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Enhancing the fire resistance of composite floor assemblies through the use of steel fiber reinforced concrete

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ABSTRACT

This paper presents a strategy for achieving the required fire resistance in composite floor systems through the use of steel fiber reinforced concrete (SFRC). Both experimental and numerical studies were carried out to evaluate the fire performance of floor systems comprising unprotected steel beams and concrete/SFRC deck slabs. The results from these studies show that SFRC composite deck slabs develop significant tensile forces (through tensile membrane action) that transfer load from fire-weakened steel beams to other cooler parts of the structure. Preliminary results indicate that the combined effect of composite construction, tensile membrane action, and the improved properties of SFRC under realistic fire, loading, and restraint conditions can provide sufficient fire resistance in steel beam–concrete deck slabs without the need for external fire protection on the floor assembly.

1. Introduction

Steel offers many advantages when used as a primary structural framing material in buildings. These advantages include high ductility, ease of fabrication, and speed of construction. However, like all building materials, steel loses strength and stiffness when exposed to fire, and hence, steel structures are required to be provided with appropriate fire protection measures to maintain structural stability and integrity in the event of fire. A series of fire incidents in high-rise buildings, such as that at One Meridian Plaza [1] and the Broadgate Phase 8 fire [2] (UK), in which steel-framed structures did not collapse even under extreme fire conditions, prompted researchers to study the performance of steel-framed structures under realistic loading, fire, and restraint conditions, and to explore the possibility of unprotected steel structures. The culmination of this was a series of fire tests on a full-scale steel-framed building built at the Cardington large building test facility in the UK, collectively known as the Cardington tests.

Results from Cardington fire tests offer considerable insight into the response of a real steel-framed building under realistic fire exposure conditions. Of the seven fire tests conducted at Cardington, the tests that have the greatest implications to the research presented here are the "restrained beam" test, "plane frame" test, "corner" test, and "demonstration" test. The primary observation from these tests is that the steel-framed structure (which incorporated unprotected steel beams) did not collapse under fire exposure despite steel temperatures exceeding 900 °C [3,4]. During fire exposure, the composite floor system used in the Cardington test building underwent large deflections (more than 640 mm) but still supported the load and survived burnout conditions. Though the steel beams lost most of their strength due to extreme temperatures, loads from the beams were transferred through the concrete slab via tensile membrane action. Following the Cardington tests, many researchers initiated research programs to study various aspects of composite construction and their contribution to fire resistance. The early experimental studies were reported in [5–7].

Bailey et al. [5] investigated the possible failure patterns in concrete floors experiencing tensile membrane action under fire conditions. The research was based on the premise that an unprotected ribbed steel deck supporting a concrete slab offers no contribution to strength due to the high temperatures (in the region of 900 °C) rapidly achieved in the steel decking. Based on this assumption, Bailey et al. [5] removed the steel deck from the bottom of a series of floor slabs and loaded them to failure at ambient temperature. Using these tests as the basis, Bailey et al. [5] concluded that the failure load of a slab experiencing tensile membrane action is well above that predicted using typical yield line theory. Based on this experimental work and the work of Hayes [8], Bailey [9] developed an equilibrium-based method for predicting the ambient temperature load capacity of a slab without the supporting metal deck.

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Lim et al. [6] conducted tests on three reinforced concrete slabs of size 3.3 by 4.3 m and 90 m, 100 mm, and 130 mm in thickness, respectively. Data from these tests was utilized to validate the shell element subroutine recently introduced in SAFIR [10]. The validation process indicated that SAFIR is able to track the progression of deflections and predict the locations of the tensile and compressive zones in the slab with good accuracy. The results from fire tests and the SAFIR analysis showed that the simply supported concrete slabs contribute to the overall fire resistance in steel-framed structures.

An experimental study to trace the failure of reinforced concrete slabs due to the rupture of reinforcement under fire conditions was conducted by Cashell et al. [7]. The tests were designed assuming that the floor slabs behaved as lightly reinforced concrete beams under fire conditions, and they were carried out at ambient temperatures. Preliminary analysis of the tested slabs has been used to show the correlation between specific parameters used in modeling and the ultimate deflection of the slab at failure. Based on these studies, and subsequent numerical simulations, the authors concluded that stress–strain curves of steel, and bond/slip characteristics between steel and concrete, have a significant influence on the fire resistance of concrete slabs.

The above fire resistance studies offer considerable insight into the behavior of composite floor systems exposed to fire. Specifically, the Cardington fire tests demonstrated that the contribution of floor slabs to overall fire resistance is substantial. However, the beneficial effect offered by traditional concrete slabs may not enhance fire resistance to a level that leads to the use of fully unprotected steel beams. Kodur and Lie [11] have shown that the use of steel fiber reinforced concrete (SFRC) filling (in place of plain concrete filling) in Hollow Structural Section (HSS) columns can significantly enhance fire resistance. As such, in the current research program, the use of SFRC in place of plain concrete for slabs is explored as a means of achieving the required fire resistance in secondary steel beams. The term fire resistance refers to the duration of time during which a structural member demonstrates stability under fire conditions. As part of this research, a fire test was conducted on an SFRC slab composite with unprotected steel beams. Data from the experimental program was utilized to validate numerical simulations which were used to investigate the effect of concrete type and fire exposure on the fire resistance of the beam–slab assembly. Numerical studies were carried out using the finite-element-based computer program SAFIR [12], wherein the realistic fire and loading scenario, material and geometric nonlinearity, and stability-based failure criterion were considered.

2. Feasibility of using steel fiber reinforced concrete for slabs

Based on the results of the experimental and numerical studies described below, the response of a beam–slab assembly to fire can be broadly grouped into four stages, as shown in Fig. 1a. A more specific and detailed discussion of the stages will be presented in Section 4.2, while the discussion here is aimed at providing an overview of the response of composite floor systems to fire. In the initial stage of fire (Stage 1), the unprotected steel beams supporting the floor system experience a quick rise in temperature. While the steel section is losing stiffness during this stage, the deflections are predominantly resulting from the thermal expansion of the steel. As can be seen in Fig. 1a, the end of Stage 1 (after about 20–25 min) is denoted by a change (decrease) in the deflection rate.

In Stage 2, deflections continue to increase due to further increase in assembly temperatures causing the steel and concrete to lose stiffness. As the slab deflections increase, toward the end of Stage 2, the assembly is unable to resist the applied load via composite action alone (due to excessive softening of the steel beams). Section A–A in Fig. 1b shows a cross-section of this slab and the forces that result from the large deflections that occur in Stage 2 of fire exposure. The center of the slab undergoes a deflection Δ due to the combined effect of loading and fire exposure. These deflections cause the concrete slab to stretch and hence develop tensile forces; this mechanism is referred to as tensile membrane action (TMA). The tensile forces being tangential to the curvature of the slab have both a vertical and a horizontal component (denoted as V_s and H_s in Fig. 1b respectively). The vertical component of these forces serves to support the applied load on the slab and transfer it to other cooler parts of the structure. The horizontal component of the force, however, gets transferred to adjacent parts of the concrete slab, and causes the perimeter of the heated slab to be in compression, as shown in Fig. 1b.

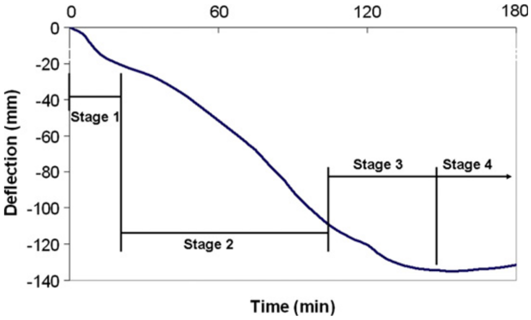

Fig. 1a. Different stages experienced by a beam–slab assembly during fire exposure.

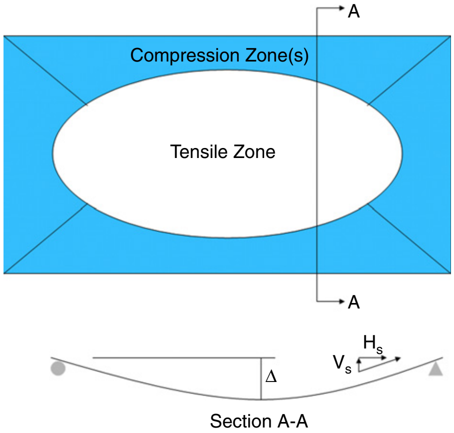

Fig. 1b. Resulting forces in a fire-exposed beam–slab assembly during tensile membrane action.

Once the fire enters the cooling (decay) phase, the slab enters Stage 3, as shown in Fig. 1a, as indicated by a reduction in the rate of deflection. Initially, the exposed steel in the beam regains strength, while the concrete (slab) which is supporting much of the load via TMA regains strength more slowly (due to the lower thermal conductivity of the concrete). When the slab attains its maximum deflection, Stage 4 (arbitrarily) begins.

With the assembly starting to rebound as the fire cools, the slab enters Stage 4. The rebound observed in Stage 4 (Fig. 1a) is predominantly due to thermal shrinkage in the assembly. The deflections continue to rebound until the structure returns to ambient temperatures. Unrecovered deflections remain as residual deflections.

The contribution from TMA is influenced by a number of factors including fire characteristics, concrete properties (tensile strength and ductility), and the presence of steel reinforcement in the slab. Therefore, if the tensile strength and ductility properties