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TOMOGRAPHIC INVESTIGATION OF THE SANDSTONE FRACTURE TOUGHNESS

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Abstract: *It is well known that the measured values of the fracture toughness of quasi brittle materials are influenced by material heterogeneity, dimensions, boundary conditions, and unequal tension and compression properties. Standard testing methods supposing isotropic material, in contrary the quasi-brittle materials differ from this theoretical expectation, therefore this approach may fail. The authors present Local Fracture Toughness Testing (LFTT) method to overcome this obstacle. LFFT based on a complex methodology using a series of tomographic reconstructions recorded during specimen loading is calculated independently of the outside boundary conditions.*

Keywords: Fracture process zone; Crack path; Quasi-brittle material; X-Ray computed tomography; Four-point bending test.

1. Introduction

The failure process of rocks and rock-like materials (such as concrete), is the result of complex mechanisms including microcrack initiation, propagation, and coalescence. Crack initiation occurs when the stress intensity factor (K) at a microcrack reaches its critical value, known as fracture toughness Kc. From that point of view, fracture toughness represents one of the most important mechanical properties in linear elastic fracture mechanics (LEFM). Fracture mechanics behavior plays role in the fracture process zone (FPZ) at the crack tip, caused by micro-cracking in the case of quasi-brittle materials. The intensity and shape of the FPZ are driven by the stress-strain field surrounding the crack tip. Therefore, different testing methods cause different FPZs. A crucial problem for quasi-brittle materials can be unequal tension and compression properties (Chamis, 1974).

In this work, a methodology for local fracture toughness testing (LFTT) is presented for which global boundary conditions are not incorporated into its calculations (Vavrik, 2021). LFTT is based on the experimental measurement of the displacement fields around the crack. Particularly, the displacement fields are derived from the time series of the computed micro tomography (4D CT) recorded during the gradual loading of the specimen.

2. Experimental

Chevron-notched cylindrical specimens of 29 mm in diameter and 195 mm in length were drilled from sandstone blocks in the laboratory of Institute of Geonics. In the center of the test specimen, a chevron edge notch with an internal angle of 90° was carved using a circular diamond blade. The width of the chevron notch was ~1.4 mm, ligament 23.5 mm. Photography of the specimen is depicted in Fig. 1.

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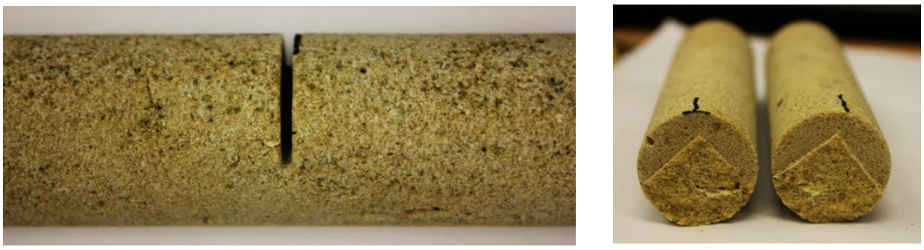

Fig. 1, Photography of the specimen before test left,
ruptured specimen right – profile of the chevron notch is visible.

For the purpose of the 4D CT loading experiment, a four-point bending device with very high stiffness and loading precision was developed (Czech national patent 307897) to allow evaluation of FPZ and fracture characteristics of quasi-brittle materials during post-peak softening. Compact design of the device enables its embedding into existing tomographic setups. In contrary to standard arrangements, the specimen is in our four-point bending device oriented vertically. This concept minimizes variation of X-ray attenuation during rotation of the sample and the loading device and allows to maximize possible projection magnification, which is necessary for detailed tomographic investigation of the loaded sample. Detailed description of the device is provided by Koudelka (2020).

During 4D CT procedure, one reference CT measurement and several consecutive CT measurements during the loading sequence have to be carried out in order to calculate the displacement/strain fields in the deformed sample. Reference CT measurement is typically realized immediately after fixation of the specimen in the loading device. The consecutive measurements are performed several times before reaching the maximal loading force and several times during the softening phase, where FPZ and crack propagation occurs. Fracture mechanics investigation based on 4D CT methodology requires application of the digital image correlation tools, see (Jandejsek, 2017). It will be shown, that obtained strain/stress fields can serve for calculation of the CTOD and stress intensity factor K_I inside of the specimen. The methods will be demonstrated by investigation of specimen manufactured from a natural sand-stone.

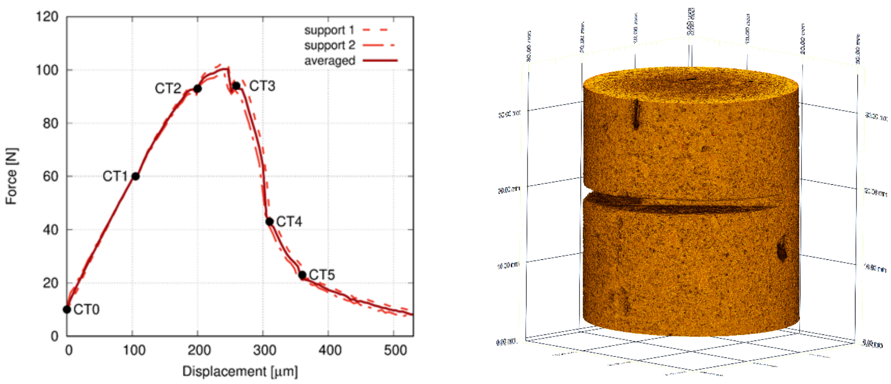

Fig. 2: The loading diagram, including the positions of the tomographic measurement (left),
an illustrative example of the reconstructed volume (right).

CT datasets were acquired by the TORATOM scanner (Laboratory of X-ray tomography of the Institute of Theoretical and Applied Mechanics, Telč) with the following parameters. The microfocus X ray tube (XWT 240 SE, X ray WorX, Germany) operated at 180 kV with a target current of 140 µA. For the X ray imaging, a CMOS flat panel X ray detector (Dexela 1512 NDT, Perkin Elmer, USA) was used. The projection magnification was set on 4.54 × to obtain the smallest possible pixel size of 16.5 µm with respect to the specimen dimensions. For each CT dataset, 1500 projections were taken, each with an acquisition time of 0.5 s. A loading diagram and an example of the reconstructed volume visualization is depicted in Fig. 2.

For the purpose of the fracture toughness evaluation, displacement fields were calculated for each loading level by comparing actual and reference state. COD values were calculated around identified crack path, consequent CTOD was identified from the COD characteristics. After that, local fracture toughness K_{IC} was expressed using well known equation:

$$K_{IC} = \sqrt{CTOD \cdot \sigma_y \cdot E \cdot m} \tag{1}$$

Where σ_y is the nominal yielding stress, E is Young's modulus and m=2 for plane strain condition, see (Anderson, 2005).

3. Results

An example of the vertical CT slice (crossing notch tip) containing the crack without any processing is shown in Fig. 3 left. Obviously, it is not simple task to identify newly developed FPZ/crack in such a heterogeneous material– crack is manifested as local decreasing of the tomographic density, therefore is hardly directly visible if the crack opening is small. However, this obstacle can be overcome by employing differential tomography, where changes in the object are emphasized by differentiation of the actual and the reference tomographic reconstruction, see Fig. 3 right.

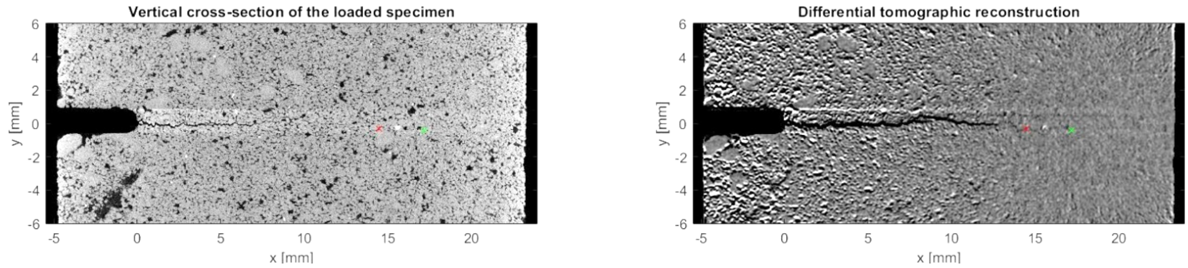

Fig. 3: The vertical slice within CT4 reconstruction showing the crack growing from the notch left. Crack path is not fully visible. The crack path is well recognizable in the differential CT right.

An example of the calculated displacement field ε_y together with identified crack path is show in Fig. 4 left, while strain field ε_y with marked FPZ right - shear bands are visible.

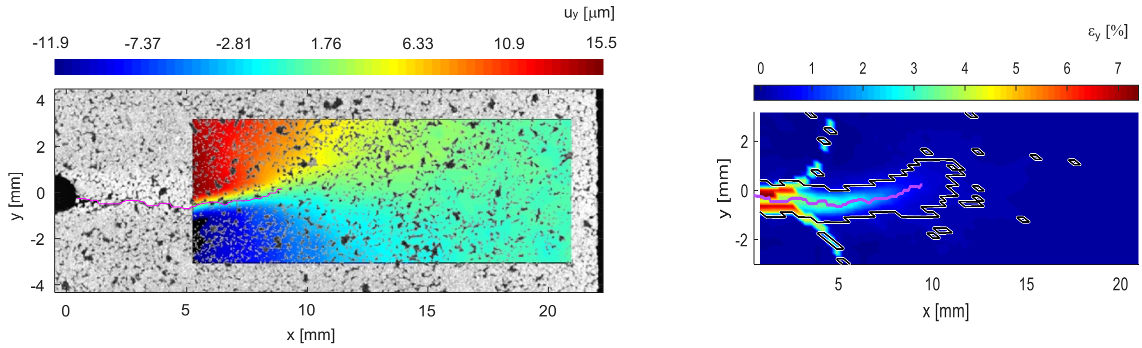

Fig. 4: . Crack development at CT3 with displacement field u_y is shown with the tomographically reconstructed slice left. The evolution of the strain field ε_y right – FPZ is surrounded by the isoline, branches growing from the FPZ are related to the shear bands.

Local COD progress in vicinity of the identified crack path at CT3 loading level is plotted in Fig. 5. COD dependence on the distance from the notch tip have approximately linear dependence for already developed crack. Change in this behavior is assumed at the crack tip – leading to estimated CTOD = 5.4 μm. Similarly, it is assumed that next inflexion point of the "COD" is related with end of the local FPZ. The length of the FPZ was therefore estimated to be equal to 2.9 mm.

Such analysis was done for all loading levels from CT1 up to CT5 in 9 neighboring slices vertically crossing crack front with a pitch of 0.5 mm (one of the vertical slices is marked by the blue line in Fig. 4 right). Therefore, evolution of the fracture toughness in Fig. 6 right as well as of the FPZ length in Fig. 6 right was obtained with good statistics. Obviously, it means, that it would be necessary to realize 45 individual tests to obtain such data utilizing standard experimental methodology for which undesirable variations of the material properties could be expected in addition. On the basis of the estimated CTOD, average local fracture toughness was calculated as equal to K_{IC} = 0.8 MPa/m$^{0.5}$ with σ_c = 3,3 MPa and E=12 GPa.

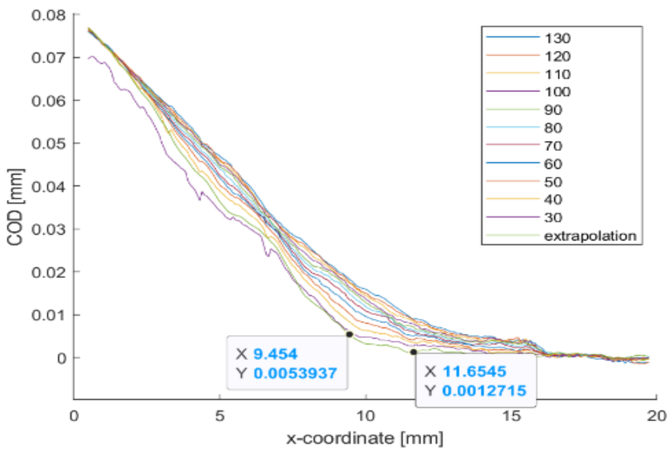

Fig. 5: COD measured at various distances from the crack path, COD extrapolated to the crack path was calculated - CTOD is measured in its significant inflexion point.

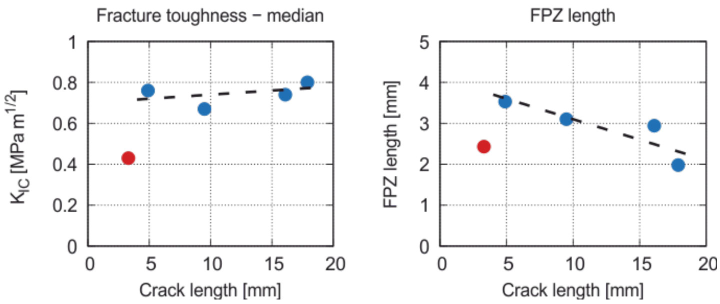

Fig. 6: The dependence of fracture toughness on crack length left – the first very short crack is not taken into account for the linear fitting. The dependence of FPZ length on crack length right – the shortening probably corresponds to the constraint growing.

4. Conclusions

A Local Fracture Toughness Testing (LFTT) method of quasi-brittle materials has been developed. This method is based on a combination of in-situ X ray computed tomography measurements acquired during loading tests, advanced post-processing of tomographic data including the identification of the crack path, and calculation of the crack tip opening from which fracture toughness is derived. Fracture toughness is calculated independently of the specimen's geometry, boundary conditions, crack length and shape, (Vavrik et al., 2021).

The unique instrumentation, in conjunction with enhanced data processing, also provided new information about crack development. This included the related stress/strain fields during FPZ branching caused by shear bands development, which was also revealed.

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