire: (1) sequentially coupled thermal-stress analysis and (2) fully-coupled thermal-stress analysis. In the sequentially coupled thermal-stress analysis approach, the heat transfer analysis is carried out first to determine temperature distributions within the concrete elements throughout the duration of fire exposure. The structural analysis is then performed for the structure under the applied load, and the changes in the mechanical properties and thermal deformations of the structure due to changes in temperatures, are accounted for as the structural analysis proceeds in time. In this approach the thermal field as assumed not to be influenced by the structural response to heating. Most current numerical modeling tools customized for fire are use this sequentially coupled approach. A key issue in this method is that because the interactions between thermal and structural analysis are ignored, if for instance spalling occurs during the fire this would not be accounted for despite the considerable changes in temperature (and mechanical stress) distributions that would result. In fully coupled thermal-stress analysis, both heat transfer analysis and structural analysis are carried out at each time step for the duration of the fire exposure. This method can thus capture the thermal/mechanical interaction effects; however, this is a much more computationally expensive approach and it is rarely used in practice (and it is not currently possible to credibly predict heat-induced spalling in any case).

Critically, computational modeling approaches for concrete structures in fire need to be validated using experimental data that represent the behavior of real structures in real fires; such validation data are effectively non-existent at present. Furthermore, despite considerable efforts expended in developing numerical models and computational tools for concrete structures' response to fire, such tools have not become easily accessible to the practicing engineers, particularly as compared to the available numerical models used for analysis of concrete structures' behavior at the ambient temperature. Computational tools for concrete are much less developed and have far inferior validation than those used for structural fire analysis of steel structures (possible reasons for this are noted in Section 2.3.1).

One of the existing computational tools customized for response evaluation of structures in fire is the SAFIR numerical analysis code [Franssen 2011]. SAFIR applications have been partially validated for different structural systems, including some validation against results of tests on concrete structural elements [SAFIR References 2014]. SAFIR has been also employed in simulations used during hybrid fire testing [Mostafaei 2013], wherein an entire 6-storey concrete structure was simulated in fire using a substructuring approach by coupling a physical substructure (an isolated test specimen within a standard column fire resistance furnace) and a numerical model substructure (real-time computational model built within SAFIR). Another customized computer program for structural modeling in fire is Vulcan [Huang et al. 2003a, b, c]. Vulcan is mainly employed for numerical analysis of steel-concrete composite slabs constructed within steel framed structures, although it has also been used in research of concrete structures in fire [e.g. Huang 2010].

In recent years, Kodur and colleagues [e.g. Kodur and Dwaikat 2011, Dwaikat and Kodur 2010, Kodur et al. 2009] have published a number of papers applying a 'macroscopic finite element model' for the analysis of concrete structural elements of various types in fires. Included in many of these studies is a purely hygro-thermal concrete spalling model, which is used to study the impacts of spalling on the structural response of concrete elements in fire. However, the spalling model is very hard to justify on the basis of the available literature on factors influencing spalling (see below), and it is not useful for purposes beyond illustrative research study.

Bespoke computational analysis codes have also been developed to model individual concrete structural elements reinforced or strengthened with FRP materials in standard furnace tests [e.g. Bisby et al. 2005], however these are research tools and are not suitable for use in design. Furthermore, such models are element based and have not generally been incorporated into numerical modeling to obtain the entire structural response. Commercial finite element computational modeling tools such as ABAQUS [Abaqus FEA 2010] or ANSYS [2014] have also been used by various researchers and practicing engineers to simulate the response of concrete structures in fire.

The main shortcoming of all of the above numerical tools is a lack of proper validation against data from full-scale whole structure tests. Currently available validation data are based almost exclusively on single-element standard fire resistance tests, and as already noted such tests do not simulate whole structures.

2.2.2 Material Models

Concrete displays extremely complex behavior under load at elevated temperatures. To perform accurate computational analysis of concrete structures in fire, validated material models are required for both thermal and mechanical properties of all materials invovled.

Many studies have been performed over several decades in an attempt to understand and characterize the thermal properties of concrete at high temperatures; for instance concretes' thermal conductivity and specific heat [e.g. Schneider 1986, Bazant and Kaplan 1996, Neville 1997, Harmathy 1993, Flynn 1999]. The thermal properties of concrete are highly temperature dependent and vary widely depending on concrete density, moisture content, and aggregate type. Eurocode 2 [EC2 1992] provides detailed variable thermal property models for concrete that have been widely used in computational fire analysis of concrete and steel-concrete composite elements and structures [Franssen 2011], and a summary of available thermal models for concretes of different types has been presented by Flynn [1999].

Determining the variations in mechanical properties of concrete at elevated temperature is essential for computational modeling of concrete structures. Most important are the stress-strain relations (in tension and compression) of the concrete and reinforcing (or prestressing steel) steel at different temperatures. For reinforcing and prestressing steels reliable mechanical properties and high temperature constitutive models are available from various sources [e.g. Harmathy 1993, Buchanan 2002, Gales et al. 2009, CEN 2004]. For instance, Eurocode 3 [CEN 2005] provides stress-strain models for structural steel materials that are used in most current numerical modeling tools. Some authors [e.g. Gales et al. 2009] have suggested a need to explicitly account for creep straining of steel at elevated temperature in computational structural fire modeling; the research community however appears divided on this issue, with most researchers appearing to feel that it is sufficient to implicitly include creep strains (as in the relationships provided in the Eurocodes [CEN 2003, 2004]) when modelling the response of steel at elevated temperature.

For concrete, numerous studies have been carried out to understand the variations in mechanical properties at elevated temperature [Schneider 1985, Fletcher et al. 2007, Buchanan 2002, Khoury 2000, Youssef and Moftah 2007, Bamonte and Gamarova 2014]. A unique mechanical property of concrete at high temperatures is its so-called ‘transient strain,’ which applies to concrete only when loaded and heated for the first time [Mindeguia et al. 2013, Khoury et al. 1985]. Ignoring transient strain in numerical modeling of concrete, particularly for elements under compressive stress may result in erroneous results [Khoury 2000, Lange et al. 2014], although again the research community appears to be divided on this issue. Stress-strain relationships for concrete at elevated temperature are mainly dependent on the concrete temperature, initial concrete compressive strength, density of concrete (e.g. lightweight or normal weight), type of aggregates (e.g. siliceous versus carbonate), and the initial applied stress. A recent summary is given by Bamonte and Gamarova [2014].

Of particular interest are material models for describing the tensile behavior of concrete at elevated temperature, since this is not well known and presents significant computational challenges. Most computational modelling approaches for concrete in fire make use of ‘smeared cracking’ models, which are unable to precisely describe the formation and widening of discrete concrete cracks. Such models are, by definition, unable to precisely predict steel reinforcement strains in the area of discrete cracks, which in practice could lead to tensile rupture of reinforcement or to reductions in shear carrying capacity due to loss of aggregate interlock. Considerable additional research is needed to better understand the properties of concrete in tension at elevated temperature, and to develop computational models that can credibly capture the necessary behaviors in order to reliably, predict failures.

Recovery and retention of mechanical properties of concrete both during and after cooling are also not well known; these have particular importance for modeling the response of concrete structures in real fires, where properly accounting for cooling phase contractions and structural interactions is essential [Concrete Society 2008].

The variation in thermal and mechanical properties of high strength concrete and high performance concrete have been also studied at elevated temperatures [e.g. Kodur and Sultan 2003, Phan 1996, Kulkarni et al. 2011]. This work has highlighted that spalling is the main shortcoming of high strength and high performance concrete during fire.

2.2.3 Spalling

Spalling, in its most general form, is defined as the violent breaking off of pieces from the surface of concrete elements when exposed to rising temperatures. Spalling takes several different forms and can severely affect the load carrying capacity of a concrete structure due to a reduction of cross section, changes in the mechanical load distribution, and a reduction in or the overall loss of the thermal protection to the steel reinforcement or prestressing. It is a complex phenomenon involving time and temperature dependent mechanical stresses, temperature diffusion, and differential thermal stresses, moisture movement, and microstructural and chemical changes with increasing temperature. A given concrete’s propensity for spalling depends not only on its material parameters (e.g. concrete mix composition, the nature of the mix constituents and their specific material properties), but also on structural parameters (e.g. geometry, boundary conditions, restraint) and applied mechanical and thermal loads.

Heat induced spalling exhibits a stochastic nature and experimental results are regularly contradictory. Whether this is due to genuine randomness or to insufficiently controlled testing methods remains unclear. However, major trends in factors increasing the risk of spalling can generally be observed. Spalling risk tends to increase (however with some exceptions presented in the available literature) when the compressive strength, the compactness of the concrete, the rate of heating, the moisture content, and the imposed compressive load increase [Meyer-Ottens 1972, Copier 1979, Jensen et al. 1987, Connoly 1995, Ali et al. 2001, Mindeguia 2009, Jansson and Bostrom 2013]. An exhaustive list of factors which are known to influence propensity for heat induced spalling has been presented by Maluk [2014] and is reproduced later.

A large number of research studies have also shown that addition of a small amount of PP microfibers into the fresh concrete mix decreases spalling risk, although the mechanisms by which the fibers reduce propensity for spalling are not known with confidence [Diederichs and al, 1995, Shuttleworth, 2001, Bilodeau and al, 2004, Salomao and Pandolfelli, 2007].

There are two main mechanisms that promote spalling and are considered in the literature and used in most computer simulations attempting to predict spalling. The first mechanism considers the thermal stresses induced by thermal gradients, differential thermal expansion, and the induced restrained deformations in heated concrete. In the second mechanism, spalling is attributed to a build up of pore pressure due to evaporation of free moisture within the concrete microstructure; this is sensitive to the compactness (density, permeability, porosity) of the concrete and its moisture content [Harmathy 1965, Kalifa et al. 2001]. Harmathy [1965] among others has proposed that the pore pressure level in heated concrete is increased by the formation of a liquid water saturated layer termed the ‘moisture clog’. This results from moisture transport (due to pressure gradients induced by heating) and condensation in the inner cooler zones within the concrete. More recently, a third mechanism has been proposed [Jansson 2008]. This mechanism considers that spalling takes place within the moisture clog layer due to a combination of a reduction of the concrete strength (due to its wet, hot state) and the absence of drying creep.

Several coupled thermo-hygro-chemo-mechanical codes attempting to simulate the stress state as a consequence of both thermo-hygral and thermo-mechanical processes have been developed and are described in the literature [e.g. Gawin et al. 2006, Zeiml et al. 2008, Lottman et al. 2013, Ožbolt and Bošnjak 2013]. However, even these very advanced models, which take into account a large number of factors using a number of mass and energy balance equations, are unable to predict spalling for a given mix under a given mechanical stress and heating regime.

Since spalling depends not only on material parameters but also on structural parameters, it is necessary to repeatably and accurately reproduce realistic conditions (e.g. geometry, boundary conditions, applied mechanical and thermal loads, etc.) when studying real concrete mixes in the laboratory.

2.3 Performance-Based Design (PBD) Practice

Structural design for fire is concerned primarily with the provision of ‘fire resistance’ to protect against loss of life and spread of fire to adjacent buildings. Fire resistance has historically been defined as the time of exposure to the standard fire [e.g. ASTM 2011, ISO 1999] during which an isolated structural element tested in a standard fire testing furnace, can resist failure due to loss of load bearing capacity under service loads, unacceptable temperature rise at the unexposed face, or passage of flames or hot gas through the element. This historical approach to fire resistance design based on furnace testing is unrealistic and irrational for reasons too numerous to discuss here [Bisby et al. 2013]. During the 1990s, the emergence of performance-based structural fire design codes, most notably in Europe [e.g. CEN 2004, 2005], enabled the use of more rational approaches to fire resistant design. These approaches allow designers to take any approach they wish to meet the performance objectives for the structure, and thus both the fire and the structural response can be rationally assessed and structural performance quantified and compared against performance objectives. In practice this typically means that structures are engineered to perform ‘at least as good’ as structures that meet the historical prescriptive guidance.

2.3.1 Should Concrete Care?

Beginning in the early 1990s the European steel industry devoted considerable funding and effort to understanding the whole structure response of steel buildings in fire; the goal was to demonstrate the ability to performance engineer (primarily through the development of validated computational modeling tools) steel structures for fire. A large number of large-scale non-standard fire tests (see Bisby et al. [2013]) led to the development and validation of structural fire design software specific to steel-framed buildings (e.g. www.vulcan-solutions.com).

The most significant result of this dedicated research effort has been development of an ability to justify (often using computational modelling) removal of large amounts of passive fire protection from steel framed structures, leading to market advantage in building construction. The concrete industry has made little effort to capitalize on PBD in structural fire engineering and has not devoted similar resources to research in this area. This is likely because – as already noted and notwithstanding the problematic structural responses noted above that are sometimes observed for real concrete structures in real fires – in the absence of heat induced cover spalling concrete structural elements tend to perform well in furnace tests, as compared with unprotected steel structural elements.

The obvious result of the above is that there is little immediate obvious economic benefit from PBD for fire of concrete structures, and hence little incentive to invest in detailed and costly testing programs to investigate and/or demonstrate the possible benefits of rationally accounting for full structure interactions and alternative load carrying mechanisms in reinforced or prestressed concrete structures during fire. Research on concrete in fire tends to receive support only when potential problems are identified (as in the case of funding for research into heat induced cover spalling in the wake of the 1999 Mont Blanc and 1996 Channel Tunnel fires); rarely in support of more rational, optimized structural design.

2.3.2 Practical Application of PBD

For the reasons noted above, practical application of PBD for reinforced concrete structures appears not to be widely implemented. Indeed, the authors are not aware of any reinforced, prestressed, post-tensioned or precast concrete structures that have ever been designed on the basis of a true PBD approach. Specific cases of PBD of concrete structures in fire appear to occur only rarely and in cases where existing concrete structures fail to meet the simplified prescriptive rules given in design codes. For instance, some historic concrete structures may fail to meet contemporary concrete cover requirements; in such cases a performance-based analysis may be used to justify safe non-compliance with the code.

2.3.3 Regulatory Hurdles

Any application of performance-based structural fire engineering requires a regulatory and building approvals system (i.e. both processes and stakeholders) that explicitly permits such approaches. However, formal permissibility of PBD of structures for fire is a necessary but non-sufficient condition for PBD to occur in real projects. In practice, even in jurisdictions where PBD for structures in fire is explicitly permitted by the building regulations (for instance in England and Wales under the Approved Document B [DCLG 2013], implementing PBD for fire can be difficult, largely because those individuals involved in the regulatory and approvals process are not sufficiently technically competent to credibly assess detailed performance based (so-called 'fire engineered') designs; and also because the regulatory system is unused to formalized third-party expert reviews of fire-engineered designs that are needed in these cases.

Thus, in addition to the technical challenges associated with credibly performing performance-based structural fire engineering of concrete elements and structures, considerable economic challenges specific to concrete structures exist (as discussed in Section 2.3.1), as well as considerable social/regulatory/competence challenges associated with properly managing, verifying, and approving performance-based designs.

One specific jurisdiction that appears to have effectively implemented performance-based design of structures for fire is London, UK (and more recently other UK cities). In these jurisdictions, steel framed multi-storey buildings are routinely structurally fire engineered to ensure optimized and robust whole structure response to fire. This appears to have been enabled in practice by a combination of:

1) formal building codes which explicitly permit the use of a PBD approach to building design for fire;
2) technically competent structural fire engineering consultancy practices;
3) technically competent and fully engaged fire and rescue services with in-house fire engineering experts who can advise regulators and approving authorities in areas where technical competence is lacking; and
4) formalized and credible expert third-party review systemd through which performance-based fire-engineered designs can be assessed and verified before being implemented.

In most jurisdictions, one or all of the above conditions may be missing, and in such cases effective application of PBD of structures on fire is difficult if not impossible in practice.

3.0 KNOWLEDGE GAPS

The preceding sections have outlined the current state-of-the-art in testing and analysis for the performance in fire of reinforced concrete structures. On this basis the following sections outline knowledge gaps, with a particular emphasis on those gaps that are relevant to PBD of concrete structures for fire.

3.1 Full-Scale Experiments

Section 2.1 outlined available knowledge from large-scale experiments and real fires in concrete buildings. The following gaps in knowledge gaps were identified or are considered relevant.

3.1.1 Fire Exposure

The standard temperature-time curve is not representative of a real fire in a real building [Bisby et al. 2013]. To truly understand the response of concrete buildings in fires, tests of concrete structures and structural elements are required under credible worst case design fire exposures. This may require experimental consideration of localized, compartmentalized, horizontally and/or vertically travelling, smouldering, or hydrocarbon fires, all of which have the potential to introduce structural actions or interactions which are not captured by standard fires, and all of which may have particular importance for different types of concrete structures (e.g. localized heating or travelling fires possibly being critical for UPT slabs, or high heating rates of hydrocarbon fires likely being critical for spalling-prone concrete mixes).

3.1.2 Structural Interactions and Asymmetry

The limited data available from large-scale fire tests and experience of real fires in concrete buildings covers a small fraction of all possible structural configurations. Structural fire tests conducted to date have generally studied regular, symmetric, idealized structures. Modern structures increasingly make use of irregular floor plates with varying span lengths, bay sizes, mixed construction materials (e.g. hollowcore concrete slabs on cellular steel beams), etc. The influences of irregular plans and complex forms needs to be investigated and understood before PBD can be performed with confidence. This issue has received limited attention (through modeling) for steel-framed buildings [McAllister et al. 2012, Flint et al. 2013]; however no attempts appear to have been made to understand similar issues for concrete buildings.

3.1.3 Failure Localizations

When concrete structures fail in fires it is rarely for reasons that would be expected based on standard furnace testing. Failure is often initiated by localised failure or structural distress, such as discrete or splitting cracking in concrete, rupture of tensile steel reinforcement, connection or anchorage failure, shear or punching shear failure of concrete slabs, rupture of prestressing tendons, secondary moments or unexpected shear forces exerted on columns due to lateral expansion of floorplates, heat-induced concrete spalling, etc. These types of failure localizations fundamentally depend on the three dimensional, whole structure interactions during both heating *and* cooling. Large-scale non-standard structural fire tests on real buildings are the only defensible means by which to observe and quantify the full suite of possible failure modes; and then to incorporate these failure modes into validated computational models to be used in PBD for fire.

3.1.4 Compartmentation and Fire Spread

The vast majority of large-scale structural fire testing (particularly non-standard testing) has focused almost exclusively on prevention of structural collapse; little attention has been paid to other fire safety goals such as maintaining fire compartmentation under large deformations. Considerable floorplate deflections (both vertical and lateral) and wide cracks have been observed in concrete buildings (Section 2.1). The impacts of vertical and lateral deformations of structural frames on fire stopping and on both horizontal and vertical compartmentation should be studied to preserve life safety in modern concrete buildings which are becoming ever more reliant on defend-in-place life-safety strategies (particularly in higrise construction). Furthermore, given that many structural fire engineers express concern regarding the quality of installed fire stopping between floors in multistorey buildings. Large-scale non-standard fire tests should therefore be considered to evaluate the structural impacts of fires burning simultaneously on more than one floor.

3.1.5 Cooling Phase Behavior and Residual Capacity

A number of localized structural failures have been observed during the cooling phase of both real fires in real buildings, in particular of concrete flat plate [Annerel et al. 2013] and hollowcore slabs [de Feijter and Breunese 2007], and non-standard heating regimes in large-scale structural fire experiments. Structural actions resulting from creep, localised and/or global plastic deformation, and thermal contraction and restraint during cooling all need to be better understood if designers are to credibly design for burnout natural fire exposures while preventing structural collapse. The importance of construction details such as proper anchorage and grouting of hollowcore slabs or other precast concrete elements is also relevant to ensure a robust response during cooling. Furthermore, the residual structural capacity of fire damaged concrete structures that have undergone large deformations or experienced cracking and spalling is not well known. The ability to predict the response of concrete structures during cooling is in its infancy.

3.1.6 Instrumentation and Measurement

More complete data are required from both standard and non-standard large-scale structural fire tests. Better information, in particular on strains and displacements, during testing are required to develop a more accurate understanding of response and to provide the data that are essential for credible computational model development, validation, and verification. Measurement of strain at high temperature is particularly problematic, and the development of accurate and cost-effective high temperature strain measurement instrumentation would yield substantial benefits for validation of structural fire models.

3.1.7 Data for Model Calibration, Validation and Verification

Experimental data from realistic large-scale tests on concrete structures of various types (e.g. flat plate, UPT, hollocore, etc) are essential for calibration, validation, and verification of both existing and emerging computational modeling techniques to simulate the response of concrete structures and structural elements in fire. This of course assumes that a relevant driver can be identified to ensure that PBD of concrete structures becomes a practical reality. The requirement for test data holds both at the material level and at the structural level. Complete high-temperature constitutive material models for concrete are needed to generate reliable input data for models and to better understand system response to fire and possible failure modes [Kodur et al. 2011]. For instance, the recovery of mechanical properties of concrete during cooling is not well known.

3.1.8 Structural Optimization and the Use of New Materials and Systems

Modern concrete structures are increasingly optimized, in many cases by the use of sophisticated computer analysis, in an attempt to reduce the mass, cost, environmental impact, carbon emissions, and embodied energy in buildings. Modern concrete structures also increasingly make use of high strength, high performance, and/or self consolidating concrete, all of which have an increased propensity for heat induced spalling and suffer more severe reductions in compressive strength on heating as compared with historical concrete materials. Modern concrete buildings also increasingly make use of efficient structural systems such as unbonded post-tensioned flat plate slabs and precast hollowcore slabs, the responses of which during fire are not well known in real buildings.

3.1.9 Connections

A range of studies have already been performed on connection performance in fire for steel structures [e.g. Yuan et al. 2011]. However, there has been little effort to understand connection performance in concrete structures and to develop and validate computational modeling capabilities to predict connection response and suggest best practice guidance to ensure structural robustness in fire. Only Bailey and Lennon [2008] have experimentally studied details for the connection of precast concrete elements in buildings to ensure robust performance in fire. It is noteworthy that useful guidance on these issues is available in the seismic design literature [e.g. Ghosh 2001] where robust connection design is essential; it may be appropriate to develop similar provisions for structural robustness of certain types of concrete structures in fire (precast concrete construction in particular).

3.1.10 Explosive Spalling of Concrete

Structural fire design of concrete structures relies on the assumption that the concrete will not spall during fire. This assumption is based largely on data from large-scale standard fire tests of concrete elements tested in isolation in furnaces during the past 70 years [Bisby et al. 2013]. However, there is legitimate concern that modern concrete structures, which incorporate concrete mixes with considerably higher concrete strengths, are more susceptible to spalling than was historically the case. Whilst preliminary guidance on the means by which spalling can be addressed by designers is available in, for instance, the structural Eurocodes [CEN 2004], additional research is needed to understand the respective roles of the various factors which are known to increase concrete's propensity for spalling [ArupFire 2005, Bailey and Khoury 2011] such that credible preventative actions can be taken. For instance, more specific and defensible guidance is needed on the requirement to add a certain amount of PP fibers to the concrete mix to prevent spalling. Interactions in real structures have the potential to significantly influence development of spalling in a fire, so large-scale tests under natural fires (i.e. variable time histories of heat flux) are needed to truly understand the propensity for, and the whole structure consequences of, spalling in concrete structures.

3.2 Structural Fire Modelling

3.2.1 Material Models and Numerical Modeling

The main knowledge gaps in current material models and numerical modeling tools for reinforced and prestressed concrete buildings and tunnels can be summarized as follows:

- Current numerical molding tools need to be validated for whole-structure performance to ensure system effects such as thermal expansion, support and restraining conditions, membrane actions, size effects, discrete cracking, rupture of tensile reinforcement and shear and structural lateral deformations are captured properly in the analyses.
- Models need to be developed to study the response of different types of concrete structural connections, in particular for structures assembled from precast concrete elements.
- Material and computational response models need to be improved to be able to credibly predict and capture the effects of concrete spalling so that both the heat transfer and structural analyses can be performed with confidence. This must explicitly include both the effects of pore water pressure in the

concrete and the development of differential thermal stress due to thermal strain (and possibly other, as yet unknown, factors which may significantly influence spalling).
- Material and computational models need to be improved to properly capture the cooling phase response and to determine the concrete residual material properties using entire structure testing to capture the potentially important system effects.
- For critical structures, such as certain types of infrastructure (notably concrete bridges and tunnels) property protection and rapid reoccupation may be essential. Current models are not validated at large-scale to obtain quantifiable structural damage levels and thresholds. Models should be developed that are useful within the context of a probabilistic performance-based framework for concrete structures in fire similar to those currently applied within the seismic design community [Lange et al. 2014]. Such an approach will also require the development of intensity measures, damage indices, performance limits, and quantification of consequences of damage [Rush et al. 2014].
- Material models and numerical modeling tools need to be updated as new structural materials emerge and find their way into practice, e.g. ultra high performance concrete, concrete structures reinforced or prestressed with FRP bars, and others [Terrasi et al. 2012].
- A test-model based certification protocol should be developed using which manufactures and producers of concrete structural materials could receive a certificate that shows performance of their product in an entire structure simulation. This could be performed by running an entire structure test for a worst-case fire scenario and estimating other identified fire scenarios using a numerical modeling, after it is validated with the worst case scenario. The ability to perform such analyses is some years away.
- Hybrid testing could be developed for tests of large structures. For instance, if a ten-storey structure need to be tested in fire; the first two storeys could be built and tested in the lab and the remainder of the structure, i.e. the upper storeys, could be simulated simultaneously using a numerical modeling approach. This would reduce the cost of the experimentation and the required lab space, and may be possible within the soon-to-be-completed NIST facility [NIST 2013].

3.2.2 Spalling

As noted above, a great deal of research has been performed to investigate parameters affecting heat induced concrete spalling [Maluk 2014]. Numerous candidate test methods have been derived and numerous attempts at computational predictive modelling (marginally successful) have been made. A great deal of additional research is needed before the factors leading to spalling are fully understood, or before credible predictive models can be put forward. All of the following (sometimes interrelated) factors are thought to increase propensity for spalling:

- Increased concrete compressive strength
- Increased in-service stress condition and moisture content
- Certain types of cement
- Certain types and shapes of aggregates and their gradation
- Fresh concrete slump or slump flow (i.e. self-consolidating, pumped, etc)
- Absence of PP fibres (PP fibre dose, diameter, aspect ratio are all relevant)
- Absence of steel fibres (dose of steel fibres is relevant)
- Certain other concrete admixtures or supplementary cementing materials (e.g. fly ash, silica fume, water reducers, air entraining agents, etc)
- Certain methods of manufacture (e.g. precast, prestressed concrete)
- Certain internal reinforcement types, ratios, geometries
- Certain sizes/thicknesses/shapes of structural elements (larger elements typically, but not always, are assumed to be more prone to spalling)
- Certain fire exposure regimes (heating rate, fire fighting operations, cooling, etc – more rapid heating typically, but not always, are assumed to be more prone to spalling)

Given the range of influencing parameters and the complexity of the potential thermal, mechanical, physical, and chemical drivers of spalling processes, some researchers (e.g Maluk [2014]) have suggested that what is needed, rather than a detailed understanding of, and ability to computationally predict, spalling, is a means by which to experimentally characterize and quantify propensity for spalling of different candidate concrete mixes under different conditions of heating and mechanical stress, with a view to eventually guaranteeing that explosive spalling will not occur for a suitably designed mix (likely by addition of an optimized dose of PP fibres); this capability is some years away from a reality.

3.3 Performance-Based Design Practice

There do not appear to be any significant knowledge gaps with respect to PBD practice for concrete structures in fire, rather there is a lack of obvious drivers or incentives. As already noted, PBD of concrete structures is not widely implemented in practice, but this largely for non-technical reasons, including:

- Concrete structures are widely considered to be 'inherently fire resistant' and even when specific concerns for certain types of buildings are voiced (e.g. spalling of high strength concrete columns, failures of precast prestressed hollowcore slabs, tendon rupture in UPT construction) these are widely ignored due to a lack of tangible evidence (i.e. no major failures of concrete buildings).
- There are currently few obvious economic benefits of PBD for concrete. Concrete structures are unlikely to change substnatially when subjected to PBD, because minimum member dimensions are typically governed by strength and serviceability criteria, and minimum concrete cover is typically governed by bond development or corrosion prevention requirements. PBD for concrete therefore rarely enables further optimization and economic savings.
- An effective regulatory structure to enable PBD is not in place in most jurisdictions. Many Authorities having jurisdiction (AHJs) lack the technical expertise to assess and approve PBD submissions, and rigorous, formalized third party review procedures are not widely in place to allow credible external reviews of performance-based designs.
- Historical inertia in the construction industry is strong, and change is generally resisted.

It is not clear at present how to address any of the above factors that hinder research PBD of concrete structures for fire.

4.0 ACTIONS AND PRIORITIZATION FOR PBE OF CONCRETE STRUCTURES

Based on the above discussions, an attempt is made in this section (with approximate temporal sequencing) to outline a possible future research strategy with respect to large-scale testing of reinforced concrete structures in support of PBE. This future research strategy relies on three fundamental assumptions:

1) that suitable drivers can be demonstrated to promote funding of ongoing experimental and computational work in this area; these may be driven either by safety or property protection concerns (challenges) or by economic, sustainability, optimization, or again property protection goals (opportunities);
2) that sufficient funding is made available to support the proposed research activities; and
3) that the international concrete construction, fire testing, research, and regulatory communities work together to address the considerable challenges noted below, recognizing and openly acknowledging the considerable unknowns regarding the performance of concrete structures in fire, as well as the serious limitations of current approaches to structural fire testing and rational design for fire.

In considering the research program presented below, two key issues should be borne in mind at all stages:

1) All of the *experiments suggested below should be modeled using the best available current modeling tools before the tests are performed* in order to (a) design the test samples, elements, or structures, (b) define the mechanical and thermal loads that the samples, elements, or structures should be subjected to, and (c) define the specific types and locations measurements to be made before, during, and after experiments are performed. This is an essential requirement to advance the science in this overall area.
2) Heat induced spalling of concrete can induce large differences in the thermal and mechanical response of concrete materials, elements, and structures to fire. *Attempts should be made to avoid spalling, both in the experiments suggested below and in practice, since spalling introduces uncertainties that are very difficult to rationally account for in design*. Experiments with spalling should be explicitly separated from those without. To guarantee that no spalling will occur, moisture content in the tested samples, elements, structures should be as 'realistic' as possible during testing, and PP fibers should be introduced in concretes mixes. It is noteworthy that the in-service moisture level of concrete in buildings is not well known, and research is needed in this area.

4.1 Zero to Three Years

4.1.1 Research Needs Identification

The first step in any future research plan must initially be to engage with all of the various stakeholders in the design, construction, and use of concrete buildings (and infrastructure) in order to determine:

- what legitimate, **specific safety concerns** (challenges) exist for concrete structures in fire; and
- what **practical drivers** (opportunities) exist for PBE of concrete structures.

At present there is a striking lack of open debate and dialogue within the concrete building community on most of the issues discussed in this report, and this will need to change for any future progress to be made.

4.1.2 Materials Characterization

The first research priority action is to improve existing material thermal and constitutive models; these are needed as inputs to any computational modeling activities. This includes:

- More reliable and complete **thermal models for concretes** of various types under various transient heating (and cooling) rates. Thermal property data are currently available but there is considerable scatter in the data and in general it is not clear which thermal properties should be assumed for a precise analysis. This research need holds for both historic and emerging modern, high strength, high performance, self-consolidating, and/or fiber-reinforced concrete mix designs.
- More reliable and complete **mechanical property models for concretes** of various types under various combinations of stress (sustained, variable), temperature (heating *and* cooling), and time – these should account for the effects of transient thermal strains and should be validated using tests at the material and element levels. Research should be performed to determine if transient creep strains must be explicitly accounted for to accurately predict response under various loading and heating scenarios for various types of structural elements.
- More reliable and complete **mechanical property models for reinforcing materials** (e.g. mild steel reinforcement, prestressing steel, and alternative materials such as FRP bars, stainless steel, etc.) – these should also account for the issues noted in the previous point.
- The development and validation of a credible, repeatable, representative, and temporally and economically efficient **test method for characterization of different concrete mixes' propensity for heat-induced spalling** in fire. Such a test method is urgently needed so that results from different international testing labs can be compared and contrasted, and so that workable and economical concrete mixes can be developed that offer a high level of confidence that heat-induced spalling will be avoided for all credible worst-case fire scenarios relevant to a given application.

4.2 Three to Six Years

4.2.1 Small Scale Structural Elements

Small scale tests on concrete structural elements are needed to provide basic validation data for computational modelling using the thermal and mechanical properties developed in years zero to three. Such tests should initially be performed on statically determinate structural elements, as is common for contemporary structural fire resistance testing, however with considerably more attention given to appropriate measurement of relevant parameters (e.g. temperatures, strains, deformations) than is typical in standard furnace testing. Test results should be compared against the results of pre-test (*a priori*) computational modeling, followed by model development/redevelopment where necessary.

Issues of particular interest in these tests (and modeling) could include studying the effects of:

- asymmetric heating;
- localized versus global heating;
- different heating (and cooling) scenarios and rates;
- sustained and varying load levels;
- effects of bond slip between internal reinforcement and concrete at elevated temperature; and
- formation of air gaps and differential thermal expansion in steel-concrete composite elements.

Assuming that a credible spalling characterization test method for concrete can be developed (as discussed in Section 4.2.1), **spalling tests and associated modeling** should be developed to account for and understand as many of the factors listed in Section 3.2.2 as possible. Some of the key issues include:

- mix design parameters (including PP and steel fibre inclusion, types, and doses);
- load levels and restraint to thermal expansion;
- specimen shape and size;
- heating scenario; and

- influence of reinforcement details on spalling.

Existing **numerical models for spalling need to be improved and validated** in two respects:

- Models to **more accurately predict occurrence of spalling** in concrete during fire are needed. Such models must account for the effects of moisture and thermal stresses. Validation is required at both the single element and whole structure levels.
- In cases where spalling cannot be avoided, **models are needed to include the effects of spalling on structural response**. This would include thermal and structural effects from changes in the geometry.

There is some question, however, as to whether validated predictive models for spalling will ever be developed given the extreme complexities of the competing processes known to be involved.

4.2.2 Large Scale Structural Elements

Whole structure systems are typically statically indeterminate and incorporate numerous redundancies and alternative load paths (this is particularly true of cast-in-place concrete strcutures); however these are highly complex and potentially difficult to understand during whole structure fire tests. Thus, **large-scale structural tests are suggested which sequentially increase the complexity of structural fire testing assemblies, eventually leading to whole structure testing** in years six to nine.

While it is difficult to propose the precise tests required, since these will depend on the research outcomes from earlier stages of proposed work, the tests should interrogate as many of the following issues as possible (note again that ***a priori* computational modeling should be performed in all cases**, with a focus on demonstrating the ability to quantitatively capture the important structural actions and failure modes):

- structural continuity;
- vertical and lateral restraint to thermal expansion;
- thermal deformations on heating (and cooling) with an emphasis on understanding the interactions between arching and thermal bowing for concrete slabs of various span-to-depth-ratios,
- shear and punching shear;
- membrane actions, including both compression membrane (arching) actions and tensile membrane (catenary) actions,
- two-dimensional (one-way acting) versus three dimensional (two-way acting) response of slabs,
- response of unbonded post-tensioned reinforcement (e.g. tendon rupture) and structural elements;
- response (and possibly connection) of precast concrete elements, probably with an initial focus on hollowcore prestressed precast elements;
- Effects of discrete cracking (as opposed to smeared cracking) and possible rupture of internal reinforcement at large cracks (including the effects of smooth versus deformed steel reinforcement).

Once computational modeling capability is developed and validated against an appropriate range of tests, **parametric modeling studies should be undertaken to understand and interrogate the overall whole structure response of various types of concrete structures**. This work is needed to determine which types of whole structure tests will provide the greatest benefit, either in terms of enhancing the fire safety of a particular type (or types) of concrete buildings, or in terms of offering opportunities for economic, sustainability, or functionality enhancement of concrete building construction.

4.3 Six to Nine Years

4.3.1 Whole Structure Testing and Modelling

The testing and modeling studies proposed above lead logically to **a small number of large-scale whole structure tests of 'exemplar' reinforced concrete buildings**. Such tests are essential to credibly validate and corroborate testing and modeling of materials, and small scale and large scale structural elements. Such tests also provide an opportunity to observe possible additional structural interactions and failure modes that may have been overlooked during smaller scale or single element testing.

It not possible at present to define the type(s) of building that might be tested on the basis of the research performed in years zero through six. Any large-scale whole structure testing of concrete buildings should be modeled *a priori* (as previously) and should seek to study the effects of:

- multiple stories and multiple structural bays;

- localized (or travelling) versus global fire exposure;
- optimized, contemporary structural arrangements (including concrete flat plates, high strength concrete columns, studrails for shear reinforcement, post-tensioned slabs (bonded and/or unbonded), high span to depth ratios, etc); and
- if deemed appropriate from the outcomes of earlier research stages, precast concrete flooring systems (including typical structural connections between precast elements).

Models must be carefully and sequentially validated for predicting whole-structure response to fire. In general, the concrete in fire research community should seek to emulate the body of research and modelling capability that has been developed by the steel in fire research community in the wake of the large-scale Cardington fire tests in the UK performed during the 1990s.

4.3.2 Property Protection Methodologies

Also of interest is research to study **property protection aspects of concrete buildings both during and after severe fires**. Tests and models are needed to allow engineers to quantify fire damage to concrete structures after different fire exposure levels. This would involve exposing structural elements or assemblies to natural fire exposures of various severities and durations, and subsequent testing to determine the damage levels obtained. Such testing and modeling would support the **development of intensity measures, damage indices, performance limits, and quantification of consequences of damage**, as discussed previously.

4.3.4 Hybrid Testing

In the long term, **validated sub-structuring methods and models need to be developed for the purpose of very large whole structure testing**, when a large part of the 'test structure' is modeled real time while a smaller portion of the structure is physically tested. For validation of the technique whole-structure tests would be required.

4.3.3 Test-Model Based Certification Protocols

A long-term goal is the **development of a structural certification methodology based on the whole structure response**. This would be an assessment method for the purposes of certification that would be based on performing validated, credible numerical modeling of a whole structure with some minimum (as yet unknown) requirement for structural fire testing and materials characterization. This methodology needs to be developed as the test data and models become available from the studies above. The method could also include a hybrid testing method for more complex systems.

5.0 OPPORTUNITIES AND SPONSORS FOR COLLABORATION FOR NIST

For the reasons noted in Sections 2.3.1 and 3.3 it is difficult to identify obvious sponsors of research intended to further enable PBD of reinforced and prestressed concrete structures. An obvious exception to this is with respect to heat-induced explosive spalling of concrete tunnel linings and structures, where there is clear evidence from real fires of potential safety and economic hazards. Other potential hazards have been identified associated with e.g. unbounded post-tensioned construction [Gales et al. 2011a, b] or precast, prestressed hollowcore concrete slabs [de Feijter and Breunese 2007], however these are not widely perceived as significant problems due to in part an absence of observed widespread failures of real structures. Opportunities and sponsors for collaboration may include the following:

- **The concrete production and construction industry (broadly construed)**: Opportunities may exist to optimize concrete structures for structural fire performance and to demonstrate superior property protection for concrete structures as compared with steel structures (particularly those that have been fire engineered to enable removal of applied fire protection to slab soffits and secondary beams). The concrete industry should consider supporting research to better understand the performance of concrete structures in credible worst case (rather than standard) fire exposures, with a view to demonstrating the resilience and robustness of structural concrete as compared with other types of construction.
- **Critical infrastructure owners**: This includes energy infrastructure such as within the nuclear power industry, transportation infrastructure owners, and emergency services infrastructure, all of whom rely heavily on property protection in fire rather than simply needing to meet the regulatory requirements for life safety during a fire.
- **Producers of high strength and high-performance concrete:** Efforts are needed to reduce or prevent the propensity for heat-induced spalling during fire.

- **Producers of steel and PP fiber materials**: Related to the above, application of fiber materials in concrete have showed to be effective in reducing concrete spalling. There is a financial incentive to steel and PP fiber producers to support research in this area.
- **Producers of novel reinforcing materials**: This includes composite materials such as FRP rebars or prestressing for application in concrete structures. Difficulty in clearly demonstrating adequate fire resistance of FRP reinforced or prestressed concrete structures remains a deterrent to their use.
- **Authorities Having Jurisdiction (AHJs)**: Currently there is a lack of proper calculation guide or standard in most jurisdictions for performance-based design of concrete structures in fire. Engineers may choose to use performance-based method for design of structures when the owners require a higher level of performance, e.g. property protection or rapid recovery after a fire. However AHJs currently suffer a lack of access to tools for evaluation and approval of advanced designs.
- **Government departments and research centers with mandates for preserving public safety**: In some cases where legitimate safety concerns might be raised, government departments should consider public funding in support of research into PBE for the specific types concrete structures in question. This includes state, national, and international research funding agencies.
- **Fire safety engineering consultancies**: Engineering consultancies with specific capabilities in PBE of concrete have a vested interest in increased use of PBE tools, and should consider supporting research in this area in order to promote change within the structural fire engineering community.

5.1 Possible Partners in The Americas (possible first contact names in brackets)

Academic partners with specific interest in fire performance of concrete (alphabetical):

- Carleton University, Canada (J Gales)
- Lawrence Technological University, USA (E Jensen)
- Lehigh University, USA (S Pessiki)
- Michigan State University, USA (VKR Kodur)
- Queen’s University, Canada (M Green)

Academic partners with specific interest in structural fire engineering (alphabetical):

- Lakehead University, Canada (O Salem)
- Princeton University, USA (M Garlock)
- Purdue University, USA (A Varma)
- University of Michigan, USA (A Jeffers)
- University of Texas at Austin, USA (M Engelhardt)

Academic Partners with a specific relevant interest in fire dynamics or fire safety engineering (alphabetical):

- California Polytechnic State University, USA (F Mowrer)
- University of Maryland, USA (J Milke)
- University of Berkeley, USA (C Fernandez-Paello)
- Worcester Polytechnic Institute, USA (L Albano)

Government or pseudo-government research/testing agencies (alphabetical):

- National Institute of Standards and Technology, USA (J Jiang)
- National Research Council of Canada (H Mostafaei)

Other noteworthy potential partners (alphabetical):

- American Concrete Institute – Committee 216, USA (N Lang, National Concrete Masonry Association)
- Cement Association of Canada (R McGrath)
- National Concrete Masonry Association (N Lang)
- Portland Cement Association, USA (S Szoke)
- Precast/Prestressed Concrete Institute, USA
- Underwriters’ Laboratories, USA
- Underwriters’ Laboratories Canada (GA Nanji)

5.2 Possible Partners in Europe (possible first contact in brackets)

Academic partners with specific interest in fire performance of concrete (alphabetical):

- Brunel University London, UK (Z Huang)
- Czech Technical University in Prague, Czech Republic (F Wald)
- ETH Zurich, Switzerland (M Fontana)
- Imperial College London, UK (G Khoury)
- Instituto Eduardo Torroja, Spain (Á Arteaga)
- Politecnico di Milano, Italy (P Bamonte)
- Technical University of Denmark (DTU) (C Hertz)
- Université de Cergy-Pontoise (A Noumowe)
- University of Edinburgh, UK (L Bisby)
- University of Ghent, Belgium (L Taerwe)
- University of Innsbruck, Austria (R Lackner)
- University of Liege, Belgium (J-M Franssen)
- University of Manchester, UK (M Gillie)
- University of Naples Federico II, Italy (E Nigro)
- University of Padua, Italy (B Schrefler)
- Universite de Pau et Pays de l'Adour, France (J-C Mindeguia)
- University of Ulster, UK (F Ali)
- Vienna University of Technology, Austria (M Zeiml)

Academic partners with specific interest in structural fire engineering (alphabetical):

- Instituto Superio Tecnico Lisboa, Portugal (J Correia)
- University of Coimbra, Portugal (A Correia)
- University of Sheffield, UK (I Burgess)
- University of Aveiro, Portugal (P Villa Real)

Academic Partners with a specific relevant interest in fire dymanics or fire safety engineering (alphabetical):

- Delft University of Technology, Belgium
- Institut Nationale des Sciences Appliques (INSA) de Rennes, France
- Lund University, Sweden (P Van Hees)

Government or pseudo-government research/testing agencies (alphabetical):

- BRE Global, UK (T Lennon)
- Centre d'Etudes des Tunnels (CETU), France
- Centre d'Etudes et de Recherches de l'Industrie du Béton (CERIB), France (F Robert)
- Centre Scientifique et Technique du Bâtiment (CSTB), France (P Pimienta)
- Centre Technique Industriel de la Construction Métallique (CTICM), France
- Efectis, Holland (R de Feijter)
- Federal Institute for Materials Research and Testing (BAM), Germany (I Vela)
- Netherlands Organisation for Applied Scientific Research (TNO), Holland
- SP Sweden (R Jansson)
- Swiss Federal Laboratories for Materials Science and Technology (EMPA), Switzerland (E Hugi)

Other noteworthy potential partners (alphabetical):

- AECOM, UK (K Anderson)
- Arup (Fire Engineering), UK (N Butterworth)
- BuroHappold FEDRA, UK (F Block)
- European Federation for Precast Concrete (BIBM)
- Promat (K Both)
- The Concrete Centre, UK (J Burridge)

5.3 Possible Partners in Asia and Australasia (possible first contact in brackets)

Academic partners with specific interest in fire performance of concrete (alphabetical):

- Gunma University, Japan (M Ozawa)
- Hokkaido University, Japan (M Henry)
- Swinburne University of Technology, Australia
- Tokyo University of Science (T Noguchi)
- Tongji University, China (J Yu)
- Tsinghua University, China (L-H Han)
- University of Canterbury, New Zealand (A Buchanan)
- University of Queensland, Australia (J Torero)

Government or pseudo-government research/testing agencies (alphabetical):

- Building Research Institute (BRI) of Japan

Other noteworthy potential partners (alphabetical):

- Cement Concrete & Aggregates Australia (CCAA) (HPG Bakes)

6.0 TECHNOLOGY TRANSFER AND INFLUENCING PRACTICE

6.1 International Symposia

The following international fire safety engineering symposia offer opportunities for technology transfer and influencing practice. In Structural Fire Engineering these include (in order of priority):

- SiF Movement
  (http://www.structuresinfire.com)
- ACI 216 Special Sessions
  (http://www.concrete.org/Default.aspx?TabID=282&committee_code=0000216-00)
- International RILEM Workshops on Concrete Spalling due to Fire Exposure
  (http://fire-spalling.sciencesconf.org/)
- Applications of Structural Fire Engineering Conference Series
  (http://fire.fsv.cvut.cz/ASFE13/)

Fire Safety Engineering:

- International Association of Fire Safety Science Symposia
  (http://www.iafss.org/symposium/)
- SFPE Conferences on Performance-Based Codes and Fire Safety Design Methods
  (http://www.sfpe.org/SharpenYourExpertise/Education/2014InternationalConference.aspx)
- International Symposia on Tunnel Safety and Security (ISTSS) series
  (http://www.istss.se/en/about/Sidor/default.aspx)
- Interflam Conference Series
  (http://www.intersciencecomms.co.uk/html/conferences/Interflam/if13.htm)
- Fire and Materials Conference Series
  (http://www.intersciencecomms.co.uk/html/conferences/fm/fm15/fm15cfp.htm)

6.2 Research-Active Codes and Standards Groups (alphabetical)

- American Concrete Institute (ACI) - Committee 216
  (http://www.concrete.org/Default.aspx?TabID=282&committee_code=0000216-00)
- European Committee for Standardization (CEN) – Horizontal Group – Fire
  (http://eurocodes.jrc.ec.europa.eu/showpage.php?id=232)
- European Federation of National Associations Representing producers and applicators of specialist building products for Concrete (EFNARC)
  (http://www.efnarc.org/pdf/Testing%20fire%20protection%20systems%20for%20tunnels.pdf)
- International Council for Research and Innovation in Building Innovation and Construction (CIB) – Working Group 14 on Fire
  (http://www.cibworld.nl/site/searchn/results.html?wtgtype=W&wtgrid=1)

- Council on Tall Buildings and Urban Habitat – Fire and Safety Working Group (http://www.ctbuh.org/AboutCTBUH/WorkingGroups/FireSafetyGroup/tabid/98/language/en-GB/Default.aspx)
- International Federation for Structural Concrete (FIB) (http://www.fib-international.org/comm-a-tgs)
- RILEM Technical Committee on Spalling of Concrete due to Fire (SPF) (http://www.rilem.org/gene/main.php?base=8750&gp_id=309)

6.3 Networks (in order of priority)

- SiF Movement (http://www.structuresinfire.com)
- Concrete in Fire Forum (www.concretefireforum.org.uk)
- Steel in Fire Forum (www.steelinfire.org.uk)
- TUD COST Action TU0904 - Integrated Fire Engineering and Response (IFER) (http://www.cost.eu/domains_actions/tud/Actions/TU0904)

7.0 MEANS FOR COALITION OF INTERNATIONAL RESEARCH PARTNERS

The authors suggest that the best means for coalition of international research partners would be to ‘piggy-back’ on existing symposia, research-active codes and standards groups, and networks; most notably those already listed above.

7.1 Joint International Research Funding

Currently there is no obvious means for joint international funding between US and international research groups in the area of structural fire engineering. Such earmarked funding is urgently needed in order to support joint work between US researchers (i.e. NIST) and international partners. Co-funding schemes between, for instance, the US National Science Foundation (NSF) and international science and engineering funding partners, as is routinely done in other research areas such as e.g. Materials Science, would be a positive first step in this regard.

7.2 Potential Sponsors

There are no obvious potential sponsors who might support coalition of research partners in the area of PBD for fire of concrete structures (for the reasons already noted).

8.0 CONCLUSIONS

This white paper has presented the current, international, state-of-the-art, large-scale experimental, modeling, and performance-based design (PBD) efforts related to structural fire resistance of concrete structures. The paper has addressed these topics with emphasis on research and development needs for large-scale experiments on fire resistance of structures to support performance-based engineering and structure-fire model validation; prioritizing those needs; phasing the needs in terms of near, medium and long term; identifying the most appropriate international laboratory facilities and collaborators available to address each need; identifying possible means to transfer the results of research to industry; and identifying a means for the coalition of international partners to review progress and exchange information on a regular basis.

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