Nonlinear Analysis of Anchorages Under Tensile Loading

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INTRODUCTION

During recent years the importance of anchorage technology with concrete structures has increased steadily. A lot of anchorage systems have to be analyzed before. All calculation methods are based on experimental results. This paper presents a nonlinear numerical approach to analyze the load-bearing behaviour and the limit loads of anchorage systems embedded in plain and reinforced concrete and loaded in tension.

STATE OF THE ART

The present formulae for calculating the limit load F_u of anchor bolt loaded in tension are (Roik et al., 1978)

$$F_u = 10.96 \cdot (h_s + d_2) \cdot \sqrt{h_s} \cdot \sqrt{\beta_W}, \qquad (1)$$

and

$$F_u = 15.5 \cdot h_v^{3/2} \cdot \sqrt{\beta_W} \qquad (2)$$

(Rehm et al., 1988), with β_W being the cubic compressive strength of concrete, d_2 being the head diameter and h_v being the embedment length of the anchor bolt (h_s stands for the bolt shank length).
Equation (1) is still the actual basis for calculating the limit loads of anchor bolts and headed studs in Germany. Influences on these limit loads, i.e. the spacing within a group or small edge distances, are not included in the formulae above, but can be considered by influence factors (æ-factors), if necessary.
These equations are based on experimental results. So it should be of great interest to verify these results by numerical analysis and if possible to give more detailed information of the load-bearing behaviour.

DEVELOPING A NUMERICAL MODEL

In order to analyze the basic effects on the load-bearing behaviour and the limit loads of anchor bolts a nonlinear finite-element model was developed. The model consists of two basic parts, the anchoring zone and the anchor bolt. Taking into account the axisymmetric form of the pull-out cone an axisymmetric analysis was performed (fig. 2).

NUMERICAL RESULTS

To estimate the load-bearing behaviour the load-displacement curves of anchor bolts embedded in concrete and loaded in tension must be studied. Fig. 3 gives three curves reflecting the results of experimental investigations (KIB, 1985). In addition fig. 4 shows the load-displacement curve which was found numerically. Both figures show in the first range a nearly linear behaviour up to a first load maximum which is about 50% of the limit load. After that the load is decreasing because there is no further equilibrium state. When a new equilibrium has been calculated the load is increasing again, although the gradient of increase is lower than before until a second load maximum is reached. With increasing deformation the load remains constant (limit load) or even decreases again. Comparing the experimental and the numerical results, fig. 3 and fig. 4 show good agreement so that a global calibration of the model is gained. For local calibration the crack propagation in the anchoring zone must be investigated. Taking into account that the computed crack propagation indicates micro-cracked zones (a smeared crack approach has been used) a good agreement with observations from experiments can be derived (fig. 5).

The following fig. 6 shows the numerical results of the stresses calculated for the radial reinforcement - the results for tangential crack propagation are similar (Jankowski, 1988) -. Obviously a significant stress development in the reinforcement can be pointed out only after the first load maximum. This indicates that up to the first maximum the load deduction is mainly carried out by concrete tensile stress transfer. After the maximum tensile strength is exceeded the load transfer is realized by aggregate interlock, dowel interaction and partially by tensile reinforcement.

The results reported above indicate that the load-bearing behaviour as well as the limit load of anchor bolts embedded in (reinforced) concrete and loaded in tension can be very well analyzed by a nonlinear numerical analysis. In the following different influencing factors will be discussed.

To show the significant influence of reinforcement on the limit load several calculations with different reinforcement ratios (bar diameters of 8 mm, 12 mm and 16 mm) were executed. Fig. 7 shows the results of these calculations as load-displacement curves of the anchor bolts. Before reaching the first load maximum the plotted curves are nearly identical while after that there is a significant influence of the reinforcement. Besides, if no reinforcement is employed the first load maximum indicates the limit load. The results are plotted in a diagram with the limit load F_{us} on the one and the reinforcement area a_s on the other axis (fig. 8). The relation between F_{us} and a_s can be given as:

$$F_{us} \sim \sqrt{a_s} \qquad (3)$$

The subscript *'s'* in F_{us} refers to the influence of reinforcing steel on the limit load.

A second influence being analyzed is the material property of the reinforcing steel. Different yield stresses were used, but the results were nearly identical which indicates that the yield stress of the reinforcing steel has no significant influence on the limit tensile load of anchor bolts.

The third parameter that turned out to be important too is the concrete strength. This was also found out by the experimental investigations. Several calculations with different strength set-ups lead to:

$$F_{us} \sim \sqrt{\beta_W}, \qquad (4)$$

which shows the proportional relation between the limit load and the tensile strength of concrete (β_W being the cubic compressive strength of concrete). It

was also found that the first as well as the second load maximum depend on the concrete strength.
Summarizing these results it can be stated that the first load maximum depends only on the concrete strength whereas the second load maximum, i.e. the limit load, depends both on the concrete strength and the reinforcement.
This gives the following expression:

$$F_{us} = k \cdot \sqrt{a_s} \cdot \sqrt{\beta_W} \qquad (5)$$

where k gives a value including the embedment length h_v and a constant factor. Using

$$\mu = a_s / h \quad \text{and} \quad h_v \approx h$$

with μ being the reforcement ratio and h being the effective height, then equation (5) becomes

$$F_{us} = 2.25 \cdot h_v^2 \cdot \sqrt{\mu} \cdot \sqrt{\beta_W}. \qquad (6)$$

It should be mentioned that h_v was kept constant in the analysis so that k could be evaluated in the way mentioned above.

Comparing equation (6) with the design concept for computing the punching load capacity of reinforced concrete slabs (Kordina/Nölting, 1986) it shows that punching of reinforced concrete slabs corresponds to pull-out of anchor bolts (fig. 9). This concept for punching reads:

$$F_{us} = 4.75 \cdot h^2 \cdot \sqrt{\mu} \cdot \sqrt{\beta_C} \cdot f_0 \qquad (7)$$

where f_0 is a geometrical factor and β_C the cylindrical compressive strength of concrete.

An interpretation of more than 50 experimental results of pull-out tests compared with the results gained from equations (6) and (7) respectively is shown in fig. 10. The diagram proves good agreement.
As equations (6) and (7) include the reinforcement ratio they are insufficient for zero reinforcement. So the question arises which equation must be used, on the one hand equation (1) or (2) and on the other hand equation (6) or (7) respectively? Investigations (Jankowski, 1988) show a negligible influence of steel reinforcement on the pull-out load of anchor bolts for embedment lengths less than 100 mm and reinforcement ratios less than 5 cm^2/m so that equation (1) or (2) should be used. If necessary, here æ-factors must be employed. For other anchorages equation (6) or (7) is more suitable.

CONCLUSION

The load-bearing behaviour and the limit loads of anchor bolts embedded in concrete and loaded in tension can be examined by a nonlinear numerical analysis. A nonlinear finite-element model is presented which is able to determine some of the most relevant influences on anchorages. Special focus is given on the influence of reinforcing steel.

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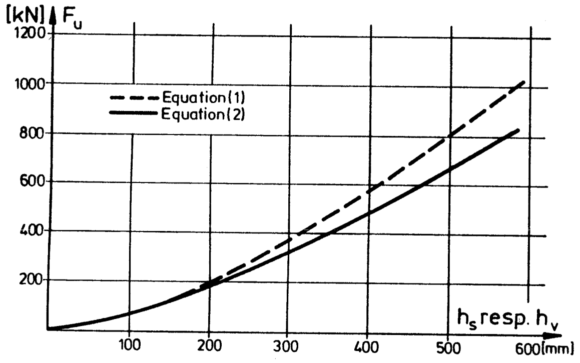


Fig. 1: Limit Loads for Headed Studs

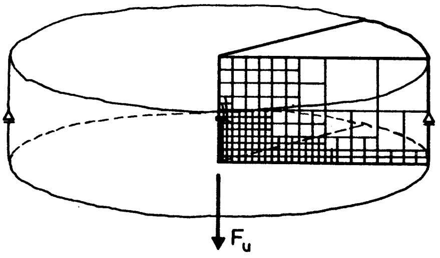
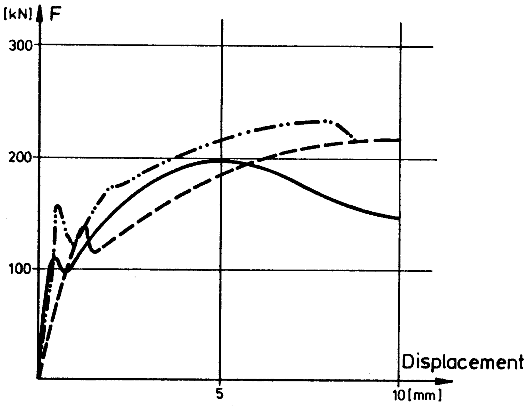
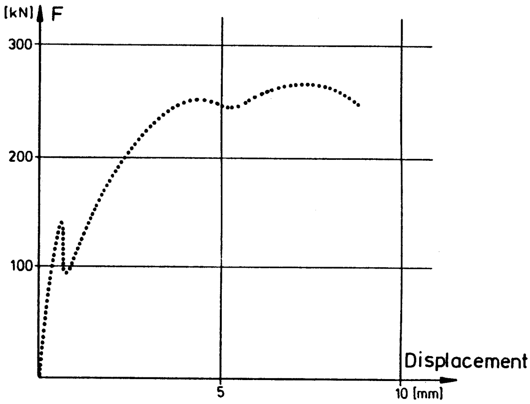


Fig. 2: FEM - Model





Load-Displacement Curves for Headed Studs

Fig. 3: Experimental Results

Fig. 4: Numerical Results

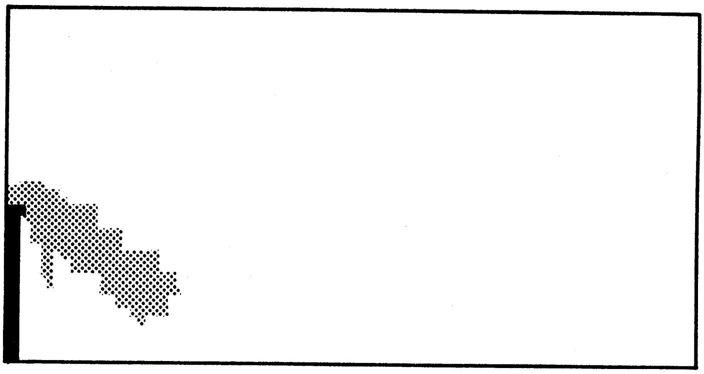


Fig. 5: Tangential Crack Propagation

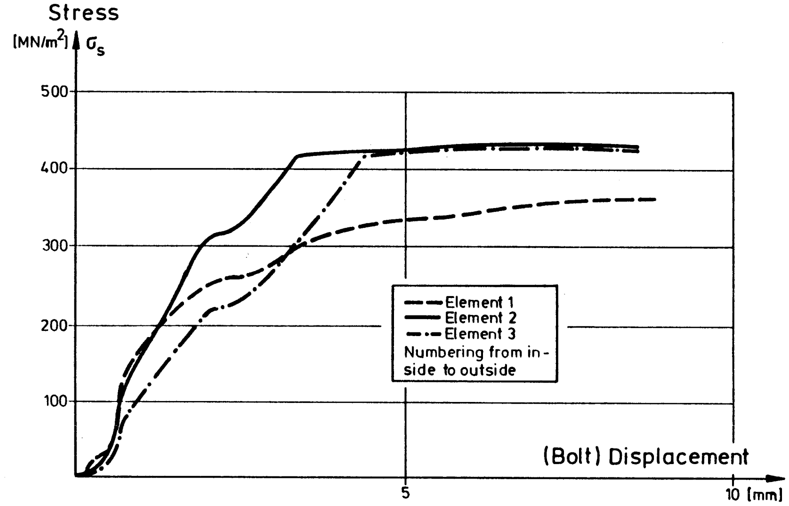


Fig. 6: Radial Reinforcement Stresses

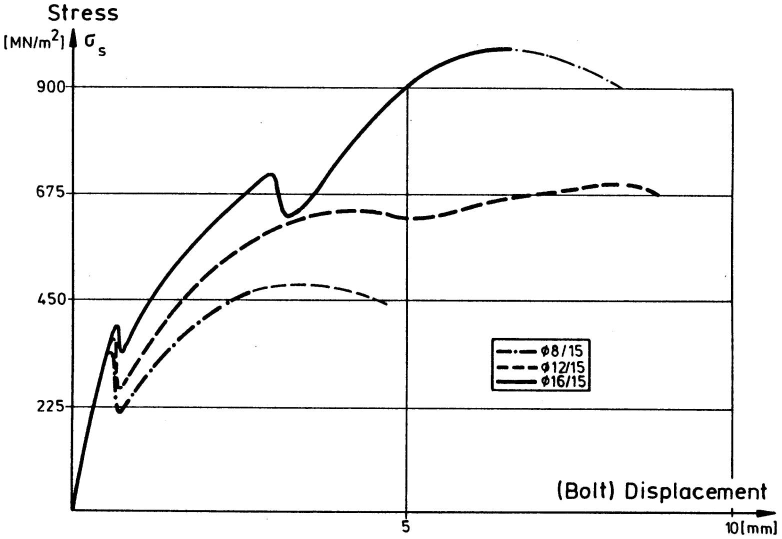


Fig. 7: Bolt Stress vs. Bolt Displacement for Different Reinforcement Ratios

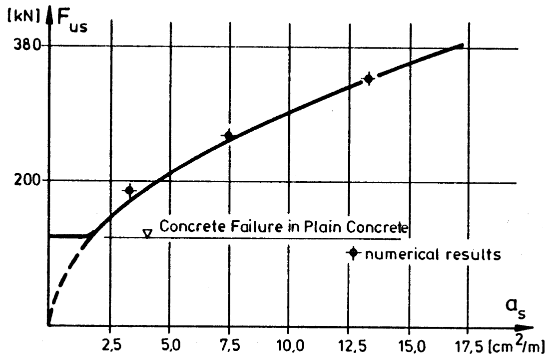


Fig. 8: Limit Loads vs. Reinforcement Ratio

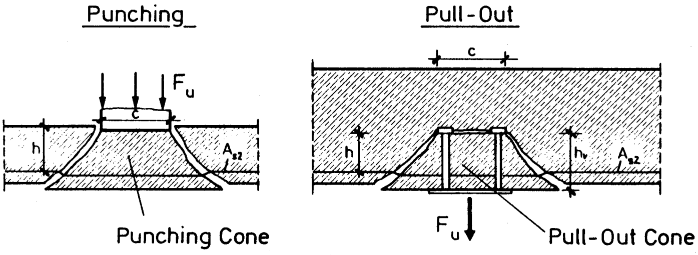


Fig. 9: Failure Cones

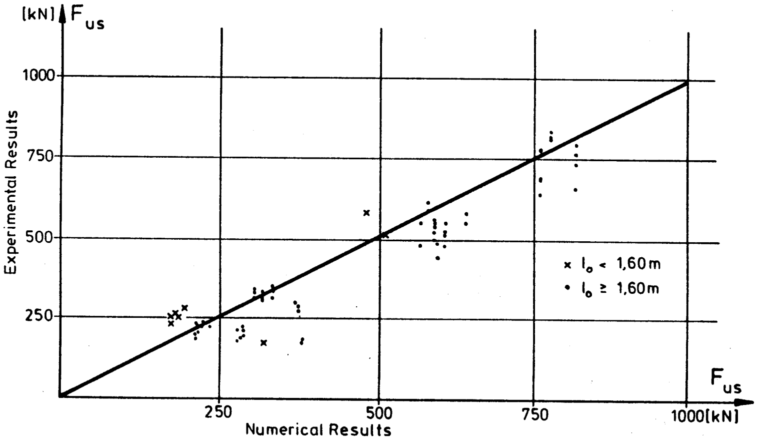


Fig. 10: Limit Loads of Headed Studs and Anchorplates
- Experimental Results vs. Numerical Results -