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Parameters affecting tensile membrane action of reinforced concrete floors subjected to elevated temperatures

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ABSTRACT

This paper numerically investigates the mechanism and influencing factors of the tensile membrane action (TMA) developed in reinforced concrete slabs at large displacements and elevated temperatures. Explicit dynamic analyses are performed using LS-DYNA. The numerical model is first validated against ambient and fire tests on simply supported slabs. It shows that the slab responses are not sensitive to the mesh size. It is found that the 30min of heating in a standard fire can be scaled down to 1 s of computing time. Parametric studies are followed to demonstrate the influence of load ratio, boundary condition, slab thickness, reinforcement layout and aspect ratio on the occurrence and development of TMA. Five failure modes of slabs, initiated by the rupture of reinforcement, are found depending on the boundary condition, reinforcement layout and aspect ratio. As the aspect ratio increases, the location of the reinforcement rupture moves from the slab center to the intersections of longitudinal and diagonal yield lines, and further extends to the corners. For the presence of horizontal restraint at perimeter, the rupture of reinforcement occurs at the longer edges of slabs. Slabs with more reinforcement placed along the long span may fail by the rupture of reinforcement along the short span at the center of the slab. The reinforcement along the short span plays a key role in the load-bearing capacity of rectangular slabs. It is found that reinforced concrete slabs may have a fire resistance of 2 h at least due to the enhancement of TMA. The critical reinforcement temperature of 600 °C is necessary to ensure the efficiency of TMA. The deflection limit of *span*/20 reasonably predict the failure of slabs although a slab can resist loads at a deflection up to *span*/12 without collapse by means of TMA. It is recommended to increase the reinforcement ratio to enhance the effect of TMA.

1. Introduction

Reinforced concrete floors play an important role in the load-bearing capacity of concrete structures or steel-framed structures, by resisting vertical loads through the development of in-plane forces within its depth, i.e. membrane action. At large displacements, the tensile membrane action (TMA) may occur in reinforced concrete slabs provided the slab's perimeter is vertically supported and horizontally restrained [1]. It is also possible for TMA to occur in two-way spanning floors that are vertically supported but have no horizontal restraint. In this case, the slab supports the load by a tension zone in its central region provided by the reinforcement and a “compression ring” forming around the edges to balance the tensile forces (Fig. 1). Early theoretical and experimental researches into the TMA of concrete slabs at large displacements [2–4], have been limited due to the difficulty in identifying any practical application, since the limited deflection required to satisfy the serviceability limits under normal working loads is too small (e.g. *span*/250) to invoke this type of behavior.

In the case of fire, where large displacements are acceptable provided that the structural collapse is prevented, the tensile membrane action finds its ample scope for its enhancement of the load-bearing capacity of concrete slabs. The TMA in concrete slabs at elevated temperature received increasing interests since the Broadgate fire and Cardington tests, where the composite floors suffered from large deflections (*span*/20) without any sign of collapse although the maximum fire temperature in the tests exceeded 1000 °C. Numerous numerical models have been developed to simulate the TMA of concrete slabs under fire conditions [5, 6–10,11,36]. proposed a simple calculation method of load-bearing capacity of concrete slabs at elevated temperature considering the enhancement from tensile membrane actions. This was considered by

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multiplying a membrane action enhancing factor on the flexural strength of slabs. This approach, however, was limited to the predefined maximum deflection and assumption of average reinforcement strain at failure. It was proposed [6] that a higher reinforcement ratio or placement further from the heated surface was preferred for the enhancement of TMA. While [12] suggested that it was advantageous to place a larger area of reinforcement low down in concrete slabs due to the better ductility and large ultimate strains of reinforcements at high temperature [13]. The three-dimensional model was extended [14] to include the geometrical nonlinearity. The results showed that concrete slabs resisted loads mainly by composite beams when the steel beam temperature was less than 400 °C. The effect of the tensile membrane action became important when the double-curvature deflection of floor slabs became large (steel beam temperature above 500 °C) [15]. Small-scale tests were conducted [16] to experimentally studied the behavior of reinforced concrete slabs at elevated temperatures. Enhancements of up to 3.5 times the yield load were achieved due to the TMA. All the tested slabs failed by a full-depth cracking across the short span. It was indicated [17] that it was reasonable to assume that the failure was initiated by tensile yielding and rupture of reinforcement which most likely at the supports where the maximum membrane tensions occurred.

The above early investigations aim to figure out the occurrence and development of tensile membrane action in reinforced concrete slabs. Recent studies are to explore the influencing factors on the tensile membrane action of slabs. It was proposed [18] that the membrane load capacity of slabs can be enhanced by continuous reinforcement or increasing fire protection. The influence of vertical supports on the membrane action of slabs in fire was investigated [19]. The tensile membrane action may disappear when the edge beams subject to large deflection. The specification of limit temperature of 620 °C for the protected edge beams was not sufficient. A bond-link element was proposed by Ref. [20] in Vulcan to model the relative slip between the reinforcement and the concrete. The results showed that the bond had an important influence on the fire resistance of RC structures, especially when the temperature of the reinforcing steel bars is high (more than 500 °C). It was proposed [21] that the Bailey method [11,36] lost its conservatism for slabs with high reinforcement ratios or larger reinforcement mesh sizes. Three small-scale fire tests were carried out [22] to investigate the effect of unprotected interior secondary beams and edge rotation restraint on the behavior of composite floors. The results showed that the reinforcement continuity and presence of interior beams can reduce the slab deflection and greatly enhance the load-bearing capacity of slab-beam systems. The presence of interior beams may affect the magnitude and distribution of stresses of reinforcements where the maximum tensile stresses may occur in the edge, thus leading to different failure modes. More recently, four large-scale fire tests on RC slabs with vertical restraint at four corners of the slab were carried out by Ref. [23]. They found that the cracking patterns were strongly dependent on the in-plane compression forces and steel reinforcement ratio. It was suggested to prevent the full-depth crack and compressive failure of concrete at the corners by increasing the reinforcement ratio. Standard fire tests were conducted [24] on four composite slabs with different concrete cover and secondary beam layout. It showed that the location of reinforcements had great effect on their temperature rise. A maximum temperature difference of about 200 °C was observed for the two slabs with a concrete cover of 21 mm and 30 mm, respectively. The effect of edge beams on the fire behavior of the floor was studied [25]. It was found that tensile membrane action was mobilized at a deflection equal to the slab thickness regardless of the bending stiffness of the edge beams.

The failure mechanism of reinforced concrete slabs depends on the development of tensile membrane action which is significantly affected by the imposed mechanical loads, boundary conditions, reinforcement arrangements and slab geometries. Only one failure mode, i.e. rupture of reinforcement across the short span, was identified from previous experiments on simply supported slabs, either ambient tests or small-scale fire tests. This identification needs to be confirmed by large-scale fire tests on slabs considering various influencing factors. In addition to large-scale fire tests, numerical simulations become the most efficient and even unique mean to investigate the tensile membrane action developed in concrete slabs. However, most of the previous numerical investigations on slabs in fire, using implicit static analyses, suffer from serious convergence problems when the deflection becomes large (e.g. span/20), and thus are not suitable to simulate the collapse of slabs since the slab can still resist loads for a deflection as large as span/10 by tensile membrane action. The objective of this paper is to explore the dependency of failure modes of reinforced concrete slabs on various influencing factors using explicit dynamic analysis. As a composite slab with profiled steel decking can be reduced to a flat slab with an equivalent thickness, this study focuses on flat reinforced concrete slabs.

This paper presented a parametric study on the development of tensile membrane action in reinforced concrete slabs. A 6 m × 9 m reinforced concrete slab with a span-to-depth ratio of 30 and reinforcement mesh near to its lower surface was used in this study, which represents typical slabs in RC construction. The parameters include load ratio, boundary condition, slab thickness, reinforcement arrangement and aspect ratio. Explicit dynamic analyses were performed, and hours' heating was scaled down to seconds' computing time to save computational cost. The numerical model was first validated against results from ambient and fire test. The influence of these parameters on the failure mode and tensile membrane action of slabs was investigated.

2. Numerical model and validation

The structural analysis of flat reinforced concrete slabs at elevated temperature was performed using the finite element software LS-DYNA. The slab was modelled by a layered composite shell formulation (*PART_COMPOSITE), in which a distinct structural material, thermal material, and thickness can be specified for each layer (Fig. 2). This allows distinct layers to be specified for the reinforcement, except for concrete through the thickness of the slab. This also allows a coupled thermal-mechanical analysis using the same slab elements. The material MAT_172 (i.e. MAT_CONCRETE_EC2) was used to model both concrete and steel. It can be directly used to model plain concrete (FRACR = 0), pure steel (FRACR = 1), or reinforced concrete with evenly distributed reinforcement (0 < FRACR<1). For modelling reinforced concrete slabs with reinforcement at its bottom and top, it has to create one material part for concrete and another for steel, both of type MAT_172, i.e. one with FRACR = 0 representing the concrete and the other with FRACR = 1

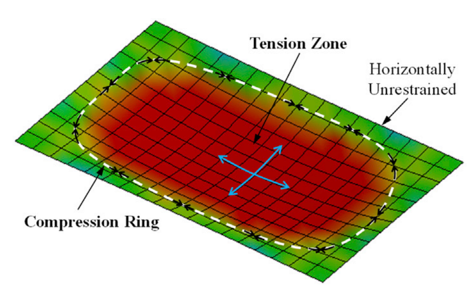

Fig. 1. Tensile membrane action in a horizontally unrestrained reinforced concrete slab.

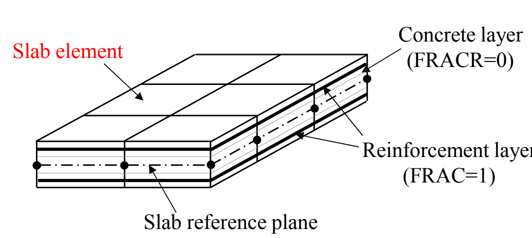

Fig. 2. Numerical model of reinforced concrete slabs in LS-DYNA.