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Analysis of notch effect on the fracture behaviour of granite and limestone: An approach from the Theory of Critical Distances

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ABSTRACT

This paper presents the analysis of the notch effect on granite and limestone fracture specimens. The research is based on the results obtained in an experimental programme composed of 84 fracture specimens, combining the two materials and 7 different notch radii varying from 0.15 mm up to 10 mm. The notch effect is analysed through the evolution of the apparent fracture toughness and the application of the Theory of the Critical Distances.

The results reveal a significant notch effect in the limestone, whereas the notch effect in the granite is negligible for the range of notch radii analysed. Both observations are justified by the corresponding critical distance of the material.

1. Introduction

On many occasions, the load-bearing capacity of a structural component is conditioned by the existence of stress risers. These may have very different natures: cracks, notches, holes, welded joints, corners, etc, all of them having different approaches when the corresponding structural integrity is analysed. Rocks, whether they are naturally in the crust or whether they are industrially exploited (e.g., quarries, masonry) or operated (e.g., slopes, foundations, boreholes), have to sustain loads, and the presence of stress risers may play a key role in the corresponding structural integrity.

This paper focuses on the fracture analysis of rocks containing notch-type defects and subjected to tensile stresses. Rock fracture mechanics (e.g., Whittaker et al., 1992; Aliabadi, 1999; Jeager et al., 2007) conveniently addresses those situations where it may be assumed that the analysed stress riser behaves as a crack-type defect, such as different applications of rock cutting, hydraulic fracturing or underground excavation. However, notch-type defects generate less demanding stress fields than crack-like defects, so it may be overly conservative to proceed on the assumption that notches behave like sharp cracks, coupled with the use of ordinary fracture mechanics. Numerous papers may be found in the literature providing different models of the stress field in the notch tip (e.g., Timoshenko and Goodier, 1951; Weiss, 1962; Creager and Paris, 1967; Glinka and Newport, 1987; Pluvinage, 1998). Basically, they all suggest a reduction in the stress acting perpendicular to the notch plane, in such a way that the larger the notch radius the more significant the stress reduction. This generally has direct consequences on the resistant behaviour of structural components (e.g., Neuber, 1958; Peterson, 1959; Pluvinage, 1998; Taylor, 2007; Cicero et al., 2012; Madrazo et al., 2012). Thus, in most cases, a given component has a higher load-bearing capacity and apparent fracture toughness in notched conditions than in cracked conditions. However, sometimes sharp notches behave like cracks and also blunt notches may not penalise the load-bearing capacity (beyond the corresponding reduction in the resistant section). Additionally, the terms "sharp" and "blunt" are not absolute, but rather they depend on the material: there are materials that present a clear notch effect (e.g., increase in load-bearing capacity and apparent fracture toughness) for very small notch radii (e.g., Madrazo et al., 2012), and there are others that require a certain notch radius to develop a notch effect (e.g., Cicero et al., 2012). This particular nature of notches has led to a great deal of research work over the last few decades, aiming to provide specific tools for the assessment of notched components, beyond the simple and generally over-conservative application of ordinary fracture mechanics. However, the analysis of these phenomena in rocks has been scarce, as detailed in the following section.

Moreover, size effects are an important issue in rock fracture mechanics, given that the material behaviour (e.g., fracture toughness, tensile strength) and the notch sensitivity may change with the size of the component being analysed (Gjorv et al., 1977; Carpinteri, 1982, 1994; Bazant, 1984, 1997, 2000; Shah, 1990; Dyskin, 1997; Borodich, 1999).

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Here, it should be noted that size effects are not directly addressed in this work, so that the obtained material parameters may not be transferable to different scales (e.g., massive rocks).

With all this, Section 2 of this paper presents the Theory of Critical Distances (TCD) as a tool for the assessment of notch-type defects in rocks, Section 3 gathers the description of the materials and the experimental programme, Section 4 provides the results and the corresponding discussion and, finally, Section 5 presents the conclusions.

2. Theoretical background: analysis of notches and the Theory of Critical Distances

The stress distribution at the region ahead of a notch tip may be represented in a bi-logarithmic plot, as shown in Fig. 1, where three regions can be distinguished (Niu et al., 1994; Pluvinage, 1998). Region I corresponds to a nearly constant stress zone, region II is a transition zone, and region III is a zone where stresses follow the expression:

$$\sigma_{yy} = \frac{K_\rho}{(2\pi r)^\alpha} \tag{1}$$

where K_ρ is the notch stress intensity factor and α is a material constant for a given notch radius.

There are two main failure criteria in notch theory: the global fracture criterion and local fracture criteria (Bao and Jin, 1993; Pluvinage, 1998). The global criterion establishes that failure occurs when the notch stress intensity factor reaches a critical value, K_ρ^c, which depends on the notch radius and the material:

$$K_\rho = K_\rho^c \tag{2}$$

K_ρ defines the stress and strain fields in the vicinity of the notch tip, as shown in Eq. (1). This approach is analogous to that proposed by linear–elastic fracture mechanics for the analysis of cracks, but its application is very limited because of the lack of analytical solutions for K_ρ (in contrast with the case of K_I, e.g., R6, 2001; BS7910, 2005; API579-1/ASME FFS-1, 2007; FITNET FFS Procedure, 2008) or/and standardised procedures for the experimental definition of K_ρ^c (in contrast with the case of K_{IC}, e.g., ASTM E, 1820-09e1, 2009).

Concerning local criteria, these are based on the stress-strain field on the notch tip and have more applicability than global criteria from a practical point of view. Amongst them, those criteria belonging to the TCD stand out. The Theory of Critical Distances (TCD) is essentially a group of methodologies, all of which use a characteristic material length parameter (the critical distance, L) when performing fracture assessments (Taylor et al., 2004; Taylor, 2007). The origins of the TCD date back to the middle of the twentieth century, with the works of Neuber (1958) and Peterson (1959), but it has been in the last years, driven by the proliferation of finite element stress analyses, that this theory has been scientifically analysed and applied to different types of materials (metals, ceramics, polymers and composites), failure or damage processes (basically fracture and fatigue) and conditions (e.g., linear-elastic vs. elastoplastic) (e.g., Taylor and Wang, 2000; Taylor, 2001; Susmel and Taylor, 2003; Taylor et al., 2004; Taylor, 2007; Susmel and Taylor, 2010; Cicero et al., 2012; Madrazo et al., 2012; Cicero et al., 2013).

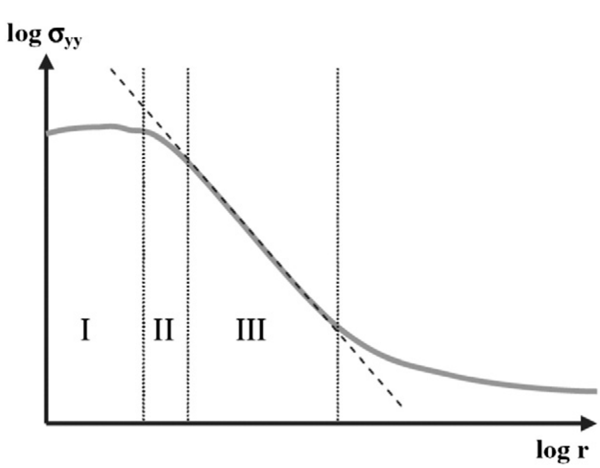

Fig. 1. Schematic showing the stress distribution at a notch tip (bi-logarithmic).

The above-mentioned critical distance is usually referred to as L and its expression is:

$$L = \frac{1}{\pi}\left(\frac{K_{IC}}{\sigma_0}\right)^2 \tag{3}$$

where K_{IC} is the material fracture toughness and σ_0 is a characteristic material strength parameter named the inherent strength, usually larger than the ultimate tensile strength (σ_u), which requires calibration. Only in those situations where there is a linear–elastic behaviour at both the micro and the macroscale (e.g., fracture of rocks) does σ_0 coincide with σ_u.

Amongst the different methodologies included within the TCD, two of them are particularly simple to apply: the Point Method (PM), also known as the Stress Method, and the Line Method (LM). Both of these are based on the stress field at the defect tip. Other methodologies, such as Finite Fracture Mechanics (FFM) and the Imaginary Crack Method are based on the stress intensity factor and their application is not so straightforward. In any case, as stated by Taylor (2007), the predictions made by all these methodologies are very similar, so that only the PM and the LM, those with a far simpler application, will be considered here.

The Point Method (PM) is the simplest methodology, and it assumes that fracture occurs when the stress reaches the inherent strength (σ_0) at a certain distance from the defect tip, r_c. It considers that the material has linear–elastic behaviour, and from the stress field in a crack tip at failure (Anderson, 2004; Taylor, 2007) and the definition of L (Eq. (3)), it is straightforward to demonstrate that r_c is L/2:

$$\frac{K_{IC}}{\sqrt{2\pi r_c}} = \sigma_0 \Rightarrow r_c = \frac{1}{2\pi}\left(\frac{K_{IC}}{\sigma_0}\right)^2 = \frac{L}{2} \tag{4}$$

The PM failure criterion is, therefore:

$$\sigma\left(\frac{L}{2}\right) = \sigma_0 \tag{5}$$

On the other hand, the Line Method (LM) assumes that fracture occurs when the average stress along a certain distance, d (starting from the defect tip), reaches the inherent strength, σ_0. Again, from the stress field in a crack tip at failure and the definition of L, it is easy to demonstrate that d is equal to 2 L:

$$\frac{1}{d}\int_0^d \frac{K_{IC}}{\sqrt{2\pi r}}dr = \frac{2}{\sqrt{2\pi}}\frac{K_{IC}}{d^{1/2}} = \sigma_0 \Rightarrow d = \frac{4}{2\pi}\left(\frac{K_{IC}}{\sigma_0}\right)^2 = 2L \tag{6}$$

Therefore, the LM failure criterion is:

$$\frac{1}{2L}\int_0^{2L} \sigma(r)dr = \sigma_0 \tag{7}$$

The TCD, and then the PM and the LM, allows the fracture assessment of components with any kind of stress riser to be performed. As an example, when using the PM it would be sufficient to perform two fracture tests on two specimens with different types of defects