GEOLOGIJA. 2008. Vol. 50. Supplement. P. S116–S120
DOI: 10.2478/V10056-008-0035-0

# Cracking anisotropy exemplified by Krosno sandstones of Mucharz (Beskid Mały Mountains)

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Dziedzic A. Cracking anisotropy exemplified by Krosno sandstones of Mucharz (Beskid Mały Mountains). *Geologija.* Vilnius. 2008. Vol. 50. Supplement. P. S116–S120. ISSN 1392-110X

The paper includes a cracking process analysis of Krosno sandstones from the Górka-Mucharz quarry (Beskid Mały Mts.) based on fracture toughness tests by the *chevron bend* method. The analysed rock material features the internal structure: a laminar location of mineral components and directional location of non-isometric grains. These features impact the anisotropy of various geomechanical properties of these rocks such as fracture toughness or compressive strength, and are the reason for a varied crack development as well. The test results and cracking process characteristic regard three orthogonal measuring directions as adopted in relation to the rock material structure and texture features described in this paper. As concluded from the interpretation of load and strain increments recorded during the test, the cracking process is at its quietest when in the same direction as the layer direction, whereas, the most rapid failure character is observed in the direction perpendicular to the layer direction and to the longer mineral grain axis.

**Key words:** geomechanics, anisotropy, rock cracking, fracture toughness

Received 29 February 2008, accepted 22 April 2008

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## INTRODUCTION

Inside rock masses, under external forces and once the critical stress values were exceeded, durable failures become visible. According to Griffith's theory (1921), the roles of damage grains for the latter ones are played by primal structural defects which are concentration zones for stresses growing with the load, and in this way the crack development is launched.

The rock cracking process depends, among other conditions, on the value of external forces acting on this rock. Irwin (1957) proposed a cracking process description which shows a relation between the increasing load and the material changes. The initial stage consists in increasing the load, with a part thereof transforming into strain, and the other part into potential energy accumulated within the rock mass. At the moment of reaching the critical value, the collected energy unloads and is used to create a crack, and at that moment the crack propagation is unstable. This moment can also be identified based on a rapid propagation of a single crack which develops under tension, for example, while testing the fracture toughness factor, $K_{Ic}$, by bending a cylindrical sample with an initiating indent.

In the year 1988, the International Society of Rock Mechanics published an instruction (ISRM, 1988) which recommended to apply the *chevron bend* method for fracture toughness tests. The method uses cylindrical samples with an initiating notch, which should generate a relatively long period of stable slot development, and facilitates control of the entire failure process. Besides, ISRM puts emphasis on the variability of the cracking resistance depending on the slot development; that is why ISRM recommends making consideration for the natural anisotropy of rock materials while testing by this method.

This paper describes a directional cracking differentiation exemplified by Krosno sandstones of Mucharz. Samples were tested under tension by the *chevron bend* method. The involved rocks feature different geomechanical parameter values depending on test direction, for example, triaxial compression strength (Łukaszewski, 2004), fracture toughness (Dziedzic, 2003a), or ultrasonic wave propagation velocity (Dziedzic, 2005).

## METHODOLOGICAL ASSUMPTIONS

The three-point bending tests for cylindrical rock samples with an initiating notch with a constant load increment facilitate assessing the crack development process against the increasing load value. The said crack resistance tests were made with a constant load increment of 15 kN/min. The following parameters were measured: width change of the initial crack, $\Delta$CMOD (with a gauge) and the increasing load value, F.

The cracking assessment consisted in the analysis of initial crack width increments ($\Delta CMOD_{10}$) for constant load increments (10 N), which allowed to distinguish three crack development stages (Dziedzic, 2003b):

– stage I – $\Delta CMOD_{10}$ increments are no bigger than 1% of the critical crack width ($CMOD_{cr}$),

– stage II – slot width increment increasing gradually from 1% up to 2% of $\mathrm{CMOD}_{cr}$,

– stage III – $\Delta\mathrm{CMOD}_{10}$ increasing rapidly, and significantly bigger than 2% of $\mathrm{CMOD}_{cr}$.

Tests were made on Krosno sandstones from the Górka-Mucharz quarry (Beskid Mały Mts.). These rocks are ranked among the most frequently spotted ones within the Carpathian flysch. The thickness of Krosno Beds reaches approx. 3000 m in the Central Carpathian Depression (Jucha, Kotlarczyk, 1959) and is estimated at 700 m within areas next to the Beskid Mały Mts. (Książkiewicz, 1951). These are the youngest layers of the Carpathian flysch, their origin time is estimated at the Oligocene.

In these rocks, two special features are visible on a macroscopic scale: the laminar layout of mineral components compliant with the material layers, and directions of non-isometric grains. The laminar structure is emphasised by dark-coloured iron compounds, and the rock texture can be described as directional and containing various micas and dark minerals. The bonding material consists of silt and carbonates with small quartz grains; the material sorting ratio is good. The mineral composition classifies these rocks as medium-grained lithic wacke or arcose wacke according to Pettijohn et al. (1972).

The special rock material feature, which means the laminar and directional component layout, was the basis for determining three cracking directions located at a right angle to one another:

– parallel to the lamination (H plane),

– perpendicular to the lamination and parallel to the longer grain axis (*Vr* plane),

– perpendicular to the lamination and perpendicular to the longer grain axis (*Vp* plane).

## CRACKING PROCESS ANALYSIS

### Stage I

In the early stage of initiating crack development, when the forced fracture direction is perpendicular to the longer axis of mineral grains (*Vp* plane), a tensile stress zone is created at longer edges (Fig. 1). Grains are being strained, and a significant energy is being accumulated at the crack forehead as a result of a bigger range of elastic strain. In our test, these strains are dependent on the grain edge length, which results in variable strain routes and, when the crack starting point is located on the relatively longer grain edge, the strain is bigger and at the same time the load increment is smaller.

In the plane perpendicular to the lamination and parallel to the grain axis (*Vr* plane), stresses also concentrate on grain edges, and the elasticity parameters are higher; this fact is evidenced by Young's modulus values determined both in the test and in an indirect way (Dziedzic, 2002). Besides, this fact is indicated by values of the dynamic elasticity modulus obtained for this direction by means of non-destructive ultrasonic tests (Dziedzic, 2005). Therefore, the pre-existing elasticity is higher in the plane parallel to the grain axis (*Vr* plane), but elastic grain strains are maintained for a shorter time. That is so because the stress zone at the initiating crack tip shifts towards the side edges of mineral grains as if, so to say, "seeking" locations more susceptible to strain, which are contact surfaces between grains, as well as spaces filled with the silica-carbonate bonding material (Fig. 1).

In the plane parallel to the lamination (H plane), with a relatively loose grain layout, stresses concentrate on those weaker areas from the very beginning. The bonding material is straining, but its strains are significantly smaller and less elastic (due to a lower value of Young's modulus). The strains were of a similar size, approx. 0.015 mm (Dziedzic, 2002), which evidences the existence of a strain limit resulting from the properties of the silica-carbonate bonding material.

### Stage II

The above-presented alterations related to the early stage of the initiating slot development are the conditions for initiating the cracking process in stage II. In case of cracking in the plane parallel to the lamination (H plane), the crack increment is at its biggest, which results from a significant development of cracks.

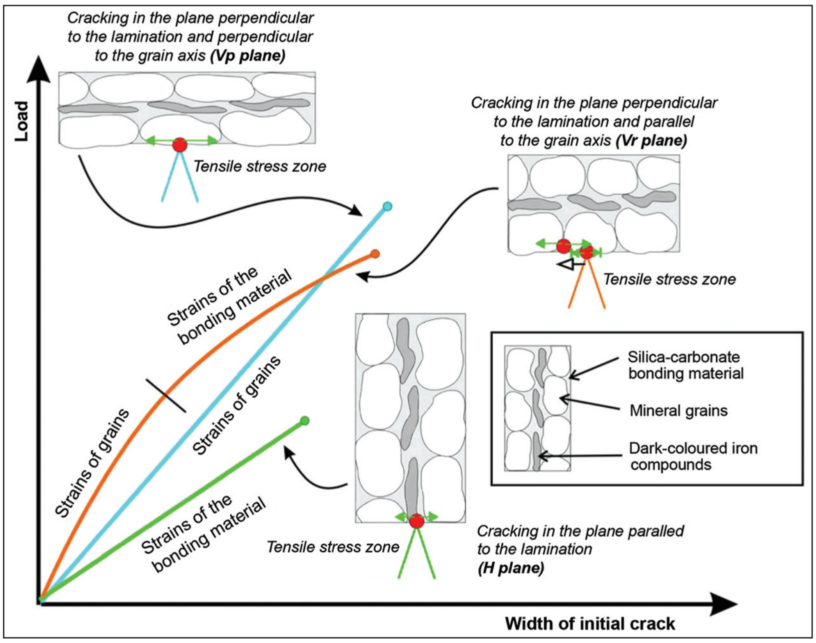

**Fig. 1.** Diagram of the initial crack development stage (stage I) in the assumed cracking planes

In case both planes are perpendicular to the lamination (Vp and Vr planes), an equalisation of crack width increments is observed; nevertheless, the share of these increments in the critical value ($\mathrm{CMOD}_{cr}$) is smaller in the plane perpendicular to the grain axis (*Vp* plane). At the same time, also in this plane a reduction of load increment is observed, which indicates that processes of straining the mineral skeleton and cumulating potential energy are continued. Nevertheless, the delivered energy is consumed in the *Vr* plane successively in cracking processes (Fig. 2).

A similar process is carried out for cracks developing in the H plane, but the stable propagation indicates its presence more significantly. Distinctively bigger crack width increments as well as relating bigger load increments indicate that, firstly, it is just there where the most extensive changes occur, and secondly, a permanent load increase is successively used for the generation thereof. Based on that fact, it should be reckoned that these alterations are related to the rock mass continuity loss (which means creation of a crack), and not to the strain of silica-carbonate bonding material (Fig. 2).

### Stage III

Before the critical state is reached, the crack widens rapidly, which is related to its unstable propagation. The widest opening, but also the most varied at the same time, was observed for the plane located in parallel to the lamination (H plane). In planes located at right angle, a bigger crack opening for the *Vp* plane is clearly marked; at the same time, the unstable cracking process has a bigger participation in this plane, which evidences that the previously accumulated energy is consumed.

In case the crack develops along the lamination, crack propagation is neither rapid nor uncontrolled because no potential energy has been accumulated. In order to make such propagation possible, an additional energy portion must be delivered by means of a permanent load growth, and along the increase, the slot crack width increment also increases. This means that, in the same plane as the lamination, the stable cracking process is being continued also when $\Delta\mathrm{CMOD}_{10}$ is bigger than 2% of $\mathrm{CMOD}_{cr}$.

On the other hand, crack development in directions perpendicular to the lamination is not dependent on the load increment only, but also on the amount of energy collected before. Higher crack opening values as observed in the plane perpendicular to the grain axis (*Vp* plane) indicate that the unstable cracking is more rapid in this case (Fig. 3).

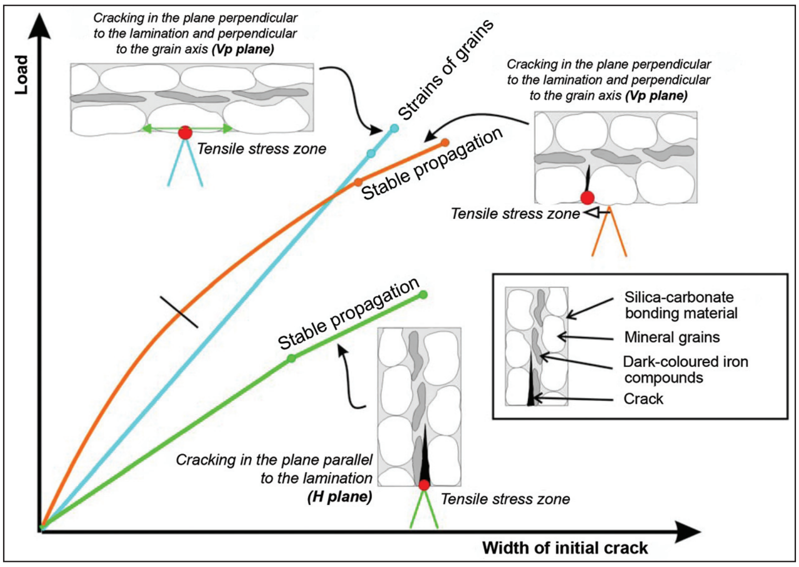

**Fig. 2.** Diagram of the initiation of cracking (stage II) in the assumed cracking planes

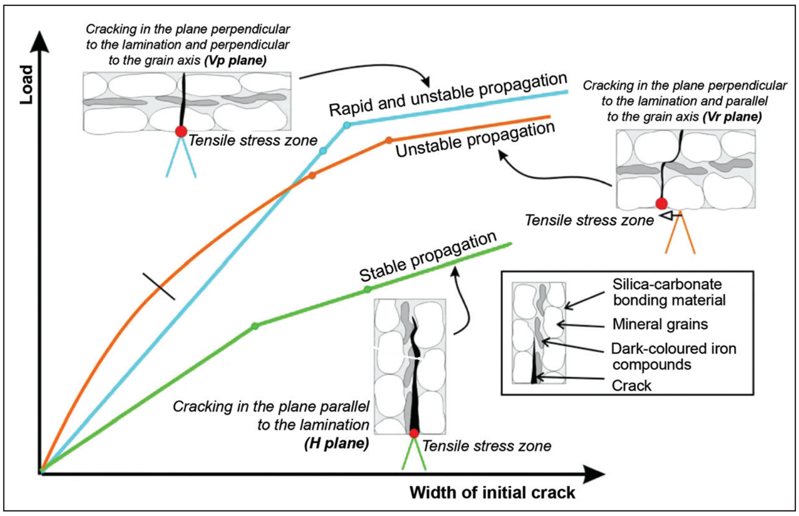

**Fig. 3.** Diagrams of unstable cracking process (stage III) in the assumed cracking planes

## CONCLUSIONS

Application of strain curves and the *chevron bend* test method for the evaluation of crack development facilitated describing this process in the aspect of its variability in relation to the internal structure of Krosno sandstones. The varied fracture toughness and compressive strength as observed in earlier tests is – to a significant extent – a result of a different crack propagation character within this anisotropic rock material. The failure is reached the easiest and – relatively – the quietest way when the crack development direction is the same as that of lamination. In such a situation, the energy delivered to the rock material is continuously used for a stable slot development. An uncontrolled and rapid cracking process had not been observed even before the critical state was reached. Whereas, in directions at a right angle to the lamination and in the early stage of the rock deforming process, part of the delivered energy is accumulated within the rock as potential energy. In particular, this observation regards the direction perpendicular to the longer grain axis, where a rapid and uncontrolled crack development is reached in the unstable cracking process stage. The fracture toughness is highest in this direction, and yet, the failure is of the most explosive character.

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## KROSNO SVITOS SMILTAINIO AIŽĖJIMO PROCESO ANIZOTROPIJOS TYRIMAI

*Santrauka*
Straipsnyje pateikiama Krosno smiltainio (Mažieji Beskidai, Mucharz) aižėjimo proceso analizė. Bandinių tyrimai atlikti pagal „chevron bend“ metodiką. Tirtas smiltainis pasižymi specifine vieline sandara: mineraliniai izotropiniai grūdeliai yra išsidėstę laminariai, o anizotropiniai – kryptingai. Šie sandaros ypatumai lemia geomechaninių savybių anizotropiją – atsparumą įtrūkiams, stiprumą gniuždant, plyšių plėtojimąsi skirtingomis kryptimis. Tyrimų rezultatai bei aižėjimo procesas analizuojami pagal tris ortogonalines matavimo kryptis, pasirinktas pagal uolienos struktūrinius ir tekstūrinius ypatumus. Apkrovos ir deformacijų didėjimo laike tyrimo duomenimis, sluoksniuotumo kryptį atitinkantis aižėjimo procesas yra lėčiausias. Aižėjimo procesas, statmenas sluoksniuotumui ir grūdelių ilgųjų ašių krypčiai, yra staigus. Nevienodas aižėjimo procesas gniuždant nulemia skirtingus plyšius. Išskiriami intergranuliariniai ir intragranuliariniai plyšiai.

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## ANIZOTROPIA PROCESU PĘKANIA NA PRZYKŁADZIE PIASKOWCÓW KROŚNIEŃSKICH Z MUCHARZA (BESKID MAŁY)

*Streszczenie*
W artykule przedstawiono analizę procesu pękania piaskowców krośnieńskich z Mucharza (Beskid Mały), opartą na badaniach odporności na pękanie metodą trójpunktowego zginania walcowej próbki z nacięciem inicjalnym (ang. *chevron bend*). Analizowany materiał skalny charakteryzuje się specyficzną dla osadów fliszowych budową wewnętrzną: laminarnym ułożeniem składników mineralnych oraz kierunkowością nieizometrycznych ziaren. Cechy te wpływają na anizotropię różnych właściwości geomechanicznych tych skał, takich jak odporność na pękanie czy też wytrzymałość na ściskanie, i są również przyczyną zróżnicowanego rozwoju szczelin. Przedstawione w artykule wyniki badań oraz charakterystyka procesu pękania dotyczą trzech ortogonalnych kierunków pomiarowych, przyjętych w nawiązaniu do wymienionych cech strukturalno-teksturalnych materiału skalnego. Analizę pękania przeprowadzono w nawiązaniu do schematu Irwina, uwzględniając również istotne w przebiegu deformacji materiałów skalnych progi mikro- i makropękania, co pozwoliło wydzielić trzy fazy rozwoju szczeliny. Określono je na podstawie przyrostów szerokości nacięcia inicjalnego, odniesionych do krytycznego rozwarcia szczeliny na granicy wytrzymałości w 10 kN interwałach wzrastającego obciążenia. Jak wynika z interpretacji przyrostów obciążeń i odkształceń rejestrowanych w trakcie badania, przebieg pękania ukierunkowanego zgodnie z uławiceniem jest najbardziej spokojny, natomiast gwałtowny charakter zniszczenia obserwowany jest w kierunku prostopadłym do uławicenia i jednocześnie prostopadłym do dłuższych osi ziaren mineralnych.

**Артур Дзиедзиц**

## АНИЗОТРОПИЯ ПРОЦЕССА РАСТРЕСКИВАНИЯ ПЕСЧАНИКОВ КРОСНОВСКОЙ СВИТЫ

*Резюме*
Анализируется процесс растрескивания песчаников кросновской свиты (Малые Бескиды, Мухарз). Образцы изучены по методике „chevron bend“. Данные песчаники характеризуются специфическим внутренним строением: минеральные изотропные зерна расположены ламинарно, а анизотропные – направленно. Особенности строения определяют анизотропию геомеханических свойств (сопротивление к растрескиванию, прочность на сжатие, развитие трещин по разным направлениям). Полученные результаты и процесс растрескивания оценивались по трем ортогональным направлениям, принятым для структурно-текстурных особенностей пород. По данным прироста во времени нагрузки и деформаций растрескивание по направлению слоистости происходит медленно. Растрескивание, перпендикулярное слоистости и направлению длинных осей зерен, происходит незамедлительно. Разное протекание процесса растрескивания определяет разное строение трещин после сжатия. Выделены интергранулярные и интрагранулярные трещины.