EFFECTS OF EDGE SUPPORT AND REINFORCEMENT RATIOS ON SLAB PANEL FAILURE IN FIRE

ANTHONY K. ABU[1], IAN W. BURGESS[2] AND ROGER J. PLANK[3]

ABSTRACT

The advancement in structural fire engineering towards more cost-effective solutions has necessitated the increasing use of performance-based approaches to the design of multi-storey composite buildings. These methods consider the real behaviour of structures and provide economic solutions which optimise fire protection usage. Optimising structures to use tensile membrane action requires the structural use of slab panels. These are vertically supported lightly-reinforced composite floor systems, allowing biaxial bending at elevated temperatures. Vertical support is achieved, in practice, by protecting a panel's perimeter beams to achieve temperatures of no more than 620°C at the required fire resistance time.

The Bailey-BRE design method, which incorporates tensile membrane action, uses these vertically supported panels to establish composite slab capacities in fire. The slab panel resistance is determined by a combination of the residual composite beam strength and the large-deflection enhanced slab resistance. The simple calculations of the Bailey-BRE method imply improved performance with higher reinforcement ratios. However, proportional increases have not been observed in the modelling work reported here. The discrepancy may be due to the geometry, composition or support conditions of the slab panels. Also, with exposure to fire, a panel's 'vertical' support can be lost. This will in turn affect the tensile membrane capacity, pre-empting a structural failure of the floor system.

This paper presents the results of a finite element investigation into the effects of reinforcements and vertical support on slab panel failure. The study examines the effect of various degrees of protection on the development of the tensile membrane action mechanism. It examines the development and failure of this mechanism, considering various degrees of edge-beam protection, and makes comparisons with the predictions of the Bailey-BRE method and various design acceptance criteria.

---

[1] Research Student, Dept. of Civil & Structural Engineering, University of Sheffield, Sheffield S1 3JD, UK
Email: cip04aka@sheffield.ac.uk
[2] Professor, Dept. of Civil & Structural Engineering, University of Sheffield, Sheffield S1 3JD, UK
Email: ian.burgess@sheffield.ac.uk
[3] Professor, School of Architectural Studies, University of Sheffield, Sheffield S10 2TN, UK
Email: r.j.plank@sheffield.ac.uk

1. INTRODUCTION

The traditional approach to structural fire engineering has been to apply prescriptive fire protection to all exposed steelwork, after completing ambient-temperature design, to achieve a fire resistance rating specified on the basis of the height and use of the building[1]. This design methodology stems from the assumption that individual structural elements behave independently in fire, ignoring interactions that may be present between various parts of the structure. Research, and observations of structural behaviour under fire conditions, over the past 20 years, have shown that load redistribution and large deflections of parts of the structure at the Fire Limit State are essential to the survival of the entire structure. Accidental fires and tests on full-scale buildings have shown that designing composite floors for tensile membrane action yields considerable savings in protection costs, and structural stability is maintained by taking advantage of this real building behaviour in fire[2]. Tensile membrane action is a mechanism that produces increased load-bearing capacity in thin slabs undergoing large vertical displacements, in which radial tension in the central area of a slab induces an equilibrating peripheral ring of compression. The conditions necessary for the effective use of this mechanism are two-way bending of the slab and vertical support along all of its edges. Due to its self-equilibrating nature, horizontal edge restraint is not required for the mobilisation of tensile membrane action.

To optimise composite floors to take advantage of this higher load capacity in structural fire engineering design, a composite floor is divided into several fire-resisting rectangular zones of low aspect ratio, called slab panels; each comprising a set of adjacent unprotected composite beams in the interior of the panel, with edges that primarily resist vertical deflection[4]. This vertical support is usually provided by protected beams along all four edges, and the panels are generally set out to lie between column gridlines, as shown in Fig. 1. The composite slabs are reinforced with light meshes (typically between 142mm^2/m and 393mm^2/m), primarily to control cracking during construction. In fire the unprotected beams lose strength and stiffness rapidly, and their loads are borne by the composite slab, which undergoes two-way bending and increases its resistance as its deflections increase.

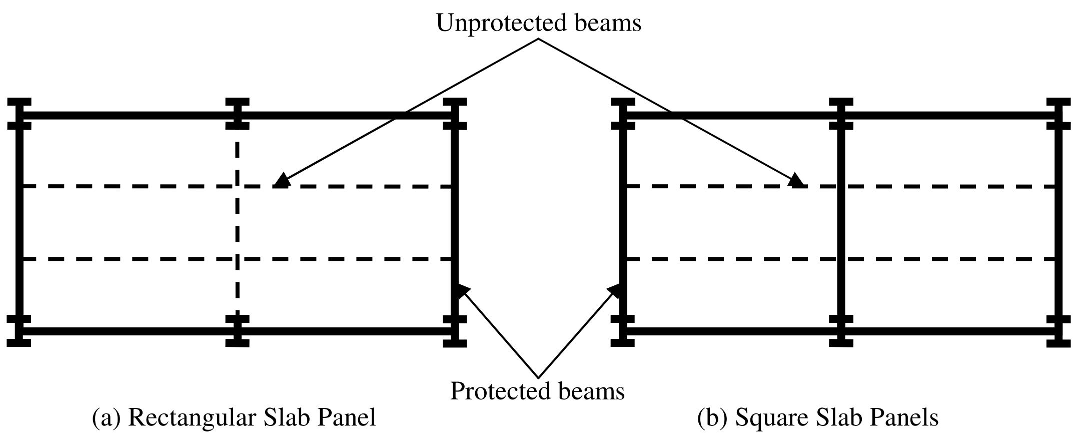

Fig. 1: Rectangular and Square Slab Panels

At large deflections and high temperatures, the slab panel capacity is dependent on the tensile capacity of the reinforcement, provided sufficient vertical support is available at the slab panel boundary. The merits of incorporating tensile membrane action into fire engineering design have prompted the development of several software packages to help quantify slab capacities in fire. Tensile membrane action, and whole-structure behaviour at high temperatures, can be modelled in a three-dimensional framework with sophisticated finite element software, such as *Vulcan*[4,5], TNO DIANA and ABAQUS, that incorporates geometrically nonlinear effects of structures. Although finite element simulations provide useful information on complete load-deformation and stress development at elevated temperatures, they can be very costly processes. Simpler performance-based methods, such as the Bailey-BRE membrane action method (which can easily be set up as a spreadsheet), are often preferred for routine design. However, there is a suspicion that the simplifications applied in some of these approaches can lead to unrealistic or over-conservative designs.

In order to assess their efficiency as tools for preliminary investigations, there is an implicit need to determine the limits of these simplified methods. The reliance of the Bailey-BRE method on the determination of enhancements to the traditional yield-line capacity of the slab, and the assumption of continuous vertical support throughout the duration of a fire, are two of the issues that need to be addressed.

The study reported here has therefore examined the credibility of the Bailey-BRE method through the use of a finite element study, with the aim of establishing slab panel capacities with respect to the amount of reinforcement within the panel and the degree of vertical support available along the slab panel boundary.

2. THE BAILEY-BRE METHOD

Based on a conservative assumption that the light slab reinforcement over protected beams will fracture in hogging moment areas of continuous composite slabs, the Bailey-BRE method[3, 6] proceeds by dividing a composite floor into several horizontally unrestrained, vertically supported slab panels. Each of these panels is composed internally of simply supported unprotected composite beams. With increasing exposure to elevated temperatures, the formation of plastic hinges in the unprotected beams re-distributes their loads to the two-way bending slab, undergoing large vertical deflections. By employing rigid-plastic theory with large change of geometry, the additional slab resistance provided by tensile membrane action is calculated as an enhancement to the small-deflection yield-line mechanism capacity. Failure is determined by the formation of a full-depth tension crack across the shorter span of the slab or by compressive failure of concrete at the corners. The method conservatively ignores any contribution of the tensile strength of concrete to the capacity of the slab, and does not provide any information on the state of the protected boundary beams, apart from the assumption that they remain vertically supported throughout a fire.

The procedure, developed from ambient-temperature conditions, assumes that the tensile membrane action mechanism at ambient temperature is maintained at elevated temperatures[3]. Research has, however, shown[7] that the development of tensile membrane action at elevated temperatures differs from the ambient-temperature development.

2.1. SCI Level 1 Design Guide and TSLAB

To facilitate the use of the Bailey-BRE method in the United Kingdom, the Steel Construction Institute (SCI) prepared a design guide (P-288) [2], which lists tables of minimum reinforcement mesh sizes required to satisfy an allowable deflection limit criterion (v) at a defined fire resistance time. This limit is based on the mechanical strain allowed in the reinforcement at yield and thermal bowing in the slab, as observed from Equations 1 and 2.

$$v = \frac{\alpha(T_2 - T_1)l^2}{19.2h} + \sqrt{\left.\frac{0.5f_y}{E}\right|_{t=20^o C} \times \frac{3L^2}{8}} \qquad (1)$$

$$v \leq \frac{\alpha(T_2 - T_1)l^2}{19.2h} + \frac{l}{30} \qquad (2)$$

In the above equations, α is the coefficient of thermal expansion; T_2 and T_1 are the bottom and top surface temperatures of the slab respectively; h is the average depth of the concrete slab; l and L are the shorter and longer spans of the slab panel and f_y and E are respectively the yield strength and Young's modulus of the reinforcing steel at room temperature.

The reinforcement sizes are based on the type of concrete, the slab panel geometry and the type of steel decking used. In addition to the design tables, the SCI has developed a Microsoft Excel-based spreadsheet called TSLAB. This tool determines whether the reinforcement selected for particular slab panel geometries will be satisfactory, and includes all the advances which have been incorporated into the method recently. However, Toh and Bailey[8] have found differences between TSLAB and the original Bailey-BRE derivation.

TSLAB performs thermal analyses on the unprotected intermediate beams and the composite slab, and then generates the total capacity of the simply-support slab panel model (by summation of the residual unprotected beam capacity and the enhanced slab capacity), using the allowable vertical deflection criterion (Equation 1) at each time step. This capacity is then checked against the applied load at the Fire Limit State. If the capacity of the panel is found to be below this applied load, then either the capacity of the internal beams or the reinforcement mesh size must be increased[2].

2.2. Influence of Reinforcement Ratios and Slab Panel Vertical Support

The Bailey-BRE method determines slab capacities by calculating the enhancements to the theoretical yield-line capacity provided by large deflections. This suggests that increasing reinforcement diameter increases the capacity of the slabs, since the yield-line capacities will be considerably increased. Therefore, with enhancement from large deflections, a considerable slab capacity is obtained by using modest increases in reinforcement area. Composite slabs are normally lightly reinforced to control cracking during construction, and therefore, may fail in compression if they are over-reinforced.

In practice, slab panel vertical support is achieved by protecting the beams around the perimeter of each panel. The assumption of continuous vertical restraint at all times during the fire is therefore unrealistic. At some point during the fire, the combination of imposed loads, together with loss of strength and stiffness of the perimeter beams, will induce vertical displacements, allowing the formation of a single-curvature slab-bending ("folding") mechanism. The slab panel will then hang from its connections, leading to a catenary-type failure of the structure. The potential for these two modes of failure has led to the series of finite element studies reported here, into the effects of reinforcement and slab panel vertical support on composite slab failure in fire.

2.3. Review of the Bailey-BRE Method

A limited number of previous studies [9-11] have compared the Bailey-BRE membrane action method with more fundamental approaches based on finite element analysis. These have highlighted a number of discrepancies between the two approaches.

An investigation by Huang *et al.* [11] into the effects of a panel's horizontal edge support conditions revealed that the Bailey-BRE method correlated very closely with a hinge-supported slab, although it was developed on the basis of simple supports. Another investigation into the effects of reinforcement ratios on slab panel capacity showed that only a marginal increase in slab panel resistance was observed in finite element models with an aspect ratio of 1.0, while disproportionately large increases in strength were observed in the Bailey-BRE models. It was also observed[11] that the finite element models compared closely with the Bailey approach when high reinforcement ratios were used in slabs of aspect ratio 2.0. The observations led Foster[7] and Bailey and Toh[6] to perform experimental tests on small-scale slabs at ambient and elevated temperatures. They examined various reinforcement ratios with varying ductilities. The experiments showed that high reinforcement ratios could cause compressive failure. The Bailey method was modified accordingly[6].

A more recent comparison by the same authors[8] between the new method and the finite element code *Vulcan* showed that long span (between 14m – 16m) finite element slab panels with aspect ratios not exceeding 1.56 satisfied the Bailey-BRE deflection limit for their design fire resistances, with the protected edge beams reaching a temperature of 550°C at the specified fire resistance time. The article, however, does not describe in detail the support conditions used in the finite element analyses.

3. SLAB PANEL FAILURE STUDY

The investigation into the Bailey-BRE method was conducted in two stages. The first stage was devoted to the effects of vertical support on slab panel failure, while the second stage examined the effects of reinforcement ratio. In total four slab panel sizes were used in the study. These are shown in Fig. 2. The 7.5m x 9m slab panel was used for the vertical support study, while the other panels were restricted to the reinforcement ratio study. For clarity, the following terminology is adopted for the research:

- Primary beams – the beams spanning between panel corners and parallel to the span direction of the decking of the composite floor.
- Secondary beams – the beams spanning between panel corners and perpendicular to the span direction of the decking of the composite floor.
- Intermediate beams – the beams spanning in the same direction as the secondary beams but end-supported at points along the lengths of the primary beams which are off the column grid.

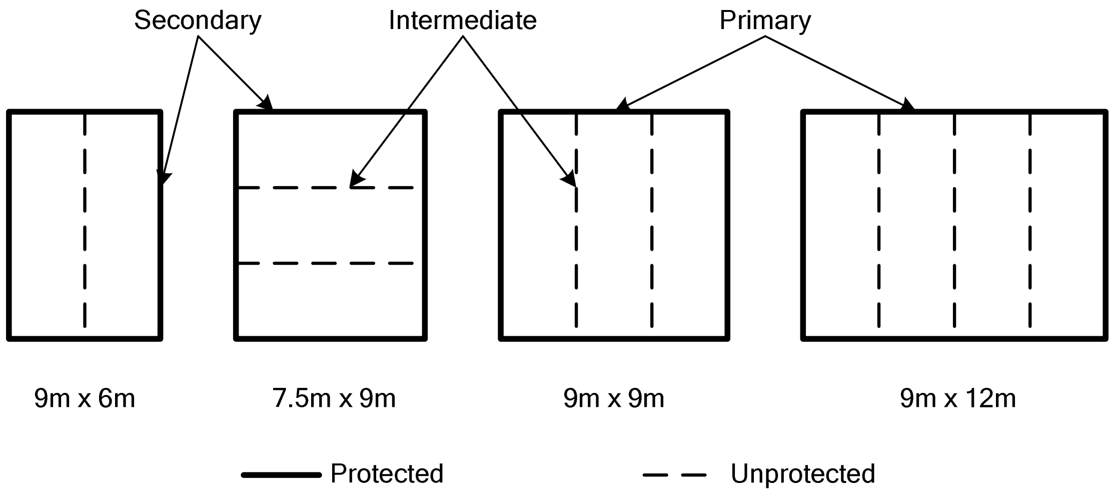

Fig. 2: Slab Panel Sizes

Using BS5950-3 and BS5950-8, the beams were designed for full composite action, using normal-weight concrete, the trapezoidal slab profile shown in Fig. 3 and the slab panel design requirements given in Table 1 (derived from SCI P-288) for a 60-minute fire resistance. The temperatures of both the primary and secondary beams were restricted to a maximum of 550°C at 60 minutes when exposed to the standard temperature-time relationship, using lightweight fire-resisting gypsum boards (density = 800kg/m^3; specific heat capacity = 1700Jkg/K; conductivity = 0.2W/mK). The results are shown in Table 2.

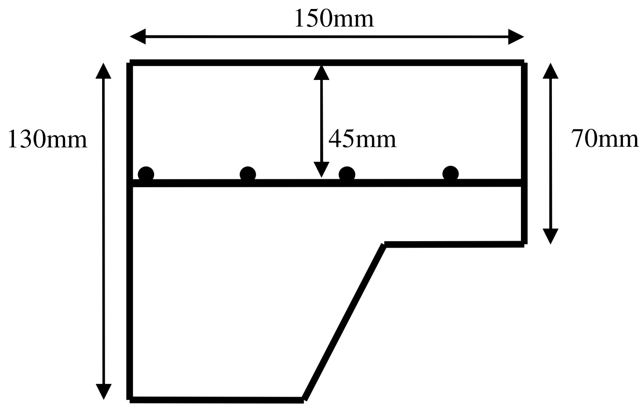

Fig. 3: Concrete slab cross-section

Table 1: Slab panel design requirements

Slab Panel size	7.5m x 9m	9m x 6m	9m x 9m	9m x 12m
Dead load (kN/m^2)	4.33	4.33	4.33	4.33
Live load (kN/m^2)	3.5	5.0	5.0	5.0
Additional load (kN)	20	14	37	49
Beam design factor	1.00	0.77	1.00	0.83
Min. Mesh size	A193	A193	A193	A252

Table 2: Protected beam design data

Slab Panel Size	Beam Type	Beam Section	Load Ratio	Limiting Temperature	Temperature at 60 minutes
7.5m x 9m	Secondary	356 x 127 x 33 UB	0.440	631°C	533°C
	Primary	533 x 210 x 82 UB	0.396	647°C	539°C
9m x 6m	Secondary	356 x 171 x 57 UB	0.426	636°C	548°C
	Primary	406 x 378 x 60 UB	0.452	627°C	549°C
9m x 9m	Secondary	356 x 171 x 67 UB	0.442	630°C	550°C
	Primary	533 x 210 x 101 UB	0.446	629°C	548°C
9m x 12m	Secondary	406 x 178 x 67 UB	0.447	629°C	548°C
	Primary	610 x 305 x 179 UB	0.471	620°C	547°C

The finite element analyses were conducted with *Vulcan*[4, 5]. This is a geometrically nonlinear specialist finite element program for structural fire engineering, developed at the University of Sheffield. Nonlinear layered rectangular elements, capable of modelling both membrane and bending effects, are used to represent slab behaviour, while beam and column behaviour are adequately modelled with nonlinear beam-column elements. Failure of concrete follows a biaxial peak-stress interaction surface.

3.1. Thermal analyses

Because of debonding of concrete from the steel deck, which is usually observed after fires, and the high temperatures applied to the soffit of a composite slab in fire, TSLAB and the Bailey-BRE method use an average-depth flat concrete slab for their structural analyses.

Therefore, with exposure to the standard temperature-time curve, a one-dimensional thermal analysis was performed on a 100mm thick flat concrete slab, using FPRCBC-T[12]. The results are compared with TSLAB temperature distributions, and are shown in Fig. 4. The finite element thermal distributions are shown as continuous lines, while those from TSLAB are shown as broken lines. It is observed that a close comparison was obtained. For unprotected beams, the TSLAB beam temperatures were used in the *Vulcan* analyses.

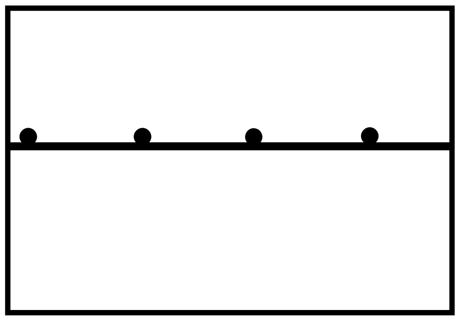

Fig. 4a: Schematic diagram of the 1D thermal analysis

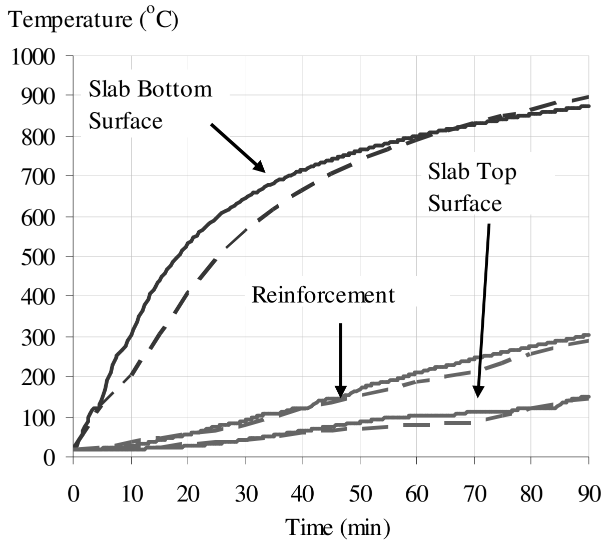

Fig. 4b: Comparison of thermal distribution through the depth of the 1D slab profile

3.2. Structural analyses

The study on the 7.5m x 9m slab panel examined various support conditions intended to provide the necessary vertical support for tensile membrane action. At this stage only one reinforcement mesh size (A193) was used, in order to adequately observe the difference in failure times which can be attributed solely to the support conditions. In trying to simulate reality, the *Vulcan* analyses model slab panel vertical support as protected perimeter beams and corner supports. For comparison, other *Vulcan* analyses were performed with differing edge support conditions, in order to determine their effects on tensile membrane action. For ease of representation of the results the various *Vulcan* models are numbered. They are:

- Generic protection and vertical support at corners (V_1),
- Generic protection with rigid vertical support along slab panel edges (V_2),
- Rotational restraint along the perimeter of the panel (V_5- V_8),
- The assumption of cold perimeter beams (V_3).

Other analyses were conducted with A252 and A393 meshes in order also to observe the behaviour of the panels. The second study was therefore designed to follow up on this aspect with the three slab panel sizes to cover a greater number of aspect ratios.

3.3. Results and discussion

The *Vulcan* and Bailey-BRE analyses were compared using three different deflection limits as ‘failure’ criteria. These were:

- The TSLAB limiting deflection curve (Equation 1),
- The maximum allowable deflection defined in the generic BRE method,
- Short span/20.

The BRE maximum allowable deflection limit is obtained by setting T_2-T_1 to 770°C for fire exposure below 90 minutes. It should be noted that, unless otherwise stated, the results show absolute maximum vertical displacements of the middle of the slab panel.

Slab panel vertical support

Fig. 5 shows the various deflection limits used in the 7.5m x 9m slab panel analyses. The Bailey-BRE method deems the A193 mesh to be adequate for this panel, as shown in the figure. A comparison of the Bailey displacement and central vertical displacements given by the *Vulcan* models V_1 – V_3 are shown in Fig. 6. The V_1 curve is the ideal representation of slab panel behaviour in fire. It however exceeds all the deflection criteria at 40 minutes, while *Vulcan* V_3, which shows the panel central displacement with edge vertical support and cold perimeter beams, just satisfies the allowable deflection limit at 60 minutes. The model with generic protection and edge vertical support (V_2) satisfies the span/20 criterion and the deflection required by the Bailey method to generate the required enhancement.

An investigation into the apparent failure of the *Vulcan* V_1 model is shown in Fig. 7 Displacements of the centre of the panel relative to the midpoints of the secondary and primary beams are plotted. It is observed that, at about 45 minutes, a reduction in the difference in deflection between the slab centre and the secondary beam begins. This continues until failure, but an accelerated reduction occurs from about 70 minutes. This is seen as the point where fully-developed plastic hinges occur in the secondary beams, thus allowing the formation of a single-curvature mechanism which runs away at failure. Increasing the mesh size does not seem to have any effect on the time at which the accelerated displacement occurs, as shown in Fig. 8. This confirms the failure of the edge beams, as the vertical support necessary to maintain the double-curvature tensile membrane mechanism is no longer available.

In Fig. 10, the Bailey-BRE displacement is compared with four continuous slab panels labelled V_5-V_8, as shown in Fig. 9. The slab panels in Fig. 9 were analysed separately, to isolate the contributions of axial restraint across a slab panel boundary. All the edge beams had generic protection, as in the previous models. Rotations were restrained across boundaries where adjacent slabs existed. The necessary additional loads on these boundaries were included in the models. The results indicate that the conservative assumption of a simply-supported slab panel in the Bailey-BRE method is aided by rotational edge-restraints of continuous slab panels for internal bays, while edge and corner bays may fail once their edge beams deflect by a considerable amount.

3.4. Edge panel failure mechanism

The results of the preceding section have identified a potential slab panel failure when edge beam stiffness is lost. They show that tensile membrane action is maintained up to a point at which the combined effects of increased edge beam loading and thermal degradation cause failure of the protected beams. Additional restraint along any slab panel boundaries improves slab panel capacity. A simple edge-support failure mechanism is therefore proposed in order to address the failure of continuous vertical support in the Bailey method.

The mechanism considers the failure of the protected primary and secondary beams, assuming they are simply-supported. The model distributes the fire limit state floor load to parallel arrangements of either primary or secondary beams (protected edge beams and unprotected intermediate beams). Failure is then determined by the loss of strength of the slab panel system. A schematic representation of the loading and failure modes is given in Fig. 11

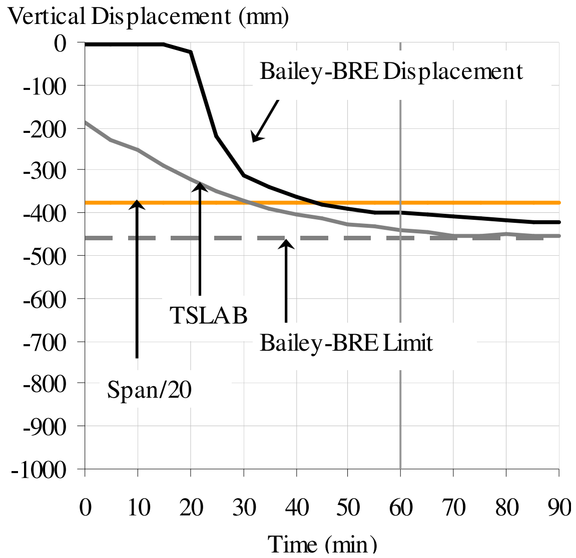

Fig. 5: Deflection limits for the7.5m x 9m slab panel

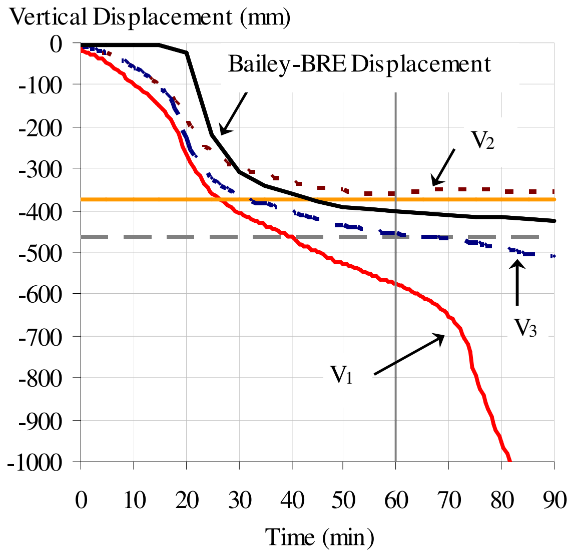

Fig. 6: Comparison of Bailey Displacement and Vulcan V1, V2 and V3

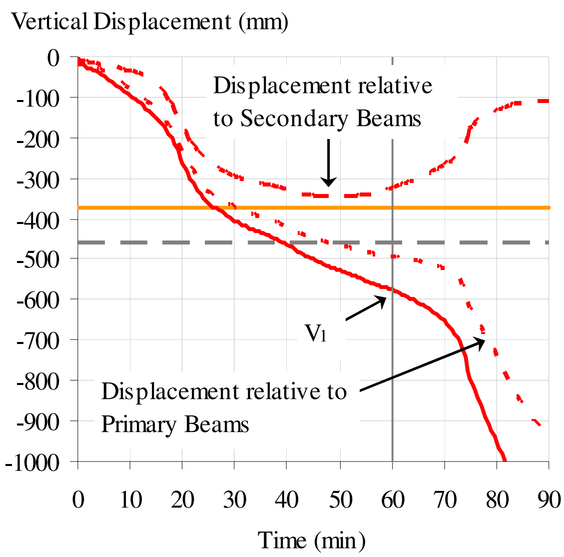

Fig: 7: Vulcan V1 edge beam failure

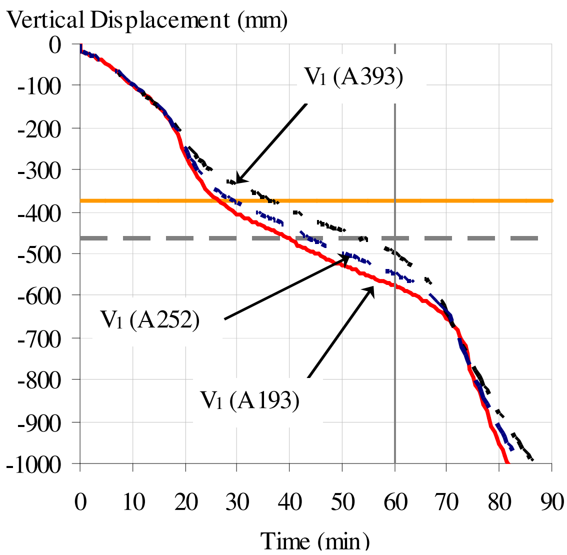

Fig. 8: Reinforcement ratio comparison

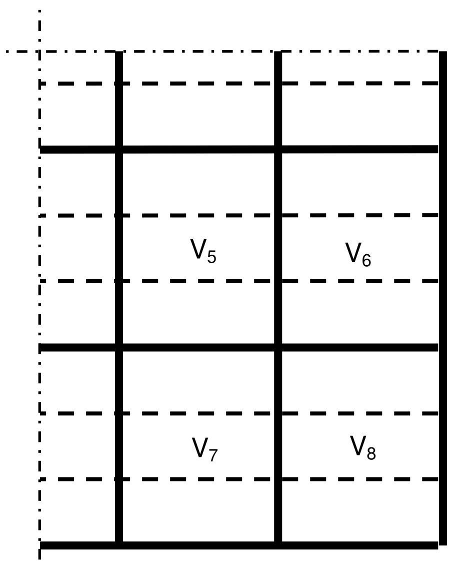

Fig. 9: Continuous slab panels – layout for fig. 10

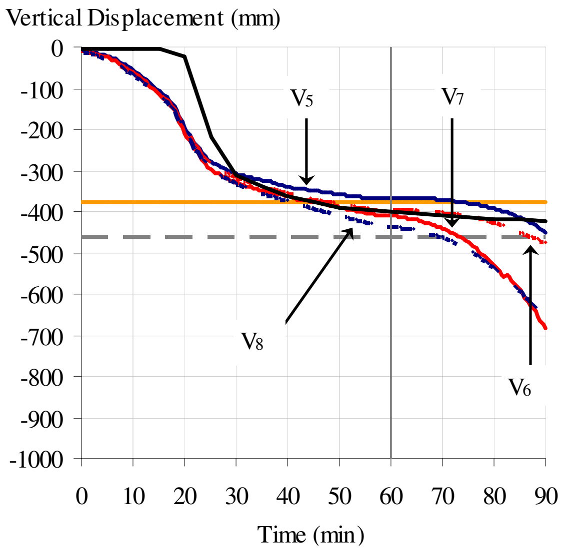

Fig.10: Influence of Rotational restraint

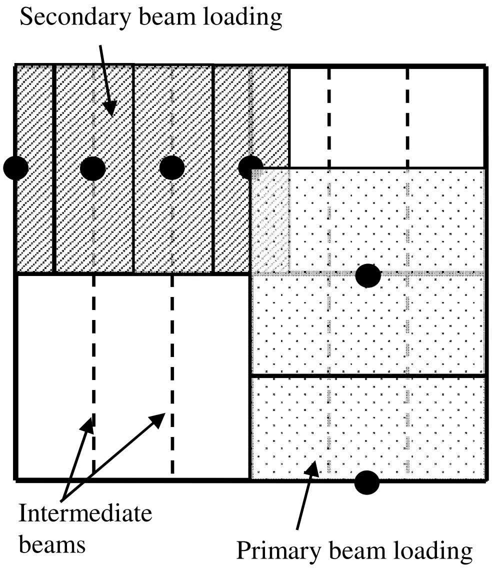

Fig. 11a Load distribution – Type 1 failure

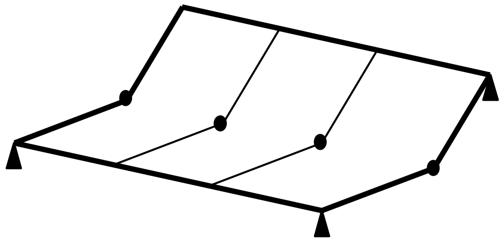

Fig. 11b: Failure of secondary beams

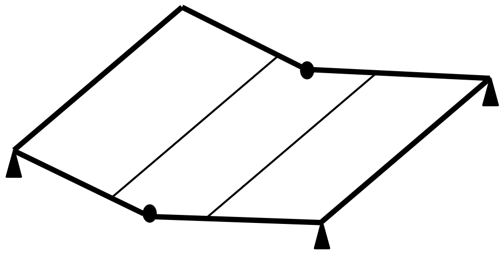

Fig. 11c Failure of primary beams

For either primary beams or secondary (and intermediate) beams, failure occurs when:

$$\sum_{i=1}^{n} M_{applied,i} - \sum_{j=i}^{n} M_{fi,t,Rd,j} \geq 0 \qquad (3)$$

In the above equation, $M_{applied,i}$ is the applied moment on each beam in the parallel arrangement, while $M_{fi,t,Rd,j}$ is the capacity of each composite beam in the arrangement at a particular time t into the fire; n is the total number of beam sections in the parallel arrangement (for primary beams, n = 2).

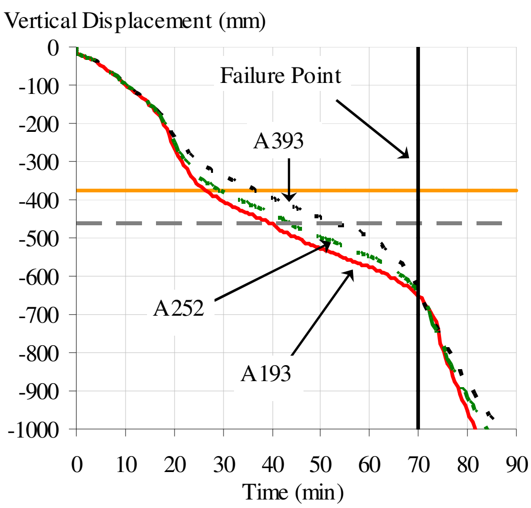

Fig. 12: Plastic failure of 7.5m x 9m slab panel

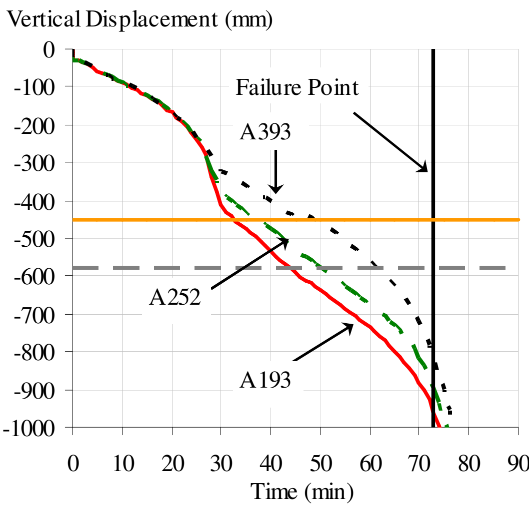

Fig. 13: Plastic failure of 9m x 9m slab panel

Figs. 12 and 13 show the 7.5m x 9m and 9m x 9m slab panels, analysed using *Vulcan* model V_1. A comparison of mesh sizes A193, A252 and A393 and the plastic failure limits of the edge beams are shown. The failure mechanism is tested for the two parallel arrangements of either primary or secondary beams. For the 7.5m slab panel, failure of the secondary beams occurred at 70 minutes with protected secondary beam temperatures at 600°C, while failure of the primary beams did not occur in 90 minutes of fire exposure. For the 9m x 9m slab panel, secondary beam failure was observed at 73 minutes, with a corresponding temperature of 621°C. Again failure of the primary beams did not occur within 90 minutes of exposure. Failures of the 9m x 6m and 9m x 12m slab panels occur at 82 minutes and 68 minutes respectively, with secondary beam temperatures at 662°C and 594°C.

3.5. Effects of reinforcement ratios

This section presents results on the effects of varying reinforcement ratios on the two slab panel models (*Vulcan* and the Bailey-BRE method). Standard and fictitious reinforcement mesh sizes were used to highlight the differences in the two methods; these were: 142, 166, 193, 221, 252, 318 and 393 (all in mm^2/m). The results (Figs. 14 and 15) show comparisons of the failure times of the Bailey method and *Vulcan* analyses by finding the equivalent times at which their deflections exceed the deflection criteria of TSLAB, the BRE vertical deflection limit and span/20. The solid lines show results from the membrane action method. Those from *Vulcan* are shown as broken lines. The unlabelled lightly-coloured lines show the failure times obtained using the BRE allowable deflection limit.

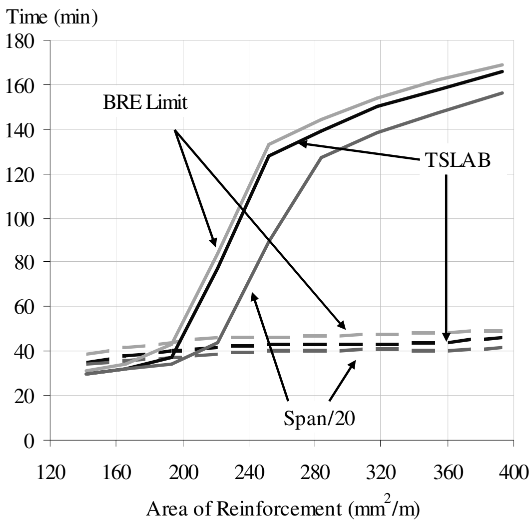

Fig. 14: Comparison of Bailey-BRE and Vulcan Failure times for 9m x 6m slab panel

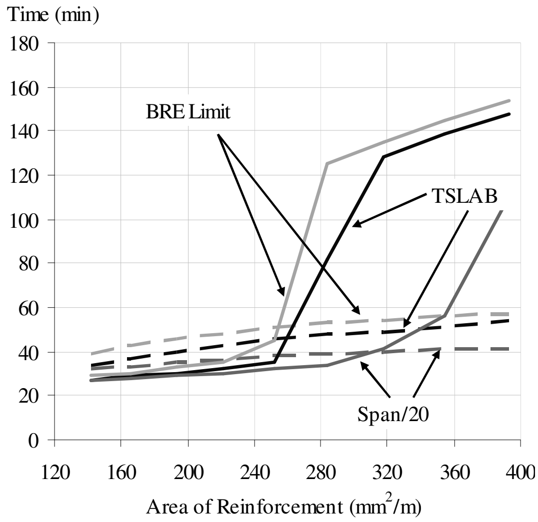

Fig. 15: Comparison of Bailey-BRE and Vulcan Failure times for 9m x 12m slab panel

The results of the 9m x 9m slab panel (not shown here for lack of space) compared very closely with the 9m x 6m slab panel (Fig. 14). The results show that, for smaller panels, there is good comparison between *Vulcan* and the BRE approach for reinforcement areas below the 195mm^2/m to 230mm^2/m range, but divergence thereafter. However, for larger panels, this good comparison stretches to about 320mm^2/m, with a span/20 criterion (Fig. 15).

4. CONCLUSIONS

A number of protection schemes and support conditions have been analysed. It has been observed that the tensile membrane action mechanism is lost when slab panel edge beams experience significant deflections. Considerable restraint is provided by either vertically supported edges or continuous slab panels. The results show that the Bailey-BRE method gives a good prediction of slab panel behaviour if the perimeter beams remain stiff for long periods of time. A plastic failure mechanism for slab panel edge beams has been proposed. It should be noted that these beams would normally be designed for critical temperatures of about 620°C. The analyses have shown that a combination of the imposed load and material degradation will cause failure. Therefore, specifying a temperature of 620°C at the required fire resistance time is not sufficient.

For slabs in the interior of a building, the restraint from adjacent slabs is clearly beneficial, but for edge or corner slab panels increasing the level of protection seems a viable option. This could potentially counter the reduction in cost given by employing tensile membrane action. However, producing safe structures should be a priority over economy.

This comparative study has shown that the Bailey-BRE method is conservative when an A142 or A193 mesh is used on a 'small' slab panel. However, the method predicts more optimistic fire resistance times than advanced analysis when higher reinforcement ratios are used on these 'small' panels or when larger panels are used with reinforcement meshes above A252. It is implied from the preceding analyses that the minimum area of reinforcement for any slab panel is proportional to its dimensions. Therefore, an increase in reinforcement ratio is required if slab panel sizes increase.

REFERENCES

[1] *The Building Regulations 2000, Approved Document B, Volume 2 – Buildings other than Dwelling Houses*, ISBN 10 1 85946 262 6, Department of Communities and Local Government, 2007

[2] Newman, G. M., Robinson, J. T. and Bailey, C. G., *Fire Safe Design: A New Approach to Multi-Storey Steel-Framed Buildings*, Second Edition, SCI Publication P288, The Steel Construction Institute, UK, 2006

[3] Bailey, C. G., *Design of Steel Structures with Composite Slabs at the Fire Limit State, Final Report No. 81415, prepared for DETR and SCI*, The Building Research Establishment, Garston, UK. 2000

[4] Huang, Z., Burgess I. W. and Plank R. J., "Modelling membrane action of concrete slabs in composite slabs in fire. I: Theoretical Development", ASCE Journal of Structural Engineering, **129** (8), 2003, p1093-1102

[5] Huang, Z., Burgess, I.W. and Plank, R.J., "3D Modelling of Beam-Columns with General Cross-Sections in Fire", Paper S6-5, Third International Workshop on Structures in Fire, Ottawa, Canada, 2004, p323-334

[6] Bailey, C. G. and Toh, W. S., "Behaviour of concrete floor slabs at ambient and elevated temperatures" *Fire Safety Journal,* **42**, 2007, p425-436

[7] Foster S. J., *Tensile Membrane Action of Reinforced Concrete Slabs at Ambient and Elevated Temperatures*, PhD thesis, University of Sheffield, 2006

[8] Toh, W. S. and Bailey, C. G., Comparison of simple and advanced models for predicting membrane action on long span slab panels in fire, Proc. Interflam 2007, 2007

[9] Huang, Z., Burgess, I.W. and Plank, R.J., 'The Influence of Tensile Membrane Action on the Behaviour of Composite Steel-Framed Buildings in Fire', Proc. ASCE Structures Congress, Washington DC, 2001

[10] Huang, Z., Burgess, I.W., Plank, R.J. & Bailey, C.G., 'Strategies for Fire Protection of Large Composite Buildings', Proc. Interflam 2001, 2001, p395-406

[11] Huang, Z., Burgess, I.W., Plank, R.J. and Bailey, C.G., 'Comparison of BRE Simple Design Method for Composite Floor Slabs in Fire with Non-Linear FE Modelling', *Fire and Materials*, **28** (2-4), 2004, p127-138

[12] Huang, Z., Platten, A. and Roberts, J., "Non-linear Finite Element Model to Predict Temperature Histories within Reinforced Concrete in Fires", *Building and Environment*, **31**(2), 1996, p109-118.