DESIGN OF FASTENINGS BASED ON THE FRACTURE MECHANICS

R. Eligehausen and J. Ožbolt
Institute of Construction Materials, University of Stuttgart,70550 Stuttgart, Germany.

ABSTRACT
In the present paper the concrete cone failure mode is reviewed. Considered are headed stud anchors loaded by tensile load (pull-out) and by shear load against an edge of a concrete member. The influence of the material and geometrical parameters on the failure load and the size effect are discussed. The numerical and experimental studies confirm that fracture mechanics governs concrete break out failure. Consequently, there is a strong size effect on the nominal concrete cone strength that can be well described by a design formula that is based on linear elastic fracture mechanics.

1 INTRODUCTION

In engineering practice anchors are often used to transfer loads into reinforced concrete members. Experience, a large number of experiments as well as numerical studies for anchors of different sizes confirm that fastenings are capable to transfer tension and shear force into a concrete member without using reinforcement. Provided the steel strength of the anchor is high enough, a headed stud subjected to a tensile load or shear load against a concrete edge normally fails by cone shaped concrete breakout. A typical pull-out concrete cone observed in experiments (Eligehausen et al. [1]) is show in Figure 1a. Similar to the tensile loading, headed stud anchor loaded in shear against edge of a concrete member fails also by formation of a concrete cone. A typical failure mode is show in Figure 1b.

a) b)

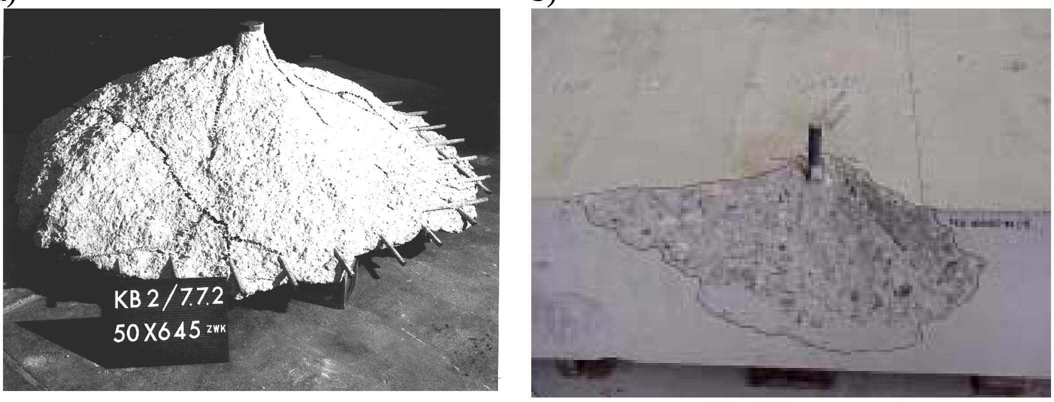

Figure 1: Typical concrete breakout cone obtained in the tests for: (a) tensile load and (b) shear load (Eligehausen et al. [1]).

To better understand the crack growth and to predict the concrete cone failure load of headed stud anchors a number of experimental and theoretical studies have been carried out (for the literature review see Eligehausen et al. [1]). Summarising these activities it can be said that the experimental results for headed anchors show a significant size effect on the concrete cone strength. Moreover, it has been demonstrated that numerical finite element studies based on macroscopic constitutive models according to the strength theory are not capable to predict the behavior of anchors as observed in the experiments (Eligehausen and Ožbolt [2], Ožbolt [3]). Therefore, more sophisticated numerical analysis needs to be carried out in which the employed computational model should account for the concrete strength and for the equilibrium between the structural energy release rate and energy consumption capacity of concrete, i.e. fracture mechanics must be taken into account.

2 EXPERIMENTAL AND NUMERICAL EVIDENCE ON THE CONCRETE CONE FAILURE

The concrete resistance of the headed stud relies only on the concrete cone tensile resistance (no reinforcement). Therefore, to design safe and economical structures it is important to fully understand the failure mechanism and to know how the variation of the material and geometrical properties influence the cone failure capacity. The first experiments in which the size effect on the concrete cone breakout strength has systematically been investigated were performed by Bode and Hanenkamp [4]. Later a number of experiments were carried out in which the embedment depth (tensile load) and edge distance (shear load) were varied up to 1500 mm, respectively (KEPRI & KOPEC [5]). To confirm the experimental results a finite element analysis has been carried out as well (Ožbolt [3]). The nominal tensile and shear cone strength for a number of experimental and numerical results are summarised in Fig. 2. The measured nominal concrete cone strengths are normalised to the concrete cube compressive strength $f_{CC} = 33$ MPa (normalising factor $=(33/f_{CC})^{1/2}$). The nominal strength σ_N is calculated as the ultimate load P_U divided by the area of a circle of a radius equal to the relevant anchor size parameter d:

$$\sigma_N = P_U/(d^2\pi) \tag{1}$$

where d is for the tensile load equal to the embedment depth h_{ef} and for the shear load is equal to the edge distance c. In the same figure a function ξ, which is based on linear elastic fracture mechanics (LEFM) is also plotted. The function reads:

$$\sigma_N = \xi(\alpha, \sqrt{G_F E_C}, d^{-0.5}) \tag{2}$$

where α is geometry dependent parameter, G_F is the concrete fracture energy and E_C is the Young’s modulus of concrete. As can be seen for tensile and shear load eqn. (2) agrees well with the experimental results for the whole size range. This means that the size effect on the nominal concrete cone strength is strong since formula based on LEFM predicts the maximal possible size effect (Reinhardt [6], Bažant [7]).

To find out the reason for the size effect and for the importance of fracture mechanics, the crack development and the distribution of the stresses along the crack surface were measured in tension pull-out test with $h_{ef} = 130$ mm, 350 mm and 520 mm (Eligehausen and Sawade [8]). In Figure 3a the strains normal to the crack surface at 30% and 90% of the ultimate load are plotted for an anchor with $h_{ef} = 520$ mm. Cracking started at about 25% of the peak load. At 90% of the ultimate load the crack length reaches approximately 35% of the total crack length at failure. The test data clearly show a stable crack growth, i.e. with increase of the crack length the resistance increases and reaches the maximum value at a critical crack length of approximately $l_{cr} = 0.35 l_{tot}$.

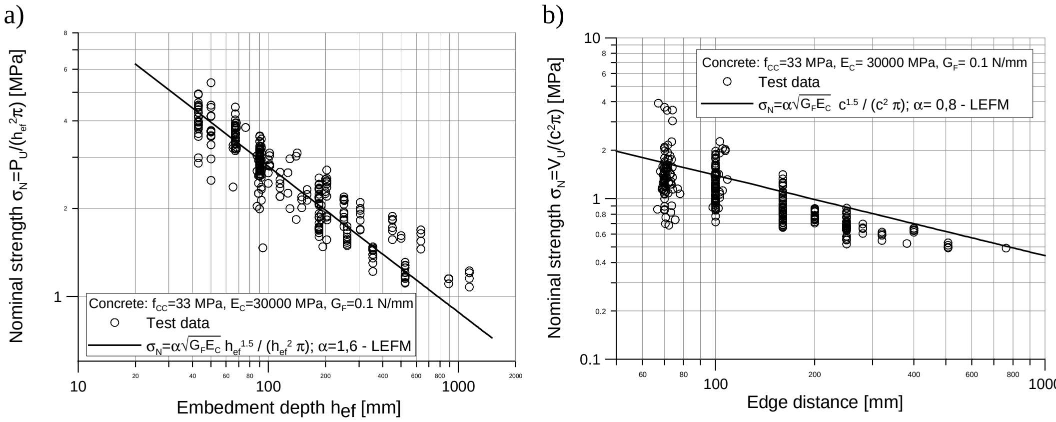

Figure 2: Concrete cone breakout - summary of experimental results and comparison with LEFM based formula for: (a) nominal pull-out concrete cone strength and (b) nominal shear cone strength.

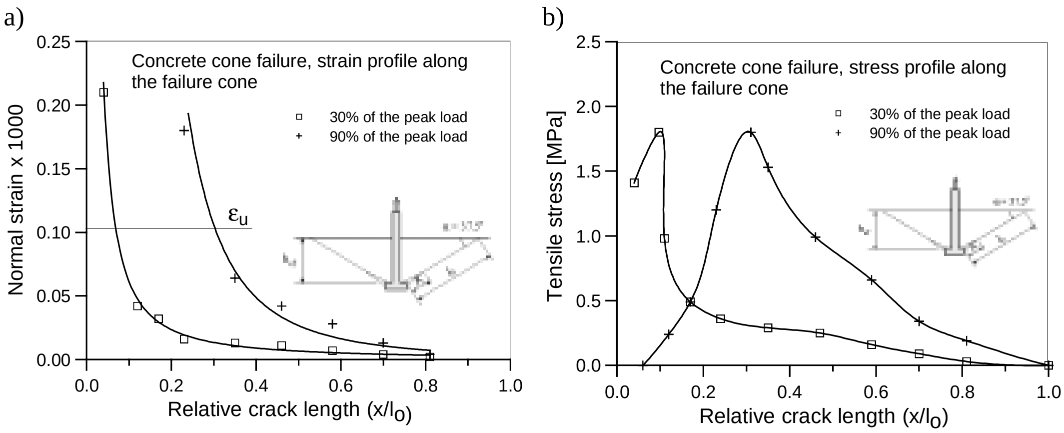

Figure 3: (a) The relative crack length at 30% and 90% of the ultimate load and (b) Distribution of stresses along the concrete cone surface at 30% and 90% of the ultimate load, h_{ef} = 520 mm (Eligehausen and Sawade [8]).

To confirm the experimental results a finite element analysis was also carried out (Ožbolt [3]). The analysis was based on the microplane model for concrete (Ožbolt et al. [9]) that accounts for the strength of concrete as well as for its energy consumption capacity (fracture energy). Typical failure modes for tensile and shear loads obtained from the 3D finite element analysis are shown in Figure 4.

It is well known that for the problems for which fracture mechanics governs the structural response, the variation of the concrete fracture energy influences much more the structural response then the variation of the material tensile strength. To investigate this a parameter pull-out study for a headed stud anchor with h_{ef} = 450 mm was performed as follows: (1) for constant G_F = 0.08 N/mm, the tensile strength was varied from 2.4 to 3.6 MPa and (2) for constant f_t = 2.8 MPa, the concrete fracture energy was changed from 0.08 to 0.14 N/mm. The calculated nominal pull-out strengths are plotted in Figure 5 as a function of the tensile strength and fracture energy, respectively. As can be seen, for the embedment depth of h_{ef} = 450 mm the nominal strength is practically independent of the tensile strength (Figure 5a). However, Figure 5b shows approximately a square root dependency between the nominal pull-out strength and the concrete fracture energy. The same result has been found by Eligehausen and Sawade [8], in a analytical study based on the LEFM and by the tests on headed studs pulled out from a glass specimen (Sawade [10]).

a) b)

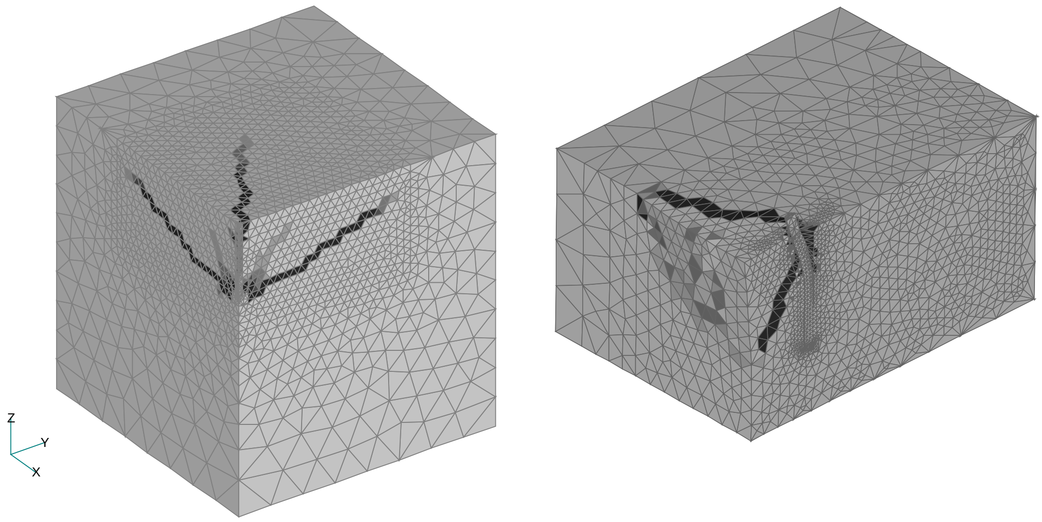

Figure 4: Typical failure modes obtained from the 3D finite element analysis: (a) tensile load and (b) shear load.

a) b)

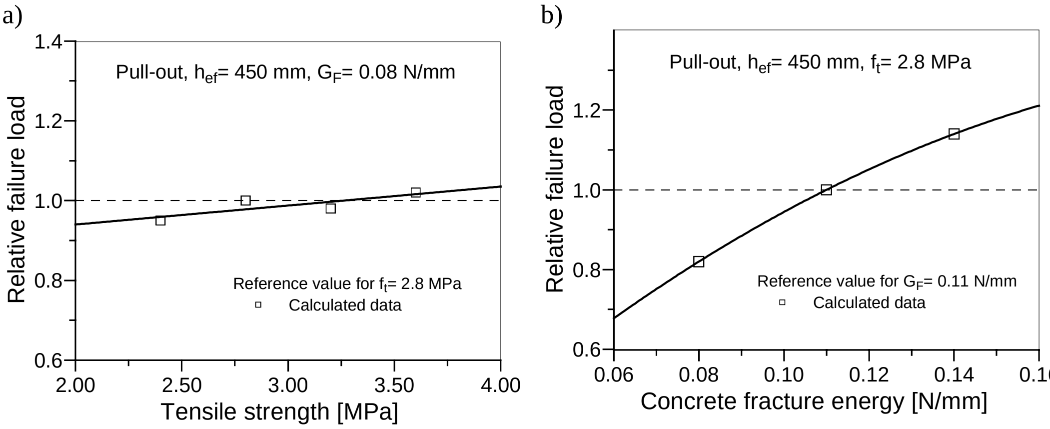

Figure 5: (a) Nominal pull-out strength as a function of concrete tensile strength (Ožbolt [3]); (b) Nominal pull-out strength as a function of concrete fracture energy (Ožbolt [3]).

3 DESIGN FORMULA BASED ON LEFM

The above discussed results clearly show that for concrete beak-out failure, cracking of concrete is an important aspect of the resistance mechanism. In contrast to a number of structures which rely only on the material strength, the concrete break out resistance relies mainly on the energy consumption capacity of concrete. To account for this the following design formula for prediction of the concrete cone failure load was proposed as (Eligehausen et al. [1]):

$$P_U = \beta \gamma \sqrt{f_{CC}}\, d^{1.5} \tag{3}$$

or in terms of the nominal strength:

$$\sigma_N = \beta^* \gamma^* \sqrt{f_{CC}}\, d^{-0.5} \tag{4}$$

where f_{cc} is concrete compressive cube strength, β and β^* are a calibration factor and γ and γ^* are geometry dependent parameters, which are for tensile load equal to one and for shear load depend on the bolt diameter and on the embedment depth.

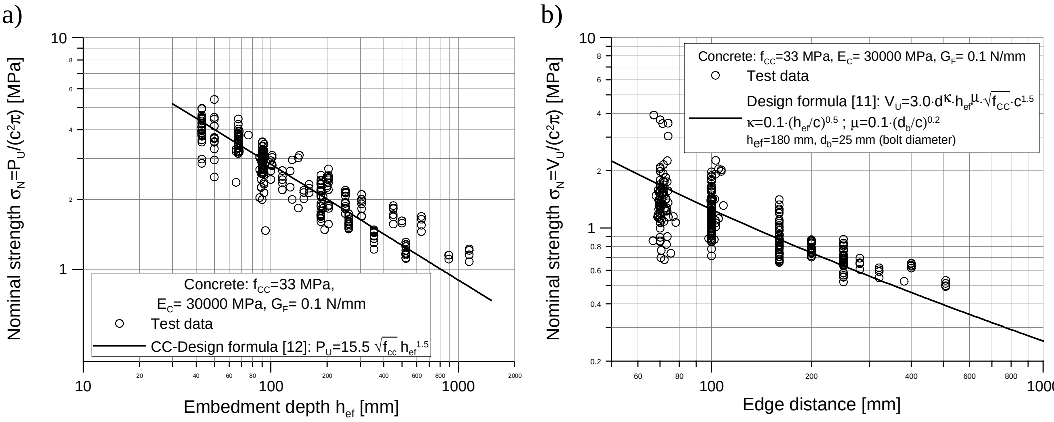

Figure 6: Concrete cone breakout - summary of experimental results and comparison with proposed design formula based on the LEFM: (a) nominal pull-out cone strength and (b) nominal shear cone strength.

Comparing eqns. (2) and (4) it can be seen that in eqn. (4) the product $G_F E_C$ is replaced by f_{CC}. This has been done for two reasons : (i) In engineering practice the compression strength rather than the fracture energy is measured and given in codes. Therefore, design equations based on the fracture energy are of limited value for the design engineer; (ii) For concrete strength classes often used in practice (15 MPa ≤ f_{CC} ≤ 60 MPa) the Young's modulus and fracture energy are approximately proportional to $f_{CC}^{1/2}$. Therefore the product $E_C G_F$ in eqn. (2) can be replaced by f_{CC}. However, E_C and G_F and thus the concrete cone capacity are influenced by size and type of aggregate (Sawade [10]). The information on this influence is lost when using eqn. (4) instead of eqn. (2). The prediction eqns. (3) and (4) are still sufficient accurate. This can be seen from Figure 6 which shows a comparison between eqn. (4) and the test data for tensile and shear concrete cone failure. As can be seen for both loading types the proposed design formula (eqn. (4)) fits the experimental results of the entire size range rather well. The design equation (3) has been incorporated in several standards [12-15] for the design of fastenings and is thus widely used in the practice.

4 CONCLUSIONS

The experimental results as well as numerical simulations confirm that a headed stud anchor embedded into a plain concrete member is able to transfer a tensile force into the concrete utilising only the tensile resistance of concrete with no need for reinforcement. The main reason for this is a stable crack growth. Consequently, the tests and the numerical studies show a strong size effect on the nominal concrete cone strength that can be well described by the prediction formula based on LEFM. Moreover, it is shown that a simple design formula, in which is because of practical reasons a governing concrete fracture parameter replaced by the concrete compressive strength, predicts concrete cone failure load realistically.

5 REFERENCES

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