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Thermal and structural behaviour of a full-scale composite building subject to a severe compartment fire

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Abstract

This paper presents a numerical investigation of the thermal and structural results from a compartment fire test, conducted in January 2003 on the full-scale multi-storey composite building constructed at Cardington, United Kingdom, in 1994 for an original series of six tests during 1995–1996. The fire compartment's overall dimensions were 11 m × 7 m with one edge at the building's perimeter, using largely unprotected steel downstand beams, and including within the compartment four steel columns protected with cementitious spray. The compartment was subjected to a natural fire of fire load 40 kg/m^2 of timber, in common with the original test series, but the composite slab forming its ceiling was subjected to a uniform applied load of 3.19 kN/m^2, which is higher than the original.

Numerical modelling studies have been performed using the numerical software *FPRCBC* to analyse temperature distributions in slabs, manual Eurocode 3 Part 1.2 calculations for beam temperatures, and *Vulcan* to model the structural response to thermal and mechanical loading. These are compared with the quite comprehensive test data, and a series of cases has been analysed in order to develop a comprehensive picture of the sensitivity of the behaviour to different assumed conditions.

The comparison between the modelling of basic cases and the test results shows very good correlation, indicating that such modelling is capable of being used to give a realistic picture of the structural behaviour of composite flooring systems in scenario-related performance-based design for the fire limit state. The extended sensitivity studies show the influence of extra protection to the connection zones of primary beams, and the effects of different vertical support conditions at the perimeter of the fire compartment. The effect of incomplete overlapping of the reinforcing mesh in the slab, which is believed to have occurred in one region, is also considered.

Keywords: Full-scale testing; Structural fire engineering; Thermal analysis; Structural behaviour; Composite construction

1. Introduction

Over the past decade, the fire engineering design of steel structures has developed considerably at its leading edge. The traditional prescriptive approach has placed reliance simply on limiting the temperature achieved by any structural component when subjected to a prescribed "Standard Fire" heating regime [1] up to the required fire resistance time, but taking no account of its position within the building or its loading condition. It has therefore been normal practice to protect steel beams and columns by using prescribed thicknesses of fire protection materials, whose purpose is simply to limit the steel temperatures to these values in the specified fire resistance time. More recent design rules [2,3] have been based on the behaviour of individual structural elements in loaded furnace tests, again subject to the Standard time–temperature curve. In two important respects these approaches fall short of realistic approaches to reality:

1. They do not incorporate heating of structure by natural post-flashover fires, whose characteristics include both growth and decay phases and are controlled by the fire load, ventilation and compartment properties. This has

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only recently [4,5] been introduced to design documentation with limitations on allowable compartment sizes.
2. They do not consider the effect of interaction and load-sharing between elements, which is particularly important in composite construction where slabs and beams in a floor interact completely as an integrated system.

In the standard test an isolated unprotected beam can only be expected to achieve 15–30 min' fire resistance if it carries any reasonable amount of load. There is a wealth of published test data from standard furnace fire tests on isolated elements; this information is of limited use in validating numerical modelling due to the drawbacks of the standard test as discussed. Tests on more complicated full-scale structural assemblies have been rare due to the costs and the complexity of such projects. Early work on fire testing of sub-assemblies was undertaken by Kruppa [6] and Rubert and Schaumann [7] which were followed later by full-scale testing on a loaded plane steel framework subject to a natural fire [8].

Accidental fires in composite steel-framed buildings, for example the well documented Broadgate fire [9] in London, have given strong indications that the performance of complete structural systems in fire is much better than is suggested by the standard test on isolated members. This poses the question of whether it is necessary to protect the structural steelwork to the extent demanded either by prescriptive documents [10] or by member-based design based on the standard fire test. In order to understand the behaviour of such continuous systems, and potentially to use this to advantage in fire engineering design of structures, it is clear from the cost of testing that the basic route must be via validated numerical modelling rather than tabulated data based on full-scale testing. However, in order to provide scientifically monitored data for validation of numerical analysis approaches, it was necessary to perform some testing on a full-scale structure constructed using current systems and site practices. The construction of the eight-storey steel framed building [11] (Fig. 1) at the Cardington Laboratory of BRE, to a design which was representative of contemporary medium-rise office buildings, was undertaken in 1994. This building was designed as a non-sway frame to BS5950 standards, to a specification which included bracing in a central core and two stairwells, providing the necessary resistance to lateral wind loads. The main steel frame was designed for gravity loads only. The floor construction incorporated a steel decking topped with a light-weight in situ concrete composite floor. The erection and fabrication of the structure was performed in accordance with normal British site practice.

Six full-scale fire tests were conducted inside the building at various locations (Fig. 2) during 1995 and 1996. The tests were extensively instrumented with thermocouples, strain gauges, and displacement transducers. The imposed load in all these tests was 2.66 kN/m^2. The total load on the floor system was 5.48 kN/m^2, representing a load ratio on the secondary composite beams of 0.44. This load was applied using sand bags which were distributed as evenly as possible on the floors. These tests have been well documented [12,13] and the results have since been useful in verifying numerical models [14,15]. The key data about each of this original series of tests are reiterated in Table 1. Perhaps the key point overall is that, while design codes based on isolated member tests in standard fire conditions [2,3] give the critical steel temperature for runaway failure of unprotected secondary beams in the region of 670 °C for all the tests at this load ratio, and the temperatures experienced were in all cases above this level, no structural failure was observed in any of them. Deflections of the floor system in most cases exceeded the normal furnace-test

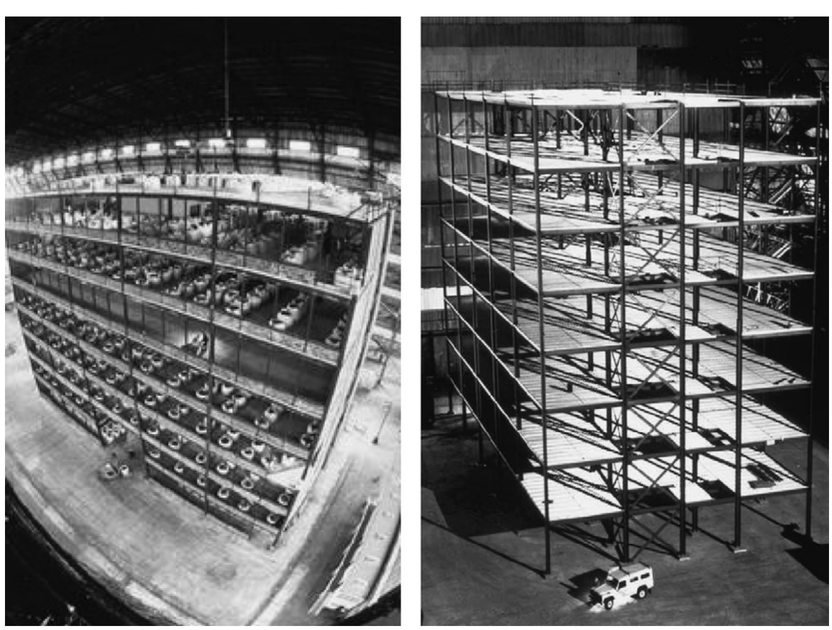

Fig. 1. The eight-storey building at the Cardington Laboratory.