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A critical review of “travelling fire” scenarios for performance-based structural engineering

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ABSTRACT

Many studies of the thermal and structural behaviour for large compartments in fire carried out over the past two decades show that fires in such compartments have a great deal of non-uniformity (e.g. Stern-Gottfried et al. [1]), unlike the homogeneous compartment temperature assumption in the current fire safety engineering practice. Furthermore, some large compartment fires may burn locally and tend to move across entire floor plates over a period of time. This kind of fire scenario is beginning to be idealized as *travelling fires* in the context of performance-based structural and fire safety engineering.

This paper presents a literature review of the travelling fire research topic and its state of the art, including both the experimental and theoretical work for the past twenty years. It is found that the main obstacle of developing the travelling fire knowledge is the lack of understanding of the physical mechanisms behind this kind of fire scenario, which requires more reasonable large scale travelling fire experiments to be set up and carried out. The demonstration of the development of a new travelling fire framework is also presented in this paper, to show how current available experimental data hinder the analytical model development, and the urgent need that the new travelling fire experiments should be conducted.

1. Introduction

The “travelling fire” methodology originating at the University of Edinburgh in 2007, due to Rein et al. [2], postulates that fires may burn locally and move across the entire floor plate over a period of time in large compartments. It was proposed on the basis of observed fire dynamics from real fires and a few experimental programmes that have occurred over the past two decades, such as [3–6].

In real life, travelling fires have been observed in several structural failures especially since 2000: the World Trade Center Towers [7] in New York City in 2001, the Windsor Tower [8] in Madrid in 2005, and the Faculty of TU Delft Architecture building [9] in Netherlands in 2008. Looking closely at an example of an open-plan modern building, i.e. the Informatics Forum that opened at the University of Edinburgh in 2009, a statistical survey indicated that traditional fire safety design methods were applicable to only 8% of the total volume of the building (other areas being out-of-range by Eurocode limitations, e.g. opening factor (> 0.2), compartment height (> 4 m), size of the compartment (> 500 m^2) [10]). These facts underline the need for a better description of fire scenarios that recognise the radically different spatial layouts preferred in contemporary architecture. There is currently greatly increased interest in methodologies for representation of more realistic fire scenarios for the purposes of fire safety engineering design.

In 2012, a review paper was published by Stern-Gottfried & Rein [11]. It summarized several fire tests conducted in the large compartments (e.g. [3–5]) as experimental evidence which clearly showed the temperature heterogeneity in such compartments. There have been three further large scale travelling fire tests performed from 2011 to 2015. In 2011, to investigate how the travelling fires impact the steel structural components especially for beam-to-column connections, a full-scale travelling fire test was conducted at the upper floor of a two-storey steel composite building in Veselí, in the Czech Republic [12]. In 2013 a series of experiments were conducted at the Building Research Establishment (BRE) in UK as part of the EPSRC funded research project ‘Real Fires for Safe Design of Tall Buildings’ [13]. The project intended to obtain a better understanding how a fire progresses in a large compartment and affects the temperature distribution spatially and temporally. In 2015, another experiment called the Tisova Fire Test [14] was conducted in the Czech Republic inside a 4-storey concrete frame building, in order to test the travelling fire methodology put forward by Stern-Gottfried & Rein [15].

Moreover, two main theoretical representations of travelling fire models can be found in the current literature, hereinafter referred to

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as: Clifton's model [16]; and Rein's model [11,15]. Clifton developed a fire model, which divides the whole large compartment into several design areas, which are then subjected to time-temperature curves individually and sequentially. In Rein's model, Alpert's correlation is adopted to calculate far field smoke temperature, and a uniform temperature (800 °C–1200 °C) is assumed for the near field. However, both models necessarily neglect some aspects of the fire dynamics. For instance, the accumulation of a hot smoke layer is ignored in both models. In Clifton's model, all elements in one 'firecell' (one design area) share the same fire exposure history. In Rein's model the uniform 800 °C–1200 °C assumption is very generic. In 2016, a new travelling fire framework was proposed by Dai et al. [17,18]. It is based on a "mobile" version of Hasemi's localized fire model, combined with a simple smoke layer calculation for the areas of the compartment away from the fire. This combined fire model enables the analysis to capture both spatial and temporal changes of the thermal field which is then automatically coupled to a thermomechanical analysis using the software framework OpenSees [19].

This paper is divided into three sections: firstly, several large-scale fire experiments are reviewed, especially the ones labelled as travelling fire tests; secondly, a literature review of the current analytical travelling fire models is summarized, including the recent travelling fire framework proposed by the authors (Dai et al. [17,18]); thirdly, a demonstration of the newly developed travelling fire framework is also presented, to show how existing experimental data hinder the analytical model development highlighting the urgent need for new travelling fire scenario experiments.

2. Experiments conducted for characterising travelling fires

This section reviews the experiments that fires in which a 'travelling' nature in large compartments, with a particular emphasis on the ones labelled as *travelling fire tests* conducted for the past five years.

2.1. Fire Tests of a 'travelling' nature before 2010

Although true dynamics of travelling fires has received "zero attention" in large scale structural fire tests [20] (as summarized by Bisby et al. in 2013), there are still some experiments where a 'travelling' nature of the fire is recorded in the literature.

In 1993, to validate the 'Time Equivalent' formula given in Eurocode 1 for buildings with large compartments, a series of nine tests were carried out at BRE Cardington laboratory [3]. The dimensions of the test compartment were 22.8 m long × 5.6 m wide × 2.75 m high (128 m^2 floor area) with uniform wood cribs as the fuel load, and the ventilation was at one end of the long compartment. The fuel was ignited at the opposite end to the ventilation (apart from Test 9, which was ignited simultaneously for comparison), and it was observed that the fire spread quickly to the ventilation side, consumed all the fuel near the vent region, and then the fire travelled back to the ignition region and burned out. Both the gas temperatures and steel temperatures of the protected and unprotected steel members were recorded for the entire duration. Cooke [21] took additional measurements including thermal radiation, gas analysis, air flow, and crib weight loss in the experiment.

In 1995–1996, an experimental testing programme took place on an eight storey steel-framed structure, at BRE Cardington Large Building Test Facility (LBTF). This research programme contains four tests, in which the fourth one - Demonstration Furniture Test - was to investigate the impact of a more realistic fire scenario to the whole structure [22]. The test compartment was 18 m wide and up to 10 m deep (135 m^2 floor area), to represent an open plan office with modern day furnishings, computers and filing systems, which are equivalent to the fuel load density of 45.6 kg of wood/m^2. Both the ignition method and the ventilation conditions were designed to assist the fire growth, which generated non-uniform (migrating) fire scenarios during the test [23]. The gas temperatures, beam and column temperatures, and the connection temperatures were all measured. Moreover, the structural response was also recorded, including the strain along the columns, the deflections of the beams and floor slabs. All these test data can be found at the One Stop Shop web site, which is maintained by the University of Manchester [24].

In 1999–2000, a further series of eight large compartment fire tests were undertaken at BRE Cardington LBTF, to validate the zone models as part of the Natural Fire Safety Concept (NFSC) framework. These eight tests were full-scale post-flashover fires conducted in a large compartment with approximate dimensions 12 m × 12 m × 3 m high (144 m^2 floor area), with different opening situations, fire load compositions (wood cribs only, or 80% wood cribs + 20% plastic), and the compartment boundary linings [25]. Thermocouples were distributed throughout the compartment for recording gas temperatures, and the steel temperatures were measured for both the structural components with and without protections. Mass loss was also recorded through the tests by using load cells. The spatial and temporal change of the heat flux fields under the ceiling were produced by Welch et al. in Fig. 1 [6]. The maximum recorded temperature was over 1330 °C.

In 2005, a series of eight experiments were conducted by Thomas et al. [26] for investigating the fire behaviour in a deep enclosure with various openings in one end. The steel enclosure for the tests has dimensions of 8.0 m long × 2.0 m wide × 0.6 m high (16 m^2 in area), with sixteen steel fuel trays containing 97% ethanol (see Fig. 2(a)). Only the front end of the enclosure was ventilated with different opening sizes for the eight tests. Both gas temperatures and steel temperatures were recorded during the test (maximum thermocouple temperature was around 850 °C) (see Fig. 2(b)), and a calorimeter hood was used for collecting the outgoing combustion products to estimate the heat release rate. A load cell was placed beneath each tray to record the mass loss of the fuel throughout the test.

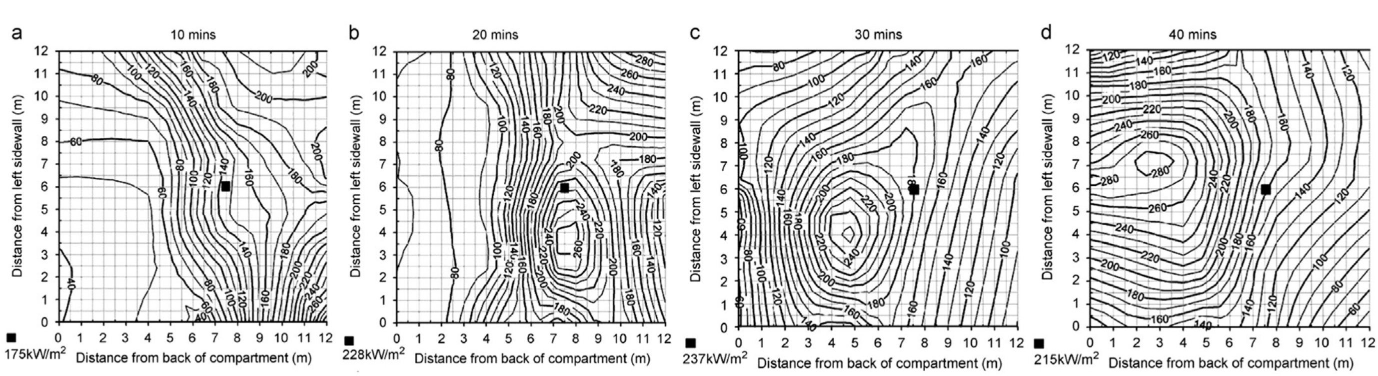

Fig. 1. Heat flux map under the compartment ceiling, reprinted from Welch et al. [6] with permission from Elsevier.