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Structural behaviour during a vertically travelling fire

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ABSTRACT

This study considers a multi-storey composite frame subject to a fire which travels vertically between three floors. Previous work has analysed the behaviour of this structure when subject to simultaneous fires on three floors. It highlighted the importance of the cooling regime adopted and the relative axial stiffness of the steel beams to the overall behaviour of the structure. This paper extends that work by investigating the more realistic case of a vertically travelling fire. Various inter-floor time delays are considered as well as two floor beam sizes. It is found that the inter-floor time delay affects the global behaviour substantially. The behaviour is also in part dependent on the stiffness of the floor beams. Axial forces caused by thermal expansion in individual floors may induce cyclic loading on the column which is not normally considered in structural fire design but may be important in determining structural behaviour. Identifying a worst-case rate of vertical fire spread is not possible due to the range of structural responses, so it is recommended that designers consider several rates of spread and ensure structural integrity for each.

1. Introduction

A performance-based approach to structural design specifies how buildings should perform rather than construction details such as material properties or member sizes, as in prescriptive design. It has been adopted in many areas of structural design in recent decades but has only recently been introduced in the field of structural fire design. It is particularly relevant to the fire safety design of high-rise structures as such buildings tend to combine large open-plan offices, long evacuation times and unusual construction methods, all of which fall outside the scope of applicability of most prescriptive-based fire design codes. However, the design of high-rise buildings to resist fire using a performance-based approach requires an understanding of their structural behaviour when heated. Several recent high-rise building fires [1–3] have shown that very large, multiple-floor fires are possible in such buildings and that the structural response will involve a similarly large portion of the structure. Consequently, attempting to analyse and understand the behaviour of high-rise structures on an element by element basis, as is common for ambient temperature design, is unlikely to meet the needs of designers using a performance-based approach. Fire in high-rise structures also tends to be difficult or impossible for fire-fighters to tackle, so much so that full burn-out may occur on one or more floors while evacuation or fire-fighting on other floors is still taking place. In such situations, ensuring the stability of the overall structure has clear life safety implications. This leads to a requirement to understand the behaviour of structures subject to fires that travel between floors, perhaps with some floors cooling after burning out while other floors are in the early stages of heating. This paper aims to build on the very limited work that has so far been devoted to understanding the global response of high-rise structures subject to multiple-floor fires.

Usmani et al. [4] and Flint [5] examined the collapse behaviour of tall buildings similar to the (undamaged) WTC towers 1 and 2 when subject to simultaneous multiple-floor fires. Depending on the relative stiffness of the floors and columns, two distinct collapse mechanisms were found for such structures [6]. More recently, it has been shown by Usmani et al. [7] that these collapse mechanisms can be reproduced in simplified, two-dimensional (2-d) models made up of column and beam sections, thus removing the need to model the complex three-dimensional (3-d) truss systems used in the WTC design. Usmani et al.'s work was only strictly applicable to structures using the unusual truss flooring systems found in the WTC towers; however, it has subsequently been shown that similar collapse mechanisms can occur in more generic tall buildings (e.g. Fig. 1) with beam spans of as little as 10 m [8].

To date, almost all studies of fire-induced collapse of tall buildings have considered only the heating phase of fires and assumed that fires occurred on all affected floors simultaneously. However, large forces may be induced in a structure during cooling from the typically highly inelastic state present after a fire and, as

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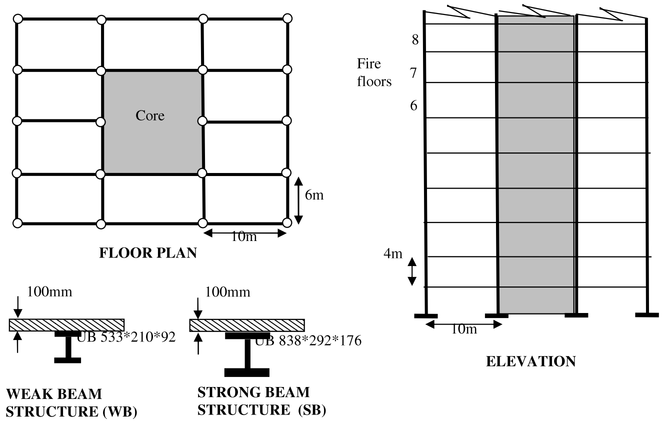

Fig. 1. Details of structures studied.

noted, the cooling phase of a fire is of design importance in high-rise construction. The only previous authors to consider the cooling regime in tall buildings were Röben et al. [9]. This work considered the effects of varying the cooling regime and of the axial capacity of floor systems on structural behaviour.

The present study extends Röben et al.'s previous work on multi-storey buildings by examining the effects of vertically travelling fires in a multi-storey building and comparing these to the effects of a fire occurring simultaneously on several floors. Considering travelling fires is more realistic than considering simultaneous multiple-floor fires as it accounts for the time it takes for severe fires to spread between floors in high-rise structures [2]. The study considers a generic high-rise structure, identical to that previously used for collapse analyses [8,9]. This structure is subjected to various fire scenarios occurring over three floors. Consideration will be given to the likely failure mechanisms and importance of the speed of fire spread between floors.

2. The nature of the study

2.1. The structure

The analyses presented here study the behaviour of the generic high-rise structure shown in Fig. 1, which is identical to that previously studied by Röben et al. [8,9]. It consists of a concrete core, which is considered completely rigid, supporting a steel–concrete composite floor system, the form of which is also indicated in Fig. 1. Such an arrangement represents, in a general manner, the wide variety of high-rise structures that adopt a central core to provide stiffness and resistance to gravity loads, together with composite floor systems spanning to edge columns that allow for open-plan office space.

The floor slabs are taken to have a thickness of 100 mm and to be made from concrete with a compressive strength at ambient temperature of 35 MPa. The slabs act compositely with steel beams having a yield strength of 355 MPa. In each case the yield strength, Young's Modulus and the coefficient of thermal expansion at high temperatures are as described by Eurocode 4 [10]. Stresses on cooling are governed by the von Mises and Drucker–Prager yield criteria for steel and concrete, respectively. Upon cooling, full recovery is assumed. Columns are on a 10 m by 6 m grid and the inter-storey height is 4 m, as indicated in Fig. 1. Loading is taken to be 5 kN/m^2 due to self-weight and office loads, and is assumed to be uniformly distributed over all floors.

Two variations of the structure are considered, and are identified as the strong beam (SB) structure and the weak beam (WB) structure, where the axial capacity of the strong beam is almost twice that of the weak beam. The section sizes of the SB and WB are UB 838 × 292 × 176 and UB 533 × 210 × 92, respectively; the column size is UC 356 × 406 × 467 in both cases. These two beams were chosen so the response of the structure with different floor system stiffnesses could be compared. They also correspond to floor systems designed for high and intermediate gravity loading.

2.2. Fire scenarios and heat transfer analyses

Temperatures in the structure were determined on the basis that the columns were fully protected and so reached a maximum temperature of 400 °C. As is increasingly common in structures designed using a performance-based approach, the beams and floor slabs were taken as unprotected; temperatures in these were determined by a heat transfer analysis of a typical 2-d composite section modelled using ABAQUS, as indicated in Fig. 2. The temperature distribution obtained from this analysis was then applied in mechanical analyses (below) to investigate the structural behaviour.

The gas temperatures for the heating phase of each fire were assumed to be described by the generalised exponential curve previously used by Flint [5]:

$$T(t) = T_0 + (T_{\max} - T_0)(1 - e^{-\alpha t}), \tag{1}$$

where $T_{\max}$ is the maximum compartment temperature, T_0 is the initial or ambient temperature, t time (this is a local time on each floor for analyses where the fires travel vertically), and α an arbitrary 'rate of heating' parameter. For the purpose of this research, $T_{\max}$ and T_0 were taken as 800 °C and 20 °C, respectively, α as 0.005 and the total time of heating as 3600 s. Eq. (1) was used to model the gas temperatures as fire dynamics analyses undertaken by Flint [5] showed it to be a better approximation for large compartments than the more commonly used "natural fire" curves given, for example, in the Eurocodes [10]. For the cooling phase a linear decrease in gas temperature was used where the ambient temperature was reached 1400 s after the end of the heating.

The thermal properties of both steel and concrete were taken from Eurocode 4 [10]. The properties of concrete were taken to be the same during heating and cooling, an assumption that holds well except for the specific heat capacity of concrete, which has a spike at around 100 °C during heating due to the latent heat of water contained within it. Since during heating there will be moisture migration and most of the moisture will escape from the concrete, this peak will not occur upon cooling. Analyses were performed to determine the influence of this brief increase in specific heat on the overall heat transfer analysis and the corresponding temperature distribution through the slab. The effect was found to be minimal, which had previously also been shown by Chung [11]. The analyses therefore strictly relate to dry concrete as defined in the Eurocode 4 but will hold to a good approximation for wetter concretes.

Fig. 3 shows the temperature distribution through the floor slab as given by the heat transfer analysis. It is clear from this figure that the bottom of the concrete slab heats up rapidly, as expected since it is directly exposed to the fire. The area of high temperature then gradually expands towards the centre of the slab as the fire continues to heat the lower surface. Once the fire has ended, the surfaces of the concrete slab quickly return to ambient temperature while the centre of the slab remains quite hot. The cooling of the centre of the slab is much slower, and this section continues to be subjected to high temperatures long after the fire has died out. Peak temperatures in the centre of the slab occur after the peak gas temperatures.

During the mechanical analyses (below), ABAQUS beam elements were used to model a suitable width of the concrete slab