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Structural response of a steel-frame building to horizontal and vertical travelling fires in multiple floors

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ABSTRACT

During previous fire events such as the World Trade Centre Towers (WTC) 1, 2 & 7 in New York (2001), the Windsor Tower in Madrid (2005), and the Plasco building in Iran (2017), flames were observed to travel horizontally across the floor plate and vertically to different floors. Such fires are not considered as part of the traditional prescriptive structural design for fire. Recently, the Travelling Fires Methodology (TFM) has been developed to account for such horizontally travelling nature of fires. A dozen of studies have investigated the structural response of steel, concrete, and composite structures to a single-floor travelling fire. 5 out of 6 of the vertically travelling fire studies have been limited to the structures with a long span composite truss system as in the WTC Towers. The aim of this work is to investigate the response of a substantially different structural system, i.e. a generic multi-storey steel frame, subjected to travelling fires in multiple floors, and varying the number of fire floors, including horizontal and vertical fire spread. A two-dimensional 10-storey 5-bay steel frame is modelled in the finite element software LS-DYNA. The number of multiple fire floors is varied between 1 and 10, and for each of these scenarios, 5 different fire types are investigated. They include four travelling fire scenarios and the standard fire. In total, 51 fire simulations are considered. The development of deflections, axial forces, bending moments and frame utilization are analysed. Results show that the largest stresses develop in the fire floors adjacent to cool floors, and their behaviour is independent of the number of fire floors. Results indicate that both the fire type and the number of fire floors have a significant effect on the failure time (i.e. exceeded element load carrying capacity) and the type of collapse mechanism. In the cases with a low number of fire floors (1–3) failure is dominated by the loss of material strength, while in the cases with larger number of fire floors (5–10) failure is dominated by thermal expansion. Collapse is mainly initiated by the pull-in of external columns (1–3-floor fires; 1–9-floor fires for 2.5% TFM) or swaying of the frame to the side of fire origin (5–10-floor fires). This study has assessed a different structural form compared to previous literature under an extensive range of multiple floor travelling fire scenarios. We find that although vertically travelling fires result in larger beam axial forces and initial deflections, simultaneous travelling fires result in shorter failure times and represent a more onerous scenario for the steel frame investigated.

1. Introduction

The understanding of the fundamental mechanics of a whole building behaviour in fire has significantly increased in the last decades, especially following the Broadgate fire in London in 1990 [1,2], which took place in a 14-storey steel framed building under construction. Even though the majority of the steelwork was unprotected and active fire protection methods were not functional, the building showed robust behaviour and did not collapse. Following this accident, full-scale tests of various multi-storey buildings were carried out in Cardington between 1994 and 1999 [3]. The Broadgate fire and Cardington tests showed that steel framed buildings as a whole performed better in fire than indicated by the prescriptive design of individual members. Therefore, prescriptive design approaches were believed to be conservative [2].

However, the prescriptive design was challenged and concerns were raised after the collapse of the World Trade Centre Towers 1, 2 & 7 in New York (2001) [4] and Windsor Tower fire in Madrid (2005). Firstly, the collapse of the buildings during these accidents showed that for buildings with non-conventional structural layout (unlike in the Broadgate fire and Cardington tests) the prescriptive guidance assuming single elements can be non-conservative [5]. Secondly, during these

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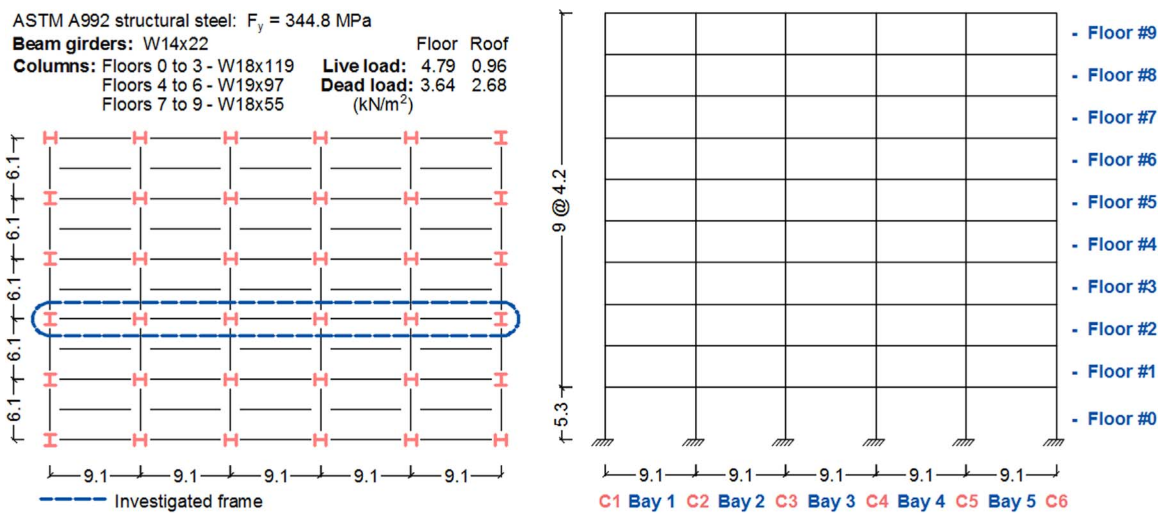

Fig. 1. Plan layout, elevation and structural member details of the investigated frame [18]. Frame dimension units are in meters.

events, fires were observed to travel horizontally across the floor plate and vertically between different floors. Such fires were not considered in the traditional prescriptive design at the time. Design codes and, thus, most of the understanding of the structural behaviour in fire were based on the assumption of uniform fires in a compartment. Recent work [5,6] has shown that, while the uniform fire assumption may be suitable for small enclosures, the large, open-plan compartments typical of modern architecture, do not burn simultaneously throughout the whole enclosure. Instead, these fires, as observed in the accidents, tend to burn over a limited area and move across floor plates as flames spread with time. They are referred to as travelling fires. To account for this travelling nature, the Travelling Fires Methodology (TFM) was developed by Stern-Gottfried et al. [6,7]. Recently, the TFM has been improved to account for more realistic fire dynamics and range of fire sizes and is referred to as iTFM [8]. Unlike traditional design methods, this methodology accounts for non-uniform temperature distributions and long-fire durations observed in the aforementioned travelling fire incidents. The methodology has been applied to investigate the thermal and structural response of steel [7,9,10], concrete [11,12] and composite structures [13,14]. In most of these studies it was concluded that the consideration of more realistic fire exposures such as travelling fires is important for the structural response and that a uniform fire assumption is not the most conservative. However, most of this work has been limited to single-storey travelling fires.

Following the 9/11 events, a lot of research has been carried out on the structural response of structural arrangements similar to WTC Towers (long-span composite truss system) subjected to multiple floor fires [2,5,15–17]. Usmani et al. [2] and Flint et al. [5] carried out computational analysis on the collapse mechanisms of the WTC Towers. The number of simultaneously heated floors and the maximum fire temperature were varied. A generalised exponential curve was used to represent the fire. Collapse was found to primarily be a result of geometric changes (i.e. inward pull-in of the external columns) and occurred at temperatures as low as 400 °C. Based on the latter work Lange et al. [16] identified two main collapse mechanisms (strong floor and weak floor) and proposed a design methodology. These collapse mechanisms were further examined by Kotsovinos and Usmani [17]. The authors performed parametric studies and established the criteria on the occurrence of strong and weak floor collapse mechanisms.

Röben et al. [15] carried out computational analysis on the steel-concrete composite structure exposed to vertically travelling fires with inter-floor time delay. The fires on each floor were represented by exponential curves adopted from the aforementioned studies. The results indicated cyclic deflection patterns of columns which were not observed previously for simultaneous multi-floor fires. The authors concluded that both simultaneous and vertically travelling fires result in different structural responses and either of them can be more onerous. One of the first studies which considered multiple floor horizontally and vertically travelling fires was conducted by Kotsovinos [14]. Fire type (i.e. uniform and travelling), size and inter-floor time delay were varied. To represent the horizontally travelling fire, the TFM [7] was used. In this study, uniform fires were found to result in higher stresses in the floor in comparison to travelling fires. Similarly to the study by Röben et al. [15], cyclic displacement patterns were observed for the cases with vertically travelling fire. In addition, results showed that small inter-floor time delay (300 s) did not have a significant effect on the structural performance.

In all of the previously identified studies significant and extensive work has been carried out to understand the structural response of high-rise structures subjected to simultaneous, horizontally and vertically travelling fire scenarios. However, most of this work on multiple floor fires is limited to structures with a long span composite truss system like in the WTC Towers. Furthermore, the focus of most of the work in [2,5,15,16] was on the collapse of the WTC, and thus the authors did not draw any generic conclusions on the effect on the structural response of the number of storeys subjected to fire. In these studies collapse was mainly associated with the stiffness of the structural members. The effect of the number of fire floors subjected to fire was only considered in the work by Kotsovinos and Usmani [17].

The aim of this work is to investigate the response of a substantially different structural system, i.e. generic multi-storey steel frame, subjected to multiple floor travelling fires and varying the number of simultaneously heated fire floors. Additionally, this work investigates how the structural response of the frame changes with inter-floor time delay, upward and downward fire spread, and opposing fire spread on different floors.

2. Computational model

2.1. The structure

The multi-storey steel frame considered in this analysis is based on the moment resistant frame published by NIST [18]. It is a 10-storey 5-bay frame representative of a generic office building with a floor layout of 45.5 m×30.5 m. It is designed according to the ASCE 7-02 standard. The plan layout and elevation of the building are shown in Fig. 1. In this study the structural fire response of a 2D internal frame with the longest beam span of 9.1 m is investigated. This frame is chosen because it is likely to be more susceptible to instabilities compared to