INFLUENCE OF CRACK SURFACE FRICTIONAL CHARACTERISTICS ON THE GLOBAL STRESS INTENSITY FACTOR

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The purpose of this paper is to present a numerical procedure which can be used to incorporate the effects of roughness and resistance of the crack surfaces on K_I and K_{II}. To this end, Barton's model for rock joints has been incorporated into a numerical Displacement Discontinuity technique so as to simulate the overall fracture behaviour in the presence of dilation and damage. The problem of a crack with irregular surfaces in an infinite medium subjected to normal and shear stresses is solved by means of a computer code, DILDD, developed on the basis of the proposed method.

INTRODUCTION

The study of the behaviour of closed cracks subjected to normal and compressive stresses and shear has received relatively little attention (see, for instance, Nemat-Nasser and Horii (1), Scavia (2)). In these studies, the development of frictional stresses on the crack surfaces and the related phenomena (dilation, damage of the surfaces) are found to be factors strongly affecting crack behaviour. As a result, a crack surface model has to be adopted for the numerical simulations. While in the above mentioned studies macroscopically smooth surfaces are considered (elastic - ideally plastic model), Ballarini and Plesha (3) assume a regular tortuosity of the crack surfaces. In their model, crack surfaces are conceived as globally smooth, roughness and friction effects being taken into account by a rigorous constitutive law at the interface between opposing crack surfaces.

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In this paper a numerical procedure is developed for the analysis of cracks with irregular crack surfaces, which undergo damage phenomena. The numerical technique is based on the Displacement Discontinuity Method (DDM). An empirical constitutive law, proposed by Barton for rock joints (4), is assumed for the crack surfaces.

NUMERICAL PROCEDURE

Constitutive Model

A typical result of direct shear tests performed on rough rock joints is shown in the shear-tangential relative displacement (σ_s - D_s) diagram in Figure 1. Two levels of frictional resistance characterize the behaviour of the joint, and namely: a) peak frictional resistance, σ_{sp}; b) residual frictional resistance, σ_{sr}, achieved for large relative displacements when joint roughness has been totally destroyed.

The following empirical relationship is provided by Barton:

$$\sigma_{sp} = \sigma_n \tan \left[\left(JRC_p \log_{10} JCS/\sigma_n \right) + \varphi_r \right] \qquad (1)$$

where:

- JRC_p is the Joint Roughness Coefficient. This varies in the 0-20 range and can be measured on the joint surface on the basis of an automatic acquisition of the inclination of microasperities.

- JCS, the Joint Compressive Strength, is indicative of the compressive strength of the material; this parameter can be easily measured through rebound hammer tests.

A study by Barton and Bandis (5) indicates that peak relative displacement D_{sp} comes to approximately 1% of the sample length. During this initial shear displacement, the residual angle, φ_r, is mobilized first, followed by roughness, which causes dilation. For displacements greater than D_{sp}, roughness is gradually destroyed or worn up. Dilation continues but at a reduced rate. If we formulate the general case in which the stresses, σ_s, at any given D_s depend on the corresponding JRC mobilized, JRC_m, we can write:

$$\sigma_s = \sigma_n \tan \left[\left(JRC_m \cdot \log_{10} JCS/\sigma_n \right) + \varphi_r \right] \qquad (2)$$

If we determine JRC_m from the diagram shown in Figure 2, eqn.(2) provides an empirical relationship between σ_s and D_s. For $D_s < D_{sp}$, joint stiffness values, K_s, can be defined.

Dilation D_n, corresponding to a given D_s value, can be found by means of the following expression:

$$D_n = 1/2\ JRC_m \cdot \log_{10} (JCS/\sigma_n)\ D_s \qquad (3)$$

Numerical Solution

In order to take into account dilation and damage of the crack surfaces, displacement discontinuity elements have been modified as follows (see Scavia (6)): a) in the tangential direction, shear stresses vary with the displacement discontinuities (relative displacements) according to eqn.(2); b) in the normal direction a displacement discontinuity, D_n, computed according to eqn.(3), is introduced in order to simulate dilation.

The behaviour of the crack, assumed to be globally smooth, is simulated by subdividing it into a set of such Displacement Discontinuity elements. The relative displacements (DDs) between the crack surfaces are computed by following a specially developed numerical procedure based on an incremental application of the external loads. K_I and K_{II} are then computed on the basis of the DDs at the midpoint of the tip elements by means of the displacement method (Carpinteri (7)). The analysis is based on the assumptions that the material surrounding the crack remains elastic and that no crack propagation occurs.

NUMERICAL RESULTS

A computer code, DILDD, developed on the basis of the proposed method has been applied to the analysis of a rough crack, subjected to normal (σ) and tangential stresses (τ) applied at infinity. While τ is linearly increased in 20 steps up to a maximum value (τ_{max}), σ is kept constant. An example of the variations of σ_s, σ_n and D_n at the crack surfaces as a function of D_s is given in Figure 3. The results refer to a central displacement discontinuity element in a 10 cm crack subdivided into 10 elements and have been obtained for the following set of data: $\varphi_r = 20°$, JCS = 50 MPa, $JRC_p = 10$, $\nu = 0.1$, E

= 500 MPa, σ_n = 1 MPa, τ_{max} = 10 MPa. Figure 4 shows the variation of the K_I / K_{II} ratio as a function of the tangential stress applied. The results have been obtained for the same set of data and for three different values of JRC_p. Based on the observation of the foregoing examples, the following remarks can be made: 1) before dilation begins (D_s < 0,33 mm, Figure 3), D_n is nil and σ_n remains constant at its initial value; 2) once the peak condition has been met (D_{sp} > 1 mm, Figure 3), the rate of increase of σ_n and D_n decreases because roughness is reduced. In this example, shear stresses, σ_s, remain almost constant due the combined effects of the reduction in roughness and the increase in normal stresses; 3) the K_I / K_{II} ratios are nil before dilation begins (Figure 4, step 5) and approach zero again once the roughness has been completely destroyed. JRC_p strongly affects the shape of the variation and the maximum value attained.

CONCLUSIONS AND FURTHER DEVELOPMENTS

A numerical technique has been developed in order to simulate the effects of the irregular roughness of crack surfaces on overall crack behaviour. With the proposed method, the evolution of some phenomena associated with dilation and damage can be predicted on the basis of very few parameters, which can all be easily determined in the laboratory. In particular, significant K_I values due to dilation are observed even for modest values of roughness. It must be emphasized that the amount of relative displacements necessary for peak resistance to be overcome has been obtained by assuming a low value of the Elastic Modulus on account of the non propagation hypothesis. In order to apply the proposed method to materials having a higher Elastic modulus, such as concrete and rocks, the latter hypothesis would have to be discarded.

Further developments of this research will include: 1) an exhaustive analysis of the influence of the main parameters on the global stress intensity factor; 2) the introduction of the proposed method into a procedure for crack propagation simulation.

SYMBOLS USED

D = relative displacement (displacement discontinuity) between the crack surfaces

φ = crack surfaces friction angle

σ = stress acting on the crack surfaces

τ = applied shear stress

JCS = joint compressive strength

JRC = joint roughness coefficient

subscripts:

$_m$ = mobilized value

$_{n, s}$ = normal, tangential direction

$_{p, r}$ = peak, residual condition

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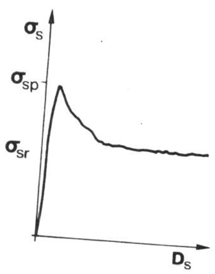

Figure 1 σ_s - D_s diagram obtained for a rough joint

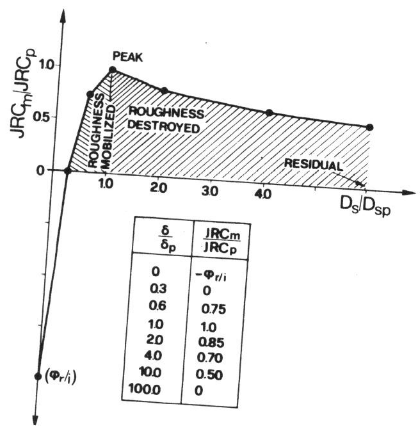

Figure 2 Barton's adimensional model

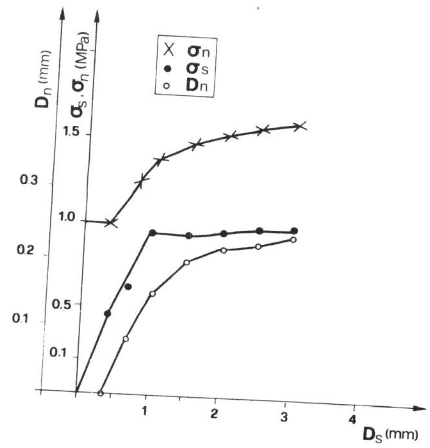

Figure 3 Behaviour of a central crack element

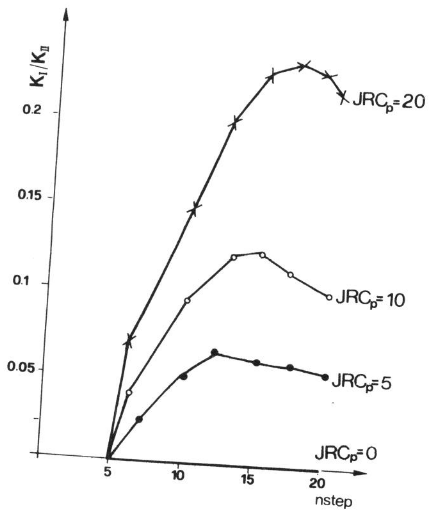

Figure 4 Influence of JRC_p coefficient on the K_I/K_{II} ratio