

NUMERICAL TESTS OF THE INFLUENCE OF THE ORIENTATION OF STRATIFICATION ON THE PROCESS OF CUTTING OF ROCKS

SUMMARY

The paper presents results of the numerical simulation of the crack propagation occurring in the course of chip element formation in case of cutting stratified rock material. As a result of the simulation, it was found that a characteristic, rapid increase of the loosening force of the chip element occurs when stratification is directed in relation to the cutting direction at an angle of ca. 160° .

Keywords: rocks cutting, stratify rocks, crack propagation, finite elements method

NUMERYCZNE BADANIA WPŁYWU KIERUNKU UWARSTWIENIA NA PRZEBIEG SKRAWANIA MATERIAŁU SKALNEGO

W pracy przedstawiono wyniki numerycznych symulacji propagacji szczeliny powstającej w trakcie formowania elementu wióra w przypadku skrawania uwarstwionego materiału skalnego. W wyniku symulacji stwierdzono, że występuje charakterystyczny, gwałtowny przyrost siły odspajania elementu wióra, w przypadku gdy uwarstwienie jest zorientowane względem kierunku skrawania, pod kątem około 160° .

Słowa kluczowe: skrawanie skał, skały uwarstwione, propagacja szczeliny, metoda elementów skończonych

1. INTRODUCTION

It has been demonstrated in theoretical analyses and proved in experimental tests that strength parameters of stratified rock materials depend to a large extent to the direction of loading action in relation to the material stratification direction. For instance, it follows from a numerical analysis (Pietruszczak *et al.* 2002) that the strength of stratified rock material depends on the foliation direction in relation to the active loading and it reaches the minimum value for an angle of ca. 45° , as in Figure 1.

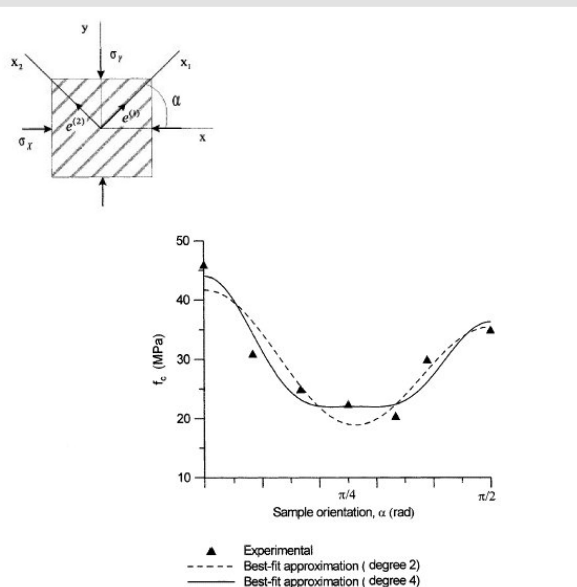


Fig. 1. Variation of uniaxial compressive strength f_c , with sample orientation, α (Pietruszczak *et al.* 2002)

The results of those considerations are confirmed partially by experimental tests, e.g. (Thuro and Saun 1996), that demonstrate that mechanical parameters of such rocks depend to a significant extent on the foliation angle, which is illustrated by Figure 2.

So distinct changes in strength parameters of stratified rocks, depending on location of strata in relation to the external loading action, are reflected, for instance, in the volume of progress in drilling with drill bits (Fig. 3), as well as in the mechanism of destruction of such rock under the impact of the bit mentioned (Fig. 4).

When the direction of drilling is right-angled to the orientation of foliation, rock material is compressed right-angled but sheared parallel to it (Fig. 4/a). Although cracks will develop radial to compression, the cracks parallel to the bottom of the borehole will be used for chipping. Usually in this case the highest drilling velocities are obtained because of the favourable schist orientation. Drilling is controlled by the shear strength of the foliated rock material. The minimum destruction work causes large sized chips and a maximum drilling performance. If the drilling axis is oriented parallel to foliation, compression also is parallel but shear stress is right-angled (Fig. 4/c). It should be clear, that less cracks will develop for reasons of higher strength right-angled to the weakness planes. Drilling is controlled by the tensile strength parallel to the foliation producing small sized fragments and minimum drilling performance. Generally, drilling is controlled by the dip angle of foliation (Fig. 4/b), submitting medium sized fragments during the crushing process. Drilling performance is – by geometrical reason – mainly a cosine function of the dip angle. Anyway,

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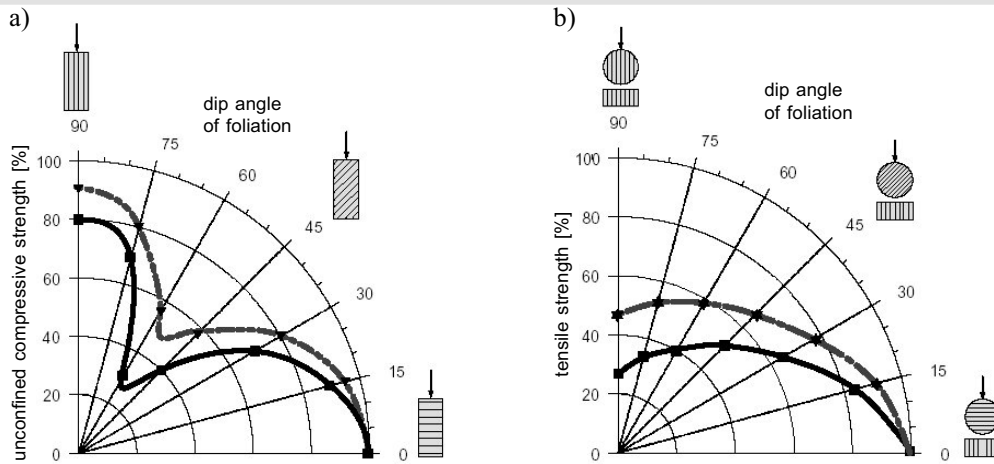


Fig. 2. Correlation between unconfined compressive strength (a), tensile strength (b) and the orientation of foliation for quartzphyllite with flat and smooth (continuous line) respectively uneven, undulating discontinuities (dashed line) (Thuro and Saun 1996)

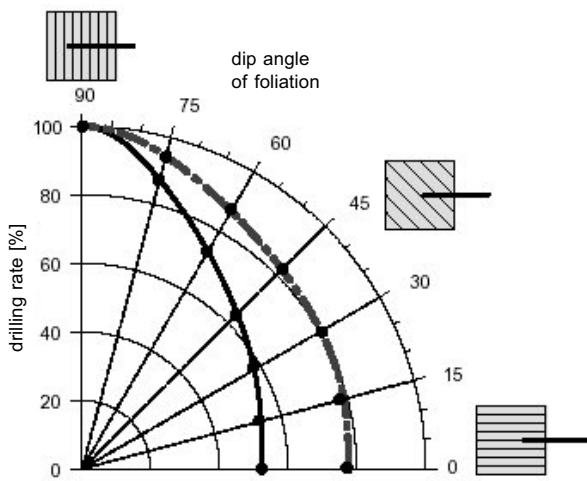


Fig. 3. Correlation between drilling rate and the orientation of foliation for a quartzphyllite with flat and smooth (continuous line) respectively uneven, undulating discontinuities (dashed line) (Thuro and Saun 1996)

it is for sure, that in the parallel case, rock properties are the highest and drilling rates are low. In addition blasting conditions are often related with drilling. So if the tunnel axis is parallel to the main foliation, drilling and blasting conditions suppose to be very poor (Thuro and Saun 1996).

In case of mining with disks, destruction of a stratified rock structure also demonstrates some analogy. When the foliation is perpendicular to direction of machine advance, rock failure occurs along foliation planes as shown in Figure 5a. This case generally represents the most favourable boreability as the foliation planes assist crack initiation and growth between adjacent cuts (Cigla M. *et al.* 2001).

One way to integrate the foliation effect in machine performance modeling is measure the tensile strength of the rock in different directions as shown in Figure 5b. The loading direction of the sample can be selected based on the machine advance with respect to foliation planes in order to represent the crack propagation across or along the weakness planes (Cigla M. *et al.* 2001).

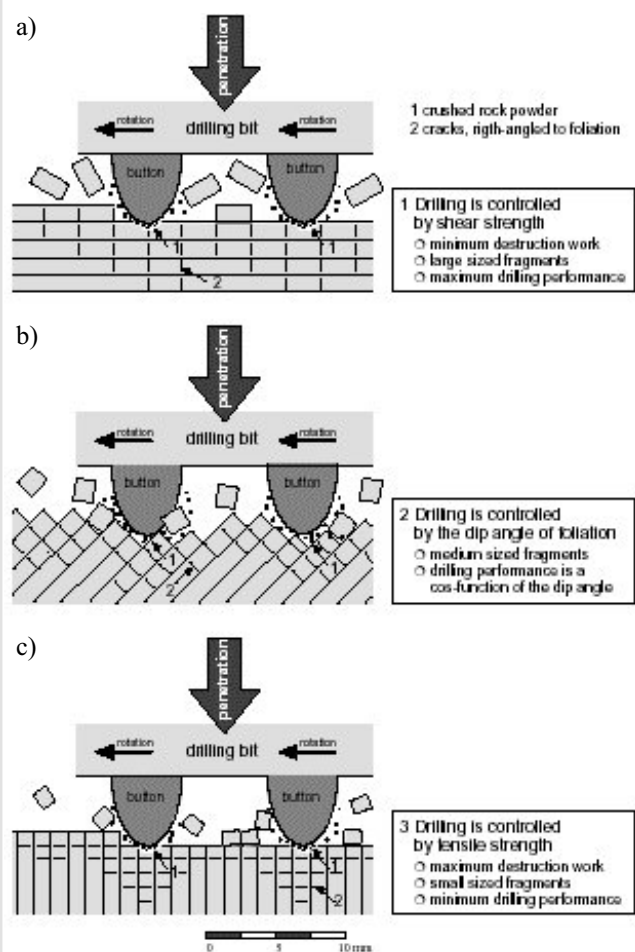


Fig. 4. Physical destruction process in foliated rock. Crushing mechanism below the bit buttons depending on the dip angle (Thuro and Saun 1996)

Consequently, the rank of the above problems in mining technology is high (mining productivity, mining tool durability, etc.), hence it is necessary to better understand the mechanics of cracking of the above materials under the impact of cutting tools so that the mining processes can be effected in an optimum way.

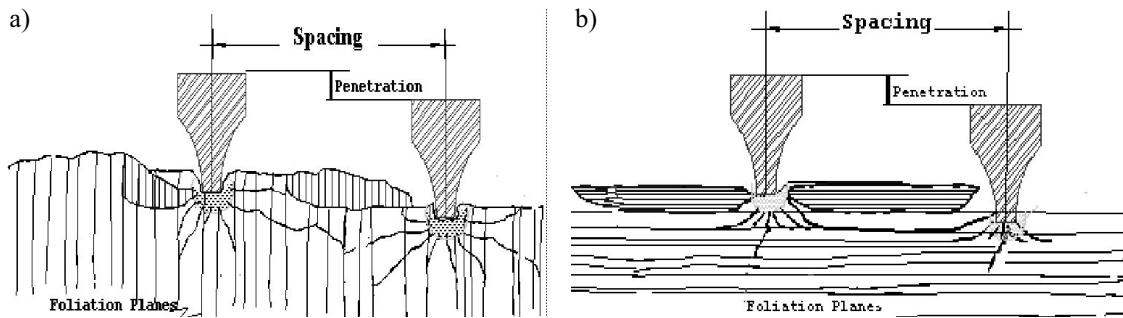


Fig. 5. Cutting direction: a) parallel; b) perpendicular to foliation (Cigla M. *et al.* 2001)

2. THE PURPOSE OF NUMERICAL TESTS

In the analysis, attention was focused on a detailed examination of the impact of the load action direction in relation to the rock material foliation on the destruction process, including in particular the propagation mechanism of the crack occurring as a result of the material structure destruction when a larger chip element is loosened in the process of cutting of stratified rocks. This subject matter is an extension of the author's previous studies on cracking of anisotropic rocks (e.g. (Podgórski 2002)) and pseudo-isotropic ones (e.g. (Podgórski 1984, 2005; Podgórski *et al.* 2004, 2005)) under the impact of mining tools. The analyses are carried out with the use of the PJ failure criterion as described in detail in (Podgórski 1984, 1985).

3. ASSUMPTIONS FOR NUMERICAL SIMULATION

In order to increase the accuracy of simulation in relation to the previously conducted studies (e.g. (Podgórski and Jonak 2005; Podgórski *et al.* 2004, 2005)), the grid density degree of the FEA model in the load impact zone was increased. There was also an increase in the number of cases of strata location in relation to the direction of the external load impact and the number of FEA elements in simulated privileged strata.

A mechanical cutting zone model was adopted for the above assumptions as illustrated by Figure 6. The β angle defining the location of privileged strata in relation to the direction of loading the rock bar with force P was increased by 5° in each step of the analysis, starting from 0° up to 180° . The impact of the edge attack on the rock is simulated in this case by the impact of a stiff plate loaded with force P to a ledge (as in Fig. 6). The edge attack angle was assumed as 0° .

Basic dimensions of the model as well as the model discretisation method with agreed complete elements are illustrated by Figure 7. The assumed layer of the basic material $a = 12$ mm, the thickness of the "weaker" material strata $b = 4$ mm.

The elements mesh was condensed in the crack propagation area. Two types of elements were applied in that area:

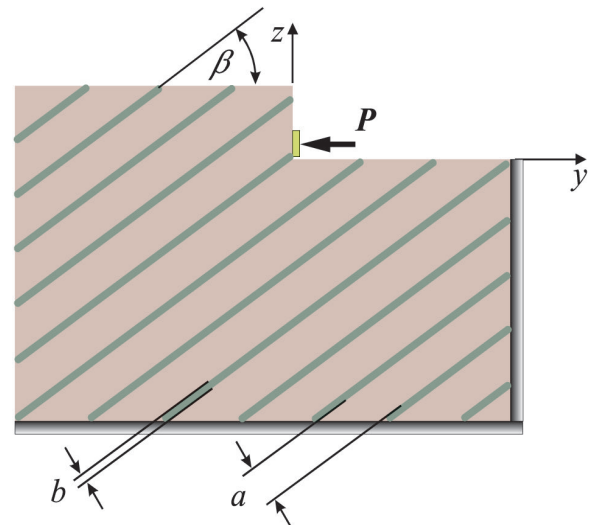


Fig. 6. Mechanical cutting zone model

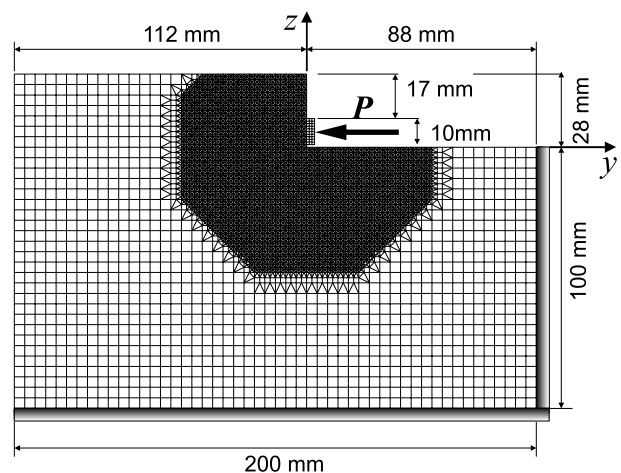


Fig. 7. Model dimensions and the method of model discretisation and fixing of boundary nodes

triangular elements with a linear shape function, and in the second version, quadrilateral elements with a bilinear shape function. The remaining procedure elements were not changed in relation to those previously analysed (e.g. (Podgórski *et al.* 2004, 2005)).

The following material characteristics were adopted in the presented stage of the study:

- for the basic material: compressive strength in the uniaxial state $f_c = 20$ MPa, and in the biaxial state $f_{cc} = 22$ MPa, $f_{0c} = 25$ MPa as well as tensile strength $f_t = 2$ MPa, Young modulus $E = 2 \cdot 10^4$ MPa, Poisson ratio $\nu = 0.2$;
- for the “weaker” layer material – $f_c = 5$ MPa, $f_{cc} = 5.5$ MPa, $f_{0c} = 6.25$ MPa as well as tensile strength $f_t = 0.5$ MPa, Young modulus $E = 1 \cdot 10^4$ MPa, Poisson ratio $\nu = 0.22$.

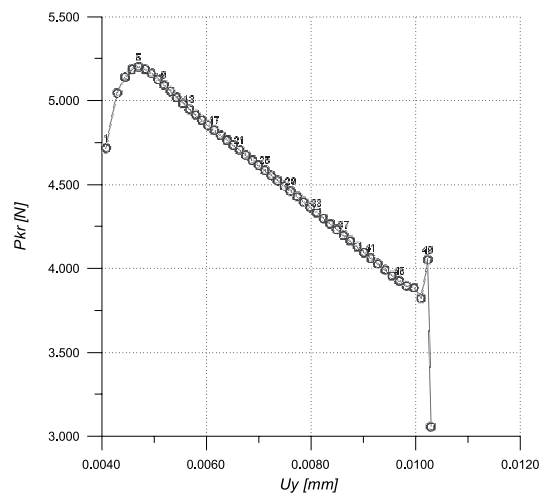
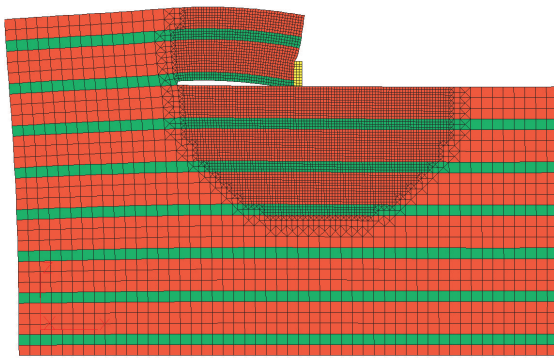
4. RESULTS OF NUMERICAL TESTS

The results obtained in the course of the simulation are presented in Figures 8. Here, deformed (scale 1000:1) element grids are shown in the variant with quadrilateral elements as well as diagrams of force-level translocation of the load application point.

It follows from the analysis that nothing particular happens till the β angle value of ca. 155° as compared with

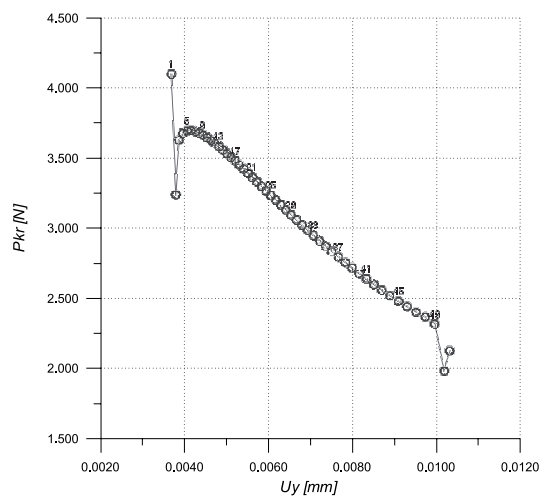
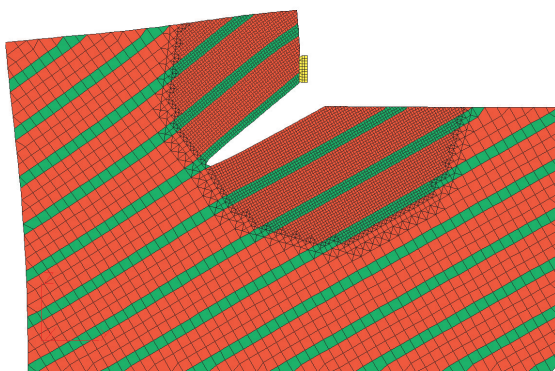
the previous simulation results. As the load grows, an open, “extended” crack occurs beyond the bar. The situation changes diametrically in the angle range of $160^\circ \div 175^\circ$. In the initial stadium, the crack opens as before, beyond the bar, then changes the propagation direction and a sliding crack appears on the layers border. Under the thrust of the external load, the material begins to slide along the penetrating surface of the crack, and at the same time, it is strongly clamped in that zone, which is indicated by the manner of deformation of the complete elements grid. For the 180° angle, the situation begins to stabilize once again. The analysis proved that the disorders in the material deformation process also effect the course of changes in the critical force, i.e. the force destroying the material structure in individual stages of the crack development. It is clearly illustrated by the diagrams of the relation of the force-level translocation of the load application point as shown in Figures 8.

a)



Foliation angle $\beta = 0^\circ$

b)



Foliation angle $\beta = 30^\circ$

Fig. 8. The course of changes in rock bar deformations under the edge attack thrust for foliation angle β as changing in the range of $0^\circ \div 180^\circ$ (a–h)

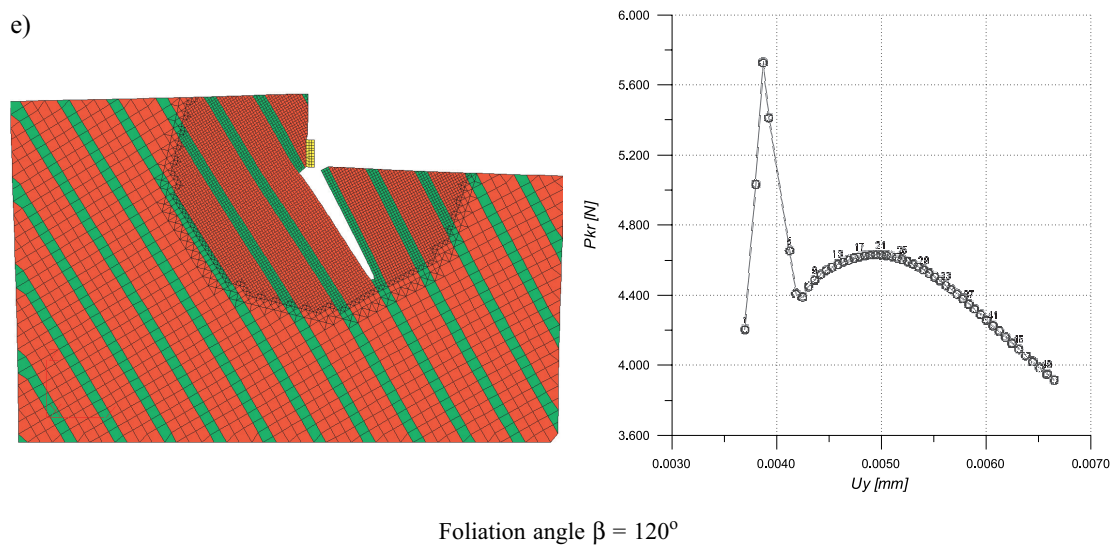
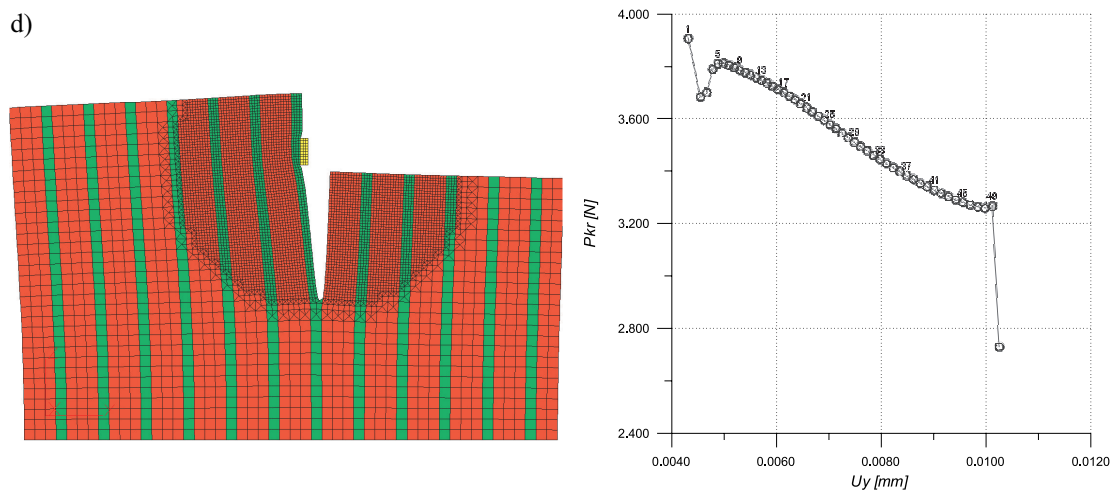
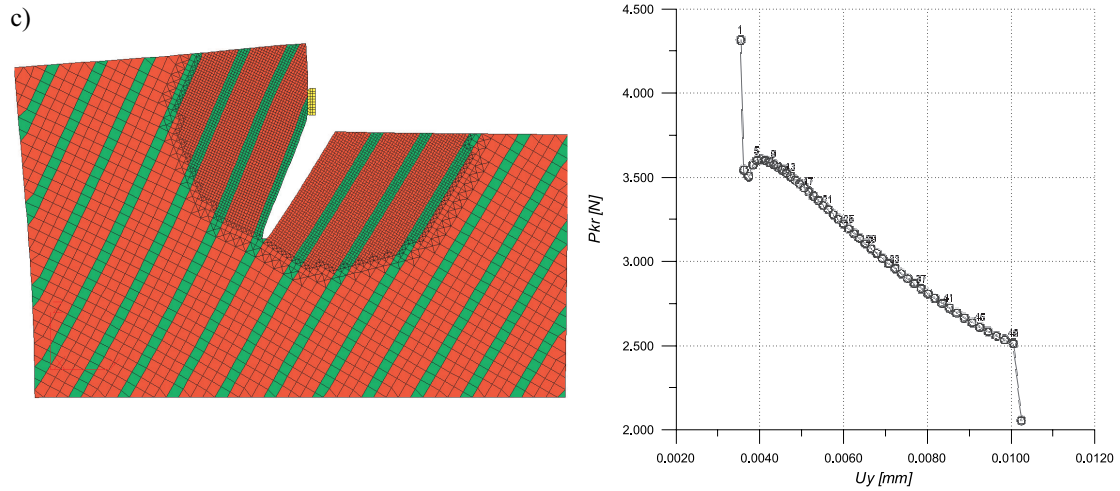
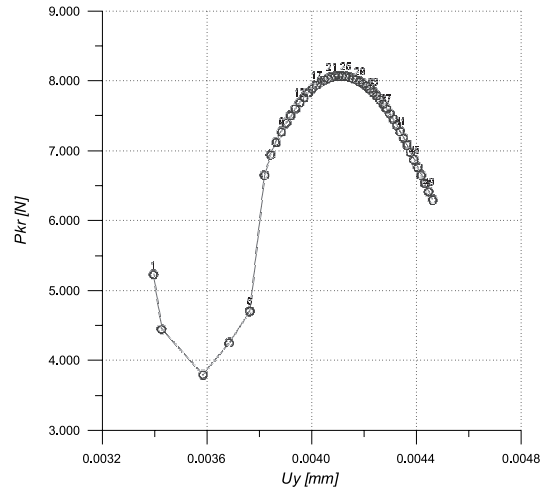
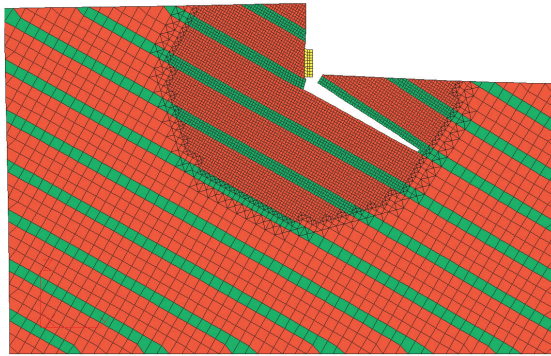


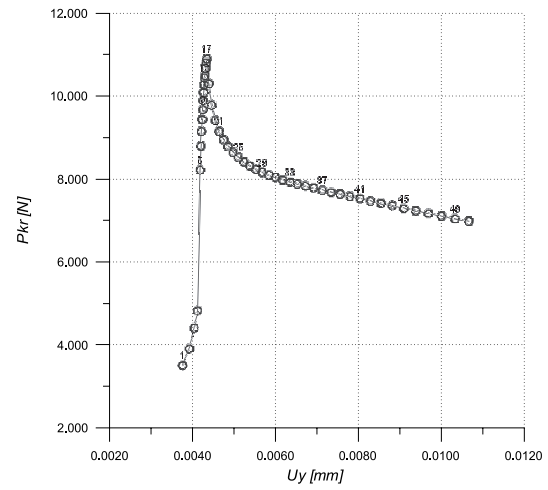
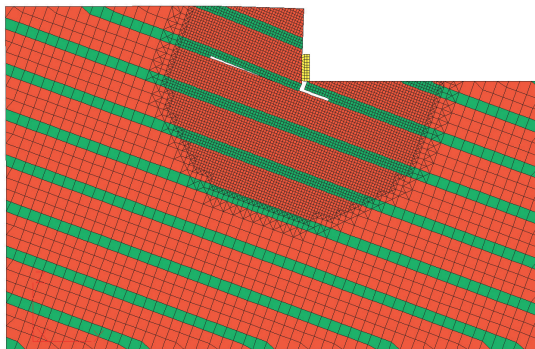
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f)



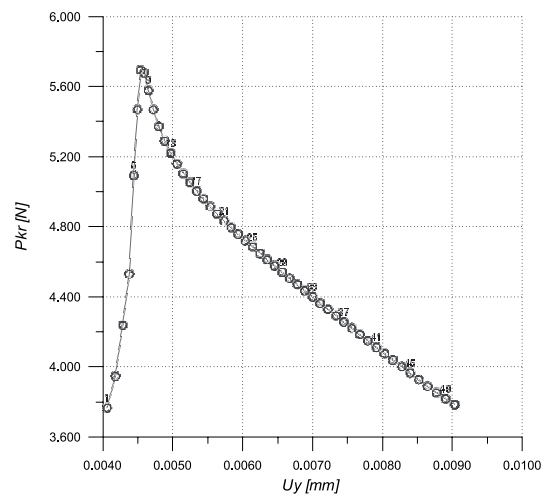
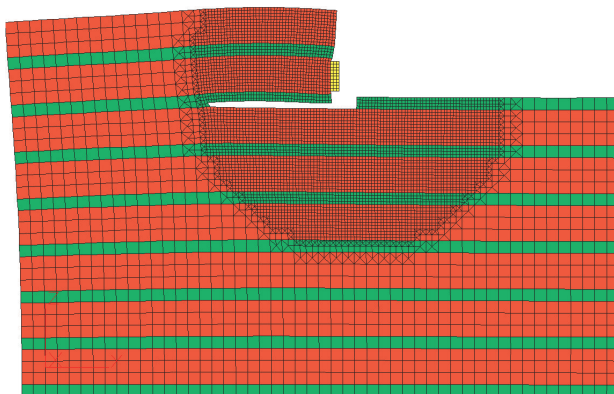
Foliation angle $\beta = 150^\circ$

g)



Foliation angle $\beta = 160^\circ$

h)



Foliation angle $\beta = 180^\circ$

Fig. 8. cont.

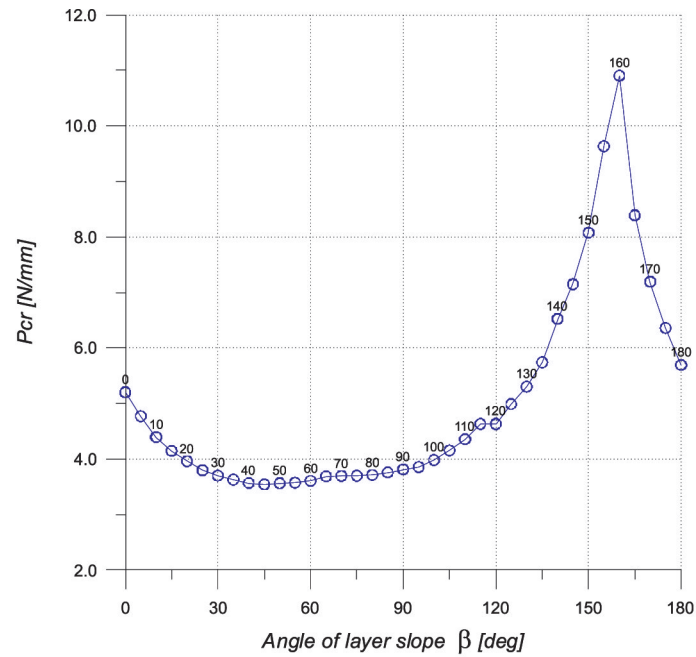


Fig. 9. Changes in the critical force in relation to the foliation angle

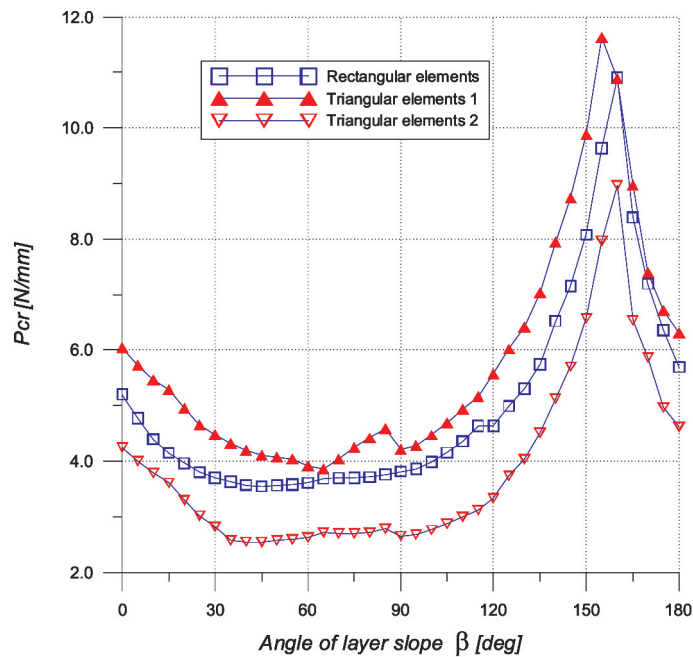


Fig. 10. The impact of changes in the complete element type to the critical force value at different foliation angles

The diagram presented in Figure 9 illustrates changes in the critical force interpreted as a local maximum in the diagrams, depending on the angle of layer slope β . An increase in the material resistance is clearly visible in the vicinity of the foliation angle $\beta = 160^\circ$, as caused by the change in the crack nature and the contribution of friction forces.

The analysed relationship is similar in the model for the triangular elements variant as presented in Figure 10. An effect of the shape and location of triangular elements on the calculated critical force value is clearly visible here. The values set for quadrangular elements, in case of which the

shape function enables a more precise determination of the model tension and dislocation values, range in the area limited by the values obtained with the use of the triangular elements.

5. SUMMARY

A decrease in the numerical simulation of the increment value of the rock material layer angle in relation to the load impact direction allowed us to observe significant changes in rock bar loosening force depending on the foliation angle

value. It follows from Figure 10 that in the range of 150° - 165° , the loosening force reaches its maximum. The effect can be explained by clamping of the chip element and the friction against the base, this friction being the most intensive for the above values of the foliation angle.

Acknowledgment

This paper has been prepared within the framework of a Polish Ministry of Science and Higher Education grant No NN 524 368337.

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