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Understanding the compressive ring in reinforced concrete slabs in fire

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SUMMARY

Fire induced geometrical changes produce large deflections in floor slabs and even if there is significant loss of strength, the change of shape of the slab allows stability to be maintained by the slab acting as a tensile membrane. This of course depends upon the amount and arrangement of reinforcement and the end restraint conditions of the slab. If the slab is continuous over the supports and the continuity of reinforcement over the support can also be assumed then the "anchoring" of the tensile membrane action is not in doubt. There is however a mechanism by which even simply supported slabs can produce a degree of tensile membrane action. In this case although there are no lateral (or in-plane) reactions available at the supports, there is a self-equilibrating mechanism that occurs in the form of a "compressive ring" between the central and perimeter regions of the slab which provides restraint to the membrane tensions (rather like the rigid ring surrounding a trampoline). Some authors have used this to develop design methods for non-continuous simply supported slabs in fire; however there is a great deficit of knowledge regarding the quantification of this effect. One of the key parameters that may govern the magnitude of "membrane enhancement" available for simply supported slabs is the ratio of slab thickness to its "overlap length" from the edge of the support. This paper will present initial conclusions obtained from this study and discuss the implications for design.

KEYWORDS: Floor slabs; fire behaviour; membrane-flexure interaction

1. BACKGROUND TO RESEARCH

1.1 Introduction

Tensile and compressive membrane stresses in concrete slabs constitute a large part of the total member behaviour but their influence has been to a large extent ignored in general design procedures. The mechanisms involved are complex due to the large number of variables involved and the non-linearity inherent in their propagation. Compressive membrane action adds to the slab strength obtained from yield line analysis. Also, tensile membrane action is a load-carrying mechanism only observed at large slab displacements which are outside practicable serviceability limits. These phenomena have undergone intensive study since the Cardington tests, in both analysing the results from the experiment (especially the corner test) and the subsequent numerical modelling investigations.

Interest in the tensile and compressive membrane phenomena has increased due to results from the Cardington tests indicating that they may play an active role in the building design process. While large displacements are unacceptable while the building is in service, during an extreme event such as a fire when occupants are likely to have evacuated the priority is on avoiding ultimate collapse. Large displacements are inconsequential at this point, and it is now recognised that slab performance and

tensile membrane action in particular plays a major role in redistributing building loads to form sustainable load paths (Allam et al [1][1], Huang et al, 2003[2]). Related to this issue is the integrity of the building's compartmentation as described earlier. A small local breach may alter the course of the initial fire and have the potential to cause greater damage. Either way, a greater understanding of membrane interactions at ambient or elevated temperatures is recommended in order to deal discuss these issues with authority.

Another example is in economy of fire protection. Reinforced or composite slabs undergoing large membrane stresses are able to maintain the stability of fire-weakened steel frame structures. Recent work has suggested that this ability nullifies the contribution of secondary beams to global stability and renders them unnecessary at elevated temperatures (Bailey, 2001)[3]. Essentially, the effect is that secondary beams need not be fire-protected to any extent. This obviously will create large savings in cost where such protection was previously deemed necessary and will be an attractive alternative to contractors. Still, more knowledge of the governing physics is recommended before there are any changes in policy regarding slab construction.

1.2 Compressive Membrane Action

Compressive membrane action is very dependent on the extent of lateral restraint to the slab. When a slab has a load incident on it, the interior part will sag. Assuming full restraint, the areas closer to the edges will undergo hogging, while sections directly adjacent to the boundaries, especially at corners, will experience little change in shape. At small deflections, slab continuity presents an incompatibility between the exterior and interior parts. The centre tries to expand, but is in a sense "tied" to the edges. Therefore a ring of tensile stress materialises around the extreme perimeter, while the interior experiences compression. These membrane forces hold each other in equilibrium and form a stable mechanism. This holds because, even though the compressive forces are usually in excess of the tension, the boundaries provide additional tensile restraint.

The bending strength of a concrete slab can depend greatly upon the axial load (membrane force). There exists an apex corresponding to the maximum theoretical bending strength, which requires a certain value of axial force to be reached. If this is done, both the axial force capacity and bending capacity are reached simultaneously in a balanced failure. This strengthening effect is considerable in deep and stocky slabs with small amounts of reinforcement (being under-reinforced, as is the norm in building design). The exact extent is difficult to determine, but generally in practice slabs can exceed their yield line ultimate load.

1.3 Tensile Membrane Action

Tensile membrane action is a load-carrying mechanism which occurs at high deflections. There has to be significant deflection from the horizontal for the effect to materialise; when in-plane forces become inclined, their vertical components can carry a small amount of incident load. This is known as catenary action: a simple analogy is a heavy chain hanging due to its own weight, where tensile forces balance the transverse load.

Usually in this situation, a compressive stress ring develops around the central area to support the interior tension. This is similar to the description of a tensile ring supporting the compression in compressive membrane action, but that only happens at low deflections. The strength enhancement effect of tensile membrane action is not large (at ambient conditions), but it does generally allow for the slab to ultimately yield with the rupture of internal reinforcement. It is extensively documented that by exploiting the additional load-carrying mechanism of membrane action, slabs can be subjected to loads much higher than those predicted by the well-established yield line analysis methods (Gillie et al, 2002[8], Newman et al 2000)[9].

The combined effects of compressive and tensile membrane action lead to a load-deflection diagram for concrete slabs similar to the general case in Figure 1 below:
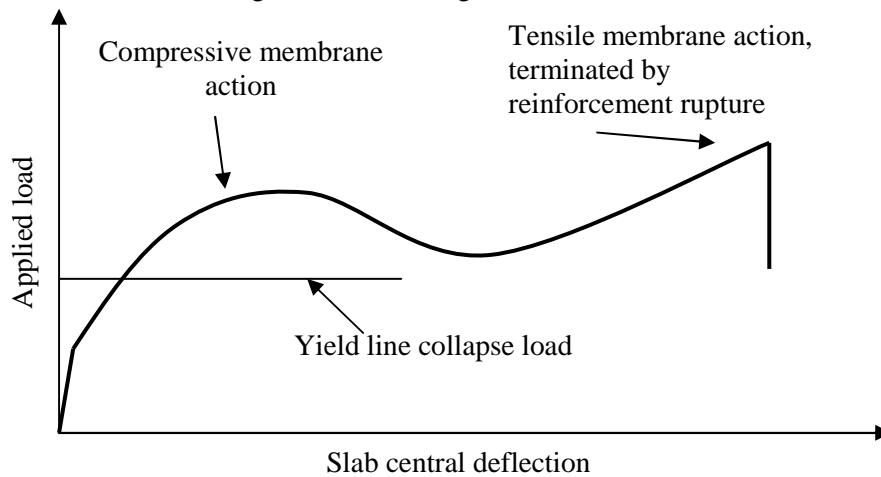

Figure 1: General Load-central deflection curve of concrete slab

This curve demonstrates the higher deflections that are possible to be maintained using membrane interactions, and the non-linearity is apparent. However, it also shows that for practical serviceability-based design, traditional yield-line analysis methods are definitely applicable.

2. ANALYSIS OUTLINE

This research involved the modelling of reinforced concrete slabs in fire. To do this, various ABAQUS analyses were conducted using a 100mm slab with the underside exposed to a 1 hour British Standard design fire. The time-temperature curve for this fire obeys the equation $T=T_o+345log(0.133t+1)$. The software used to relate this temperature curve to a thermal distribution throughout the slab was the University of Edinburgh's in-house program Slabcap0.

2.1 Introduction to Slabcap0

Predominantly Slabcap0 is used to find the limit capacity of RC slabs in fire but part of its function is deducing through-slab temperatures for a range of parameters such as type of concrete, slab depth and fire specification. A normal weight concrete slab 100mm thick subjected on its underside to a 1-hour British Standard design fire was analysed. The through-slab temperature distributions produced are given in Figure 2.
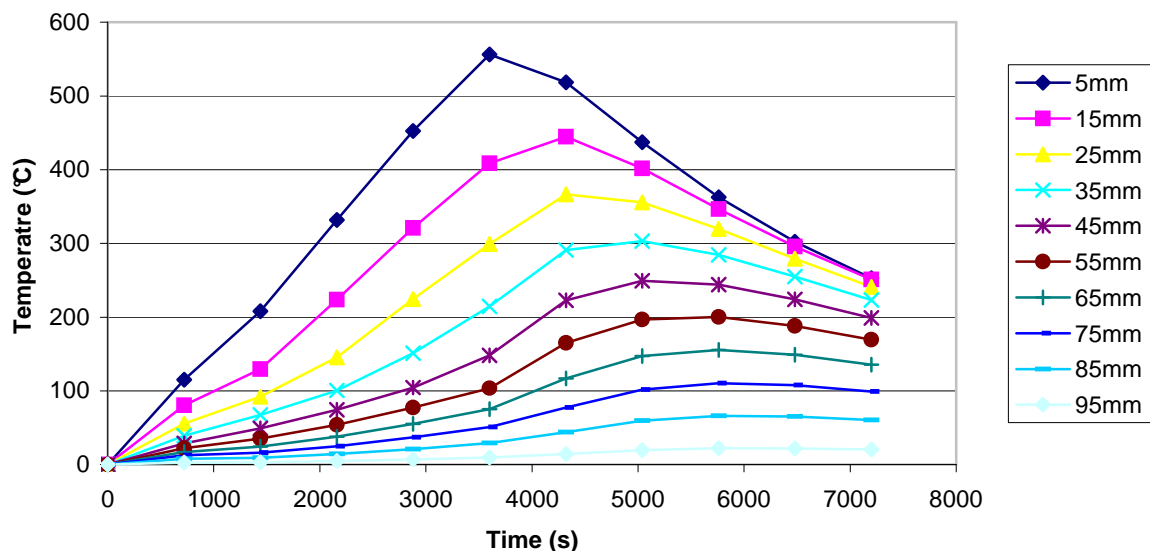
This data was used in the direct specification of slab section temperatures during the ABAQUS slab analysis.

2.2 ABAQUS Analyses

The numerical simulation package ABAQUS was used to compare via simulation the behaviour of fully restrained and fully unrestrained R.C. concrete slabs exposed to the same fire conditions. To do this a square slab of 6m edge and 100mm depth was modelled. Generic concrete material properties and temperature relationships were used. Reinforcement consisted of two 200mm centre steel meshes, one placed 20mm from the base with 12mm diameter bars, the other 20mm from the top with 6mm bars. This detail was chosen to provide reasonable deflections compatible with effective membrane stresses. An ambient pressure load of 5 KPa was applied to the top face before attributing the temperature distributions from the fire. This allowed the slab's mechanical response to be observed and compared to the behaviour in fire. In the first instance the edges were restrained and in the second, an edge beam was modelled to provide support only against a downward vertical deflection. A differentiation must be made between the terms 'unrestrained' and 'simply supported': a simply supported slab would require the edges to be pinned, allowing local rotations at the edges but not translations. This case would provide restraint against thermal expansion and would anchor the edges of the slab in three directions. It is obvious that in a fully unrestrained case, with the slab resting on edge beams and free to slide, the edges of the slab overlapping the edge beams would theoretically 'curl up' due to compatibility with the slab, as it is entirely in sagging bending. This is despite the overall pressure load acting down on these regions. In this case the overlap is equal to the slab depth, which is 100mm. The slabs were modelled using a 10 x 10 mesh of CPS4R shell elements. In order to save processing time and provide economy of data, only quarter-slab models were used with appropriate boundary conditions used to provide structural symmetry in two axes. Figure 3 below shows the two different meshes: the left model represents the fully restrained case (boundary specification not visible) while the right model clearly shows the edge beam part used to provide support. In each model the top right node (numbered 121) represents the centre of the 6m slab. The edge beam was modelled as rigid by giving it unrealistically stiff material properties. The interaction property between the slab and beam was designated as frictionless. This was deemed acceptable as a simple theoretical case was being modelled.
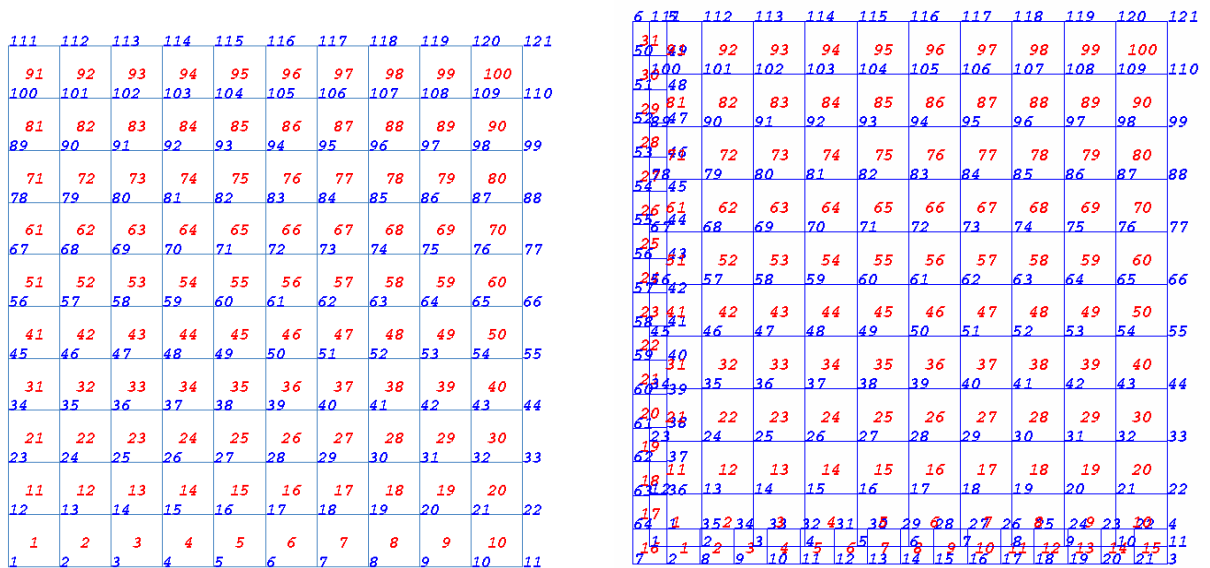

Figure 3: ABAQUS meshes for slab analyses

Output was requested for 9 section depths throughout the slab. These were the bottom face, 12.5mm, 25mm, 37.5mm, 50mm, 62.5mm, 75mm, 87.5mm and the top face. With this data it is possible to see, despite using shell elements, the through-depth in-plane stress response of the slabs. This provides

useful information on the location of any compressive ring effect and its propagation throughout the slab with increasing deflection.

3. DISCUSSION OF RESULTS

3.1 Analysis of restrained slab

The first case to be modelled was the fully restrained slab in fire. The stresses observed in the early stages of the fire validate the claims made in Section 2 concerning tensile membrane theory. The deflections are very low (less than 25mm) and stress states consistent with tensile membrane action are visible. The centre experiences compression while low tensile stresses form a ring around the sagging region. The graph of central deflection of the slab versus time is shown in Figure 4:
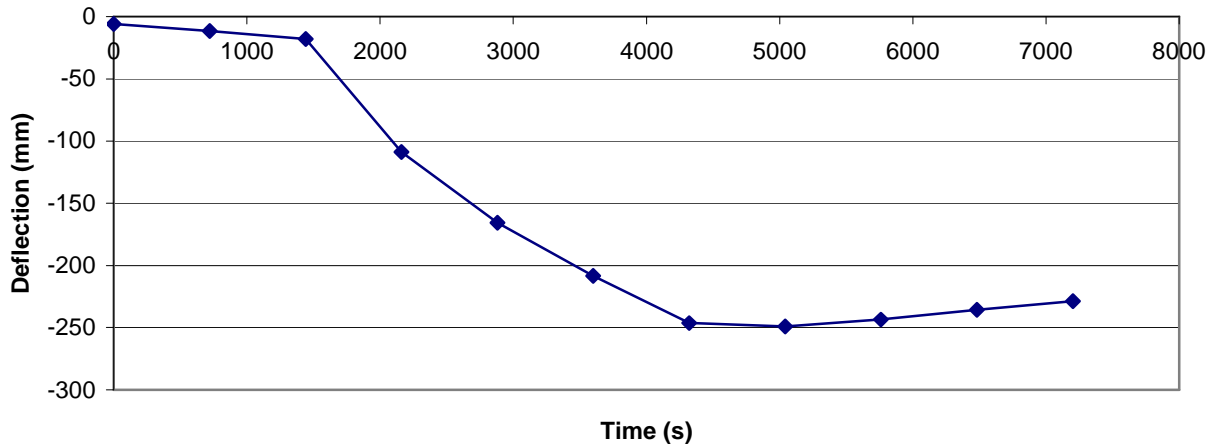

Figure 4: Central deflection against time for restrained slab

Central deflection slowly increases from the ambient loading value of –5.9mm to a very obvious point of 'snapping-through' at around 1450s. This corresponds with a sharp increase in the in-plane compressions at a position roughly 900mm-1500mm from the slab edge.
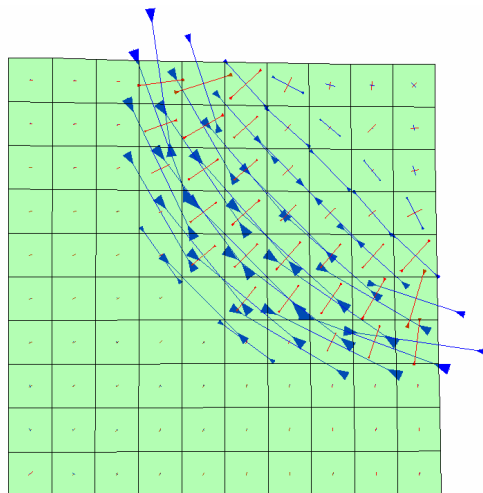

Figure 5: Representation of compressive ring – top face of 100mm slab, t = 5041s

As the deflection increases and the temperatures in the slab rise, the initial stress state changes to that shown in Figure 5. Here there is a very obvious ring of compressive stress surrounding the area of highest deflection. This is predicted by the tensile membrane theory. Small tensile stresses are evident in the centre, where a tensile net mechanism has been developed. Figure 6 below shows the variation in compressive stress from the middle of one edge to the slab centre at different depths, for the end of the heating regime (t=3601s).
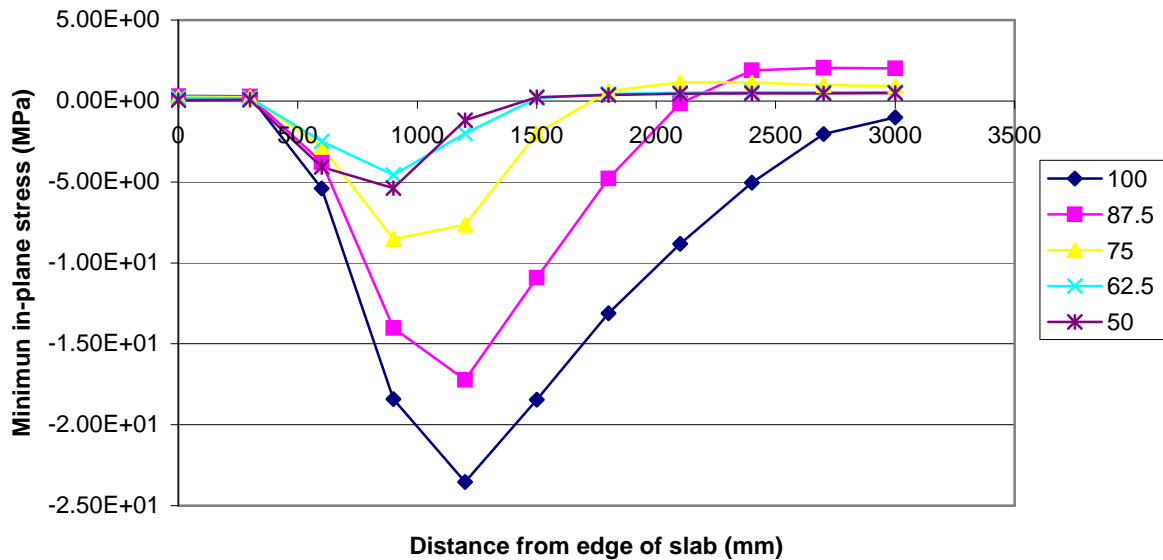
Figure 6: Through-depth stress profiles from slab edge to slab centre

Figure 6 shows that generally the highest membrane compressive stresses occur towards the top of the slab. The figures in the legend correspond to positions throughout the slab depth, measured from the bottom. It shows that the tensile action in the slab centre has not yet propagated to the top surface, as the line representing this section terminates below 0 (compressive stresses being negative, tension positive). The locations of the peaks in compression correspond to the location of the compressive ring relative to the slab edge in Figure 4. Therefore it is shown that the compressive effect declines through depth. The reversal in deflection evident in Figure 6 corresponds to the effect of the cooling phase of the heating regime, which is an area where more study is needed. The complex mechanisms of thermal shrinkage coupled with non-uniform, post-cracking concrete material properties means that this poses a particular challenge to techniques of numerical simulation. Nevertheless, it has been shown that deflections will increase with an increase in temperature, but only very slowly once the tensile membrane action occurs. This result is delivered by the decreasing gradient of the temperature-deflection graph in Figure 4.

3.2 Analysis of fully unrestrained slab

It was found that upon simulating the 100mm thick unrestrained slab, deflections increased with temperature as was expected but the stress state which developed was not fully consistent with membrane theory. As expected, there was no regime of tensile membrane action, as the lack of lateral restraint meant that no tensile forces could be supported at the boundary. However, the compressive stresses generated lay parallel to the classical yield lines predicted by Johanssen's yield line theory. It was decided to increase the slab section to 200mm as a less slender slab would be less likely to deform in the folding manner observed. This was deemed acceptable as the objective was to examine for beneficial membrane tensions supported by a compressive ring in an unrestrained slab, irrespective of depth. The time-deflection chart of the 200mm analysis is shown in Figure 7. This shows that around t=2880 there is a decrease in deflection rate. In the early stages of the fire, compressive membrane stresses increase towards the centre, as was shown in the unrestrained case of Section 3. Again, a very obvious point of 'snapping-through' is reached and the compression at the centre decreases till tensile membrane action appears. Importantly, compression is shown to increase around the perimeter of the slab.

Figure 7: Deflection history of 200mm unrestrained slab

Figure 7 shows that around t=2880 there is a decrease in deflection rate. In the early stages of the fire, compressive membrane stresses increase towards the centre, as was shown in the unrestrained case of Section 3. Again, a very obvious point of 'snapping-through' is reached and the compression at the centre decreases till tensile membrane action appears. Importantly, compressi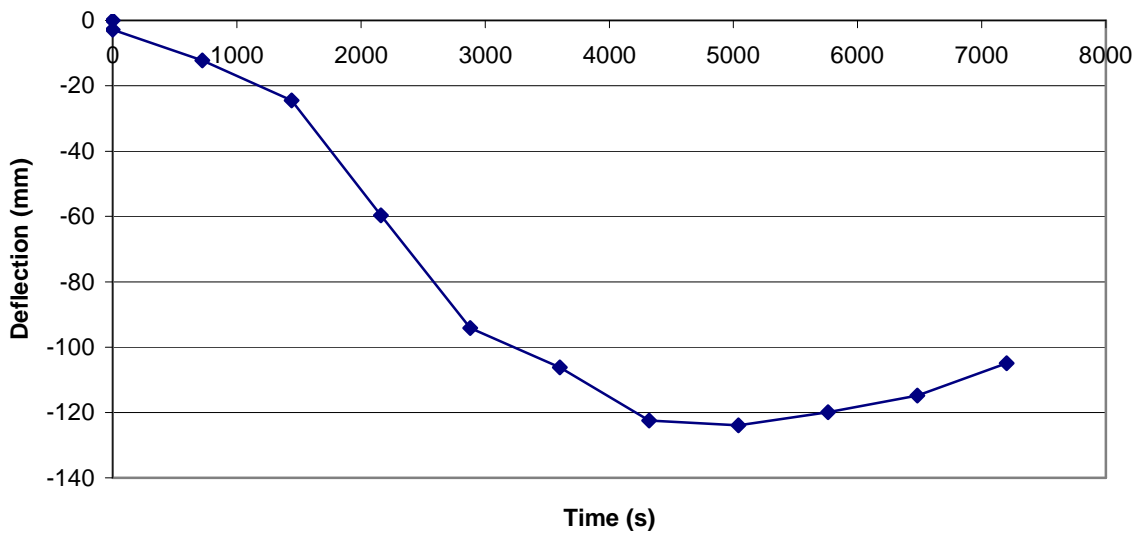on is shown to increase around the perimeter of the slab. Figure 8 represents the stresses in the top face at t=4321s and clearly shows this effect:

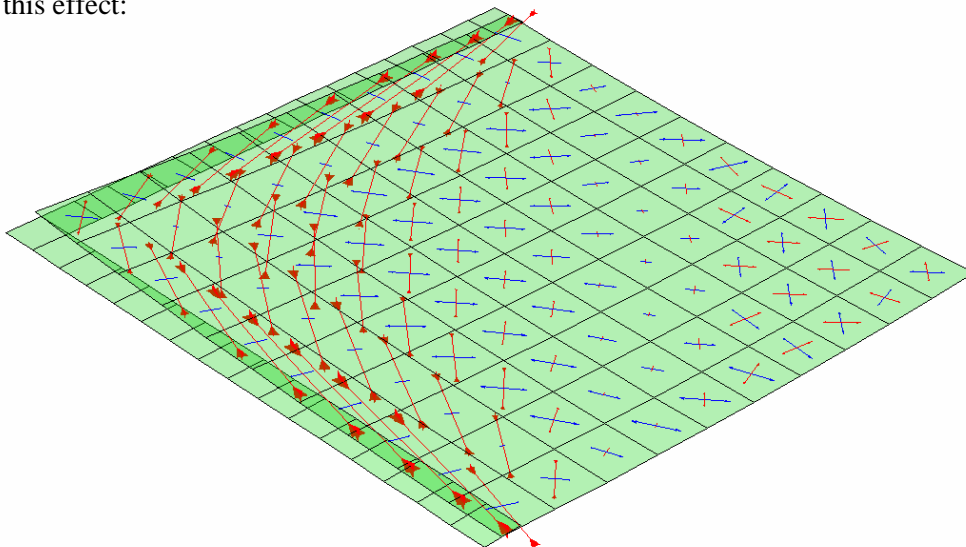
Figure 8: Stress state in 200mm unrestrained slab at t=4321s

Figure 8 describes the tensile membrane stress state responsible for the decrease in deflection rate between t=2880s and t=4321s. Note how the corner of the slab has deflected upwards, indicating that the model has adopted the expected deformed shape. Figure 9 shows the through-depth in-plane stress variation at t=3601. It is important to note that these values presented are in-plane stresses and not those of the forces comprising the membrane load carrying mechanism.
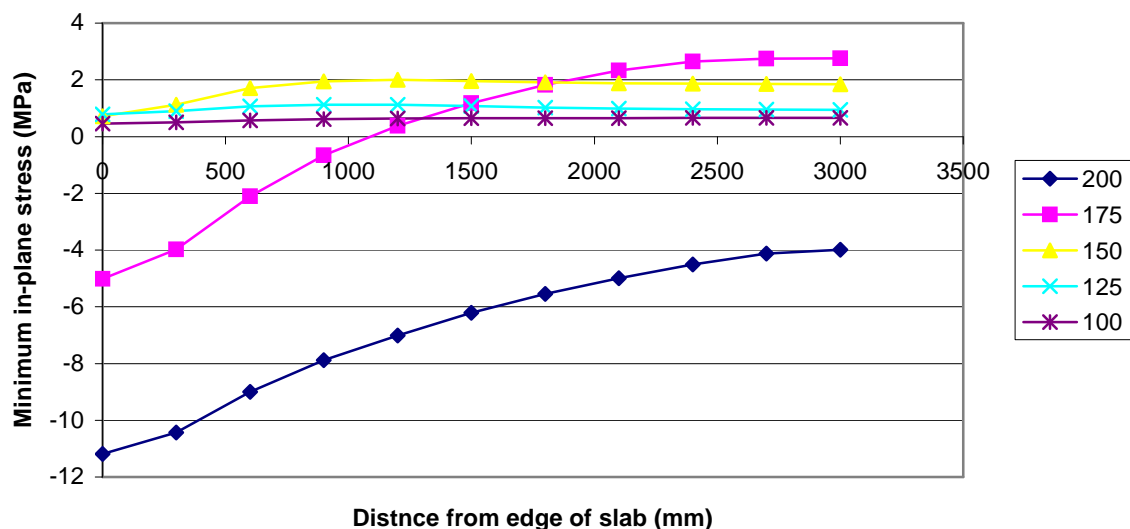
Figure 9: Through depth stress profiles from edge to slab centre

Figure 9 describes the high compressions at the perimeter of the slab, but these are only evident in the upper portions. Here the compressive ring is confined to an area at the edge within the upper quarter (50mm) of the slab. Again, it is expected that this holds due the upper areas of the slab retaining much of their ambient strength, as temperatures in these regions do not increase greatly due to concrete's low conductivity. However, this phenomenon is of course dependent on the duration and severity of the fire. The line representing the 87.5mm section is characteristic of tensile membrane theory, in that there is an obvious change from compression at the edge to a tensile net evident in the slab centre.

4. OVERLAP ANALYSIS

An aim of this research was to investigate the nature of the overlap on slab behaviour in the frictionless simply supported case. Specifically, this is the amount of area where the slab has a bearing on the supporting edge beam. This was carried out in the context of understanding more about the nature of the membrane action load-carrying mechanism which arises at the high deflections in fire. The amount of bearing support provided ought to have consequences for the slab's global behaviour. Generally, a greater bearing support ought to decrease the space available for the slab to deflect through, reducing the overall displacement. Another factor is that because of the UDL on the slab, part of the load will counteract the slab's tendency to uplift at the edges and corners through compatibility. Ideally, the slab is free of axial loads at the supports and is completely unrestrained.

As before, the investigation centred on the case of a 100mm deep 6 by 6 metre simply supported slab. A uniform pressure load was applied, of 5 kPa. The width of the supporting edge beam was changed to give slab depth/overlap ratios of 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75 and 2.00. Simulations were carried out at ambient conditions and with the soffit exposed to a 1 hour British standard fire.

No obvious trends, concerning either deflection profile or internal stress, were observed from changing the overlap. The slab deflection histories were the same to within 1.2 mm, and stress plots were very similar throughout. This seems to indicate that the amount of overlap has little effect on slab behaviour. Another more reasonable conclusion is that the changes in the edge beam width were too small to influence the finite element slab model, especially since the slab mesh was of low density. While a finer element mesh for the slab would create a more accurate approximation of real slab behaviour, this approach would not wholly solve the problem. The computational method used requires revision if the practical effects of varying slab-beam overlap are to be represented.

5. CONCLUSIONS

An investigation into the membrane stresses in a reinforced concrete slabs subjected to fire has been presented. Computational finite element software was used to simulate the slab mechanisms and retrieve data. Two computer programs were used in the analysis procedure: firstly, the slab depth and fire specification were inputted to the one-dimensional heat transfer code Slabcap0. This gave as output the temperature distributions in the slab at certain points in time throughout the fire. This information was then used as input to an ABAQUS analysis which produced the deflection and stress histories. The slab boundary conditions were varied in the analysis. The aim was to observe how boundary restraint affected the propagation of load-carrying mechanisms due to membrane interactions. Observing deflected slab profiles and the associated in-plane stress distributions formed the basis of the research. The analysis carried out in this report has led to the following conclusions:

- Where full restraint is supplied, the ABAQUS simulation of a basic 100mm slab exposed to a one hour fire gives results which closely resemble the theoretical stress resultants required to bring about compressive membrane action at low deflections and tensile membrane action at high deflections.

- For a fully restrained slab in fire, the initial deflection rate is low as tensile membrane action keeps the slab stiff at low deflections. After a period of time, however, "snapping through" is observed and the slab quickly deforms to its next stable state. This is usually where the top of the slab is resisting the load in tension with the formation of a compressive ring around the sagging region to support the mechanism.

- Increasing the depth of a concrete section massively enhances its ability to resist fire-induced deflections.

- Tensile membrane action is observed in a fully unrestrained slab resting on edge beams. The slab has to be thicker than a fully restrained slab for the same geometry for the in-plane stresses at high deflections to have an effect on the slab strength.

6. FURTHER WORK

Membrane force analysis

The ultimate goal of the membrane interaction analysis is to quantify the compressive ring and it's enhancement to overall load bearing capacity. With an understanding of all the governing factors, a slab design methodology which incorporates membrane action at high temperatures will be possible. Work will be carried out to establish the links between temperature profile, rebar provision, membrane stresses, membrane forces and load-carrying enhancement.

Slab-beam overlap analysis

In order for the results from the overlap analysis to be discussed fairly, a greater understanding of computational contact mechanics would be beneficial. Simple two-dimensional high-temperature unrestrained beam analyses are to be carried out with a focus on the interaction between nodes and elements in contact at supports. For a loaded beam in fire, the expected behaviour is thermal expansion pushing beam elements over the support, then a reversal in direction as the beam is pushed through the space. Studying results from these analyses will be useful in creating realistic numerical models of fully unrestrained slabs suitable for slab-beam overlap analyses.

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