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Study of rock splitting failure based on griffith strength theory

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ABSTRACT

It is argued here that often-cited result that the Griffith theory leads to a uniaxial compressive strength that is twelve times greater than uniaxial tensile strength is erroneous. A uniaxial compressive load can lead to the maximum tensile stress at longitudinal crack tips when the ratio of minor axis to major axis of the Griffith's crack is finitely small, but it is smaller than the maximum tensile stress of inclined crack under the same pressure. According to the characteristics of the maximum tensile stress distribution on the perimeter of the Griffith's crack, and the splitting characteristics of rock failure process, the conditions of axial splitting failure of rock specimens are proposed, and the mechanism of splitting fracturing of rock specimens is clarified as well.

1. Introduction

Axial splitting failure is one peculiar phenomenon of brittle materials, which has been noticed by researchers since the 1930.[1] The basic characteristics of splitting failure involve some phenomena that the failure surface is generally parallel to the direction of the main acting line, and the failure process is quite quick. Such failure is a kind of tensile failure, but on whose surface there is no tensile load. This splitting of rock specimens often happens in uniaxial loading test, especially when the loading rate is very high or impactive.

During the 1970s to the 1980s of the last century, it was discovered in zonal disintegration in surrounding rock mass of deep mines in South Africa, a phenomenon like splitting, that the failure surface in intermittent distribution is parallel to surrounding contour of roadways.[2] This kind of failure phenomena were subsequently observed in Russian and Chinese deep mines, and it was verified by simulation tests.[3,4] In recent years, splitting failure that the main fracturing surface is parallel to major acting axis has also been found in unloading experiments using rock specimens by Chinese researchers.[5,6]

The unloading test means the experimental process of putting synchronous triaxial loading (axial load and confining pressure) onto the specimens to a certain stress level, then keeping axial pressure or axial displacement while reducing confining pressure gradually, thus causing the failure of rock specimens. In addition, the authors of this paper conducted unloading tests under multiaxial loading condition using thick-walled cylinder specimens, i.e., put triaxial loading on two end faces, outer wall and inner wall of thick-walled cylinder specimens synchronously, forming multiaxial compressive stress state that axial stress was distributed uniformly, radial stress and tangential stress established were conforming to Lame's formula in elastic mechanics, then reduce the pressure on outer wall and inner wall respectively or at the same time up to loss carrying capacity of cylinder specimens and fracturing ultimately.[7] The main cracking surface of the broken specimens is parallel to main axis of specimens in quite a few specimens and the annular cracking has appeared in both ends of thick-walled cylinder specimens. The broken rock fragments forms when the annular and radial cracks have cross connection (see Fig. 1). This kind of ring-like breakage of thick-walled cylinder specimens is similar to zonal disintegration phenomenon in surrounding rock mass of roadways.

It was traditionally considered that the strength theory of maximum deformation is suitable to brittle rock-like materials but there existed opposing opinions on this viewpoint.[8,9] In practice, even under the same uniaxial compressive tests, splitting failure is just one of failure patterns for rock specimens and another is shearing failure, whose fracturing surface is inclined to main axis of rock specimen (it is shorten as oblique shear). It is obvious that one of the same strength theories can not explain two different failure patterns. The zonal disintegration of rock mass around deep roadway was explained in Ref. 10 through Poisson's effect that it has the same failure mechanism as rock pillar on high pressure will lead to rock splitting by lateral expansion. This viewpoint is similar to the above deformation analysis. Poisson's phenomenon is a deformation characteristic that almost all materials have while rock splitting under axial compression doesn't appear in uniform materials. Therefore, the mechanism of rock splitting failure should be taken into account the structural feature of rock material itself.

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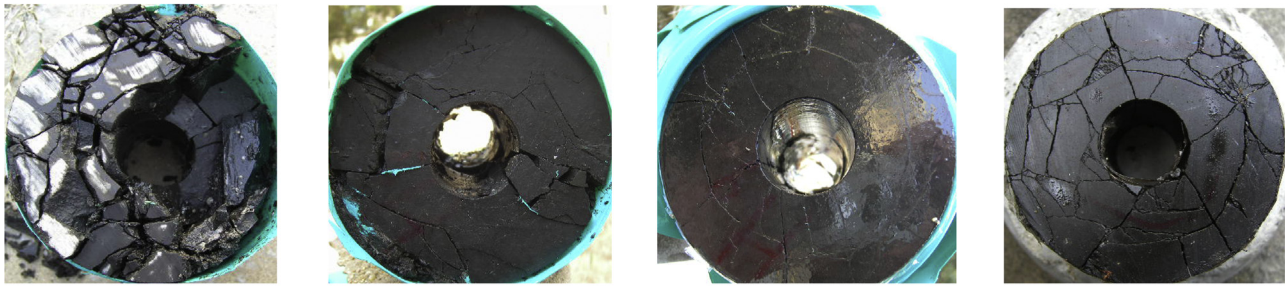

(a) XZH limestone 7 (b) XZH limestone 9 (c)XZH limestone 92 (d) XZH limestone 8

Fig. 1. Failure patterns of thick-walled cylinder specimens.

Some researchers think that splitting is resulted by the wedging of rock fragments of broken specimens. It is certain that splitting failure caused by wedging does exist. However, not all splitting failure is induced by wedging. Splitting failure of a rock specimen is different from wedging failure to some degree because wedging is attributed to external effect while splitting failure is owing to internal effect caused by tensile stress. They can be referred to as intrusion fractures and internal fractures, respectively.[11] However, the cause of internal fractures has not been accounted for so far.

The theories describing the failure of rock specimens mainly include Mohr–Coulomb and Griffith criteria. It is evident that Mohr–Coulomb criterion can not explain the phenomenon of splitting failure for rock material under axial pressure. Some researchers on materials such as concrete, composite material and rock have considered the influence of inside defects on splitting failure.[12-14] But the detailed influences of internal defects are not specifically analyzed in these discussions.

Griffith's theory that considers the effect of the internal defect through analyses on maximum tensile stress in the periphery of Griffith's crack in rock can be applied to the discussion of the splitting failure of the rock. This approach has aroused a lot of scholars' concern, including the modification to this approach in the 1960s[15] and Murrell's extension of the 3D Griffith criterion in 1963.[16]

The conclusion of plane Griffith's criterion can be presented as:

$$\sigma_3 = -T_0(\sigma_1 + 3\sigma_3 < 0) \quad (1)$$

$$\frac{(\sigma_1 - \sigma_3)^2}{4(\sigma_1 + \sigma_3)} = 2T_0\,(\sigma_1 + 3\sigma_3 \geq 0)$$

where T_0 is the uniaxial tensile strength.

From the above equations, it is known that there are two forms of fracture of Griffith's crack, that is, the tensile fracture on the crack tips along major axis of the crack caused by the maximum tensile stress arises from the pull in vertical direction to the major axis of the crack, and tensile fracture near the crack tips in the tangential direction, which the maximum tensile stress near the crack tips arises from various compressive states including biaxial compression and uniaxial compression. Griffith's criterion also draws the conclusion that uniaxial compressive strength of rock is eight times of its tensile strength.

Through the discussion on Griffith's criterion, it has also proved that the cracking propagation direction of the crack is $\gamma = -2\beta$ or $\gamma = \pi - 2\beta$ in compressive state.[17] Where γ is the angle between the propagation direction of the crack and major axis of the crack; β is the angle between major axis of the crack and the direction of the maximum principle stress.

This conclusion shows that crack propagation along the major axis of the crack happens inside the plane of itself, and it is rapid. While in the situation of compressive state, the fracture of the crack will deviate from the plane of the crack and finally turn to the direction of the maximum principle stress. In this way, when the fracture extends further in compressive state, the original stretching fracture model will change[18] and require more energy consumption. This phenomenon is termed as fracture indurations.[19] The above research indicates the results that all tangential cracking under various compressive states will not cause final failure of rock specimens according to Griffith theory, except cracking on crack tips along its axis arising from the tension perpendicular to the axis. To explain final fracture of the rock, the modification of the Griffith's strength criterion based on the shearing strength appears was consequently performed.[15]

But whether in Griffith's Theory itself or the afterwards discussions, the reasons for the splitting of rock under uniaxial compression have not been clearly explained. The existence of two forms of rock failure; splitting and shearing under uniaxial compression really shows the instability of rock failure behavior. This paper illustrates the cause of instability of the styles of rock failure and explains the mechanical essence of splitting failure by stress analysis of Griffith's crack. It also provides a basis for the analysis of zonal disintegration in surrounding rocks of the deep roadways.

2. Discussions of the maximum tensile stress on the perimeter of Griffith's crack

2.1. The location of maximum tensile stress

It is assumed that all the cracks in rock matrix are long and thin ellipses in Griffith strength theory and the cracks are distributed randomly. According to the assumption of Griffith theory, the inclination of cracks is the master variable of tangential stress at crack tips and the tangential stress (σ_b, see Fig. 2) on the perimeter of a slender ellipse can be expressed by Inglis's formula:

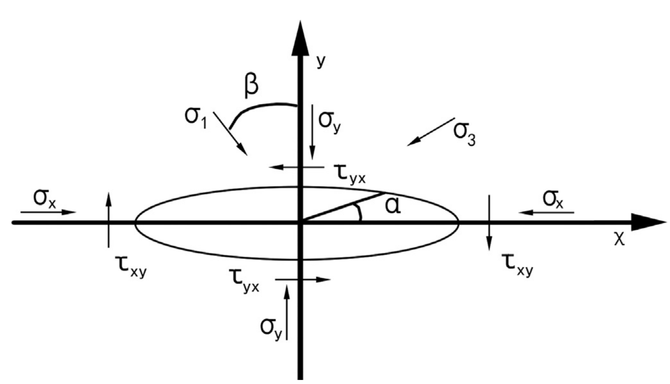

Fig. 2. Stress state of Griffith crack.