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Fire behaviour of continuous reinforced concrete slabs in a full-scale multi-storey steel-framed building

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ABSTRACT

To further understand the fire behaviour of reinforced concrete floor slabs, a fire test was performed on six continuous panels (two by three) in a full-scale three-storey steel-framed building. In this paper, the test building, specially designed furnace and relevant experimental phenomena are briefly introduced. The furnace temperatures, temperature distributions, failure patterns as well as horizontal and vertical displacements of some structural components during the heat-up and cool-down phases were recorded and discussed in detail. The test data indicate that deformations of the heated panels have an important relationship with the boundary constraints around the heat panels. The plateau phenomenon of deflections at various measuring points mainly depends on the heated beams around the heated panels. The steel beams do not show partial buckling or failures due to constraints provided by other structural elements. Thus, taking advantage of the intrinsic design strength of the steel beams without applying fire retardant coatings can provide sufficient safety margins in similar engineering design scenarios. Moreover, the cracking characteristics at the upper surface of the heated panels have a direct relationship with the number and location of the heated panels in the floor. Several rational suggestions for the renovation of buildings subjected to fire can be quickly provided by utilising the cracking information.

1. Introduction

The annual economic and personal costs due to fire damage are immense. Fires are random events and thus cannot be prevented. Therefore, the goal of fire safety engineering is to reduce its risk to acceptable levels. Traditional methods for structural fire safety design are based on the conclusions of the fire resistance testing of single structural elements and relevant numerical modelling [1–6]. In such tests, the boundary conditions are tailored to represent the assumption that sustains a theoretical method, and the test data are used to calibrate analytical models, validate the predictive models or serve as a simple parameter that corresponds to the output data of a theoretical model. Thus, these simplified fire tests neglect the complex interactions between members in real structures or change the loading and supporting conditions. In other words, the actual rate of fire safety in any building is impossible to quantify. Relevant published documents indicate that a complete structural response in fire is often much better than suggested by these standard fire tests [7–11].

In recent years, many investigations have focused on the structure response of steel frames with composite floor systems in fire making by using large-scale components or small-scale test models [12–14]. However, these traditional laboratory tests cannot truly represent the behaviour of a complicated building with installed floor slabs, in-filled walls and other non-structural components because they attempt to isolate the sub-assemblies from the real buildings by introducing idealised conditions or ignoring their size effect. Correspondingly sub-assembly testing alone cannot answer all the questions that result from interactions between the structural and non-structural elements within a real building on fire. In other words, the global or local failure behaviour of the building and the effectiveness of both structural and non-structural repairs can be proven only with tests on a number of different types of completed buildings. In response to this need, a limited number of full-scale fire tests have been carried out to study structural response to fire. These tests included real building fires, such as Broadgate Phase 8, the Churchill Plaza fire, etc. and the fire tests including BHP fire tests, Cardington fire tests, etc. [7,12]. These well documented fire tests have given strong indication that no sign of structural failure was observed. The unprotected composite slab integrity was maintained even the maximum atmospheric temperature of 1254 °C. Among the fire tests, famous Cardington fire tests provided the most useful

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information [12]. The test building of the Cardington tests is a steel frame structure, and has steel-deck and lightweight in-situ concrete composite floor construction. Six full-scale tests were conducted on the test building in the BRE Cardington Laboratory. These experiments explored the behaviour of structural elements and the interaction between these elements under fire conditions that have not been observed in individual or skeletal frame tests, and relevant results leaded to various computer models to better understand the real structural behaviour of steel frame structures in fire and tensile membrane in composite slabs [8,18,19]. However, the test results can only be applied to buildings of the same form. In addition, the computer models verified by the above tests can predict accurately the steel-deck composite floor system, but whether they can be applied to conventional floor system is still to be examined.

To extend the understanding of the structural response of the entire steel frame with conventional floor slab systems, Dong [14,15] conducted a series of standard fire tests on full-scale composite steel frames with slim floor slabs or conventional floor slabs at Qingdao Technological University in China. Although Dong's tests furthered the knowledge of behaviours of composite steel frames under fire, they did not fully consider the effect of floor slabs on these heated steel frames. In Dong's tests, each storey only featured a 1000 mm wide slab to constrain the interacting members, which did not reflect the three-dimensional effect of a conventional floor slab system.

To further understand the above floor slab systems, a full-scale composite steel frame building with conventional floor slab construction that was representative of a civil architecture style in China, as shown in Fig. 1, was built within a civil engineering laboratory in Shandong Architectural University according to Chinese construction design codes in 2006. Yang [16] and Wang [17] carried out three tests to investigate the structural response of conventional floor systems under fire from 2009 to 2011. The three tests are named Tests 1–3, according to the testing date. Test 1 was a single corner panel test, while Test 2 was a single interior panel test. Both single panel tests were conducted on the top floor of the building [16]. Test 3 was a four (two by two) continuous panel test on the third floor [17]. In Tests 1–2, all the supporting members, including steel beams, columns and beam-to-column connections, were insulated from fire, while in Test 3 only steel-columns and beam-to-column connections were protected from direct fire exposure. The three tests showed a better fire-resisted capacity than isolated tests. The results of Tests 1–3 [16,17] could be concluded as follows:

- The structural fire behaviour of single panels strongly depended on not only the constraints provided by the adjacent structural but also the number and location of the heated panels in the floor slab. The higher restraint provided by the adjacent structural members leaded to better fire resistance.
- Two exterior edges of the corner panel underwent outward displacement during the initial stage of heating and inward displacement as the central deflection within the panel increases, while the two interior edges continuously moved inward throughout the heating phase. However, the four edges of the interior panel continually moved inward due to the higher lateral restraints.
- The cracking patterns of heated panels depended on the boundary constraints. However, for the unheated panels they depended on the number and location of the heated panels in the floor.
- The weld-bolted connections, as shown in Fig. 2, behaved better than high-strength bolt connections in terms of effectively releasing stress and preventing the steel beams from local buckling.

The fire test reported in this paper is a part of a series of tests of conventional floor system mentioned above and can thus be named Test 4. Based on the three tests above (Tests 1–3), this test continued to investigate the effect of the number and location of continuous panels on the fire behaviour of a conventional floor system. The test results were compared with those published in the literature [14–17]. Furthermore, the test can supply data to verify relevant computer models and provide the basis for a more rational design methodology of the fire behaviour of conventional floor systems.

2. Experimental building

The full-scale steel-framed building is three stories with the same height of 3.0 m, and each floor contains square areas that are three bays long (3×4.5 m^2) and three bays wide (3×4.5 m^2) for a total area of approximately 182 m^2, as shown in Fig. 1. The floor slabs (120 mm deep) consist of grade 30 normal-weight concrete whose average moisture content is 2.3% by weight measured seven days before the fire test. The test panels are located on the second floor of the building between grid line B–D and 1–4 with an area of approximately 110 m^2. To easily report the experimental results, the nine panels are labelled as Panels A-I in order, as shown in Fig. 3. All beams are designed to be simply supported as shown in Fig. 2, and they acted compositely with the floor by using

Fig. 1. Picture of the test building.

Fig. 2. Picture of the beam-to-column connection.