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ANALYSIS OF TENSILE MEMBRANE ACTION IN COMPOSITE SLABS IN FIRE

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ABSTRACT

Tensile membrane action can have a major influence on the performance of composite floor structures, and a number of design tools have been developed to take account of this. These represent a major advance on previous design methods and generally compare well with available test data. However, uncertainties remain about suitable failure criteria and the relative importance of various assumptions. This paper reports on a project to study these issues, comparing results obtained using different design methods, and also with tests on model scale slabs.

Introduction

Experience from real building fires and from large-scale fire tests at Cardington has shown that it may not be necessary to apply fire protection to all exposed steel beams, provided that the floor is of composite construction. This is because tensile membrane action in the composite floor slabs provides support to the unprotected steel beams as they lose strength and stiffness with increasing temperatures. A range of design tools has been developed to take advantage of this. These include sophisticated finite element-based computer models, such as Vulcan (Huang et al, 2002, 2003), accounting for whole-structure behaviour and providing a complete deformation-temperature history which needs to be interpreted with respect to structural stability and, where relevant, integrity. Numerical instability in the analysis, evident by the inability to converge on a solution, is generally taken as an indication of instability. However, the consideration of large deflections is less clear because there is insufficient understanding about the real failure condition, particularly in concrete floor slabs. A number of model scale tests have been conducted at both ambient and elevated temperatures, providing data on slab behaviour up to collapse, and part of the present work is to extend these tests to examine in more detail the effect of parameters such as load level, reinforcement type and ratio, and slab thickness. These and other previously reported tests provide valuable data for validating the software and defining the conditions for failure.

The use of finite element analysis is not always suitable for routine design, and a number of simpler performance-based design methods have been developed such as that originally published by BRE (Bailey 2000, 2001). Various refinements to the BRE method have been developed, including HERA's Slab Panel Method (Clifton & Beck, 2003), and formulations based on classical plate theory. These generally compare well with the limited test data available, and represent a major advance on traditional approaches. However insufficient experimental data is available to allow a proper exploration of some of the assumptions implicit in these simplified design methods. A preliminary study is therefore being conducted by analytical means.

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Design Methods Using Tensile Membrane Action

To take advantage of tensile membrane action in composite floors, a common design strategy is to divide the floor plate into panels which are vertically supported around their edges by protected beams on the column grid-lines. The beams within each panel are left unprotected, leading to significant economies in fire protection costs. The deflections of the floor are often significantly greater than would be the case if all beams were protected, and the strategy is therefore often used in buildings fitted with sprinkler suppression systems. In such cases the sprinklers themselves arguably provide the first line of defence for the structure. This approach ensures that structural stability is maintained, even if the sprinklers fail, but the requirement for integrity may be relaxed. Some simplified approaches are used where the floor is required to maintain compartmentation, and although a limit is imposed on deflections due to mechanical effects, thermal deformations are generally unlimited.

The BRE design method estimates the enhancement provided by membrane action to the traditional flexural capacity of the slab. Failure is based on the formation of a full-depth crack across the shorter span of the slab, and the enhancement factor is calculated as a function of a maximum allowable deflection. This is based partly on thermal deformations and partly on a strain limit in the reinforcement, with an upper limit corresponding to test observations. It assumes that the reinforcement across the perimeter of the panel fractures, due to large induced hogging moments, so individual panels are treated as simply supported. Any contribution from the steel deck to the capacity of the concrete slab is ignored and the floor is represented as a flat slab.

Comparison between Test Results and Analytical Approaches

A series of tests has been conducted by the first author, and together with those by Foster et al. (2004, 2005), provide data for comparison with design approaches based on this membrane action. The tested slabs have been analysed using the Vulcan software, and the failure temperature has also been compared with that predicted by the simplified BRE method. In both cases, the temperatures recorded experimentally were used as input data. In general the temperature-deflection history predicted by Vulcan compared very well with the results, and a typical comparison is shown in Fig. 1.

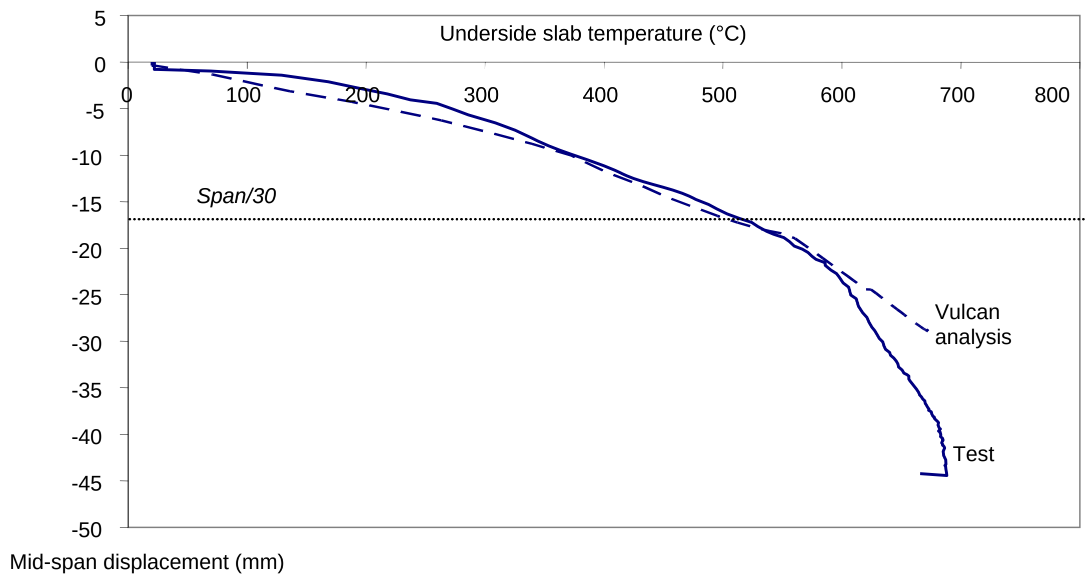

Figure 1 Comparison between test deflections and Vulcan analysis

The simplified BRE method does not provide a complete deflection-temperature history so it is not possible to make a direct comparison with the test results throughout the full temperature range. However, the method can be compared by calculating the displacement required to provide sufficient tensile membrane action to resist the applied loads. At low temperatures the floor structure is able to provide sufficient bending strength and the required enhancement from membrane action is therefore zero. As the temperature increases the flexural strength of the floor reduces, and will fail if insufficient membrane strength is mobilized – ie if the vertical displacement is too small. Fig. 2 shows such a comparison with the full temperature-deflection history predicted by Vulcan and test results. It can be seen that the required deflection remains well below the test deflections throughout, but the two converge as the slab approaches failure. In this example the comparison between the test results and Vulcan is less good, almost certainly because of uncertainties in the temperature profile through the slab thickness. The relative contribution of thermal and mechanical effects to the structural behaviour varies depending on particular conditions (Abu et al, 2006), but in these tests the former were dominant. This is demonstrated by analytical data for identical slabs in an unloaded condition, showing that the deformations prior to failure are predominantly due to thermal bowing rather than material softening. In all cases the temperature at which the analysis terminated (indicating structural instability) and the test slab failed compared very closely.

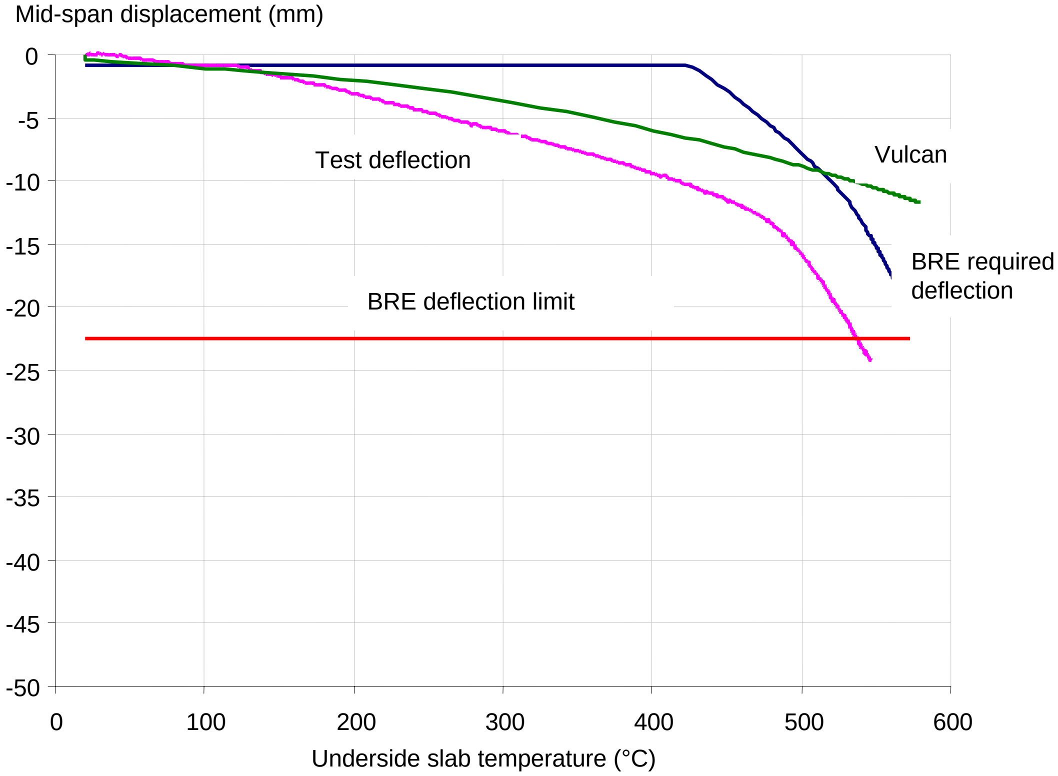

Figure 2 Comparison between test deflections, deflection required according to the BRE method, and Vulcan analysis

In determining the enhancement to the yield line load, the simplified method considers the total deflection, but imposes a limit on the mechanical deflection only, allowing any magnitude of deflection due to temperature variations through the slab. Control of deflections is a traditional way of defining failure under conditions of fire exposure, but it is only strictly necessary if there are concerns about integrity. However, if the floor is required to provide compartmentation, it is advisable to consider the expected magnitude and form of deformations. Although under suitable conditions thermal deflections can develop without mechanical stresses, these are unlikely to be realised in practice. It may therefore be wise to limit total deflections rather than simply those due to mechanical effects.

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Effect of vertical support

The simplified approach assumes that the edges of the slab do not deflect vertically. In practice the supporting beams will suffer some deflection even under ambient temperature conditions, and these will increase at the fire limit state. This is partly because the beams will soften, since any applied fire protection only slows down the rate of heating. Furthermore, the development of tensile membrane action in fire is often associated with a change in load paths, resulting in some beams attracting an increased load. To investigate the effect of edge deflections on the behaviour of the slab, two analyses have been conducted, with the edge beams protected in one case and kept at ambient temperature in the other. The results are compared in Fig. 3. It can be seen that if the edge beams are assumed to be normally protected the structure reaches a limiting deflection of span/20 after about 24 minutes, but this increases dramatically to 37 minutes if the edge beams remain at 20°C. This gives some indication of the significance of the vertical support conditions at the edges.

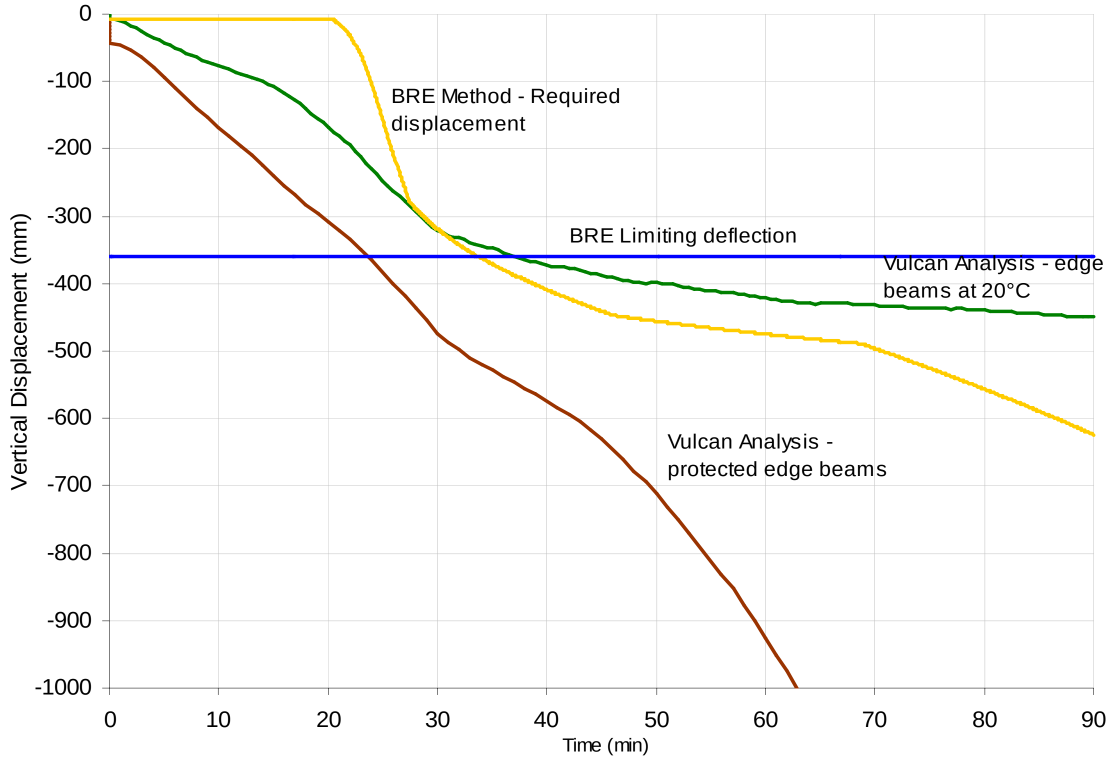

Figure 3 The influence of vertical restraint at slab edges

Effect of continuity

The simplified approach generally assumes that there is neither rotational nor horizontal continuity at the slab edges. This is clearly conservative and is illustrated in Fig. 4 which compares two analyses conducted using Vulcan for two cases in which the rotation at the edges is firstly fully restrained and then free.

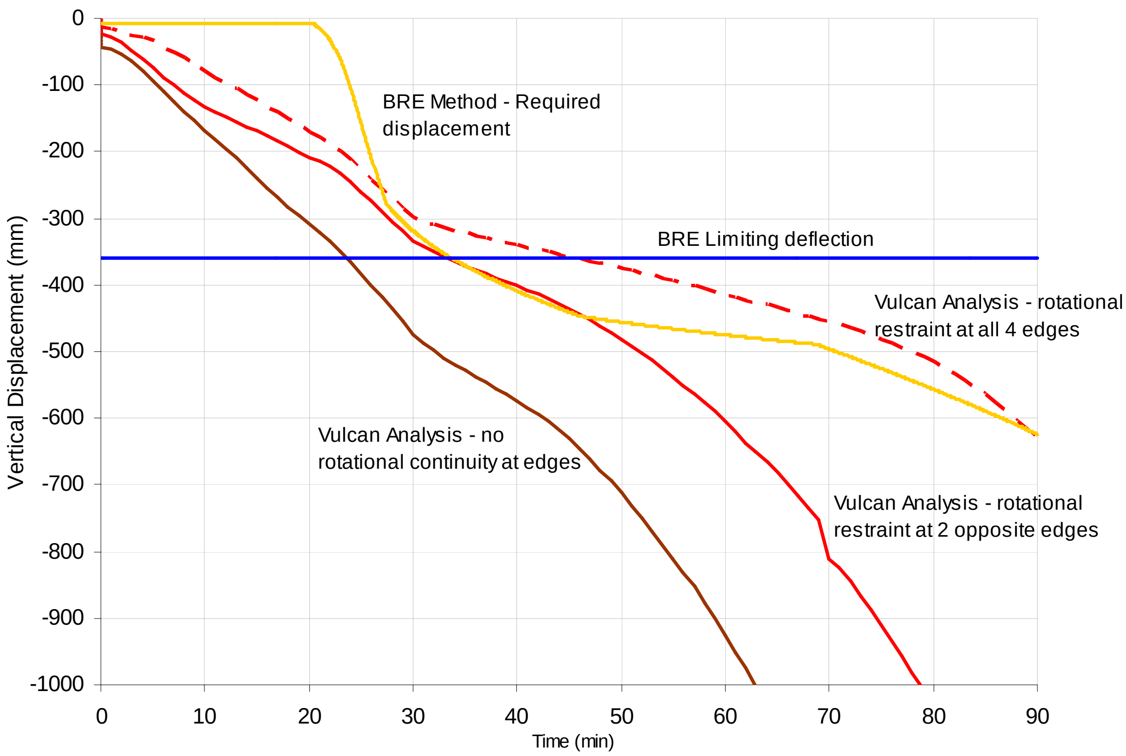

Figure 4 The influence of rotational restraint at slab edges

A variation on the simplified design method has been proposed by Cameron & Usmani (2005). This is based on classical large-deflection theory and assumes that the tensile membrane forces are balanced by restraint at the edges of the slab rather than by a peripheral compression ring within the panel itself. For internal panels this is assumed to be provided by the adjacent slabs, but requires edge beams and their connections to be designed so that they can create the necessary lateral restraint in addition to the vertical support. Studies conducted using Vulcan have shown that the effect of such horizontal restraint can be very large, but that it is not essential. In all of the model tests and the analyses outlined above, the edges of the slab were horizontally unrestrained, suggesting that horizontal support is not necessary to sustain the tensile membrane mechanism.

Effect of concrete tensile strength

The simplified approaches generally ignore any stiffening effect associated with the tensile strength of the concrete. This is clearly a conservative assumption and is illustrated in Fig. 5 which compares two analyses conducted using Vulcan, one ignoring the tensile strength of concrete, the other allowing for a strength equivalent to 10% of the compressive strength. It can be seen that the limiting deflection is reached at 37 minutes in the latter case, but this reduces to 27 minutes if the tensile strength is ignored.

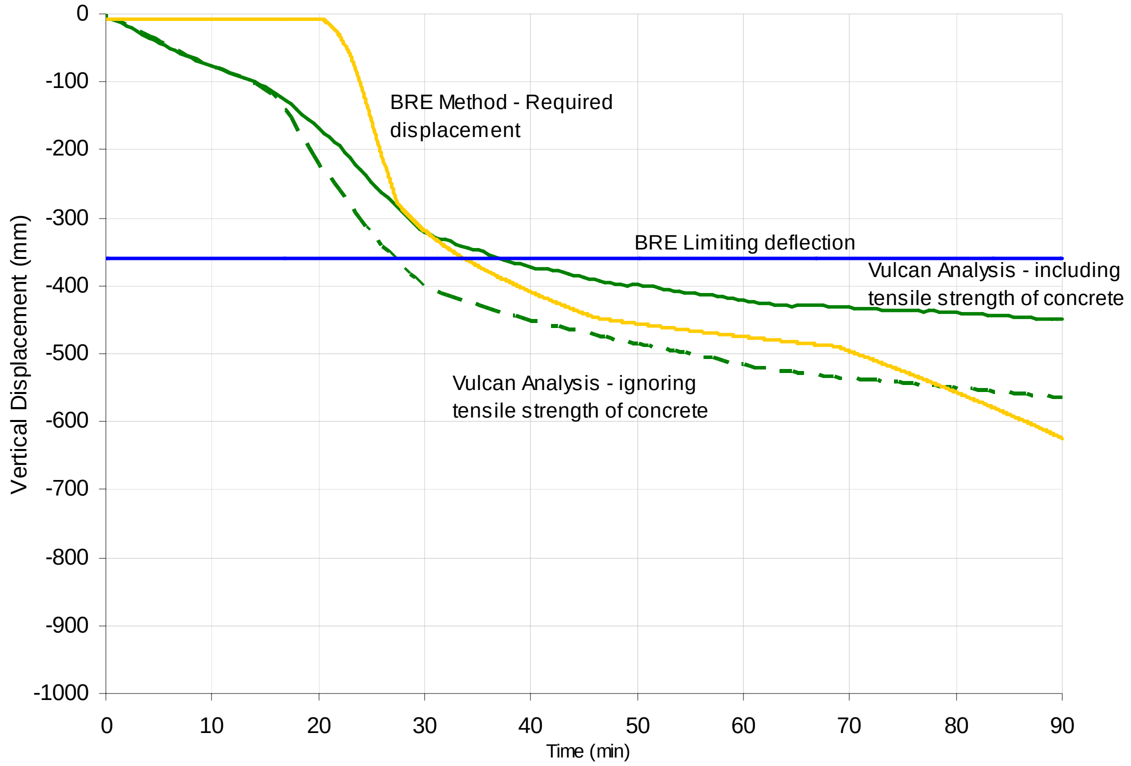

Figure 5 The influence of tensile strength of concrete

Conclusions

It is now well recognized that tensile membrane action is a very important influence on the real structural fire resistance of a building. In order to generate this action the slab edges must be effectively supported vertically; horizontal restraint is not essential but it will significantly affect performance. A number of simplified methods have been developed and these generally compare well with tests and finite element analyses, particularly in relation to the stability criterion. However, they are based on a number of simplifying assumptions, some of which are conservative, but some are not. The preliminary comparisons outlined here show the relative effect of some of these. It is clearly conservative to ignore the tensile strength of the concrete and any rotational continuity at slab edges, but the assumption of rigid vertical edge support is unconservative. It may be that in practical conditions these effectively balance, but there is insufficient data to be confident that this will be so in all cases, and investigations into this are continuing. Similarly the relative importance of thermal and mechanical deflections, and the deflection limits imposed in cases where integrity is a design criterion, needs further study.

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