EUROSTEEL 2008, 3-5 September 2008, Graz, Austria

FAILURE ASSESSMENT OF COMPOSITE SLABS UNDER FIRE CONDITIONS

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INTRODUCTION

This paper is concerned with the ultimate failure of composite floor slabs in an extreme loading condition such as a fire. The tolerance for high deformations becomes unimportant in these situations and so alternative load paths can be established and mobilised, thereby facilitating secondary load carrying mechanisms after the conventional strength limits have been reached. These secondary mechanisms are largely related to membrane forces developing in the slabs. There is a need to establish the appropriate failure criteria of floor slabs based on a fundamental assessment of behaviour rather than from an empirical or semi-empirical approach.

This study focuses on the failure state associated with rupture of the reinforcement in slab strips, which become lightly reinforced due to the early loss of the steel deck and unprotected beams. In this context, quantitative solutions have been proposed by researchers at Imperial College for isolated slab strips at both ambient and elevated temperatures [1,2]; these have been further developed to accommodate full floor slabs in the same conditions [3]. An experimental investigation has been completed at ambient temperature to validate the proposed analytical model for slab strips and the findings will be discussed herein. The experimental program also includes tests on full slabs, and these will be reported on at a later stage.

1 FAILURE MODELS

Analytical models representing isolated strip elements in slabs have been developed, which predict the deformation and load levels corresponding to failure. Restrained specimens are accommodated in this approach, at both ambient and elevated temperature. There are two versions of the model; the first (detailed model) captures the full behaviour of the specimen, including both compressive arching and tensile membrane action as illustrated in *Fig. 1*. The second (simplified model) deals only with failure in the tensile stage. The extent of axial restraint provided is highly influential to the performance, especially in the compressive arching stage. Some tensile membrane action can develop in an unrestrained specimen if the geometry is such to allow the formation of a compressive ring around the edges to support tension in the centre.

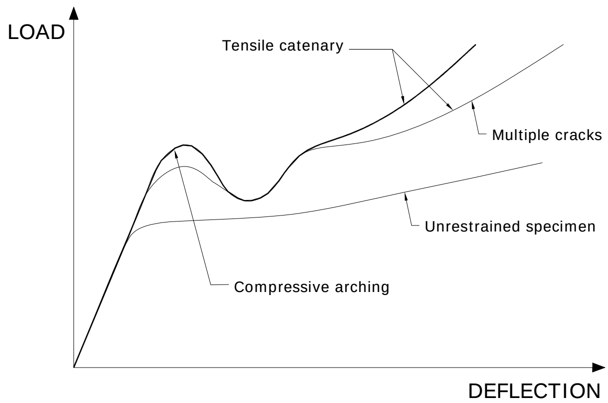


Fig. 1 Idealised behaviour of RC strip

One of the primary failure criteria associated with the failure of lightly reinforced members, particularly at high deformations, is fracture of the reinforcement. This is directly related to strain localisation across the cracks and therefore the steel material model, as well as the bond stress-slip relationship, is highly significant to the behaviour. Both of these are incorporated into the models. The steel is represented using the commonly-adopted Ramberg-Osgood model, whereas the bond relationship is rigid-plastic. High ductility, low bond stress and multiple cracking each have the effect of delaying failure; these models conservatively assume that a single crack forms. It has been shown that a single crack will form with certain axial stiffness conditions [1]. Despite an assumption of full axial restraint in the models, it is important to acknowledge that a single crack is a necessary assumption when full axial restraint is not guaranteed. A full list of assumptions made in the models has been previously published [1]. Further to the assumptions of a single crack and full axial restraint, the models also assume that the bond-slip is neglected in the region close to the supports and that the beam has a rectangular cross-section with a single layer of reinforcement. The models account accurately for local equilibrium as well as compatibility at large displacements. They result in a system of highly nonlinear equations which require an incremental-iterative strategy for solution. The Maple software package has been utilised for this purpose [4].

2 EXPERIMENTAL PROGRAM

The primary objective of the laboratory experiments is to gain a greater understanding of the full behaviour of slabs and to provide the necessary data to substantiate the failure assessment approach previously discussed. It is considered that the material properties along with the bond stress-slip relationship will be of great significance to the performance. Consequently, much effort has gone into ascertaining these relationships. The full experimental program can be divided into the following sections: (i) material tests, (ii) bond tests, (iii) strip tests and (iv) full slab tests. This paper will mainly focus on the strip tests, however brief details on the material and bond tests will be presented herein.

2.1 Material tests

Four types of reinforcement have been used in the tests, namely 6mm plain bars (R6), 6mm ribbed bars (T6), 6mm ribbed mesh (M6) and 6mm plain mesh (P6). Tensile tests were completed to ascertain the constitutive relationship for each and a synopsis of the properties is presented in *Table 1*. The plain mesh was welded at Imperial College using the plain bars previously mentioned (R6); therefore the material characteristics are identical. The concrete had a target compressive strength of 40N/mm^2 in all castings.

Table 1. Material data for the reinforcement

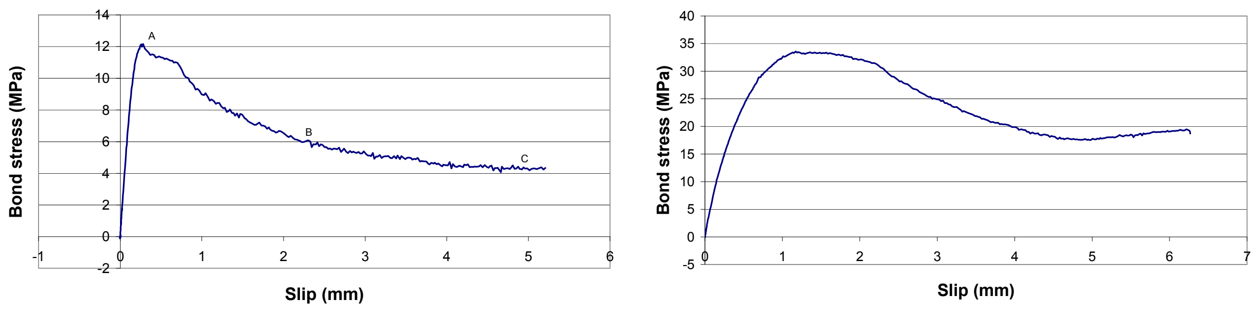
BAR TYPE	f_y **(N/mm^2)**	f_{ult} **(N/mm^2)**	ε_{ult} **(%)**
6mm plain	250	330	20
6mm ribbed	520	600	5
6mm ribbed mesh	550	580	4
6mm plain mesh	250	330	20

2.2 Bond tests

There are several different types of bond tests, will the most common being the pull-out test and the beam test. In selecting the most appropriate test method for the purposes of this study, the following considered criteria were that the tests should (i) give a realistic representation of bond behaviour, (ii) give a measurable estimate of the bond that exists and (iii) be relatively simple and feasible to set-up. A new specification developed through a recent European collaboration [5] was selected as it includes a pull-out test as well as a splitting test to measure the bond stress that can be achieved near the surface. Examples of the bond stress-slip curves resulting form these tests are depicted in *Figure 2(a)* for R6 and *(b)* for T6. M6 was almost identical to T6, with a slightly higher bond.

The plain bars clearly showed the simple mechanism of bond that is developed between these bars and the surrounding concrete. In contrast the tests involving ribbed bars displayed a bond behaviour that is more complex, but also developed a higher bond stress than the plain bars. The pullout tests generally showed that length had a significant impact on the results—for shorter lengths, a greater average bond stress developed. However this was not the case in the splitting tests which suggests that the concrete confinement has an effect on the development of bond stress.

In the analytical model, the influence of bond-slip on the overall member response is approximated using a rigid-plastic relationship which is a reasonable assumption as the member is lightly reinforced. Accordingly, a single value for bond stress (σ_b) is required, the value of which is a percentage of the maximum value achieved in the pullout tests. As this is such a complex relationship, the investigations into bond-slip are ongoing.

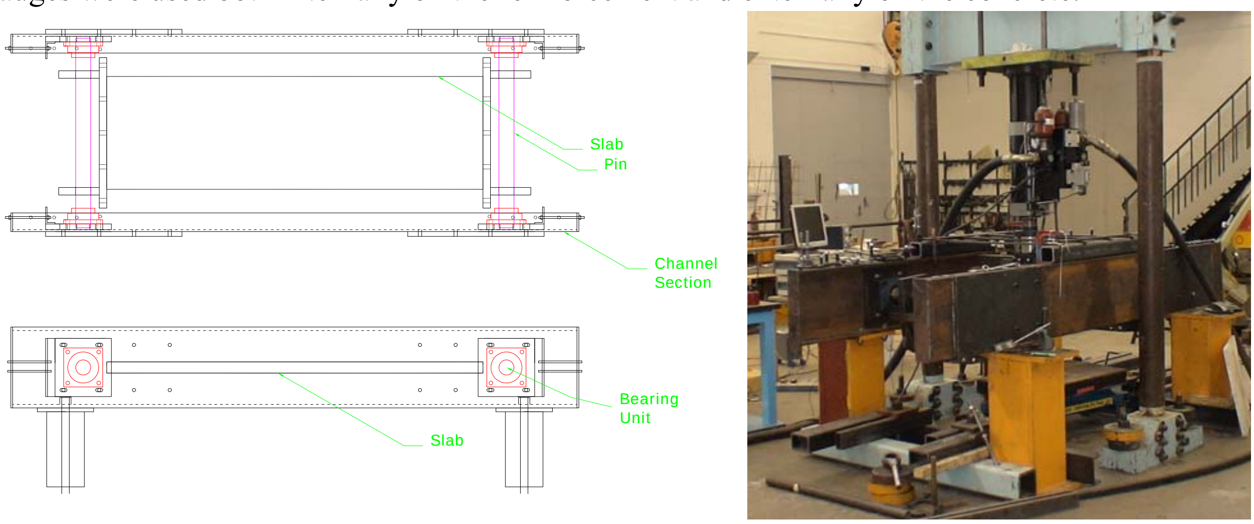


(a) (b)

Fig. 2 Bond stress-slip experimental relationships for (a) R6 and (b) T6

2.3 Slab strip tests

A purpose-built test rig has been designed and constructed; a schematic and a photograph are presented in *Fig. 3*. The set-up accommodated vertically supported specimens, both with or without axial restraint. Load was applied via two closely-spaced loading points (100mm apart) using a 100kN hydraulic jack. The tests were performed in displacement control using the data acquisition equipment DATASCAN, which logged the load, strain, displacement and input voltage. Transducers were placed at various locations around the rig to monitor movements and strain gauges were used both internally on the reinforcement and externally on the concrete.



(a) (b)

Fig. 3 (a) Schematic of test rig and (b) photograph

Twenty tests have been completed to date, the details of which are presented in *Table 2*. The restrained specimens were 1500mm in length whereas the unrestrained were 1000mm.

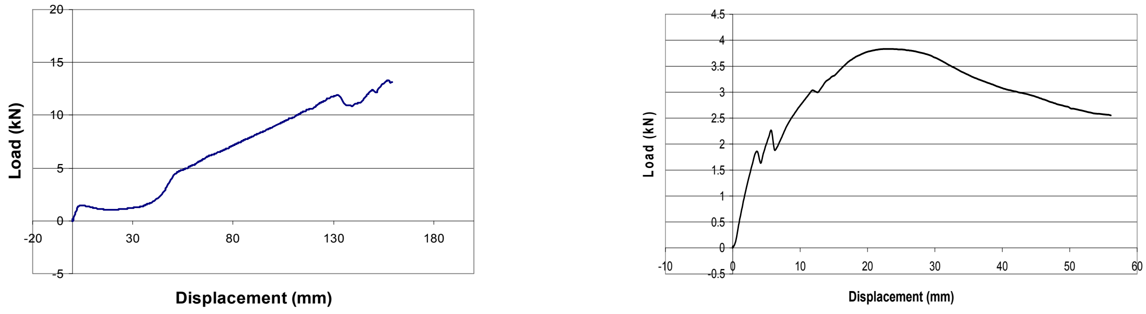
Table 2 Experimental Details for strip tests

Test	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Bar	R6	T6	R6	T6	R6	T6	R6	T6	M6	R6	M6	R6	M6	P6	M6	R6	M6	R6	P6	R6
Support	R	R	R	R	R	R	R	R	R	R	R	R	U	R	U	U	R	R	R	R
Type	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	//	//	⊥	⊥
ρ (%)	0.23	0.23	0.52	0.52	1.17	1.17	0.52	0.52	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Position	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↑	↑	↓	↓	↓	↓	↑	↑	↑	↑

The support conditions were either restrained (R) or unrestrained (U); the slab type was either flat (—), profiled with ribs parallel to the span (//) or profiled with perpendicular ribs (⊥); and the position of the specimen was either in-line with the pins (↓) or raised by a distance of 24mm (↑). All flat strips were 60mm deep.

Tests 1 and 2 were the control specimens for the restrained strips containing plain and ribbed reinforcement respectively; the load-displacement data is presented in *Fig. 4* for each of these.

It is seen that the test containing the more ductile plain bars, experienced compressive arching initially followed by tensile membrane action. However, due to the brittle nature of the ribbed bars, failure in Test 2 occurred during compressive arching.



(a) (b)

Fig. 4 Load-displacement responses for (a) Test 1 and (b) Test 2

The important values from each of the restrained tests reinforced with plain steel are presented in *Table 3*, where U_f is the failure displacement, P_{peak} is the peak load during compressive membrane action, P_{yield} is the calculated yield capacity and P_{ult} is the load at failure. The failure displacements were relatively similar in all cases with the largest failure displacement occurring in the most heavily reinforced specimen (Test 5). The earliest failure displacement was recorded in Test 14—120mm—which contained the lowest reinforcement ratio (0.23%) in plain mesh. Mesh has a higher bond than plain bars and therefore it was anticipated that failure would be earlier. The highest and lowest ultimate loads were also recorded in Tests 5 and 14 respectively. The P_{peak}/P_{yield} ratio is an indication of the increase in load as a result of compressive membrane action. This is at its highest value in Tests 12 and 20 which were raised specimens. Raising the specimen had the effect of increasing the amount of compressive arching that occurs. It also resulted in a delay in the initiation of tensile membrane action; however the failure displacement very similar to the in-line condition. The overall depth of the profiled specimens was 84mm, and the reinforcement was 24mm above the support. So they could be considered to be "raised" specimens. In reference to the profiled members, it was observed the ribs had very little influence on the failure displacement or the load-carrying capacity in the tensile membrane range.

Table 3 Data from restrained tests containing plain steel

Test:	**1**	**3**	**5**	**7**	**10**	**12**	**14**	**18**	**19**	**20**
U_f (mm)	142	152	186	152	151	168	120	181	183	176
P_{peak} (kN)	3.1	3.7	7.7	4.1	1.7	4.1	1.6	2.2	2.1	4.1
P_{yield} (kN)	1.5	2.8	5.4	2.8	1.5	1.5	1.5	1.5	1.5	1.5
P_{peak}/P_{yield}	2.1	1.3	1.4	1.5	1.1	2.7	1.1	1.5	1.4	2.70
P_{ult} (kN)	11.8	22.4	55.3	22.4	11.8	12.6	10.7	10.5	13.2	12.7

The equivalent values for the restrained tests using ribbed reinforcement are displayed in *Table 4*. Again, it is seen that the failure displacements are similar throughout with the highest value measured in the most heavily reinforced test (Test 6) and the lowest U_f occurring in Test 9 which contained ribbed mesh as opposed to straight bars. All of these tests failed in the compressive arching stage after P_{peak} and so the values of P_{ult} are insignificant—they are included here for completeness.

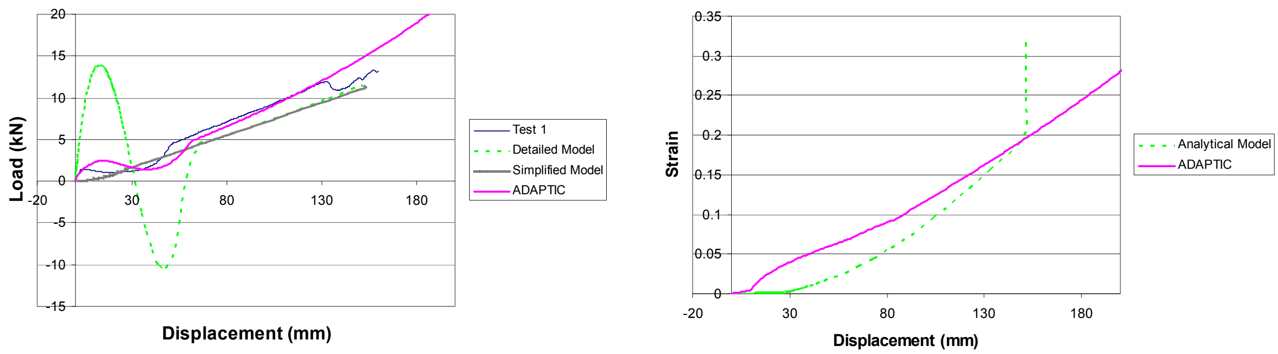
Table 4 Data from restrained tests containing ribbed steel

Test:	**2**	**4**	**6**	**8**	**9**	**11**	**17**
U_f (mm)	60	71	85	71	56	64	65
P_{peak} (kN)	4.3	7.9	16.8	8.3	3.8	4.9	4.8
P_{yield} (kN)	3.4	5.9	8.7	5.9	3.4	3.4	3.4
P_{peak}/P_{yield}	1.3	1.3	1.9	1.4	1.1	1.4	1.4
P_{ult} (kN)	2.6	9.2	55.3	17.4	2.5	1.4	1.6

The tests have shown that for both plain and ribbed reinforcement, the bond stress developed as a result of using a mesh arrangement causes an earlier failure than using straight bars. Also, the position of the specimen relative to the support is significant, as a raised slab experiences considerably more compressive arching. The extent of this enhancement is dependant on the specimen geometry.
Three unrestrained tests have also been completed and the details of these will be published at a later date.

3 ANALYTICAL STUDIES

One of the primary objectives of these experiments was to provide the necessary data for verifying the analytical model that has been developed at Imperial College. This failure assessment approach has been further developed to include full slab models and so its validation is imperative. The model will be further verified using the nonlinear structural analysis software ADAPTIC. One-dimensional beam-column elements are employed which account for both geometric [6] and material nonlinearity [7]. It has previously been mentioned that the analytical model uses a Ramberg-Osgood representation for the steel; ADAPTIC employs a bilinear elastic-hardening idealisation. For the bond stress-slip, both the analytical model and the FE analysis use a rigid-plastic relationship. The ADAPTIC model is numerically very difficult because of the nonlinearities, and so a fine level of discretisation is used in order to achieve convergence.
The experimental load-displacement data for Test 1 is depicted in *Fig. 5(a)* along with the numerical analysis from both the Maple analytical models and the Adaptic finite element models.



(a) (b)

Fig. 5 Analysis for Test 1 (a) Load-displacement and (b) Steel strain-displacement

The value of σ_b that is assumed in the analytical model is found by referring to the failure displacement in the test (142mm). The bond stress corresponding to this level of failure is established as 3.33% of the maximum value from the appropriate bond test, i.e. 0.4N/mm^2. This assessment appears to be in agreement with the guideline range in the CEB-FIP report into bond [8] where it was suggested that the bond stress for plain bars is in the range of (0.2-0.8)f_{ct}. *Fig. 5(b)* shows the predictions for steel strain with increasing displacement, and it can be seen that with this value of bond, the failure displacement is satisfactorily predicted. It is observed that, in terms of load capacity, the detailed analytical model predicts a much greater load in the compressive arching stage than occurred in the test. It was evident during the tests—and confirmed by the transducer readings—that a small slip occurred (≈ 1mm) at the ends of the specimen between the concrete and the clamps. This was due to experimental practicalities (bolt clearances, slightly irregular concrete surface etc.), and has a severe influence on the generation of compressive membrane forces. The finite element model has been adjusted to account for this slip by including spring elements at the edge, with a stiffness allowing 1mm of movement. To account for the effect that this flexibility has on the failure displacement, the bond stress is increased to 0.6N/mm^2. It is clear from *Fig. 5(a)* that the finite element model reflects the experimental behaviour very well. Also, it is noticeable that the slip does not affect the load-carrying behaviour once the member is acting as a tensile catenary. The stiffness' in this range are comparable between both sets of numerical results and the test data. The small discrepancies are attributable to the slightly different material relationships. Given the difficulty in achieving full axial restraint in the laboratory, it confirms that the single crack supposition is in fact a necessity.

4 CONCLUDING REMARKS

An extensive experimental program has been completed on isolated slab strips in order to validate the analytical model, a summary of which has been included here. It has been shown that the model is accurate in its prediction of failure and in the load-carrying capacity in the tensile membrane range; however it has not been possible to compare the compressive arching data as full axial restraint was difficult to achieve. The material and bond properties entered into the models are highly influential, and the latter of these is particularly difficult to quantify and assess. An extensive program of bond tension tests has been completed, and this will extend to bending tests in the future. Although outside the scope of this paper, the testing of a large number of full slab experiments is underway also in order to validate the failure predictions made by the analytical models, and the results appear to be positive.

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