Realistic Modelling of Composite and R/C Floor Slabs under Extreme Loading – Part II: Verification and Application

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ABSTRACT

This paper deals with the large displacement behaviour of floor slab systems under extreme loading conditions. The analytical model, presented in the companion paper, is verified through comparisons against existing experimental results on both reinforced concrete and composite slabs, with flat or ribbed profiles. The new model incorporates a novel shell element and accounts for material and geometric nonlinearities under ambient as well as elevated temperatures. The verification studies examine the response of reinforced concrete slabs under unrestrained and restrained edge conditions. An assessment of the behaviour of ribbed floor slabs is also undertaken, in addition to simulation of the structural response of a full-scale composite beam-slab floor system under a realistic compartment fire situation. The results show good correlation between the experimental findings and numerical predictions, and demonstrate the reliability and robustness of the proposed analytical model. Additionally, the studies and discussions presented in this investigation provide an insight into the key behavioural aspects of floor slabs under extreme conditions. In particular, the significance of compressive arching and tensile membrane actions, under various boundary conditions, is illustrated. Also, the importance of adopting a realistic representation of the composite slab geometry is highlighted. The proposed analytical model is of particular relevance to developments in performance-based structural fire design, where realistic assessment of the floor slab response is of paramount importance.

CD Database subject headings: Composite structures; Concrete structures; Finite elements; Fires; Nonlinear analysis; Slabs.

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INTRODUCTION

Considerable attention has been directed in recent years towards investigating the performance of structural systems under fire conditions. This has been driven by the need to develop rational design approaches that are based on true behaviour, rather than idealised representations of isolated elements which fail to account for interactions that occur between various structural components in a fire. There has therefore been a move towards improving current codified methods, which are primarily of a prescriptive nature and typically based on individual member assessment through unrealistic fire tests or over-simplified analytical estimations.

For steel and composite structures, the application of fire protection materials according to available codes has generally led to satisfactory behaviour in normal building fires. The mounting attention directed to structural fire performance in the last few years has in fact been largely motivated by the desire to achieve more cost-effective construction by reducing the amount of fire protection (e.g. Johnson, 1998; Robinson, 1998). However, from a more general perspective, the main purpose for the advancement of understanding of structural fire response is to improve the rationale of design. Even when fire protection is fully or partially utilised, the assessment of structural behaviour in an extreme loading scenario, in which existing protection could be rendered ineffective, is also necessary.

The structural fire performance of buildings with composite steel-concrete floors has been the subject of extensive research investigations in recent years. A large testing programme was completed on a full-scale eight-storey building (Kirby, 1997; O'Connor and Martin, 1998, O’Connor et al, 2003). To complement the results of the fire tests, numerical simulations were carried out by several researchers (e.g. Wang et al, 1995; Elghazouli et al, 2000; Izzuddin and Moore, 2002). These research investigations have identified the crucial 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
elevated temperature. Although the slab exhibits significantly lower bending capacity, the development of tensile-membrane action coupled with several sources of over-design leads to considerable fire resistance capabilities (Elghazouli and Izzuddin, 2000). Consequently, progress in the development of improved design approaches needs to be based on extensive assessment of the behaviour of floor slabs, using reliable and realistic modelling approaches, coupled with the application of appropriate failure criteria.

As described in the companion paper (Izzuddin *et al.*, 2003), several difficulties have been encountered in modelling the large displacement behaviour of composite floor slabs. These have been primarily related to the geometric orthotropy, as well as to the numerical problems associated with biaxial concrete material models, particularly under non-monotonic strain histories which exist under fire and other extreme loading conditions. The numerical model proposed in the companion paper addresses these difficulties and provides a realistic and efficient tool for the analysis of composite-ribbed, as well as flat reinforced concrete, slabs. The analytical developments include a novel shell element and a robust material model for concrete, and are incorporated within the nonlinear analysis program ADAPTIC (Izzuddin, 1991).

In this paper, verification of the proposed analytical model is undertaken by comparison against selected experimental results. Tests on reinforced concrete slabs, with various boundary conditions, span-to-depth proportions and reinforcement ratios, are considered. Beside validation of the analytical model, the results are used to illustrate important behavioural issues, with emphasis on those related to membrane effects. The numerical model is then utilised in examining the behaviour of ribbed floor slabs through a simulation of the response of a composite beam-slab system subjected to a realistic full-scale compartment fire test, followed by comparison against an experiment on an isolated unrestrained slab. Within the discussions, observations related to the behaviour of floor slabs under extreme conditions are highlighted, and their implications on the structural fire performance of buildings are discussed.
ANALYTICAL MODELS

The growing interest in assessing the actual performance of whole structures, particularly under extreme loading conditions, has led to an increasing attention towards providing realistic, yet relatively efficient, modelling techniques. For composite slabs, the orthotropic geometry represents an additional modelling difficulty. This renders their modelling with conventional 2D shell elements of uniform thickness unrealistic and their modelling with conventional 3D solid element computationally prohibitive. In the absence of appropriate shell elements, approximate modelling based on a grillage analogy using 1D beam-column elements has been widely used to assess the response of composite floors under fire conditions (e.g. Elghazouli and Izzuddin, 2001). However, the approximations involved in grillage representations can lead to inaccuracies, some of which may be attributed to the difficulty of incorporating a realistic shear modelling capability within one-dimensional beam-column elements (Izzuddin et al., 2002). Consequently, a new 2D shell element, which accounts for material and geometric nonlinearities as well as incorporating the geometric orthotropy in a realistic and efficient manner has been proposed in the companion paper (Izzuddin et al., 2003).

The new analytical developments are implemented within the nonlinear analysis program ADAPTIC (Izzuddin, 1991), which is particularly suitable for modelling the large displacement structural response. The program has been initially developed to model framed structures and has therefore focused on beam-column elements, including quartic and cubic formulations, in conjunction with uniaxial material models (Izzuddin, 1991; Izzuddin and Elnashai, 1993). The capabilities of the program have also been extended to model the nonlinear structural response under elevated temperatures (Izzuddin, 1997; Song et al., 2000). Careful attention has been given throughout the stages of development of the program for combining a high level of numerical accuracy and stability with optimum computational efficiency.

The recently-developed shell element, described in the companion paper (Izzuddin et al., 2003) modifies the Reissner-Mindlin hypothesis through the inclusion of additional rib freedoms, and incorporates the effects of material and geometric nonlinearities. As indicated
in Figure 1, the model is developed to represent composite-ribbed slabs, of which RC flat slabs are a special case. A biaxial concrete model accounting for compressive nonlinearity and tensile cracking, as shown in Figure 2, is proposed with the aim of providing a realistic simulation and simultaneous numerical robustness. This model can also represent the influence of elevated temperature on thermal expansion and on degradation of the material properties. Basic analytical verification illustrating the merits of the new shell element is given in the companion paper, whilst application and validation against experimental results are presented in this paper.

**RESPONSE OF R/C SLABS**

Before discussing the performance of composite profiled slabs, which have additional behavioural features related to geometry and constitution, it is important first to validate the analytical model for flat reinforced concrete slabs. This would have direct application for reinforced concrete systems, or composite floors with flat reinforced concrete slabs. Moreover, it provides a necessary basis for understanding the fundamental behaviour of ribbed composite slabs.

In this section, previous work on membrane action in slabs is briefly described. This is followed by comparisons between selected experimental results on reinforced concrete slabs against the predictions of ADAPTIC incorporating the proposed new developments. The key parameters influencing the response are outlined and the main aspects of behaviour are discussed.

*Membrane Action in Slabs*

As mentioned previously, this work focuses on the membrane action in slabs due to its crucial importance for the performance of floor systems under extreme conditions, particularly compartment fires. For composite floors, internal steel beams become ineffective at an early
stage due to high temperatures. However, the slabs are usually able to sustain the gravity loads over larger spans through compressive arching at relatively low deflections and, most importantly, through tensile membrane action at larger deflections, provided that sufficient restraint can be mobilised through external or internal mechanisms (Elghazouli and Izzuddin, 2001). It is also important to note that even when slabs are designed as one-way spanning in composite floors, the ineffectiveness of internal secondary beams in extreme fire situations causes two-way action to prevail. Although recent work on structural fire behaviour has led to renewed interest in membrane action in slabs, these mechanisms have clearly been recognised for many years. Early studies on compressive and tensile membrane effects in slabs include the work of Ockleston (1958), Wood (1961), Park (1964), Kemp (1967), Brotchie and Holley (1971) and others.

Despite the increase in load-carrying resistance due to membrane action over the capacities obtained from traditional yield-line methods (Johansen, 1962), this enhancement has not been incorporated in conventional design owing to several reasons. These include difficulties related to assessing the extent of available external restraints as well as the large deflections associated with the development of tensile membrane action, which would not be acceptable in normal design situations. Nevertheless, the importance of membrane action, particularly tensile mechanisms, for accidental design situations has been recognised earlier by some researchers (e.g. Mitchell and Cook, 1983), who considered these effects in examining progressive collapse of buildings, well before the current interest in structural fire behaviour. Evidently, deflection limitations would be different in the case of accidental loading conditions, where relatively large deformations may be tolerated. Whereas compressive arching may largely be considered as a transient phenomenon, which influences the behaviour at relatively low deflections, tensile membrane action plays a significant role in the performance of floor systems under extreme loads. Further assessment of these effects is presented in subsequent discussions.
Comparison with Test Results

Although several researchers have examined the membrane behaviour of slabs, as discussed before, the experimental investigations carried out in the 1960’s and 1970’s have been mainly undertaken for validation of closed-formed equations or modifications of the yield line capacities rather than for obtaining predictions of the full response history. Consequently, few of the reported test programmes provide sufficient information to enable detailed comparison with finite element results. In this study, tests conducted by Brotchie and Holley (1971) are selected, and the experimental results are compared with numerical simulations. It should be noted that only basic material properties of the test specimens are reported in available publications, hence some assumptions have to be made in the required input to the analytical models. Also, the experimental load-deflection curves are approximately digitised from printed graphical curves.

The experimental programme of Brotchie and Holley (1971) included tests on scaled square reinforced concrete slabs of span 381 mm x 381 mm, with various reinforcement ratios, span-to-depth proportions and boundary conditions. The slabs were reinforced near the bottom with smooth wire, uniformly and equally distributed in both directions. Uniform loading was simulated by hydraulic fluid pressure within a neoprene membrane. Analytical comparisons are carried out hereafter with eleven tests from this test programme, for which experimental load-deflection graphs are available. The details of these specimens are summarised in Table 1, which gives the span-to-depth ratio (L/d), depth (d), reinforcement ratio (ρ), effective reinforcement depth (d’), concrete strength (f’c), steel yield strength (f’y) as well as the measured maximum arching load (Pu). Two support conditions are considered: (i) simple, corresponding to vertical support on rollers with teflon and steel strips, and (ii) clamped, representing full support along the edges against vertical deflection, rotation and planar deformation, through top and bottom steel plates together with epoxy resin filling.
In the analysis using ADAPTIC, a mesh comprising 20 x 20 uniform-thickness shell elements is selected, based on a mesh sensitivity assessment, to model the reinforced concrete slab. The geometric and material properties given in Table 1 are utilised. The steel yield stress and concrete compressive strength are based on the values reported with the tests. The elastic modulus for steel is assumed as $210 \times 10^3 \text{ N/mm}^2$, whilst a low strain hardening modulus of 0.5% is employed for the reinforcement. Other properties required for the biaxial concrete model, shown in Figure 2, are assumed as indicated in Table 2. The analysis is performed through displacement-control of the central point of the slab, considering a uniformly distributed vertical loading.

Figures 3 to 5 show the experimental and numerical results for 11 tests, plotted in terms of uniform load against central deflection. Figure 3 depicts the comparison for four simply-supported slabs (S8, S9, S12 and S15) with two reinforcement ratios and two span-to-depth ratios. On the other hand, Figure 4 shows the comparative results for four fully-clamped slabs with L/d of 20 and $\rho$ varying between zero and 2%. Similarly, Figure 5 shows the experimental and numerical results for three fully-clamped specimens with L/d of 10 and $\rho$ varying between zero and 2%.

As observed in Figures 3 to 5, very good agreement is obtained between the experimental and numerical results. The initial stiffness and peak load are estimated within 10-15% in most cases, and the effects of reinforcement ratio, span-to-depth ratio and restraint condition on the response are all correctly reflected in the analysis. However, there are some discrepancies in the results which, in addition to the modelling idealisations, may be caused by several sources of inaccuracy, such as those related to the variability of assumed material characteristics. It should also be noted that whereas the experimental procedure utilises fluid pressure to apply the loading, the analysis is based on uniformly distributed vertical gravity loading, which corresponds to some discrepancies in the effective load orientation, particularly at large deflections. Nevertheless, the comparisons clearly demonstrate the overall accuracy and reliability of the analytical model in predicting the large displacement response of RC slabs.
The above-described analytical results are utilised in the following section to discuss the influence of restraint condition on the behaviour in more detail.

**Influence of Restraint Conditions**

The comparisons presented in the previous section offer a clear illustration of the influence of restraint conditions on the behaviour of RC slabs. As evidenced in Figures 4 and 5, slabs provided with a full external planar restraint (i.e. S46, S47, S48 and S49) develop significant membrane effects. Compression arching, which occurs at low deflection is gradually released at deformation levels approaching the depth of the slab. Thereafter, tensile membrane action is observed and the resistance increases steadily with growing deformation. Clearly, at relatively large deflections (with respect to the depth and the span), the reinforcement mesh effectively behaves in a catenary manner, as a hanging net in tension, providing significant enhancement of capacity with increasing deflection up to the point of reinforcement fracture. On the other hand, the behaviour of the horizontally-unrestrained slabs, shown in Figure 3 for various reinforcement and span/depth ratios, is markedly different. Although the figure indicates that a degree of tensile membrane action does occur in the absence of an external horizontal restraint, due to the formation of a compressive ring in the slab, the effectiveness of this internal mechanism is strongly dependent on the geometric and material properties of the slab.

It is important to evaluate the behaviour of the slabs considered above, in comparison with theoretical assessments of the tensile membrane action expected in restrained slabs. This is performed by considering the theoretical solution of Park (1964), which assesses the equilibrium of forces within only the reinforcement as the deflection is increased. The main assumptions are that the concrete is fully cracked and the reinforcement is all at yield, ignoring strain hardening effects. Based on this, a relationship is derived between the uniformly applied vertical loading \(w\) and the central deflection \(\delta\), given as:
\[
\frac{wL_y^2}{T_y \delta} = 4 \sum_{n=1,3,5,\ldots}^{\infty} \frac{1}{n^3} \frac{(-1)^{(n-1)/2}}{1 - \frac{1}{\cosh \left( \frac{n\pi L_x}{2L_y} \sqrt{T_y/T_x} \right)}}
\]

(1)

in which \(L_x\) and \(L_y\) are the spans in the long and short directions, respectively, whilst \(T_x\) and \(T_y\) are the reinforcement yield forces in the \(L_x\) and \(L_y\) directions, respectively.

Equation (1) provides a very good representation of the behaviour, both experimental and numerical, once the tensile membrane zone is reached. This is shown in Figure 6 in which the numerical results of the four restrained slabs (S46-49) are used for comparison. In the figure, the deflection is normalised to the depth in order to emphasise that the tensile action only develops when the deflection is well above the slab depth. Since the results presented in Figures 6a and 6b are for specimens with \(L/d\) ratios of 20 and 10, respectively, the different extent of tensile action is clearly limited by the constraint on the experimental deflection. Most importantly, the agreement between both Equation (1) and the analysis on one side, and the experimental results on the other, indicates the effectiveness of the external restraint used in the tests.

Having examined the fully restrained situation above, it is important to assess the extent of tensile membrane action for other support conditions. To investigate this, the simply-supported Specimen S9 is used as a reference, and the planar and rotational restraints along the perimeter edges are varied. Three different cases are considered as follows:

i. No planar and rotational restraint (unrestrained, i.e. S9)

ii. Full planar restraint without rotational restraint (planar-restraint)

iii. Full planar and rotational restraint (full-restraint)
The slab in cases ii and iii is prevented from pull-in along the edges, whereas in the first case it is subjected to the minimal planar restraint against rigid body movement. The case of providing planar restraint at the corners of the slab only, results in similar response to the unrestrained situation and is therefore not presented herein.

The response of the slab for the three support conditions is shown in Figure 7a together with the prediction of Equation (1) for the tensile membrane range. To illustrate the influence of the slab aspect ratio, Figure 7b depicts the response for the same cases except that the square slab is replaced by rectangular slab of \( L_x \times L_y \) of 571.5 mm \( \times \) 381 mm, i.e. \( L_x/L_y \) of 1.5, and the mesh is represented by 30 x 20 elements, with all other parameters retained. In both figures, the uniform load is normalised to the maximum compressive arching load of the unrestrained square slab S9, whilst the deflection is normalised to the slab depth. Clearly, in the cases with planar or full restraint, the slab is able to develop the full tensile action predicted by Equation (1) once the deflection approaches the depth of the slab, with the fully restrained slab exhibiting higher initial stiffness and capacity due to the rotational restraint. The same behaviour is observed in the rectangular slab, but at relatively lower resistance, as expected. In contrast, any tensile membrane action that develops in the unrestrained slab is considerably lower than that in the restrained cases. Examination of stresses and planar deformations within the unrestrained slab clearly indicates the formation of a compressive ring in the slab, as illustrated in Figure 7c, which provides a degree of planar restraint. However, the level of restraint is limited by the stiffness and strength of this ring, which is subjected to relatively high stress concentration causing early deterioration in concrete strength.

In summary, the comparisons demonstrate the accuracy and reliability of the new analytical models in representing the nonlinear large displacement behaviour of RC slabs. The results
also illustrate the influence of slab edge restraint conditions on the behaviour. Whereas tensile membrane action can be utilised in horizontally-restrained slabs, prior to the fracture of steel reinforcement, the internal mechanisms occurring in unrestrained slabs may only be partially effective, depending on the properties of the slab under consideration. Subsequent sections of this paper deal with the application of the analytical models to the assessment of the fire response of composite ribbed slabs.

**FIRE BEHAVIOUR OF COMPOSITE FLOORS**

In this section, application of the analytical models to composite floors with profiled slabs is illustrated. Firstly, a detailed model is described, which is used to simulate one of the main fire tests performed on the full-scale building at Cardington, UK. This is followed by an analytical assessment of the results of a more focused experimental study conducted at the Building Research Establishment (BRE), in which a full-scale isolated ribbed slab was tested to failure.

**Full-Scale Compartment Fire Test**

As mentioned before, the renewed interest in the large displacement behaviour of slabs has been largely related to recent work on the response of composite buildings in fire. In the UK, a considerable research activity has been associated with the fire tests conducted on the full-scale eight-storey building at Cardington. The details of the tests have been provided in several publications (e.g. Kirby, 1997; O’Connor and Martin, 1998, O’Connor *et al*, 2003). The Cardington tests were fundamental in identifying important response mechanisms, particularly in terms of the key role played by the slab. However, the complexity and scale of the experiments, especially in terms of the measured temperature distribution and material properties, would only enable analytical comparison with the overall response rather than
close examination of specific structural members or components. Moreover, findings from previous analytical studies (Elghazouli and Izzuddin, 2001) have shown that the response was largely dominated by thermal expansion effects. Consequently, rather than focusing on a detailed assessment, this section uses one of the Cardington tests, namely the corner compartment, as a demonstration of the application of the new analytical developments in representing the fire response of actual composite floors.

In the corner compartment (Test 3), the heated area enclosed two primary and three secondary beams, as indicated in Figure 8, which shows a plan and cross-section of the floor. As indicated in the figure, the composite slab had an overall depth of 130 mm, and consisted of a 0.9 mm steel deck and light weight concrete including a nominal reinforcement mesh with an area of 142 mm²/m in both directions. The design gravity load was simulated by placing sandbags, which were spread evenly such that the deadload plus a third of the live load was applied, giving an assumed total load of 5.48 kN/m². The columns and connections within the compartment as well as the external beams were fire protected. All other steelwork including beam-to-beam connections was left unprotected. Inside the compartment, the maximum temperatures in the lower flange of the internal secondary beams approached 1000°C at around 80 minutes. The maximum temperature in the external edge beams, which were fire protected, was typically about 400°C, but was reached after more than 100 minutes. On the other hand, the maximum temperature in the deck of the composite slab approached 900°C at around 80 minutes, whilst the temperature at the top surface of the slab typically remained under 150°C.

A detailed numerical model is constructed as a sub-structure around the heated compartment, including the corner column, and representative restraint and loading conditions are applied at the boundaries. A general view of the model is shown in Figure 9. The new shell elements are used to model the actual geometry of the composite slab. On the other hand, the steel members are represented by three-dimensional elasto-plastic cubic beam elements (Izzuddin and Elnashai, 1993), employing a bilinear kinematic material model, and are connected to the shell elements through special beam-to-slab rigid links (Izzuddin, 2003). The ambient material properties reported in the tests are utilised, whilst the variation of concrete and steel material properties with temperature as well as the thermal strain are based on typical approaches (EC4, 1995; Buchanan, 2001). As indicated in the companion paper (Izzuddin et
al., 2003), the precise value of the concrete softening parameter does not influence the large displacement response significantly, and hence it may be reasonably assumed to vary with temperature in the same manner as the concrete tensile strength. The temperature histories in various structural elements are based on a simplified representation of the measured data as reported in previous studies (Elghazouli et al., 2000).

Figure 10 depicts the experimental deflections, together with the numerical predictions, at mid-span of the secondary beam on Grid Line 1/2 as well as of the primary beam on Grid Line E. The figure also compares the vertical deflections obtained from the same analysis, but without thermal expansion. As shown, excluding thermal expansion reduces the maximum deflection to about 20% of the actual value. It is clear that there is sufficient planar restraint, which results in a substantial increase in vertical deflection when thermal expansion effects are included. It should also be noted that the edge beams, which were fire protected, retain a relatively high stiffness and consequently contribute to providing a significant planar restraint to the heated floor area. Further findings and observations regarding the Cardington tests and associated numerical simulations can be found elsewhere (Elghazouli and Izzuddin, 2001; Izzuddin and Moore, 2002).

Overall, the model and results presented in Figures 9 and 10 illustrate the application of the new models for assessing the fire behaviour of composite floors. In general, the numerical model predicts the level of deformation in the floor with reasonable accuracy, although some discrepancies are present, most notably in the shape of the displacement time history. These inaccuracies are to be expected given the modelling uncertainties, particularly in terms of the temperature distribution within the compartment coupled with idealisations in the boundary conditions and the temperature-dependent material properties.

**Performance of Isolated Ribbed Slabs**

As discussed previously, the fire tests conducted on the full-scale building at Cardington have provided valuable information on the actual structural interactions that take place in fire. The work also demonstrated the important role played by the composite steel/concrete floor slab in supporting gravity loading, particularly after the deterioration of the strength of steel beams at elevated temperature. These experimental results, coupled with analytical studies,
have pointed towards the need for more focused examination of the extreme behaviour of composite ribbed slabs in fire. To provide experimental data for this purpose, BRE conducted recently a test on an isolated ribbed slab (Bailey et al, 2001) with the aim of assessing the ultimate behaviour of simply supported ribbed slabs. Hereafter, the main results from this test are discussed, and comparison is made against the analytical predictions of the models developed in the companion paper (Izzuddin et al, 2003).

**Numerical assessment**

The BRE test (Bailey et al, 2000) was performed at ambient temperature, but, importantly, the steel deck was removed to simulate the effect of its deterioration at elevated temperature. The edge restraints simulated simply supported conditions, with the presence of columns at the corners. The slab had dimensions of 9.5 m x 6.46 m, with the ribs running along the short direction. A reinforcement mesh representing an area of 142 mm²/m in each direction was used, for which the average yield and ultimate strengths were about 580 and 640 N/mm², respectively. Light weight concrete was used in the slab, for which the average cube strength was about 50 N/mm². After the concrete was cast, the steel deck was removed, causing an initial deflection under the self weight, which was estimated as 2.3 kN/m². The slab was then tested to failure by gradually applying additional loads through a number of actuators, hence simulating uniformly distributed loading conditions.

A detailed model of the test was constructed using the developed geometrically orthotropic shell element, and employing the biaxial concrete model. A general view of the slab model is shown in Figure 11, together with the cross-section details. The mesh includes 30 element divisions in the short direction, whereas the long direction uses the necessary number of rib and flat elements to represent faithfully the actual geometry of the slab. The slab is supported vertically along the edges, and is only provided with planar restraint at the four corners. The actual material properties reported in the test are used, whilst the remaining parameters needed for the biaxial concrete model are adopted based on the values given in Table 2.
Figure 12a shows the measured experimental deflection at the center of the slab against the applied equivalent uniformly distributed load. It is important to note that the test procedure involved removal of the steel deck and completion of the test after one day. This caused considerable creep to occur under the self weight of the slab of about 2.3 kN/m². Thereafter, loading was continued gradually. Classical yield line theory estimates the slab capacity to be about the same as the self weight of 2.3 kN/m², which indicates that higher loads would be largely sustained through tensile membrane action. The slab continued to carry additional load until failure occurred at about 4.8 kN/m², which was accompanied by a large rate of increase in displacement from about 220 mm to nearly 700 mm at that load level. Failure occurred primarily through the formation of a large central crack through the full depth of the slab running across most of the shorter span.

Analytical results using the detailed model are also shown in Figure 12a. The analysis predicts the experimental results very well except in the deflection range of 100-150 mm in which the long testing pause is thought to have caused a considerable creep effect. For comparison purposes, the analysis is also carried out using a uniform slab with average thickness. As shown in Figure 12a, some differences between the two analyses exist in the initial flexural range, but they both converge at a deflection of about 100 mm at which tensile membrane effects start to dominate. If the slab is simulated with full restraints at the edges, as shown in Figure 12b, the difference between the ribbed and uniform models becomes more pronounced prior to the activation of tensile membrane action. This illustrates the importance of accounting for the actual geometry of the slab for adequately representing the load-deflection response.

**Stress distribution**

The validity of the analysis is also supported by the predicted stress distributions and crack patterns over the slab. It is clear from the magnified deformed shape at a deflection of 220 mm, as shown in Figure 13, that considerable extension has occurred in the central cover
region, indicating the formation of a through-depth crack in the cover running along the short direction, a prediction matching the experimental failure mode. This is further confirmed by observing that the predicted stress in the long direction within the central cover region is tensile throughout the depth, whereas the stress in the short direction within the same region is found to be tensile at the bottom but compressive at the top of the slab. Careful consideration of the stresses in the long and short direction identifies a compressive ring, particularly within the top part of the slab, classical flexural yield lines and a central through-depth crack in the short direction, all of which are consistent with experimental observations. Clearly, the formation of a compressive ring enables the development of tensile membrane action, leading to the attainment of a load carrying capacity exceeding the predictions of yield line theory. Quantification of this aspect of behaviour requires further treatment and discussion, which is beyond the scope of this paper, but is a current subject of detailed assessment by the authors.

It is important to point out that modelling the ribbed slab with conventional shell elements using an equivalent uniform thickness models may offer a reasonable prediction of the load-displacement response. The accuracy of this approach depends on the assumptions employed in approximating the slab geometry. In general, the load-deflection results can be within 10-15% of that of the newly developed geometrically orthotropic shell element at ambient conditions, but could lead to larger discrepancies at elevated temperature. More importantly, however, great inaccuracies arise in the stress distributions, thus influencing the quantification of the deformation level at which failure is predicted. This effect is demonstrated in Figure 14, where the realistic long direction stress in the steel reinforcement varies between the ribbed and cover region, attaining the highest concentration in the central cover region. On the other hand, the model based on an equivalent uniform thickness cannot represent such variations between the ribbed and cover regions, and in fact predicts the greatest steel stress occurring in the short rather than the long direction. Such differences
between the realistic and simplified models are magnified further for slabs with small aspect ratios (i.e. approaching a square geometry) and for rectangular slabs that lose the supporting secondary beam at elevated temperature. Furthermore, it can be shown that the effects of thermal curvature and rotational restraint at the edges increase the differences further, both in terms of the load-displacement response as well as the stress distribution.

**Failure criteria**

Finally, it is important to note that the unrestrained ribbed slab test discussed above has highlighted the need for further assessment of the observed failure mode. Evidently, in the absence of the steel deck, simulating deck disintegration at elevated temperature, failure occurs by fracture of the reinforcement across a localised through-depth crack running along the short span of the slab. This localisation is primarily due to the fact that the only available reinforcement is a nominal steel mesh, which is rather light and hence unable to generate further cracks within the concrete, thus leading to high strain concentrations within the steel. In order to take this failure criterion into consideration, it is important to determine the levels of deformation that may safely be sustained by the lightly reinforced floor slab. A conventional smeared crack approach provides good predictions of the load-deflection response of lightly reinforced structures, but cannot assess reliably the strain concentrations across cracks, since such concentrations would be unrealistically dependent on the element size instead of the geometric and material characteristics of the structure.

A fundamental step towards quantifying the failure of lightly reinforced members under ambient and fire conditions has been recently suggested by the authors. A simplified model of restrained lightly reinforced concrete members has been proposed (Izzuddin and Elghazouli, 2004) and has been used to investigate the factors influencing fracture of the light reinforcement, both at ambient and at elevated temperatures (Elghazouli and Izzuddin, 2004).
As expected, in addition to a number of important geometric and material characteristics, the bond strength between the steel reinforcement and concrete plays a major role in determining the failure displacement, though not influencing the load-deflection response greatly. Furthermore, it has been shown that elevated temperature increases the failure deflection, which is attributed mainly to thermal expansion effects. However, elevated temperature can also have a negative influence on the failure deflection when it leads to a significant thermal gradient over the depth of the member. It is expected that further experimental and analytical studies would enable the generalisation of these failure criteria in a manner that would enable their incorporation within the developed analytical models. These would ultimately be employed for undertaking focused parametric studies with leading to the provision of improved performance-based design approaches.

**CONCLUSION**

This paper addresses the large displacement nonlinear behaviour of composite and RC floors under extreme loading conditions. Use is made of new analytical developments, described in the companion paper, incorporating a novel shell element and a robust biaxial concrete model. The new shell element accounts for the geometric orthotropy of ribbed slabs in a realistic, yet extremely efficient manner in comparison with 3D solid elements. The biaxial concrete model accounts for compressive nonlinearity and tensile cracking. The analysis can also represent the influence of elevated temperature on thermal expansion and degradation of material properties.

The analysis is first validated by comparison against experimental results on flat reinforced concrete slabs with various reinforcement ratios, span-to-depth proportions and boundary conditions. The agreement between the numerical simulations and experimental findings demonstrate the overall accuracy and reliability of the analytical models in predicting the
large displacement response of reinforced concrete slabs. The analysis also enables a detailed examination of the influence of the planar restraint condition on the development of compressive and tensile membrane actions. For slabs provided with a full planar restraint, the reinforcement mesh acts as a hanging net in tension at relatively large deflection, providing gradual enhancement in of capacity up to the point of reinforcement fracture. This behaviour is predicted by the analysis as well as theoretical assessments. On the other hand, for simply supported slabs, although a degree of tensile membrane action occurs in the absence of an external horizontal restraint due to the formation of a concrete compressive ring, the effectiveness of this internal mechanism is dependent on the geometric and material properties.

The application of the new analytical models to composite floors is illustrated through a simulation of one of the main compartment fire tests carried out on a full-scale eight-storey building. The detailed numerical model is shown to provide a good prediction of the experimental response. The analysis is also used to demonstrate the significant influence of restraint to thermal expansion on the behaviour, and the important role played by the slab in supporting the gravity loading after the deterioration of the steel beams at elevated temperature.

Attention is finally given to the analysis of the large displacement behaviour of isolated ribbed slabs. In this respect, comparison is performed against an experimental study in which a simply supported slab is loaded up to failure, where very good correlation between the analytical and test results is observed. In addition to agreement on the load-deflection response, the accuracy of the analysis is supported by the predicted stress distribution and crack patterns over the slab. The analytical results are also used to provide an insight into the main behavioural mechanisms, particularly in terms of the development of tensile membrane action and the associated failure criteria. Overall, the studies carried out in this paper demonstrate the accuracy and robustness of the newly developed nonlinear analysis models. This permits a reliable examination of the large displacement behaviour of floor slab systems.
leading to the development of improved performance-based design provisions for extreme loading situations.

ACKNOWLEDGEMENT

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NOTATION

\(a_t\)  tensile softening modulus

\(b_c\)  compressive interaction parameter

\(d\)  slab depth

\(d'\)  effective depth of reinforcement

\(E_c\)  initial linear modulus for concrete

\(f_c\)  compressive strength for concrete

\(f_t\)  tensile strength for concrete

\(f_y\)  yield strength for steel reinforcement

\(L\)  span of square slab

\(L_x\)  span in long direction of rectangular slab

\(L_y\)  span in short direction of rectangular slab

\(P_u\)  maximum arching load

\(r_c\)  residual post-crushing strength parameter

\(s_c\)  initial compressive nonlinearity parameter

\(T_x\)  yield force of reinforcement in \(L_x\) direction

\(T_y\)  yield force of reinforcement in \(L_y\) direction

\(w\)  uniformly applied loading

\(\alpha_s\)  shear softening parameter

\(\beta_s\)  shear retention factor

\(\delta\)  central deflection of slab

\(\phi_s\)  shear interaction parameter

\(\rho\)  reinforcement ratio
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Table 1. Details of selected tests by Brotchie and Holly (1971)

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<td>Shear softening parameter ($\alpha_s$)</td>
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Table 2. Concrete material properties used in the analysis
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