ARTICLE IN PRESS

Fire Safety Journal xxx (2017) 1–9

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Motivation, drivers and barriers for a knowledge-based test environment in structural fire safety engineering science

Cristian Maluk

School of Civil Engineering, The University of Queensland, Australia

ARTICLE INFO

Keywords:
Structural response
Structural design
Fire test
H-TRIS
Thermal boundary conditions

ABSTRACT

Structural fire testing has traditionally relied on the use of the standard fire resistance test (i.e. furnace test) for assuring regulatory compliance of structural elements and assemblies, and in many cases also for developing the scientific understanding of structural response to fire. Conceived in the early 1900s and fundamentally unchanged since then, the standard testing procedure is characterized by its high cost and low repeatability. A novel test method, the Heat-Transfer Rate Inducing System (H-TRIS), resulting from a mental shift associated with controlling the thermal exposure not by temperature (e.g. temperature measured by thermocouples) but rather by the time-history of incident heat flux, was conceived, developed, and validated within the scope of the work presented in this paper. H-TRIS allows for experimental studies to be carried out with high repeatability, imposing rationally quantifiable thermal exposure, all at low economic and temporal cost. This works aims at demonstrating that a rational, and practical, understanding of the fire performance of structural systems during real fires is unlikely to be achieved only by performing additional standard fire resistance tests. Hence, H-TRIS presents an opportunity to help promote an industry-wide move away from the contemporary pass/fail and costly furnace testing environment.

1. Introduction and background

Rapid growth in the use of new construction techniques, innovative materials, and ground-breaking designs in building construction has been driven by the need for optimization, energy efficiency, sustainability, and architectural imagination and creativity. Ideally, the numerous building design stakeholders (e.g. building owners, architects, structural engineers, etc.) operate within a flexible and dynamic environment that allows for an iterative process in an open, knowledge-based, and responsive dialogue.

Fire safety considerations in the design of buildings' structural systems have traditionally been based on the concept of ‘compliance,’ wherein the design of individual structural elements is required to comply with specified ‘acceptability’ criteria, with little consideration to the ideal iterative, knowledge based process described above; this is likely to result in inefficient and sub-optimal designs. A broader view of the potentials for integrated fire safety design considerations throughout the design of contemporary buildings has been presented by Maluk et al. [1]. This general idea is clearly not unique to fire safety design in buildings, as others have extensively reflected upon the current state and potential benefits of an integrated approach to design on structural optimization, life cycle cost, energy saving, climate control, lighting, acoustics, and various other relevant design considerations [2–5].

The current building construction industry has ‘solved’ most problems by operating within a structure in which architects and structural engineers, whether aware of it or not, have the means to design, with little or no rational engineering judgement, structural elements that comply with the prescribed fire safety performance criteria defined by the regulatory authority having jurisdiction (e.g. Ref. [6]). More than a century of research and development in structural fire testing has essentially converged into widespread use of the standard fire resistance test (i.e. large scale furnace test) as the means to experimentally rate (in the artificial time domain of ‘fire resistance’) the load bearing capacity of a structural element exposed to a ‘standard’ fire. The result is a simplified, comparative regulatory system in which the true performance of materials and structures in real fires is rarely questioned (or known, or acknowledged). Additionally, 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 (e.g. unexposed column that grows eccentric because of thermal expansion due to fire in an adjoining beam), evidence that the complexities of real fires in real buildings are not captured in standard fire resistance tests [7].

The structural fire safety community has, particularly since the early 1990s, devoted tremendous effort and resources to develop, support, and

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E-mail address: c.maluk@uq.edu.au.

http://dx.doi.org/10.1016/j.firesaf.2017.05.009
Received 23 April 2017; Received in revised form 5 May 2017; Accepted 8 May 2017

Please cite this article in press as: C. Maluk, Motivation, drivers and barriers for a knowledge-based test environment in structural fire safety engineering science, Fire Safety Journal (2017), http://dx.doi.org/10.1016/j.firesaf.2017.05.009

implement so-called performance-based approaches for structural fire safety engineering design [8–20], in parallel with the development of science-based design tools (e.g. Refs. [21–23]). Despite the efforts and resources expended, the fundamental regulatory constraint of designing for a presumed equivalent level of safety as that 'demonstrated' by structural elements in a standard fire resistance test simply results in 'sophisticated' tools being used to design against a simplified performance criterion; i.e. design a structural element so as to achieve a prescribed time to 'failure' during a fire resistance test, rather than design a structural system to perform 'satisfactorily' in a real fire.

> *"Most of the existing tests had to be developed by trial and error, and they are open, it is true to the objection that they do not truly indicate how a material will behave in an actual fire. They may tell us which is the better of two materials, but not whether one or both is good enough for the job."* [24]

2. Origins of the contemporary test environment

During the late 19th Century, an era of rapid innovation within the construction industry, brought on by novel structural designs with structural configurations and materials developed in an effort to save space and build higher, promoted the early developments of supposed "fire-resistant" construction [25,26]. So-called "fire and water" tests became common practice for manufacturers of these emerging fire resisting materials and systems, who attempted to advertise their products' "fire proof" characteristics by resorting to whatever they considered a satisfactory means of demonstration (e.g. Ref. [27]); this approach soon (and predictably) became unreliable.

The subsequent establishment of federal, municipal, and private experimental testing facilities, with recognized credentials and purported impartiality, introduced an environment in which testing facilities could systematically test materials and systems under presumed 'uniform' conditions, initially for the purposes of comparative examination only. At the time that these test methodologies were conceived, no standard failure criteria were defined for tested elements, although techniques for the assessment of load bearing capacity, integrity, and insulation where already common practice [28].

At the turn of the 20th Century, efforts were made both by American and European testing organizations, as well as by other stakeholders involved in the building construction community, to define a uniform 'standard' fire resistance test (e.g. Refs. [27,28]). As indicated by Ira Woolson, then Chairman of the National Fire Protection Association's (NFPA) Committee on Fire- Resistive Construction, the overarching goal of these efforts was to "unify all fire tests under one single standard and remove an immense amount of confusion within the fire testing community" [29].

In 1903, at the International Fire Prevention Congress held in London, UK, Edwin Sachs presented a set of suggested standards for a fire resistance test which proposed the use of an essentially arbitrary "fierce" fire represented by a sustained minimum temperature over a defined period of time (1500 °F or 1800 °F, equivalent to 816 °C or 982 °C, respectively), as well as suggesting minimum requirements for 'fire resistance' of structural elements, for which the level of 'protection' was classified as 'temporary', 'partial' or 'full' [30].

In the US, a standard testing methodology was gradually adopted during the 1920s, as seen in transcripts of the discussions which took place at several annual NFPA meetings [29,31,32]. At the 1917 NFPA annual meeting, Woolson stated that; "we want to get it as nearly right as possible before it is finally adopted, because, after it is adopted by these various associations, it will be pretty hard to change it" [29]. A tentative standard time-temperature curve (Fig. 1) was proposed at the 1917 NFPA annual meeting and presented for final adoption in the subsequent annual meeting [32]. The time-temperature curve was delineated by "points on the graph" defined by a committee composed by numerous technical bodies with 'interests' in the subject (e.g. NFPA, American Society for Testing and Materials, Underwriters' Laboratories, Association Factory Mutual Fire Insurance Companies, American Institute of Architects, American Society of Civil Engineers, American Concrete Institute). The actual source behind the selected "points on the graph" remains unknown by the author of this paper. Since it was originally adopted in 1918, the standard time-temperature curve has been basically unchanged and is now widely used in modern fire resistance testing standards (e.g. Refs. [33,34]).

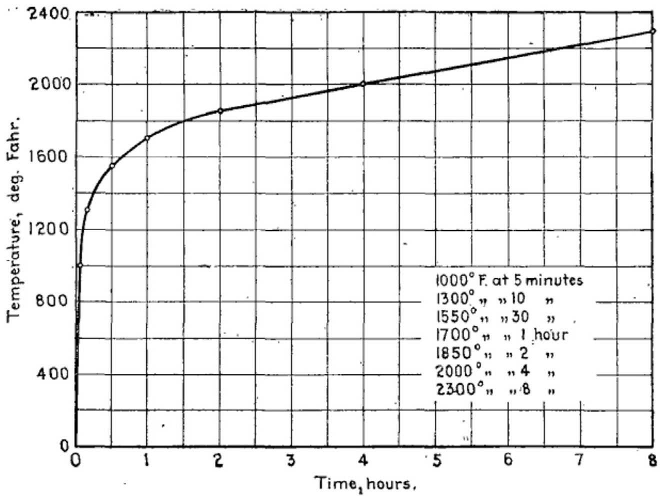

Fig. 1. Standard time-temperature curve presented for adoption at the 1918 NFPA annual meeting [32].

With an agreed standard fire resistance test methodology, subsequent decades saw the fire testing community experience considerable growth (and thus to develop considerable inertia) in the number and cost of standard fire testing facilities and the amount of large scale experimental studies carried out around the world. Early versions of 'standard' testing furnaces were capable of testing mechanically loaded specimens during heating.

In 1928, based on recognition that the standard time-temperature curve was not a 'real' fire, Simon Ingberg presented a method for quantifying a fire's 'severity' resulting from burnout of all the combustible contents in a compartment [35]. Ingberg attempted to correlate this to the severity of heating imposed during the standard fire resistance test. To do this he introduced the 'Equal Area Concept', which in theory allowed designers to define the required time of standard fire resistance (derived from a furnace test) for structural elements based on the actual fuel load within a given compartment [36]. This was accomplished by equating the total area under the real fire's time-temperature curve (measured during numerous full scale fire tests in compartment fitted with office furniture) to the area under the standard fire curve for a given duration of standard fire exposure (see Fig. 2).

Despite it not being obvious at the time, Ingberg's publications on this topic fundamentally (and unfortunately) linked the concept of 'time' to the performance objectives used to define the 'fire resistance' of structural elements. In the decades that followed, alternative severity metrics were introduced, and in some cases adopted, by the structural fire engineering community. These included: the 'Maximum Temperature Concept', the 'Minimum Load Capacity Concept', and the 'Time Equivalent' Formulae [37,38]; however, all of these were fundamentally linked to results from isolated elements tested under the 'standard' time-temperature curve.

For the remainder of the 20th Century, various highly renowned fire safety practitioners and researchers reflected upon fundamental concerns with the design process used to define and verify structures' fire resistance, and various aspects of the standard fire resistance test (e.g. Refs. [39–44]). The following paragraphs briefly describe the views of some of