FEM 3D analysis of rock cone failure range during pull-out of undercut anchors

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Abstract. The paper presents the results from FEM (Finite Element Method) analysis of the process of pulling out of the undercut anchor. Anchors of this type are generally used to fasten steel structural elements in concrete buildings. However, the presented issue concerns a new area of application of these fasteners, i.e. in the aspect of the potential mining of rock in atypical situations, such as in mining rescue operations. Generally, in such situations there is no possibility of mechanical mining of rock with the use of mining machines and the use of explosives is even prohibited. There are only manual loosening methods whose effectiveness is unknown. Currently, the basic issue is to gain insight into the mechanism of loosening, the mechanics of the process in terms of the extent of loosening and shaping the force of pulling out anchors in a given rock. An effective tool in this type of analysis is FEM analysis, the results of which are presented in the paper.

1. Introduction

Numerous construction solutions for anchors are found among fastening methods (figure 1, 4) [1,2]. Each is slightly different in terms of the mechanism of transferring the load from the anchor to the rock and the mechanism of the potential destruction of the structure of concrete or rock [1–19]. The anchors in figure 1a are used in the form of foundation bolts and are fixed in concrete when the concrete is poured. The remaining ones are fastened after drilling appropriate holes in the material in an adequate technological process.

Figure 1. Common mechanical anchor types [1,2]: a) Cast-in headed stud; b) Torque-controlled expansion anchor (bolt type); c) Displacement-controlled expansion anchor; d) Undercut anchor.
In the engineering practice, there are two simplified mechanical models (figure 2) describing the potential course of destruction of the material of a structure in which the anchor is mounted [1,3–7].

**Figure 2.** (a) Conical failure surface. (b) Four-sided pyramid failure surface [15,19,20].

In earlier models, conical damage was taken into account (concrete breakout in tension) of half-angle of the cone, equal to 45° [15,20]. Currently, the cone angle is slightly larger, since the mean value of the angle between the plane perpendicular to the axis of the cone (anchor) and the one creating a cone (figure 2, figure 3) is approx. 35° [1,3–7,21]. The practice and some analyses [22], however, indicate that the value of this angle changes within wide range and the loosening of the surface has a more complex shape, which translates into the extent of loosening measured on the free surface [2,9–19,22].

**Figure 3.** Concrete cone behaviour using the tensile damage parameter in ABAQUS [30].

The models above are used to analyse the extent of potential loosening, i.e. breakaway cone (damage), as well as estimating the maximum load-bearing capacity of the anchor for the assumed effective anchorage depth and strength parameters of the surface (e.g. concrete). This force is at the same time the minimum (under given conditions) force pulling out anchors from the surface.

Due to the number of construction solutions of anchors, the specificity of conducted numerical tests, numerical models implemented using, for example, FEM (e.g. [17], figure 3), also do not give unambiguous answers when this issue is concerned.

The aspect of precisely defining the extent of loosening is vital from the point of view of research because it determines the volume of loosening material being removed in one pull-out of the anchor. Therefore, there is a need for further research in the subject matter, especially with the use of FEM, as this method offers the most spectacular results in terms of fracture mechanics development in simulations.
2. Numerical tests using FEM

Actually, FEM systems are effectively used in many areas of research, e.g. in medical sciences (e.g. [23–25]), aviation (e.g. composite fracture [26–28]) and other engineering activities.

The influence of undercut anchors type Hilti HAD-P [29] on rock has been tested (figure 4).

![Pre-set undercut Hilti HDA-P anchor](image)

Figure 4. Pre-set undercut Hilti HDA-P anchor [14].

2.1. Numerical simulation assumptions

The numerical analysis was carried out using the FEM ABAQUS system (e.g. [30,31]). The geometric model of the analysed problem is shown in figure 5. The 3D model was obtained by rotating a flat model (figure 5a) around the longitudinal axis of the anchor. Figure 5b shows the quarter of the model obtained this way. This model was discretised with C3D8R elements (linear, continuum 3-D element, 8-node reduced integration). The impact of the anchor head (conical part) on rock was modelled in a simplified way by applying vectors of elemental forces in the nodes of the surface of hypothetical contact of the anchor with rock. Fixings: external vertical plane lower side and bottom - fixed, vertical middle plane - symmetry (figure 5c). The analysis was carried out for the geometrical parameters of the model: \( L = 700\text{mm}, \ h_{ef} = 100\text{mm} \).

![Scheme of the task](image)

Figure 5. Scheme of the task.
The sandstone material was modelled as linear-elastic with Young modulus $E = 14.276$ GPa, Poisson’s ratio $\nu = 0.247$, tensile strength $f_t = 7.74$ MPa, and the fracture energy $G_F = 0.335$ N/mm.

The paper presents the results of simulation when the coefficient of friction of the anchor against rock $\mu = 0$ (elementary force vector in the node is perpendicular to the surface of the conical anchor, it is $\mu = \tan \rho = 0 \Rightarrow T = 0, N_i = N, N = P/\cos \gamma$).

In the simulation, the active force (pulling the anchor) $P$, forcing the movement of the anchor along the OY axis (figure 5b), was replaced by the equivalent action of an equivalent load, distributed in the surface of the undercutting anchor’s cone, as in figure 6. Otherwise, $P = \sum N_i \cos \gamma$. The angle $\gamma$ value was determined on the basis of the characteristic data of the anchor (figure 5c).

Figure 6. A fragment of the FEM mesh of an axially symmetrical 3D model of the tested undercut anchor.

Figure 7 presents a quarter of the model illustrating how to fix nodes located on its lateral external surface and in the base.

Figure 7. Boundary conditions of the model, restraint, load.
3. Computer simulations

Figure 8 illustrates the numerically obtained failure (cracking) surface and distribution of maximal principal stresses.

As it can be seen, the crack near the top edge began to distort and return. This is related to the limitations of ABAQUS procedures. The state of stress here was so complex that the programme probably could not decide how to lead the crack. For various programme settings and different mesh, it was not possible to cause the crack to go through to the end (see [16,30,31]).

Figure 9 illustrates the outline (in YZ-plane) axisymmetric failure surface and the average value of the angle of the concrete cone failure. The value is 25°, which is the lowest value among those available in literature sources (for example [16,19,32]).
4. Conclusions
The tests indicate that for the assumed mechanical parameters of rock and the depth of undercutting the rock with an anchor (\(h_{ef}\), figure 1), the value of the angle of the cone failure is approximately 25°. In experimental studies carried out in the conditions of Polish stone mines, the obtained values of this angle were by almost 40% lower.

With a view to further verification and investigation, other simulation conditions are set to be investigated (material data, depth of undercutting \(h_{ef}\), undercut anchor groups).

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