CONCRETE CONE FAILURE OF HEADED STUD UNDER DIFFERENT FIRE EXPOSURE

BETONAUSBRUCH VON KOPFBOLZEN BEI UNTERSCHIEDLICHER BRANDBEANSPRUCHUNG

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SUMMARY

The paper presents the results of numerical investigations on the concrete cone failure of single headed stud exposed to different fire. The fire exposures investigated include the standard fire and hydrocarbon fire as per EN1991-1-2. A sequentially coupled 3D thermal-stress analysis is performed using Ansys® Mechanical for the investigation. The unique feature of the Finite Element model is that it uses quadratic (higher order) elements. A good comparison between the predicted degradation in concrete cone capacity in the present study and other numerical results available in literature (for standard fire exposure) demonstrates the usability of the model. The concrete cone capacities under hydrocarbon fire exposure were reached 30 minutes earlier as compared to standard fire exposure.

ZUSAMMENFASSUNG

Der Beitrag stellt die Ergebnisse numerischer Untersuchungen zum Betonausbruch von brandbeanspruchten Einzelkopfbolzen vor. Zu den untersuchten Brandbeanspruchungen gehören der Standardbrand und der Hydrokarbon-Brand gemäß EN1991-1-2. Die Untersuchungen wurden mit einer sequenziell gekoppelten 3D thermischen Spannungsanalyse mit Ansys® Mechanical durchgeführt. Die Besonderheit des Finite-Elemente-Modells besteht darin, dass es quadratische Elemente (höherer Ordnung) verwendet. Ein Vergleich zwischen der Betonausbruchskapazität in der vorliegenden Studie und anderen in der Literatur verfügbaren Ergebnissen liefert eine gute Übereinstimmung (für den Fall der Einheitstemperaturkurve-ETK) und zeigt die grundsätzliche Anwendbarkeit des verwendeten FE-Modells. Im Falle von Betonausbruch unter Hydrokarbon-Brandkurve wird dieselbe Tragfähigkeit 30 Minuten früher erreicht als unter der ETK.

1. INTRODUCTION

The failure of fasteners used for structural applications or for installing safety related systems or any other equipment, can pose threat to human life during the escape and firefighting phase. Hence, the fasteners should have a fire resistance at least equal to that of the element in which the fastener is installed or the elements connected by fasteners.

Generally, steel failure is found to be the decisive failure mode in most cases of unprotected fasteners loaded in tension. But due to the negative effects of fire on concrete namely, the increase in temperature of concrete; development of steep thermal gradients; degradation in material strength & stiffness; thermal cracking etc., the capacities of failure modes associated with concrete are also reduced drastically. Therefore, for fasteners made of stainless steel which performs better during fire and/or larger (bolt) sizes, concrete cone failure may become the decisive failure mode for small anchorage depths. In the recent experiments performed by Lakhani and Hofmann (2021) [1], it was found that for expansion anchors made of stainless steel, bolt sizes M12 & M20 and corresponding embedment depth of 70 mm & 100 mm, concrete cone failure occurred before steel failure under standard fire exposure.

The fire resistance of fasteners can be estimated by using simplified design method as per Annex-D of EN1992-4:2018 [2] when the fire resistance values are not given in corresponding European Technical Approvals (ETAs). As per EN1992-4 the reduction factor for concrete cone capacity is a directly proportional to embedment depth (h_{ef}). For fire exposure up to 90 minutes the reduction factor is given by $h_{ef}/200$, which is further reduced to $0.8 \times h_{ef}/200$ for fire exposure between 90 to 120 minutes. The basis for these guidelines is the extensive numerical study conducted by Periškić (2009) [3] on headed studs.

The current design procedure is prescriptive in nature and is applicable only for standard fire exposures [4]. But, in practice, there are often requirements to qualify the fasteners for specific/special application where the fire exposure is defined by different temperature-time curves other than standard fire exposure. For example, in tunnel applications where the anchors need to be qualified for more severe fire exposures like the hydrocarbon fire, RABT curve (as per the directives of the equipment and operation of road tunnels, Germany), RWS (Rijkswaterstaat, Netherlands) etc. Furthermore, there is also an increased emphasis on performance-based fire design of structures (evident from the increased number of publications on this topic e.g., [5,6]) where the fire exposure is based on the calculated fire load rather than standard fire exposure.

It has been seen in practice that fire tests are performed to get approval for fasteners for fire exposure. But most of the times, due to economic considerations such tests are limited to investigation of steel failure or pull-out failure. And the failure modes associated with concrete failure are assessed using numerical tools.

Even without fire, it is a numerically challenging task to simulate the concrete cone failure of fasteners loaded in tension. This is because fasteners are one of the few applications which relies on the tensile capacity of concrete and the material model should be able to correctly simulate the complex mix mode fracture of concrete which occurs during the concrete cone failure. The problem gets even more complicated at elevated temperature due to various well know complexities associated with modelling concrete behaviour at elevated temperature.

The paper not only presents the concrete cone capacity degradation of headed studs during standard and hydrocarbon fire. But also discusses a 3D sequentially coupled thermo-mechanical model which can successfully solve this numerical challenging problem and can be used to further investigate concrete related failure modes of headed studs during fire.

2. NUMERICAL INVESTIGATION

A sequentially coupled 3D thermomechanical analysis is performed using commercially available FE analysis software Ansys ® Mechanical [7]. For the presented study a headed stud with embedment depth (h_{ef}) of 50 mm, not influenced by the concrete edges (i.e., casted at an edge distance of $4 \times h_{ef}$ in both directions) is simulated. To optimise the simulation run time, only one-fourth of the geometry is modelled taking advantage of the geometric symmetry. Fig. 1 gives further details of the concrete and headed stud geometries used for the simulations.

To investigate the concrete cone failure capacity of headed studs after exposure to different durations (30, 60, 90 & 120 minutes) of standards fire and hydrocarbon fire. First, a transient heat transfer analysis is performed to compute the spatial and temporal distribution of temperature in the geometries due to different fire exposures. In the second step a thermal stress analysis is performed using the temperatures computed in the first step. The two analyses are performed in a sequentially coupled manner which means there is only one way dependency of stress fields on the temperature fields, but the temperature fields are computed independent of the stress fields. The two analyses steps along with the results are discussed in detail in the following sections.

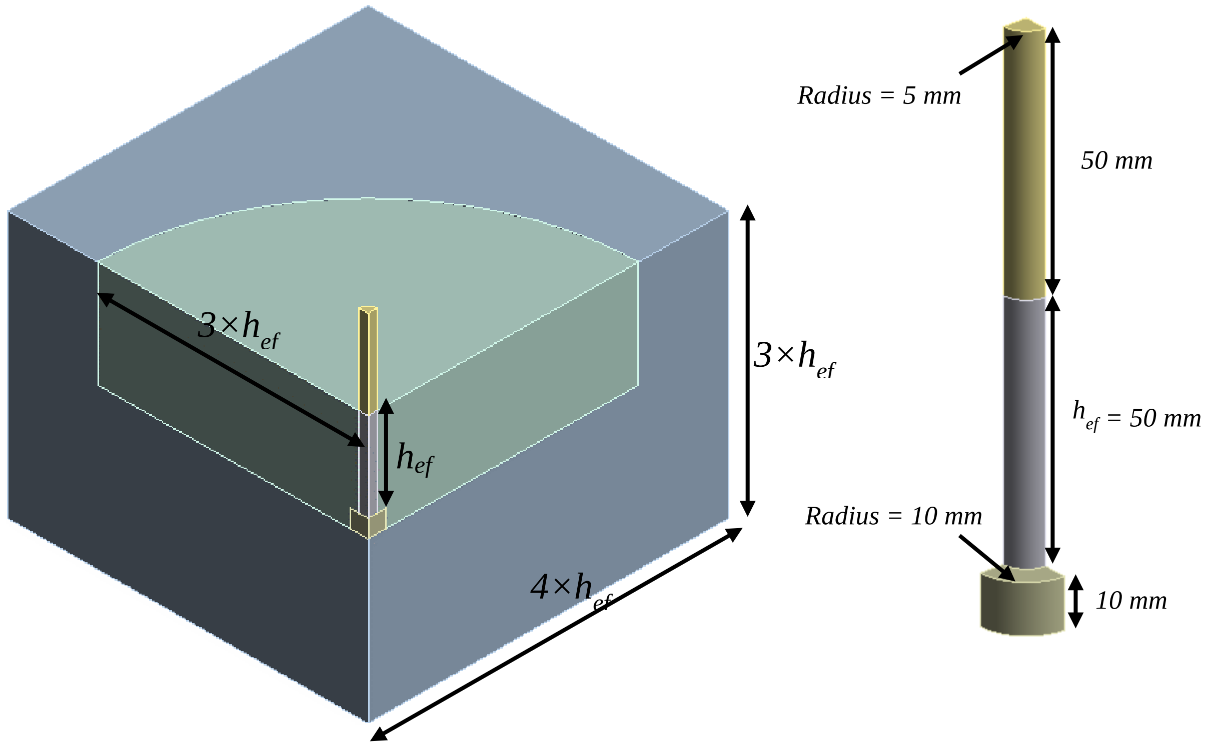


Fig. 1: Geometric details of the headed stud and the concrete volume

2.1 Transient heat transfer analysis

The concrete slab and headed stud were exposed to fire only from one side i.e., the side on which it was set. The fire exposure was defined using standard temperature time curve and hydrocarbon curve as per EN1991-1-2:2002 [8] given by equations (1) and (2), respectively.

$$T_g = 20 + 345 \log_{10}(8t + 1) \tag{1}$$

$$T_g = 1080(1 - 0.325e^{-0.167t} - 0.675e^{-2.5t}) + 20 \tag{2}$$

Where,

T_g is the gas temperature in the fire compartment in °C

t is the time in minutes

The heat transfer from the surrounding hot gases to the exposed surface was modelled using radiation (emissivity=0.8) and convection. The connective heat transfer coefficient for standard fire is taken as 25 W/m^2 K and for hydrocarbon fire is taken as 50 W/m^2 K as recommended by Eurocode 1 [8]. The temperature dependent density, specific heat and conductivity of concrete are taken from Eurocode 2 [9]. Specific heat for dry concrete and lower limit conductivity is used for the simulations. The choice of thermal properties for concrete is based on the validation performed by Lakhani et al. (2013) [10]. The temperature dependent thermal properties of steel are taken according to Eurocode 3 [11]. The contact between headed stud surface and concrete surfaces were taken as bonded for the thermal analysis. The geometries are discretised using quadratic elements (Solid291 for concrete and Solid279 for steel/headed stud), which have a single degree of freedom i.e., temperature at each node. Fig. 2 shows the discretized model. The average element size in the inner concrete volume (cylinder with radius of 3 h_{ef}) is 12 mm and in outer volume is 17 mm.

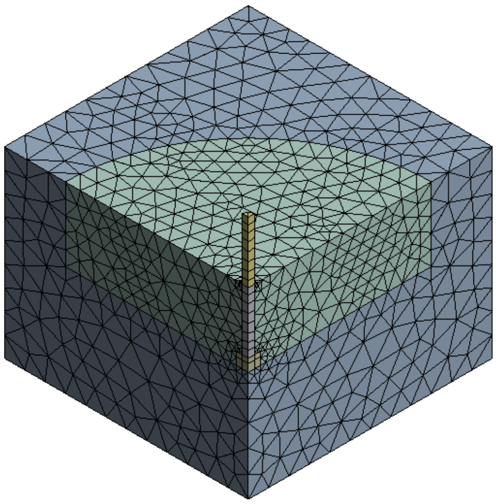
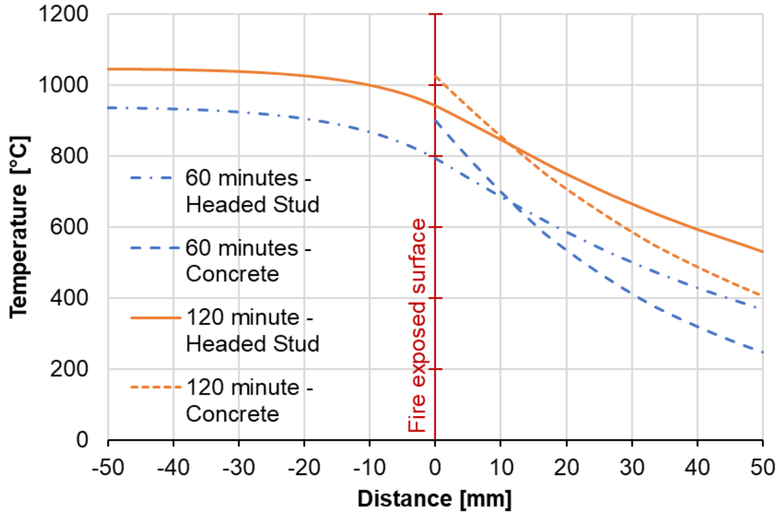
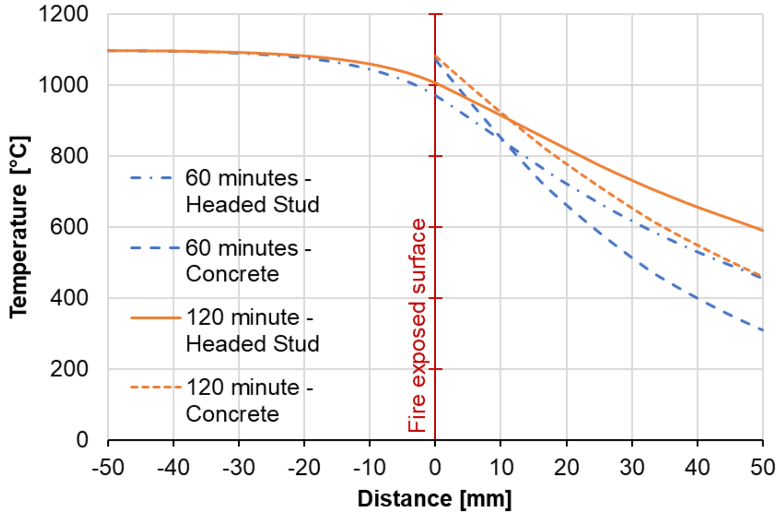


Fig. 2: Discretization of the geometry

Since the fire exposure on concrete slab is assumed to be uniform across the complete exposed surface the heat transfer takes place only along the concrete slab thickness (this means that the temperature along the slab thickness could also be computed using 1D heat transfer simulation). Thus, thermal gradients would develop only along the slab thickness and remain same along its width or length. But, due to the presence of (steel) headed stud there also exist a relatively gradual radial thermal gradient (radiating out from the headed stud) due to the higher conductivity of steel in comparison to concrete. The calculated temperature gradients along the headed stud and the thickness of the concrete slab away from the headed stud, are shown in Fig. 3 (a) & (b) for standard fire exposure and hydrocarbon fire, respectively.



(a) Standard fire exposure



(b) Hydrocarbon fire

Fig. 3: Temperature gradients along headed stud and concrete thickness

In Fig. 3 (a) & (b), 0 mm represents the fire exposed concrete surface, and the positive distance means depth inside concrete slab, whereas negative distance represents the length of the headed stud projecting outside the concrete slab. Due to higher thermal conductivity of steel the concrete temperature near the exposed surface is reduced and at the same time the temperature at deeper points along the embedment depth of the headed stud is increased (i.e., higher than temperatures for concrete not influenced by the presence of headed stud).

2.2 Thermal stress analysis

The nodal temperature computed in transient heat transfer analysis are imported into the static structural analysis to carry out the thermal stress analysis. The load-deformation behaviour of headed stud at different duration of fire exposure, namely, 30, 60, 90 & 120 minutes are computed for both standard fire and hydrocarbon fire.

The headed stud is free to expand during the targeted exposure duration (30, 60, 90 & 120 minutes) and thereafter is loaded by applying incremental displacement on the top face of the anchor. The boundary conditions applied during the thermal stress analysis are shown in Fig. 4. A frictionless contact based on Pure Penalty formulation is defined between the headed stud and concrete for the thermal stress analysis.

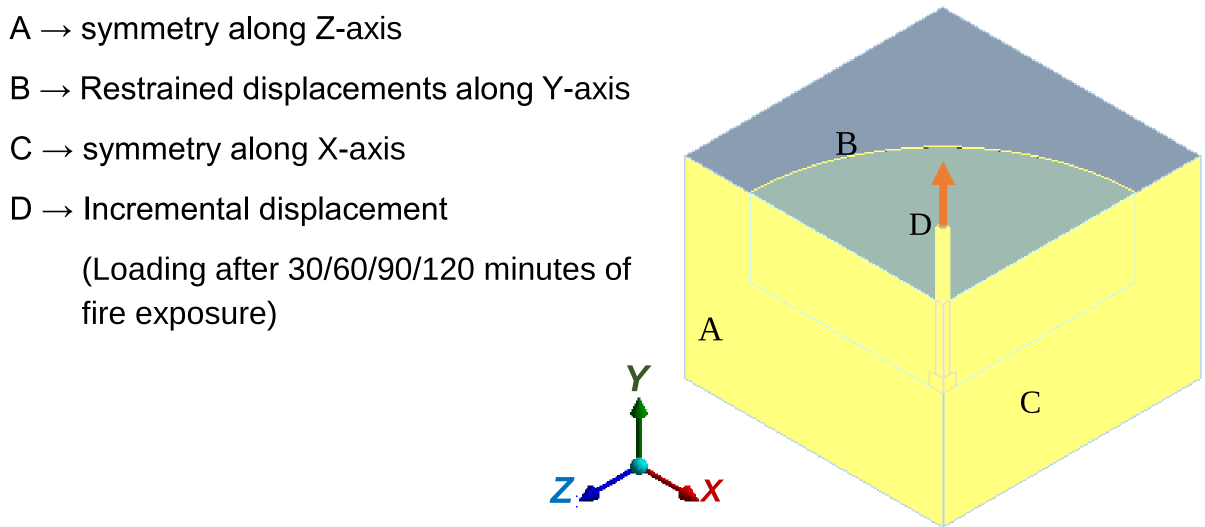


Fig. 4: Boundary conditions for thermal stress analysis

The geometry was discretised using quadratic (higher order) 3-D 10-node tetrahedral elements (CPT 217) and 20-noded hexahedral elements (CPT 217) for concrete & steel, respectively. The steel was assumed to be linear elastic (Young's modulus = 200,000 MPa and Poisson's ratio = 0.33). This assumption can be justified since in the presented study only concrete cone failure was investigated. The thermal strain for steel is considered according to Eurocode 3 [11].

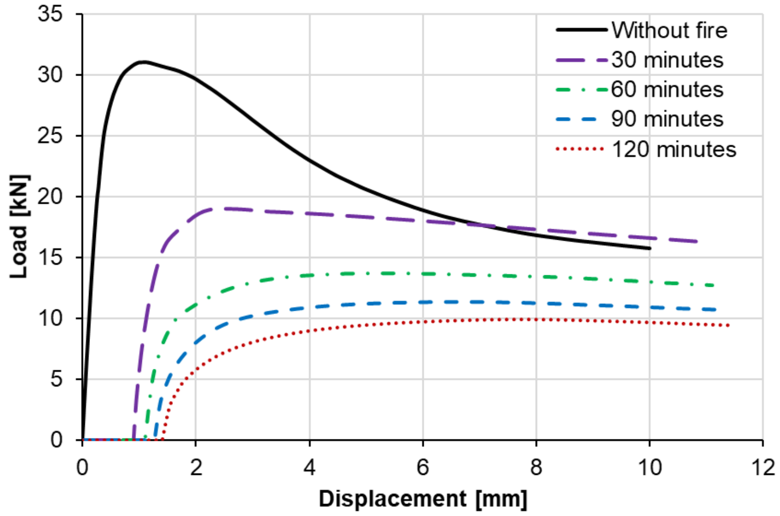
The concrete was assumed to be made of calcareous aggregates. The corresponding compressive strength degradation and thermal strain from Eurocode 2 [9] are used with slight modification above 1000°C (for temperature above 1000°C the same degradation as for 1000°C is used). The degradation in tensile strength is also taken from Eurocode 2 but with slight modification for numerical reasons. Thus, the tensile strength at and above 600°C is kept constant at a value corresponding to 10% of ambient value. These modifications were made to avoid numerical difficulties which can arise due to zero material strengths. The following material properties are used for concrete at ambient temperature:

1. uniaxial compressive strength = 25 MPa,
2. uniaxial tensile strength = 2.0 MPa,
3. Poisson's ratio = 0.18,
4. biaxial compressive strength = 28.75 MPa (1.15 × uniaxial compressive strength) and
5. fracture energy = 0.07 N/mm.

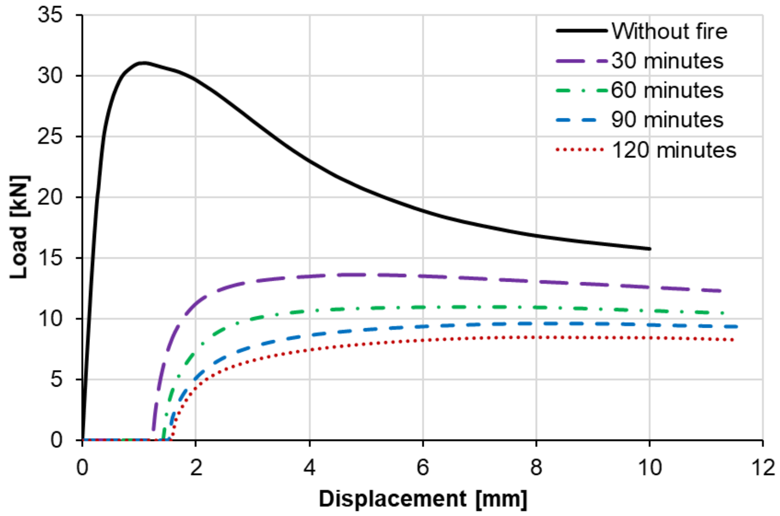
The Menetrey-Willam plasticity model with exponential softening, available in Ansys® mechanical is used for modelling the temperature dependent nonlinear behaviour of concrete. The dilation angle, 28° and fracture energy were assumed to be independent of temperature. The uniaxial stress-strain constitute law was defined using power law until a stress level corresponding to 85% of the peak stress in the descending branch, followed by exponential softening. The concrete is assumed to be linear up to 30% of the peak stress at each temperature. The residual stress level at each temperature, beyond ultimate strain is assumed to be 20% (of correspond compressive strength at that temperature) under compression and 10% (of corresponding tensile strength at that temperature) under tension.

Fig. 5 (a) an (b) shows the predicted load-displacement response of headed stud at 30, 60, 90 & 120 minutes of standard fire and hydrocarbon fire exposure, respectively. As one would expect, the displacement of the anchor at target exposure duration (before being loaded) increases with increasing exposure duration. The magnitude of displacement due to thermal strains is higher in case of hydrocarbon fire because of higher temperature.

It is observed that the reduction in concrete cone capacity is significant during early phase of fire, both for standard and hydrocarbon fire exposure. In the presented case the concrete cone capacity reduces to 61% (with reference to its capacity at ambient temperature) & 44.2% in 30 minutes for standard fire and hydrocarbon fire, respectively.



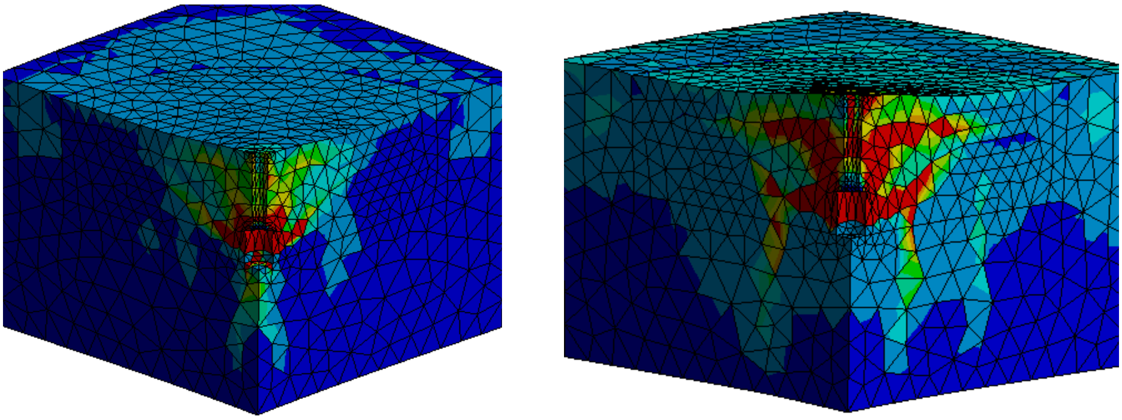
(a) Standard fire exposure



(b) Hydrocarbon fire

Fig. 5: Load displacement response of headed stud at different fire durations

The crack pattern corresponding to the peak load at 30 minutes for the two investigated fire exposures is shown in Fig. 6 (a) and (b). The principal strain contour indicted by red colour in Fig. 6, corresponds to a crack width greater than 0.3 mm. In addition to the cracks formed due to the conical concrete cone breakout, there are also vertical cracks along the slab thickness due to thermal stresses. Clearly, a higher level of damage is seen in the concrete slab in case of hydrocarbon fire exposure. Moreover, damage is also seen the edge of the concrete slab which is due to the combined effect of the specimen geometry and thermal stresses due to steep thermal gradients in concrete.



(a) Standard fire (b) Hydrocarbon fire

Fig. 6: Crack pattern at peak load at 30 minutes of exposure duration

Furthermore, numerical results from Ozbolt et al. (2004) [12] for headed stud with effective depth of 50 mm exposed to standard fire are compared with the results obtained in the current study. As can be seen in Fig. 7 a very good comparison is found between numerical results available in literature and the results predicted in the present study. Thus, validating the presented numerical model.

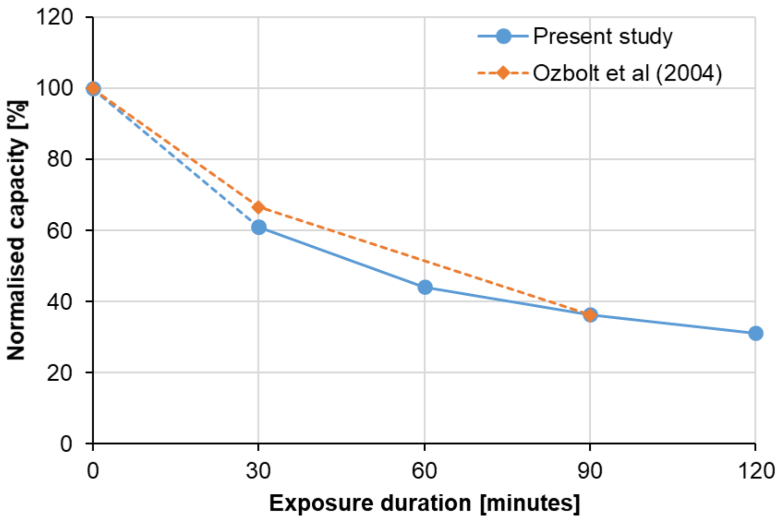


Fig. 7: Comparison between results predicted in this study and those from literature (for standard fire exposure only)

3. CONCLUDING REMARKS

The paper presented a numerical study to investigate the concrete cone failure capacity of headed stud under standard fire and hydrocarbon fire using on a 3D sequentially coupled thermo-mechanical model developed in Ansys®. On the bases of the results obtained in this study the following conclusions can be drawn:

- A good comparison is obtained between the presented numerical results and results from different study from literature for standard fire exposure. Thus, showing the capability of the model to predict concrete cone failure during fire. Therefore, the model is suitable for further studies needed on this topic.
- For the investigated embedment depth of 50 mm, it was found that in case of hydrocarbon fire exposure the same concrete cone capacities are reached 30 minutes earlier as compared to standard fire exposure as shown in Fig. 8.

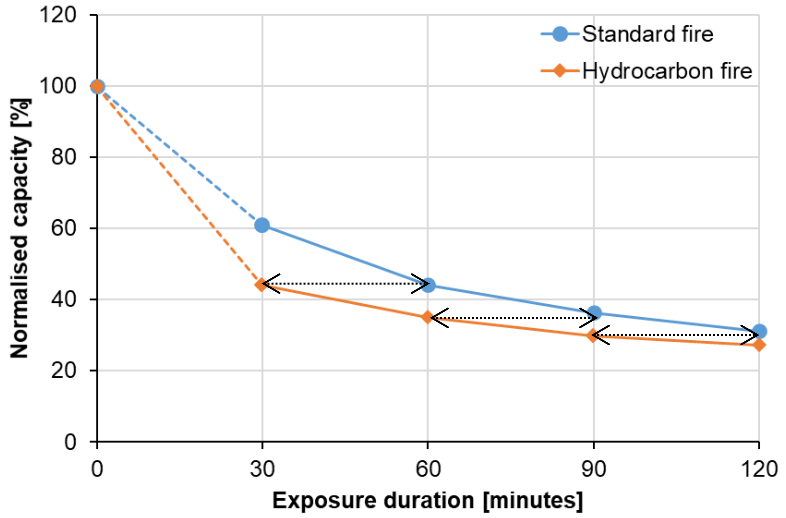


Fig. 8: Predicted reduction of concrete cone capacity for standard fire and hydrocarbon fire exposure

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