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An experimental and numerical study of fracture coalescence in pre-cracked specimens under uniaxial compression

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ABSTRACT

This study presents crack initiation, propagation and coalescence at or near pre-existing open cracks or flaws in a specimen under uniaxial compression. The flaw geometry in the specimen was a combination of a horizontal flaw and an inclined flaw underneath. This flaw geometry is different from those reported in the previous studies, where a pair of parallel flaws was used. Three materials were used, PMMA (Poly Methyl MethAcrylate), Diastone (types of molded gypsum), and Hwangdeung granite. Crack initiation and propagation showed similar and different patterns depending on the material. In PMMA, tensile cracks initiated at the flaw tips and propagated to the tip of the other flaw in the bridge area. The cracks then coalesced at a point of the inclined flaw, which is affected by the flaw inclination angle. For Diastone and Hwangdeung granite, tensile cracks were observed followed by the initiation of shear cracks. Coalescence occurred mainly through the tensile cracks or tensile and shear cracks. Crack coalescence was classified according to the crack coalescence types of parallel flaws for overlapping flaw geometry in the past works. In addition, crack initiation and coalescence stresses in the double-flawed specimens were analyzed and compared with those in the single-flawed specimen. Numerical simulations using PFC^{2D} (Particle Flow Code in two dimensions) based on the DEM (Discrete Element Method) were carried out and showed a good agreement with the experimental results in the coalescence characteristics in Hwangdeung granite. These experimental and numerical results are expected to improve the understanding of the characteristics of cracking and crack coalescence and can be used to analyze the stability of rock and rock structures, such as the excavated underground openings or slopes, tunneling construction, where pre-existing cracks or fractures play a crucial role in the overall integrity of such structures.

1. Introduction

Rock contains a large number of discontinuities resulting from a variety of geological processes. Pre-existing discontinuities or cracks in rock play important roles in initiating new cracks. When a load is applied, new cracks start to grow at or near the tips of pre-existing cracks and propagate toward the direction of the major principal stress, sometimes coalescing with other cracks. A series of cracking processes eventually control the overall behavior of the rock, which have prompted extensive experimental studies of pre-cracked specimens of different materials, including rock-like brittle/semi-brittle materials and natural rocks: glass (Hoek and Bieniawski, 1965), Columbia Resin 39 (Bombolakis, 1968), Plaster of Paris (Lajtai, 1971, 1974), molded gypsum (Bobet, 2000; Park, 2001; Shen, 1995; Bobet and Einstein, 1998a,b; Reyes and Einstein, 1991; Sagong and Bobet, 2002; Wong and Einstein, 2008a,b), sand-stone-like material (Mughieda and Alzo'ubi, 2004; Wong and Chau, 1998; Wong et al., 2001), granite (Miller and Einstein, 2008), marble (Park, 2001; Jiefan et al., 1990; Li et al., 2005; Wang et al., 1987), granodiorite (Ingraffea and Heuze, 1980; Wong et al., 2008), limestone (Ingraffea and Heuze, 1980), clay (Vallejo, 1987, 1988), etc. Although there are differences in the crack pattern, common characteristics have been observed: tensile cracks are initiated at the tips of the flaw and propagate in a curvilinear direction with increasing load and shear cracks grow at the tips of the flaw nearly coplanar to the flaw. In particular, Wong and Einstein (2009) reviewed previous studies and suggested that the terminology in the seven different types of the tensile and shear cracking (three types each for tensile and shear cracking and one type of mixed mode cracking) be standardized based on high-speed camera observations rather than by fractography.

Experimental research on a gypsum specimen with a pair of parallel flaws (the term 'flaw' denotes an artificially made pre-existing crack in a specimen) under compression has found a range of crack coalescence patterns according to the nature of crack initiation and coalescence. Shen (1995) reported that three different

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types of failure occurred depending on the bridge inclination angle: tensile failure, shear failure or mixed-mode failure. Bobet and Einstein (1998a) carried out uniaxial and biaxial compression tests on gypsum specimens with pre-existing cracks and identified five different types of coalescence with a combination of tensile and shearing processes. Wong and Chau (1998) also categorized the crack coalescence patterns in nine cases from the results of a series of uniaxial compression tests. Park (2001) carried out uniaxial compression tests on Diastone (types of molded gypsum) and Yeosan marble with double flawed specimens and identified seven different types of coalescence patterns with tensile, shear, or mixed-mode cracks. Sagong and Bobet (2002) produced three or sixteen flaws in gypsum specimens and carried out uniaxial compression tests to observe the coalescence patterns in double flawed specimens to be extrapolated to multiple flawed specimens. Wong and Einstein (2008a) performed similar experiments on Carrara marble and gypsum using a high-speed camera that could observe the very instant of crack initiation to differentiate shear cracking from tensile cracking. Seven different types of cracking from a single flaw were identified and nine different types of coalescence were classified.

Many numerical methods have been developed to simulate crack initiation and propagation. These numerical methods include the finite element method (FEM), boundary element method (BEM), and displacement discontinuity method (DDM) (Tang et al., 2001). For the last few decades, various criteria were proposed for crack initiation and propagation at the flaw tips. For practical purposes, three criteria are mainly applied (Bobet and Einstein, 1998b; Vásárhelyi and Bobet, 2000): the maximum tangential stress theory (Erdogan and Sih, 1963), maximum energy release rate theory (Hussian et al., 1974), and minimum energy density theory (Sih, 1974). The damage model (Reyes and Einstein, 1991) and F-criterion (Shen and Stephansson, 1994) have been evolved specifically for crack coalescence in the rock bridge area through secondary cracks. Recently, a numerical simulation code, RFPA^{2D} (Rock Failure Process Analysis), was used to simulate crack propagation and coalescence in a rock bridge area. It successfully modeled the global failure of a rock specimen as well as local cracking at the flaw tips (Li et al., 2005; Tang et al., 2001; Tang and Kou, 1998). In addition, DEM (Discrete Element Method) developed by Cundall and Strack (1979) was used to simulate the cracking process in brittle clay specimens (Vesga et al., 2008) and revealed a good agreement with the experimental results. They used PFC^{2D} (Particle Flow Code in two Dimensions) which can reproduce the cracks directly by bond breakage between the circular particles instead of using fracture mechanics theories where complex mathematical equations relevant to the stress intensity factor and fracture toughness at the crack tips are implemented. Therefore, PFC^{2D} was selected as a numerical tool to model the crack propagation and coalescence patterns in this study.

In this study, new double-flaw geometry was introduced to observe crack coalescence in a bridge area. The flaw geometry consisted of a horizontal flaw and an underneath inclined flaw. The new geometry of a double-flaw in this study is expected to improve the understanding of crack propagation and coalescence because en-echelon type of cracks can propagate out of fracture plane to be non-parallel each other according to the orientation of the local stresses as shown in Fig. 1 (Lajitai et al., 1994; Mandal, 1995; Roering, 1968). Three materials for the specimen, such as PMMA (Poly Methyl MethAcrylate), Diastone and Hwangdeung granite, were selected. For each material, the characteristics of crack propagation and coalescence were observed and analyzed. Crack initiation and coalescence stresses in a double-flawed specimen were analyzed and compared with those in the single-flawed specimen. In addition, a numerical simulation using PFC^{2D} was carried out for the Hwangdeung granite specimens.

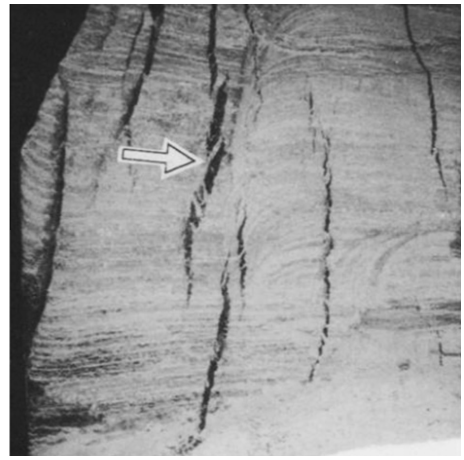

Fig. 1. A photo that contains non-parallel cracks; (a) at a three meter high face of a yield pillar at the Cominco mine in Vanscoy, Saskatchewan (after Lajitai et al., 1994).

2. Specimens and testing apparatus

Both single-flawed and double-flawed specimens were prepared. The flaw geometry in a double-flawed specimen was a combination of a horizontal flaw and an underneath inclined flaw as shown in Fig. 2. The inclined flaw had an inclination angle of 30–90° in 15° intervals. In case of the single-flawed specimens, a flaw inclination angle of 0° was added. The reason why different lengths of flaws were used for different materials as shown in Fig. 2(a) and (b) was to avoid the abrupt rupture of a specimen and not to exceed the loading capacity of the testing facilities. The bridge length of the flaws (2b) as defined in Fig. 2(a) and (b) for different materials was set to 10 mm in order to allow the possible crack coalescence (Bobet and Einstein, 1998a). The procedures for specimen preparation for each material are explained as follows.

Rectangular prismatic specimens of PMMA, 60 × 120 × 25 mm in size, and Hwangdeung granite, 60 × 120 × 30 mm in size, were prepared. A water-jet system was used to produce flaws instead of a diamond saw. High-pressurized water mixed with a garnet abrasive ejected from the 0.75 mm diameter nozzle produced the flaws of 1 mm in aperture thickness. The flaw had rounded tips with a slightly larger aperture thickness at its starting point as shown in Fig. 3(a) and (b) because the water-jet enlarged the hole for the time during which it penetrated the specimen thoroughly. The Diastone specimens of 60 × 120 × 25 mm in size were prepared by mixing Diastone powder and water at the mixing ratio of 1 : 0.26 by weight. The mold with an internal volume of 60 × 120 × 30 mm and covered with two flexible plastic films with two slits at the location of the flaws were used. The flaws of 0.3 mm in aperture thickness were produced by inserting steel shims through the slit after pouring the mixture and removing them after Diastone became hardened. After making flaws, the surfaces of all specimens were polished before the experiment. Fig. 3 shows the PMMA, Diastone, and Hwangdeung granite specimens.

Several specimens with the same flaw geometry were prepared to check out the reproducibility of the test results as summarized in Table 1. The specimen number presents the type of material, number of flaws, flaw inclination angle, and sequential number of specimens. The type of material is presented as A, D and G for PMMA, Diastone, and Hwangdeung granite, respectively, and the number of flaws is expressed as S and D for single and double-flawed specimens in that order. The flaw inclination angle, which is denoted by α, was followed by the sequential number of