FASTENING ELEMENTS IN CONCRETE STRUCTURES

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Abstract

Anchoring elements such as headed-, expansion-, grouted or undercut anchors are often used for the transfer of loads into concrete members. In order to better understand the failure mechanism, a large number of experiments has been carried out in the past. In the present paper the influence of geometrical and material parameters on the concrete cone resistance of headed anchors is shown. The numerical study is carried out by employing a nonlocal finite element code and the microplane model for concrete. Comparison between experimental and numerical results indicates reasonable good agreement. When using a local (crack band) approach the numerical results are generally mesh dependent. It is observed that the failure mechanism is governed by fracture energy rather than by tensile strength of concrete. As a consequence, the size effect is strong and close to the prediction based on linear elastic fracture mechanics.

1 Introduction

In current engineering practice, fastening elements are used to transfer load into reinforced concrete members. Experience, a large number of experiments and numerical studies confirm that fastenings are capable to introduce tensile force into a reinforced concrete member without using reinforcement. As shown by Eligehausen and Sawade (1989b) and Ožbolt and Eligehausen (1992), the main reason for this is a stable crack propagation up to the peak load as a consequence of the three-dimensional stress-strain state in the load transfer zone. Since no reinforcement is present, the fracture process zone is relatively small and failure is relatively brittle. Therefore, it is important to clearly understand the failure mechanism and the influence of different geometrical and material parameters on the load capacity. This is not simple because in the practice many types of fastenings exist as well as a number of different geometrical configurations.

The simplest fastening case is a single headed anchor transferring a tension force into a large concrete block. Provided the steel strength of the stud is high enough, headed studs embedded in a concrete block subjected to tensile loading fail by pulling a concrete cone out of it. The failure is due to the failure of concrete in tension by forming a circumferential crack growth in so-called mixed mode (Eligehausen and Sawade, 1989b). In the past, several attempts have been made to understand this growth and to predict the pull-out load of headed studs (Ottosen, 1981; Eligehausen and Sawade, 1985; Krenchel and Shah, 1985; Ballarini, Shah and Keer, 1986). Summarizing these activities it can be said that material models based on plasticity and on macroscopic stress-strain relationships together with stress criteria are not capable to predict the behavior of anchors as observed in experiments (Eligehausen and Sawade, 1989a). A better explanation of anchorage failure mechanism can be expected using more general material models based on fracture mechanics. These models must describe the material nonlinearity and the fracture process in concrete correctly.

2 Numerical example - single headed anchor

Due to the fact that the ultimate load of headed anchors relies only on the concrete cone resistance (no reinforcement), it is important to know how the variation of the embedment depth influences the pull-out failure load. Therefore, in the past a number of experiments have been carried out (Eligehausen and Sawade, 1989; Eligehausen et al., 1992). In these experiments, the concrete properties have been kept constant and only the geometry of the headed anchor and the embedment depth were scaled proportionally. Most of the available experimental data exist for embedment depths between $d=$ 50 to 450 mm and only one set of experimental results is available for an embedment depth up to $d=$ 520 mm. These experimental results indicate a strong size effect on the nominal pull-out strength in the whole size range investigated.

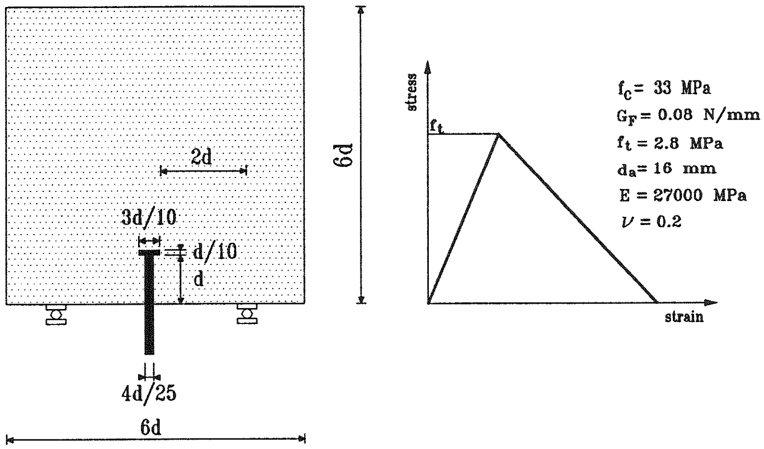

Fig. 1 Geometry and material properties used in the analysis.

To check the experimental results, a numerical analysis is carried out for a broad size range. The nonlocal axisymmetical FE-code based on the microplane model is used (Ožbolt and Bažant, 1995). The specimen geometry and principal concrete properties employed in the analysis are shown in Fig. 1. Five similar geometries with embedment depths $d=$ 50, 150, 450, 1350 and 2700 mm are considered (range 1:54). Besides the embedment depth, the anchor bolt diameter and anchor head diameter are scaled proportionally.

In Fig. 2a the calculated load-displacement curves are plotted. Fig. 2b shows the calculated peak loads as a function of the embedment depth. For comparison the experimental results are also plotted and compared with Bažant's size effect law, the size effect design formula proposed by Eligehausen and Sawade (1989) and the design formula given by ACI-349, 1980, which neglects the size effect. As can be seen, the numerical results are in a good agreement with the experimental results. In the investigated broad size range ($d \leq$ 2.7 m), the numerical results agree well with Bažant's size effect law and are in close agreement with the design equation proposed by Eligehausen and Sawade (1989), which is based on linear elastic fracture mechanics. Obvious disagreement with the no size effect formula can be seen. As a consequence of a stable crack growth before reaching the peak load, the proportionality of the crack length at peak load is approximately assured and the size effect is strong in a broad size range.

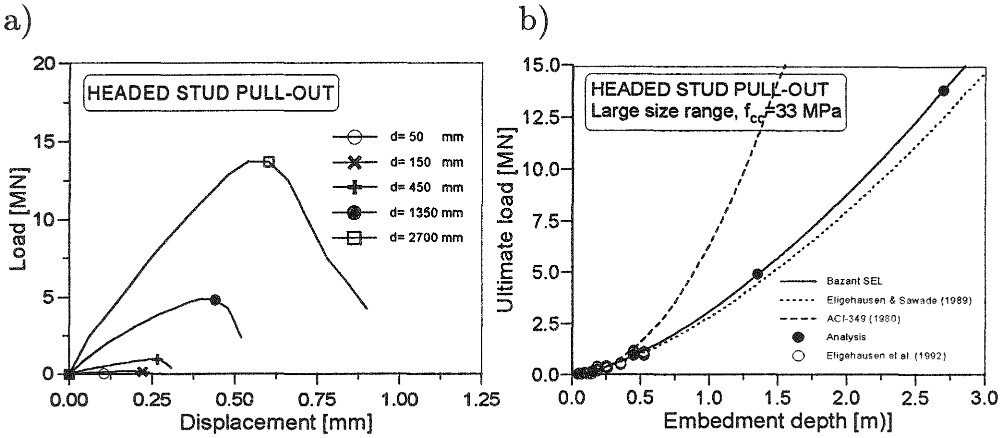

Fig. 2 Pull-out failure load; a) Calculated load-displacement curves and b) comparison of numerical and experimental results with Bažant's size effect law, no-size effect design formula (ACI-349, 1980) and size effect design formula (Eligehausen and Sawade, 1989).

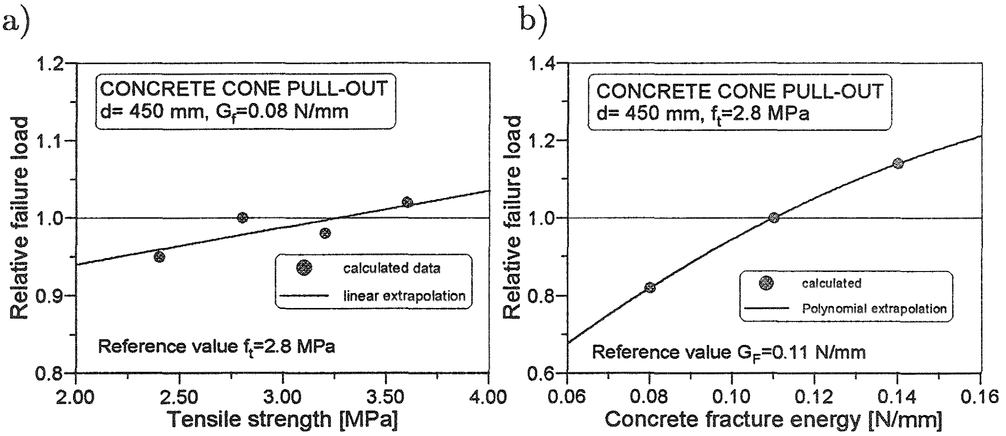

Fig. 3 Calculated relation between the concrete cone failure load for an embedment depth d= 450 mm: a) As a function of the tensile strength (G_f= const); b) As a function of the concrete fracture energy (f_t= const).

Since stable cracking is assured, the concrete fracture energy should significantly contribute to the failure resistance. To demonstrate this, in Fig. 3a,b the calculated relative pull-out loads are plotted as a function of the concrete tensile strength and fracture energy respectively. As can be seen, the failure load is practically independent of the tensile strength (Fig. 3a), however, it is approximately proportional to the square root of the concrete fracture energy. The same results have been confirmed in an experimental study of Sawade (1994), in which a headed stud was pulled out of a glass specimen.

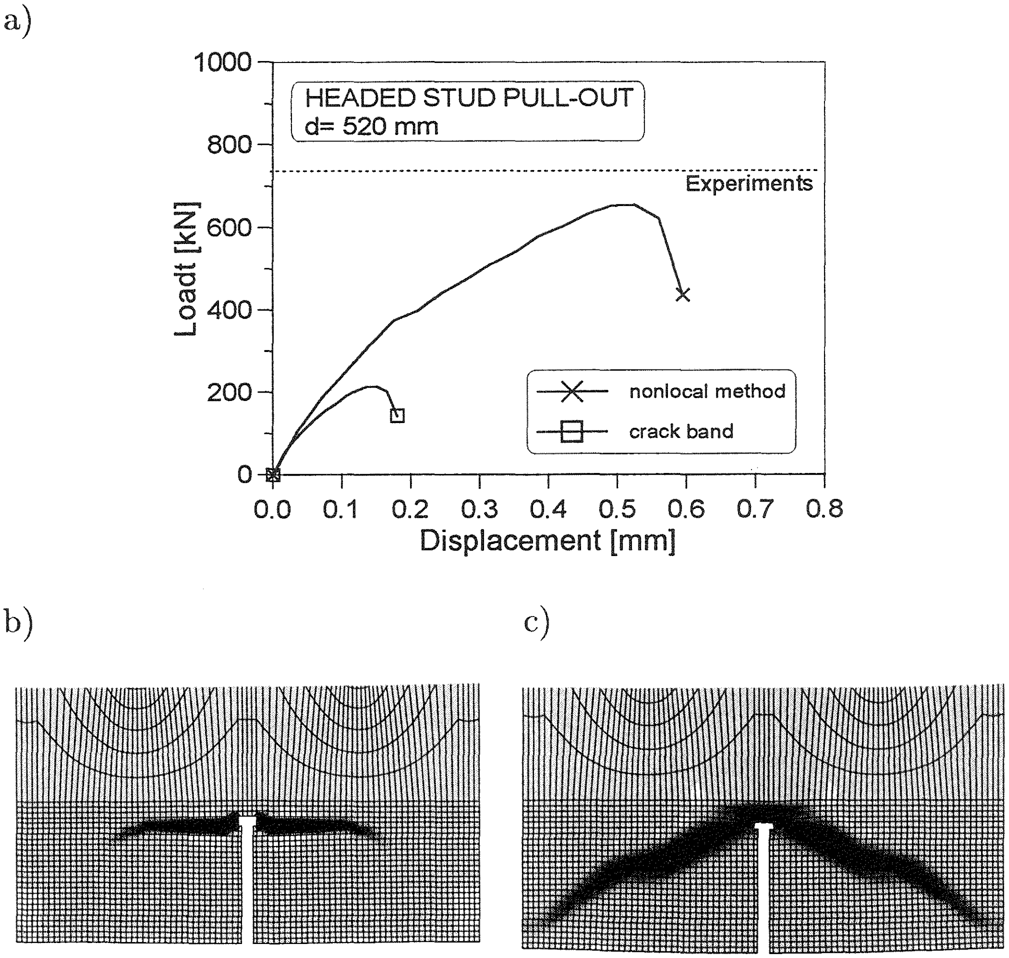

Fig. 4 Comparison between local (crack-band) and nonlocal analysis; a) Load-displacement curve, b) crack pattern – crack band approach and c) crack pattern – nonlocal analysis.

The above numerical results obtained using a nonlocal FE code show a good agreement with the experimental results. On the contrary, when using a local FE code based on the crack band approach, the results are mesh dependent. To demonstrate this, in Fig. 4a the calculated load-displacement curves are plotted, obtained for the above geometry with an embedment depth $d=$ 450 mm using a local (crack band approach) and nonlocal analysis. Furthermore, the predicted crack patterns at peak load are shown in Fig. 4b (local analysis) and Fig. 4c (nonlocal analysis). Although the same meshes and the same material parameters have been employed in both studies, it is obvious that the local analysis significantly underestimates the measured failure load. The nonlocal analysis predicts the experimental result with sufficient accuracy. Comparing the failure modes it can be seen that when using the crack band approach the critical crack propagates along the mesh alignment (see Fig. 4b) and not diagonally to the support direction, as observed in tests and in the nonlocal analysis (see Fig. 4c). Obviously, a local (crack band) analysis of headed stud anchors pulled out from a concrete block generally leads to results which are mesh sensitive.

3 Conclusions

- In engineering practice different types of anchorage elements are effectively used for the transfer of loads into a concrete member. In most cases this load transfer relies only on the concrete tensile resistance. The load-transfer mechanism is rather complicated.
- The results of the presented nonlocal finite element analysis of a single headed anchor embedded into a large concrete block are in good agreement with experiments. They indicate a stable cracking process before reaching peak load. Therefore, the concrete fracture energy significantly contributes to the peak resistance and the size effect on the pull-out strength is strong in a broad size range.
- A nonlocal smeared finite element fracture analysis is able to correctly reproduce the failure mechanism and resistance of headed anchors as observed in experiments. However, when a local finite element code based on the crack-band approach is used, in general the numerical results are mesh dependent. Only in the special case when the mesh direction approximately coincides with the direction of the failure crack one may expect realistic results.

4 References

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