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Slab panel vertical support and tensile membrane action in fire

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Abstract. The increasing use of performance-based approaches in structural fire engineering design of multi-storey composite buildings has prompted the development of various tools to help quantify the influence of tensile membrane action in composite slabs at elevated temperatures. One simplified method which has emerged is the Bailey-BRE membrane action method. This method predicts slab capacities in fire by analysing rectangular slab panels supported on edges which resist vertical deflection. The task of providing the necessary vertical support, in practice, requires protecting a panel's perimeter beams to achieve temperatures of no more than 620°C at the required fire resistance time. Hence, the integrity of this support becomes critical as the slab and the attached beams deflect, and large deflections of the perimeter beams may lead to a catastrophic failure of the structure. This paper presents a finite element investigation into the effects of vertical support along slab panel boundaries on the slab behaviour in fire. It examines the development of the membrane mechanism for various degrees of edge-beam protection, and makes comparisons with predictions of the membrane action design method and various acceptance criteria.

Keywords : tensile membrane action; slab panels; fire; concrete; enhancement factors; Bailey-BRE method; TSLAB.

1. Introduction

The design of steel structures for fire safety has traditionally been characterised by design of the entire structure for loading cases at ambient temperature, and subsequent application of the required thickness of fire protection to all steelwork, to achieve a fire resistance rating specified on the basis of the height and use of the building. This prescriptive 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 re-distribution and large deflections of parts of the structure at the Fire Limit State are essential to the survival of the entire structure (Usmani

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et al. 2001). In particular, it has been observed that, if composite floors are allowed to undergo large vertical displacements in biaxial bending, they generate load-bearing capacities several times greater than their traditional yield-line capacities, through a mechanism known as tensile membrane action (Bailey 2001). 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 and vertical support along the edges of the slab. Due to its self-equilibrating nature, horizontal edge restraint is not required for the mobilisation of tensile membrane action.

In order to take advantage of this higher load capacity in structural fire engineering design a composite floor is divided into several fire-resisting rectangular zones, called slab panels; each comprising a set of adjacent unprotected composite beams in the interior of the panel, with protected beams along all four edges. These panels are generally set out to lie between column gridlines (Fig. 1). In fire the unprotected beams lose strength and stiffness rapidly, and their loads are borne by the composite slab, which increases in capacity as its deflections increase.

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* (Huang *et al.* 2002, 2003a, 2003b). Finite element simulations, however, can be very costly processes. As such, simpler performance-based methods, like the Bailey-BRE Membrane Action Method (which can easily be set up as a spreadsheet), are often preferred for routine design. However, 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 study reported in this paper has examined the credibility of the Bailey-BRE method through the use of a finite element study, with the aim of establishing what constitutes acceptable levels of vertical support along the boundaries of the slab panels.

2. The Bailey-Bre membrane action method

The Bailey-BRE method (Bailey 2000, 2001, 2003a, 2004) proceeds by dividing a composite floor

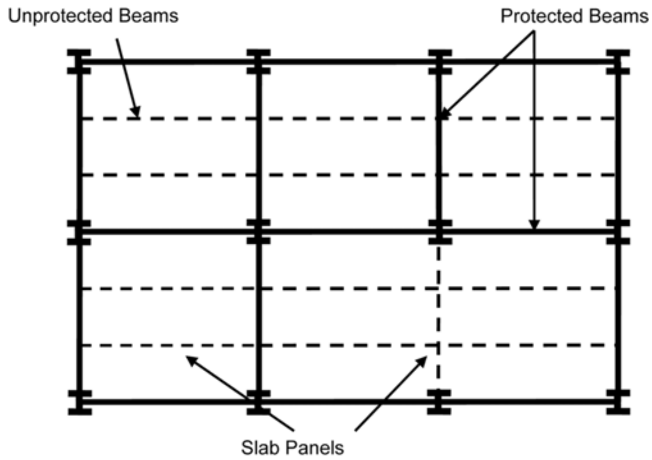

Fig. 1 Typical slab panels

into several horizontally-unrestrained, vertically supported slab panels. Each of these panels is composed internally of simply-supported unprotected beams. With increasing exposure to elevated temperatures, the formation of plastic hinges in the beams re-distributes the loads to the two-way bending slab, undergoing large vertical deflections. Based on rigid-plastic theory with large change of geometry, the additional slab capacity provided by tensile membrane action is calculated as an enhancement to the small-deflection yield-line capacity. Failure is determined by the formation of a full-depth tension crack across the shorter span of the slab. The method, initially developed for isotropic reinforcement (Bailey 2000, 2001), has been extended to include orthotropic reinforcement (Bailey 2003a). Recently the change of in-plane stress distributions and crushing failure due to the ring of compressive membrane stress have been added (Bailey and Toh 2007). The procedure, developed from room temperature conditions, assumes that the tensile membrane action mechanism at ambient temperature is maintained at elevated temperatures (Bailey 2000). However, research has shown that the development of tensile membrane action at elevated temperatures differs from the ambient-temperature development (Cameron and Usmani 2005, Foster *et al.* 2005, Abu *et al.* 2006). 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 are vertically supported.

2.1 SCI P-288 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), which lists tables of minimum reinforcement mesh sizes required to satisfy an allowable deflection limit criterion at a defined fire resistance time (Newman *et al.* 2006). This limit is based on the mechanical strain allowed in the reinforcement at fracture and thermal bowing in the slab. 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 a particular slab panel geometry will be satisfactory, and includes all the advances which have been incorporated into the method recently, whilst the tables in P-288 serve as a basic guide in choosing the minimum reinforcement for any given geometry.

TSLAB has been developed as an extension to the basic Bailey-BRE membrane action method. It begins by performing thermal analyses on the unprotected intermediate beam and the composite slab. Then, using the temperatures of the individual components and its allowable vertical deflection criterion, it calculates the total capacity of the simply-supported slab panel model (by summation of the residual unprotected beam capacity and the enhanced slab capacity). This capacity is then checked against the applied load in the Fire Limit State. If the capacity of the panel is found to be below the applied load at the fire limit state, then either the capacity of the internal beams or the reinforcement mesh size must be increased (Newman *et al.* 2006).

2.2 Panel vertical support

In practice, slab panel vertical support is achieved by good connection detailing and 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, a combination of imposed loads and loss of strength and stiffness of the perimeter beams will induce them to displace vertically, allowing the formation of a single-curvature slab-bending mechanism. The slab panel will then hang from its connections, leading to a catastrophic failure of the structure if these connections are not adequately designed against such forces(Bailey 2003b). The potential for this type of failure has led to the series of finite element studies reported here, into the adequacy of vertical support along slab panel boundaries.

3. Thermal and structural analyses of slab panels

For these analyses, a slab panel of dimensions 9.0 m × 7.5 m and a 60-minute fire resistance period were chosen, using normal-weight concrete and the trapezoidal slab profile shown in Fig. 2. The panel has secondary beams spanning in the shorter direction with its primary beams spanning in the longer direction. The secondary beams are at 3 m spacings. From SCI P-288 (Newman *et al.* 2006) the required minimum reinforcement mesh size for the slab panel, with the design loading given in Table 1, is A193 (193 mm^2/m in each direction). This allows for additional distributed line-loads of 20 kN on the protected secondary beams and a maximum intermediate beam design factor of 1.00.

Ambient- and elevated-temperature design of the floor beams was carried out using BS5950 Part 3 (BSI 1990) and BS5950 Part 8 (BSI 2003) and assuming full composite action. This resulted in the choice of 356 × 127 × 33UB and 533 × 210 × 82UB as the secondary and primary beams respectively (Fig. 3). The protected beams are shown in Fig. 3 as solid lines, while the unprotected beams are

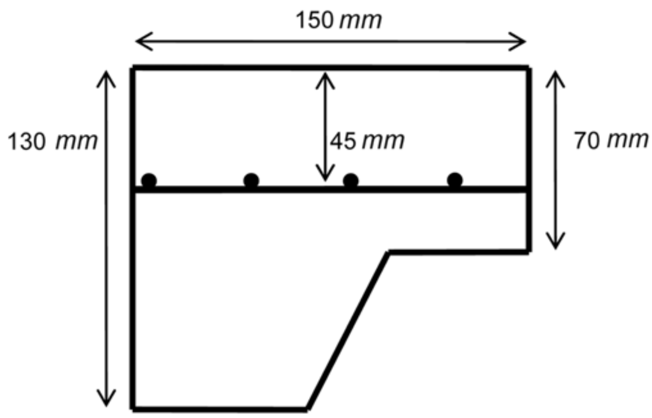

Fig. 2 Concrete slab profile

Table 1 Slab panel design loading

Permanent Load	kN/m^2
Slab self-weight	2.40
Beam self-weight	0.20
Reinforcement	0.03
Imposed Load	
Variable load	3.5
Ceilings/ Services	1.7

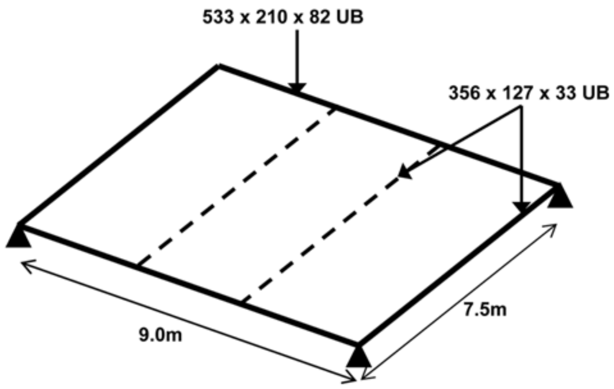

Fig. 3 Slab panel, showing protected and unprotected beams

represented by broken lines. With guidance from the ASFP Fire protection guidelines (ASFP 2002) and steel temperature calculations from Eurocode 3 part 1.2 (CEN 2005), a protection scheme was adopted with lightweight fire-resisting gypsum boards (density = 800 kg/m^3; specific heat capacity = 1,700 Jkg/K; conductivity = 0.2 W/mK) to ensure that protected beam temperatures were limited to a maximum of 550^{o}C at 60 minutes. The actual design safety factor of the intermediate beams was calculated as 0.74. Table 2 presents details of load ratios and limiting temperatures of the protected beams used in the finite element analyses.

The finite element analyses were performed with *Vulcan* (Huang *et al.* 2002, 2003a, 2003b), a geometrically nonlinear finite element program which includes the effects of nonlinear material behaviour at elevated temperatures. In *Vulcan* reinforced concrete slabs are modelled with 9-noded nonlinear layered rectangular elements, which represent temperature distributions through the depth of the slab by assigning different, but uniform, temperatures to each layer of the slab element. Bending and membrane effects at large displacements are also represented. Reinforcement is modelled in layers with uniaxial properties, being smeared across the area of the slab element. The program uses a biaxial failure surface for concrete and can, as a result, represent failure in tension or compression. Beams are modelled using 3-noded nonlinear beam elements.

3.1 Thermal analysis

A series of thermal analyses were conducted to ascertain the temperature distributions through the depths of the two (BRE-TSLAB and *Vulcan*) slab panel models with time. TSLAB performs two analyses to determine the distribution of temperatures through the slab, and in particular to calculate the temperature of the reinforcement. These consider sections through the slab at its thickest and thinnest points - i.e. through a rib and through the topping respectively. A weighted average of these temperatures is then used. However, the basic Bailey-BRE method uses an average-depth flat concrete slab for its

Table 2 Protected beam design properties

Protected Beam type	Beam Section	Load Ratio	Limiting Temperature (°C)	Temperature (°C) at 60 mins
Secondary	356 × 127 × 33 UB	0.440	631	537
Primary	533 × 210 × 82 UB	0.396	647	542

structural calculations (Bailey 2000). Two *Vulcan* models were therefore analysed under exposure to the standard temperature-time curve; the first was a two-dimensional model in which a weighted average of the reinforcement temperatures through the ribs and thinner parts was calculated; the second considered an equivalent solid slab of thickness equal to the average depth of the composite slab (100 mm). The one- and two-dimensional thermal analyses were performed with the program FPRCBC-T (Huang *et al.* 1996).

TSLAB intermediate beam temperatures were used for the both the Bailey-BRE and *Vulcan* analyses. Comparisons of slab temperature distributions in the *Vulcan* and TSLAB models, for a 90-minute exposure to the standard temperature-time curve are shown in Figs. 4a and 4b. TSLAB results are shown as broken lines while the *Vulcan* temperature distributions are shown as continuous lines.

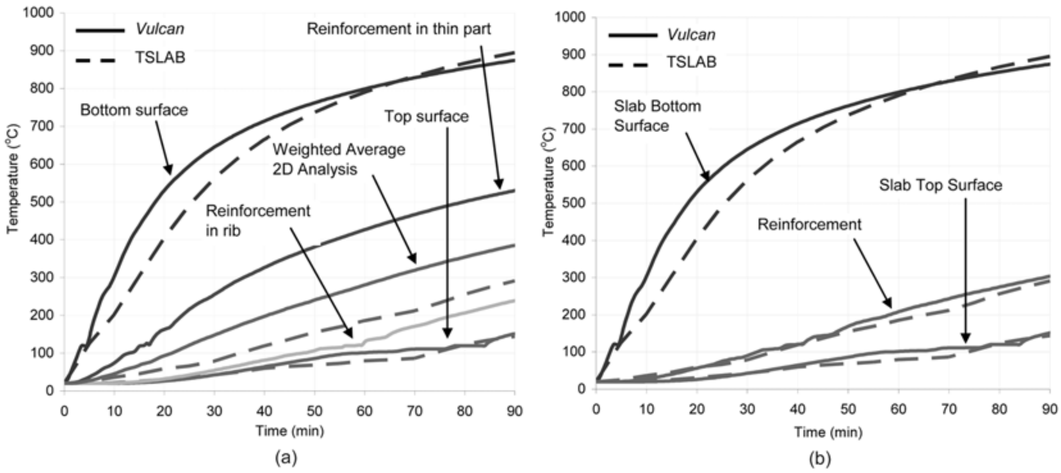

Fig. 4 (a) 2D Thermal analysis with 130 mm deep slab (solid lines show *Vulcan* analyses with TSLAB analyses in dashed lines), (b)1D Thermal Analysis with 100 mm deep slab (solid lines show *Vulcan* analyses with TSLAB analyses in dashed lines).

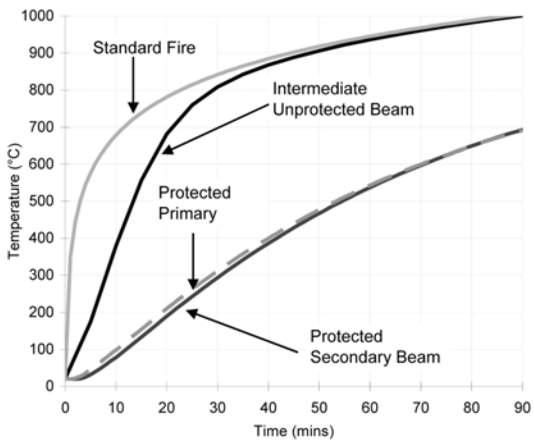

Fig. 5 Temperature-time relationships for the *Vulcan* Analyses

It can be observed from Figs. 4a and 4b that there was generally good correlation between the thermal distributions in the *Vulcan* and TSLAB models for the second analysis, in which an average depth of concrete was used. Consistent with assumptions of the basic Bailey-BRE method, a depth of 100 mm was used for the structural analyses of the *Vulcan* and Bailey-BRE models. Beam temperature distributions for the *Vulcan* models are shown in Fig. 5.

3.2 Structural analyses

TSLAB does not output the fire resistance time that a particular slab panel arrangement can achieve. Instead, the user specifies the required fire resistance and the software checks if the model complies with the specification. Since the generic Bailey-BRE method was used in this research, TSLAB was only used to generate the allowable maximum vertical displacements with time, and a spreadsheet was written to simulate the calculations embodied in TSLAB whilst outputting results in a form suitable for direct comparison with the other approaches.

The primary *Vulcan* analysis attempted to simulate the behaviour of the actual slab panel vertical support in fire conditions. This was achieved by vertically restraining the corners of the model, but allowing vertical displacements of the protected beams on the panel perimeter. For comparison, other *Vulcan* analyses were performed with differing edge support conditions to determine their effect on tensile membrane action. Variations, of which the details are given in Table 3 included:

- Rigid vertical support along the perimeter of the slab panel,
- Rotational restraint along the perimeter of the panel,
- Using twice the amount of generic protection on the perimeter beams,
- The assumption of cold perimeter beams.

The results of the *Vulcan* analyses were compared with:

- The TSLAB limiting deflection curve,

Table 3 *Vulcan* analyses and parameters

	Vulcan Analyses								
Condition	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9
Generic Protection	√	√			√	√	√	√	
2X Generic Protection									√
Cold Perimeter Beams			√	√					
Corner Vertical Restraint	√	√	√	√	√	√	√	√	√
Edge Vertical Restraint		√	√	√					
Concrete Tensile Strength ignored				√					
Rotational Restraint on 2 edges								√	
Rotational Restraint on 3 edges						√	√		
Rotational Restraint on 4 edges					√				

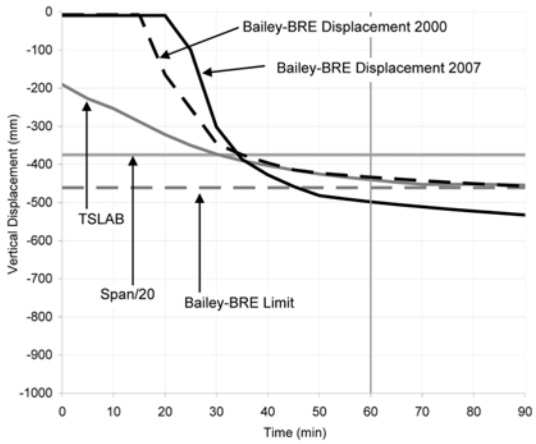

Fig. 6 BRE vertical displacements and deflection criteria

- The Bailey-BRE allowable vertical deflection limit,
- The required vertical deflection (from the generic Bailey-BRE approach),
- A limiting deflection of span/20 (7,500 mm/20 = 375 mm).

Fig. 6 compares the vertical deflection criteria used in the study. The TSLAB deflection limit at each time-step is obtained from the following equation:

$$v = \frac{a(T_2 - T_1)l^2}{19.2h} + \sqrt{\frac{0.5f_y}{E} \times \frac{3L^2}{8}} \leq \frac{\alpha(T_2 - T_1)l^2}{19.2h} + l/30 \tag{1}$$

where α is the coefficient of thermal expansion (12×10^{-6} for normal weight concrete), 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, f_y and E are the yield strength and Young's modulus of the reinforcing steel, which reduce in magnitude with increasing fire exposure. To obtain the Bailey-BRE allowable vertical deflection limit, $T_2 - T_1$ is assumed equal to 770°C for fire exposure below 90 minutes.

The difference between the two displacements of the Bailey-BRE method highlights the effect of recent changes to the method (Bailey and Toh 2007), and questions the adequacy of the A193 mesh for the chosen slab panel size. This is contrary to the SCI design guide (Newman *et al.* 2006) and the findings of Abu *et al.* (2007), which were based on the Bailey-BRE method as presented in 2000 and 2001.

4. Results and discussion

The results of the various *Vulcan* analyses are presented in Figs. 7~9 and Figs. 11~13. It should be noted that, unless otherwise stated, the results presented in this section all show absolute maximum vertical displacements of the centre of the 9.0 m × 7.5 m slab panel system reinforced with A193 mesh.

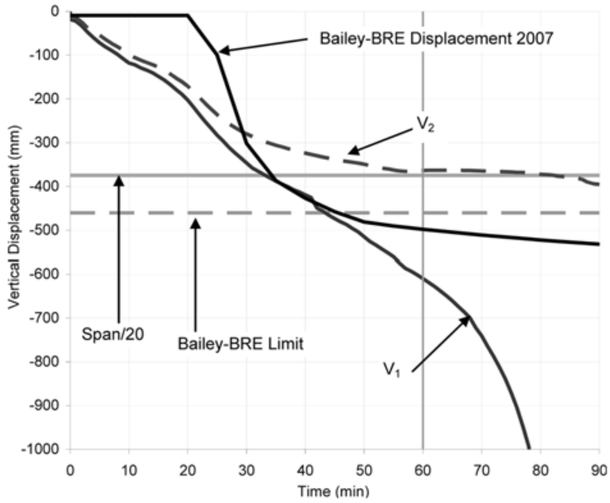

Fig. 7 Comparison of *Vulcan* V_1, V_2 and the BRE displacement

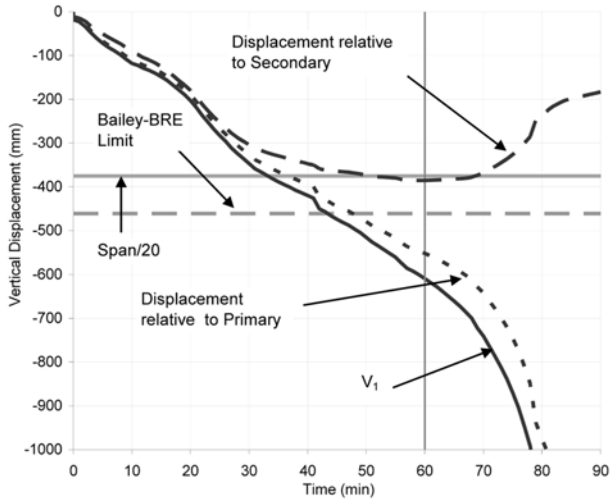

Fig. 8 Failure analysis of the *Vulcan* V_1 model

4.1 Vertical restraint

Fig. 7 shows plots from the first two *Vulcan* analyses and the Bailey displacement. The V_1 and V_2 models were identical, except that V_2 included vertical support to its perimeter beams. The advantage of this continuous vertical support is immediately apparent with the Bailey-BRE method and V_2 giving vertical displacements of 498 mm and 363 mm respectively at 60 minutes, as compared with 600 mm in the V_1 model. Fig.7 also confirms that the idealised behaviour on which the Bailey-BRE approach is based is very conservative, as it shows no sign of failure. Fig. 8 examines the failure mode of *Vulcan* model V_1. Displacements at the centre of the slab panel relative to the midpoints of the protected

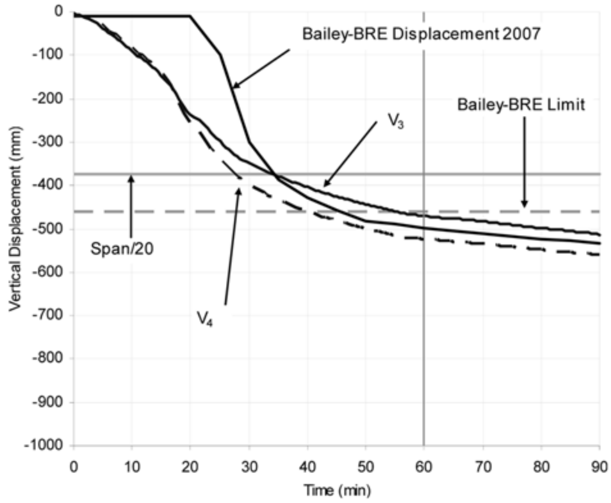

Fig. 9 Comparison of BRE deflection and *Vulcan* V_3 and V_4

secondary and primary beams are shown. It can be seen that there is a lessening difference between the displacements of the middle of the slab and the midpoints of the protected secondary beams, with a steady increase in the displacement of the middle of the slab panel relative to the primary beams. This indicates the loss of tensile membrane action and the progressive development of a single-curvature bending mechanism, which eventually 'runs away'. The accelerated deflection of the protected secondary beams just before 'failure' of the slab panel system (at about 70 minutes) can be observed from Fig. 5 to occur as the beams reach temperatures of 600°C.

4.2 Influence of the tensile strength of concrete

Fig. 9 shows a comparison between analytical results for the Bailey-BRE model and for *Vulcan* slab

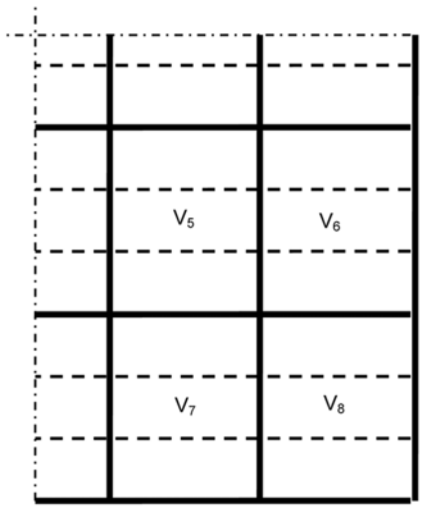

Fig. 10 Continuous slab panels - layout for Fig. 11

panels with perimeter beams which are kept at 20°C throughout the fire and are vertically supported along their edges. Model V_3 includes the effects of the tensile strength of concrete, and predicts a greater slab capacity than the Bailey-BRE model. Model V_4 requires larger displacements for tensile membrane action to be mobilised, as its tensile capacity is entirely dependent on the reinforcement. The close comparison between the Bailey-BRE model and the *Vulcan* models confirms the importance of the simplified method's assumption of complete vertical edge-support. This is an unconservative assumption, as the real perimeter beams will achieve temperatures higher than 20ºC, and will experience vertical displacement due to their applied loads and loss of strength.

4.3 Effect of continuity at the panel boundary

The effect of slab panel continuity on the development of tensile membrane action was also investigated. Fig. 10 shows one quarter of a typical composite floor divided into slab panels of dimensions 9.0 m × 7.5 m. To isolate the effect of rotational restraint at the panel boundaries the panels were analysed as being independent, with no axial restraints but rotational restraint about their edges where adjacent slabs were present. Fig. 11 shows the central vertical displacements of four *Vulcan* models with various degrees of rotational restraint about their edges. The results indicate that continuity with adjacent slabs helps to maintain some level of vertical support, as the protected perimeter beams are not allowed to rotate about their axes. The results also indicate that continuity across protected primary beams is advantageous to tensile membrane action. The results are consistent with Cardington corner Tests 3 and 4 (Martin and Moore 1999). Structural collapse of the British Steel Corner Bay Test (Test 3) was not observed, due to the vertical support provided by the protected edge beams and the adjacent cold structure (Martin *et al.* 2001). Wind posts connecting the heated perimeter beams to upper storeys provided the necessary vertical edge support in the BRE Corner Bay Test (Martin and Moore 1999).

Fig. 12 shows a comparison of the results presented in Fig. 11 with the Bailey-BRE deflections. The graph shows that the Bailey-BRE method predicts good results with continuous slabs, although the same cannot be said for simply supported slabs. However, the presence of axial restraint would have caused higher deflections in the initial stages of fire exposure, because of thermal buckling due to

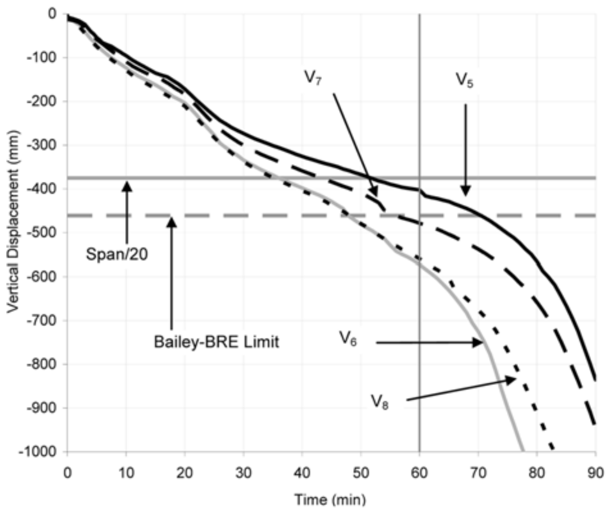

Fig. 11 *Vulcan* analyses with rotational restraints and generic protectionrestraint and the BRE deflection

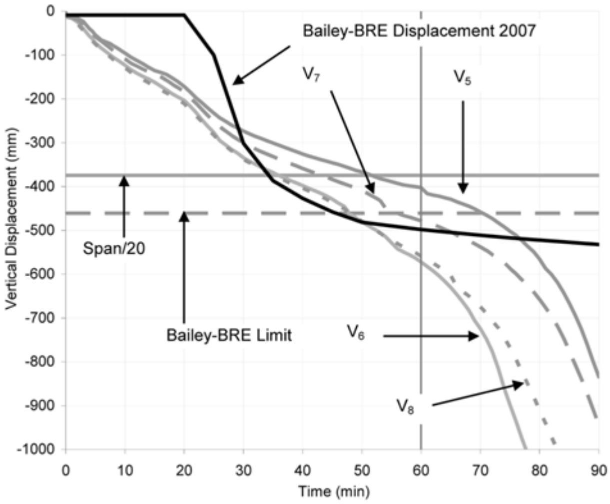

Fig. 12 Comparison of *Vulcan* analyses with rotational

restrained thermal expansion, and the appropriateness of the Bailey-BRE prediction would be called into question.

4.4 Thickness of the protection material

Fig. 13 shows a comparison of the Bailey-BRE deflection, *Vulcan* model V_1 and *Vulcan* model V_9, which had twice the required thickness of generic protection on the protected boundary beams. It can be observed that V_9 satisfies the TSLAB and BRE limits, suggesting that the requirement for vertical restraint at the boundaries of the slab panel may involve the use of heavier sections or thicker

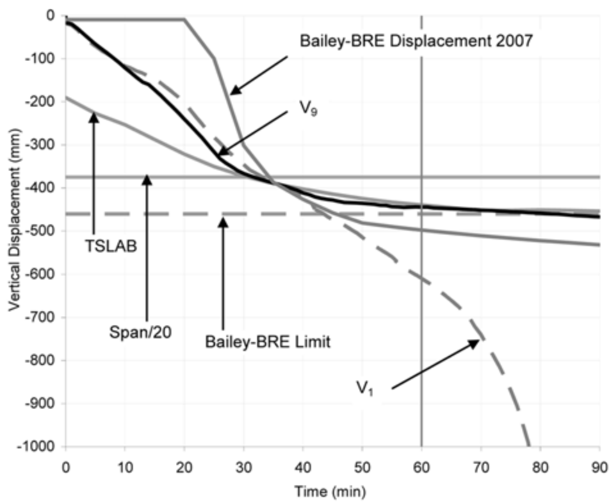

Fig. 13 Comparison of *Vulcan* analyses with twice the generic protection and the BRE displacement

protection, which may be costly.

5. Conclusions

A number of protection schemes and support conditions have been analysed. It has been observed that the Bailey-BRE method gives a good prediction of slab panel behaviour if the perimeter beams remain stiff for long periods of time (i.e. in an overprotected state or when restrained by the presence of continuous slabs).

Beams would normally be designed for critical temperatures of about 620°C. The analyses presented have shown that tensile membrane action is lost when protected beam temperatures exceed about 600°C. At this stage plastic hinges form in the edge beams, due to the effects of increased loading, reduced capacity and inadequate support stiffness.

For slabs in the interior of a building, the restraint from adjacent slabs is clearly beneficial, but for slab panels which have edges on the façade of a building, increasing the level of protection seems a viable option. However, this could potentially lead to increased construction costs, and would call into question the economic benefits of employing tensile membrane action in fire engineering design.

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