COMPARISON OF BRE SIMPLE DESIGN METHOD FOR COMPOSITE FLOOR SLABS IN FIRE WITH NON-LINEAR FE MODELLING

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ABSTRACT

On the basis of test evidence a new design method has been recently developed by one of the authors, for calculating the performance of composite flooring systems subject to fire. The method models simply the influence of tensile membrane action in the composite floor slabs. The objective of this paper is to show some detailed comparisons between the simple design method and finite element modelling using the computer program *Vulcan*, which has been developed at the University of Sheffield, in order to check the applicability and inherent conservatism of the method. Initially a 9m x 9m square ribbed concrete slab, for which all four edges are vertically supported, is analysed. Different temperature distribution patterns across the thickness of the slab are used to investigate the influence of thermal curvature on the structural behaviour. The effect of changing the edge support conditions is also analysed.

As part of this study a large generic composite flooring system with a footprint of 36m x 36m has been designed. The frame is based on a regular 9m x 9m column grid. A series of analyses has been performed, based on different patterns of fire protection to the downstand steel beams. The influence of the proportion of steel reinforcement on the structural behaviour has been investigated, and it is evident that the presence or absence of tensile membrane action in the concrete slabs is a major influence on the ultimate integrity of the flooring system at high distortions. The ability of the slab reinforcement to sustain the tensile stresses caused at high temperatures and deflections is clearly a key factor in ensuring that fracture of slabs does not occur. From both the *Vulcan* modelling and the simplified design method it is shown that tensile membrane action can be important in carrying the loads applied to the slabs at high temperatures and deflections. However it is apparent that the simple design method predicts a greater contribution to load-carrying capacity due to tensile membrane action than does the *Vulcan* modelling, especially for high reinforcement ratios, and that further work needs to be done to resolve this discrepancy.

Keywords: *fire resistance, composite floor slabs, tensile membrane action, FE modelling.*

INTRODUCTION

The six large fire tests carried out in 1995-96 on the full-scale composite building at the BRE Fire Research Laboratory at Cardington [1] demonstrated conclusively that unprotected composite slab systems have significantly greater fire resistance within real multi-storey buildings than when they are tested as one-way-spanning isolated members. This appears to be due to interaction between the heated members within the fire compartment, the concrete floor slabs and the adjacent elements of the steel frame structure. The most significant general observation from the fire tests was that in none of the six was there any indication of run-away failure, which happens in all isolated member tests if temperatures are progressively increased. This is particularly remarkable since in some cases the unprotected steel beams reached well over 1000°C, at which temperature the steel strength is reduced by over 95%; deflections always exceeded *span/30* and in some cases exceeded the usual testing limit of *span/20*.

It seemed probable that tensile membrane action in the concrete floor slabs could have played an important role in preventing run-away failure of the structure during the fire tests, especially when deflections had become very large. Based on this theory and on the test evidence, a new design method was developed at BRE [2, 3], which calculates the enhanced load capacity due to membrane action of composite flooring systems subject to fire. The method models simply the influence of tensile membrane action in the composite floor slabs. Space does not permit a complete re-statement of this method here. Briefly, however, it calculates an enhancement to the slab’s normal yield-line bending strength, which is based on the undeflected configuration, on the assumption that deflection continues to take place using the original yield-lines as hinges. It is assumed that the slab yields simultaneously in ultimate tension across the whole of its shorter centre-line, and that fracture finally takes place according to a limiting average-strain criterion. The method has been incorporated into a fire-safe design guide [4] published by SCI for multi-storey steel-framed buildings.

In this paper some detailed comparisons are made between the simple design method and the computer program *Vulcan* [5-9], which has been developed at the University of Sheffield to model the behaviour of composite buildings in fire, in order to check the applicability and inherent conservatism of the method. Initially a 9m x 9m square ribbed concrete slab is analysed, whose four edges are vertically supported. Different temperature distributions are used across the thickness of the slab to investigate the influence of thermal curvature on structural behaviour. The effect of edge support conditions is also analysed.

As part of this study a large generic composite flooring system with footprint 36m x 36m has been designed. The frame is 4 bays wide and 4 bays deep, each bay having dimensions 9m x 9m. The load ratio on all internal secondary beams at the fire limit state is 0.42, resulting in a total floor loading of 6.1 kN/m^2. A series of analyses has been performed, based on different patterns of fire protection to the downstand steel beams. The influence of the steel reinforcement on the structural behaviour has been investigated, and it is evident that the presence or absence of tensile membrane action in the concrete slabs is a major influence on the ultimate integrity of the flooring system at high distortions.

THEORETICAL BASIS OF THE PROGRAM

In the 3-dimensional non-linear finite element procedure which is the theoretical basis of *Vulcan*, a composite steel-framed building is modelled as an assembly of finite beam-column, spring, shear connector and slab elements. It is assumed that the nodes of these different types of element are defined in a common reference plane, which is normally assumed to coincide with the mid-surface of the concrete slab element. Its location is fixed throughout the analysis. The beams and columns are represented by 2-noded line elements. The cross-section of each element is divided into a number of segments to allow two-dimensional variation of the distributions of temperature, stress and strain through the cross-section. Both geometric and material non-linearities are included. To represent the characteristics of steel-to-steel connections in a frame, a 2-noded spring element of zero length, with the same nodal degrees of freedom as a beam-column element, is used [5, 6].

The interaction of steel beams and concrete slabs within composite steel-framed buildings is represented using a linking shear-connector element, which is two-noded and has zero length; it employs three translational and two rotational degrees of freedom at each node. The shear-connector element permits the modelling of full, partial and zero interaction at the interface between the concrete slab and the steel beam [8]. In order to model the composite slabs including their ribbed lower portion, a modified layered orthotropic slab element has been developed. This element is based on the previously developed formulation [7], in which the slab elements are modelled using a layered plate element based on Mindlin/Reissner theory and each layer can have different temperature and material properties, which may be associated with thermal degradation. An effective-stiffness model has been incorporated into the layered procedure to take account of the orthotropic properties of composite slabs, for which a maximum-strain failure criterion has been adopted. A smeared model has been used in calculating element properties after cracking or crushing has been identified at any Gauss point. After the initiation of cracking in a single direction, concrete is treated as an orthotropic material with principal axes parallel and perpendicular to the cracking direction. Upon further loading of singly cracked concrete, if the tensile mechanical strain in the direction parallel to the first set of smeared cracks is greater than the maximum tensile strain then a second set of cracks forms. After crushing, concrete is assumed to lose all stiffness. The uniaxial properties specified in EC4 [10] for concrete and reinforcing steel at elevated temperatures were adopted in this model. Full details of the modified layered procedure used are given in reference 9.

The layered procedure mentioned above has been further extended to include geometric non-linearity in the modelling of reinforced concrete slabs in fire [11]. A quadrilateral 9-noded higher-order isoparametric element developed by Bathe [12] is used in place of the previous 4-noded geometrically linear element, and a Total Lagrangian approach is adopted. In this geometrically non-linear layered procedure all previous developments in the modelling of material non-linearity are retained, including the effective stiffness modelling of ribbed composite slabs.

ANALYSIS OF SQUARE RIBBED CONCRETE SLAB AT ELEVATED TEMPERATURES

Before attempting the modelling of composite floor systems isolated uniformly loaded (6.1kN/m^2) 9m x 9m ribbed reinforced concrete slabs with different edge support conditions were modelled at elevated temperatures using both *Vulcan* and the simple design method. The slab comprised ribbed concrete of 130mm total depth including 65mm deep ribs and an A393 anti-cracking mesh placed at the bottom of the upper continuous part, which means that in a composite decking slab it would have been resting on the corrugated deck before the slab was cast. The effective stiffness factors parallel and perpendicular to the ribs were then 0.72 and 0.34 according to reference 9. The geometry of the slab and the finite element mesh used are shown in Figure 1. Only one quarter of the plate has been modelled, because using the symmetry of the plate and its loading reduces the computational effort. The compressive strength of the concrete and the yield strength of the reinforcing mesh have been assumed to be 35 MPa and 460 MPa, respectively.

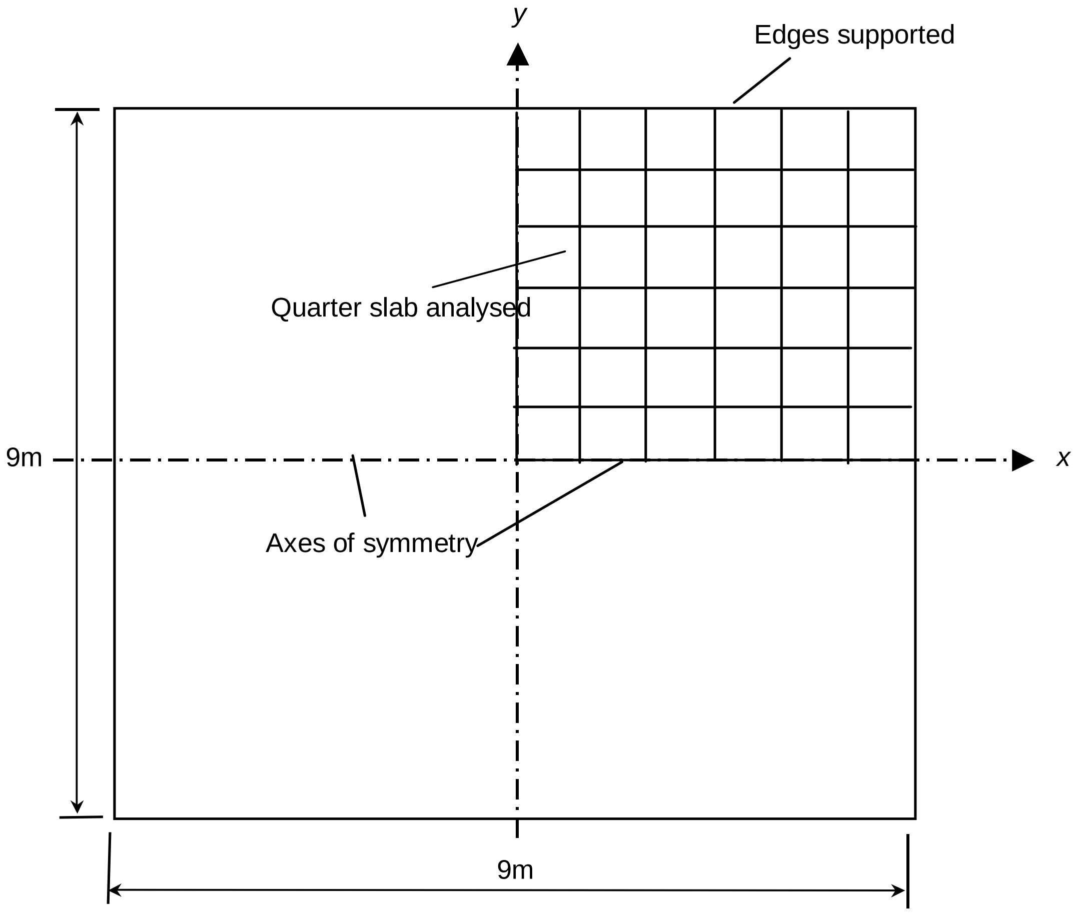

FIGURE 1: Representation of the ribbed reinforced concrete slab subject to uniform loading at elevated temperature, using the symmetry of the case.

In order to make more precise comparisons with the simple design method a linear temperature distribution across the thickness of the slab was adopted. This is one of the assumptions of the simple design method. The temperature of the top surface of the slab is assumed to be 15% of the bottom surface temperature. In this comparison the temperature of the steel reinforcement is used as reference parameter. Two *Vulcan* analyses have been performed, assuming simple (pull-in allowed) and hinge-supported pull-in prohibited) edge conditions. The central deflections of the slab are plotted in Figure 2 against the reinforcing steel temperature for these two cases, together with the limiting cases calculated using the simple design method.

It is evident that the central deflections predicted using *Vulcan* with simply supported edge conditions are greater than those calculated using the simple design method, both at ambient and elevated temperatures. It should be noted that the simple design method always assumes simply supported edge condition. It is interesting that the central deflections predicted by *Vulcan* using hinge-supported edge condition are in good agreement with the simple design method's calculations. In order to investigate the extent to which the deflection of the slab at elevated temperatures is caused by thermal curvature a case with uniform temperature distribution across the thickness of the slab was also analysed using *Vulcan* for simply supported edge conditions.

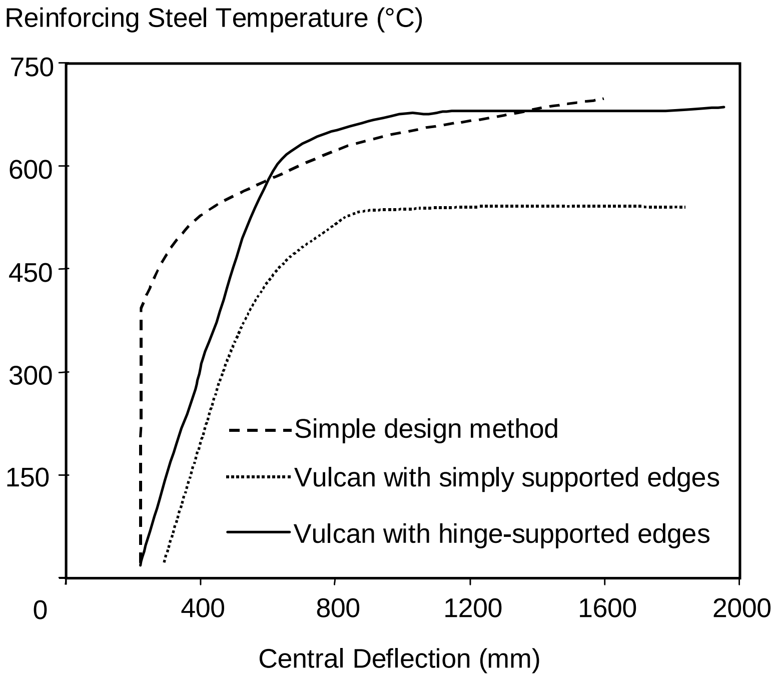

FIGURE 2: Comparison of predicted central deflections using the simple design method and *Vulcan* with different support conditions.

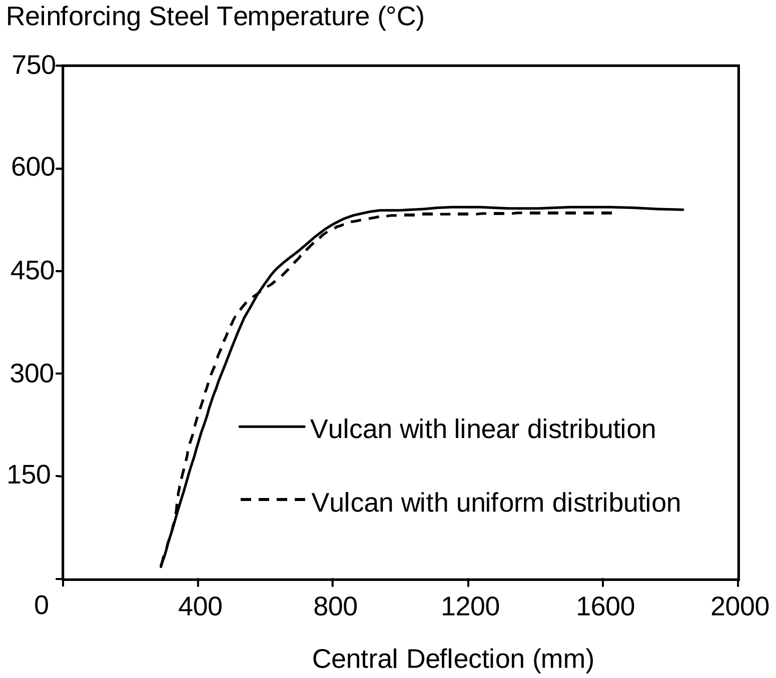

FIGURE 3: Comparison of predicted central deflections using *Vulcan* with different temperature distribution patterns across the thickness of the slab.

Figure 3 shows the comparison between the cases of linear and uniform temperature distribution for simple support conditions. It can be seen that the difference between the two cases is marginal. The ambient-temperature deflection of the slab was high (300mm) in this case, and hence the contribution of thermal curvature of the slab generated by temperature distribution through its thickness was relatively small.

ANALYSIS OF COMPOSITE FLOORS IN FIRE

This study was based on a composite 36m x 36m floor structure comprising 4 bays 9m x 9m in each direction (Figure 4), subject to a whole-storey fire. All primary and secondary beams were standardised as 533x210x92UB and 356x127x39UB sections respectively. A ribbed lightweight concrete slab of 130mm total depth was used, acting compositely with PMF CF70 profiled metal decking. The characteristic dead and imposed loads were assumed to be 4.08kN/m^2 and 2.5kN/m^2 respectively. From BS 5950: Part 8 [13], the partial safety factors in fire are 1.0 for dead loads and 0.8 for non-permanent imposed loads, giving a total design load of 6.1kN/m^2 at the fire limit state. This loading is used throughout the paper, and represents load ratios of 0.42 for secondary beams and 0.41 for primary composite beams if S275 steel and C35 concrete are assumed.

In order to investigate the extent to which fire protection of the steel beams may be reduced as a result of the beneficial influence of the slab, two different protection regimes were considered:

- **Protection Regime I.** All beams on the main gridlines were protected but other secondary beams were unprotected (Figure 4).
- **Protection Regime II.** Similar to I, but secondary beams on Gridlines 2 and 4 were also left unprotected.

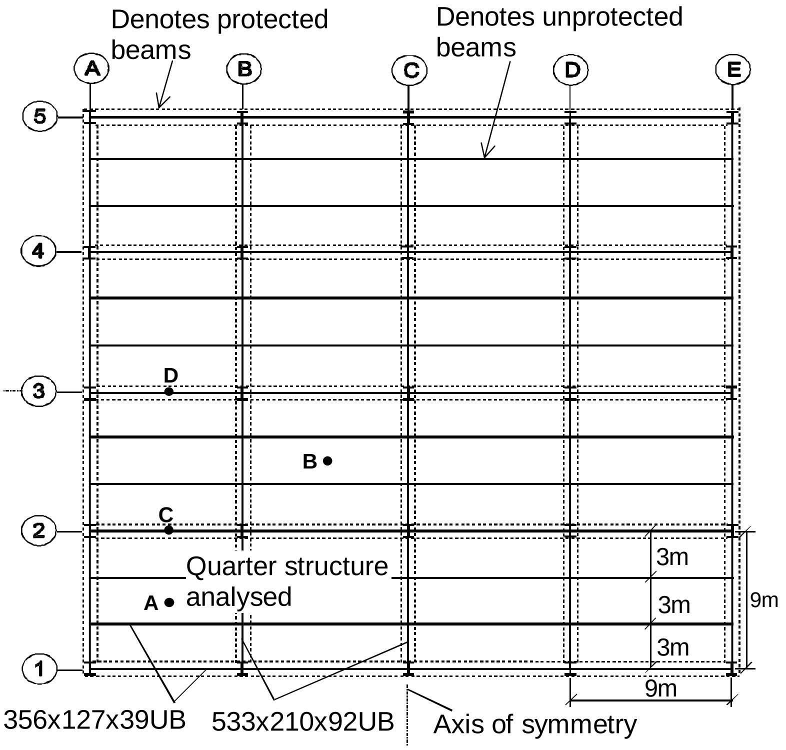

FIGURE 4: Composite floor layout assumed for Protection Regime I

The temperature distributions in the unprotected beams were assumed to follow the patterns indicated in the Cardington tests [14]. These were represented by considering the cross-section as three zones - bottom flange, web and top flange - of the steel beams, the temperature of each being taken from the Cardington test data. The temperatures in the protected beams were assumed to be 50% of those of the unprotected beams. A linear temperature distribution pattern was used across the thickness of the concrete slabs, in which the temperature of top surface of the slab was assumed as 15% of the bottom surface. All beams were assumed to be hinge-connected. To save computing time, advantage was taken of symmetry of the floor layout (see Figure 4), so that only a quarter of the floor system needed to be analysed. In order to demonstrate the effect of the slab reinforcement on the structural behaviour two different meshes, A142 and A393, were considered. In the following text the temperature of the bottom flange of the unprotected beams is used as the key temperature, against which results are quoted in all figures.

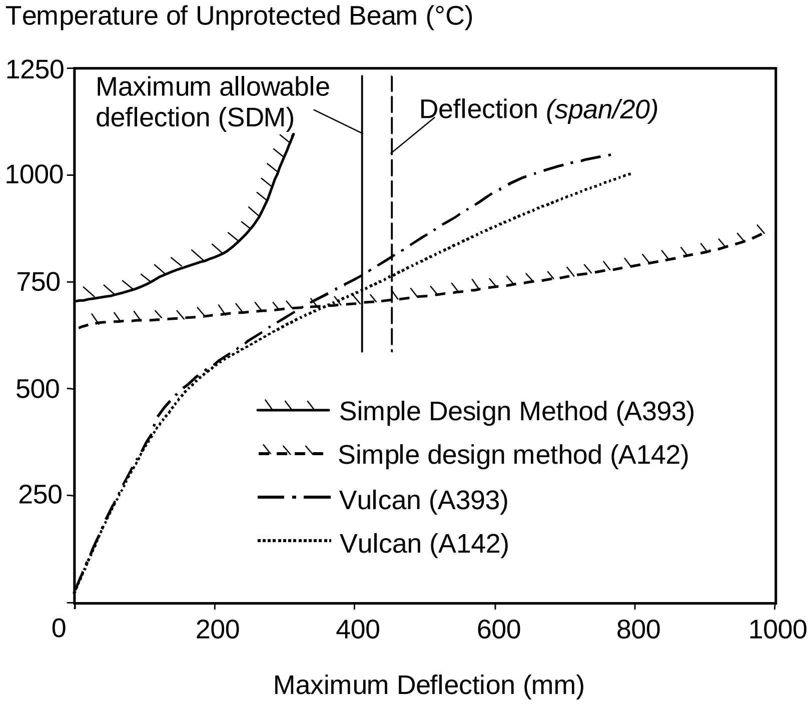

FIGURE 5: Protection Regime I: Predicted deflections using *Vulcan* and simple design method with different slab reinforcement.

For Protection Regime I, Figure 5 compares the maximum vertical deflections predicted by *Vulcan* and the simple design method for the two reinforcing meshes. It can be seen that for the numerical modelling the influence of reinforcement is negligible up to about 600°C, but that beyond this point it becomes increasingly significant. At these higher temperatures the steel beams have lost most of their original strength and stiffness, and support of the loads becomes increasingly the role of the concrete slab, with tensile membrane action being a key factor. When using the simple design method for calculation, the ultimate load-carrying capacity of the concrete slabs appears to be significantly increased for A393 mesh compared with A142. The discrepancy seems less significant when comparing the *Vulcan* modelling for two meshes, and it is evident that the effect of tensile membrane action predicted by the simple design method for mesh A393 is significantly greater than in the numerical modelling.

One of the assumptions of the simple design method is that all edges of the slab are vertically supported, whereas in this example the protected beams which form the slab supports do deflect as their temperatures rise. To investigate the influence of this edge deflection on the slab deflection, the A393 case was re-run in *Vulcan* with 100% protection to the protected beams, so that their temperature was kept at 20°C throughout. The results are shown in Figure 6, together with the simple design method's limit predictions. It is evident that it becomes progressively more important to maintain the vertical edge support provided by the protected beams in order to continue to mobilise tensile membrane action at high temperatures.

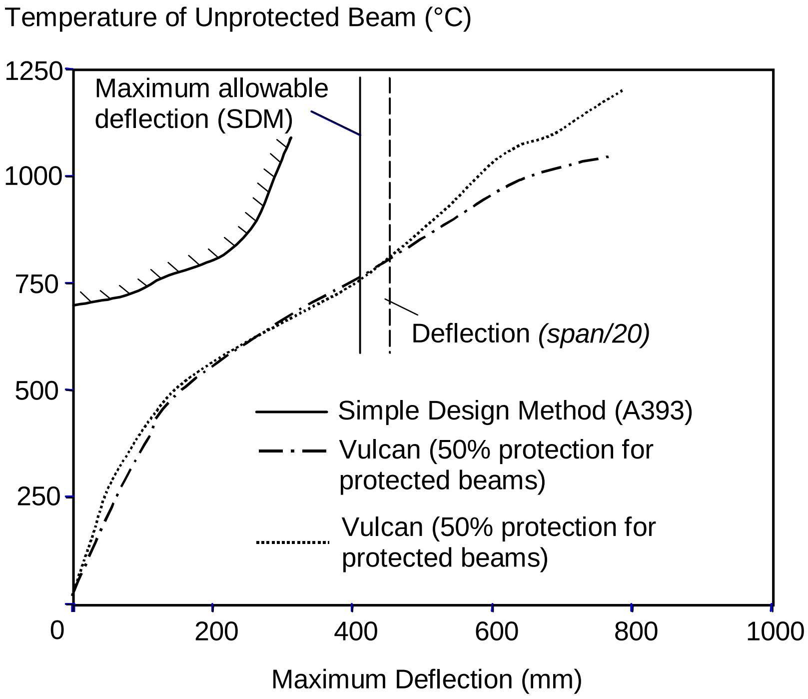

FIGURE 6: Protection Regime I: Predicted deflections using *Vulcan* with different degrees of protection for protected beams (mesh A393).

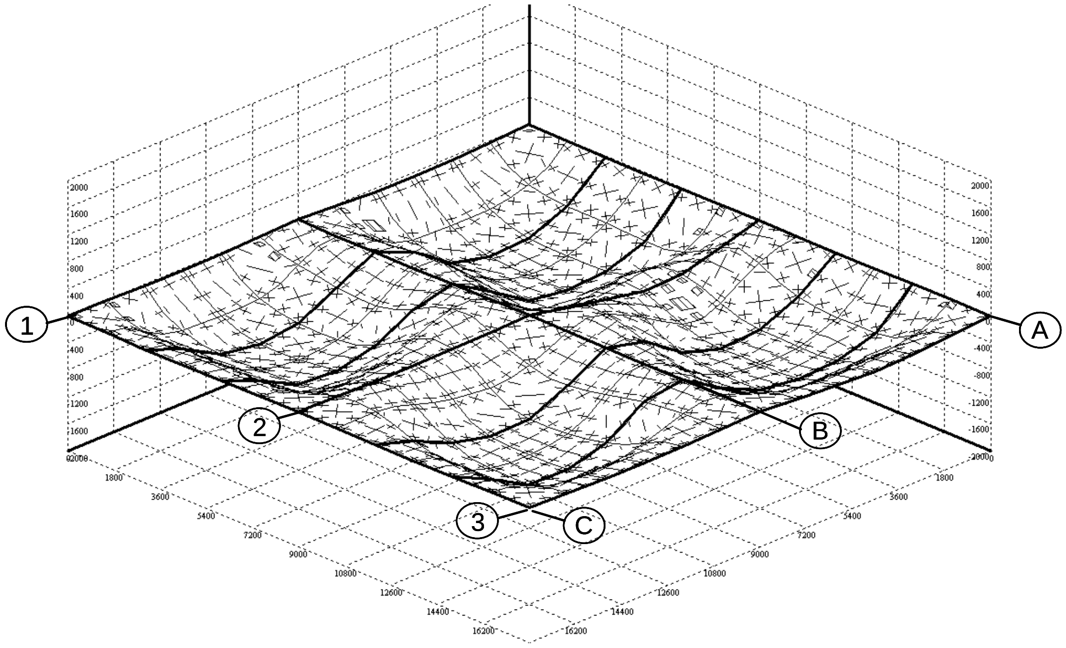

FIGURE 7: Protection Regime I: Deflection profiles at 1200°C, with cracking patterns of top layer of floor slab.

Figure 7 shows the deflection profiles at 1200°C for the case with 100% protected beams and A393 mesh reinforcement. Because the protected beams are now strong enough to vertically support the slab edges the slab is forced to deform in double curvature, which generates significant membrane action to carry the loads.

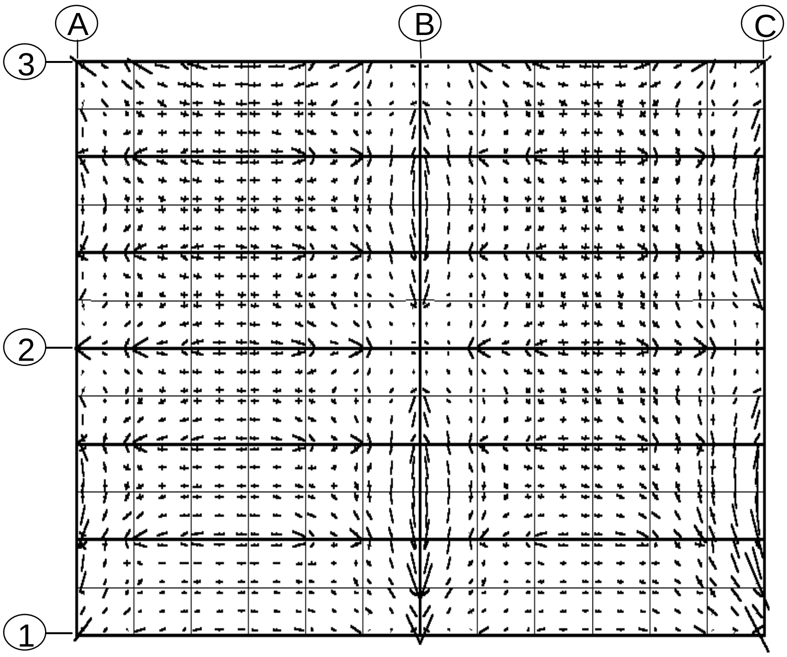

FIGURE 8: Protection Regime I: Principal membrane tractions at 20°C.

Figure 8 shows a vector plot of the distribution of principal membrane tractions (forces per unit width) at the Gauss points of the slab elements at ambient temperature. In this plot the lengths of the vectors are proportional to their magnitudes; thin vector lines denote tension and thick lines compression. The slabs above the secondary and primary beams act according to the normal engineering assumption for the flanges of composite beams, being in compression parallel to the beam. This reduces in the areas mid-way between adjacent beams due to shear lag. In contrast, the membrane tractions within the slab at 1200°C, plotted in Figure 9, clearly show the tensions in the mid-zone of each square panel together with the peripheral compression "rings" which are characteristic of tensile membrane action.

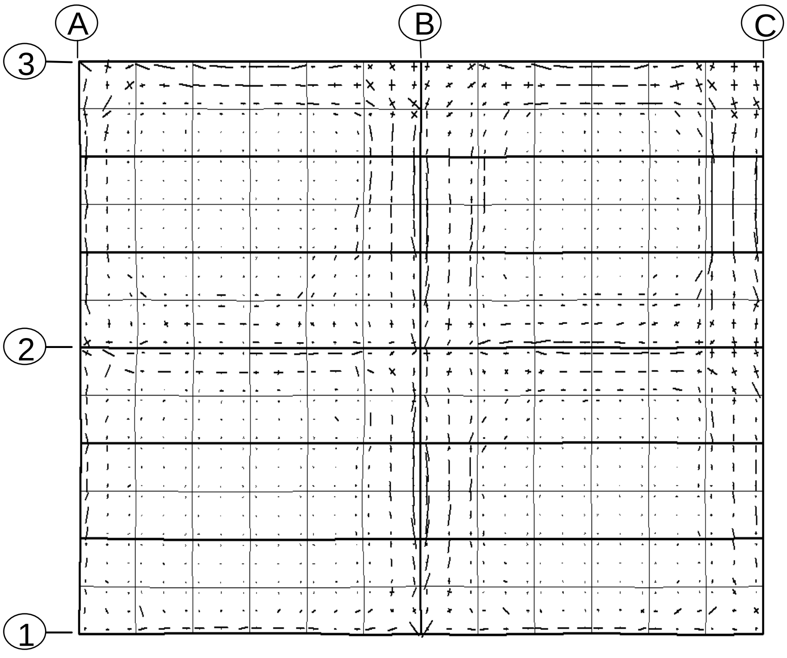

FIGURE 9: Protection Regime I: Principal membrane tractions at 1200°C.

It is clear that Protection Regime I effectively optimises the potential for tensile membrane action in the concrete slab by providing, in its pattern of protected beams, edge-supported bays which are square in plan.

Protection Regime II shows the considerable difference in tensile membrane action which is engendered when the protected beams support non-square slab bays. For this regime the maximum deflections were found in the *Vulcan* modelling to occur at position C, the mid-point of the 9m x 18m unprotected slab. Figure 10 compares the vertical deflections at position C predicted by *Vulcan* and the limits given by the simple design method for two reinforcing meshes. In these analyses the protected beams were assumed to heat at 50% of the rate of the unprotected beams. It can be seen that for temperatures up to about 650°C the slab reinforcement makes very little difference. Between 650°C and 850°C some enhancement of capacity is generated by the slab reinforcement, but this is associated principally with catenary action, rather than with tensile membrane action. This is because the pattern of vertical support provided by the protected beams results in rectangular rather than square bays, and the slab hangs essentially in single curvature between its protected edges. At high temperatures the strength of the protected beam on gridline 3 begins to reduce significantly, and this further compromises the ability of the slab to develop any membrane action. It is also clearly shown that the simple design method indicates very little enhancement of capacity due to tensile membrane action.

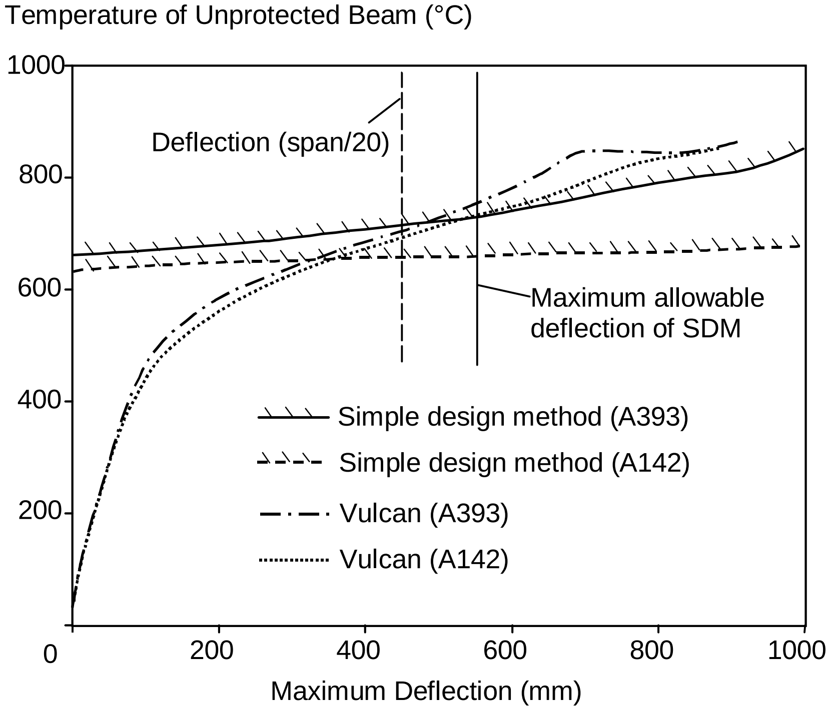

FIGURE 10: Protection Regime II: Predicted deflections using *Vulcan* and simple design method with different reinforcement.

CONCLUSIONS

The main objective of this paper has been to make some detailed comparisons between the simple design method and numerical modelling using the computer program *Vulcan*. From this study some conclusions can be drawn as follows:

- It is evident from both the *Vulcan* modelling and the simplified design method that the presence or absence of tensile membrane action in the concrete slabs can be a major influence on the ultimate integrity of the composite flooring system at high distortions. The ability of the slab reinforcement to sustain the tensile stresses caused at high temperatures and deflections is clearly a key factor in ensuring that tensile membrane action can legitimately be used in structural fire engineering design.
- The extent of tensile membrane action occurs depends very largely on the aspect ratios of the slabs between protected or otherwise supported edges. This is usually a product of the pattern of fire protection adopted for the steel downstand beams. In order to optimise the mobilisation of tensile membrane action it is important to make sure that the concrete slab is forced to deform in double curvature, and that it is incapable of producing folding mechanisms which do not involve membrane straining. Square slabs will always be most effective in producing the effect. For high aspect ratios catenary action of slabs may occur, in which tension which is essentially uniaxial may be resisted by in-plane restraint from adjacent bays, beams and columns. However, this mechanism is much more likely ultimately to lead to run-away structural failures than is tensile membrane action.
- Comparing *Vulcan* solutions with the simple design method it is clear that the simple design method may predict a greater enhancement of capacity due to tensile membrane action than is apparent from *Vulcan* analysis. That means the simple design method may predict greater fire resistance due to tensile membrane action than *Vulcan* modelling does. This is particularly the case for highly reinforced square slabs, for which the simple method predicts very large enhancement. Cases with reinforcement which is typical of anti-crack mesh, as well as the less square slabs, show less enhancement, and the disparity is less apparent.

Tensile membrane action clearly has the potential to become a useful tool as a part of a performance-based fire engineering design approach, but it is clear that work remains to be done in resolving the discrepancies between results which have been shown in this paper.

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