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Experimental studies on cracking processes and failure in marble under dynamic loading

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ABSTRACT

The loading conditions influence not only the strength but also the cracking behaviors of rocks. The crack behavior study in various rock types containing artificially created flaws under the quasi-static loading condition has been extensively studied in the past. In the present study, the research of cracking processes in a natural rock is extended to dynamic loading conditions, which are then compared with the quasi-static results. Carrara marble specimens containing a single pre-existing open flaw are tested. The dynamic loadings are generated by the Split Hopkinson Pressure Bar (SHPB) system with the high-speed data acquisition subsystem and the high-speed video subsystem. Firstly, the influences of the flaw inclination angle on the compressive strength of the marble specimens are discussed and compared under these two loading conditions. Secondly, the cracking processes of marble are analyzed, which are found to consist of two stages—the development of white patches and the growth of macro-cracks. In the first stage, under these two loading conditions, the white patch patterns are generally similar with only minor differences. Significant differences with respect to the macro-crack types and the failure modes are found in the second stage. Under the quasi-static compression, the tensile wing and anti-wing white patches evolve into the closed tensile wing cracks (only for low flaw inclination angle specimens) and the open anti-wing cracks, subsequently leading to the specimen failure. In contrast, under dynamic compression, only the anti-wing and shear patches evolve into two symmetrical pairs of shear cracks, which result in the specimen failure. The flaw inclination angle appears not to influence the shape and orientation of the shear crack trajectories far away from the flaw tips. Therefore, the failure mode under quasi-static compression is dominantly diagonal, while the failure mode under dynamic compression is "X" shape regardless of the flaw inclination angle.

1. Introduction

The mechanical behaviors of rock are generally different under quasi-static and dynamic loadings. A number of previous studies revealed that both the compressive and tensile strength of many brittle materials including rocks are strain rate dependent (Christensen et al., 1972; Ross et al., 1995; Frew et al., 2001; Grote et al., 2001; Mahmutoglu, 2006; Wang et al., 2006; Kim and Keune, 2007; Ma and An, 2008; Wu et al., 2010; Cusatis, 2011; Zhao, 2011). The three modes of fracture toughness, which describe the ability of a material containing a crack to resist fracture, are also dependent on the strain rate or the loading rate to different extents (Hodulak et al., 1980; Toshiro et al., 1988; Kishi, 1991; Kalthoff and Bürgel, 2004; Dai et al., 2011; Foster et al., 2011). Therefore, due to the strain rate effect on mechanical properties e.g. strength and fracture toughness, and the dynamic inertia effect, the crack initiation and propagation are also dependent on the strain rate or loading rate (Meyers, 1994; Anderson, 2005).

The quasi-static strength and cracking processes of rock or rock-like materials under low strain rates have been well studied experimentally (Brace and Bombolakis, 1963; Einstein and Hirschfeld, 1973; Lajtai, 1974; Hoek and Bieniawski, 1984; Horii and Nematnasser, 1986; Bobet, 1997; Einstein and Stephansson, 2000; Ingraffea et al., 2001; Wong and Einstein, 2006, 2009a; Wong, 2008). Besides the intact specimens, specimens containing artificially-cut flaw(s) under quasi-static compression are well investigated with respect to the crack initiation and propagation (Bobet, 1997, 2000, 2001; Bobet and Einstein, 1998; Yang et al., 2008; Park and Bobet, 2009; Wong and Einstein, 2009a). Under dynamic loading conditions, the conventional fracture mechanics theory under quasi-static loadings is not entirely applicable (Lawn, 1993). There has been little experimental literature discussing the cracking processes of rocks under high strain rates (dynamic loadings) (Cheatham, 1968; Kutter and Fairhurst, 1971; Subhash et al., 2008). Such studies focus mostly on intact specimens or large scale rock masses. Since most of the rock masses contain inherent defects or flaws, the experimental and theoretical researches on dynamic crack growth in the specimens containing flaws are of paramount importance for the studies of explosion or blasting in rock. In the present study, the dynamic cracking processes of marble specimens containing a single

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flaw of varying inclination angles are investigated and compared with those under quasi-static loadings.

As a widely used instrument for dynamic loading tests, the Split Hopkinson Pressure Bar (SHPB) system is applied in the present study. The strain rates generated by the SHPB typically range from 50 to 1000 s^{-1} (Kaiser, 1998). According to the theories provided by Kolsky (1949), the dynamic stress–strain relationship in the specimen can be calculated from the strain histories recorded by the strain gauges attached on the incident and transmitted bars ahead and behind the test specimen separately. In the study of cracking events, a high-speed video subsystem and a high-frequency data acquisition subsystem are usually utilized together with the SHPB subsystem. Both compressive and tensile loading tests can be conducted by the SHPB subsystem. However, in the present paper, only the traditional compressive tests are performed and compared with the results obtained in quasi-static tests conducted on a servo-controlled uniaxial loading machine. Since size effects are reported to occur in both quasi-static and dynamic tests (Pankow et al., 2009; Darlington et al., 2011), test specimens used in the present study are all of the same dimensions in order to minimize the effects of size on the strength and cracking behaviors.

As a popular test material, Carrara marble, which originates from Italy, consisting of 99% calcite crystals ($CaCO_3$) and 1% organic impurities is tested in the present study. Its low intrinsic crack density, fine crystal and low porosity favors rock mechanics tests over the past decades (Jaeger, 1967; Edmond and Paterson, 1972; Atkinson, 1979; Alber and Hauptfleisch, 1999; Wong and Einstein, 2006; Wong, 2008; Migliazza et al., 2011). One of the distinct characters of marble is the development of conspicuous white zones or patches commonly much earlier before the appearance of visible macro-cracks under quasi-static loading (Huang et al., 1990; Li et al., 2005; Wong and Einstein, 2009b; Wong et al., 2013; Zhang and Zhao, 2013). Apart from marble, the white patch is also observed in the loading tests of granite specimens (Morgan et al., 2013). Such a white patch or zone was also called shear belt or white belt. The white patch was speculated to be associated with the clustering of micro-cracks due to the severely stripped or even crushed materials of marble near the white patches (Huang et al., 1990), while the deviation and failure of crystalline grains in marble was considered to be responsible for the appearance of the white belt (Li et al., 2005). Based on the scanning electron microscope (SEM) observation, Wong and Einstein (2009c) revealed that the macroscopic white patches consist of a variety of micro-cracks. Furthermore, the nanomechanical investigation based on the nanoindentation technique (Brooks et al., 2010, 2012) found that the micro-cracking zones of the white patch possess a reduced nanoindentation hardness and nanoindentation modulus, hence representing a partially damaged zone. Optical methods such as photoelastic method (Gomez et al., 2002) and image correlation methods (Grantham et al., 2004; Zhang and Zhao, 2013) are sometimes used to obtain the information of the stress–strain fields and the cracking processes. In the present study, an image comparison software is utilized for the identification of the subtle development of the white patches, which plays a significant role in the deformation of white marble.

The white patch development in marble specimens containing a single flaw under dynamic loadings has been observed and reported in a preliminary study by the authors (Wong and Zou, 2012). In the present study, the white patch patterns in marble specimen containing a series of differently-oriented single flaws under dynamic loadings are systematically studied and compared with those obtained under quasi-static loadings, which is rarely discussed in the previous dynamic studies of rocks. The differences and similarities of the development of white patches, macro-cracks and failure modes of such marble specimens in both quasi-static and dynamic tests are presented and compared. The influences of the flaw inclination angles are also discussed. The results provide some insights of the mechanical analysis of rock blasting processes and protective constructions in rock.

2. Experiments

2.1. Specimen preparation

Rectangular prismatic specimens are first cut from Carrara marble slabs of an approximate thickness of 20 mm. A straight open flaw of a length of 5 mm and an aperture of 1 mm is then cut into the specimen center by an abrasive jet cutter machine (OMAX 2626 Jet Machining Center). The quality of the cutting with respect to the disturbance of the water jet to the flaw was investigated by Wong (2008) and Wong and Einstein (2009c), who showed that only a very narrow damage zone is induced around the flaw by using the SEM (Figure 1). The flaw inclination angle β ranges from 0° to 90° with an interval of 15°. For each flaw inclination, six or more specimens are fabricated: three for quasi-static tests and three for dynamic tests.

In order to reduce the friction effect on the interface between the specimen and the SHPB bars (dynamic) or the loading platen (quasi-static), too short specimens are avoided. The marble specimens are prepared with a length-to-width ratio of 2:1. The dimensions of the specimens are shown in Fig. 2. The small dimensions are however due to the considerations of the stress equilibrium requirements of the high strain rate loading by the SHPB.

2.2. Loading tests

Loading tests on the single-flawed specimens stated above are conducted to investigate the similarities and differences of the mechanical

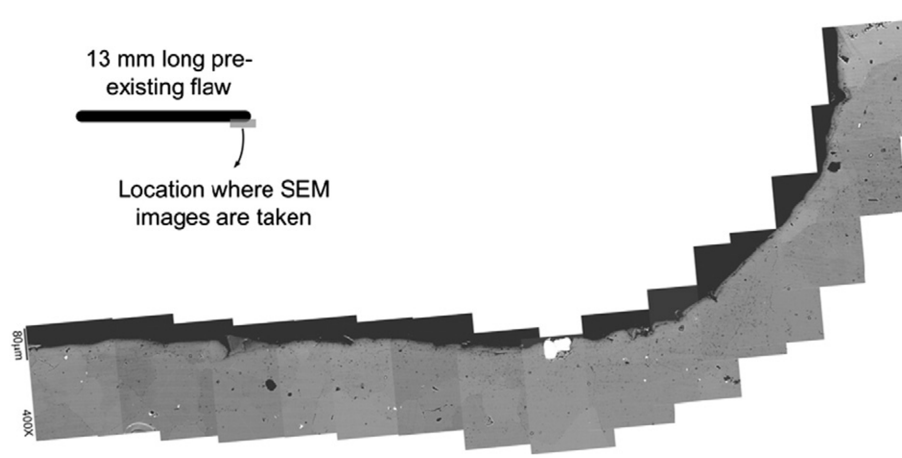

Fig. 1. Assembly of SEM images of a flaw tip cut by an abrasive jet machine. The length of the pre-existing open flaw is around 13 mm (Wong, 2008).