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Experimental and analytical assessment of ductility in lightly reinforced concrete members

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ABSTRACT

This paper is concerned with the ultimate behaviour of lightly reinforced concrete members under extreme loading conditions. Although the consideration given to the assessment of ductility is of general relevance to various applications, it is of particular importance to conditions resembling those occurring during severe building fires. The main purpose of the investigation is to examine the failure of idealised members representing isolated strips within composite floor slabs which become lightly reinforced in a simulated fire situation due to the early loss of the steel deck. An experimental study, focusing on the failure state associated with rupture of the reinforcement in idealised concrete members, is presented. The tests enable direct assessment of the influence of a number of important parameters such as the reinforcement type, properties and ratio on the ultimate response. The results of several tests also facilitate a detailed examination of the distribution of bond stresses along the length. After describing the experimental arrangements and discussing the main test results, the paper introduces a simplified analytical model that can be used to represent the member response up to failure. The model is validated and calibrated through comparisons against the test results as well as more detailed nonlinear finite element simulations. The results and observations from this investigation offer an insight into the key factors that govern the ultimate behaviour. More importantly, the analytical model permits the development of simple expressions which capture the influence of salient parameters such as bond characteristics and reinforcement properties, for predicting the ductility of this type of member. With due consideration of the findings from other complementary experimental and analytical studies on full slab elements under ambient and elevated temperatures, this work represents a proposed basis for developing quantified failure criteria.

1. Introduction

The performance of steel-framed buildings with composite steel–concrete floors under fire conditions has been the subject of considerable research effort in recent years. The mounting attention directed to this area has been driven partly by the desire to achieve more cost-effective steel construction and, importantly, by the need to advance the understanding of structural fire response with a view to improving the rationale of design. A significant part of earlier activities in this area has been related to the fire tests conducted in the UK by the Building Research Establishment and Corus (formerly British Steel) on the full-scale eight-storey building at Cardington [1,2]. The findings of these tests, coupled with other numerical and experimental studies e.g. [3–8], have identified the important role played by the composite floor slab in carrying the gravity loading within the fire compartment after the loss of strength in the supporting secondary steel beams due to the elevated temperature. Moreover, due to the early development of high temperatures in the thin steel deck located at the bottom of the composite slab, its contribution to the resistance becomes insignificant. As a result, the slab behaves similarly to a lightly reinforced concrete member with an effective reinforcement mesh that remains at a comparatively low temperature.

Previous theoretical, numerical and experimental studies e.g. [3–8] have permitted a greater insight into the large displacement behaviour of floor slab systems. Comparison with available fire tests has also illustrated that the main elevated temperature effects, namely reduction in material properties as well as thermal expansion and curvature, can be closely replicated in the analysis. However, there remains a need for a fundamental examination of appropriate failure criteria that can be implemented within design guidance. One of the key failure conditions is that related to the rupture of reinforcement in the slab. Although the adoption of a conventional smeared crack approach within numerical models provides good predictions of the load–deflection response of lightly reinforced members, it cannot reliably assess the strain concentrations across cracks. This is because such concentrations are unrealistically dependant on the element size rather than the

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geometric and material characteristics. Due to the complexity of the problem and the absence of more detailed investigations, typical design methods e.g. [4,5] account for the limiting criteria using simplified approaches. These methods generally ignore the influence of several important material and geometric properties, such as reinforcement ratio and bond characteristics.

Recent studies carried out at Imperial College have focused on developing analytical models for assessing failure e.g. [9–11]. New procedures which predict the deformation and load levels corresponding to failure, at both ambient and elevated temperatures, have been proposed. The approach was firstly developed for slab strips [9,10] and more recently extended to represent slabs of various geometry and boundary conditions [11]. The models realistically capture the effects of key material and geometric parameters including bond characteristics, member length, steel material response and temperature effects. This paper describes the first phase of complementary laboratory studies; it forms part of a wider research programme which includes experimental and analytical assessments on isolated strips as well as full slab elements covering a wide range of material properties, geometric considerations and boundary conditions. In particular, this paper describes tests carried out on thirteen simply supported specimens representing isolated strip elements. For comparison purposes, the reinforcement ratio was varied between 0.24% and 0.52%, and both plain and deformed bars, as well as mesh configurations, were considered. Three of the tests were instrumented with strain gauges embedded within the reinforcement in order to investigate the distribution of bond along the length.

After describing the experimental arrangements and discussing the main test results, the paper introduces a simplified analytical model that can be used to represent the member response up to failure. The model is validated and calibrated through comparisons against the test results as well as more detailed nonlinear finite element simulations. Importantly, the comparative assessments enable the calibration of realistic levels of idealised bond properties that can be used in analytical models for predicting the ultimate response. Although the work presented in this paper is restricted to one-dimensional strip elements, it accounts for the influence of key material and geometric parameters and represents a necessary step towards a full assessment of failure in slab elements. With appropriate consideration of equilibrium and kinematic approaches [12], it should be possible to generalise the findings from this work to other structural and loading configurations.

2. Experimental programme

A total of thirteen ambient tests were conducted on lightly reinforced concrete (LRC) strips with a view to: (i) gain a greater understanding of the mechanisms dominating the ultimate behaviour; (ii) assess and quantify the key parameters influencing the response; and (iii) provide the necessary information to validate and calibrate the analytical models. To this end, several important geometric and material properties have been varied so that their effect could be examined. Tests carried out to characterise the material properties for steel and concrete are firstly described below, followed by a detailed account of the idealised member tests.

2.1. Material properties

In order to examine the influence of the specific properties of steel on the behaviour, several reinforcement configurations, providing a range of material characteristics, were employed in the experimental study. Four types of reinforcement were considered, namely: (i) plain bars with a diameter of 6 mm (P6); (ii) deformed bars with a diameter of 6 mm (D6); (iii) deformed bars of 8 mm diameter (D8); and (iv) A142 welded mesh consisting of 6 mm deformed bars spaced at 200 mm centres (M6). At least three

Table 1
Steel reinforcement properties.

	f_{sy} (N/mm^2)	f_{su} (N/mm^2)	ε_{su}
P6	252	330	0.203
D6	553	602	0.041
M6	552	589	0.025
D8	555	601	0.041

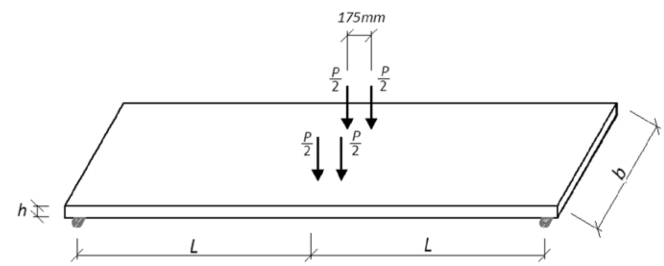

Fig. 1. General schematic of test-rig.

tensile tests were carried out for each type, in accordance with EN ISO 15630-1 [13]. The tests were conducted using an Instron testing machine, operating in displacement control at a rate of 4 mm/min. A carefully-selected extensometer was employed to measure extension up to fracture of the bar, which enabled a full representation of the stress–strain response over a gauge length of 100 mm.

The key mechanical characteristics resulting from the tensile reinforcement tests are summarised in Table 1 where f_{sy} and f_{su} are the yield and ultimate strengths, respectively, and ε_{su} is the corresponding ultimate strain, measured through the extensometer. In terms of the reinforcement categories used in Eurocodes and other guides, the values given in Table 1 indicate that D6, M6 and D8 fall within the definition of Class 'A' reinforcement while P6 satisfies the requirements of Type 'C'. The plain bars were hot-rolled and hence f_{sy} was easily distinguishable in the stress–strain response. In contrast, the other reinforcement-types were cold-worked and therefore displayed a more continuous constitutive relationship. Accordingly, the yield point was defined as the stress corresponding to a permanent strain of 0.2%. The values given in the table are the average obtained from at least three specimens for each type of bar. The coefficient of variation was lower than 0.03 for both f_{sy} and f_{su} and lower than 0.06 for ε_{su} in all cases.

2.2. Idealised member tests

A schematic of the testing arrangement is illustrated in Fig. 1, and a general view of the testing arrangement is shown in Fig. 2. The specimens were supported vertically on rollers and hence were free to move both axially and rotationally at the two ends. Loading was applied at the middle of the specimen through closely spaced points to simulate mid-span loading. This was preferred to a single point load to avoid interfering with the wide crack that typically occurred at mid-length. A hydraulic actuator, operating in displacement control, was used in all cases. In each test, the displacement was gradually increased until failure occurred, typically by fracture of the reinforcement, which was accompanied by a significant reduction in load capacity.

This paper focuses on the results from a series of thirteen tests, within which the geometric characteristics related to length, width and depth were varied, together with the reinforcement type and configuration. The details of each specimen are described in Table 2 which gives the half-length (L), width (b), depth (h) and reinforcement ratio (ρ). Also included in the table is the effective depth of the reinforcement from the compressive face (d_s), as well as the compressive (f_c') and tensile (f_{ct}) strength of concrete.