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LARGE-SCALE STRUCTURAL FIRE TESTING – HOW DID WE GET HERE, WHERE ARE WE, AND WHERE ARE WE GOING?

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ABSTRACT

Structural fire testing is experiencing a renaissance. Both the research and regulatory communities are currently confronting the inherent problems associated with using simplified, single element tests on isolated structural members subjected to standard temperature-time curves to demonstrate adequate structural performance of buildings in fires. Indeed, this international symposium on "Fire Testing and Experimental Validation" is an indication of renewed interest in this area. This involves a shift in testing philosophy from prescriptive standard fire testing to large-scale non-standard fire testing using real fires. This follows more than a century during which the standard fire resistance test has been the predominant means of characterizing the response of structural elements and materials in fires. Large-scale non-standard tests performed around the world during the past three decades have identified numerous shortcomings in our understanding of real building behaviour in real fires; these could not have been observed through standard tests. However, while identifying many of these shortcomings appears as novel insight, many such insights have been well known for decades but have remained largely unaddressed due to the pervasive use of the standard fire test. Only now, with a keen interest in understanding and a willingness to change our testing, design, and regulatory approaches, can these shortcomings be addressed. This paper briefly reviews the available data and knowledge from large scale non-standard fire tests conducted in the past thirty years, and defines current gaps in knowledge and research needs for rational and holistic fire-safe structural design of buildings.

Keywords: real fire tests, standard fire tests, structural fire design, research gaps

1 BACKGROUND AND OBJECTIVES

Structural engineering design of buildings requires attention to many different load types and combinations (i.e., wind, earthquake, etc); however a structure's complex behaviour in fire is currently overly simplified during design. Fire is not typically considered as a load during the structural design of a building. This simplification is justified on the basis of results from standard fire tests of simple building elements or isolated structural assemblies in testing furnaces which subject the loaded elements to a *standard* temperature-time curve. The result of such tests is a time to failure subject to the standard fire; this is termed a fire resistance rating. The current system of fire rating building elements has been in existence since the turn of the last century and remains (largely) unchanged since its initial development, despite major advances in both fire safety science and structural fire modelling. This paper discusses the origins of the standard fire resistance test, some of the limitations in using this for fire testing or design, some of the complexities of the response of real buildings in fire, and the resulting research gaps that currently exist.

The origins of the standard fire test stem from early attempts to make a fire resistive comparison of different building materials and systems to assess claims of "fire proof" construction in the late 19th century (Woolson, 1916). The fire resistive principal, originally studied by Ira Woolson, was not meant to be a final 'solution' to the structural fire design and regulatory problems that were being encountered at the turn of the 20th century; rather it was meant to serve as a practice correction at that time, specifically in the wake of the Baltimore and San Francisco conflagrations (Fitzpatrick and Condron, 1914). At that time, the building construction industry was being flooded with various 'fireproof' building system patents which had either never actually been tested or which failed to provide appropriate levels of protection in real fires (Fitzpatrick and Condron, 1914). The standard fire test thus emerged as a test for comparative performance in the most severe possible fire. The earliest references to standard fire resistance tests are found from New York, a city which was undergoing rapid innovation in construction during the late 1800s, brought on by novel lightweight structural designs (e.g. the emergence of corrugated iron and concrete composite floor systems). Structural configurations and materials were quickly changing in efforts to save space and build higher.

The city's building fire codes initially began with the restrictions on certain structural materials known to be problematic in fire (New York Building Code, see Smith, 1905), but subsequently called for comparative performance of materials in floors and partitions for strength in fire *and after cooling*. Walls and floors were crucial for *stopping fire spread* and *preventing conflagrations* in dense urban centres. The original test for a floor (though not a national standard at the time) called for a sustained 'average' gas phase temperature equivalent to 927ºC (1700ºF) for 4 hours (with peaks to 1093 ºC (2000ºF)), hose stream cooling, and finally residual testing to higher loads (4 times the sustained fire service load) for a further 24 hours. If after this test the floor's deflection did not exceed 1.4% of its span, the element was assumed to have 'passed' (Stewart and Woolson, 1902). See Figure 1. The thermal scenario was *intended* to be more severe than a real fire – according to popular opinion "*no ordinary room would have enough inflammable material in it to maintain a 1700ºF fire for more than 30 minutes*". The basis for this heating regime was fire fighters' qualitative experience in New York. Ira Woolson stated regarding his test method, "*when fearful consequences may result from a failure of a structure due to fire, no test is too severe which reasonable care and expense in construction can resist*". Similar work was also underway in the UK at this time led by Edwin Sachs (Sachs, 1902).

Fig. 1 Ira Woolson's 'furnace' in 1902 (Stewart and Woolson, 1902)

Changes to the *standard* time temperature curve were made through the years in various iterations of ASTM standards (though with increasingly less emphasis on residual capacity of the elements after a fire), and by the late 1920s the fire test had been extended to include columns and other various structural elements (Hull and Ingberg, 1925); evolving into the various similar standard fire test(s) currently used internationally. Even in the late 1920s however, it was widely known that the standard fire was by no means representative of reality, and efforts principally by Simon Ingberg (1928a) began to correlate a fire *severity* – using measurements from real burn out compartment tests – to the standard fire curve based on the Equal Area Concept. Other researchers continued with the development of new concepts of equivalent fire severity based other severity metrics (Maximum Temperature Concept, Minimum Load Capacity Concept, and Time-Equivalent Formulae). Buildings could then be re-classified, not only by fire activation risk, but also by functions of fuel load, and building elements which had 'equivalent' standard fire resistance times could then be specified. Today, fire safe structural design still relies predominantly on the concepts of equivalent fire severity, and is based on a considerable oversimplification of real fire (and structural) behaviour by assuming unrealistic standard fires for design and comparative fire testing.

By the early 1980s, over-reliance on standard fire testing was widely recognized as limiting innovation in architecture and construction, and technical papers began to appear which openly questioned the rationality and applicability of standard fire tests. For example, pioneering fire engineer Margaret Law noted that (Law, 1981);

1. the standard temperature-time curve is not representative of a real fire in a real building – indeed it is physically unrealistic and actually contradicts knowledge from fire dynamics;
2. the required duration of fire exposure in the standard test (or the time equivalent exposure) is open to criticism on a number of grounds and should be revisited; and
3. the loading and end conditions are not well defined – and clearly cannot represent the continuity, restraint, redistribution of loads, and membrane actions in real buildings.

Fire engineering researcher David Jeanes (Jeanes, 1982) also commented in 1982 that "*although the traditional approach of assigning time for a given structural element or assembly allowed for a comparative measure between different types of construction; it is hard pressed to represent actual structural performance in a real fire due factors of restraint, redistribution of loads, moment resistance, as these are difficult to quantify and duplicate in tests*."

While admittedly structures fail only very rarely in fires, when they do fail it is almost always for reasons that would not be expected on the basis of standard fire resistance testing (Beital and Iwankiw, 2008). The complexities of a real fire and real buildings are not captured in standard tests (Figure 2, discussed later). Efforts made in testing and design for other extreme loads such as earthquake and wind design have advanced tremendously over the past century, however the fire community still uses (essentially) the same (oversimplified) principals developed more than a century ago to 'demonstrate' or 'certify' fire safety in buildings.

The structural fire engineering community is now waking up to the pitfalls of using standard fire testing and the opportunities that a more rational approach might present. A gradual shift in testing philosophy to large scale non-standard fire testing using real fires, rather than standard temperature-time curves, seems now to be underway, and a fire testing renaissance is occurring aimed at not merely capturing the comparative structural performance of isolated

Structural Model / Fire Model		Materials & Partial Elements	Single Elements	Sub-Frame Assemblies	Transiently Simulated Restrained Assemblies	Full-Scale Structures
Elevated Temperature Exposures (transient or steady-state)	T, Steady-state, Transient-state, t	Generate design/model input data	O/R [T]	M/C	M/C	M/C [E.1-2]
Standard Fires	T, ISO 834, t	Generate design input data	**Obtain fire resistance ratings (STANDARD)** [T]	O/R [O]	M/C [W]	M/C [A]
Equivalent Fire Severity to a Standard Fire	T, ISO 834, t	Validation of fire severity concept	Obtain fire resistance ratings (using alternative metric for fire severety) [Q]	O/R	O/R	M/C [B];[G];[N]
Parametrically Defined Model Fires	T, Fire = f ( ), t	Generate design input data (highly dependant time-temperature phemnomenon)	O/R	O/R [K];[M];[R];[S]	O/R	O/R [E.3-5]; [H];[J];[L];[U];[V]
Localised Model Fires		Generate design input data (highly dependant time-temperature phemnomenon)	O/R	O/R	O/R	O/R
Zone Model Fires		Research (highly dependant time-temperature phemnomenon)	M/C	O/R	O/R	O/R [I]
Field Model Fires		Research (highly dependant time-temperature phemnomenon)	M/C	M/C	O/R	O/R
Real Fires	T, Real fire, t	Research (highly dependant time-temperature phemnomenon) [P]	M/C	M/C [C];[D];[F]	O/R	**Research REAL behaviour in a REAL fire** [E.6]

M/C− of Marginal Credibility; O/R− used for Occasional Research

* Reference Table 1

Fig. 2 Objective of structural fire testing based on the structural assembly and the time-temperature exposure

Table 1 Non-standard large scale tests

Test*	Year	Name of the test and/or main institution involved	Reference
[A]	1982	AISI / NBS, USA	Jeanes, 1982
[B]	1985	Stuttgart-Vaihingen University, Germany	British Steel, 1999
[C]	1992	BHP - William's Street, Australia	British Steel, 1999
[D]	1994	BHP - Collins Street, Australia	British Steel, 1999
[E]	1996	British Steel and BRE Cardington (six tests)	British Steel, 1999
[F]	1998	CTICM, France	Vassart and Zhao, 2011
[G]	1999	BRE Cardington, United Kingdom	Lennon et al., 2000
[H]	2001	BRE Cardington, United Kingdom	Bailey, 2002
[I]	2003	BRE Cardington, United Kingdom	Wald et al., 2006
[J]	2003	CTU, Cardington, United Kingdom	Wald et al., 2006
[K]	2006	CTU, Ostrava, Czech Republic	Chlouba et al., 2009
[L]	2007	Harbin Institute of Technology, China	Dong and Prasad, 2009a
[M]	2007	BRE, United Kingdom	Bailey and Lennon, 2008
[N]	2008	CTU, Mokrsko, Czech Republic	Wald et al., 2010; Chlouba and Wald, 2009; Wald, 2011
[O]	2008	FRACOF, Metz, France	Vassart and Zhao, 2011
[P]	2008	COSSFIRE, Metz, France	Vassart and Zhao, 2011
[Q]	2010	Hong Kong Polytechnic University, China	Wong and Ng, 2011
[R]	2010	CCAA-CESARE, Australia	CCAA, 2010
[S]	2010	University of Ulster, United Kingdom	Nadjai et al., 2011
[T]	2011	TU, Munich, Germany	Stadler et al., 2010
[U]	2011	TU, Vienna, Austria	Ring et al., 2011
[V]	2011	University of Edinburgh / Indian Inst. of Tech., Roorkie, India	Sharma et al., 2012
[W]	2011	NRC, Ottawa, Canada	Mostafaei et al. 2011a; Mostafaei et al. 2011b
[X]	2011	CTU, Veseli, Czech Republic	Wald et al., 2011
[Y]	Planned	University of Victoria / CESARE, Melbourne, Australia	Proe and Thomas, 2010

* Reference Table 2 and Figure 2

materials, but at rationally defining the full suite of interactions to be expected in real buildings in real fires. A survey of the literature (e.g. Almand, 2012) shows that more than thirty such tests have been performed internationally during the last 30 years. Much like the boom in early structural fire testing following the conflagrations of the early 20th century, which led eventually to the standard fire test (and which has apparently 'largely' resolved the conflagration issue in the developed world), the majority of these large scale structure fire tests occurred after tragic events such as September 11th 2001 and have demonstrated unique structural fire failures which are not captured by current standard fire test practices.

Given the goal of the current symposium within this conference on experimental mechanics, this paper discusses non-standard large scale structural fire testing, giving several examples or exemplar tests available in the literature and identifies knowledge gaps and research needs identified in these tests – specifically with respect to fire exposure (dynamics), measurement methods, structural optimization issues, and failure modes and definitions. Through a review of the literature in this area it is clearly shown that many needs have been identified in the past 30 years through large scale non-standard fire tests but remain unaddressed.

2 REPRESENTATIVE NON-STANDARD LARGE SCALE STRUCTURAL FIRE TESTS

Many large scale non-standard fire tests are reported in the literature (refer to Table 1), however it is beyond the scope of the current paper to describe all of these. Table 2, which runs throughout this paper at the bottom each page, provides a timeline of the various large scale non-standard tests which have been performed around the world since 1982, along with a brief description of the test performed and a reference to the original testing report or research publication. No significant discussion of Table 2 is included in the current paper, but the interested reader is encouraged to consult the source references provided.

The renaissance of large-scale structural fire testing started with tests performed by the American Iron and Steel Institute (AISI) and the National Building Standards (NBS) in the early 1980s with the objective of assessing the *global* behaviour of steel-concrete composite frame structures and validating a computer model, FASBUS II, for structural response to fire (Jeanes, 1982). A large scale non-standard structural fire test was executed circa 1982, on a two story, four bay (4.9 m × 6.1 m each in plan), composite steel-framed building. The test structure as meant to represent a corner section of a typical mid-rise office building.

A fire compartment was built into the corner bay of the structure. A fire load was supplied by propane burners which 'reproduced' 100 minutes of the ASTM E119 (ASTM, 1980) standard time temperature curve. Water tanks were used to simulate the design live loads. This test

Table 2(a) Non-standard large scale tests time line (1982-1992)

1982	1985	1992
AISI/NBS, USA	**Stuttgart-Vaihingen Univ., Germany**	**BHP - William's Street, Australia**
Two storey, four bay steel frame with concrete slab (9.75 × 12.2 m), fire exposure using a ASTM E119 furnace curve. Validated the computer modelling program, FASBUS. [A]	Water and concrete-filled columns with composite steel concrete construction, fire exposure using timber cribs. Demonstrated the performance-based refurbishment of building post fire. [B]	Steel concrete composite frame (4 × 4 m compartment), fire exposure using office furniture. Demonstrated use of sprinkler system to prevent collapse, suggested fire protection was not necessary for underside of composite slab. [C]

demonstrated ‘full structure’ response to a fire, and highlighted a number of differences in response between the performance of a real structure and the performance of an isolated structural element, albeit in both cases under a standard fire heating scenario. Despite the compelling evidence provided by this early test that standard fire testing is not representative of reality, it was more than 10 years before the next major test programme was performed, this time in the United Kingdom but again supported by the steel industry.

During 1996 a number of exemplary large-scale non-standard structural and non-structural (fire dynamics) fire tests were performed in an eight story composite steel-framed test building constructed at the Cardington test site of the UK Building Research Establishment (British Steel, 1999). This test program surely represents the most comprehensive and realistic test series that has ever been performed, and is a key reason why the steel industry has been able to aggressively promote performance-based structural fire design in the subsequent decades, with significant economic and sustainability benefits in steel-framed buildings. The 21 m × 45 m building was three bays by five bays, and had a total height of 33 m. All beams were designed as simply supported, acting compositely with a floor slab on steel decking. Beam-to-beam connections were made using fin-plate connections and beam-to-column connections using flexible end plates. Sandbags were used to simulate gravity loads for typical office occupancy in the tests. In particular, Test #6 of Cardington’s 1996 tests series was meant to assess the global structural behaviour of a large rectangular corner-compartment. The fire load was given by representative office furniture, which, based on previous fuel surveys, resulted in more fuel than the 80% fractile fire load recommended by the European standards. In this test, as with most compartment fire tests performed during the Cardington test program, the columns were protected to avoid local buckling as was experienced in one of the early tests. A subsequent Cardington test was performed in 2003 (Wald et. al, 2006). All of the compartment fire tests executed during the Cardington tests series were done exposing the structure to both a heating and cooling phase; in some occasions this resulted in failures (local buckling near the connections and cracking of the composite slabs) during the cooling phase. This behaviour has also been seen in real fires and in other non-standard large scale structural fire tests (e.g. Harbin, China in Dong and Prasad, 2009) reviewed for this paper. Taken together, the seven Cardington tests demonstrated many important aspects of the full-structure response of composite steel-framed buildings during fire. In particular, they shed light on the secondary load carrying mechanisms which can be activated during fire to prevent collapse, the potential importance of restraint to thermal expansion on heating (and thermal contraction on cooling) on localized buckling and/or connection failures, and the fact that full-structure response in fire is markedly different than that observed in standard fire resistance tests performed in furnaces. In the case of regular grid plan composite steel-framed buildings such as the one tested at Cardington, the

Table 2(b): Non-standard large scale tests time line (1994-1996)

1994	1996	
BHP - Collins Street, Australia	**British Steel and BRE, Cardington, United Kingdom**	
Steel concrete composite frame (8.4 × 3.6 m), fire exposure using office furniture. Test argued no fire protection for beams and external steel columns were necessary. [D]	Steel concrete composite frame, Test 1 of restrained floor beam assembly (9 m), fire exposure using a purpose built gas furnace. Test observed tensile failure of connections during cooling. [E.1]	Steel concrete composite building, Test 2 of long pane frame (21 m), fire exposure using a purpose built gas furnace. Non protected column portions buckled locally, shear failure of bolts in cooling. [E.2]

fire resistance appears to be far greater than is normally assumed on the basis of standard furnace tests.

In 2001, as part of the European Concrete Building Project (Bailey, 2002), a test on a seven storey reinforced concrete building was performed, also at the Cardington UK test site. The full-scale building represented a typical commercial office building. The three bays by four bays building had total dimensions of 22.5 × 30 m, with two core areas, which included steel cross-bracing to resist lateral loads. The test took place inside a 15 m × 15 m ground floor compartment. The main purpose of the test was study the global behaviour of the reinforced concrete building, with special attention in assessing the influence of restraint from the surrounding cold structure. Also, the impact of spalling on the structure's load-bearing capacity was a focus of the analysis. Vertical loads were applied, throughout the whole building, by means of evenly distributed sand bags, replicating design imposed loads, partitions, raised floor, ceiling and service loads. The fire load was given by timber cribs evenly distributed (40 kg/m^2) to simulate one of Eurocode's parametric fire (CEN, 2004). 40 kg/m^2 is known as a representative fuel loading of an office structure (see Lennon and Moore, 2003). Structural stability was maintained during testing. However, significant deformation of perimeter columns was observed. This was attributed to lateral thermal expansion of the slab undergoing compressive membrane action. Severe spalling of the underside of the floor slab was also observed, starting six minutes from the start of the test. This was attributed to the high in-plane compressive stresses within the slab undergoing compressive membrane action. This test again demonstrated that the performance of real structures in real fires is markedly different than the response of isolated elements tested in standard furnaces, both in terms of structural response and potential failure modes.

In 2010, Cement Concrete & Aggregates Australia in collaboration with the Centre for Environmental Safety and Risk Engineering, executed a large scale non-standard fire test inside a 30 m^2 purpose built fire test enclosure (CCAA, 2010). In this test, post-tensioned concrete slabs and high strength concrete columns were tested. The fire load was given by timber cribs evenly distributed at 124 kg/m^2 within the enclosure, in order to replicate the AS 1530.4 (AS, 2005) standard time-temperature curve (similar to ISO 834 (1999) used in Europe). A number of variables were studied to assess the behaviour of the post-tensioned members exposed to fire with a particular focus on propensity for explosive concrete cover spalling – e.g. concrete compressive strength, aggregate type, addition of polypropylene fibres, and spacing of reinforcement ties. The assessment of multiple variables in large scale structural fire is common practice due to the high costs and time involved in the execution of these types of tests. No realistic mechanical restraint was provided during testing, and members were tested as single elements, despite the fact that all of these issues are known to

Table 2(c): Non-standard large scale tests time line (1996)

1996 (continued)

British Steel and BRE,
Cardington, United Kingdom

Steel concrete composite building, Test 3 of floor compartment (9 × 6 m), fire exposure using timber cribs. Test observed membrane actions and load path changes, structure behaved 'well'. [E.3]	Steel concrete composite building, Test 4 of floor compartment (9 × 6 m), fire exposure using timber cribs. Test observed interaction between exposed and non-exposed structure. [E.4]	Steel concrete composite building, Test 5 of large compartment (18 × 21 m), fire exposure using timber cribs, though not as severe as tests 3 and 4. Test observed connection failures in cooling. [E.5]

be crucial in real structures during fire. The analysis of the test results only confirmed that the addition of polypropylene fibres reduced propensity for spalling.

The above paragraphs highlight a handful of the large scale non-standard tests available in the literature. Due to the costs and uniqueness of non-standard large scale structural fire tests, such tests are typically densely instrumented with the objective of gleaning as much useful information as possible. Thermocouples (measuring gas and structural elements' temperatures, at the surface or embedded inside elements), plate thermometers, heat flux metres, pressure gauges, displacement gauges (mechanical and laser based), load cells, inclinometers, GPS based monitoring displacement system (Ring et. al, 2011), video cameras, thermal imaging cameras, and other means of visual and acoustic (particularly for assessing the occurrence of fire induced spalling) sensors have all been used in many of the tests reviewed for this paper.

3 THE STANDARD FIRE TEST VERSUS REALITY

The full suite of non-standard large scale structural fire tests reviewed for this paper (see Table 2) present an opportunity to identify real structural responses (and failure modes) when subjected to real fires, and then to use this knowledge to predict the behaviour of coupled building systems in fire. Unfortunately, in many cases, the tests failed to address the importance of using a realistic fire exposure by explicitly choosing to replicate a *standard* time-temperature curve by the burning of a fire load (e.g. timber cribs, gas burners, pool fire, etc.) under a pre-calculated ventilation condition. In only a few occasions has the aim been to replicate a realistic, dynamic fire with the spatially and temporally variable thermal conditions which this implies (non-homogeneity, high increase of temperature during flashover, and cooling phase). It is the authors' view that this clearly exposes a lack of understanding of fire dynamics and heat transfer from the structural fire testing community. In many cases, researchers have chosen to increase the complexity (realism) of the tests by scaling up the realism of the structural assembly or system tested, without similarly scaling up the complexity (realism) of the fire scenario.

In developing and performing a large scale non-standard fire test, researchers should apply the principle of 'consistent crudeness' (Buchanan, 2001). This principle was originally coined by Platt et al. (1994) in describing a defensible approach to computational modelling of structural response to fire, in that modellers must use similar degrees of crudeness in performing a structural analysis for fire as they do in modelling the thermal insult to the structure. It is not defensible to perform a detailed computational fluid mechanics analysis of a fire scenario and then impose this on an isolated concrete beam, nor is it defensible to apply the standard fire exposure to a detailed multi-storey finite element model of a building – the same principle

Table 2(d): Non-standard large scale tests time line (1996-1999)

1996 (continued)	1998	1999
British Steel and BRE, Cardington, United Kingdom	**CTICM, France**	**BRE, Cardington, United Kingdom**
Steel concrete composite building, Test 6 of floor compartment (162 m^2 not square), fire exposure using office furniture. Steel mesh lap error during construction, cracking around columns developed during cooling. [E.6]	Car park building, unprotected composite steel concrete frame (16 × 32 m), fire exposure using 3 cars, beams reached a temperature of 700ºC with no collapse. Tests highlighted beneficial membrane actions. [F]	Timber frame building, compartment fire (24.1 × 12.4 m). fire exposure using timber cribs, global behaviour assessed as well. Some worries over potential for fire spread in adjoining compartments and vertically through the windows. [G]

applies to large scale non-standard structural fire testing. An attempt to partly address these issues has been carried out at the NRC (2011), by implementing a system (Hybrid Fire Testing) in which single elements are tested and mechanical boundary conditions are transiently modified in a loop feedback system, in order to replicate those in a real building in fire (see entry 2:4 in Figure 2). To the knowledge of the authors, this system has only been executed using a standard fire test, and although a number of the assumptions, both in the thermal and mechanical domain, have not been fully resolved, this approach represents one of the few efforts in realistically replicating the mechanical boundary conditions in fire.

The implications of the principle of consistent crudeness with respect to structural fire testing are shown schematically in Figure 2, where possible options for treatment of both experimental fire exposure and structural test assembly/configuration are shown in a matrix format. The vertical axis shows the levels of complexity with which the ‘fire’ can be treated (from simple, steady-state or transient heating all the way up to a real fire), and the horizontal axis shows the complexity of the ‘structure’ from material and component testing all the way up to a real, three-dimensional structure. Selected cells in the matrix show what the objective of using a particular combination of fire and structural model might be. For instance, entry 2:2 in the matrix shows the combination of a standard fire curve with a single structural element – this is the standard fire test from which all prescriptive structural fire resistance ratings are obtained.

In order to ensure consistent crudeness in structural fire testing, diagonal movements should be followed in the table, with increasing complexity in both the vertical and horizontal directions; this leads naturally to the 8:5 entry, which represents real building response to a real fire. It is noteworthy that while most structural engineers will understand the important differences between material or member testing and full structure testing in terms of structural response, very few are sufficiently competent in fire science to understand the important differences between uniform heating, the standard fires, a zone fire model, a field fire model, or a real fire. One consequence of this is that most large scale structural fire tests which have been performed over the years have sought to reproduce the standard fire, rather than to simulate a real fire. Paradoxically, it is the authors’ belief that most of the true opportunities in structural fire engineering will be found by taking more rational account of the fire, rather than by increasing the complexity of our structural test assemblies.

Also given in Figure 2 are assessments of whether certain combinations of fire and structural simplification are used for occasional research (O/C) or are of marginal credibility (M/C) in the opinion of the authors. It is clear from the matrix that the structural fire engineering community takes far more account of realistically treating the structure than realistically treating the fire, and in doing so we head closer toward the areas of the matrix with marginal credibility.

Table 2(e): Non-standard large scale tests time line (2001-2003)

2001	**2003**	**2003**
BRE, **Cardington, United Kingdom**	**BRE,** **Cardington, United Kingdom**	**Czech Technical University (CTU),** **Cardington, United Kingdom**
Concrete frame building, Compartment floor fire (2 × 2 bays, 225 m^2), fire exposure using timber cribs. Compartment failed and most instrumentation lost, beneficial membrane action demonstrated in building, spalling observed. [H]	Eight hollow core concrete frame building tests (12 × 12 m), fire exposure using timber/plastic cribs. Tests studied fire dynamics of growth, burning, and cooling stages of fire studying effect of Insulation, openings, and fuel load. [I]	Steel concrete composite building, of large compartment (11 × 7 m), fire exposure using timber cribs, loaded to 56% of its ambient temperature capacity. Cracking occurred at column heads, sustained greater deflections than earlier tests. [J]

4 KNOWLEDGE GAPS AND RESEARCH NEEDS IN STRUCTURAL FIRE TESTING

Considering the complexities of real fires in real buildings shown in Figure 2, structural fire testing is a difficult and complicated endeavour. The last 30 years of non-standard large scale fire testing (refer again to Table 2 and Figure 2) have demonstrated renewed scientific interest in the various issues involved, however considerable research is still needed to safely define the true behaviour of real structures in real fires.

4.1 Fire Behaviour

As noted by authors going back to (at least) 1981, the standard temperature-time curve is not representative of a real fire in a real building. In order to truly understand the response of real buildings in real fires, tests of structures and structural elements are required under credible worst case natural fire exposures. Depending on the type of structure and the occupancy under consideration, 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 the standard fires.

Investigations into combustion and the affects of ventilation on real fires had begun in the late 1700s (Richardson, 2003). At this time it was well known that ventilation, fuel load, and other factors could affect the behaviour of a fire in a building (Holland, 1793). However no rational method of fire prediction was available during this time. Real fire behaviour was not really considered in any meaningful way until Simon Ingberg's 1928 paper on the severity of building fires. Ingberg's contribution was to relate the standard fire to an 'equivalent' real fire on the basis of a 'time-temperature-energy' comparison. Ingberg simplified real fire behaviour using a prescriptive approach of relating fuel load to the standard fire time by 'implicitly' including most other effects known to govern fire behaviour; *"shutters in the walls were regulated to give what was deemed to be the proper amount of air for maximum fire conditions within the room"* (Ingberg, 1928a). This method proved popular, largely because it enabled the fire testing community to continue to use the standard fire despite the acknowledged (even in 1928) unrealism. Ingberg's work still serves as a fundamental basis for contemporary standard fire resistance rating requirements.

The simplification of complex real fire behaviour continues in current practice. The Eurocode's parametric fires (CEN, 2004), for example, seek to empirically account for various factors such as fuel load, type, ventilation conditions, thermal properties of the boundaries, radiant heating from walls, compartment size, etc. These fires represent the most

Table 2(f): Non-standard large scale tests time line (2006-2007)

2006	2007	2007
CTU, Ostrava, Czech Republic	**Harbin Institute of Technology, China**	**BRE, United Kingdom**
Steel concrete composite building (3.8 × 6 m), fire exposure using timber cribs, only gas and steel temperature measured. No structural implications discussed. [K]	Steel concrete composite frame (2, 3.6 × 3.6 m bays), fire exposure using four oil fired burners. Beam to column connections failed in cooling, tensile cracking of slabs observed near ends. [L]	Hollow core prestressed concrete slab building (18 × 7 m), fire exposure using timber cribs. Test demonstrated that properly designed and detailed buildings would behave well in a fire, with some cooling phase fractures though. [M]

'advanced' fire models which would typically be used for structural fire analysis is most building structures. However, as recently as 2003 compartment tests performed in the UK (Lennon and Moore, 2003), relating parametric fires to real fire behaviour showed problems with this approach. The Parametric fires were developed on the basis of fires in small compartments which are not representative of many modern 'open' structures. It is well known that a fire does not behave homogenously within a compartment (even in Ingberg's time (1928)) and that temperatures exceed those considered 'average' (Stern-Gottfried et al. 2009). To date, no modern non-standard large scale fire test has considered the global structural effect (loss of stiffness to the frame to maintain beneficial membrane actions etc.) of a travelling vertical fire.

In the absence of additional test data to verify new fire behaviour models for various types of modern structural configurations, we are forced to extend empirical fitted relations which may not hold, making our predictions and structural design for safety in fire sometimes difficult to justify. To hold true to the original intention that a structure is to be designed for the credible worst case fire, we must better understand (and implement in design) true fire behaviour and its effects on different building materials and configurations.

4.2 Measurement Methods

Some large scale non standard fire tests had been conducted prior to 1980 (e.g. Ingberg, 1928b). Most of these tests considered wooden structures, which were mostly functions of easily observable qualitative charring analysis (Holland, 1793). Qualitative analysis can be limited; subsequently with improved technology around 1900, quantitative measurement of structures in fire emerged that considered deflection and temperature measurement (see Stewart and Woolson, 1902). Today, non-standard large scale structural fire tests are densely instrumented, further increasing the costs and time to setup, as well as adding a degree of practical complexity to the actual execution of the test.

Most SFE authors agree that more complete data are required from both standard and non-standard structural fire tests. Better information on strains and displacements during testing would allow a more accurate understanding of response, and would provide additional data which are essential for high quality computational model development and validation. The need for new types of sensors, such as wireless sensors to be used during fire tests, has been noted previously (Kodur et. al, 2011). However, the authors of the current paper feel that what is really needed is a better understanding of what is being measured; i.e. What should be measured in order to truly understand the global performance of the element of the structure being tested?

Table 2(g): Non-standard large scale tests time line (2008)

2008	2008	2008
CTU, **Mokrsko, Czech Republic**	**FRACOF,** **Metz, France**	**COSSFIRE,** **Metz, France**
Steel concrete composite building (12 × 18 m), mix of different components and structural systems. fire exposure using timber cribs. Various localized failure modes were observed using a variation of instrumentation. [N]	Steel concrete composite sub frame (8.8 × 6.7 m), corner compartment fire, fire exposure using gas furnace. Insulation integrity failure due to improper mesh lapping, though system behaved well in heating and cooling. [O]	Steel concrete composite sub frame (6.7 × 9 m), corner compartment fire, fire exposure using gas furnace. No global collapse despite flexural failure of secondary beam, rated building achieved its standard fire rating time. [P]

4.3 Structural Optimization

Modern structures are highly optimized, increasingly by the use of sophisticated computer analysis, in an attempt to reduce the mass, cost, environmental impact, carbon emissions, and embodied energy in buildings (Terrasi, 2007). Modern structures also increasingly make use of innovative materials, such as high strength, self-consolidating concrete, fibre reinforced polymers (FRPs), structural adhesives, stainless steel, etc, and innovative structural systems such as unbonded post-tensioned flat plate concrete slabs, the responses of which during fire are not well known in many cases. New materials and structural systems must be rationally understood before they should be applied with confidence in buildings; such an understanding demands large-scale non-standard fire testing, in particular because the standard furnace tests that were developed for conventional construction materials and systems are based on structural response and failure definitions which often are not applicable to the innovative ones (e.g. Bisby and Kodur, 2007).

4.4 Structural Interactions and Asymmetry

The available test data from large-scale non-standard fire tests, while extensive, still cover only a tiny fraction of the possible structural configurations that are represented within the current global building stock, let alone the highly optimized and sustainable buildings of the future. With a few notable exceptions, the majority of structural fire tests conducted to date, whether standard or non-standard, have studied regular, symmetrical, highly idealized structures. Modern structures increasingly make use of irregular floor plates with varying span lengths, bay sizes, construction types, etc. The possible influence of irregular floor plans and complex building forms needs to be investigated, both experimentally and numerically, if performance-based structural fire engineering of both conventional and modern buildings is to be credibly performed with confidence. Indeed the importance of irregular building layouts, the position of service cores, and lateral restraint to thermal expansion are already known (through computational modelling studies of real highrise buildings) to be potentially important for full-structure response to fire.

4.5 Compartmentation and Fire Spread

To date, most large-scale structural fire testing has focused on prevention of structural collapse during fire, and relatively little attention has been paid to preservation of compartmentation under large deformations in real structures during fire; this is particularly of concern given the large floorplate deflections and wide discrete cracking which have been widely observed in large-scale fire tests on steel-concrete composite slabs (refer to the Cardington tests). The impacts of vertical and lateral deformations of structural frames on fire stopping and both horizontal and vertical compartmentation should be studied in order to

Table 2(h): Non-standard large scale tests time line (2010)

2010	2010	2010
Hong Kong Polytechnic University, China	**CCAA-CESARE, Australia**	**University of Ulster, United Kingdom**
Reinforced concrete (7.8 × 4.8 m),. fire exposure using ethanol pool fire, spalling and associated protection of concrete columns emphasized from tests. [Q]	Multi strand post tensioned slabs on high strength columns (6 × 5 m), fire exposure using timber cribs, spalling primarily observed with some remedial design suggestions regarding polypropylene fibres. [R]	Composite steel (cellular)-concrete building (15 × 9 m), fire exposure using timber cribs, unprotected cellular beams demonstrated beneficial membrane action. [S]

preserve life safety in buildings which are now becoming ever more reliant on defend-in-place life-safety strategies (for instance in highrise buildings where fire safety strategies are often fundamentally based on the assumption that a fire will be confined to the floor (and even room) of origin and phased evacuation is put in place).

Furthermore, given that many structural fire engineers already have serious concerns about the quality of installed fire stopping between floors in multi-storey buildings, large-scale non-standard fire tests should perhaps be considered in which vertical fire spread is explicitly simulated using natural fires to evaluate the structural impacts of credible worst case fires burning simultaneously on more than one floor of a structure.

4.6 Detailing and Construction Errors

Taken together, the large-scale non-standard fire tests reported in the literature highlight a number of important construction details and potential construction errors which may appear inconsequential to a building contractor, but which may have a profound impact on the structural fire response and integrity of a building during fire. Examples of this include integrity of fire stopping during large deformations (refer to above), lapping of steel reinforcing mesh, anchorage of steel reinforcing mesh over shear studs on protected perimeter beams, use of deformed versus smooth bars for reinforcement (potentially leading to strain localization and tensile failure of deformed steel bars during fire), proper anchorage and grouting of hollowcore slabs, use of specific types of bolted steel connections to promote connection ductility and rotational capacity during fire, quality, uniformity, and robustness of structural fire protection materials (either passive or intumescent), and so on. Serious unknowns continue to surround many, if not all, of these issues, and there is a need for testing to support the development of best practice guidance which can be used to provide quality assurance programs on construction sites of so-called ‘fire engineered’ buildings.

4.7 Cooling Phase Behaviour and Residual Capacity

A number of localized structural failures or adverse structural responses of steel connections, concrete flat plate slabs, and hollowcore slabs have been observed during the cooling phase of both real fires in real buildings (e.g. Firehouse.com, 2004; Bamonte et. al, 2009) and non-standard heating regimes in large-scale structural fire experiments (e.g. Bailey and Lennon, 2008; British Steel, 1999). Structural actions resulting from creep, localised and/or global plastic deformation, local buckling, and thermal contraction and restraint, all need to be better understood for all types of structures if designers are to realistically be expected to design for burnout of a fire compartment without structural collapse (which was the explicit intent of current SFE requirements when originally envisioned and developed during the 1920s).

Table 2(i): Non-standard large scale tests time line (2010-2011)

2011	2011	2011
TU, Munich, Germany	**TU, Vienna, Austria**	**University of Edinburgh / Indian Inst. of Tech., Roorkie, India**
Steel-concrete composite (5 × 12.5 m), fire exposure using timber cribs, information is currently sparse on these tests. [T]	Reinforced concrete frame abutment, fire exposure gas burners, demonstrated benefits of polypropylene fibres to prevent spalling and give unusual structural shape data for model development. [U]	Reinforced concrete building (9 × 12 m), fire exposure using kerosene pool fire, frame was pre damaged to simulate fire after a earthquake without collapse, no spalling observed. [V]

Furthermore, the residual structural capacity of fire damaged structures which have undergone large deformations is not well known, meaning that many fire-damaged structures will need to be demolished after a fire (e.g. New York Times, 1997). This is particularly true for so-called fire-engineered composite steel frames, which explicitly *rely* on large deformation behaviours to mobilize the tensile membrane actions in fire which are necessary to support gravity loads (British Steel, 1999).

4.8 Data for Model Calibration, Validation and Verification

Experimental data are essential for calibration, validation, and verification of both existing and emerging computational modelling techniques to simulate the response of structures and structural elements in fire. This requirement holds both at the material level and at the structural (i.e. system) level. As noted by Kodur et al. (2011), high-temperature constitutive material models are needed to generate reliable input data for models and to better understand system response to fire and possible failure modes. Such data must be developed using an appropriate framework for understanding the stress-temperature-time-strain interrelationships at play in most engineering materials. An excellent framework for materials characterization at elevated temperature has been presented more than two decades ago by Anderberg (1986), but the complexities shown in this framework are rarely explicitly acknowledged in SFE analysis or design.

4.9 Connections

As noted previously, a range of studies have already been performed on connection performance in fire (largely for steel structures) (e.g. Ding and Wang, 2007; Yu et. al, 2009; 2011; Yuan et. al, 2011). However, given the range of possible connection types, full-structure responses to fire, and failure modes, additional research is needed to better understand the full range of possible connections, to develop and validate computational modelling capabilities to predict connection response, and to suggest best practice guidance to steel fabricators on the types of connections which should be applied in practice to ensure structural robustness in fire. Proper details for the connection of precast concrete elements in buildings to ensure robust performance in fire is also required (Bailey and Lennon, 2008). Important lessons can be learned on these issues by studying the literature and available design provisions on the seismic design of structural connections (FEMA, 2000a; FEMA 2000b; AISC, 2005); it may be appropriate to develop similar provisions for structural robustness against fire.

4.10 Explosive Spalling of Concrete

Structural fire design of modern reinforced and prestressed concrete structures relies on the

Table 2(j): Non-standard large scale tests time line (2011-)

2011	2011	Planned
NRC, **Ottawa, Canada**	**CTU,** **Veseli, Czech Republic**	**University of Victoria / CESARE,** **Melbourne, Australia**
Single reinforced concrete column, fire exposure using gas furnace, realistic transient support conditions were replicated using the Hybrid Fire Testing (HTF) approach. Test demonstrated the successful implementation of HTF. [W]	Steel-concrete composite (10.4 × 13.4 m), fire exposure using timber cribs, information and insight is currently sparse on these tests. [X]	Planned steel concrete composite test which data is not available. [Y]

assumption that the concrete will not spall during fire. This assumption is based largely on data from standard fire tests of concrete elements tested in isolation in furnaces during the past 60 to 70 years. However, there is legitimate concern (Kelly and Purkiss, 2008) that modern concrete structures, which incorporate concrete mixes with considerably higher concrete strengths, are more susceptible to spalling than was historically the case. While preliminary guidance on the means by which spalling can be addressed by designers is available in the structural Eurocodes (CEN, 2004), research is badly needed to understand the respective roles of the various factors which are known to increase a concrete's propensity for spalling during fire (e.g. high strength, high stress, high moisture, low permeability, small amounts of bonded reinforcement, use of silica fume, rapid heating, etc) (Arup, 2005; Bailey and Khoury, 2011), such that defensible preventative actions can be taken (for instance the requirement to add a certain amount of polypropylene fibres to the concrete mix). Interactions in real structures have the potential to significantly influence development of spalling in a fire, so large-scale tests under natural fires are needed to truly understand the propensity for, and the structural consequences of, spalling in real buildings.

4.11 Failure Modes

As already noted, when real structures fail in fires it is rarely for the reasons that might be expected on the basis of standard fire resistance testing. In many cases, global failure is precipitated by some form of localised failure or structural distress, such as discrete cracking in concrete, rupture of tensile steel reinforcement, failure of a connection, local buckling of structural steelwork, shear (punching) failure of a concrete slab, rupture of an unbonded prestressing tendon, etc. Unfortunately, the only way to observe and understand such failure localizations, which depend in virtually all cases on the three dimensional interactions between elements of structure during both heating *and* cooling, is to perform large-scale non-standard structural fire tests on real buildings. Only once the possible failure modes are *known* can they be rationally incorporated into computational models for full structure response.

5 CONCLUSION: WHERE DO WE GO FROM HERE?

This paper has briefly reviewed the historical basis of the standard furnace test, summarized (Table 1 and 2) more than 24 large-scale non-standard structural fire tests performed during the last three decades, and highlighted research gaps in structural fire engineering – many of which have actually been known since the early years of standard fire resistance testing – which remain with respect to our understanding of the real structural performance of buildings when subjected to real fires.

The original intent of the standard fire test was to provide a worst case comparative test for competing building materials and systems, and is based on an extremely limited knowledge of fire dynamics. The initial intent was to address a specific concern at the time the test was developed, rather than to develop a compliance test which would be used, unchanged, for more than a century. However, once the standard fire test was set out in codified form, the inertia of the compliance industry has made it difficult and painful to change or to take more rational approaches, despite the many economic and sustainability benefits that might be realized.

As a result, the structural fire engineering community finds itself in a difficult situation; we feel able to perform detailed, optimized, performance-based structural design for fire, yet we have neither the industry wide motivation to do this nor the validation tests required to show that our computational analysis tools and methods are truly defensible for the full range of possible building types and geometries. Structural fire testing is typically restricted to being performed in standard furnaces, and are evaluated based on meeting the criteria of this test – this is the *de facto* performance metric. Even when performance-based design is permitted and undertaken, the performance metric is often taken as 'equivalent to the standard fire.' The standard fire has thus inadvertently become the performance objective, rather than a proper performance objective taking into account the range of fire risks and failure consequences for the specific building being designed.

The current lack of dedicated research efforts or funding to investigate real structural performance in fire means that the few large-scale non-standard tests which are occasionally performed tend to be 'demonstration' fire tests – they rarely use credible real fire loads, and as noted they invariably attempt to link performance back to the 'assumed' performance objectives of the 'equivalent' standard fire exposure. As a result, most such tests have limited scientific value and typically yield only a small fraction of the useful information that they could; in each case a research opportunity is lost.

The result of the above approaches is a continuing and genuine lack of understanding of all the research gaps noted in the previous section. As a community, we remain in a situation that when structural failures are observed in real fires they are rarely for the reasons that would expected on the basis of standard furnace testing. The obvious rhetorical question seems to be: *Are we 'pretending' to engineer structures for fire and simply getting 'lucky' because fires are statistically rare events, and because our structures are so rarely challenged to the levels we assume in the standard fire test?*

In the future, structural fire testing must surely move away from the standard fire resistance test. In particular, the continuing development of computational analysis tools, both for fire modelling and for modelling structural response during heating are advancing on a weekly basis. Rather than focus on standard fire tests, the structural fire engineering community might better focus efforts on developing better material inputs for computational models; for instance on developing a true ability to predict, model, and prevent spalling, or an ability to model discrete cracking and fracture during fire. We might also better focus on large scale non-standard fire resistance tests which genuinely build an understanding of, and ability to predict, full structure response to fire. This will necessitate real fire tests in real buildings (e.g. Rein et. al, 2007) with sufficient instrumentation to rationally understand both the fire *and* the structural response. Alternatively, tests are needed such as those envisioned for the new structural fire testing facility which is (encouragingly) currently under construction at NIST, USA (NIST, 2011). In both of the above cases, *a priori* round robin modelling studies are needed to defensibly demonstrate the ability to model full structural response to fire. Only with the above steps taken will the structural fire engineering community be certain that our full structure analysis and design (for structures other than regular steel-concrete composite frames) are true engineering rather than fortuitous pretence.

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REFERENCES

AISC, 2005. ANSI/AISC 341-05 – Seismic Provisions for Structural Steel Buildings. *American Institute of Steel Construction (AISC)*, Chicago, 334pp.

Almand K, Phan L, McAllister T, Starnes M, and Gross J, 2004. SFPE Workshop for Development of a National R&D Roadmap for Structural Fire Safety Design and Retrofit of Structures. *NISTIR 7133, National Institute of Standards and Technology*, Gaithersburg, MD, 188pp.

Almand K, 2012. Structural Fire Resistance Experimental Research Priority – Needs of U.S. Industry, final report. *The Fire Protection Research Foundation (FPRF),* 55pp.

Anderberg Y, 1986. Modelling steel behaviour. *Presented at the International Conference on Design of Structures Against Fire*, Aston University, Birmingham, UK, April 15-16, 5pp.

Anon T, 1986. *Brand Verhalten von Stahl und Stahlverbund Konstructionen (Fire Behaviour of Steel and Composite Construction)*, Verlag TUV Rheinland.

Arup Fire, 2005. Fire resistance of concrete enclosure – Work Package 2: Spalling categories. *Elaborated for the Nuclear Safety Directorate of the Health and Safety Executive (HSE)*, London, UK, 36pp.

AS, 2005. AS 1530.4-2005 – Methods for fire tests on building materials, components and structures - Fire-resistance test of elements of construction. *Australian Standards*, 151pp.

ASTM, 1980. ASTM E119. Fire testing of building construction materials. Standard E-119. *American Society of Testing Materials*, PA, 1980.

ASTM, 2011. ASTM E119-11a: Standard methods of fire test of building construction and materials. *American Society for Testing and Materials*. West Conshohocken, PA, 34pp.

Bamonte P, Felicetti R, and Gambarova PG, 2009. Punching Shear in Fire-Damaged Reinforced Concrete Slabs. *ACI Special Publication 265, American Concrete Institute*, Farmington Hills, USA, pp. 345-366.

Bailey CG. Lennon T, and Moore D, 1999. The behaviour of full-scale steel framed buildings subjected to compartment fires. *The Structural Engineer*, 77 (8) pp. 15-21.

Bailey CG, 2002. Holistic behaviour of concrete buildings in fire. *Proceedings of the Institution of Civil Engineers, Structures and Buildings*, 152 (3), pp. 199-212.

Bailey CG and Lennon T, 2008. Full scale fire tests on hollowcore slabs. *The Structural Engineer*, 86 (6), pp. 33-39.

Bailey CG and Khoury GA, 2011. *Performance of Concrete Structures in Fire – An in-depth publication on the behaviour of concrete in fire*. Ruscombe Printing Ltd, Reading, UK, 203pp.

Beitel J and Iwankiw N, 2008 Analysis of Needs and Existing Capabilities for Full-Scale Fire Resistance Testing. *NIST GCR 02-843-1 (Revision), National Institutes for Standards and Technology*, 98pp.

Bisby L and Kodur V, 2007. Evaluating the fire endurance of concrete slabs reinforced with FRP bars: Considerations for a holistic approach. *Composites Part B: Engineering*, 38 (5-6), pp. 547-558.

British Steel, 1999. *The behaviour of multi-storey steel frame buildings in fire*. British Steel, Rotherham, United Kingdom, 82pp.

Buchanan A, 2001. *Structural design for fire safety*. Wiley, 444pp.

CCAA, 2010. Fire Safety of Concrete Buildings. *Cement Concrete & Aggregates Australia - CCAA T61*, 37pp.

CEN, 2004. BS EN 1992-1-2:2004 – Eurocode 2: Design of concrete structures — Part 1.2: General rules — Structural fire design. *European Committee for Standardization*, Brussels, 100pp.

Chlouba J and Wald F, 2009. Connection Temperatures during the Mokrsko Fire Test. *Acta Polytechnica*, 49 (1), pp. 76-81.

Chlouba J, Wald F, and Sokol Z, 2009. Temperature of Connections during Fire on Steel Framed Building. *International Journal of Steel Structures*, 9 (1), pp. 47-55.

Ding J and Wang YC, 2007. Experimental study of structural fire behaviour of steel beam to concrete filled tubular column assemblies with different types of joints. *Engineering Structures*, 29 (12), pp. 3485-3502.

Dong Y and Prasad K, 2009a. Experimental Study on the Behavior of Full-Scale Composite Steel Frames under Furnace Loading. *Journal of Structural Engineering*, 135 (10), pp. 1278-1289.

Dong Y and Prasad K, 2009b. Thermal and structural response of a two-story, two bay composite steel frame under fire loading. *Proceedings of the Combustion Institute*, 32 (2), pp. 2543-2550.

FEMA, 2000a. FEMA-350 – Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings. *Federal Emergency Management Agency (FEMA)*, 224pp.

FEMA, 2000b. FEMA-3555D – State of the Art Report on Connection Performance," prepared for the SAC Joint Venture Partnership, *Federal Emergency Management Agency (FEMA)*, 305pp.

Firehouse.com, 2004. Seven Swiss fire fighters die in collapsed parking garage. Available at http://www.firehouse.com/news/lodd/seven-swiss-firefighters-die-collapsed-parking-garage, created November 27 2004, accessed on 31st March 2011.

Fitzpatrick F and Condron T, 1914. Fire proof construction. *American School of Correspondenc*e, Chicago, 337pp.

Holland H, 1973. Resolutions of the Associated Architects. *Associated Architects (defunct)*, 81pp.

Huang S, Burgess I, and Davidson B, 2011. A structural fire engineering prediction for the Veselí fire tests. *Proceedings of the International Conference on Applications of Structural fire Engineering*, Prague, Czech Republic, pp. 411-416.

Hull WA and Ingberg SH, 1925. Fire resistance of concrete columns. *Notes from US bureau of standards. Tech paper 272*, pp. 379-381.

Ingberg S, 1928a. Tests of the Severity of Building Fires. *NFPA Quarterly*, 22, pp. 43-61.

Ingberg S, 1928b. Fire Test of Brick Joisted Buildings. *NFPA Quarterly,* 22, pp. 62-68.

ISO, 1999. ISO 834-1:1999: Fire Resistance Tests - Elements of Building Construction -Part 1: General Requirements. *International Organization for Standardization*, Geneva, Switzerland, 25pp.

Jeanes D, 1982. Predicting Fire Endurance of Steel Structures. *American Society of Civil Engineers (ASCE) National Convention*, Las Vegas, Nevada, April 26-30, 1982. Preprint 82-033.

Joyeux D, Kruppa J, Cajot LG, Schleich JB, Van de Leur P, and Twilt L, 2001. Demonstration of real fire tests in car parks and high buildings, CEC Agreement 7215–PP/025. CTICM, France – Profil-Arbed Receherches, Luxembourg – TNO, The Netherlands.

Kelly F and Purkiss J, 2008. Reinforced concrete structures in fire: a review of current rules. *The Structural Engineer,* 86 (19), pp. 33-39.

Kodur V, Garlock M, and Iwankiw N, 2011. Structures in fire: State of the art, research and training needs. *Fire technology* (in press).

Law M, 1981. Designing fire safety for steel – recent work. *Proceedings of the ASCE Spring Convention, American Society of Civil Engineers*, New York, 16pp.

Lennon T, Bullock M, and Enjily V, 2000. The fire resistance of medium-rise timber frame buildings. *World Conference on Timber Engineering*, Whistler Resort, British Columbia, Canada. July 31 - August 3 2000, 10pp.

Lennon T, 2003. The Natural fire safety concept- full scale tests at Cardington. *Fire Safety Journal*, 38. 623-643.

Mostafaei H, 2011a. Hybrid Fire Testing for Performance Evaluation of Structures in Fire – Part 1: Methodology, *Research Report No. RR-316, NRC Institute for Research in Construction*, August 26th, 20pp.

Mostafaei H, 2011b. Hybrid Fire Testing for Performance Evaluation of Structures in Fire – Part 2: Application, *Research Report No. RR-317, NRC Institute for Research in Construction*, September 28th, 34pp.

Nadjai A, Bailey C, Vassart O, Han S, Zhao B, Franssem J, and Simmsm I, 2011. Full-scale fire test on a composite floor slab incorporating long span cellular steel beams. *The Structural Engineer*, 89 (21), pp. 18-25.

New York Times, 1997 Philadelphia to Raze Site of High-Rise Fire. Available at http://www.nytimes.com/1997/11/14/us/philadelphia-to-raze-site-of-high-rise-fire.html, created November 14 1997, accessed 31st March 2012.

NIST, 2011. The National Fire Research Laboratory. Available at http://www.nist.gov/el/fire_research/nfrl.cfm, created 27th April 2011, accessed 31st March 2012.

Platt DG, Elms DG, and Buchanan AH, 1994. A probabilistic model of fire spread with time effects. *Fire Safety Journal,* 22 (4), pp. 367-398.

Proe D and Thomas I, 2010. Planning for a Large-Scale Fire Test on a Composite Steel-Frame Floor System. *Proceedings of the 6th International Conference on Structures in Fire (SiF'10),* June 2-4, Michigan State University, East Lansing, Michigan, USA, pp. 390-397.

Proe D and Bennetts I, 1994. Real Fire Test in 380 Collins Street Office Enclosure, *BHP Research Report No. BHPR/PPA/R/051/SG021A.* September 1994, 79 pp.

Richardson K, 2003. History of Fire Protection Engineering, *National Fire Protection Association,* Quincy, MA.

Rein G, Abecassis C, and Carvel, RO (editors), 2007. The Dalmarnock Fire Tests: Experiments and Modelling. *Published by the School of Engineering and Electronics, University of Edinburgh*, 211pp.

Ring T, Zeiml M, and Lackner R, 2011. Large scale fire tests on concrete design and results. *Presented at the 18th Inter-Institute Seminar for Young Researchers (IIS18),* Budapest, Hungary, September 23-25 2011.

Sachs EO, 1902. Facts on Fire Prevention, Vol. 1 and 2, Batsford publisher, London.

Sharma U, Bhargava P, Singh B, Singh Y, Kumar V, Kamath P, Usmani A, Torero J, Gillie M, Pankaj, P, May I, and Zhang J, 2012. Full Scale Testing of a Damaged RC Frame in Fire. *Proceedings of The Institution of Civil Engineers, Structures and Buildings, Special issue on "Structures in Fire"* (in press).

Smith C, 1905. Building code recommended by the National Board of Fire Underwriters New York. James Kempster printing. 1st edition. 275 pp.

Stadler M, Mensinger M, Schaumann P, and Sothmann J, 2011. Munich Fire Tests on Membrane Action of Composite Slabs in Fire – Test Results and Recent Findings. *Proceedings of the International Conference on Applications of Structural fire Engineering*, April 29th 2011, Prague, Czech Republic, pp. 177-182.

Stewart P and Woolson IH, 1902. Making Buildings safe: Fire Proof Materials and methods of construction. *New York Tribune,* October 19 1902.

Terrasi GP, 2007. Prefabricated Thin-walled Structural Elements made from HPC Prestressed with Pultruded Carbon Wires," *Proceedings of the 8th International Symposium on Fiber Reinforced Polymer Reinforcement for Concrete Structures (FRPRCS-8),* University of Patras, Greece, July 16-18 2007, 10pp.

Thomas IR, Bennetts ID, Dayawansa PH, Proe DJ, and Lewins RR, 1992. Fire Tests of the 140 William St Office Building. *BHP Research – Melbourne Laboratories Rep No. BHPR/ENG/R/92/043/SG2C*, February 1992.

Thomas IR, Bennetts ID, Poon SL, and Sims J, 1992. The Effect of Fire in the Building at 140 William St, *BHP Research – Melbourne Laboratories Rep No. BHPR/ENG/R/92/044/SG2C*, February 1992.

Vassart O, and Zhao B, 2011. FRACOF Engineering Background. *Report developed for the project Leonardo Da Vinci: Fire Resistance Assessment of Partially Protected Composite Floors (FRACOF)*. 132pp.

Wald F, Simões da Silva L, Moore D, Lennon T, Chaldna M, Santiago M, Beneš M, and Borges L, 2006. Experimental behaviour of a steel structure under natural fire. *Fire Safety Journal*, 41 (7), pp. 509–522.

Wald F, 2010. Fire Test on an Administrative Building in Mokrsko. *Printing house Česká Technika, Czech Technical University in Prague*. 152pp.

Wald F, 2011. Large Scale Fire Tests. *COST Action TU0904: Integrated Fire Engineering and Response Working Group*, Prague, Czech Republic, April 30 2011, 5pp.

Wald F. Jána T, and Horová K, 2011. Design of joints to composite columns for improved fire robustness – To demonstration fire tests. *Printing house Česká Technika, Czech Technical University in Prague*, 26pp.

Woolson I, 1916. Dwelling Houses: A code of Suggestions for constructions and fire protection recommended by the National Board of Fire Underwriters, *American Institute of Architects*. New York, 137 pp.

Wong YL and Ng YW, 2011. Technical Seminar - Effects of Water Quenching on Reinforced Concrete Structures under Fire, *presented at The Institution of Fire Engineers (Hong Kong Branch)*, August 23rd 2011, Kowloon Tong Fire Station, Kowloon Ton, Hong Kong.

Yu H, Burgess IW, Davison JB, and Plank RJ, 2009. Experimental investigation of the behaviour of fin plate connections in fire. *Journal of Construction Steel Research*, 65 (3), pp. 723-736.

Yuan Z, Tan KH, and Ting SK, 2011. Testing of composite steel top-and-seat-and-web angle joints at ambient and elevated temperatures: Part 2 – Elevated-temperature tests. *Engineering Structures*, 31 (9), pp. 2093-2109.