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Ultimate load of composite floors in fire with flexible supporting edge beams

T.-T. Nguyen *,1, K.-H. Tan 2

School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

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ABSTRACT

A number of previous analytical studies have been conducted to predict the enhanced load-bearing capacity of a concrete slab due to tensile membrane action. These analytical approaches are based on an implicit assumption that the vertical supports along the slab panel boundaries during a fire do not deform. In reality, the edge beams do deflect even though they are fire-protected, and this assumption may not be valid. This may render any approaches based on this assumption to be unconservative when there is significant deflection of protected edge beams. This work looks at the actual boundary condition where the protected edge beams do deflect, and the slab still bends in synclastic curvature. The authors propose a semi-analytical model which can predict the load-bearing capacity of composite beam–slab floor systems enhanced by tensile membrane action under fire conditions, but weakened by deflection of protected edge beams. The novelty is that the slab enhancement factor actually takes account of the deflections of protected edge beams. The new model can consider the beam–slab interaction under fire conditions and give information of the edge beams. Validations with the test results show that the new model gives fairly accurate and conservative predictions of the load-bearing capacity of composite beam–slab systems.

1. Introduction

At ambient temperature, the applied load on the slab in a composite floor system is distributed from the slab to the secondary beams in one-way action, and then to the main beams and the columns. Under severe fire conditions, if the secondary interior beams are unprotected, they will form plastic hinges and the load path at ambient temperature cannot be maintained. The load-carrying mechanism changes from one-way spanning to a two-way system. The load applied to the slab panel is distributed to supporting edge beams, and then to the columns. The slab panel develops its load-bearing capacity in the deformed state through a combination of yield-line mechanism and tensile membrane action.

Tensile membrane action (TMA) can enhance the load-bearing capacity of a slab under fire conditions at large deformations. There have been some research studies on membrane action in reinforced concrete slabs in the 1960s and a number of analytical models have been proposed. Hayes [1] made a significant contribution to the development of tensile membrane action theory for simply-supported rectangular slabs with orthotropic reinforcement.

Bailey and Moore [2] adopted Hayes's method with some modifications and developed a new design approach for composite slabs under fire conditions, namely, the Bailey-BRE method. This method has been adopted in the SCI Publication P288 [3] and applied in the UK practice. Based on the rigid-plastic theory with large change of geometry, the additional slab capacity provided by TMA is calculated as an enhancement to the small-deflection yield line capacity. The method, initially developed for isotropic reinforcement, has been extended to include orthotropic reinforcement [4]. The change of in-plane stress distributions and the incidence of compressive failure of concrete have been added [5]. Bailey implicitly assumes that the vertical supports along the slab panel boundaries at all times during a fire do not deform and the stiffness comes from the protected edge beams. However, in reality in case of fire the deflections of protected edge beams can be considerable and therefore this assumption is questionable.

Usmani and Cameron [6] proposed an alternative three-step method that analyses the load-carrying capacity of laterally restrained reinforced concrete slabs in fire. An Airy stress function is adopted to obtain the deflected shape of the isotropic flat slab based on linear elastic material assumption. The principle of virtual work is then applied to establish the load-deflection response. This method only considers geometric non-linearity with the assumption of material linearity with an increase in temperature. However, under fire conditions the slab will experience large inelastic deformation. On the other hand, the method still needs validation, either by computational predictions or available experimental tests.

* Corresponding author. Tel.: +65 67904151.
E-mail address: nguyentt@ntu.edu.sg (T.-T. Nguyen).
1 Research Associate.
2 Professor of Structural Engineering.

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Notation

$p_{y,\theta}$	yield-line load of the slab at temperature θ
α	coefficient of thermal expansion (12×10^{-6} for normal weight concrete)
h_s	slab thickness
l and L	shorter and longer spans of the slab panel, respectively
a	aspect ratio of the slab (L/l)
μ	ratio of the yield moment capacity of the slab in orthogonal directions
e_{1m} and e_{2m}	contribution of membrane forces to the load-bearing capacity of elements 1 and 2, respectively
e_{1b} and e_{2b}	factors which consider the effect of membrane forces on the bending resistance due to the presence of axial force of elements 1 and 2, respectively
e_1 and e_2	enhancement factors of elements 1 and 2 calculated with the rigid supporting edges
e_1^* and e_2^*	enhancement factors of elements 1 and 2 calculated with the deformed supporting edges
k and b	parameters determined from the equilibrium of in-plane stress distribution
$w_{zx}(x)$	deformed shape of beam 1
$w_{zy}(y)$	deformed shape of beam 2
w_m	maximum slab deflection
T_{2b1} and T_{1b1}	respective temperatures at the bottom and the top surfaces of the edge beam
h_{b1}	total depth of the composite beam including the concrete slab
h_{sb1}	depth of the steel beam only
$T_{,zb1}$ and $T_{,zb2}$	thermal gradient over the total depth of composite beams 1 and 2, respectively
$\alpha_1, \beta_1, \gamma_1, \delta_1, \alpha_2, \beta_2, \gamma_2, \alpha_3, \beta_3, \overline{A},$ and $\overline{B}$	parameters to calculate the enhancement factors

Omer et al. [7] presented a model for the failure assessment of simply-supported, lightly-reinforced concrete slabs which were unrestrained in-plane considering the stress concentrations at cracked locations. The interesting feature of this approach is that it takes account the bond stress developed between the reinforcing bars and the surrounding concrete. However, there is still a lack of experimental data of the bond strength at elevated temperatures to validate this model. Li et al. [8,9] presented an alternative method to determine TMA, in which the slab is divided into five parts connected by the yield lines and the ellipse (a centre-elliptic part and four rigid parts) at the limit state. The contour of the central part under tensile membrane action is assumed to be an elliptic parabola, which was observed in their test [10]. The slab is assumed to be both vertically and horizontally restrained along all four boundaries. The ultimate load-bearing capacity could be obtained based on the equilibrium equations of forces and bending moments.

All the aforementioned models adopt the assumption of rigid vertical supports under fire conditions. This implies that the supporting edge beams need to be sufficiently protected so that they maintain rigid supports for the slab throughout the fire duration. The effects of strength and stiffness of the edge beams on the development of TMA are ignored. However, in reality the edge beams do deform even though they are fire-protected, and this assumption may not be valid. This may render the predictions unconservative when there is significant deflection of protected edge beams. On the other hand, TMA can still be mobilised although the protected edge beams deform, provided that plastic hinges do not form on the edge beams. Once the plastic hinges form on the protected edge beams, a folding mechanism develops across the slab, and TMA will disappear.

This work looks at the actual condition when the protected supporting edge beams do deflect, and the slab still bends in synclastic curvature. The authors propose a semi-analytical model which can predict the load-bearing capacity of the slab enhanced by TMA. The innovative feature is that the proposed model, which was developed based on the Bailey-BRE method [5], can take account of vertical deflections of the protected edge beams.

2. Discussions on the Bailey-BRE method

The Bailey-BRE method begins by dividing a composite floor system into several horizontally-unrestrained, vertically supported slab panels — floor design zones. Each of these floor design zones consists of simply-supported unprotected interior beams. As temperature increases, formations of plastic hinges in the interior beams shift the load to the two-way bending slab which undergoes large vertical deflections. Based on the rigid-plastic theory with large change of geometry, the additional slab capacity provided by TMA is calculated as an enhancement to the small-deflection conventional yield-line capacity of the concrete slab panel. By assuming that under the tensile membrane stage, the dominant load-carrying capacity of the system is due to the composite slab, the following assumptions are adopted in the Bailey-BRE method:

(1) The slab is assumed to be simply-supported, and the edges are unrestrained from planar movement. This implies that TMA is formed in the central region of the slab and a compressive ring is formed around the perimeter of the slab.
(2) The load carried by the flexural behaviour of the grillage of composite beams, within the fire compartment, is based on the lower-bound mechanism for the interior beam with the highest load ratio (i.e. the beam which will 'fail' first in the fire). The beams are assumed to be simply-supported and will support a loaded area assuming the slab is simply supported.
(3) The load supported by the flexural behaviour of the composite slab is calculated based on the lower-bound yield-line mechanism, assuming that the unprotected interior beams have zero flexural resistance.
(4) The enhancement due to membrane action in the concrete slab is based on the lower bound yield-line mechanism of the slab.
(5) The load-carrying capacity of the composite interior beams and the slab (enhanced due to membrane action) are added together.

The first question arises as to whether the heated interior panels can be classified as restrained or unrestrained against horizontal movement. Based on the authors' tests conducted at Nanyang Technological University [11], it has been shown that in all the tests, reinforcement had been fractured above the edge beams of the slab. This suggests that the heated slab panels can be considered as unrestrained against horizontal movement at the tensile membrane stage. Therefore, this assumption is accurate.

The second question is based on the first assumption that vertical supports along the slab panel boundaries remain rigid at all times during a fire. To provide the necessary vertical support the edge beams of a slab panel must be protected to a required fire resistance and should be fairly stiff. However, in reality, the edge beams may deform considerably even though they are fire-protected, and this assumption may be nullified. Therefore, in the proposed approach the authors estimate the slab load-bearing capacity which is enhanced by TMA, but weakened by the deflections of the protected edge beams.

The last question is based on the 5th assumption. When calculating the contribution of unprotected interior beams to the total load-bearing capacity of the slab, Bailey treated these beams as composite beams. Under the tensile membrane stage, since the load path has changed, if the interior beams are treated as composite beams, the