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Punching shear tests on flat concrete slabs exposed to fire

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ABSTRACT

Underground parking structures often consist of flat slabs connected by columns, for which punching shear is often the most critical design criterion. In fire conditions, the punching load can increase due to restraint of the thermal curvature of the slab or due to the expansion of the columns. This increase of the punching load is discussed in the paper by means of a literature review. On the other hand, during fire the punching resistance of the slab decreases due to a gradual reduction of the material properties. This reduction in bearing capacity is studied by means of real scale fire tests, consisting of 6 slabs measuring $3.2 \times 3.5 \times 0.25$ m with a connected column stub and tested for punching shear with a specially designed loading frame. Two reference tests are executed at ambient temperature conditions and four slabs are submitted to ISO 834 curve for 120 min. Comparison of the test data with the expected increased axial load due to thermal restraint found in the literature, shows a potential danger for premature punching failure of flat slab-column connections exposed to fire.

1. Introduction

Underground structures such as car parkings are often constructed as flat slabs supported by a grid of columns. This type of structure is sensitive to punching failure, since the slabs have a large span-to-depth ratio (24 to 30 in reinforced concrete slabs; 35 to 40 in precast concrete slabs [1]) and both the bending moments and shear forces are locally high due to the point support by the columns. When the load increases, bending cracks will appear first at the top side of the slab, which start from the centre and gradually extend in radial direction. These bending moments at the supports are resisted by the top reinforcement in the tensile zone and by the concrete near the column face, as well as the bottom reinforcement in the compression zone. On the other hand, the actual punching failure occurs as a result of the development of tangential cracking in the concrete slab, starting from the column face and spreading to the top of the slab. In this way, a punching cone is developed. To improve the punching resistance of the slab, specific shear reinforcement can be provided within the critical perimeter to resist these developed shear stresses.

This paper deals with the effect of fire on the punching resistance of concrete thin slabs. Therefore, real scale fire tests are performed on flat concrete slab specimens.

1.1. Modelling of punching shear

Building codes (e.g., Eurocode 2) provide design guidelines to resist punching failure, based on simplified design models. The last decades, significant research was performed resulting in more detailed calculation approaches. In fib Bulletin 12 "Punching of Structural Concrete Slabs" [2] the following approaches are distinguished: flexural capacity approach, plasticity approach, Kinnunen/Nylander approach, failure mechanism approaches with concrete tensile stresses in failure surface, truss models or strut-and-tie models and facture mechanics approach. In 1960, Kinnunen and Nylander proposed a model that takes into account the kinematics of the cracked zone close to the column, as well as other phenomena like aggregate interlock. This model was modified by Hallgren in 1996 introducing parameters reflecting the brittleness of concrete and the size effect. This latter parameter takes into account the effective depth of the slab.

Recent developments are published in fib Bulletin 57 Shear and Punching Shear in RC and FRC Elements [3], where The Critical Shear Crack Theory of Muttoni and Ruiz developed in 2008 is discussed. This method is based on the assumption that the shear resistance in members without transversal reinforcement is governed by the width and the roughness of a shear crack which develops through the inclined compression strut carrying shear. The shear strength under this assumption can be derived from the moment–curvature relationship of the slab. This approach has shown to be simple and to provide accurate results.

1.2. Contributions of fire to punching shear failure

In most cases, concrete structures behave very well during a fire and demonstrate to have a remaining bearing capacity [4]. Nevertheless, some concrete structures collapse partially or completely due to fire [4]. This was also the case at Gretzenbach (Switzerland) on 27 November 2004, where the roof of an

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underground car park collapsed due to punching failure caused by an excessive soil cover thickness [5]. Investigations afterwards revealed design and execution errors. As a result, this particular slab had a lower safety factor with respect to punching failure than expected from the design. However, the decreased punching shear capacity resulted in failure only during the event of a fire.

The following aspects are considered in this paper:

(1) The effect of fire on the punching resistance which is basically related to the degradation of the material characteristics, and additionaly to restraint of thermal deformations that may induce a significant additional punching load.
(2) The remaining load bearing capacity after exposure to fire is determined and compared to the value at ambient temperature. It is investigated how much the overload coming from an increase of the axial load due to thermal restraint is allowed to be before failure occurs.

Considering the response of complete concrete structures during fire, several factors can increase the sensitivity of flat slabs with respect to punching failure as discussed hereafter. First, due to heating the constituent materials will lose strength and stiffness, logically resulting in a loss of the punching shear capacity. Second, a restraint of the thermal curvature of the slabs can increase the bending moments at the supports. Due to one sided heating and the low conductivity of concrete, a thermal gradient will appear over the slab thickness. Consequently, the outer concrete layers will expand more than the inner layers, which will result in a thermal curvature towards the fire. At the column-slab connection, these rotations are restrained, introducing a thermal moment into the slab and an increased supporting moment which affects the punching resistance.

The effect of the restraint of the thermal curvature of slabs was studied by Bamonte [6]. A finite element analysis was performed on a typical underground parking structure consisting of a flat slab supported by two rows of square columns and four perimeter walls. A span-to-depth ratio of 23 was considered. A fire scenario of subsequently burning of 6 cars was used, resulting in maximum temperatures near the ceiling of about 550 °C and a total fire duration of close to 120 min. Only the slab was modelled, whereas the column tops were considered as fixed supports in vertical direction. In case a temperature dependent elastic modulus was used, an increase of the axial load at high temperatures of up to 50% was found compared to ambient temperatures for the most heavily loaded column. The model did not consider concrete cracking and rebar yielding which could have reduced the restraining effect. It is noticed that the used temperature field is relatively low and if increased, the calculated axial load would increase as well. Also, Kordina [7] reported for a specific scenario an increase of the column load of less than 15%, between 20% and 45% and a maximum of 70%, depending on the location in a grid of 6 by 6 m.

Third, a restraint of the thermal expansion of the column can increase the axial load at the support. When concrete columns are heated, they will expand. However, this expansion will be restrained by the weight and stiffness of the surrounding structure, resulting in a reaction force in the column-slab connection. The resulting displacement of the column top can be obtained from the free thermal strain, after reduction of several load and temperature dependent strains, namely creep, instantaneous stress-related strain and transient strain. These load dependent strains are grouped together as Load Induced Thermal Strain [8] and have a major influence because for load ratios of about 40% of the initial compressive strength, the total expansion is very limited [9,10]. In the international literature, these phenomena have been studied since a long time resulting in several applicable models [9–12]. Martins [13] found an increase of the axial load due to the restraining force from experiments with factors ranging from 1.02 to 2.64 depending on the longitudinal reinforcement ratio, the slenderness of the column, the restraint level, the load level and the load eccentricity. Martins [13] also mentioned that restraint of the thermal elongation of reinforced concrete columns does not affect the fire resistance of the column significantly, if the increased axial load can be redistributed to the surrounding structure. This redistribution of the forces might be limited for flat concrete slabs given their sensitivity to punching shear.

1.3. Large scale fire tests related to punching

Concerning the punching resistance of flat concrete slabs exposed to fire, only a limited number of test results are available in the international literature.

Kordina [7] reported 14 real scale experiments on flat concrete slabs to study the punching resistance under fire conditions. The test setup was similar to the one used for the experiments discussed in this paper. The square slabs with side lengths of 2.5 m had a thickness of 0.2 m or 0.15 m. A column stub with dimensions $0.25 \times 0.25 \times 0.4$ m was connected to the flat slab specimens. For 10 slabs with a thickness of 0.2 m two values of the longitudinal reinforcement ratio were chosen i.e., 0.56% and 1.54%, for which only 3 slabs had shear reinforcement (452 mm^2 or 678 mm^2). For 4 slabs with a thickness of 0.15 m, a longitudinal reinforcement ratio of 1.75% was used and no shear reinforcement was provided. According to Table 5.9 of EN 1992-1-2 [14] about the fire resistance of flat slabs, the slabs with a thickness of 0.2 m should have a standardized REI 180 (minimum slab thickness larger than 200 mm, axis distance of the reinforcement smaller than 50 mm) and the slabs with a thickness of 0.15 m should have a REI 30 (minimum slab thickness larger than 150 mm, axis distance of the reinforcement larger than 10 mm). The cylinder (Ø 150 mm, height 300 mm) compressive strength at the time of testing (88–178 days) was ranging from 33 to 51 N/mm^2. The slabs were loaded prior to heating by a service load calculated as 0.7 times the ultimate state design punching resistance of the slab according to EN 1992-1-1 [15]. For 4 of the 14 slabs, this load was maintained during the fire test for, respectively, 92, 120, 120 and 180 min of fire, after which the load was increased until punching failure occurred. Comparing these punching shear test values with the service load, a safety factor between 1.28 and 2.14 was found. For the other slabs, the service load was increased during the first 30 min of the ISO 834 fire in order to simulate the increased load during fire coming from thermal restraint effects (see above mentioned second and third contributions). By increasing the applied load, the slabs failed within 8–29 min of fire in case spalling of the concrete cover of the bottom reinforcement occurred. The average spalling depth was 50 mm. The failure load was then ranging from 1.20 to 1.67 times the service load. It is noticed that at the moment of testing, the moisture content of the slabs was about 4%. In case the slabs did not spall, the load was increased during fire to a level ranging from 1.26 to 1.46 times the service load. After 90 min of fire, the load was further increased until failure, resulting in a remaining safety margin of 1.60–1.80 with respect to the service load. At each test, a punching cone was developed which varied in the top diameter between 1.28 and 1.86 m and had an average cone angle of 32°. Further, the deflections of the slabs with 0.2 m thickness were found to be directed against the load action for the complete test period. Therefore, the thermally induced deformation (directed towards the fire) is larger than the deflection due to the load. The slabs with 0.15 m thickness showed the same behaviour during the first 30 min of fire, after which the deflection reversed and followed the direction of loading.

This paper describes the results of a test programme concerning punching shear at both ambient and fire conditions. Similarities with the test programme of Kordina [7] are found in the test setup, the