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Experimental study on concrete edge failure of single headed stud anchors after fire exposure

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ABSTRACT

In the present study different single headed stud anchors are exposed to various durations of fire and loaded in shear perpendicular to and towards the free concrete edge up to failure after cooling. The effects of concrete edge distance, nominal diameter, embedment depth and concrete compressive strength on the load-bearing behaviour of the anchors at various durations of fire are experimentally investigated. The standard fire curves ISO-834 with the corresponding durations of 15 min and 60 min are employed to study the effect of fire on the residual capacities of the anchors. Even more than expected, the results demonstrate that the anchor behaviour is significantly influenced by the fire exposure. Under ambient conditions, the influence of the edge distance on anchor resistance is very strong while the influence of the anchor diameter and the embedment depth is relatively weak. However, after fire exposure the influence of the edge distance reduces and the influence of the diameter and the embedment depth on the shear resistance increases. The influence of fire exposure is significant on the concrete edge capacity of the anchors. After only 15 min of fire duration, the reduction of more than 50% of the reference value is reported.

1. Introduction

Building fire disaster commonly starts with the burning and falling of the claddings and attachments fastened to the main concrete structure. The fire resistance of the attachments itself is of great importance; meanwhile the fire resistance of the mechanical fasteners is structurally vital for fire safety of the whole structure. In composite or pre-fabricated structures, the fire safety of the connections is without doubt very significant. Unfortunately, there are no unified fire test procedures and no commonly accepted fire design rules for fastening systems till now. The current Eurocode 2, Part 4, Annex D [1] gives only informative recommendations for reduction of anchor resistance for the fire exposure up to 90 min and 120 min, and in ACI 318 [2] code anchor resistance under fire is not yet considered.

Due to the softening of steel at high temperatures in case of fire, steel failure might be the governing failure mode [3]. The anchor steel failure under tension and shear loads were tested in different laboratories and were summarized by Reick [4], on which it was based the characteristic steel strengths for fasteners under fire were proposed and were described in Eurocode 2 [1] for fire design purpose. However, considering fire safety in structural fire engineering the steel parts must be designed and protected against fire, which comprises protective measures of sprays, castings, intumescent coatings, claddings, etc. [5,6].

Concrete breakout failure and its resistance after fire, either under tension or under shear, is a more complex subject for fire engineering. It is known that the strength of concrete is substantially reduced with fire exposure [7–9]. This leads to strong influence on the capacity of connections between steel and concrete, namely, the load-bearing behaviour of fasteners in concrete corresponding to concrete breakout failure considering fire safety. Particular cases are those with the fasteners located close to the edge of a concrete member and loaded in shear towards free edge or anchorages installed with shallow embedment depth and loaded in tension. After fire exposure the concrete becomes damaged, which can result in strong reduction of failure capacity of fasteners. Currently in the literature there are only limited experimental and numerical studies devoted to the residual capacity of fasteners failing in concrete under fire exposure.

Reick [4] also performed experimental and numerical analyses on fire resistance of undercut and headed stud anchors under fire associated with the concrete cone capacity under tension loads. It is reported that the diameter of the concrete cone developed in case of tests after fire is larger than the diameter of the fracture cone obtained for the corresponding case at ambient temperature. The relatively rapid temperature decrease with increasing depth in the concrete corresponded to the

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increase of the relative concrete capacity with increasing embedment depth of the anchor. Thus, the concrete cone capacity for fire exposure up to 90 min of ISO-834 fire is considered using Eq. (1):

$$N_{u,fi(90)} = \left(h_{ef}/200\right)\cdot N_{u,c} \tag{1}$$

where h_{ef} stands for embedment depth in mm and $N_{u,c}$ is the concrete cone capacity at room temperature in kN. This is also implemented into the current Eurocode 2 [1].

Ožbolt et al. [10] carried out numerical simulations based on 3D thermo-mechanical FE modelling on headed stud anchors with different embedment depths exposed to fire and loaded in tension. It was demonstrated that the concrete cone resistance of anchors with relatively small embedment depth can be significantly reduced due to fire exposure. For anchors with large embedment depth, compressive stresses may be generated, which can lead to no reduction of resistance or even slightly higher capacity due to restraining conditions of concrete under fire. This so called confining effect was also found experimentally in the previous experimental tests for anchors loaded in shear towards free edge under fire (in hot state) [11].

Bamonte et al. [12] conducted experimental research on the tensile capacity of undercut fasteners installed in thermally damaged concrete. These fasteners were installed in low strength concrete, normal strength concrete and high strength concrete with various depths after exposure of the concrete to different temperature levels by electric furnace. Results showed that after reaching only 400 °C the pull-out capacity was roughly 20% of the values obtained from reference tests without high temperature exposure. If standard fire was applied, which means a significantly higher heating rate, especially at the beginning phase, the residual capacity could be reduced further by at least 25%, depending on the embedment depth. This study also showed that the concrete grade plays only a marginal role on the residual capacity of fasteners for temperature exposure above 200 °C.

Periškić [13] performed experimental tests and numerical simulations on the load-bearing behaviour of single anchor and group anchors located close to concrete edge and away from concrete edge under tensile load at high temperatures, considering the fire exposure on one side and two sides of the edge. It was shown that for anchors located away from concrete edge, the embedment depth of anchor plays a main role on the residual capacity of anchors loaded in tension under fire exposure, the larger the embedment depth is, the smaller the reduction in the failure load. When the anchor is located close to an edge, the two-sided fire on the edge induces strong reduction of the tensile capacity under fire exposure, which is reasonable due to the thermal penetration of heat into concrete member from both sides of the edge.

From the viewpoint of heat penetration, the concrete edge failure of anchors loaded in shear towards free edge may represent the most critical case. Single fastener or a group of fasteners close to an edge of concrete member may fail by concrete edge breakout because the concrete becomes extremely weak under fire scenario, especially after cooling.

According to the current Eurocode 2 provisions, Part 4 [1], which is based on the concrete capacity method [14–16], the mean shear resistance of a single anchor in un-cracked concrete at room temperature is calculated according to the following expression:

$$V_{u,c}^{0} = 3.27\cdot d_{nom}^{\alpha_0}\cdot l_f^{\beta_0}\cdot\sqrt{f_{cm}}\cdot c_1^{1.5} \tag{2}$$

where $\alpha_0 = 0.1\cdot(l_f/c_1)^{0.5}$, $\beta_0 = 0.1\cdot(d_{nom}/c_1)^{0.2}$, 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_{cm} is the mean concrete cylinder compressive strength measured on concrete cylinder of 150 × 300 mm at the time of the test, which is convertible from $f_{cc,150}$ (mean cube compressive strength with side length of 150 mm), and c_1 stands for the edge distance. Considering exposure to fire, the provisions in the current Eurocode 2, Part 4, Annex D [1] for the resistance of concrete edge failure for the ISO-834 fire exposure up to 90 min and 120 min are as follows:

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

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

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 room temperature in un-cracked concrete, respectively. Note that this formula applies for fasteners with fire exposure from one side only.

The previously conducted experimental studies confirmed that the post-fire capacity, which was obtained after cooling from 90 min of fire exposure, shows a remarkable reduction [11]. It demonstrates that the current provision in Eurocode 2, Eq. (3) overestimates the shear resistance of anchors in cold state but underestimates the resistance in hot state. This finding also confirms that the post-fire (residual) capacity is more critical. When discussing the fire safety of fasteners in concrete, it is more reasonable to be clear about the structural response according to fire resistance classification in EN 13501-2 (i.e., 30, 60, 90 or 120 min) [17]. Therefore, in the present study the load bearing capacities of headed stud anchors loaded in shear perpendicular to the free edge after fire exposures of 0 min (reference), 15 min and 60 min of standard fire curve are experimentally investigated. The effect of concrete edge distances c_1 of 75 mm, 100 mm and 150 mm, together with the influence of different concrete compressive strength f_{cm} of grade C20/25 and C40/50, nominal diameter d_{nom} of 16 mm, 25 mm and 32 mm, and embedment depth h_{ef} of 70 mm, 95 mm and 140 mm on the load-bearing behaviour of the anchors at various durations of fire were carried out. Based on the test results, a more sophisticated model for predicting the residual capacity corresponding to concrete edge failure after fire can principally take the following form:

$$V_{u,c}^{fi} = k_{fi(t)}\cdot d_{nom}^{\alpha_{fi(t)}}\cdot h_{ef}^{\beta_{fi(t)}}\cdot f_{cm}^{\gamma_{fi(t)}}\cdot c_1^{\varepsilon_{fi(t)}} \tag{5}$$

Where d_{nom}, h_{ef}, f_{cm} and c_1 are the same as in Eq. (2), $fi(t)$ represents fire duration in minutes defined by the standard fire curve ISO-834. Thus, the following parameters are required to be obtained as a function $\phi()$ of fire duration $fi(t)$:

$$k_{fi(t)} = k_0\phi(fi(t)) \tag{6}$$

where $k0 = 3.27$ at room temperature.

$$\alpha_{fi(t)} = \alpha_0\phi(fi(t)) \tag{7}$$

$$\beta_{fi(t)} = \beta_0\phi(fi(t)) \tag{8}$$

$$\gamma_{fi(t)} = \gamma_0\phi(fi(t)) \tag{9}$$

where $\gamma 0 = 0.5$ at room temperature.

$$\varepsilon_{fi(t)} = \varepsilon_0\phi(fi(t)) \tag{10}$$

where $\varepsilon 0 = 1.5$ at room temperature.

This paper is intended to provide first-hand experimental data and conclusions related to the resistance of anchorages loaded in shear perpendicular to free edge after fire exposure.

2. Experimental study

2.1. Anchorage configuration

The headed stud anchors, as shown in Fig. 1a, were produced using structural steel S235J2. The production of the headed stud corresponding to the materials, mechanical properties and dimensions according to EN ISO 13918 [18]. The typical anchor configuration used in the tests is