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CONCRETE CONE FAILURE OF POST INSTALLED FASTENERS DURING FIRE

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Abstract. *The fire resistance of fasteners needs to be verified for all failure modes applicable at ambient conditions. Generally, in most cases, for unprotected fasteners loaded in tension, steel failure mode is decisive. But for fasteners made of stainless steel and/or larger (bolt) sizes, concrete cone failure may be the decisive failure mode for small anchorage depths. Due to practical difficulties associated with loading an anchor during a fire test, very limited experimental data is available in literature and that to for relatively small embedment depths. The paper presents the results (6 nos) of the fire tests conducted on expansion anchors (made of stainless steel) with sizes M12 (h_{ef} = 70 mm) and M20 (h_{ef} = 100 mm). Moreover, the paper also compares the reduction in the concrete cone capacity with exposure duration, predicted as per the current design guidelines and the new set of experimental data obtained in this study.*

1 INTRODUCTION

The use of anchors in concrete structures to connect elements to beams, walls, etc., has increased in recent years, due to the flexibility it offers in planning and construction [1]. Since, designing a structure against fire is an integral part of the standard design procedure. Any anchor used for structural applications should also, at least, have the same fire rating as the elements being connected. Hence, the fire resistance of fasteners has gained attention of increasing number of researchers [1,2].

As per the current design guidelines [3], the fire resistance of fasteners is checked for all failure modes as for ambient conditions. The failure modes which are required to be verified at ambient conditions under tension loads are namely, steel failure, concrete cone failure, pull-out failure, combined pull-out & concrete failure (for bonded anchors), concrete splitting failure (non-cracked concrete) and concrete blow-out failure. In an event of fire, steep thermal gradients are induced in reinforced concrete members due to its low thermal conductivity and high specific heat. Due to these thermal gradients and degradation of mechanical properties of concrete with increase in temperature, the capacities of failure modes of fasteners associated with concrete is also reduced significantly. In general, for most of the cases, with unprotected fasteners made of carbon steel and loaded in tension, steel failure is found to be decisive. It should be noted that the previous statement is not applicable to bonded fasteners, for which pull-out failure mode would be decisive [4,5]. But for protected anchors or for example expansion anchors made of stainless steel, concrete cone failure may be the decisive failure mode.

The current prescriptive design for steel failure is based on the evaluation of a large experimental data set for steel failure by Reick (2001) [6]. These characteristic steel stresses for different fire resistance durations are dependent on the diameter of the fastener and steel viz., carbon steel and stainless steel.

In contrast to steel failure, the characteristic pull-out resistance of mechanical fasteners is based on very limited experimental results [1] and is given as 25% & 20% of the value at cold state, for 90 minutes & 120 minutes of standard fire exposure, respectively.

In case of concrete cone failure, the reduction factor is a linear function of embedment depth. For fire exposure up to 90 minutes the reduction factor is given by $h_{ef}/200$, which is further reduced in a step to

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$0.8 \times h_{ef}/200$ for fire exposure between 90 to 120 minutes. The influence of fire on concrete cone capacity decreases with increasing embedment depth, because the cracking starts at the deepest point of the anchorage depth. For fasteners with h_{ef}= 200 mm which are far away from edge, the capacity is unaffected up to 90 minutes of fire exposure. The basis for these guidelines is the extensive numerical study by Periskic (2009) [7] on headed studs. The numerical model used by Periskic was validated against very limited experiments on headed studs (with embedment depth of 40, 50 & 60 mm) [8]. It should be acknowledged that the existing guideline for concrete cone failure lacks an extensive experimental backing for post installed mechanical fasteners. Moreover, no attempts were made in the past to expand the (very limited) experimental database to embedment depths commonly used in practice. This is mainly because of two main reasons:

1. As mentioned previously, in general, for fasteners made of carbon steel with embedment depths commonly used in practice, mostly steel failure is the decisive failure mode.
2. Performing fire tests is very demanding both economically and technically. Moreover, the high levels of load that need to be applied on stainless-steel fasteners during the fire tests imposes a serious practical limitation and challenges.

Recently, a new medium scale fire testing facility for anchors was developed by Department for Fastening and strengthening, Institute of Construction materials, at MPA, University of Stuttgart, to overcome the practical limitation mentioned above in point 2. This new test setup made it possible to generate new experimental data for post installed mechanical fasteners with load levels from 8 – 28 kN, presented in this paper.

2 EXPERIMENTAL INVESTIGATION

Experiments were conducted on torque-controlled expansion anchors with (bolt) thread sizes M12 and M20, made of stainless steel. The effective embedment (h_{ef}) was 70 mm & 100 mm, for sizes M12 & M20, respectively. The concrete slabs in which the anchors were installed had an age of more than 90 days and were made of C20/25 grade concrete. The setting position of the anchors was defined with respect to the edge distance (c_1 / c_2) from the two nearest edges of the slab. Table 1 gives the details of the concrete slab and the anchors tested.

Table 1: Details: setting position and concrete slabs.

1	Anchor size M12 2	Anchor size M20 3
h_{ef} [mm]	70	100
Setting position c_1 / c_2 [mm]	100 / 115	140 / 200
Load levels [kN]	18.75 / 12.25 / 8.00	28.40 / 26.00 / 22.00
Slab thickness [mm]	150	200
Cube compressive strength @ 28 days [MPa]	29.75	28.5
Age of concrete slab on the day of testing [days]	107 / 177	131 / 133

In case of fire tests performed in bigger furnaces, the concrete slabs, with anchors installed in them, are placed on top of the furnace as covering slab. But in contrast to these traditional fire tests, in the present experimental setup, the concrete slab was placed on the floor of the furnace. This was possible due to the appropriate medium scale of the furnace. Such a placement of specimen in furnace allows us to use a loading setup very similar to that used for ambient tests. The furnace being used is a single burner small test furnace as shown in figure 1.

The concentric tension load was applied on the anchors through a loading fixture which was connected to a loading rod of size M30. The loading fixtures were designed as per the guidelines provided in EOTA TR020 [9]. The loading rod extended all the way through the furnace covering blocks. The loading rod was then connected to the extractor rod outside the furnace, passing through the hydraulic cylinder and the load cell. The required loads on the anchors were applied using the hydraulic hand pumps. The loads were applied approx. 5 minutes before the fire test and were maintained constant during the test duration. The load history was continuously monitored and recorded using the data acquisition system. The loading histories for 6 reported tests are shown in figure 2.

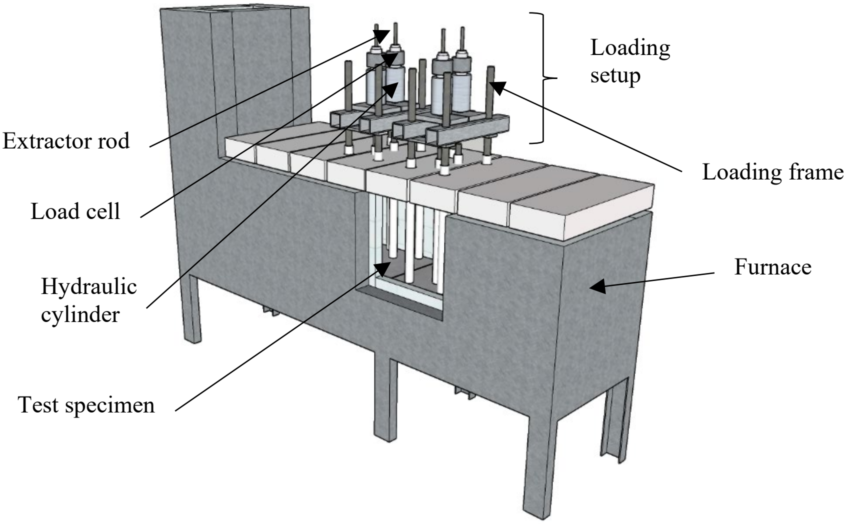


Figure 1. Schematic representation of the test facility and loading setup.

The loaded anchors were then exposed to fire defined by standard temperature time curve [10]. The slab was exposed to fire only from the side on which the anchors were installed and all other sides were insulated. The furnace temperature was measured using two plate type thermocouples. Figure 3 shows the average furnace temperature along with the target standard fire exposure.

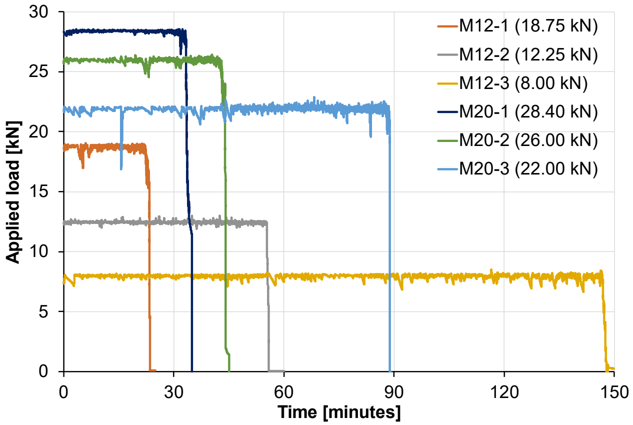


Figure 2. Applied loading histories.

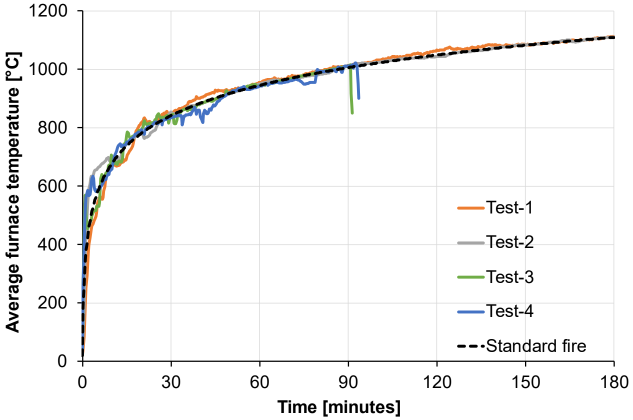


Figure 3. Average furnace temperature during different fire tests.

3 EXPERIMENTAL RESULTS

The time at which the applied load could no longer be maintained on the anchor, was noted as the time to failure. The time to failure of the anchor can be easily identified and read from the applied load histories shown in figure 2. The experimentally obtained variation of concrete cone capacity with exposure time is shown in figure 4. It was observed that for both the embedment depths investigated the reduction in concrete cone capacity is steep for short fire duration as compared to longer fire durations.

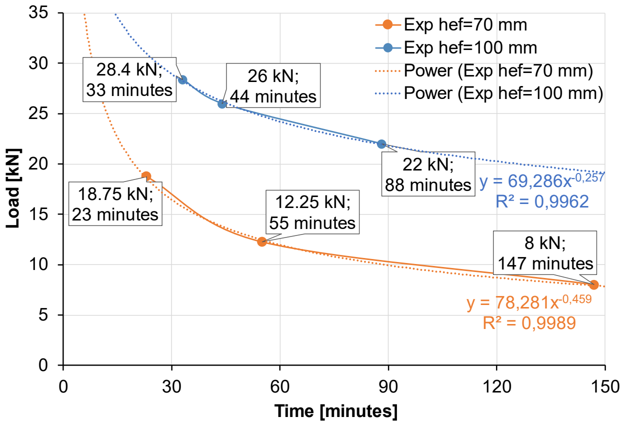
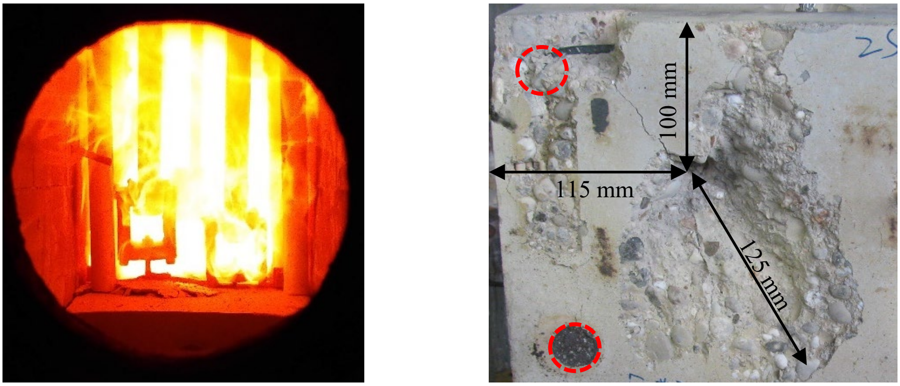


Figure 4. Experimental results for concrete cone failure.

The typical concrete cone failure observed in the experiments is shown in figure 5 & 6, for sizes M12 and M20, respectively. It should be noted that the formation of a complete concrete cone breakout was prevented due to the loading frame support points, shown by red dotted circles in figure 5 & 6.



(a) (b)

Figure 5. Typical failure mode for expansion anchor size M12 (h_{ef} = 70 mm) (a) image during the fire test and (b) after the fire test.

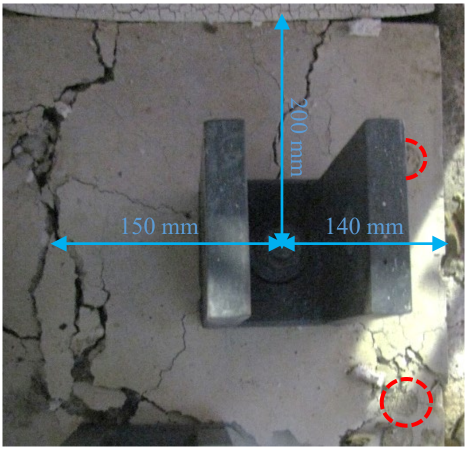


Figure 6. Typical concrete cone failure for expansion anchor size M20 (h_{ef} = 100 mm).

4 COMPARISON WITH CURRENT DESIGN GUIDELINES

As per section 7.2.1.4 of EN 1992-4:2018 [3], the concrete cone failure resistance of a fastener at ambient conditions can be obtained by using equation (1).

$$N_{u,C} = N^{0}_{u,C}\,\frac{A_{Cn}}{A^{o}_{CN}}\,\psi_{s,N}\,\psi_{re,N}\,\psi_{ec,N}\,\psi_{M,N} \qquad (1)$$

Where,

$A_{cN} \,/\, A^{o}_{cN}$ accounts for the geometric effects like spacing and edge distances. In case of fire exposure, the reference projected area (A^{o}_{cN}) is calculated as *16* times the square of effective embedment depth (h_{ef}) as compared to 9 times at ambient conditions. This is due to increased requirements on characteristic spacing ($s_{cr,N} = 4 \times h_{ef}$) and edge distance ($c_{cr,N} = 2 \times h_{ef}$),

$\psi_{s,N}$ is a factor that account for the change in stress distrbution in concrete due to the proximity of an edge of the concrete member. It is a function of smallest edge distance *(c)* and characteristic edge distance ($c_{cr,N} = 2 \times h_{ef}$; *in case of fire*) (equation (2)),

$$\psi_{s,N} = 0.7 + 0.3 \frac{c}{c_{cr,N}} \leq 1 \tag{2}$$

The factors to account for shell spalling ($\psi_{re,N}$) and eccentric loading ($\psi_{ec,N}$) are not applicable in the present case. Hence, are taken as 1.0. Moreover, there are no investigations available until now if this factor is applicable under fire conditions at all. Since spalling above the reinforcement is very likely under fire perhaps this factor may also be valid for a lower amount of reinforcement.

The factor $\psi_{M,N}$, which accounts for the positive effect of presence of compression force between fixture and concrete is conservatively taken as 1.0. Since the stress state in the concrete under fire does not only depend on the applied forces but also on the thermal stress distribution. Hence, this factor should not be accounted for during fire. The beneficial stress state may be changed by superposing the thermal stresses.

$N_{u,c}^{0}$ is the resistance of a single fastener not influenced by adjacent fasteners or edge of the concrete member. In case of fire exposure, this value is to be replaced with the values given by equations (3) & (4) for standard fire exposure up to 90 minutes and between 90 & 120 minutes, respectively.

$$N_{u,fi(90)}^{0} = \frac{h_{ef}}{200} N_{u,c,20°C}^{0} \leq N_{u,c,20°C}^{0} \tag{3}$$

$$N_{u,fi(120)}^{0} = 0.8 \times \frac{h_{ef}}{200} N_{u,c,20°C}^{0} \leq N_{u,c,20°C}^{0} \tag{4}$$

The concrete cone failure capacity at ambient conditions, $N_{u,c,20°C}^{0}$, is calculated using equation (5). Due to the presence of thermal cracks, the calculation assumes that the concrete is cracked during fire. The value of k_{cr} is typically taken as 0.7 times the coefficient (k_{ucr}) for uncracked concrete [11].

$$N_{uc,20°C}^{0} = k_{cr} \sqrt{f_c}\, h_{ef}^{1.5} \tag{5}$$

To make comparisons at mean level, the value of k_{ucr} proposed in Eurocode cannot be used because those values are applicable at characteristic level. Hence, the value proposed by Eligehausen et al., (2012) at mean level are used, i.e., $k_{ucr} = 14.6$ when fc is cylinder compressive strength. Thus, k_{cr} is equal to $0.7 \times 14.6 = 10.22$.

The cube strengths for the concrete were measured only at age of 28 days but tests were performed at age between 107-177 days. Hence, the concrete compressive strength on the day of testing was calculated using equation (6), taken from fib Model Code 2010 [12]. Table 2 summarises the compressive strength calculations for concrete on different days of testing.

$$f_c(t) = exp\left\{s\left[1 - \sqrt{\frac{28}{t}}\right]\right\} \times f_{cm} \tag{6}$$

Table 2: Calculation of cylinder compressive strength on the test day as per fib Model Code 2010.

Specimen 1	$f_{c,cube}$ *@28 days* 2	$f_{c,cyl}$ *@28 days = 0.8* $\times f_{c,cube}$ 3	Age of concrete on testing day 4	Coefficient *"s" (for 32.5 N cement type)* 5	$f_{c,cyl}$ on test day *(as per equation 6)* 6
	[MPa]	[MPa]	[days]	[-]	[MPa]
M12 – 1 (18.75 kN)	29.75	23.8	107	0.25	26.89
M12 – 2 (12.25 kN)	29.75	23.8	177	0.25	27.67
M12 – 3 (8.00 kN)	29.75	23.8	177	0.25	27.67
M20 – 1 (28.40 kN)	28.5	22.8	131	0.25	26.08
M20 – 2 (26.00 kN)	28.5	22.8	133	0.25	26.10
M20 – 3 (22.00 kN)	28.5	22.8	133	0.25	26.10

The computed cylinder compressive strengths are then used for computing $N^0_{uc,20°C}$ using equation (5). The computed concrete cone capacity of fasteners not affected by concrete edges at ambient conditions and under fire (90 & 120 minutes), in cracked concrete are summarised in Table 3. The concrete cone capacity of fasteners accounting for the edge distance are given in Table 4.

The comparison between the average concrete cone capacity under fire as per EN 1992-4:2018 and the experimental results obtained in this study are shown in figure 7.

Table 3: Computation of concrete cone capacity (for cracked concrete).

Age [Days] 1	h_{ef} [mm] 2	k_{cr} [-] 3	f_c [MPa] 4	$N^0_{uc,20°C}$ [kN] 5	$N^0_{u,fi(90)}$ [kN] 6	$N^0_{u,fi(120)}$ [kN] 7
107	70	10.22	26.89	31.04	10.86	8.69
177	70	10.22	27.67	31.48	11.02	8.82
131	100	10.22	26.08	52.19	26.10	20.88
133	100	10.22	26.10	52.22	26.11	20.89

Table 4: Computation of concrete cone capacity accounting for edge influence.

h_{ef} [mm] 1	c_1/c_2 [mm] 2	Age [Days] 3	$N^0_{u,fi(90)}$ / $N^0_{u,fi(120)}$ [kN] 4	Acno [mm²] 5	Acn [mm²] 6	$\frac{Acn}{Acn0}$ [-] 7	$\Psi_{s,N}$ [-] 8	$\Psi_{re,N}$; $\Psi_{ec,N}$; $\Psi_{M,N}$ [-] 9	$N_{u,fi(90)}$ / $N_{u,fi(120)}$ [kN] 10
70	115 / 100	107	10.86 / 8.69	78400	61200	0.78	0.914	1.00	7.75 / 6.20
70	115 / 100	177	11.02 / 8.82	78400	61200	0.78	0.914	1.00	7.86 / 6.29
100	140 / 200	131	26.10 / 20.88	160000	136000	0.85	0.910	1.00	20.19 / 16.15
100	140 / 200	133	26.11 / 20.89	160000	136000	0.85	0.910	1.00	20.19 / 16.16

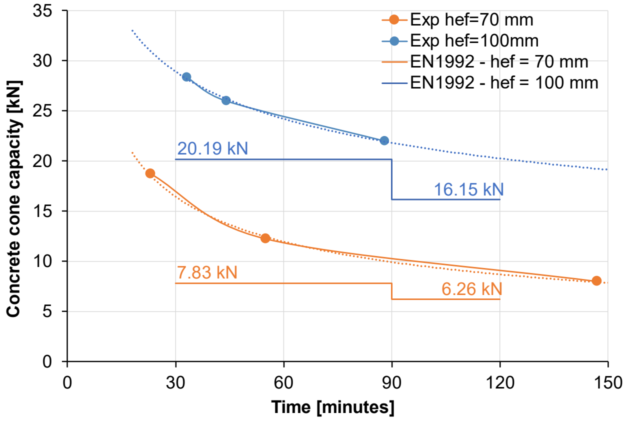


Figure 7. Comparison between the experimental results and current design guidelines.

5 CONCLUDING REMARKS

The paper presented the first set of experimental results for concrete cone capacity of expansion anchors under fire. The paper also briefly described the new test facility developed by Department for Fastening and strengthening, Institute of Construction materials, at MPA, University of Stuttgart, which now makes it possible to test anchors under high loads and fire exposure.

The results validated the EN 1992-4:2018 design guidelines for concrete cone resistance of post installed fasteners under fire. It was found that the current design guidelines are on the conservative side and the safety margins are high for short fire durations, but they reduce with increase in fire duration and embedment depth.

Moreover, there is a significant lack of knowledge regarding the validity of the reduction and increasing factors given in equation (1) in case of fire exposure. In addition, the first results show that a step function related to the fire durations of 30, 60 ,90 and 120 minutes could be more accurate.

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