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Experimental study on the formation of faults from en-echelon fractures in Carrara Marble

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ABSTRACT

En-echelon fractures have been commonly observed in a fault zone. To better understand how en-echelon fractures interact to produce a fault, rock specimens containing multiple artificial flaws (en-echelon flaws) under uniaxial compression are examined in the present study. The fracture process zone (white patch), linking behaviors of flaws, structures in fault tips and correlations between stress and flaw configuration are investigated in detail by the usage of an optical microscope and an image recording system. The results suggest that two typical white patches characterized by different appearance in both unaided and microscopic observations, would develop in Carrara Marble prior to the occurrence of visible cracks. The linking behaviors are controlled by the regime of configurations, where only tensile cracks occur in the extensional regimes and different types of shear cracks are involved in the contractional regimes. Although the linking (coalescence) behaviors between en-echelon flaws are observed to be similar to those of two flaws in previous studies, special linking phenomena are particularly observed in specimens of $\delta = -15°$ and $\delta = -30°$, where δ is the flaw-array angle. The influence of en-echelon flaw geometries is also reflected by the structures in fault tip and the development of tensile wing cracks. Stress analysis shows that the configurations of en-echelon flaws dictate the coalescence stress. With the increase of flaw inclination angle β, the coalescence stress increases in the contractional regime but decreases in the extensional regime. Finally, by comparing the coalescence stress and the corresponding linking behaviors of each en-echelon flaw configuration, a correlation between the coalescence stress and the linking crack types is proposed. Linking patterns of fault segments obtained from both experiments and field investigations are discussed towards the end of the paper.

1. Introduction

En-echelon fractures, which occur as a unique set of subparallel fractures, have been commonly found in natural fault damage zones (Aydin, 1978; Kim et al., 2003; Martel and Boger, 1998; McGrath and Davison, 1995). In rock engineering, hourglass structures associated with en-echelon fractures are observed in some of the yield pillars in underground mines (Lajtai et al., 1994). Jointed rock masses sliding along a stepped failure path consisting of en-echelon joints were also reported (Einstein et al., 1983; Siad and Megueddem, 1998). In laboratory experimental studies, en-echelon fractures have been observed in shear damage zone in different scales (Cloos, 1955; Knauss, 1970; Petit and Barquins, 1988; Wong and Einstein, 2009a).

The en-echelon fractures reported in literature may be categorized into two types. The first type is related to the pre-existing rupturing plane. Stress field in front of the crack tip is suggested to account for the appearance of en-echelon fractures (Granier, 1985; Knauss, 1970; McGrath and Davison, 1995; Petit and Barquins, 1988). Two typical subtypes—Mode II and Mode III can be identified when considering the relations between the location of en-echelon fractures and movement direction of the rupturing plane (Fig. 1a). The en-echelon fractures in front of a Mode II tip in PMMA were described in detail by Petit and Barquins (1988) experimentally, and in limestone and other rocks by McGrath and Davison (1995) and Kim et al. (2003) in field studies. The en-echelon fractures in front of Mode III tip were probably first produced by Cloos (1955) and shown sharply by Knauss (1970) in laboratory. Investigations over this subtype have been followed by many researchers (Granier, 1985; Kim et al., 2003; McGrath and Davison, 1995). These two typical subtypes are characterized by different damage zone shape, spacing and overlapping of en-echelon fractures. Because a fault may not slip exactly perpendicular or parallel to the fault tip, en-echelon fractures of complicated geometries may also be found in field (Kim et al., 2004).

The second type of en-echelon fracture accompanies the faulting of an intact rock, which has been observed in the yield pillars in underground mines and the failed specimens after uniaxial compression (Fig. 1b) (Lajtai et al., 1994; Peng and Johnson, 1972). A field example similar to this condition was reported by Mollema and Marco (1999).

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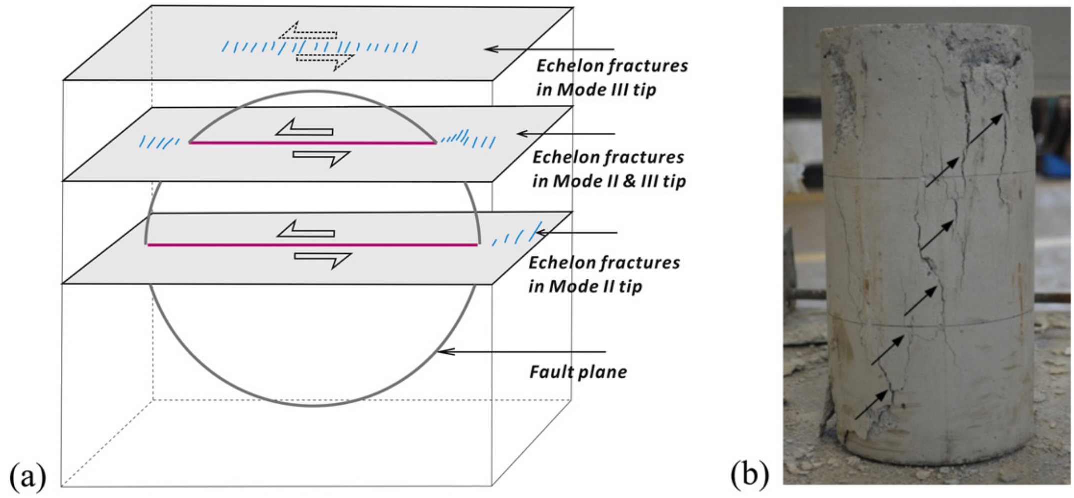

Fig. 1. En-echelon fractures observed in practice. (a) Conceptual model showing the en-echelon fractures related to an existing rupture (adapted from Kim et al., 2003) (b) En-echelon fractures (indicated by arrows) observed in a concrete cylinder failed under uniaxial compression (Φ150 mm).

The appearance of this kind of fracture does not involve any pre-existing ruptures. On the contrary, en-echelon fractures usually initiate first to weaken a zone of certain width in the rock. Linkage of these fractures occurs subsequently. A rupture consisting of these earlier developed en-echelon fractures and subsequently developed linking fractures is thus formed (Mollema and Marco, 1999; Peng and Johnson, 1972).

Whatever the type of en-echelon fractures is, the en-echelon fractures generally are connected by breaking the rock bridges between the fractures to produce a fault. Tchalenko and Ambraseys (1970) applied the Mohr–Coulomb criterion to explain the connection of en-echelon fractures associated with the Dasht-e Bayaz (Iran) earthquake. Gamond (1987) pointed out that tensile and compressive bridges in fault zones are characterized by different structures of breaking. Two important differences were suggested by Myers and Aydin (2004) in the investigation of shearing zones in sandstone. Wing cracks or block rotations may fragment rock bridges to connect en-echelon fractures distributed around a Mode II tip (Kim et al., 2004; McGrath and Davison, 1995). Synthetic faults, which may originate as extensional fractures, were observed to connect the en-echelon fractures distributed around a Mode III tip (Kim et al., 2003, 2004). Some previous reviews on strike-slip faults suggested that the connection patterns of en-echelon fractures are very complex, which are dependent on the fault geometry, stress field, material property, etc. (Crider and Peacock, 2004; Kim et al., 2004; Kim and Sanderson, 2006).

While such an extensive field investigation on en-echelon fractures has been made, the corresponding rock mechanics experiments have been inadequate to elucidate the factors influencing the linking (coalescence) process comprehensively. A few relevant studies have been conducted. However, only limited flaw configurations are explored. Most of such tests are not focused on how the rock bridges are damaged to form a through-going fault. Although experimental studies on other materials, such as glass (Brace and Bombolakis, 1963), resin (Horii and Nemat-Nasser, 1985), gypsum (Gehle and Kutter, 2003; Sagong and Bobet, 2002) and plaster (Prudencio and Van Sint Jan, 2007; Wong et al., 2001) can provide some insights into the mechanics, these materials differ from natural rocks in terms of texture, strength and brittleness. As such, the present study is dedicated to investigate the formation of a fault in crystalline rock which involves the growth and propagation of cracks between en-echelon flaws. The influence of flaw configurations on the coalescence cracks and wing cracks is the focus of this paper. The results obtained from this study and some other previously-conducted experiments will be discussed along with the fault structures reported by field investigations.

The first significance of the present study on en-echelon flaws is due to their widespread existence in fault zones as introduced in the first paragraph. The research outcome will provide a better understanding on the breakage of interlocks between en-echelon fractures leading to the formation of a fault, and the subsequent development of structures at fault tips. The second significance is that, en-echelon flaws tend to produce a weak zone along their trend which facilitates the formation of faults and thus a linking pattern different from two flaws may be observed. Although two parallel long flaws could produce such a weak zone, they can only behave as synthetic faults but not antithetic faults, such as the geometry used by Lin and Logan (1991). Actually both roles of synthetic faults and antithetic faults can be played by en-echelon fractures according to field investigations (Kim et al., 2003, 2004; Willemse et al., 1997).

2. Experiment

2.1. Material property

Because of its homogenous nature and popularity in previous laboratory studies, Carrara marble was studied in the present research. This rock is white but containing sparsely distributed dark gray thin stripes. These thin stripes consist of more than 50% of calcite, and the other components are melanocratic minerals. Grain size in these stripes is small—ranging from several microns to tens of microns. Carrara marble, which is characterized by a mutually interfering growth pattern, shows a well-fused interlocking crystalloblastic fabric. Nearly all grains (with an average size of 50 to 300 μm) display either a quadrilateral or pentagon shape (Fig. 2). The overall porosity of this rock is very low at a value between 0.4% (Alber and Hauptfleisch, 1999) and 1.1% (Edmond and Paterson, 1972). Careful inspections on specimens without subjected to any experimental loading reveals that few intragranular micro-cracks are present, and inter-granular micro-cracks in grain boundary are also not observable. On the contrary, lots of grains are characterized by one or two sets of twinning lamellae which often terminate at grain boundary and wax and wane as the polarization changes. These two features can be used to differentiate neighboring grains of a similar color (Fig. 2).

2.2. Specimen preparation

Prismatic marble blocks are cut from marble slabs in dimensions of 152 mm height, 76 mm width, and 31–32 mm thickness (Fig. 3(a)). Specimens of similar size have been tested previously by other