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# Visualization of the Evolution of the Fracture Process Zone in Sandstone by Transmission Computed Radiography

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## Abstract

The article deals with the use of computed X-ray radiography to visualize the development of the fracture process zone in the rock samples. For radiographic observations during the three-point bending loading, glauconitic sandstone from the Řeka quarry (sometimes also referred to as Godula sandstone) was used. The chevron-notched cylindrical specimens with the diameter of 29 mm and 120 mm nominal length were prepared from the sandstone blocks. These specimens were subjected to the Chevron Bend (CB) test carried out in accordance with the ISRM suggested methodology; the span was 94 mm. The evolution of the fracture process zone was continuously scanned using X-ray radiography during the realized Mode I fracture toughness tests (FTT). The scanning was conducted using an industrial X-ray micro-tomographic inspection system equipped with a flat panel X-ray detector of 4,000 × 4,000 pixels and micro-focus X-ray source with reflection target, which are very suitable for obtaining highly detailed radiographic images during the FTT tests. Three-point bending tests were carried out using an in-house designed table-top loading device, construction of which allows precise control of the loading during testing. Continuous X-ray examination and subsequent radiographic image analysis enable investigation of the crack initiation and the process zone development during FTT and represents a useful tool for a better understanding of failure behavior of the rock material during the loading process.

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*Keywords:* Fracture process zone; fracture toughness; Chevron Bend (CB) test; glauconitic sandstone; X-ray radiography

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## 1. Introduction

The process of crack formation in quasi-brittle materials leads to the damage of the material and to energy consumption in the direct proximity of the crack, i.e. in the fracture process zone (FPZ). The shape of the fracture process zone during the crack growth varies, and simultaneously the consumption of energy needed for crack propagation changes. The damage area in quasi-brittle materials macroscopically differs from the plastic zone developing at the crack tip in ductile materials (e.g. metals) [1]. Advanced computational tools to analyze fracture behavior of elements and structures of quasi-brittle materials (cement composites, concrete) have recently been created [2]. The FPZ in concrete is currently being studied using experimental techniques, such as high speed photography, acoustic emission testing, scanning electron microscopy (SEM) and laser-speckle interferometry [3]. Numerous numerical analyses of FPZ in concrete specimens have also been performed in this scientific field.

The research in fracture behavior of rocks and analyses of the scope and shape of the FPZ in rock materials builds on the advances of all the above mentioned studies and techniques and, therefore, is based on the advanced theories of damage of these quasi-brittle materials. So far, FPZs in rocks have been investigated experimentally and numerically in a number of studies. Experiments were performed on various types of test specimens and using different types of tests, in particular SCB (Semi-Circular Bend test) [4], CCNBD (Crack Chevron Notched Brazilian Disc test) [5], and three point bending test [1, 6]. In connection with the size effect, the FPZ was also analyzed using the method of acoustic emissions [1, 4], or laser speckle interferometry [7]. As in the case of other quasi-brittle materials, many numerical studies [1, 6] and mathematical models revealing regularities of the development of FPZ of rocks were made. Also, fracture behavior of rocks at static and various cyclic loadings was observed [5]. After the tests, X-ray computed micro-tomography (X-ray CT) was applied. The finding that fracture bifurcation is significantly higher during cyclic loading of the sample is one of the basic outputs of that research. From this point of view, the X-ray CT as well as computed radiography represent a novel and useful laboratory technique allowing for 3D visualization and analysis of FPZ in different types of materials [8].

This article presents experimental monitoring of the development of the FPZ in glauconitic sandstone using radiography imaging during the Chevron Bend (CB) fracture toughness test (FTT). The whole process of FPZ evolution until specimen rupture was on-line recorded and subsequently compared with the obtained load–displacement diagrams. The X-Ray CT scanning of tested samples during selected FTT tests was performed too, but due to the sample size it was not possible to reconstruct the CT volume for successful subsequent image analysis of FPZ development. The main advantage of the X-ray radiography, as well as the X-ray CT is, in particular, the possibility of spatial analysis of the FPZ development.

## 2. Experiment setup

### 2.1. Test specimen and rock material

Cylindrical CB specimens (29 mm in diameter, 120 mm in length) were drilled from a sandstone block in the laboratory. The core drilling was carried out parallel to the bedding planes. In the middle of the test specimen the chevron edge notch using a circular diamond blade was cut (Fig. 1). The width of the chevron notch was 1.4 mm.

The glauconitic sandstones from the Řeka quarry (Moravian-Silesian Beskids Mountains, approx. 30 km NE from the city of Ostrava, Czech Republic) have been deliberately selected for this study. These greenish so-called Godula sandstones are mainly formed by quartz grains (ca 40–60 % of the whole rock volume); feldspars grains (ca 7–15 % vol.) and mica flakes (ca 5 % vol., muscovite > biotite) occur less frequently. The average grain size of the quartz fragments ranged from 0.18 mm to 0.39 mm. Lithic clasts (5–20 %) are represented mainly by fine-grained quartzite with similar grain sizes to the quartz grains. In some samples, the microfossils are relatively common. A clay matrix (10–20 %) is formed by dominant illite. Small, sub-rounded to rounded green-colored pellets of authigenic glauconite (up to 0.7 mm, 1–5 % vol.) occur frequently. Rock cement includes early diagenetic quartz, a very variable content of authigenic calcite and dolomite, and traces of fine-grained pyrite. Rock texture is psammitic, sub-angular, and poorly sorted, with long (flattened) to partly sutured grain contacts (for more detail, see [9]). Basic physical and mechanical properties of the Godula sandstones are shown in Table 1.