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Numerical modelling of the contact condition of a Brazilian disk test and its influence on the tensile strength of rock

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ABSTRACT

The stress distribution and failure process in the Brazilian test disk are numerically studied using the continuum-based discrete element method. The stress distribution in the immediate contact vicinity between disk and jaws with two types of contact conditions are compared, and the position of failure initiation is determined based on the generalised Griffith criteria. Moreover, the whole process of the Brazilian test is modelled for disks with various material properties under two contact conditions and the modelled Brazilian tensile strengths of the disks are obtained. Numerical simulations show that the distribution of stress components in the vicinity of the contact have remarkable differences between the two contact conditions, and the difference increase with the increasing of loading level and disk's elastic modulus. However, the stress distributions exhibit almost no difference on the disk's centre area. The disk's elastic modulus and the ratio of compressive strength to tensile strength are the main factors that influence the distribution of stresses in the vicinity of the contact, thereby affecting the failure initiation and tensile strength, especially under no-cushion contact conditions. The thin plastic cushion can alleviate the stress concentration in the vicinity of the contact between the disk and jaws, and cracks initiating from the vicinity of the contact can be avoided for almost all of the rock-like materials. However, the enlarging contact ranges will result in a larger deviation between the test results and the real tensile strength. An improved Brazilian test method considering two contact conditions of with and without cushions for rock and rock-like material is proposed.

1. Introduction

Because of the convenience in preparing the specimens and conducting the tests, the Brazilian disk testing method has been widely used to obtain the tensile strength of rock and rock-like material. The Brazilian disk test was proposed independently by Carneiro and Akazawo in 1943.[1,2] Although various aspects of the Brazilian disk test were critically discussed in 1964,[3,4] it has been gradually accepted in international academia. In 1978, ISRM [5] presented a suggested method for performing the experiment using the apparatus schematically shown in Fig. 1, and in 1988, ASTM established the specifications for the testing procedure and the specimen preparation.[6] The apparatus consists of two steel loading jaws of predefined internal radius of curvature R_j=1.5R_s, where R_s is the radius of the specimen.

The theory is based on two critical aspects: one is the biaxial stresses distribution in a circular disk with diametrically compressed [7] (shown in Fig. 2a and Eq. 1); the other is Griffith's strength criterion, which can be simply described as the phenomenon of most rocks in biaxial stress fields failing in tension at their uniaxial tensile strength when one principal stress is tensile and the other finite principal stress is compressive with a magnitude not exceeding three times that of the tensile component [8].

$$\sigma_{p\theta} = +\frac{2P}{\pi D_s t} \tag{1a}$$

$$\sigma_{pr} = -\frac{2P}{\pi D_s t}\left(1 - \frac{4D_s^2}{D_s^2 - 4r^2}\right) \tag{1b}$$

where P is the load (kN), and D_s and t are the diameter and thickness of the specimen, respectively.

However, in practice, the load P cannot pointedly bear on the specimen (i.e., as a line loads in three dimensions); rather, the load would result in a stress distribution over arcs (i.e., strips in three dimensions) of finite width; thus, the distribution of the principal stress components along the compressed diametric line vary with the width of finite arcs, especially in the immediate vicinity of the contact points of the jaws and the specimen (Fig. 2b). In 1959, Hondros [9] provided the solution of the principle stress components σ_{sr} and $\sigma_{s\theta}$ as:

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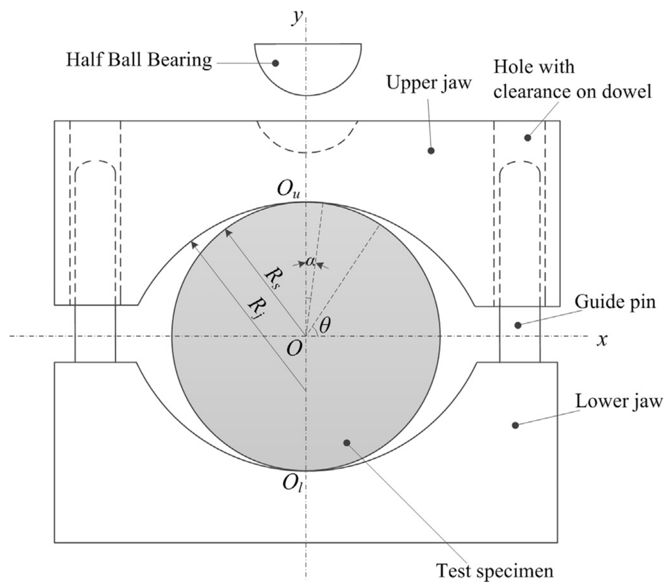

Fig. 1. Suggested apparatus for the execution of the Brazilian test by ISRM.

$$\sigma_{s\theta} = +\frac{2P}{\pi D_s t}\left(\frac{\sin 2\alpha}{\alpha} - 1\right) \tag{2a}$$

$$\sigma_{sr} = -\frac{2P}{\pi D_s t}\left(\frac{\sin 2\alpha}{\alpha} + 1\right) \tag{2b}$$

If 2α is less than 15°, then the error induced by the arc of contact for the approximate expression for $\sigma_{s\theta}$ is less than 2%; in this case, $\sigma_{p\theta}$ and $\sigma_{s\theta}$ have the same expression (Eq. 1a and Eq. 2a), despite the apparent difference of the loading distribution. Therefore, the tensile strength of the specimen σ_t can be calculated by the component of $\sigma_{p\theta}$ in Eq. (1a) or $\sigma_{s\theta}$ in Eq. (2a), when P reaches its maximum value, namely, at the failure of the specimen.

However, the principle stresses in the immediate vicinity of contact area are much higher than that at the centre area of disk specimens and are very sensitive to the variation in the contact conditions. The main problem is that it is the contact conditions themselves that determine whether failure will initiate in the central part of the specimen or in the vicinity of contact parts.

Proceeding from the equality between the strains of two materials in contact area, Fairhurst,[3] Mellor and Hawkes,[10] and Fadeev [11] represented the maximum contact stress. The jaws with internal curvature were proposed by Mellor and Hawkes, and accepted by ISRM and ASTM and widely used in Brazilian test. The contact conditions between the jaws and the disk were more consistent than the contact conditions for plane plates and small steel bars. Andreev [12,13] provided the maximum stress in the Brazilian test and the breadth of the contact strip for both curve and plane loading devices and analysed the advantages of the soft inserts for a more uniform distribution of the loading. Based on the complex potentials method, the analytic results for the pressure distribution and the contact width was presented, considering the specimen and the jaws as a system of elastic bodies according to the approach of Kourkoulis and Markides [14,15]; however, the strain distribution, which exhibited a saddle shape, obtained by the Digital Image Correlation system in the test was not consistent with the loading types exerted on the specimen in the theoretical analysis. Markides and Kourkoulis's recent research [16] focused on the influence of jaw's curvature on the results of Brazilian disk test, they consider that the proper range of curvature (0,0.67) need to make the stress field at the disk's centre independent of contact conditions while keeping at the same time the contact range large enough to reduce the stress concentrations and risk premature fracture initiation around the contact vicinity. With assumption of elliptic normal contact stresses and no contact friction between specimen and loading platens, Japaridze [17] given the displacements and stresses distribution for various loading curvature and stiffness and gotten the conclusion that the concentrated loads and corresponding equation of tensile stresses always gives a greater or smaller overestimation of maximum tensile stress in the centre of disk.

Although such approaches were rather rough approximations of reality or even had evident limitations, they were widely considered and employed for test purposes.[18–24] The main reason for this situation is that it is generally accepted the stress field in the centre area of disk does not vary obviously with the contact conditions. But, the local stress field on the contact vicinity, which is critically influenced by the contact length, the magnitude of the radial pressure, and also the relative deformability of the jaws and disk, vary significantly with the contact conditions. Therefore, the high magnitude of stress field in the contact area often results in premature local factures; although it is just failure in a small region, it has a tremendous effect on the whole stress distribution, or even the validity of the Brazilian test.

In this context, a numerical method named CDEM (Continuum-based discrete element method), which combines the FEM (Finite Element Method) and the DEM (Discrete Element Method), is able to model continuous or discontinuous deformation and asymptotic failure under static or dynamic loads,[25–28] is used to model the distribution of stresses and the initiation and propagation of cracks in the Brazilian disk test. The distribution of stresses in the immediate vicinity of the contact and its variety with the contact conditions and material properties are analysed in detail. Moreover, the failure initial positions are determined based on the distribution of stresses and the failure criteria of General Griffith. Finally, the tensile strengths modelled by

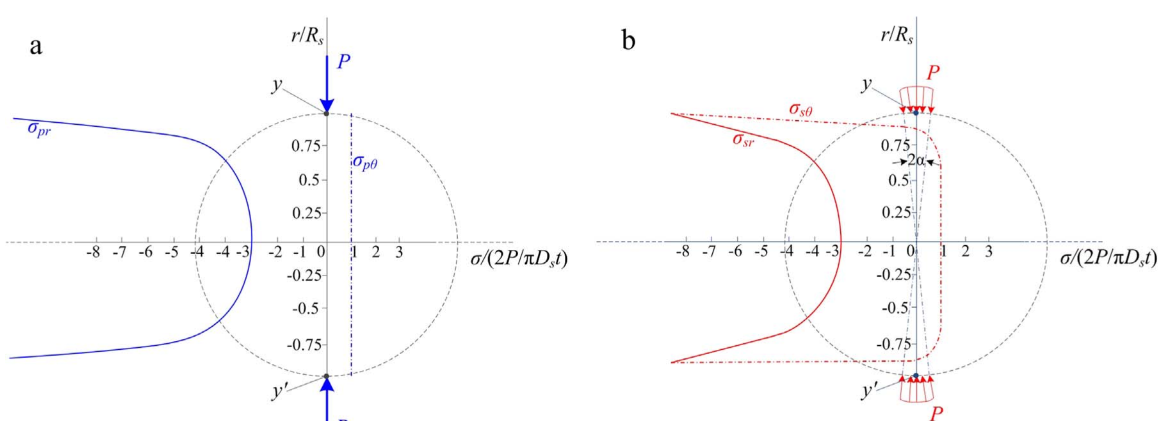

Fig. 2. (a) Principal stress components along the diametric line compressed by a point load; (b) Principal stress components along the diametric line compressed by a strip load. The dashed circle presents the disk specimen. The stress components are normalised by $2P/\pi D_s t$, and conventionally, the quantity of the tensile component is positive.