Comparison of crack propagation analyses in a pull-out test*

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Abstract

This paper describes the computer analysis of the pull-out test for determining the force needed to pull out a rock fragment and the shape of this fractured fragment. The material analyzed is sandstone. Two tasks were analyzed depending on the length of the pulling anchor. The analysis also included a comparison of the various crack propagation methods in computer programs using the Finite Element Method. It is planned to perform laboratory tests to verify the accuracy of selected computer methods.

Keywords: X-FEM, crack, pull-off test, numerical analysis, sandstone, rock mechanics

1. Introduction

The authors of this paper performed series of computer analyses of the pull-out test in which the Hilti anchor is pulled out of the sandstone rock. Typically, these anchors are used to anchor various construction elements. The described test is intended for the opposite purpose - to pull out the anchor together with a part of the rock. These analyses are intended to be used in mining, including mine rescue, where it is not possible to destroy rocks with explosives, which is a popular method today. Pre-set undercut Hilti HAD-P [1] anchors will be used for this purpose. The picture of this anchor is shown in Figure 1.

Figure 1: Pre-set undercut Hilti HDA-P anchor

To mount this anchor, it is placed in a prepared hole in a rock surface, and then the anchor is pressed. Then while drilling it will undercut itself with deflecting elements. This means that during an attempt to remove this anchor, there is no significant contact between the rock and the side of the anchor, but with formed, small undercut. Upon reaching the right critical force, a crack in the rock appears in the area of the anchor undercut, which grows with increasing force, causing the rock to break and pulling out its part.

Similar problems are the subject of many papers, but most commonly the examined material is concrete, not rock, as in articles [8] and [9]. In addition, instead of undercut anchors, steel bars fixed to the surface of the examined material are used usually. Thus the characteristics of this test are completely different from those described in this paper. The article [9] also presents the computer simulations of this experiment.

The authors have attempted to estimate the critical force and to determine the size of the pulled fragment of the rock in two variants of anchor lengths – 10 cm and 20 cm and two computer methods of crack modeling – X-FEM method and the author's method of finite element deletion.

2. Description of the numerical models

Two computer programs were used for calculations. Abaqus was used for the X-FEM method, and the element deletion method was adapted in the Algor program. Since these are axially symmetrical tasks, they are modeled in 2D layout. The computational models is presented in Figure 2, where h is the length of the anchor. The load was simulated by the y-direction displacement. The sandstone material was modeled as linear-elastic with Young modulus $E = 27$ GPa, Poisson ratio $\nu = 0.2$, and tensile strength $f_t = 2$ MPa. Additional laboratory tests of material parameters are planned.

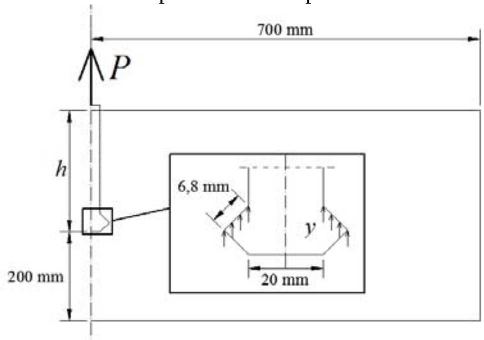

Figure 2: Scheme of the task

Tensile strength is also the stress that initiates the crack. The critical force is determined by the sum of the vertical reactions in nodes with applied displacement.

It was attempted to analytically estimate the critical force, as shown in Figure 3.

Stress in the area near the crack tip was obtained from a Moslemi cohesive zone model [4] and Dugdale method. It was simplified to a rectangular shape. The cohesive zone length was calculated from:

$$l_{Ic} = M \cdot E \cdot \frac{G_{Ic}}{\sigma_{Ic}^{\;2}} \tag{1}$$

where $M=\pi/8$ is a parameter for Dugdale model, E is the Young modulus, $\sigma_{Ic}=f_t$ are the stresses that initiates the crack growth. G_{Ic} is the critical strain energy release rate for mode I:

$$G_{Ic} = \frac{K_{Ic}^{\;2}}{E} \tag{2}$$

K_{Ic}=14.56 N/m$^{3/2}$) is the stress intensity factor in mode I for sandstone which was adopted from Rechtorisz et al. [7].

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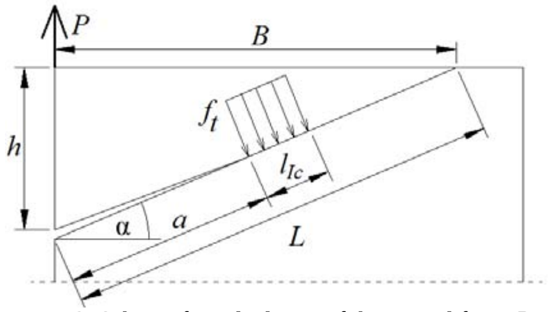

Figure 3: Scheme for calculation of the critical force P

The force P was calculated from equilibrium of vertical forces. P is equal to vertical component of stress field volume, which is a solid of revolution:

$$P(a) = 2 \cdot \pi \cdot \cos^2(\alpha) \cdot \left(a + \frac{l_{Ic}}{2} \right) \cdot f_t \cdot l_{Ic} \tag{3}$$

where a is a variable crack length, the adopted angle α is 25°. For anchors of 20 cm lengths the maximum force was about 99.4 kN, and for 10 cm anchors the force was about 48.6 kN

3. X-FEM method

X-FEM (Extended Finite Element Method) is a method of simulating a fracture in the Finite Element Method, which is independent of the mesh. Modification of the shape function of element allows the finite element to be separated anywhere [3].

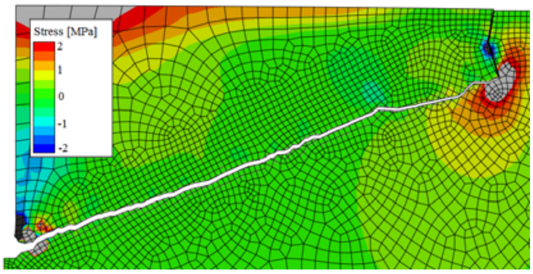

Figure 4: Maximal principal stress distribution and crack propagation path in FEA model for 20 cm anchor using X-FEM method. Stress greater than f_t = 2 MPa is omitted.

In the above example, the simplest criterion for crack initiation is chosen, which is, when the tensile stress exceed the value of the tensile strength [2]. In this case the critical force was 167.4 kN for the 20 cm anchor and 45.1 kN for the 10 cm anchor. It is interesting that the force grows all the time of simulation. This is due to the fact that as the crack grows, the stress increases at the top edge of the element. The length B, that is, the diameter of the broken fragment was about 45 cm for the longer anchor and 23 cm for the shorter anchor, which means that the angle α equals ca. 25°.

4. Element deletion method

Deleting elements in which the stresses meet the material destruction criterion is a very simple method of crack propagation analysis. Its drawback is a strong dependence on the mesh geometry of the elements, both as to their size and the directions of the edge lines. Using this method requires careful selection of these two grid parameters and their confrontation with experimental data. In the presented analysis, 5 parameters Podgórski criterion [5] was used, which is a modification of Ottosen 4 parameter condition. CrackPath3 computer code [6] was used to detecting and removing damaged elements. The size of the model elements was selected from the numerical tests so that the element was removed in a state close to that predicted by the cohesive zone model.

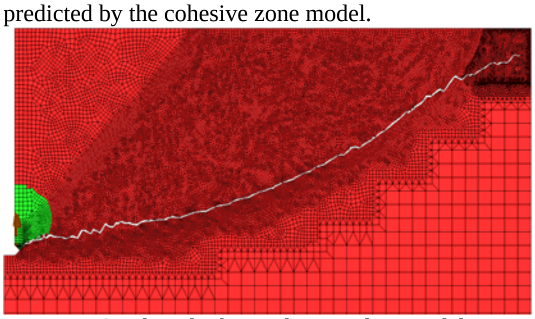

Figure 5: Crack path obtained using element deletion method

As a result of this simulation, the pulling force of a 20cm anchor for sandstone with a tensile strength of f_t = 2MPa was estimated at approx. 35 kN. The planned experiment will allow to check the accuracy of predicted critical forces obtained by various methods and to check the correctness of material data taken in numerical simulations.

5. Summary

As it can be seen, the results for the various methods have proved to be quite distant. That's probably because this two methods requires different parameters, which can be inaccurate at this state of research. Therefore, it is also planned to perform the calculations with other methods: a plasticizing method in which the plasticized material will allow for large displacements, so it will simulate the crack and method of element deletion done also in Abaqus. In addition, it is planned to perform the above mentioned experiments in laboratory tests, including material parameters to better reflect the actual pull-out test in numerical simulations.

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