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# Experimental and numerical study of crack propagation and coalescence in pre-cracked rock-like disks

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ABSTRACT

The pre-cracked disk specimens (Brazilian disks containing single and double cracks in the middle part of the disk) of rock-like materials were experimentally tested under compressive line loading. The specimens were prepared from Portland Pozzolana Cement (PPC), fine sands and water. The failure load of the pre-cracked disks was measured, showing the decreasing effects of the cracks and their orientation on the final failure load. The breakage process of the disks was studied by inserting single and double cracks with different inclination angles. It was observed that wing cracks are produced at the first stage of loading, and start their propagation toward the direction of compressive line loading. The same specimens were numerically simulated by an indirect boundary element method known as the displacement discontinuity method. Finally, a numerical simulation was conducted to study the effect of crack length and its orientation on the cracks coalescence and breakage path.



## 1. Introduction

The presence of pre-existing cracks may reduce the fracture toughness of brittle materials [1]. The mechanical behavior of brittle materials may be affected by the micromechanical behavior of the cracks. Nevertheless, the extension of cracks depends on the properties of cracks such as size, location, orientation and loading condition. The production and propagation of cracks play a vital role in predicting the cyclic breakage process of rock specimens [2].

In a crack propagation process of a brittle material such as pre-cracked rock specimens, usually two types of cracks are observed originating from the original tips of pre-existing cracks – wing cracks and secondary cracks. Wing cracks are usually produced due to tension, whereas secondary cracks may initiate due to shear. Therefore, initiation of wing cracks in rocks is favored relative to secondary cracks because of the lower toughness of these materials in tension than in shear [3]. The pre-existing cracks in rocks are normally under compressive loading rather than under tension, shear or mixed mode loading [4]. It is mainly expected that crack initiation will follow in the direction (approximately) parallel to the maximum compressive load [5].

Many experiments have been devoted to study the crack initiation, propagation path, and eventual coalescence of the pre-existing cracks in specimens made of various substances, including natural rocks or rock-like materials under tensile and compressive loadings [7–24] [7. The Brazilian disk test is one of the most suitable tests in evaluating the static and dynamic fracture toughness of rocks and rock-like specimens containing central pre-existing crack or cracks. These tests may also be used to study the crack initiation, propagation path and cracks coalescence of brittle substances such as rocks [25–32]. This testing procedure used extensively to measure the tensile strength, fracture toughness and mixed mode breakage process in the uncracked and pre-cracked disk specimens of various brittle substances under compressive line loadings [33–42]. It should be noted that in Brazilian disk specimens, the crack initiation and breakage process of the specimens often happen very soon due to the low tensile strength of rocks and rock-like materials. For example, Al-Shayea [42] experimentally studied the crack propagation paths in the Central Straight Through Crack Brazilian Disk (CSCBD) specimens of brittle limestone with different crack inclination angles under mixed mode I/II loading and investigated the influence of confining pressure and temperature on the crack initiation and propagation of the rock samples. The experimental results were compared with theoretical predictions of crack initiation angle. Ghazvinian et al. [32] have done analytical, experimental, and numerical studies for a better understanding of crack propagation process in the CSCBD specimens. The existing experimental and numerical analyses also confirmed the effect of crack inclination angle and crack length on the fracturing processes of brittle materials.

Various numerical methods have been developed for the simulation of crack propagation in brittle substances, e.g. Finite Element Method (FEM), Boundary Element Method (BEM), Discrete Element

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Method (DEM) etc. Three important fracture initiation criteria were proposed to study the crack propagation mechanism of brittle materials i.e. (i) the maximum tangential stress ($\sigma_\theta$-criterion) [43], (ii) the maximum energy release rate (G-criterion) [44] and (iii) the minimum energy density criterion (S-criterion) [45]. Some modified form of the mentioned criteria e.g. F-criterion which is a modified form of energy release rate criterion proposed by Shen and Stephansson [46] may also be used to study the failure behavior of brittle substances [47–49]. Several computer codes were used to model the breakage mechanism of brittle materials such as rocks, for example, FROCK code [17], Rock Failure Process Analysis (RFPA$^{2D}$) code [50], 2D Particle Flow Code (PFC$^{2D}$) [23,32,51].

However, in most of the published investigations usually specimens with a single center crack have been studied. In the present study, the Brazilian disks of rock-like materials containing either single or double cracks in the central part of the specimen are being analyzed both experimentally and numerically. The center single and double cracked disk specimens (prepared from PCC, fine sands and water) tested in a Brazilian Testing Apparatus. The stress and displacement fields, the crack propagation and cracks coalescence through the specimens and in the bridge area (the area in between the two cracks in the specimens containing double cracks) of pre-cracked rock-like disk specimens have been studied both experimentally and numerically. Some of the experiments are simulated numerically by a modified higher order displacement discontinuity method and the crack propagation and cracks coalescence in the bridge area are studied based on Mode I and Mode II stress intensity factors (SIFs). The experimental results are compared with the numerical results which are in good agreement with each other and illustrate the accuracy and validity of the present work. The numerical simulation makes the necessary flexibility in the analysis so that it is readily possible to investigate the effects of crack length and its orientation on the breakage process of pre-cracked disk specimens.

## 2. Specimen preparation and testing

The pre-cracked rock-like disk specimens with 100 mm, diameters and 30 mm, thickness are specially prepared from a mixture of Portland Pozzolana cement (PPC), fine sands and water. The mechanical properties of the prepared rock-like specimens tested in the rock mechanics laboratory before inserting the cracks are: compressive strength: $\sigma_c = 28$ MPa; Young's modulus: $E = 15$ GPa; Brazilian tensile strength, $\sigma_t = 3.81$ MPa; and Poisson's ratio, $\nu = 0.21$.

Various Brazilian tests were conducted on rock-like disk specimens containing either a single crack or two cracks 1 and 2. These cracks were created by inserting one thin metal slim with 30 mm width and 1 mm thickness for CSCBD specimens, and two thin metal shims with 20 mm width and 1 mm thickness in double cracked specimens (during the specimens casting in the mold). Fig. 1 shows a schematic view of rock like CSCBD specimen containing a single crack. The crack length, $2b$, is equal to 30 mm, and the crack inclination, $\beta$, takes the values of 0°, 15°, 30°, 45°, 60° and 90°.

The disk specimens with double cracks are prepared in such a manner that crack1 is the same as that of single crack (with a constant inclination angle, $\beta = 90°$) and crack2 is oriented at different angles with respect to the direction of crack1, i.e. at the angles $\varphi = 0°$, 30°, 60° and 90° (in a counterclockwise direction), as schematically shown in Fig. 2. The compressive line loading, $F$, was diametrically applied and the loading rate was kept at 0.5 MPa/s during the tests. Fig. 2 demonstrates a schematic view of the geometry of two cracks (i.e. crack 1 and crack 2) with the equal lengths, $2b = 20$ mm and the crack length to diameter ratio of $b/D = 0.1$.

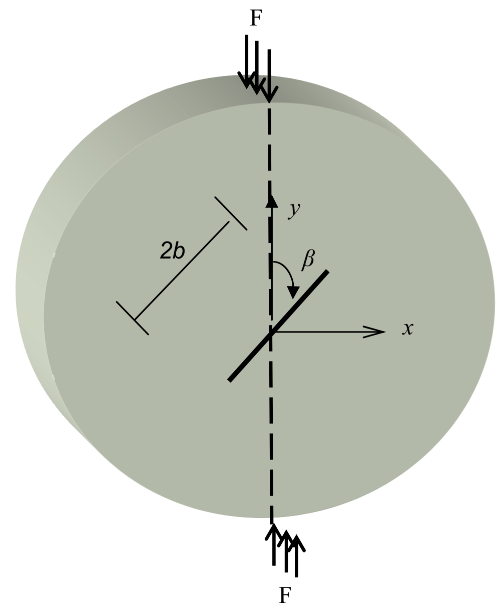


**Fig. 1.** Schematic view of rock like CSCBD specimen.

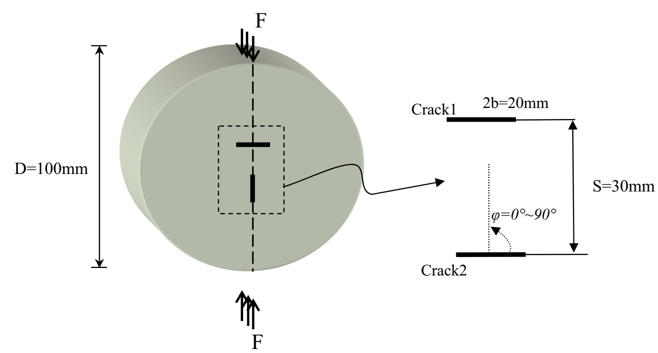


**Fig. 2.** Geometry of two cracks in a rock-like disk specimen under diametrical compression.

Three experiments were carried out, and for each experiment, four specimens were prepared. These double cracked disk specimens containing crack 1 and crack 2 located at the centerline of each specimen with the spacing $S = 30$ mm as shown in Fig. 3. Spacing is taken as the vertical distance between the centers of two cracks expressed in mm.

## 3. Experiments and results

The specially prepared (rock-like) specimens were tested experimentally and the results were used to analyze the failure loads and the crack propagation process of the pre-cracked disk specimens. The crack propagation process of the disk specimens is discussed below, considering the two cases of disk specimens with: (i) single crack and (ii) double cracks.

### 3.1. Failure load analysis of the pre-cracked disk specimens

It is obvious that the pre-cracked rock-like disk specimens have a lower strength compared to the un-cracked specimens (specimens having no cracks). The failure load analysis of the pre-cracked disk specimens containing either a single crack or two cracks with different orientations is of paramount important to