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Strength Failure and Crack Evolution Behavior of Rock Materials Containing Pre-existing Fissures

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(断续裂隙岩石材料强度破坏与裂纹演化特性)

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Foreword

Fractures in natural rocks have a marked effect on the stability and safety of rock mass. In rock engineering practice, it is often necessary to evaluate strength failure and crack evolution behaviour. Until now, the problem of coming to terms with these features of fissured rock material has had no satisfactory solution, because of the complex role of fissure geometry and confining pressure. But using advanced acoustic emission and photographic monitoring techniques, the author of this book has carried out many valuable experimental investigations to fill the knowledge gap.

By means of a 2014 Endeavour Research Fellowship from Australian government, Professor Sheng-Qi Yang commenced these studies in my group at Monash University as a visiting professor. As his host supervisor, I have been very much impressed with Professor Yang's contributions at Monash. As an exemplary worker, he has pursued his project diligently and has progressed extremely well with his research results. On a close consideration of this book, I am pleased to note its logical organisation and clear presentation, which make for easy and enjoyable reading.

The book is an integration by the authors of research results over the past five years. The project obtained support from National Natural Science Foundation of China, the National Basic Research 973 Program of China and the Program for New Century Excellent Talents in University. Many of the experimental results have been published in major international journals, such as *International Journal of Rock Mechanics and Mining Sciences*, *Rock Mechanics and Rock Engineering*, *Journal of Structural Geology*, *Engineering Geology* and *International Journal of Fracture*. The international peer review process for these English language journals is an additional guarantee of quality.

In comparison with other works on the topic, this book clearly succeeds in at least five aims: (1) to investigate the influence of fissure geometry on strength failure and crack evolution behaviour of real rock material; (2) to analyse the effect of pre-experiment high-temperature treatment on fracture mechanical behaviour of rock material with a single fissure or two parallel fissures; (3) to compare quantitatively simulated results using discrete element modelling and experimental results of fracture mechanical behaviour of rock material with two fissures; (4) to construct the relationship between crack evolution processes and acoustic emission distribution of pre-fissured rock material under entire deformation; and (5) to discuss the crack evolution mechanism of pre-fissured rock material with respect to different confining pressures.

All things considered, I believe that the publication of this book offers a sound experimental basis for developments in discontinuous rock mechanics. It increases our understanding of the unstable failure mechanism in all kinds of rock engineering (deep underground, dam base, jointed rock slope projects, nuclear waste disposition projects, and more). I am pleased to commend this book to all interested readers.

May 2015

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Preface

Natural rock is a complicated geological medium that usually contains all kinds of fissures with unequal scales. Under an applied load, new cracks are readily initiated at the tips of nearby pre-existing fissures, and these new cracks propagate along the direction of axial stress in the rock, resulting in an unstable failure due to crack initiation, propagation and coalescence. With the increase of engineering scales and depths, strength failure and crack coalescence behaviour of rock material have become more and more important. In order to understand deeply the fracture mechanism of rock mass containing intermittent structures, in this book, a lot of experimental and numerical investigations are carried out for all kinds of rock materials containing different fissure geometries, such as a single fissure, two fissures and three fissures.

This book includes nine chapters. Chapter 1 summarises the crack evolution behaviour of rocklike materials and real rocks from the experimental and numerical viewpoint. Chapters 2–4 deal with the strength failure and crack coalescence behaviour of brittle sandstone specimen containing a single fissure, two fissures and three fissures, respectively. Chapters 5 and 6 summarise a systematical analysis on fracture coalescence behaviour of red sandstone containing two unparallel fissures under uniaxial compression by the experimental and numerical simulation. Chapters 7 and 8 summarise the experimental analysis of the effect of high-temperature heat treatments and confining pressure on the strength failure and crack evolution behaviour of pre-fissured rock material. Chapter 9 deals with a numerical investigation on the failure mechanical behaviour of red sandstone containing two coplanar fissures under conventional triaxial compression.

This book was supported by the National Natural Science Foundation of China (Grant Nos. 51179189 and 41272344), the National Basic Research 973 Program of China (Grant No. 2013CB036003), the Program for New Century Excellent Talents in University (Grant No. NCET-12-0961) and Outstanding Innovation Team Project in China University of Mining and Technology (Grant No. 2014QN002), which are greatly appreciated. At the same time, I obtained financial support from a 2014 Endeavour Research Fellowship in Australia, which was greatly appreciated. When I stayed in the Department of Civil Engineering, Monash University (Clayton

campus), Melbourne, as a visiting professor, my host supervisor Prof. P.G. Ranjith often discussed with me and brought me a lot of valuable insights, which greatly improved this research. At the same time, Prof. P.G. Ranjith made a foreword for this book, which was also greatly appreciated.

Finally, I would also like to express my sincere thanks to Prof. Hong-Wen Jing from China University of Mining and Technology, Prof. Jian Zhao from Monash University, Dr. Mike Heap from University of Strasbourg and Prof. Tao Xu from Northeastern University for their valuable comments, which have greatly improved this book. I am extremely grateful to my wife Xiao-Qin Chen for many years of personal support and understanding. I would like to thank my daughter Ai-Chen Yang for bringing me a lot of joyfulness and happiness.

June 2015 Sheng-Qi Yang

About the Author

Dr. Sheng-Qi Yang was born in December 1978. In 2003, he started his Ph.D. research, in Hohai University, Nanjing, PR China, and got Geotechnical Engineering of Doctor's degree in April 2006. In 2007–2008, he continued his postdoctoral work in Ecole Polytechnique de Paris, France. In 2014–2015, he obtained an Endeavour Research Fellowship in Australia and commenced his research in the Department of Civil Engineering, Monash University, as a visiting professor. From 2012, he has been promoted as a full-time professor and a Ph.D. supervisor in China University of Mining and Technology. In March, 2014, he was elected as an assistant director of State Key Laboratory for Geomechanics and Deep Underground Engineering.

In 2013, he was awarded the Program for New Century Excellent Talents in University from Ministry of Education. He obtained the Youth Science and Technology Award from Chinese Society for Rock Mechanics and Engineering and Sunyueqi Foundation Council. In 2011, he also obtained the Second Prize of Science and Technology Progress from Ministry of Education. In the past 5 years, he took charge of more than ten key scientific projects including three projects from National Natural Science Foundation of China (NSFC). His research interests focus mainly on deep-fissured and jointed rock mechanics; rock creep (time-dependent) experimental and model mechanics; and deep underground rock mass engineering and reinforced technique.

To date, Professor Sheng-Qi Yang has published one Chinese book with the title *Study on the Mechanical Behaviour of Fissured Rock and Its Time-dependent Effect Analysis* (Beijing: Science Press, 2011). He has also published about 80 papers, in which more than 20 English papers (indexed by SCI) were published in International Journal of Rock Mechanics and Mining Sciences, Rock Mechanics and Rock Engineering, Tunneling and Underground Space Technology, Journal of Structural Geology, Engineering Geology, International Journal of Fracture, Engineering Fracture Mechanics, Canadian Geotechnical Journal, etc. He has applied for 10 national invented patents, among which three patents have been awarded. He is the editorial board of two journals *The Scientific World Journal* and *Journal of Basic Science and Engineering*. He has also made six lectures in some important academic conferences, e.g. 2014 International Symposium on Soft Rock.

Contents

Chapter 1
Introduction

Rock is a complicated geological medium that usually contains all kinds of fissures with unequal scales. Under an applied load, new cracks are readily initiated at the tips of nearby pre-existing fissures, and these new cracks propagate along the direction of axial stress in the rock (Li et al. 2005; Wong and Einstein 2009a, b; Park and Bobet 2009; Yang and Jing 2011), resulting in an unstable failure due to crack initiation, propagation, and coalescence. With the increase of engineering scales, rock masses transform from an intact state to a heavily fractured rock mass (Fig. 1.1) (Hoek 1998). As a result, the mechanical behavior of intact rock can rarely be used to characterize the strength and deformation characteristics of fractured rock masses. Therefore, in order to understand and explore the fracture mechanism of various rock engineering, such as dam-base rock engineering, jointed rock slope project, nuclear waste disposition project, etc., extensive studies (Nemat-Nasser and Horii 1982; Bobet 1997; Shen and Stephansson 1993; Shen 1995; Zhu et al. 1998; Wong et al. 2001) have been conducted for the mechanical behaviors of pre-existing fissured materials (artificial material and real rock material). The results have shown that the geometries of fissures in the rocks have an important influence on the strength, deformation, and failure behaviors.

1.1 Experimental Studies for Rock-Like Materials

A number of experimental studies have been carried out for rock-like materials (model specimens) because rock-like material is easy to fabricate. Rock-like material is fabricated by a mixture of gypsum, cement, barite, and water with a different mass ratio to simulate and reflect the mechanical behavior of real rock material. By inserting mica, paper, or thin steel disk, etc., open or closed fissures

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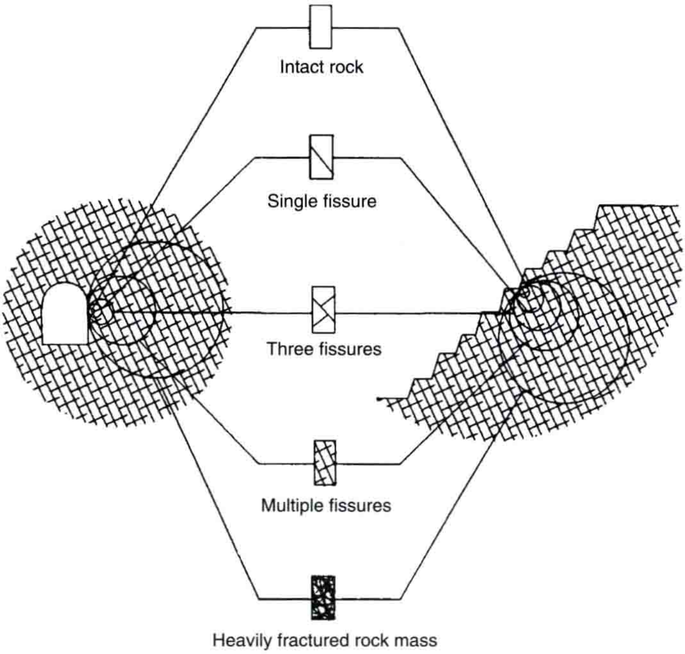

Fig. 1.1 Idealized diagram showing the transition from an intact state to a heavily fractured rock mass, with increasing specimen scale (after Hoek 1998)

are pre-fabricated to investigate the initiation, propagation, and coalescence behavior of cracks in model materials in two-dimensional (2-D) conditions.

Nemat-Nasser and Horii (1982) investigated the mechanisms of crack interactions and failure modes in flaw plates (model material) under uniaxial and biaxial compression, which showed that flaw length is one of the parameters controlling the failure mode of specimen. Bobet (1997), Bobet and Einstein (1998), Zhu et al. (1998), Wong and Chau (1998), Vásárhelyi and Bobet (2000) investigated the 2-D cracks propagation and coalescence on rock-like materials containing two inclined open or closed fissures. Figure 1.2 shows typically three main modes of 2-D crack coalescence in two fissured specimens under uniaxial compression by Wong et al. 2001. Under uniaxial and biaxial conditions, the experimental investigation of coalescence of two nonoverlapping fissures confirmed the well-established behavior. It also revealed many important new physical phenomena (Bobet and Einstein 1998). Wing cracks occurred at fissure tips as is well known. But these wing cracks shifted toward the middle of the fissures and did not occur as confining stresses increased. Wong et al. (2001) investigated experimentally crack coalescence and peak strength of model materials containing three parallel frictional fissures. The results showed that the mechanisms of 2-D crack coalescence depended on fissure arrangement and frictional coefficient on the fissure surface. Prudencio and van Sint (2007) presented the results of biaxial tests on