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Detection of crack onset in double cleavage drilled specimens of plaster under compression by digital image correlation – Theoretical predictions based on a coupled criterion

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ABSTRACT

Geomaterials such as rocks and concrete are brittle or quasi-brittle materials. Tensile tests carried out to observe the initial phases of crack nucleation are difficult to achieve because of the unstable nature of the tests. Instead, compression tests on drilled specimens offer a greater stability. When subjected to a compressive loading, two opposite cracks take place and grow from the cavity, parallel to the load. This crack nucleation is experimentally studied in rectangular drilled specimens of plaster with a centred cylindrical hole which size is assumed to be small with respect to the dimensions of the specimen. The results are compared to a theoretical prediction of the crack onset derived from the coupled criterion of Leguillon. Due to the difficulty of determining the crack initiation directly by the naked eye, 2D Digital Image Correlation is used. The nucleation event is determined by analysing the history of deformations at some points where the crack is expected to start. The predictions are proving to be in good agreement with the experimental results.

1. Introduction

In civil engineering and rock mechanics, compression tests like the Brazilian test (see Li and Wong (2013) for a review) or the double cleavage drilled compression test (DCDC) (Sammis and Ashby, 1986; He et al., 1995; Fett et al., 2005, 2009; Plaisted et al., 2006; Plaisted and Nemat-Nasser, 2007; Wong et al., 2006) are often preferred to tensile ones because they offer a greater stability. Under a compression load, a tension crack (mode I) initiates in the direction of the compression loading, then it grows gradually and stably as the loading increases without resulting in the complete failure of the specimen. However, it should be noted that in all the above mentioned papers, it is the growth of a crack from a pre-cut that is studied, not the initiation of the crack itself which is the subject of the present analysis.

The aim of this paper is to study the crack initiation in quasi-brittle materials using drilled specimens. Plaster is chosen as a model of brittle geomaterial, it is cheap and easy to handle. Moreover some authors pointed out that it can also be a model for industrial ceramics (Vekinis et al., 1993; Meille et al., 2003).

The prediction of crack initiation cannot be carried out using classical brittle fracture criteria because they lead to a paradox. The Griffith criterion based on energy is unable to predict new crack nucleation and the maximum tensile stress condition often results in unrealistic conclusions. To solve the paradox, one of the authors proposed a coupled criterion, which involves two conditions that must be satisfied simultaneously: one based on energy and the other on stress (Leguillon, 2002). The energy condition derives directly from an energy balance between un-cracked and cracked states. As a consequence of this balance, it is derived that the crack jumps a given length. The stress condition states that the tensile stress must be greater than the tensile strength all along the expected crack path (jump).

The verification of this theory is based here on compression tests carried out on drilled specimens made of plaster. The crack onset is experimentally determined using Digital Image Correlation (DIC) (Peters and Ranson, 1982; Sutton et al., 1983; Chu and Peters, 1985). Our goal is not to definitively validate the theory but only to provide a positive additional element of appreciation for this criterion. In particular, we have tried to show experimentally that the

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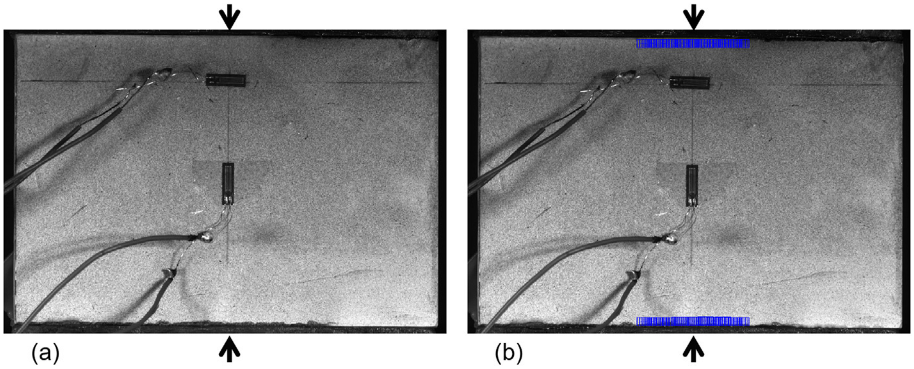

Fig. 1. Measurement of Young's modulus using (a) strain gauges, (b) DIC (blue lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

initiation takes place by a jump of the discontinuity and that the model gives acceptable results even if data contain some uncertainty and randomness.

Remark: For simplicity reasons, throughout this work, the numerical simulations are conducted within the plane strain elasticity assumption. With axial symmetry, they are the only 2D eligible simplifying hypotheses, especially in the presence of a singularity along a smooth front (crack tip or V-notch root). They are the only ones that allow reconstructing a 3D solution and are frequently used approximations providing satisfactory predictions for failure. This will be discussed again in Sects. 3.2 and 5.1.

2. Experimental procedure

2.1. Plaster samples preparation

Dry plaster is used as a quasi-brittle model material (Meille et al., 2003; Vekinis et al., 1993). Thanks to its short hardening time, a plaster powder of Siniat Company named Prestia Profilia 35® is used in this work. Preparation of plaster samples involves the following steps: The required amount of water and powder are calculated based on the volume of the final sample so as to satisfy a mixing ratio W/P (mass of water to mass of plaster) equal to 0.33. The amount of powder is poured gradually in the mixer containing water. Mixing water and plaster is done at a very low speed (65 rpm) to avoid the formation of air bubbles. In order to homogenize the slurry, the mixture is kneaded by hand with the arm of the mixer. The slurry is then mixed again for 1 min by the mixer at a very low speed. Then the mix is poured into the mould of the desired final sample. The removal of the sample from the mould is done 1 h after pouring. The surface of the obtained specimens looks dry but they are still wet inside. A visual inspection showed no major defects on the surface of the samples. Before drilling and testing, samples of plaster are left for 72 h at room temperature. Note that it is very important to observe a constant period of drying because the mechanical properties of plaster change dramatically all along the drying process (Vekinis et al., 1993).

In order to avoid inaccuracies resulting from the drying, Young's modulus, toughness and tensile strength are measured on appropriate samples at the same time.

2.2. Young's modulus measurement

Uniaxial compression tests on samples of dimensions (100 mm × 65 mm × 20 mm) are carried out to determine the Young modulus of the plaster used in the specimens.

Two strain gauges (Fig. 1) are glued on each side (front and back faces) of the plaster samples for strain measurements (lateral and axial strain). Compression machine allows recording the force applied to the specimen during the test. The compression stress is then determined dividing the prescribed force by the loaded surface. Drawing the tangent to the stress strain curve, Young's modulus is computed by taking the slope of this tangent on each sample side. The average of the Young moduli measured on both sides of the samples gives $E = 13.5$ GPa, but there is some scattering.

In order to confirm this value, an optical technique called Digital Image Correlation (DIC) is used. The principle of this technique is detailed in Sect. 4. It is based on a comparison between successive pictures taken during the loading and acts as a kind of optical strain gauge for strain determination. Before starting the compression test, a black speckle pattern is randomly sprayed on the front face of the samples. When a specimen is compressed, a series of images is captured by a camera. On an image chosen as the reference frame, regularly distributed points are defined in a grid in the upper and lower central parts of the tested specimens (blue points in 3). DIC allows determining in the next images (each image corresponds to a load step) the displacement of the grid points previously defined. The global deformation of the sample at each step (image) is taken as the difference between the average displacements respectively of the upper and lower zones. The strain is determined dividing the result by the height of the specimen (65 mm). Young's modulus is determined by taking the slope of the stress/strain curve (stress given by the machine and strain determined by DIC) in the load direction. The Young modulus found by DIC is $E = 12 \pm 0.4$ GPa not far from the value found using gauges, with a greater confidence in the latter method. Hereinafter E is taken equal to 12 GPa.

2.3. Tensile strength determination

Three-point-bending tests on un-notched samples (Fig. 2a) are used to determine the tensile strength of the material. In these tests, load is continuously applied at a constant speed equal to 0.1 mm/min. The tensile strength corresponds to the maximum value of the tensile stress reached in the sample along the lower surface (Fig. 4a) just before failure.

The failure of the specimen occurs in mode I: an opening crack takes place at the middle of the lower edge and then runs through the entire height and width of the sample causing its failure. Cracks repeatedly opening roughly in the middle of the specimen shows that the surface defects are not critical in this measurement. They are small, not visible at the naked eye, and uniformly distributed.