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COMPUTER SIMULATION OF FASTENERS IN CONCRETE UNDER FIRE

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Abstract
A numerical study was performed to investigate the behavior of a headed anchor subjected to fire in case of concrete cone failure. Headed stud anchors were analyzed using the improved non-local microplane material model. The influence of heating of the specimen was modeled by choosing specific material properties in different temperature layers. The development of the failure cone was simulated for fasteners with four embedment depths under normal conditions and in case of fire. The load-displacement behavior of the fastener, crack propagation and evolution of stress and strain fields in the concrete during the loading process up to concrete cone failure are obtained from the analysis and by graphical postprocessing. Conclusions from the comparison of simulations of fasteners under fire and in cold state are drawn.

1 Introduction

Metallic anchors are increasingly used in the building industry e.g. to fasten supplementary equipments to concrete structures. These fasteners are embedded into concrete, and they transfer load from the fastened element to the building structure. The fasteners commonly used are able to transfer rather large forces into the concrete mass. A typical failure mode of fasteners is pulling out a concrete cone (Rehm, Eligehausen and Mallée, 1992).

While the behavior of fasteners under normal conditions has been studied intensively and is rather well known (CEB, 1994), their behavior in case of fire has not been studied sufficiently. Nevertheless, the load bearing capacity of fasteners under fire loading should be guaranteed, especially for mounting of pipes for sprinklers, cables, air conditioning channels and similar equipments. However, only some test results are available (Kordina, 1993; Reuter, 1993) and therefore a lot of questions are still open.

A numerical study was performed in order to investigate the behavior of headed stud anchors subjected to fire in case of concrete cone failure.

2 Structures and materials under fire

If the anchors are used to fasten important parts or equipments to the structure, their behavior in case of fire must be taken into account in the design. In general, the required minimum resistance time for such structural elements under fire is 90 minutes (DIN 4102, 1994). At that time, the temperature at the concrete surface reaches about 950°C.

The properties of the structural materials are strongly affected by rising temperatures. The concrete compressive strength f_c, tensile strength f_t, as well as modulus of elasticity E_c decrease significantly with increasing temperature. This can be seen from Fig.1, which shows relative concrete material properties as a function of temperature. In Fig.1, also the concrete temperature at a certain distance from the concrete surface (taken from Kordina and Meyer-Ottens, 1981) is given after a fire exposure of 90 minutes.

3 Numerical model

A numerical study of the behavior of fasteners under fire was performed using the finite element method. For the simulation of the nonlinear concrete behavior, a finite element program based on the nonlocal microplane material model (Ožbolt and Bažant, 1995) was used. The effect of fire loading was modeled by means of using different material properties in zones of the concrete specimen with different temperatures.

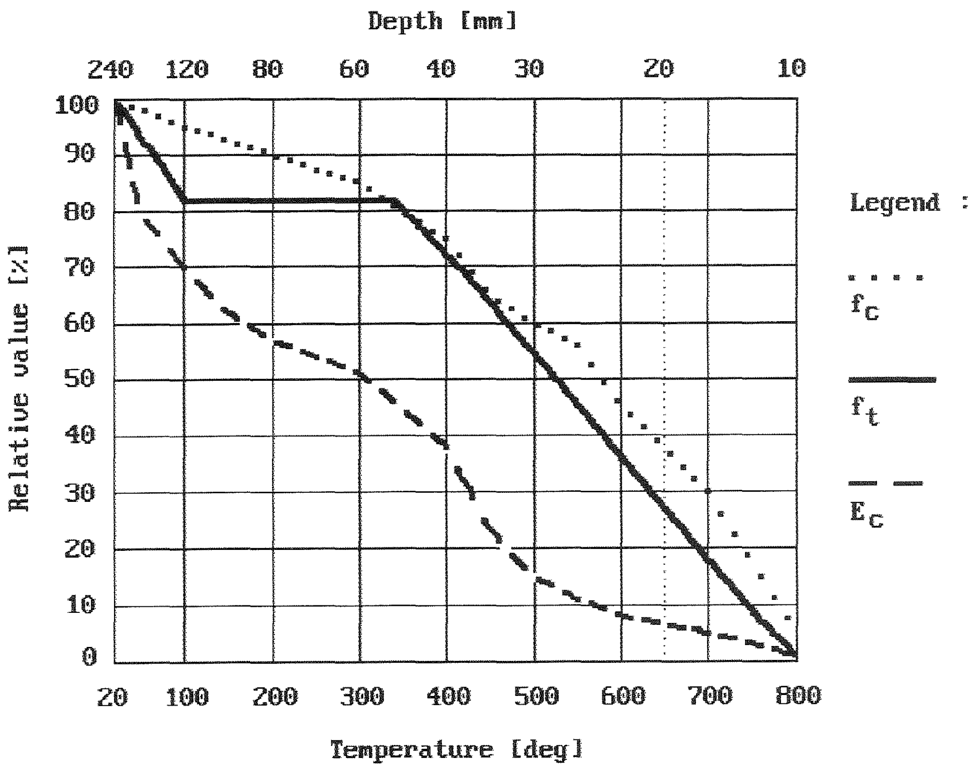

Fig.1 Degradation of concrete properties with temperature/depth (after Kordina and Meyer-Ottens, 1981)

Material properties in the microplane model are characterized separately on a final number of microplanes, planes of various orientations within the material. The state of each microplane is described by normal and shear strain components. The stress-strain relations are defined by exponential functions. Parameters for these functions are given as input data. The macroscopical material behavior is an integral response of all microplanes. Material softening in tension based on nonlinear fracture mechanics is employed.

The nonlocal concept with microcrack interaction approach is used in order to avoid mesh sensitivity problems caused by spurious strain localization. In this model the opening of the microcrack at a certain place influences the microcrack development in neighborhood points in the normalizing volume. This volume is defined by the characteristic length, related to the concrete maximum aggregate size and the finite element size. Microplane material parameters used in the analysis should be adjusted in such a way that the local material properties (together with the characteristic length) correspond to the concrete properties measured in experiments.

The nonlocal microplane material model has been succesfully used for simulations of the behavior and for the determination of the load carrying capacity of fasteners in concrete members under normal conditions inclusive size effect (Ožbolt and Eligehausen, 1992).

Additional extensions to the original finite element code by Ožbolt were necessary for the numerical simulation of fasteners under fire loading. Input of several material types was enabled for modelling of the heated concrete specimen by different material properties in different temperature zones. Special precautions were implemented in order to avoid numerical problems by handling the material which degradates due to high temperature.

Incremental loading in axial direction with displacement control was used for the simulation of the pullout behavior of fasteners. The goal of the study was a comparison of the response and of the load carrying capacity of fasteners in cold and warm state. The principal difference between these two cases in the numerical simulation was in the use of material properties for concrete which were temperature dependent. In the cold state, the material properties for a concrete with a compressive strength of 25 MPa at a temperature of 20°C were adjusted and used within the entire specimen. In the warm state, the assumed temperature within the concrete specimen corresponds to the distribution after 90 minutes of fire exposure. The finite elements modelling the specimen were divided into zones with the same (or very similar) temperatures. Material properties for these zones were interpolated according to the relationships shown in Fig.1. For the fracture energy the same relative degradation as for the tensile strength was used. The zones of equivalent material properties were ordered in layers parallel to the slab surface, except for the case studying the heat conduction of the anchor. In this case the temperature along the fastener was higher and corresponding material properties were adjusted.

The pullout behavior of fasteners with embedment depths h_{ef} of 40, 50, 80 and 150 mm was simulated by the numerical analysis. The thickness of the concrete slab h was 300 mm for fasteners with embedment depths of 40, 50 and 80 mm, and 900 mm for fasteners with an embedment depth of 150 mm.

The behavior of an axisymmetrical part of the concrete slab surrounding the fastener was modeled. The remaining structure was substituted by appropriate boundary conditions. Loading was done by prescribing displacements in the contact area between the anchor head and the concrete. The scheme of the axisymmetric analytical model is shown in Fig.2. Two finite element meshes were used - a coarse mesh with about 250 finite elements, and a fine mesh with about 1000 elements. The coarse mesh (appropriately scaled) was used for the analysis of specimens with embedment depths of 40, 50 and 80 mm, the fine mesh was used for specimens with embedment depths of 50 and 150 mm. The results from the analyses with both finite element meshes for the embedment depth of 50 mm were compared in order to check the objectivity of the analysis with the coarse mesh.

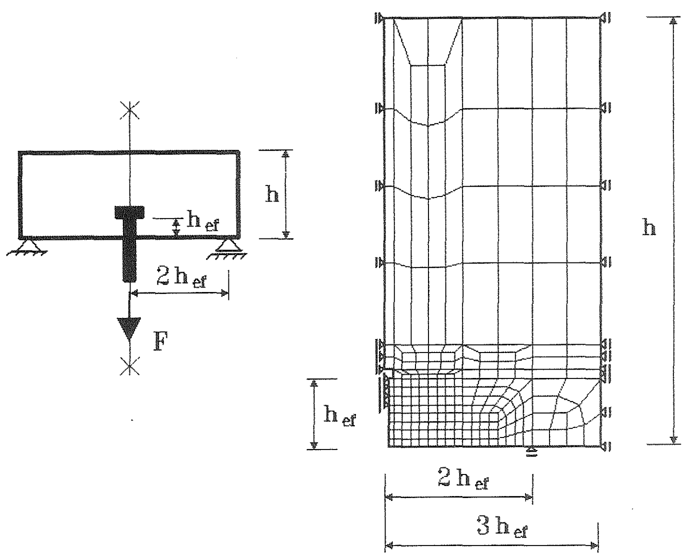

Fig.2 Scheme of the analytical model and finite element mesh

A further analysis for the embedment depth of 50 mm was performed with additional lateral compressive stresses in order to simulate more realisticly the state of stresses due to thermal expansion of concrete and service load on the slab. These stresses were produced by prescribing radial displacements in such a way, that the desired distribution of the additional stresses was reached at peak load.

4 Results from the analysis

The failure load of fasteners in a concrete slab under fire related to the value valid for the cold state is shown in Fig.3 as a function of the embedment depth. The concrete cone failure load of fasteners subjected to fire is considerably lower than in the cold state due to the reduction of the concrete tensile properties with increasing temperature. The difference decreases with increasing embedment depth. For an embedment depth of 40 mm, the remaining capacity is only 22%, for an embedment depth of 150 mm, the remaining capacity is about 55% of the value in the cold state.

Additonal compressive stresses due to thermal expansion of concrete (even if they are reduced due to service load on the slab) increase the remaining load bearing capacity of the fastener - for an embedment depth of 50 mm from 28% to 37% of the value in the cold state. On the contrary, the influence of the heat conduction of the fastener on the failure load is negligible.

The refinement of the finite element mesh for the specimen with an embedment depth of 50 mm has no influence on the failure load as well as on the stress/strain distribution during the entire loading process. Therefore, the results from the analysis with the coarse mesh are objective.

A comparison of the load-displacement diagrams for an embedment depth of 50 mm in Fig.4 shows that the behavior of fasteners under fire is more ductile, and the maximum displacements are larger than in the cold state. A similar behavior was obtained also for specimens with other embedment depths.

The concrete cone development in the cold and warm states is compared in Fig.5. The principal tensile strains at peak load and at termination of the analysis are shown. Large tensile strains are depicted by dark color. The large tensile strains represent the crack process zone, conturing the concrete cone. By comparing the slope of these cones, it can be seen that at peak load the shape of the cone under fire is smaller as in the cold state. This difference in the concrete cone shape is kept until failure.

5 Conclusions

- The behavior of fasteners under fire can be succesfully modeled by a non-linear analysis using the improved microplane model with microcrack interaction. Satisfactorily accurate results can be obtained using a relatively coarse finite element mesh.
- The concrete cone failure load of fasteners subjected to fire is considerably lower than in the cold state due to a reduction of the concrete tensile properties with increasing temperature. The difference decreases with increasing embedment depth.

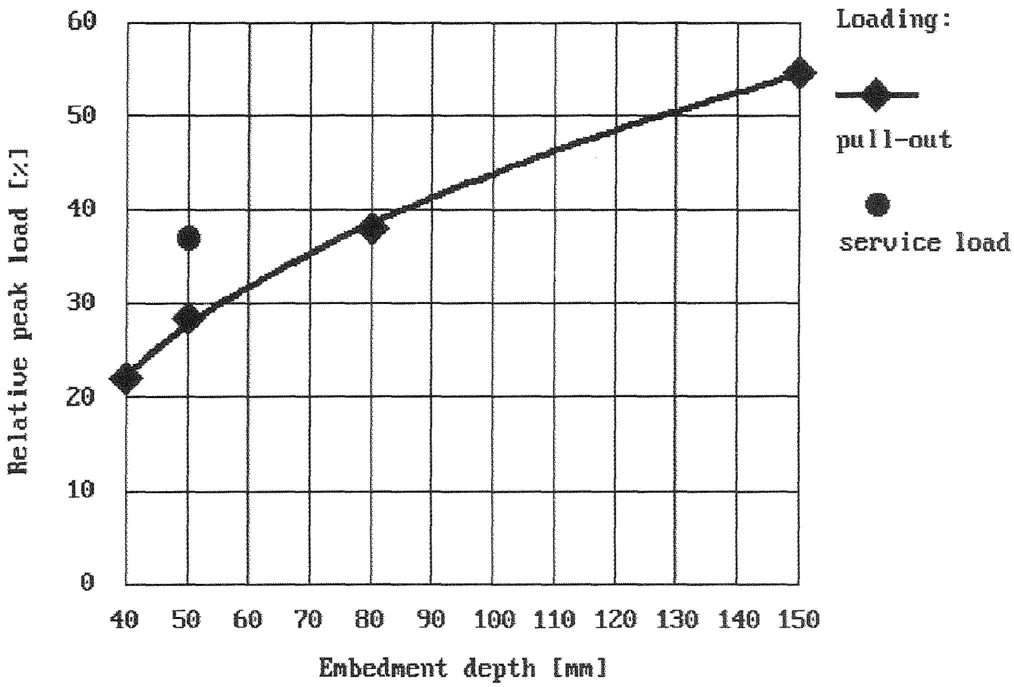

Fig.3 Remaining load carrying capacity under fire

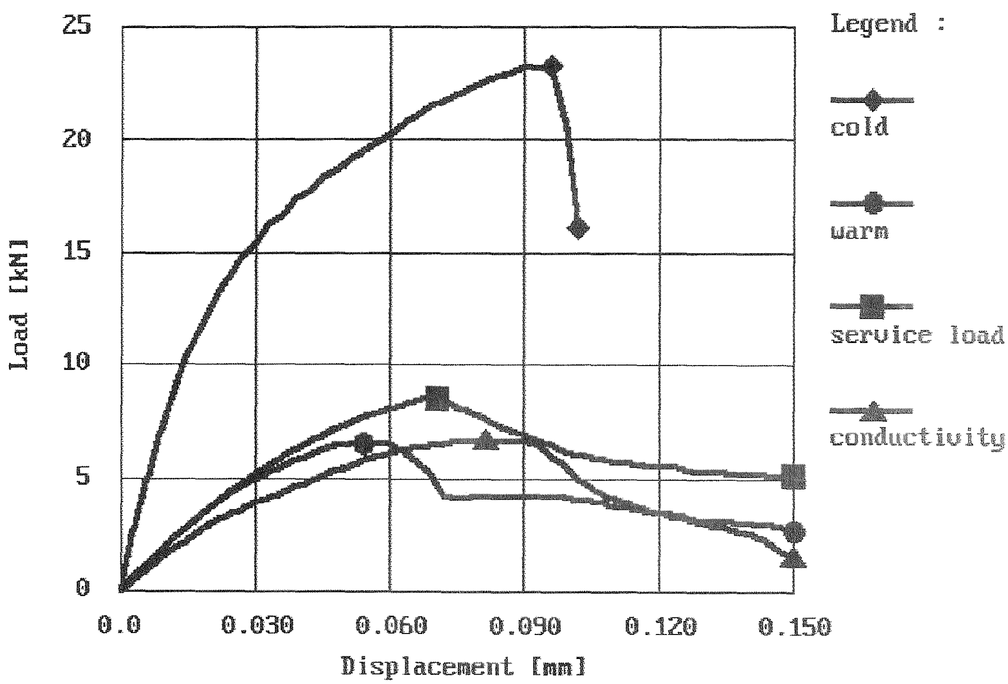

Fig.4 Load-displacement diagrams for an embedment depth 50 mm

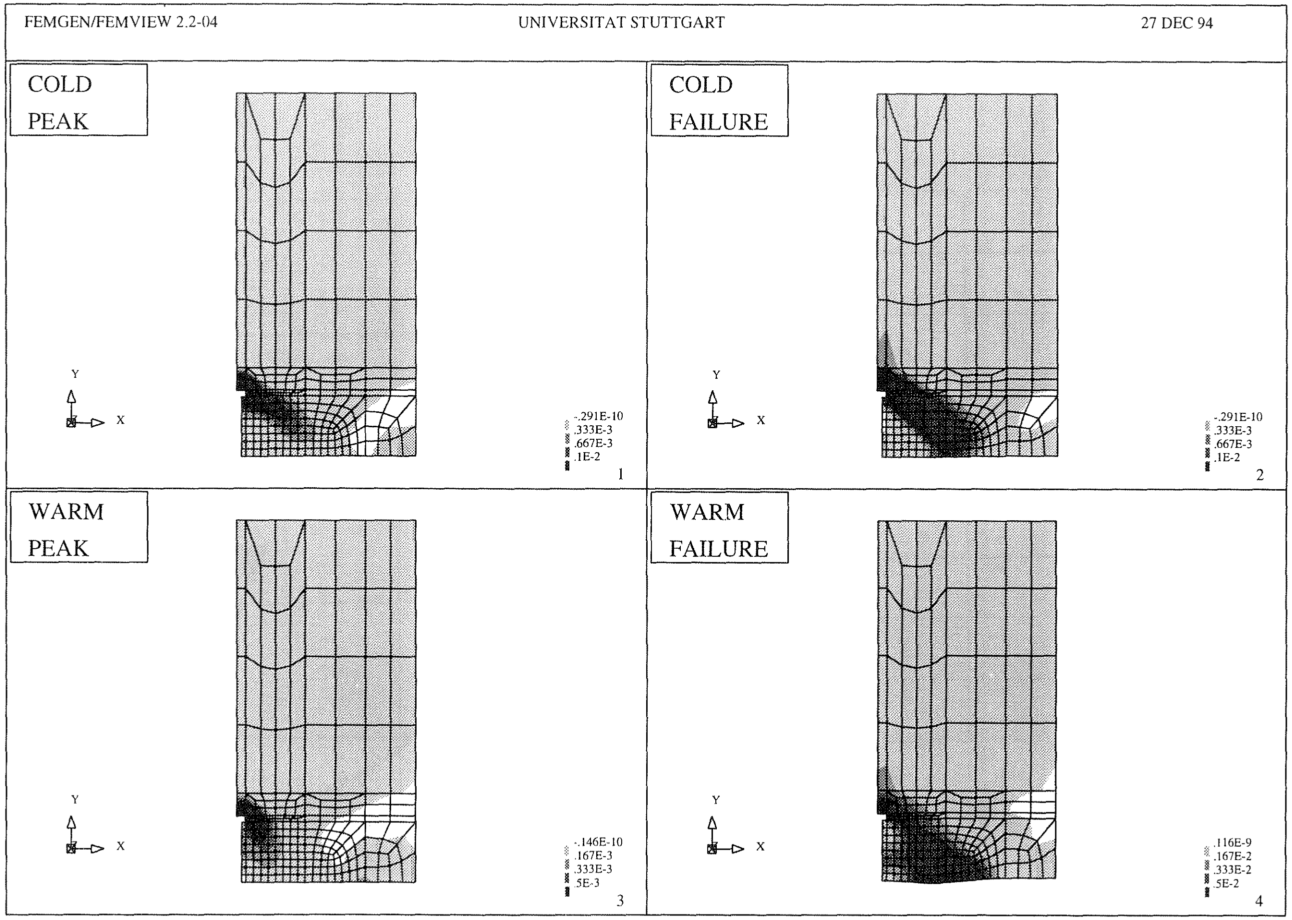

Fig.5 Distribution of principal tensile strains at peak load and at termination of the analysis, embedment depth 50 mm

- The behavior of fasteners under fire is more ductile and the maximum displacements are larger than in the cold state.
- Under fire the diameter of the concrete cone is smaller than in the cold state.
- The heat conduction of the fastener has no significant influence on the failure load.
- Additional lateral compressive stresses increase the load carrying capacity under fire, especially for fasteners with a small embedment depth.
- Because the results of the analysis depend significantly on the assumed material properties, tests are urgently needed to allow a comparison of numerical and experimental results.
- In practice, the concrete is often cracked and the crack widths in the interior of the slab will increase during fire. These cracks will influence the concrete cone failure load and the pullout capacity of cast-in-place and post-installed fasteners. Both effects were not modeled in the analysis. Therefore, much more research (experimental and numerical) is needed to fully understand the behavior of fasteners under fire.

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