Fire Safety Journal 89 (2017) 22–40

Contents lists available at ScienceDirect

Fire Safety Journal

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

An experimental study of full-scale open floor plan enclosure fires

J.P. Hidalgo[a,c], A. Cowlard[a,b], C. Abecassis-Empis[a,b], C. Maluk[a,c,*], A.H. Majdalani[a], S. Kahrmann[a], R. Hilditch[a], M. Krajcovic[a], J.L. Torero[a,c]

[a] *School of Engineering, The University of Edinburgh, UK*
[b] *TAEC, UK*
[c] *School of Civil Engineering, The University of Queensland, Australia*

ARTICLE INFO

Keywords:
Enclosure fire dynamics
Full-scale experiments
Compartment fire framework
Tall buildings
ETFT
Large open-plan compartment

ABSTRACT

A full-scale experimental series is undertaken to generate a comprehensive data set to study and characterise fires in large open-plan spaces, typical of contemporary infrastructure and Tall Buildings in particular. Developments in the understanding of enclosure fire dynamics for large spaces is intended to complement the knowledge of relatively smaller, low ventilation spaces developed from the extensive body of research that underpins the original *compartment fire framework*.

A total of twelve experiments are conducted, ten using box gas burners and two using a bed of wood cribs. Both the fire development and ventilation characteristics are varied systematically to enable the careful examination of the effect of each on the fire dynamics within the compartment. For this set of tests, sensor instrumentation is, as far as practicable, provided at a resolution to enable benchmarking of field models. These tests form part of the Real Fires for the Safe Design of Tall Buildings Project.

The current paper, the first in a series of publications, provides a thorough description of the full-scale experimental compartment, the various sensing techniques deployed within it, and the range of combined fire and ventilation conditions for each of the twelve tests performed. Characteristic results from the first experiment that forms part of the 'Edinburgh Tall Building Fire Tests' (ETFT) test series are presented.

1. Introduction

The period of history from the 1920s to the 1990s encompasses the majority of the fundamental research conducted in the field of fire safety engineering, with the most pioneering work undertaken in the decades between the late 1950s to 1990. From this work stemmed the *compartment fire framework,* defining fire dynamics as a function of the restrictions provided by compartmentation with limited openings, typical of relatively small compartments. The historical evolution of architecture over this same period shows that '*compartments*'consisting of open-plan volumes and large interconnected spaces were not the exception of the avant-garde, but already a common and key element in mainstream architecture[1,2]. Thus there was a clear disparity in the range of applicability of the state-of-the-art definitions of compartment fire dynamics and the architectural norm, which still persists today. Such open-plan volumes and interconnected spaces are typical of Tall Buildings. Provision of fire safe design of Tall Buildings[3]requires a fire safety strategy that incorporates three essential components: (1) effective vertical compartmentation; (2) structural integrity beyond burnout; and, (3) maintaining of clear egress routes. The main input parameter for the design of each one of these components is the characterisation of the fire dynamics past the early growth stages of a fire, thus the above-mentioned disparity becomes particularly poignant.

As established by the early pioneers of the field, the evolution and characteristics of compartment fires are intrinsically linked to their surroundings (*e.g.* geometry, air supply, fuel, wall lining) by means of a complex, circular interaction [4].Despite this level of complexity, it is desirable from a designer's perspective to have simplistic engineering tools such as analytical expressions and correlations which can provide informative, rapid and adequate quantification of the performance of a design without excess and unwarranted complexity. Typical expressions and plots (*e.g.* nomograms) resulting from the *compartment fire framework* typified this form. It is clear though that while undoubtedly valuable for a fire safety design, for such tools to be utilised successfully, they must adequately reflect the relevant characteristics of the compartments to which they are applied.

---

[*] Correspondence to: School of Civil Engineering, The University of Queensland, Brisbane QLD 4072, Australia.
E-mail address: c.maluk@uq.edu.au (C. Maluk).

http://dx.doi.org/10.1016/j.firesaf.2017.02.002
Received 21 April 2015; Received in revised form 4 February 2017; Accepted 8 February 2017

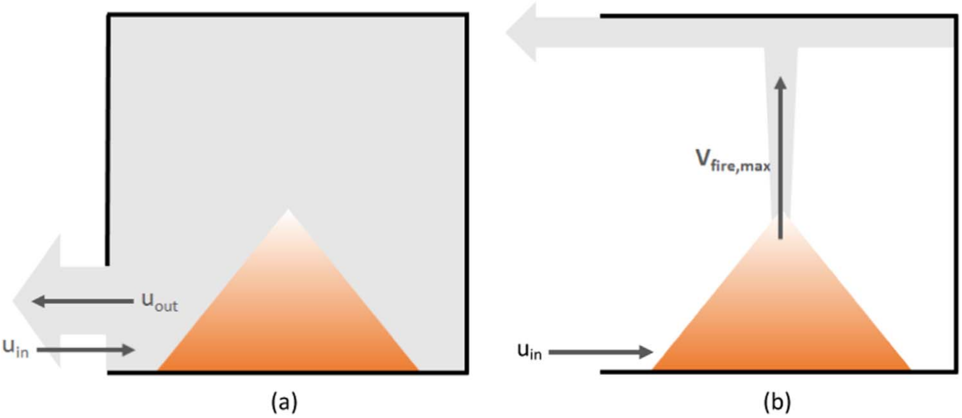

Fig. 1. (a) Represents the classical Regime I post-flashover fire and compartment where the fire is of comparative dimensions to the compartment, the gas phase inside the compartment is a uniform high temperature with zero internal flows, and the principle flow is induced by a hydrostatic pressure difference at the opening between the hot inner gases and cold outer gases; (b) Represents a classical Regime II post-flashover fire compartment where the fire is also of comparative size to the compartment. Much larger openings however result in hot gases flowing out of the compartment leaving the fire plume as the principle driver of flows and the average compartment temperature typically lower than in Regime I.

1.1. The Compartment fire framework

The primary focus behind the *compartment fire framework* was in defining the thermal load for the assessment of structural fire protection requirements, thus the majority of efforts were aimed at characterising the behaviour of fully-developed compartment fires[5].The significant stream of research that resulted in the *compartment fire framework*was a reaction to the fire resistance test [6], widely used for research development and regulatory approval in the structural fire safety industry. An early attempt at refinement of this method postulated fire load as a measure of fire severity[7],although no physical basis was demonstrated to justify this relationship.

Early work by Fujita [8] and Kawagoe [9,10] demonstrated a link between burning rate and the geometrical characteristics of compartment openings. Further exploring the link between the fire environment and the compartment openings, Thomas [11] identifies a specific range where the opening geometry completely governs the physical behaviour and beyond this, where the openings are sufficiently large to no longer be the limiting factor. Thomas labels these behaviours *Regime I*, the low ventilation regime, and *Regime II*, the high ventilation regime, each represented schematically in Fig. 1. These findings are corroborated and elaborated by Harmathy [12] and recently observed experimentally by Majdalani et al. [13].

The *compartment fire framework* focuses principally on *Regime I*, as not only were the researchers able to articulate it theoretically, but it was also deemed as more ‘severe’ from a structural fire behaviour perspective. On this basis, this pioneering research proceeded to characterise the energy produced within, flowing out of, and trapped (or absorbed) within a compartment, solely defined as a function of the opening geometry. This elegant set of tools, which enables a rapid and conservative bounding of the thermal load on a structure, and the *Regime I* description on which they are based, are now comprehensively integrated into both key texts [4,14] and design guidelines [15,16] for practitioners looking to design fire safe structures.

Regime II, while perhaps more representative of the potential fire scenarios in large, open-plan spaces [17,18] is comparatively more complex and thus has never been theoretically developed and bounded with the elegance and simplicity of *Regime I*. The dimensioning and scale of the experimental set-up adopted in these classical experiments gave a propensity for smoke to flow out of the more ample openings (Fig. 1b), *i.e. Regime II* scenarios [19]. This typically resulted in a lower average compartment temperature, hence why *Regime II* was deemed less severe from a structural perspective. Thus, while the fire characteristics from *Regime II* appear closer to the fire characteristics in contemporary infrastructure, the current framework does not extend to these forms [19].

On a more realistic scale, and in more realistic forms, it is likely that smoke, and by extension heat, will be transported away from the fire but remain within the compartment or building [12], thus continuing to exchange energy with the structure and unburnt fuel, even in areas remote from the fire. This therefore introduces the concept of spatially variant energy distribution within a compartment, a complete contrast to the classical *Regime I* definition, and still also a significant deviation from the classical *Regime II* definition.

1.2. Research significance

The *compartment fire framework* provides an extensive array of convenient tools developed for practitioners. Analysis of the range of applicability of these tools by Majdalani [19] confirms that they are strictly limited to scenarios where a low level of ventilation dominates both the fire behaviour and the resultant thermal load/exposure to structural elements and compartmentalisation barriers. In contrast, modern buildings are typically non-compartmented (*e.g.* open-plan office buildings), exemplified by spaces increasingly beyond this range of applicability.

Computational Fluid Dynamics (CFD) tools may well be capable of providing spatial and temporal representation of energy transport but their complexity and associated time scales are far less convenient than the tools that sprang from the *compartment fire framework*. Furthermore, the data available for validation of such tools in these particular conditions are very limited [20]. There is therefore a clear need to supplement existing frameworks and models to characterise the full range of potential fire dynamics and energy transport for fires in compartments representative of real buildings.

For this purpose a series of full-scale experiments has been conducted as part of the Real Fires for the Safe Design of Tall Buildings Project [21]. A compartment was designed with ventilation that could be varied to encompass both *Regime I* and *Regime II* and a number of discrete points in between. In tandem, the fire source was defined in a manner such that a range of fire development modes could be replicated. The following sections describe the compartment designed and constructed for this series of tests, and the array of sensors installed within and around it. Details of the range of ventilation characteristics and fire modes are described, as are the combinations of these that make up the experimental matrix.

Given the scale of the experimental compartment and degree of resolution of the sensor arrays, it is impossible to provide all the necessary detail as well as the full set of results in a single paper. Thus, this paper delivers all details of the test set-up, along with characteristic data typifying a single experiment in the series. Subsequent papers will focus on the specific experiments and further analyses based on the