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Concrete edge failure of single headed stud anchors exposed to fire and loaded in shear: Experimental and numerical study

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ABSTRACT

In the present study the results of experimental tests and numerical simulations on single headed stud anchors cast in concrete member and loaded in shear against concrete edge are presented and discussed. The anchors were exposed up to 90 min of fire and loaded in shear under hot and cold conditions up to failure. The temperature distribution, load-displacement curves and failure patterns were recorded. The numerical simulations were conducted using a thermo-mechanical model that was implemented into a three-dimensional finite element (3D FE) code. The constitutive law for concrete was the temperature dependent microplane model. The results of numerical analysis, including the temperature history profile, load-displacement response and the failure load, were verified by the experimental results. Subsequently, a parametric study was carried out. The experimental and numerical results show that the shear capacity of headed stud anchors is strongly affected by the fire exposure. Especially the cooling process leads to severe loss of load capacity. It is shown that the design formula according to Eurocode 2, Part 4 (Annex D) for concrete edge failure at 90 min of fire is rather conservative for the loading in the hot state, however, it overestimates the resistance for the cold state.

1. Introduction

Shear connectors between concrete and steel are important and frequently used in composite or pre-fabricated structures. The safety of connections in case of fire, for instance the anchors for attaching curtain wall on a concrete slab edge (Fig. 1a) or for fastening "I" or "H" steel beam to a concrete beam (Fig. 1b), can be critical. The failure of fasteners can cause human loss or injury, accelerate the spread of fire entering into adjacent spaces and endanger the integrity of the entire structure.

With respect to concrete failure of commonly used anchors, the shear load resistance of an anchor located sufficiently away from edge (corresponding to pry-out failure) is usually much higher than that of an anchor located close to edge and loaded towards free edge (corresponding to concrete edge failure). From this point of view, concrete edge failure is more critical.

Numerous investigations on concrete edge failure of anchors loaded in shear at ambient conditions exist so far [1–9]. Some of the main results were concluded in a code background paper by Fuchs et al. [2], in which the concrete capacity design (CCD) approach was developed. The breakout angle with respect to the edge is about 35° on average. The effective fracture surface is simplified as $1.5c_1$ (c_1 is edge distance) to a depth at the front face of the concrete edge and also $1.5c_1$ to each side of the anchor along the direction of the edge. The shear failure load of anchor increases in proportion to ${c_1}^{1.5}$. The support spacing should be larger than $3c_1$ to avoid the influence of supports on the load-bearing behaviour. Eq. (1) was proposed for the mean shear resistance and its characteristic form is applied in the current ACI 318 [10]:

$$V_{u,c}^{0} = \sqrt{d_{nom}}\cdot(l_f/d_{nom})^{0.2}\cdot\sqrt{f_{cc,200}}\cdot c_1^{1.5} \quad (1)$$

where d_{nom} is the nominal diameter, which equals to shaft diameter d for headed stud anchor, l_f is its effective embedment depth, which is h_{ef} for headed stud anchor, $f_{cc,200}$ is the mean concrete compressive strength measured on concrete cube 200 × 200 × 200 mm at the time of the test, which is convertible from $f_{cc,150}$, and c_1 stands for the edge distance.

In the current provisions of Eurocode 2, Part 4 [11], which is based on the analyses conducted by Hofmann [4,5], the shear resistance of a single anchor in un-cracked concrete at ambient conditions is calculated according to the following expression:

$$V_{u,c}^{0} = 3.0\cdot d_{nom}^{\alpha}\cdot l_f^{\beta}\cdot\sqrt{f_{cc,200}}\cdot c_1^{1.5} \quad (2)$$

where $\alpha = 0.1\cdot(l_f/c_1)^{0.5}$, $\beta = 0.1\cdot(d_{nom}/c_1)^{0.2}$.

However, the load-bearing behaviour of anchors installed close to concrete edge and loaded in shear at elevated temperatures, such as

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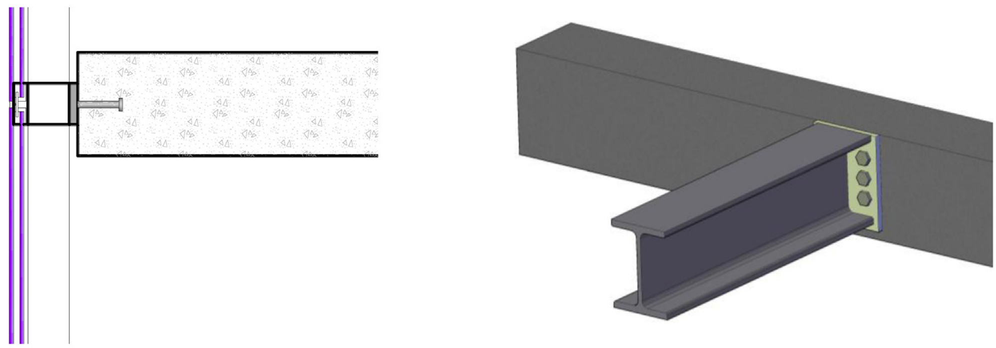

(a) (b)

Fig. 1. Typical shear-critical connections: (a) curtain wall and (b) connection between steel and concrete beam.

fire, has barely been investigated. Due to the softening of steel at high temperature, steel failure might be the governing failure mode. Some studies were focused on the steel failure under fire. Yasuda et al. [12] investigated the temperature distribution along the headed stud in concrete and the shear strength of the stud due to steel failure under fire. It was found that the most crucial place is the part of the stud at the surface of the concrete, where the highest temperature presents and the failure occurs. At relatively low temperature (below around 400 °C) the local concrete failure is dominated, however, at relatively high temperature the stud failure is decisive. Reick [13] summarized the results of pull-out and shear tests, performed in different laboratories, on anchors under fire exposure that were failed via steel failure. Based on the experimental results, the characteristic steel strength of fasteners under fire exposure was proposed, which was later incorporated in Eurocode 2 [11]. However, the steel parts must be designed and protected against fire, which comprises protective measures of sprays, castings, intumescent coatings, claddings, etc. [14,15]. Single fastener or group of fasteners close to edge of concrete member may fail by concrete edge breakout because the concrete is known to become extremely weak under fire scenario [16]. Moreover, the degradation of concrete at high temperatures (hot state) is different from that after cooling (cold state). Abrams [17] and Malhotra [18] conducted experiments and proved that the residual strength of concrete tested after cooling (cold state) is lower than the strength tested at high temperatures (hot state). At elevated temperatures, the restrained thermal expansion of concrete gives rise to compressive stresses parallel to the exposed concrete surface and tensile stress in perpendicular direction [19,20]. For concrete edge it is heated on two sides. In the most severe cases, explosive spalling starts at the edges or corners of the concrete member. Therefore, to design safe and economical connections between steel and concrete it is important to understand the behaviour of fasteners both in the hot and cold states, especially if they are installed close to concrete edge that is directly exposed to fire.

Regarding the concrete edge failure of anchors, loaded in shear perpendicular to the free edge and exposed to fire, the current Eurocode 2 gives only recommendations for fire exposure up to 90 min and 120 min whereas in ACI 318 code anchor resistance under fire is not considered, due to very scarce experimental data from fire tests. The recommendation for cracked concrete according to Eurocode 2 reads:

$$V^0_{u,c,fi(90)} = 0.175 \cdot V^0_{u,c} \text{ for fire exposure up to 90 min} \tag{3}$$

$$V^0_{u,c,fi(120)} = 0.14 \cdot V^0_{u,c} \text{ for fire exposure up to 120 min} \tag{4}$$

The resistance of a single anchor after 90 min and 120 min of fire exposure is equal to 17.5% and 14% of the resistance of a single anchor at ambient conditions in un-cracked concrete. Note that this formula applies to fasteners with fire exposure from one side only. In the absence of sufficient experimental data, it is not clear how reliable this formula is and if it is widely valid under high temperature (hot state) or also after cooling concrete member to ambient temperature (cold state).

Periškić [21] studied experimentally and numerically the tensile resistance of single anchors and anchor groups under fire exposure. The studied anchors were located both close to the concrete edge and far away from the concrete edge. It was found that the two-sided fire on the edge induces stronger reduction of the tensile capacity of anchors under fire. Therefore, in this study we performed a fundamental test for 90 min of ISO 834 fire to investigate the concrete failure corresponded load-bearing behaviour of single anchors loaded in shear perpendicular to and towards the free concrete edge in both hot and cold conditions. The fire exposure on one side and two sides of the concrete edge was considered.

The experimental tests under high temperature are extremely demanding and expensive. Therefore, to support the experimental investigations it is important to have a realistic numerical tool. In the present study numerical simulations are performed using a three-dimensional (3D) thermo-mechanical (TM) model that was implemented into a three-dimensional finite element (FE) code [22]. The constitutive law for concrete is the temperature dependent microplane model [23]. In the present study the shear load capacity for anchors of different geometries exposed to 90 min of fire is first experimentally tested for hot and cold states. Based on the test results, the numerical model is first verified and calibrated, i.e. the numerical models with the same geometry and boundary conditions as in the experiments are employed to simulate the heating and cooling processes and the loading history on the anchors, and the results obtained numerically are compared with the experimental data. Special effort has been made to simulate and calibrate the preloading, heating and reloading of anchors in the hot state. The correct modelling of boundary conditions, supports and application of load, is important to obtain objective results. Namely, due to the thermal strains unrealistic thermally induced stresses and damage can be generated and this is one of the main difficulties when modelling structural details such as fasteners in concrete exposed to elevated temperatures. Subsequently, the numerical model is employed in a parametric study in order to investigate the behaviour of anchors close to concrete edge under fire exposure. Finally, the experimental and numerical results are compared with the prediction formula based on the design code recommendation in the current Eurocode 2 [11].

This paper is intended to provide first-hand experimental data and conclusions for the load-bearing behaviour of anchorages loaded in shear perpendicular to free edge after 90 min of ISO 834 fire, in both hot and cold states.

2. Experimental program

2.1. Anchors

The experimentally tested fastener consists of a headed stud, a steel plate and a nut (Fig. 2). The dimensions of the headed studs were taken