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Energy distribution analysis in full-scale open floor plan enclosure fires

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ABSTRACT

Within a fast evolving built environment, understanding fire behaviour and the thermal exposure upon structural elements and systems is key for the continued provision of fire safe designs and solutions. Concepts of fire behaviour derived from research in enclosure fires has traditionally had a significant impact in general building design. At present, open floor plan enclosures are increasingly common – building design has drastically drifted away from traditional compartmentalisation. Nevertheless, the understanding of fire behaviour in open floor plan enclosures has not developed concurrently. The *compartment fire framework*, first conceived for under-ventilated fires in cubic compartments, has remained as standard practice. Although energy conservation within the enclosure was the basis for the current *compartment fire framework* that defines under-ventilated enclosure fires, little effort has been carried towards understanding the distribution of energy in design frameworks conceived for open floor plan enclosure fires. The work presented herein describes an analysis of the energy distribution established within an experimental full-scale open floor plan enclosure subjected to different fire modes and ventilation conditions. The results aim to enable the designer to estimate the fraction of the total energy released during a fire noteworthy to structural performance.

1. Introduction and background

Rapid growth of the built environment has been driven by developments of new construction techniques, innovative materials, and ground-breaking designs motivated by cost optimisation, energy efficiency, ease of construction, and architectural innovation. Concepts on fire behaviour and fire safety design methods derived from research in enclosure (or compartment) fires have traditionally had significant impact in general building design [1]. Explicit consideration of the fire behaviour becomes key for a continued provision of fire safe designs and solutions [2].

As established by the early pioneer researchers in the field of fire safety science [3–8], the severity of the fire upon structural or boundary compartment elements within an enclosure is intrinsically linked to characteristic parameters of the enclosure by means of a complex interaction (e.g. geometry, ventilation, fuel load, or thermo-physical properties of the solid boundaries). Despite this relatively high degree of complexity, simple rather than complex design tools are preferable in engineering/practice.

Early work conceived the *compartment fire framework*, defining the fire behaviour (i.e. average maximum steady state temperature and burning rate) under a fully-developed phase as a strong function of a ventilation factor; illustrated with now widely used expressions and plots (e.g. nomograms) [9]. It is clear though that for such tools to be utilised appropriately, they must adequately align with the hypotheses under which they were derived, i.e. the geometry configuration. Thomas [7] and Harmathy [8] investigated the effect of the enclosure geometry and openings on the thermal fields within the enclosure, and identified a range of ventilations conditions where the opening geometry fully governs the thermal field; beyond this, the openings are sufficiently large to no longer be the dominant factor. Thomas [7] labels the former behaviour as *Regime I* (ventilation-controlled fire), while the latter is defined as *Regime II* (fuel-controlled fire).

Upon revision [1], the *compartment fire framework* links the average maximum steady state temperature and burning rate to the ventilation condition of the enclosure (i.e. opening factor). This is a simple, yet robust way to describe the behaviour of a *Regime I* fire. The conditions of a *Regime I* fire are defined by a series of very strong assumptions that establish a well-defined direct link between temperature, burning rate, and opening factor. Nonetheless, for a *Regime II* fire, there is no theoretical link between the ventilation conditions and the gas-phase temperature. Moreover, any experimental evidence of a link is accompanied by great scatter of the data. This is not a new observation; the scatter of the data within *Regime II* fires was

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Main nomenclature listing

$\dot{Q}_{fire}$	heat release by the burners (W)
$\dot{Q}_{in,opening}$	heat gained through the opening (W)
$\dot{Q}_{out,opening}$	heat lost through the opening (W)
$\dot{Q}_{boundaries}$	net heat transferred to solid boundaries (W)
$\dot{Q}_{gas}$	gas-phase energy variation (W)

emphasised from the very early studies by Thomas et al. [7]. There is significant experimental data that show conditions under which the assumptions of the *compartment fire framework* are not valid, however there are no systematic studies that truly address the boundaries of validity of this approach. As a result, the limits of validity of the design methodologies based on this classical framework are currently unknown.

2. Research significance

The fire behaviour of a modern open floor cannot be represented by a *Regime I* fire [1]; therefore, the widely used *compartment fire framework* does not extend to these forms. Experimental studies in *Regime II* fires typically resulted in a lower average enclosure temperature [10], hence *Regime II* fires have traditionally been considered less severe from a structural fire performance perspective, and therefore, little effort has been given towards investigating enclosures of this nature. Studies within the original compartment fire framework that focused on *Regime II* configurations did not examine compartments representative of the typical modern open-plan compartments of today. The compartment sizes were identical to the corresponding *Regime I* experiments, except with larger openings. Thus, heat flowing away from the fire location by default flowed out of the compartment. This is not necessarily representative of an open-plan compartment fire where heat moving away from the fire location can still remain within the compartment, thus possibly heat structural elements and other building components. Then, while locally the fire may not be deemed as severe as with *Regime I*, the effect of the energy must still be accounted for.

Despite the fact that energy conservation within the enclosure was the basis for the *Regime I compartment fire framework*, scarce research has been carried towards understanding the ratios of energy distribution for open floor plan enclosure fires. The distribution of energy is a fundamental aspect of the thermal solicitation of the different structural and boundary components, thus an unavoidable path for the analysis of a structure subject to a fire. This paper describes a study completed within the Real Fires for the Safe Design of Tall Buildings project, and more specifically, focused on the series of experiments based on gas burners from the 'Edinburgh Tall Building Fire Tests' (ETFT) programme. These series of experiments precisely controlled the input energy in the compartment, thus allowing a study of the distribution of energy to the different elements of the thermodynamic system represented by the enclosure. The work presented herein describes an energy distribution analysis carried out for an experimental full-scale open floor plan enclosure.

3. Experimental enclosure fire

A detailed description of the experimental enclosure is presented by Hidalgo et al. [11]. The internal dimensions of the enclosure were 17,800 mm×4900 mm×2000 mm (refer to Fig. 1). The dimensions of the enclosure are such that they represent the maximum possible length and depth viable for the BRE Burn Hall where the experiments were performed. The height of the experimental enclosure was sized to represent a slightly scaled down version of a typical open floor plan enclosure [11].

One side of the enclosure was fully open with a 500 mm overhang (refer to Fig. 2b), and a custom-built shutter system designed to partially cover the 15 independent segments (or vents) of the opening. This system allowed to individually control the number of open segments during experiments (i.e. fully open or partially closed). Segments across the length of the opening were 1100 mm wide and 1500 mm high, and separated by 100 m thick protected square columns (refer to Fig. 2a).

The solid boundaries of the enclosure (i.e. ceiling, walls, and floor) were built in accordance with energy efficiency criteria towards EU 2020 legislation [13]. The *U–value* for each enclosure partition was calculated considering the conventions for *U–value* calculations given by Anderson [14] and in BS EN ISO 6946 [15].

3.1. Relevant instrumentation

A detailed description of the instrumentation used in the experimental enclosure is described by Hidalgo et al. [11]. The primary aim of the experimental study was to provide a sensor density such that spatial and temporal variation of the distribution of thermal energy could be investigated. The enclosure was densely instrumented with more than 1800 gas-phase temperature gauges (K-type Inconel sheathed thermocouples), 274 Thin Skin Calorimeters (TSCs), 30 gas flow velocity gauges (McCaffrey probes), and 12 twelve custom-built sand gas burners. The following sections describe a summary of the sensors used in the experimental enclosure, and relevant to the analysis presented herein. Data during experiments were collected with a frequency of 1 Hz.

3.1.1. Gas-phase temperature gauges

Type K thermocouples (with a 1.5 mm bead) were used throughout to measure the gas-phase temperature distribution within the enclosure and at each of the openings. *Thermocouple trees* were positioned within a floor grid spaced 600 mm along the depth of the enclosure (x-axis, refer to Fig. 3a) and spaced 700 mm along the length of the enclosure (y-axis, refer to Fig. 3b). Each thermocouple tree had thermocouples positioned at the following heights (from the floor of the enclosure): 300, 600, 900, 1200, 1400, 1600, 1800, and 1950 mm. Additionally, thermocouple trees were positioned at the centre line of each opening segment (refer to Fig. 4); thermocouples were positioned at the following heights: 180, 430, 680, 930, and 1180 mm.

3.1.2. Thin skin calorimeters

Incident radiant heat flux at the boundaries of the enclosure was quantified using Thin Skin Calorimeters (TSCs). The TSC gauges were designed and calibrated according to the methodology described by Hidalgo et al. [12]. The TSCs were made out of a 10 mm diameter and 0.5 mm thick 304b stainless steel plate, with a Type KX thermocouple welded to the centre of the unexposed surface of the plate. The plate was embedded onto the surface of 80 mm diameter and 50 mm deep Ceraboard® cores. The thermocouple wires passed through the Ceraboard® and exited through the rear. Thin Skin Calorimeters were embedded onto the ceiling, walls, and floor of the enclosure; remaining flush with the exposed surfaces. Thin Skin Calorimeters were placed on all five internal surfaces of the enclosure. There were 45 on the ceiling, in a grid of 3 rows of 15 gauges. This arrangement was a mirror of those on the enclosure floor. Further 45 gauges were located on the back wall, with a grid of 3 gauges in height and 15 gauges along the length of the enclosure (refer to Fig. 3). The shorter end walls had 15 gauges each, with 3 rows of 5 gauges.

3.1.3. Gas flow velocity gauges

For each of the 15 segments of the opening, two bi-directional velocity gauges [16] were positioned at the following heights (from the floor of the enclosure): 220 mm and 1230 mm (refer to Fig. 4). Due to the position of the gauges, the bottom gauge accounted for *'cold'* air

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