SIMPLE INVESTIGATIONS OF TENSILE MEMBRANE ACTION IN COMPOSITE SLABS IN FIRE

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Abstract: This paper presents some results of a behavioural study of the action of slabs at very high deflections at normal temperatures and in fire. This has been performed at different levels in order to illustrate both the logic of the behaviour and also to test the order of the effects on representative framing layouts. The simplest level is to model the slab as a beam grillage using non-linear beam elements. Initially, simply supported and fixed-edge slabs are studied. This is extended to heated slabs with different levels of horizontal restraint stiffness from adjacent structures.

1. INTRODUCTION

It has become apparent recently that the ultimate survival of composite framed buildings in fire is to a large extent controlled by the ability of the concrete slabs covering the fire compartment to sustain their loading when acting as tensile membranes at very high deflection. This occurs when temperatures are very high, so that exposed steelwork has lost almost all of its strength. The membrane action is a geometrically non-linear behaviour whose exact nature depends on the conditions of vertical support which can be maintained around the boundaries of the fire compartment, and on the restraint to in-plane edge movement imposed by surrounding structure. In the development of design principles based on the ultimate maintenance of compartmentation against fire spread it is important that this form of structural action should be fully understood, so that it can be implemented into the design procedure for buildings as part of an integrated fire engineering design approach.

Two options are available for studies of this action; direct finite element modelling using geometrically non-linear flat shell elements, and use of a grillage analogy. This paper deals with some studies which have been made using the latter method. The grillage analogy has the advantage that it makes it very easy to rationalise the structural behaviour of the slab, albeit using a reduced set of structural actions, and to illustrate the loading paths. If the slab is rationalised as a grillage composed of geometrically nonlinear beam-column finite elements this has the ability to handle slabs of almost any kind and complication. The phenomenon of tensile membrane action, and the way in which it is affected by edge restraint, is first investigated in grillages at very high deflection at ambient temperature. In order to illustrate the additional effects introduced by fire on the performance at high deflections, analyses carried out under elevated temperature conditions are then presented.

2. STRUCTURAL MODEL

The structure investigated consists of a grillage of concrete beams representing a concrete slab. Use is made of an advanced non-linear analysis program VULCAN, which includes temperature-sensitive material models and accounts for geometric and material non-linearities [1]. Simple concrete and reinforced concrete beam-column elements have been implemented within this program, and are used in these analyses.

The idealisation can be made manageable by assuming Poisson's ratio to be zero, thereby eliminating the need for the torsion-free diagonal members [2]. Member properties of the resulting assembly of orthogonal beams, are given by:

$$I_x = [L_y]\frac{t^3}{24} \tag{1}$$

$$I_y = [L_x]\frac{t^3}{24} \tag{2}$$

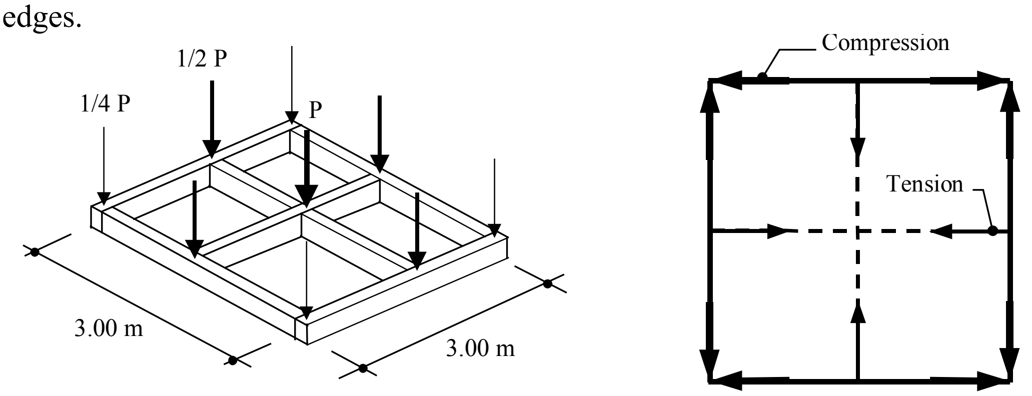
In an assembly of orthogonal beams, the moment in a beam depends only on the curvature of the assembly in the direction of the beam. The corresponding moment in a slab depends not only on the curvature in the direction of the moment but also on the slab curvature in the perpendicular direction. This slab action is represented by the following equations for the moments per unit length in the *x* and *y* directions:

$$M_x = -D\left[\frac{\partial^2 w}{\partial x^2} + \nu\frac{\partial^2 w}{\partial y^2}\right] \tag{3}$$

$$M_y = -D\left[\frac{\partial^2 w}{\partial y^2} + \nu\frac{\partial^2 w}{\partial x^2}\right] \tag{4}$$

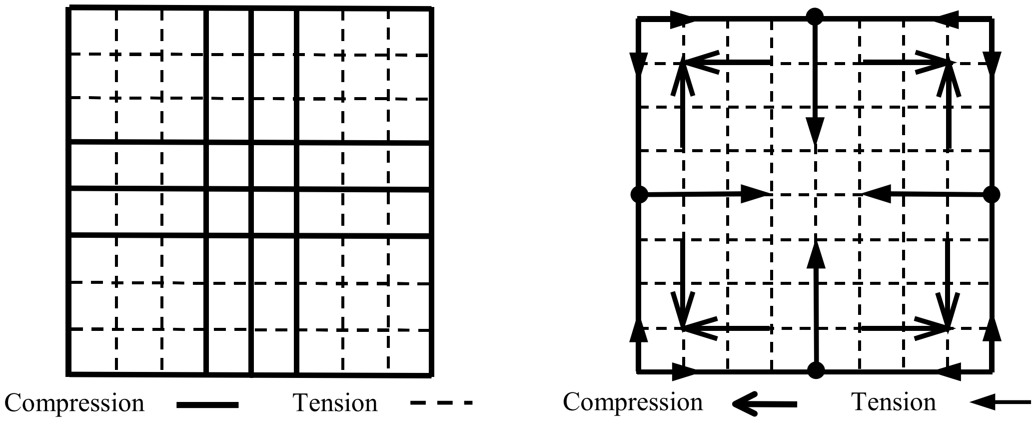
The second terms in the above equations account for the effect of curvature in the direction perpendicular to that of the moment. It can be seen that the effect of curvature in the other direction, which is directly related to ν, would not be picked up by an idealisation that neglects ν. Ignoring Poisson's ratio leads to an underestimation of moments, which is usually negligible for longitudinal moments in a concrete slab.

A variety of grillage sizes have been tested to look at the natural behaviour of the grillage at high deflections when the boundary conditions allow pull-in. In Figs. 1(a) and (b) a very simple version of the grillage is tested under the effects of increasing vertical applied loads at constant ambient temperature. The edges are supported vertically, allowing rotation but no vertical movement, and with no horizontal restraint against pull-in. At a high deflection the edges attempt to move inwards, forming a compression ring. This compression ring provides a self-equilibrating condition to the grillage, balancing the tension across the middle region and compensating for the absence of the horizontal support in the system. The tension forces developed at high deflection across the middle zone of the slab will assist in carrying the load applied to this part by hanging from the compression ring around the edges. This behaviour is again clearly illustrated in Figs. 2(a) and (b) when the same loading and boundary conditions are applied to more extensive grillage system. The compression zones at the corners can be seen to be linked together via rings of compression force around the periphery, with the central group of members acting in tension extending towards the edges.



(a) (b)

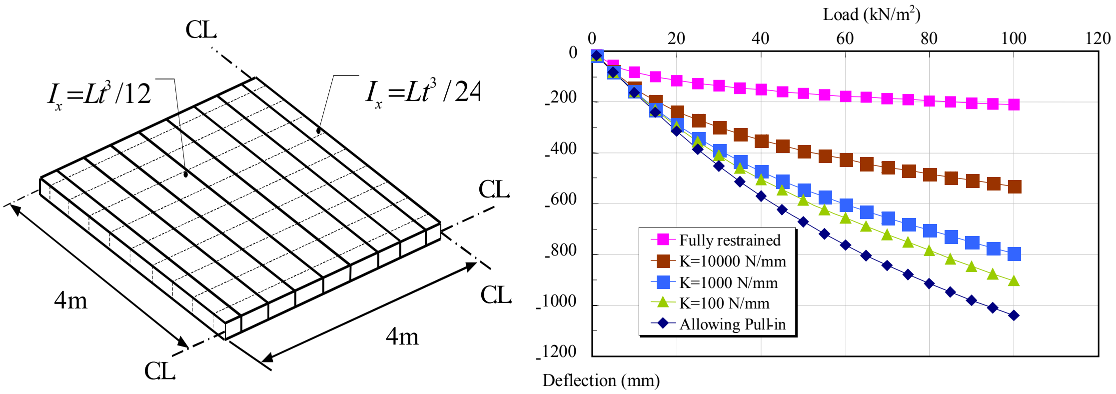
Fig.1. (a) Simple structural model, (b) Force action



(a) (b)

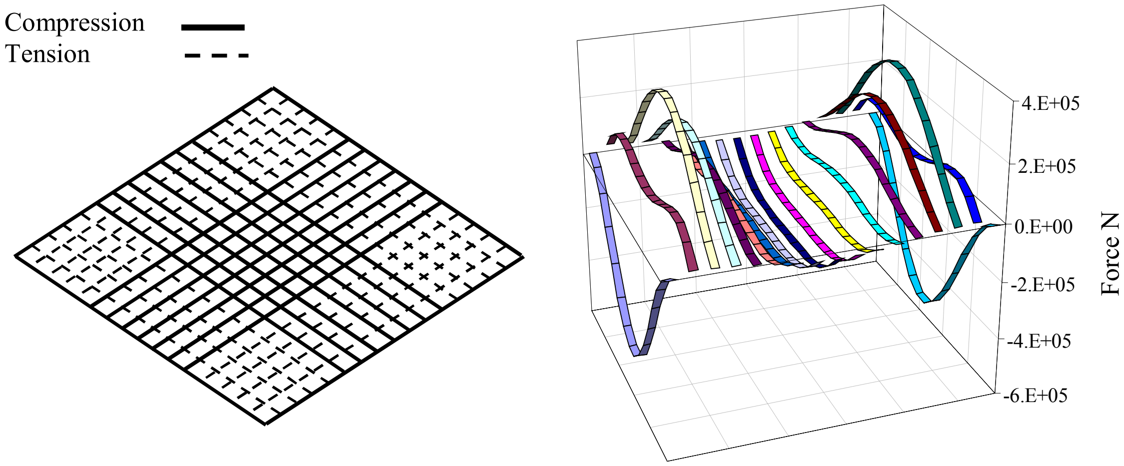
Fig.2. (a) Force distribution for 4m x 4m grillage system at high deflection, (b) Force actions.

When a finer grillage is used to represent a slab, it is possible to model the behaviour in more detail. For example, the quarter-slab shown in Fig. 3(a) has been analysed using the whole slab's inherent symmetry in order to study the effect of in-plane edge restraint. A range of edge stiffnesses have been used, producing the set of load-deflection curves shown in Fig. 3(b). The induced force distribution for the simply-supported case is shown in Fig. 4(a), and the profiles of forces along continuous grillage members are plotted in Fig. 4(b). The latter shown clearly the zone of tension in the central zone, changing to compression towards the periphery of the plate.



(a) (b)

Fig. 3. (a) Grillage idealisation of one quarter of perfectly elastic concrete slab, (b) Load-deflection curves for this system with different axial stiffness applied at the edges.



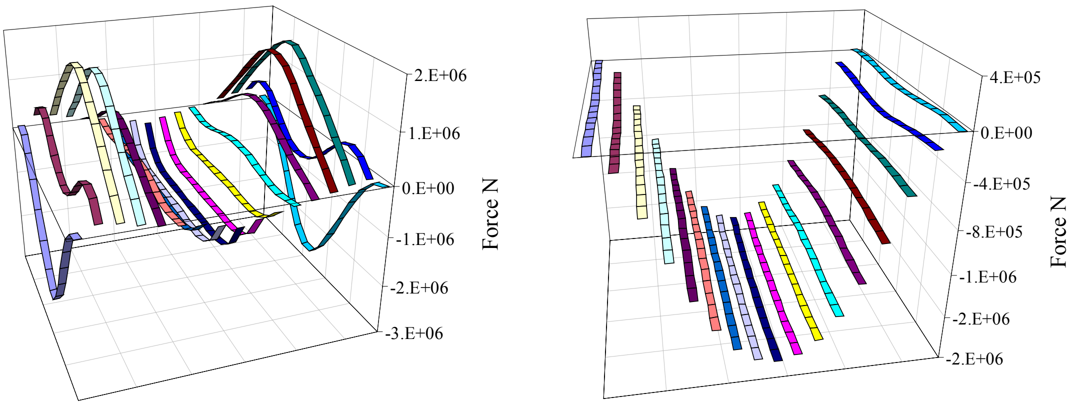
(a) (b)

Fig. 4. (a) Force distribution for simply supported elastic concrete grillage at high deflection, (b) Force profile for grillage members.

3. THE EFFECT OF EDGE RESTRAINT ON REINFORCED CONCRETE SLABS

When cracking occurs in a concrete slab with steel mesh at its mid-surface, the neutral axis (or zero-strain axis) is displaced towards the compression face, and the cracked part ceases progressively to function structurally. The middle plane of the slab, where the steel mesh is placed, is thus effectively subjected to an expansion. Such an effect can occur both in the middle zone in sagging bending and at the edges in hogging bending. Where these expansions are resisted by a stiff boundary, additional compressive forces develop, and where the slab is thick the eccentricity of resultant compressive force produces an arching action which can enhance the load-carrying capacity. This mechanism is present in reinforced concrete even in highly redundant structures under ambient temperature conditions, due to the very large lever arm between their hogging and sagging neutral axes when deflections are low. However, when deflections exceed this order the membrane stresses in the middle zone become tensile, and the slab begins to hang from its edges rather than simply transmitting shear forces to them.

Figs. 5(a) and (b) illustrate the force profiles at high deflection of reinforced concrete slabs with simply supported and clamped edges. In this case, normal failure criteria apply to both concrete and steel. Clearly, the figures show that the mechanisms of resisting membrane tension change when the resistance to pull-in is increased. However both use tensile membrane action to increase their load capacity.



(a) (b)

Fig. 5. (a) Force profile for reinforced concrete grillage system - simply supported allowing pull-in, (b) Force profile for the same grillage with fully restrained edges.

Calculations for the load carrying capacity of a reinforced concrete slab are usually based on the slab failing under pure bending. This represents the first failure mode of a simply supported slab at small deflections. If the slab is laterally restrained it will arch from boundary to boundary. This results in the development of a compressive membrane force in the concrete slab. This is a low-deflection phenomenon which enhances the inherent safety of the slabs in ultimate strength design. However, irrespective of whether such restraint is present, as high deflections grow the compression changes to increasing tension in the middle zones. If there is no horizontal restraint this is a self-equilibrating action with peripheral compression forming in rings around the edges. These rings vary according to the slab dimensions as well as the aspect ratio. With high restraint to horizontal edge movement the compression rings disappear, and the tensile stresses are equilibrated by reaction against the edge restraint. Tests on buildings and laterally restrained individual slabs [3] confirm the enhanced load carrying capacity of concrete slabs due to tensile membrane action. As the slab deforms further, the depth of the cracked concrete increases and the available uncracked concrete resisting tensile stress diminishes. When cracking extends over the entire depth of the concrete cross-section, the applied load on the reinforced concrete slab can be regarded as being taken only by the tensile membrane action of the steel reinforcement. During this stage of loading, the applied load on the slab is supported by the net of reinforcement in tension at the middle hanging from the compression rings or from continuing structure at the edges.

Whilst tensile membrane action exists from relatively small deflections, it is more efficient at large deflections in reinforced concrete slabs. For a normal design, at ambient temperature, these large deflections would not be acceptable because of serviceability limit states. However, high deflection can be acceptable when the slab is subjected to abnormal loading conditions such as a fire. It is, therefore, appropriate to explore the enhanced load carrying capacity of a reinforced concrete slab due to tensile membrane action at large deflection to assess its collapse strength for fire resistant design.

4. DISCUSSION AND CONCLUSIONS

Composite steel-concrete frames have significantly more fire resistance than individual structural steel members, due to their ability to redistribute loads to relatively stiffer parts of the structure. Observations of real fires and fire experiments [4] have shown that such redistribution clearly exists. Membrane action in floor slabs has been identified as the primary mechanism to account for the stability of a structural member at large deflection and for providing an alternative load path after the failure of some structural members [5].

It can be seen that simply supported slabs can form a self-equilibrating system at high deflections, in which the central regions are in tension and the perimeter zones form a compression ring. As the edge restraint is varied this changes until with infinite restraint to pull-in the compression rings essentially vanish. Tensile membrane action plays a major part in supporting the slab from fairly low deflections up to the final failure of reinforcement.

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