Laboratory-scale instabilities characterized within a progressive shear-sliding failure via optical and acoustic emission techniques

Xiong, Qiquan

2019

Xiong, Q. (2019). Laboratory-scale instabilities characterized within a progressive shear-sliding failure via optical and acoustic emission techniques. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/136509>

<https://doi.org/10.32657/10356/136509>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

**LABORATORY-SCALE INSTABILITIES
CHARACTERIZED WITHIN A PROGRESSIVE
SHEAR-SLIDING FAILURE VIA OPTICAL AND
ACOUSTIC EMISSION TECHNIQUES**

XIONG QIQUAN

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

2019

**LABORATORY-SCALE INSTABILITIES
CHARACTERIZED WITHIN A PROGRESSIVE
SHEAR-SLIDING FAILURE VIA OPTICAL AND
ACOUSTIC EMISSION TECHNIQUES**

XIONG QIQUAN

School of Civil and Environmental Engineering

A thesis submitted to the Nanyang Technological University

in partial fulfilment of the requirement for the degree of

Doctor of Philosophy

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

02 September 2019

Date

A rectangular box containing a handwritten signature in black ink. The signature appears to be 'Xiong Qiquan' written in a cursive style.

.....
Xiong Qiquan

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

03 September 2019

.....

Date

Supervisor: Zhao Zhiye

Authorship Attribution Statement

This thesis contains material from 3 paper(s), one has published in the peer-reviewed journal where I was the corresponding author; the others have been submitted in peer-reviewed journal or under preparation.

Chapter 3, and 4, and Appendix contain the material from Wong, L.N.Y., Xiong, Q., 2018. A Method for Multiscale Interpretation of Fracture Processes in Carrara Marble Specimen Containing a Single Flaw Under Uniaxial Compression. Journal of Geophysical Research: Solid Earth. Volume123, Issue8, Pages 6459-6490. DOI:10.1029/2018JB015447.

The contributions of the co-authors are as follows:

- Wong, L.N.Y. helped in revising the language of the original manuscript and checking the grammar errors of the paper.
- Wong, L.N.Y. helped in revising the language in the response to the reviewers' comments.
- Wong, L.N.Y. have encouraged the corresponding author's research work.

- I completed the tests in Singapore, as Wong, L.N.Y. had left Singapore July 2015.
- I re-designed the tests based on a literature review independently, and a series of try-and-error tests independently.
- I independently completed the MATLAB code for AE data analysis, and completed a manual for the convenience of further usage of these codes. I also completed the whole analyses which includes finding, correlating, and compiling all the mechanical, AE and optical phenomena reported in this paper.

Chapters 3 and 5 contain the material from Xiong, Q. and Lin, Q., Laboratory-Scale Instabilities within a Progressive Shear-Sliding Failure. under preparation.

The contributions of the co-authors are as follows:

- I completed the tests and provided rough data analysis results.
- Dr. Lin and I have discussed and defined the novelty of the manuscript based the experimental results.
- Dr. Lin provided me useful literature for completing the discussion.

- Dr. Lin has helped me revise the language of the original manuscript and check the grammar errors of the manuscript.

Chapter 6 contains the material from Xiong, Q. and Wang, Y. And Hampton, J.C., Non-local triggering dynamics in rock fracture. under preparation.

The contributions of the co-authors are as follows:

- I completed the data analysis; and through it, I discovered the non-local migration path of AEs.
- Dr. Wang provided me references in the discipline of physics for explaining the non-local triggering phenomenon.
- Dr. Wang and I have discussed and defined the novelty of the manuscript based on the data analysis results.
- I discovered further statistical evidences to support the conclusions of the paper under Dr. Wang's suggestions.
- Dr. Wang has helped me revise the language of the original manuscript and check the grammar errors of the manuscript.

- Dr. Hampton has helped me in discovering further evidences in completing the connection between laboratory-scale created rock fractures under loading and the natural rock fractures.

22 January 2019

Date

A rectangular box containing a handwritten signature in black ink. The signature appears to be 'Xiong Qiquan' written in a cursive style.

.....

Xiong Qiquan

ACKNOWLEDGEMENT

First and for most, as my Ph.D. scholarship has expired since August 2018, I have to acknowledge my mother's financial support in tuition and living cost for helping me complete this Ph.D. research. It is impossible for me to complete the Ph.D. without her financial support!

Second, I would like to acknowledge the encouragement from Dr. Lin Qing at China University of Petroleum, Beijing, Dr. Wei Shengji at Earth Observatory Singapore, Dr. Wang Yan in the Department of Statistics at Iowa State University, and Dr. Cheng Yi at China University of Geosciences, Wuhan, at the moments I was hesitating about continuing my Ph.D. under the financial pressure in recent half year.

In the technical aspect, I firstly should acknowledge Dr. Lin Qing for kindly working with me since later May of 2018. Secondly, I should thank for the help from Dr. Wei Shengji in teaching me some basic knowledge of waveform analyses. I also acknowledge an email response from Dr. Grzegorz Kwiatek at GFZ German Research Centre for Geosciences, Potsdam for solving one of my crucial problems in acoustic emission signal analysis. In addition, I must attribute the success of my experimental tests to the constant and immediate discussions with and suggestions from the NTU technician Mr. Phua throughout the first three years. I cannot imagine the quality of the experimental results without the discussions with him and his suggestions. Three engineers Simon Hao Xinji, and Tom Bittner working at MTS, and Jason Dong working at Physical Acoustic Corporation are also acknowledged. Lastly, I acknowledge the literature suggested by Dr. Wang Yan, which have greatly expanded

my knowledge scope.

Forth, I acknowledge my supervisor Associate Prof. Zhao Zhiye, for kindly taking over me as a candidate of Ph.D. in three and a half years ago after my ex-supervisor has left NTU. I should also acknowledge the equipment support from Nanyang Centre for Underground Space, and the four years financial support from NTU Ph.D. Research Scholarship.

I do admit the fact that Dr. Louis Ngai Yuen Wong was my supervisor for the first year and was my co-supervisor for another two years and nine months. And I acknowledge his effort in helping me get the NTU Ph.D. admission and his help for revising my QE report and the ARMA conference paper “Comparison of Three Source Types for Calibrating AE Sensors used in Fracture Coalescence Tests”.

TABLE OF CONTENTS

ACKNOWLEDGEMENT	i
TABLE OF CONTENTS	iii
SUMMARY	vii
LIST OF PUBLICATIONS	viii
LIST OF TABLE	ix
LIST OF FIGURES	x
Chapter 1 Introduction	1
<i>1.1 Motivation</i>	1
<i>1.2 Thesis organization</i>	5
Chapter 2 Literature Review	8
<i>2.1 Introduction of this Chapter</i>	8
<i>2.2 Concepts for laboratory investigations on earthquake mechanisms</i>	9
2.2.1 Laboratory stick-slip mechanism—an analogue of natural earthquake mechanism	12
2.2.2 Slip nucleation at small section (or small volume) of the final rupture fault plane.	15
2.2.3 Massive strain energy release as the tests approaches the mechanical slip instabilities	18
2.2.4 Unstable growth of slip nucleation section	21
2.2.5 Slip behavior is highly influenced by the asperity system along the fault.....	22
<i>2.3 Some improvements of recent studies</i>	25
<i>2.4 Previous applications and associated limitations of prismatic specimens with preexisting flaw(s)</i>	31
<i>2.5 Summary of this Chapter</i>	39
Chapter 3 Experimental procedure and data analyses methods	41
<i>3.1 Specimen preparation and testing approach</i>	41
<i>3.2 Data analyses methods</i>	48
Chapter 4 Multiscale interpretation of fracture processes in Carrara Marble specimen	

containing a single flaw under uniaxial compression	52
4.1 <i>Introduction</i>	52
4.2 <i>Experimental results of the individual observation systems</i>	55
4.2.1 Optical observation results (macro-scale).....	55
4.2.2 Mechanical results	57
4.2.3 AE source location and moment tensor inversion results	58
4.2.4 Temporal evolutions of AE crack type ratios and relative AE moment-frequency distributions.....	66
4.3 <i>Cross comparison among the results provided by different systems</i>	72
4.3.1 Comparison on $\beta = 70^\circ$ test.....	73
4.3.2 Comparison on $\beta = 90^\circ, 60^\circ, 45^\circ, 30^\circ$ tests	77
4.4 <i>Discussion on the experimental result of single flaw tests</i>	85
4.4.1 Mechanical stress drops, perturbations and inflection points on stress curves and corresponding meso-scale AE crack type changes	85
4.4.2 Cross comparison between optical observable changes on fracture process and meso-scale AE crack type changes	86
4.4.3 New phenomena observed under the aid of multi-scale comparison	89
4.4.4 New understanding on the role of stress drop (stress release) period in the development of fracture process zone.....	90
4.4.5 Implication of limitations on AE source location analysis	91
4.4.6 Issues on the selection of meso-scale AE crack type thresholds	92
4.4.7 Moment-frequency distribution of relative AE moment.....	92
4.5 <i>Conclusions on experiments containing single pre-existing flaw</i>	95
4.6 <i>Support documents for experiments on specimens containing single flaw—white patch, brightening dots, and wrapped sections</i>	97
Chapter 5 Stick-slip, fracture creation, and laboratory-scale instabilities within a progressive shear-sliding failure	99
5.1 <i>Introduction</i>	99
5.2 <i>Periodical features of AE activities during the mechanical instabilities</i>	102
5.3 <i>Fault- development and its slip in the progressive shear-sliding failure</i>	107
5.3.1 Stage 1—Fault initiation or incipient fracture creation	107
5.3.2 Stage 2—Instability 1, extension and connection of the white patches, initiated fault widening.....	109
5.3.3 Stage 3—Instability 2, a fully-developed fault.....	112
5.3.4 Stage 4—Instability 3, fault slip	116
5.3.5 Summary of experimental results	119
5.4 <i>Discussions on the experimental result of double flaw test 60-1</i>	121
5.4.1 Key features of a well-formed fault and its transition from fault creation—macro-scale crack, powder gouge, zig-zag shape and asperities, and their implications for previous understandings from laboratory stick-slips experiments	122

5.4.2 Key features of the stick-slip—gouge growth in the fault sliding, and their implications to field and laboratory observations	127
5.4.3 Reveals of different physical processes—comprehensive understanding on AE and optical observations for fault creation and fault slip.....	128
5.4.4 Inspiration of present experimental data analyses from previous studies and issues related to geometrical settings	131
5.5 Conclusion on the experimental investigation of double flaw test.....	133
5.6 Support documents of double flaw test 60-1	134
Chapter 6 Cascading non-local triggering in rock fracture process.....	137
6.1 Summary and highlights of this Chapter.....	137
6.2 Introduction	139
6.3 Results	142
6.3.1 Network triggering.....	142
6.3.2 Patterns of non-local triggering	145
6.3.2 Physical scenario of non-local triggering dynamics in rock fracture	150
6.4 Discussion and conclusion.....	152
6.4.1 Typicality of the results.....	152
6.4.2 Robustness of the results.....	152
6.4.3 Roots	153
6.4.4 Non-local triggering and stress peak; length issue	154
6.4.5 Natural mechanism	155
6.5 support documents—methodology and supplementary evidences of the analyses in Chapter 6.....	156
6.5.1 Extracting the AE information—the source to regenerate the data and its relation with the data in the support document of Wong and Xiong (2018).....	156
6.5.2 Data shuffling and determination on the existence/non-existence of event-event triggering.....	157
6.5.3 Magnitude-frequency distribution and magnitude of completeness	159
6.5.4 Determination of fractal dimension	160
6.5.5 Temporal location of the roots for the dominant trees	161
6.5.6 Phenomenon of sudden spatial tree size growth in post-peak	163
6.5.7 Features for the AE clusters of dominant trees	165
6.5.8 Non-local triggering—amplifying the stress perturbation and as precursor of the much more massive energy releases	166
Chapter 7 Discussion, conclusions, and suggestions of future work.....	169
7.1 Process of finding the post-peak analogue phenomena of seismic activity in uniaxial compression tests on pre-flawed specimens	169
7.2 Conclusions on the experimental results and data analyses of the tests presented in this thesis.....	172

7.3 limitations of the experimental scale results on uniaxial compression tests.....	174
7.4 Future works and some preliminary results	181
7.4.1 Existence and non-existence of the Poisson process in laboratory rock fracture process.....	182
7.4.2 Off-fault rupture barriers and rupture types for laboratory fault	183
7.4.3 Re-evaluation of the fracture coalescence pattern classifications and a comprehensive understanding on the relations between the pre-peak patterns of the fracture process zones and the following post-peak phenomena.....	185
References.....	187
Appendix I influence of the AE data acquisition parameters on waveform picking	194
Appendix II procedure of in-situ relative calibration	196
Appendix III Algorithm on judging whether the source-to-sensor path were intercepted by the pre-existing flaw or not.....	198
Appendix IV measurement of P-wave and S-wave velocity	200

SUMMARY

Three successive instabilities are generated in a progressive shear-sliding failure under uniaxial compression. These instabilities show the distinctive acoustic emission (AE) features that display strong similarities with stick-slip experiments on core specimens. However, detailed AE and optical analyses reveal the differences: (1) AE features are divided into two groups: fault-development and fault-slip. The former is similar to AE features from an intact rock, while the latter is similar to tectonic-scale seismic activities; (2) optical observations display a series of phenomena that also can be categorized as: fault-development includes fault initiation, its widening and fully-development, off-fault crack development; fault-slip involves creation and growth of marble powder gouge in the fault, and migration of brightening grains along the fault. Thus, the discovery from the study is the first and second instabilities are two different stages during the fault-development, and only the third instability represents the actual stick-slip along a well-formed fault.

LIST OF PUBLICATIONS

Wong, L.N.Y. and Xiong, Q.(Corr), 2018. A Method for Multiscale Interpretation of Fracture Processes in Carrara Marble Specimen Containing a Single Flaw Under Uniaxial Compression. Journal of Geophysical Research: Solid Earth. Volume123, Issue8, Pages 6459-6490. DOI:10.1029/2018JB015447.

Xiong, Q.(Corr) and Lin, Q., Laboratory-Scale Instabilities within a Progressive Shear-Sliding Failure. Under preparation

Xiong, Q.(Corr) and Wang, Y. and Hampton, J.C., Non-local Triggering Dynamics in Rock Fracture. Under preparation

LIST OF TABLE

Table 3.1. (after Wong and Xiong (2018) and Xiong and Lin (under preparation)) a. geometrical parameters of the specimens. b. loading procedure. c. parameters used for the AE data acquisition system. And d. high-speed camera settings	43
Table 4.1 Macro-scale crack type classification	56
Table 4.2. Divided time sections and corresponding number of source locations (in parentheses)	62
Table 4.3 Comparison on $\beta = 90^\circ, 70^\circ, 60^\circ, 45^\circ, 30^\circ$ tests.....	82
Table 7.1 Variation of geometrical parameters of the specimens	186

LIST OF FIGURES

Figure 2.1 two types of friction test on stacking rock blocks, (a) after Dieterich (1972) and (b) McLaskey et al. (2014), (c) intact rock rupture tests	11
Figure 2.2 specimen configurations and jerky motions on stress-displacement curves for cylindrical core samples under tri-axial stress (after Brace and Byerlee (1966)).....	14
Figure 2.3 slip nucleation at small volume or small section. (a) for core sample (after Reches and Lockner (1994)), and (b) and (c) for precut fault (after Ohnaka and Kuwahara (1990)) .	16
Figure 2.4 experimental examples of massive energy release when the tests approach the mechanical slip instabilities in intact rock. (a) Lei et al. (2000a), and (b) after Zang et al. (1998)	20
Figure 2.5 experimental example of massive energy release when the tests approach the mechanical slip instabilities in sample with precut plane. (a) Thompson et al. (2005), and (b) test configuration	21
Figure 2.6 AE frequency-amplitude distributions of rough and smooth surfaces (Sammonds and Ohnaka (1998))	23
Figure 2.7 experimental configurations of Thompson et al. (2009) (a) with precut fault, and (b) with “natural” fault	24
Figure 2.8 (a) specimen configuration with precut guides. (b) b-value variation (Goebel et al. (2013)) and (c) variation of AE moment tensor components with stick-slips (Kwiatek et al. (2014b)).....	27
Figure 2.9 (a) experimental configuration of rotational ring test, (b) example of half rotary rock ring (upper-left) and post mortem powder of different scales (Reches and Lockner, 2010). An video example of this type of test can be found in http://www.youtube.com/watch?v=YTfwJ3Elw5s	29
Figure 2.10 (a) direct shear test configuration, after Lajtai (1969), and (b) post-mortem photos (Lajtai (1969)).....	32
Figure 2.11 experimental schematic draws of (a) single pre-existing flaw (Lajtai (1971)), and (b) single inclusion of different shapes (Lajtai (1974)), and (c) the photos of the post-mortem specimens (Lajtai (1971))	33

Figure 2.12 illustration of the prismatic specimen containing a pair of pre-existing flaws for fracture coalescence tests	34
Figure 2.13 (a) schematic draw of first fracture and secondary fracture (on the left), and photo on the specimen (on the right) (Ingraffea and Heuze (1980)). (b) weak and non-distinguishable first fracture propagation (generated from the same raw data used by Wong and Xiong (2018))	37
Figure 3.1 Illustrations of specimens and sensor array configurations and locations of calibration points for (a) specimens containing a single flaw (after Wong and Xiong (2018)), and (b) specimens containing coplanar flaws (after Xiong and Lin (under preparation)).....	42
Figure 3.2 Assembly of the (1) acoustic emission system, (2) camcorder, (3) high-speed camera, (4) MTS loading frame, and (5) light sources, edited based on a same photo that used by Wong and Xiong (2018)	47
Figure 4.1. Crack type classification, re-drawn after Wong and Einstein (2009a)	56
Figure 4.2 Stress, strain vs time curves for (a) $\beta = 90^\circ$, (b) $\beta = 70^\circ$, (c) $\beta = 60^\circ$, (d) $\beta = 45^\circ$, and (e) $\beta = 30^\circ$. The flaw inclination angle β is measured from the horizontal direction as shown in Figure 3.1(a).....	58
Figure 4.3 Histogram plots of the AE source location for all tests	60
Figure 4.4. Illustration of 3 crack types presentations, (a) tensile crack, (b) shear crack, (c) mixed-mode crack, (d) pre-existing flaw (color figure online), (e) crack normal and crack motion	61
Figure 4.5 (Top) AE source locations and moment tensor inversion results of each time section. (Bottom) corresponding screenshots for $\beta = 90^\circ$ test	63
Figure 4.6 (Top) AE source locations and moment tensor inversion results of each time section. (Bottom) corresponding screenshots for $\beta = 70^\circ$ test	64
Figure 4.7 (Top) AE source locations and moment tensor inversion results of each time section. (Bottom) corresponding screenshots for $\beta = 60^\circ$ test	65
Figure 4.8 (Top) AE source locations and moment tensor inversion results of each time section. (Bottom) corresponding screenshots for $\beta = 45^\circ$ test	65
Figure 4.9 (Top) AE source locations and moment tensor inversion results of each time section. (Bottom) corresponding screenshots for $\beta = 30^\circ$ test	66
Figure 4.10 (a) AE classified crack type, (b) relative AE moment, and (c) relative AE moment-frequency distribution for $\beta = 90^\circ$ test.....	67
Figure 4.11 (a) AE classified crack type, (b) relative AE moment, and (c) relative AE moment-frequency distribution for $\beta = 70^\circ$ test.....	68

Figure 4.12 (a) AE classified crack type, (b) relative AE moment, and (c) relative AE moment-frequency distribution for $\beta = 60^\circ$ test.....	69
Figure 4.13 (a) AE classified crack type, (b) relative AE moment, and (c) relative AE moment-frequency distribution for $\beta = 45^\circ$ test.....	70
Figure 4.14 (a) AE classified crack type, (b) relative AE moment, and (c) relative AE moment-frequency distribution for $\beta = 30^\circ$ test.....	71
Figure 4.15 $\beta = 70^\circ$ (a) Stress, and AE crack type ratios plot (only plotted from 3200s to end of the test). Changing points of AE crack type ratios are labelled as 1 – 11 in the plot. The i-th time sections (in Table 4.2), which are separated by vertical dashed-dotted lines, are labelled as Si (blue letters) at the top of the plot. (b) camcorder screenshot (enlarged as necessary) at AE crack type changing points (labeled with its time of occurrence)	76
Figure 4.16 $\beta = 90^\circ$ (a) Stress, and AE crack type ratios plot (only plotted from 3000s to end of the test). Changing points of AE crack type ratios are labelled as 1 – 3 in the plot. The i-th time sections (in Table 4.2), which are separated by vertical dashed-dotted lines, are labelled as Si (blue letters) at the top of the plot. (b) camcorder screenshot (enlarged as necessary) at AE crack type changing points (labeled with its time of occurrence)	78
Figure 4.17 $\beta = 60^\circ$ (a) Stress, and AE crack type ratios plot (only plotted from 2000s to end of the test for the top plot, and from 3250s to end of the test for the bottom enlarged plot). Changing points of AE crack type ratios are labelled as 1 – 15 in the plots. The i-th time sections (in Table 4.2), which are separated by vertical dashed-dotted lines, are labelled as Si (blue letters) at the top of each plot. (b) camcorder screenshot (enlarged as necessary) at AE crack type changing points (labeled with its time of occurrence)	79
Figure 4.18 $\beta = 45^\circ$ (a) Stress, and AE crack type ratios plot (only plotted from 2000s to end of the test for the top plot, and from 2400s to 3400s of the test for the bottom left enlarged plot, and from 3900s to end of the test for the bottom right enlarged plot). Changing points of AE crack type ratios are labelled as 1 – 14 in the plots. The i-th time sections (in Table 4.2), which are separated by vertical dashed-dotted lines, are labelled as Si (blue letters) at the top of each plot. (b) camcorder screenshot (enlarged as necessary) at AE crack type changing points (labeled with its time of occurrence)	80
Figure 4.19 $\beta = 30^\circ$ (a) Stress, and AE crack type ratios plot (only plotted from 2000s to end of the test for the top plot, and from 2600s to 3350s of the test for the bottom enlarged plot). Changing points of AE crack type ratios are labelled as 1 – 12 in the plots. The i-th time sections (in Table 4.2), which are separated by vertical dashed-dotted lines, are labelled as Si (blue letters) at the top of each plot. (b) camcorder screenshot (enlarged as necessary) at AE crack type changing points (labeled with its time of occurrence)	81
Figure 4.20 Illustration of (a) white patch, (b) brightening dots, and (c) wrapped sections....	98
Figure 5.1. (a) AE event histogram, relative AE moment release rate, and axial stress vs. the	

loading time, where the three mechanical instabilities are clearly demonstrated in the AE activities; (b) b-value and axial stress vs. the loading time; (c) AE crack type ratios, and axial stress vs. the loading time, where the ratios of different AE crack types are represented by different lines (see shear crack type as red dash line; tensile crack type as blue dot line; mixed-mode crack type as green plus line)..... 104

Figure 5.2. Systematical changes of AE crack type ratios along with axial stress drops for (a) pre-peak small stress drop, (b) first instability, (c) second instability, (d) third instability. Vertical dashed lines in (a-d) indicate starts and ends of mechanical instabilities. Different AE crack types are represented by different lines (see shear crack type as red dash line; tensile crack type as blue dot line; mixed-mode crack type as green plus line)..... 106

Figure 5.3. Crucial changes of fault initiation stage. Labels 1 and 2 on stress curve indicate the moments of the two screenshots on its right side. As similar to Figure 5.1, the AE source locations of red, blue, and green are for shear, tensile, and mixed-mode AE crack types..... 108

Figure 5.4. Crucial changes of instability 1. Labels 3 and 4 on stress curve indicate the moments of the two screenshots on its right side. The AE source locations are presented by the same convention of Figure 5.3..... 110

Figure 5.5. Sudden and drastic widening of the white patch along the core region of the fault during the fast stress drop of instability 1 112

Figure 5.6. Crucial changes of instability 2. Label 5 on stress curve indicate the moment of the two screenshots on its right side. The AE source locations are presented by the same convention of Figure 5.3 and 5.4 113

Figure 5.7. Creation of macro-scale crack which is filled with a thin gouge layer in instability 2 115

Figure 5.8. Instability 3 – fault slip. (a) Crucial changes of instability 3. Label 6 on stress curve indicates the moments of the screenshot on its right side. The AE source locations are presented by the same convention of Figure 5.3, 5.4 and 5.6; (b) Comparison between digital images at 4183s (instability 2) and 4312s (instability 3); (c) fault sliding under high-speed image and moment release behavior of three instabilities in the lower-right insert..... 118

Figure 5.9. The macro-crack location, the white patch channel and its associated AE locations in instability 1 124

Figure 5.10. Brightening dots migration, which is believed to be caused by the grain splitting and crushing; In the end of brightening dots migration, the boundary of some dots will become dimmer, and then dimmer sections are filled with gouge marble powders after the macro crack forms 125

Figure 5.11. Illustration for extending and changing of the outer boundary of the white patch zone from instability 2 to instability 3 126

Figure 5.12 (a) comparison of AE activities between foreshock type and aftershock type, (b) moment release behaviors of two different physical processes: fault creation and fault slip 130

Figure 5.13. Source locations of (a) fault initiation, (b) initiated fault widening, (c) fully-developed fault, and (d) actual fault slip. Presentation of source locations follows the convention of Wong and Xiong (2018). Screenshots of camcorder recording (for (a), (b), and (c)) and screenshot of high-speed video recording (for (d)) at ends of all periods are supplemented in lower row 134

Figure 5.14 peaks of moment release rate at and after the fast stress drops of three instabilities. Correspondingly, $\log_{10}1.576.39232.8092 = 0.9563$, $\log_{10}1.555.78841.4174 = 1.0634$, $\log_{10}1.531.88360.6068 = 1.1462$, respectively 135

Figure 5.15. (a) Illustration of off-fault fractures by post-mortem exam and the alternative transitions of AE activity on on-fault and off-fault fractures, edited after the Figure 5(b) of Thompson et al. (2009), (b) schematic draw illustration of the off-fault fracture in present test 136

Figure 6.1 (a) PDF of interevent time ration for specimen containing 60 °preexisting flaw based on the AE events from after 1000 s to first AE histogram peak, or from after 1000 s to stress peak (upper insert). (b) density distribution of event-event connections for specimen of 60 ° preexisting flaw, and specimen of 70 °preexisting flaw (lower insert). (c) node number vs. average leaf depth $\langle d \rangle_f$ for specimen of 60 °preexisting flaw, and specimen of 70 °preexisting flaw (upper insert)..... 145

Figure 6.2 (a) Y' projection of the events included in the dominant tree for specimen of 60° preexisting flaw and (lower-right insert) spatial span of the topological structure of dominant tree (b) spatial distribution and its (right insert) Y projection distribution of triggering and triggered events (c) frequency magnitude distributions of non-local triggering and triggered events and all AE events (d) frequency of inclination angles of the connections between non-local triggering and triggered events and (middle insert) temporal correlations between non-local triggering peaks and AE event peaks 147

Figure 6.3 Within the dominant tree of specimen containing 60 °preexisting flaw, examples of (a) spatially non-crossing root-to-leave path, (b) spatially crossed and returned root-to-leave path, (c) spatially crossed and not returned root-to-leave path, and (d) a root-to-leave path spatially transversal the whole fracture length in a chain reaction like manner. The titles of these figures are indicating the number sequences of the root and leaves among all AE events. Sizes of all circles for the events are proportional to their magnitudes. Two events in (a) are indicated with their relative moment magnitudes for aiding the understanding of the relationship between circle size and moment scale. Also in (a), the 1st-8th events are filled with red color, indicating the local accumulation of damage around the root at the onset of first SOC state. Lower inserts of these figures are the Y projections of the events along these paths versus time, and AE histogram. These inserts help to understand the temporal relationship between crossing migration and AE activity 149

Figure 6.4. Distribution of randomized AE data in normalized spatial ($l * i - t_o - j$) and time ($\tau * i - t_o - j$) space	158
Figure 6.5. AE relative magnitude-frequency distribution	160
Figure 6.6 Density distribution of AE event to the AE cluster center, and the linear regression results for Df (upper-right insert).....	161
Figure 6.7 AE event histogram and peak stress	162
Figure 6.8 Appearance of a tree that has spatially migrated across the open section (the flaw). The network of this tree includes only the AEs from pre-peak loading to the temporal location immediately after the stress has entranced the peak perturbation period	164
Figure 6.9 Y projections of AE events of three dominant clusters (left Y axis) for specimen containing 70° preexisting flaw versus time, and stress (right Y axis) versus time. Three dominant trees are represented by dots of red, blue, and green, respectively. Lower insert is the Y projections of the AE events of these three dominant clusters (left Y axis) and AE histogram (right Y axis) versus time	166
Figure 6.10 More specifications on the non-local triggering as precursor of more massive AE release based on Figure 6.2(d) middle insert	168
Figure 7.1 illustration of two post-stress-peak based rock fracture behavior	176
Figure 7.2 Illustration for the disappearing of Poisson Process AEs in faster loading test ...	183
Figure 7.3. Illustration of find the on-fault/off-fault fracture development sequence (a) plot of containment spheres, (b) first fracture nucleation location, (c) development of on-fault fracture unveiled by AE observation, (d) optical fracture development sequence.....	184
Figure A1. Illustration of the AE data acquisition parameters, reproduced from the Figure A2 of Wong and Xiong (2018)	195
Figure A2. Illustration of the logic algorithm on judging whether the source-to-sensor path is intercepted by the pre-existing flaw or not, reproduced from the Figure A5 of Wong and Xiong (2018).....	199
Figure A3. (a) and (b) measurement of P-wave and S-wave velocity, reproduced from the Figure A4 of Wong and Xiong (2018).	200

Chapter 1 Introduction

1.1 Motivation

Since Brace and Byerlee (1966) have proposed that laboratory scale stick-slips along a shear type fault can be viewed as a mechanism of earthquakes, many researchers have devoted into investigating the earthquake mechanisms through laboratory scale rock mechanics tests using similar experimental configurations. To name a few recent publications from the long list, e.g. Goebel et al. (2015); Goebel et al. (2013); Kwiitek et al. (2014b); McLaskey and Glaser (2011); Thompson et al. (2005, 2009). The laboratory scale stick-slip can be induced by a variety of laboratory settings, i.e. healed failure plane (Charalampidou et al., 2014), smooth faulted plane (Thompson et al., 2005), or “natural” fault plane prepared through saw-cut notches (Goebel et al., 2012; Goebel et al., 2015) as well as AE feedback control (Lockner et al., 1991; Thompson et al., 2009).

Moreover, the stick-slip mechanism of earthquake has also been investigated by a variety of other similar but slightly different experimental configurations, such as, frictional slip tests on contacting surfaces of rock blocks i.e. (Dieterich, 1981), rotational slip tests on hollow rock cylinders i.e. (Reches and Lockner, 2010), etc. Here, a variety of experimental configurations demonstrate a fact such that, “presently, there is no common and universal practice for the laboratory tests to best approximate the analogue between natural and laboratory created fault—the complexity of a real fault and its evolution process are far away from well known, as well as the knowledge on the process of creating a laboratory-scale fault is very little to date”.

On the contrary, among the engineering rock mechanics investigations, the mechanical behavior of specimens containing artificially created pre-existing flaw(s) has been extensively investigated. To name a few publications from the long list, e.g. Bobet and Einstein (1998); Cheng et al. (2015); Shen et al. (1995); Wong and Einstein (2009a, 2009b); Wong and Einstein (2009c). It is interesting to notice that, the shear type failures along two coplanar pre-existing flaws can be generated in uniaxial compressive tests on prismatic specimens

(Nguyen et al., 2011; Shen et al., 1995), although the analogue laboratory seismic releases, i.e. the periodical acoustic emission (AE) releases, have hardly been recorded among the literature on the experimental researches of such type. Additionally, the technical simplicity and convenient of application of optical and other techniques enable this type of uniaxial compression experiments to provide a more detailed information on the phenomena included in the processes from the forming of rock fracture process zone(s) to the final shear failure rupture(s). These two facts draw one's interest in that—can this type of tests generate the shear type failure displaying analogue feature(s) of laboratory seismic activity, and simultaneous that/those analogue feature(s) can be quantitatively observed through multiple observations, such as, optical, mechanical and AE observations?

This thesis tries to extend the knowledge on the experimental failure process on pre-flawed specimens using various types of observation methods, i.e. advanced AE analyses as well as normal and high-speed optical observations and mechanical investigations. However, regardless this type of uniaxial tests has been extensively conducted for over several decades, the primary focus and analyses of this thesis are around the laboratory analogue feature(s) of seismic activity in this type of tests, which are distinctively different with the foci and analyses of previous researches on this type of tests.

First, uniaxial compressive tests will be conducted on specimens containing a single pre-existing flaw of different inclination. The results of these tests will be extensively described in Chapter 4. Primarily due to the simplicity of conducting tests on specimens containing a single pre-existing flaw, these experiments provide the researcher a chance of verifying the multiple observations through the cross comparisons on the results of different observations, and through the interpretations of the results in different scales. The experimental method as well as the newly observed and characterized phenomena has been reported in Chapter 4 as well as the publication of Wong and Xiong (2018). It is stated as “the first time the continuous picture on the white patch extension and the accumulation and clustering of different types of cracks in meso-scale can be obtained in such type of test (uniaxial compression tests on specimens with preexisting flaw(s))”.

Using this newly proposed method (Wong and Xiong, 2018), the progressive shear-sliding failure process and the phenomena within a continuous fault creation as well as fault slipping laboratory process along two coplanar preexisting flaws will be extensively investigated. An induced “natural” fault from an intact rock material inherently represents a different but very interesting laboratory analogue of a field scale fault, which involves the phenomenon of stick-slip and poses a great interest for seismic research in geophysics. In the test, it observes the laboratory shear-type fault is “naturally” created along two coplanar artificial flaws through several successive mechanical instabilities. Those mechanical instabilities have been generated under uniaxial compression. The AE observations on these instabilities display a strong similarity with previous laboratory stick-slip tests (Goebel et al., 2012; Goebel et al., 2015; Kwiatek et al., 2014b; Thompson et al., 2009). For example, periodical changes of AE activities and b-value are also identified in the instabilities, which have been viewed as evidence of good analogue of field and laboratory stick-slips in previous publications. However, detailed analyses combining the AE and optical observations present a different picture. It characterizes out two distinctively different physical processes within these successive mechanical instabilities. One is related to the laboratory fault development and the other is related to fault slip, because a macro crack is missing until the completion of the fast stress drop stage in the second instability and the frictional shear-sliding movements along this macro crack have been clearly captured by the high-speed video during the third instability. More detailed observations and interpretations on the experimental phenomena will be described in Chapter 5. The study of that Chapter helps to improve the understandings on the analogue between laboratory fault and tectonic-scale natural fault as well as the understandings on natural earthquake mechanisms.

Lastly, through the experimental observation and data analyses of Chapter 4 and Chapter 5, it is found that the post-stress-peak evolvement of the fracture process zone is existed. This post-peak evolvement as well as the analogue of seismic phenomena within this evolvement can hardly be found in previous engineering rock mechanics experimental investigations on specimens containing pre-existing flaw(s). None the less to say any literature can elucidate the analogue between post-stress-peak evolution and seismic activities. This reality poses a

strong reason to investigate the AE activity through some data analysis methods of seismology instead of following the methodology of previous engineering rock mechanics publications on this type of tests. The scale invariance property of the earthquake dynamics as interpreted by the self-organized criticality (SOC) theory (Bak and Tang, 1989; Sornette, 2006), gives much credence to the investigation of triggering dynamics based on AE events. Thanks to the high quality of the data and the novel phenomena observed in the experiments of Chapter 4, to combine a well-established method in seismology (Davidsen et al., 2017; Gu et al., 2013; Moradpour et al., 2014; Zaliapin and Ben-Zion, 2013a; Zaliapin et al., 2008) into the data analyses of laboratory AEs, the topological structure of the AEs brings one novel understandings on the triggering effect of the creeping aseismic fault section through the investigation of the idealized laboratory model tests. The data analyses and the corresponding interpretations will be described in Chapter 6.

In summary, the experimental observations of this thesis have unveiled the fracture and failure process of the uniaxial compression tests on pre-flawed specimens into an unprecedentedly detailed level. Various analogue phenomena of real seismic activity have been observed in the post-stress-peak evolvement of the fracture process zone(s). Instead of following the previous mechanical investigations on the failure process of pre-flawed specimens under compression, this thesis has proposed and extensively used a new method to combine the observations and interpretations of different systems into the investigation of post-peak fracture evolvement. As laboratory analogue phenomena of seismic activity have extensively displayed in this post-peak fracture evolvement, and possibly it is the first time such evolvement and its correlation to seismic activity have been extensively investigated in the experiments on pre-flawed specimens, this thesis brings novel understandings on the rock fracture mechanisms as well as the understandings on the analogue relationship between laboratory fracture process and tectonic scale seismic activities.

1.2 Thesis organization

This thesis contains 7 Chapters

Chapter 2 provides a literature review about the experimental setups in previous stick-slip studies. This literature review primarily covers several fundamental achievements along the long history of laboratory investigation on stick-slip mechanism, which under the traditional perspective should belong to the research of geophysics or seismology. Although the author's experimental configurations have drawn a great inspiration from previous engineering rock mechanics investigations on pre-flawed specimens, due to the author's own limited view and experience, the author has failed to find any literature out of the engineering rock mechanics publications which has put its primary focus on the investigation of the post-stress-peak fracture evolution. Considering this reality, only short review on previous laboratory investigations on pre-flawed specimens will be given in Chapter 2. Indeed, any missing about important works is inevitable.

Chapter 3 describes the experimental settings and data analysis methodology used in the present study. The primary feature of the experiments in this thesis is, it combines multiple observation systems, i.e. the mechanical system of stress and strain records, the AE system of signal waveform records, the optical systems with normal and high-speed optical observations, into one comprehensive observation on the rock fracture process of pre-flawed specimens. A preliminary application example of this methodology can be found in a recent publication in the *Journal of Geophysical Research: Solid Earth*, which is titled as "A Method for Multiscale Interpretation of Fracture Processes in Carrara Marble Specimen Containing a Single Flaw Under Uniaxial Compression" (Wong and Xiong, 2018). The main content of that publication (Wong and Xiong, 2018) will be described in Chapter 4. The experimental methodology of this thesis has been further improved from the methodology presented in Wong and Xiong (2018), and has been used for the experimental work of Chapter 5. As such, this Chapter will combine the experimental settings and data analysis methodology of two individual papers, "A Method for Multiscale Interpretation of Fracture Processes in Carrara Marble Specimen Containing a Single Flaw Under Uniaxial Compression" (Wong and Xiong,

2018), and “Laboratory-scale instabilities within a progressive shear-sliding failure” (Xiong and Lin (under preparation)).

Chapter 4 describes the experimental results and the new discoveries and interpretations based on the experiments on specimens containing a single pre-existing flaw. The corresponding material has also been reported by Wong and Xiong (2018).

Chapter 5 describes the experimental results especially the new phenomena observed in the experiment on a specimen containing a pair of coplanar pre-existing flaws. Based on these phenomena, the author (I) makes the argument that, “different stages are contained in the forming process of laboratory scale fault; the mechanical instabilities are not necessarily to be stick-slips—these mechanical instabilities can actually be divided into fault forming stages, and actual fault slip”. The contents of Chapter 5 are primarily from a manuscript titled , “Laboratory-scale instabilities within a progressive shear-sliding failure” by Xiong and Lin (under preparation).

Chapter 6 provides an investigation on the topological structure of the AEs released from the fracture process zone under symmetry/quasi-symmetry extension. With the high-quality of the experimental data as well as the detailed investigations on the topological AE network, it readily uncovers the effect of large-scale imperfection on inducing the non-local triggering in rock fracture process, which analogue the earthquake mechanism of the triggered subsequent earthquakes in geologically remote regions.

Chapter 7 provides a short review on the process of finding the post-peak analogue phenomena of seismic activity in the uniaxial compression tests on pre-flawed specimens—a type of experiments which has been extensively conducted for over several decades, i.e. over 50 years for specimens containing a single pre-existing flaw, and at least over 20 years for specimens containing a pair of flaws. This discovery constitutes one of the main contributions of this thesis. The findings and conclusion in Chapter 4, Chapter 5, and Chapter 6 will be combined and summarized in this Chapter. Also, suggestions and some preliminary results of the future works will be introduced in this Chapter.

The author has also noticed that, some journals focusing on engineering topics may prefer to use past tense for their publications. However, for the journal where the author has published his paper as corresponding author—Journal of Geophysical Research: Solid Earth, the reviewer suggests “present tense should be used through the majority of the paper”. The usage of present tense has also been prevalingly used among the publications in the journals that the author is planning to submit the works of Chapter 5 and Chapter 6 into. As such, the present tense will be primarily used in this thesis.

Chapter 2 Literature Review

2.1 Introduction of this Chapter

The author hopes this chapter can provide a concise but necessary background for understanding the arguments the author will make in Chapter 4, Chapter 5, and Chapter 6. It approaches this goal in the following aspects: first, in Section 2.2, the author will shortly review the concepts of laboratory investigation on earthquake mechanisms. Second, in Section 2.3, the author will provide a review of some recent laboratory discoveries on the stick-slip mechanism. These discoveries will be extensively referenced in the following Chapters especially Chapter 5, when the author tries to interpret the experimental results. For Section 2.4, the author will briefly review the previous publications using similar uniaxial compressive configuration—uniaxial compression tests on specimens containing preexisting flaws. Indeed, the author's tests have drawn certain inspirations from the configurations of previous experiments on pre-flawed specimens. However, as the primary foci of previous investigations on this type of tests are distinctively different with the foci of the present thesis, no extensive review on this aspect will be provided. At the end of this chapter, a short summary will be given.

2.2 Concepts for laboratory investigations on earthquake mechanisms

The mechanisms of earthquakes are complex. There are parallel hypotheses for describing the mechanisms of earthquakes. For instance, the concepts of friction and rupture both have already existed for over 100 years (Reches, 1999). The influences of several other mechanisms are also known to be existed, such as the lubrication mechanism of powder gouge materials (Di Toro et al., 2004; Han et al., 2010; Passelègue et al., 2016; Reches and Lockner, 2010), and healing and re-cement mechanism of the gouge material under the thermal and fluid effects (Karner et al., 1997; Marone, 1998; Reches, 1999). Recently, the phenomenon of phase transformations of metastable crystal(s) has also been proposed as a mechanism that can facilitate the nucleation of earthquake in deep focus (Schubnel et al., 2017). However, the powder lubrication mechanism, the gouge material re-cement mechanisms, and the phase transformation mechanism, can hardly be reproduced together with the laboratory fault creation process within one continuous laboratory process. The laboratory fault creation process refers to initiate the laboratory fault from the fracture process zone on intact rock material. As such, in the present thesis, those mechanisms will not be investigated together with the friction and/or rupture mechanisms. The latter two mechanisms are possible to be observed together with the laboratory fault creation process in one continuous laboratory rock fracture process. The laboratory stick-slip tests, which are the theme of the present study, will be focused in the following literature review.

The literature review of this thesis aims to provide the readers necessary background in understanding the interpretations of the experimental results presented in Chapter 4, Chapter 5, and Chapter 6. It is worthy to emphasis that, an induced “natural” fault from an intact rock material inherently represents an interesting laboratory analogue of a field scale fault for its inherent natural and randomized asperities. This analogue feature poses a great interest for seismic research in geophysics. As such, in this thesis, efforts have been devoted into generating an laboratory process where the laboratory fault creation process on intact rock material can be extensively observed with multiple observation methods, and simultaneously the rupture or/and slip mechanism(s) of earthquake can occur within this laboratory process.

The concepts of slip and rupture are the two concentrations for many laboratory investigations on earthquake mechanisms (Reches, 1999). Correspondingly, the slip tests on contacting rock surfaces (Dieterich, 1972, 1979, 1981; McLaskey and Kilgore, 2013; McLaskey et al., 2014; Ohnaka and Kuwahara, 1990; Okubo and Dieterich, 1984; Sammonds and Ohnaka, 1998) (see Figure 2.1 (a) and (b)) and the intact rock rupture tests (Graham et al., 2010; Kwiatek et al., 2014a; Lockner and Byerlee, 1975, 1991; Lockner et al., 1991; Ohnaka and Mogi, 1982; Stanchits et al., 2006; Zang et al., 1996; Zang et al., 1998) (see Figure 2.1 (c)) have been extensively conducted. Examples of the testing configurations of these two types of tests are presented in Figure 2.1 (a), (b) and (c), respectively.

Figure 2.1 (a) is drawn following Dieterich (1972). As it shows, three solid rock blocks subjected to normal stress, σ_n , are enforced to slip by the force F_A . The letter “R” labeling on the blocks indicates that the blocks are rock. Other blocks without letter “R” are loading platens. The middle rock block is sometimes enforced to slip at a prescribed constant velocity (Reches, 1999). As such, the letter for the upper downward arrow was labeled by letter “v” for velocity in the corresponding publications. In Figure 2.1 (b), another type of friction test on stacking rock blocks has been presented. In this type of test, one rock block was cut through along its diagonal line which has been illustrated by a red thick line in the figure. The subfigure 2.1(b) is edited based on Figure 1 of McLaskey et al. (2014), which stated to be the identical loading configuration of Dieterich (1981) and many other publications. Differential stresses are applied on its four boundary lines so that it can slip along the cut through surface. The surface roughness can be controlled by different gritting procedures so that to achieve different surface roughness (McLaskey et al., 2014; Okubo and Dieterich, 1984; Sammonds and Ohnaka, 1998). The upper-right insert represents the holding and loading frame of the test configuration. An example of the configuration of intact rock rupture tests has been presented in Figure 2.1(c). In this type of test, the rock specimens are subjected to axial loading σ_1 and confining pressure σ_2 . The dashed inclined line indicates the future failure plane, which usually are deviated by 20° to 30° from the maximum loading direction. This range of inclination angle is in accordance with the theoretical prediction of a natural sliding fault (Reches and Lockner, 1994).

One thing should be mentioned for the reader. Although the scales of the specimens in some specific publications which are referenced in this Chapter are of some specific values, the principal presumption of the experimental investigations on the earthquake mechanisms through its laboratory analogues is that, the earthquake mechanisms are of scale-invariant feature. Consequently, specimens of different sizes/scales are used by different researchers. As such, the dimensions of the specimens will not be on purposely specified in most of the illustration Figures of this Chapter.

Figure 2.1 two types of friction test on stacking rock blocks, (a) after Dieterich (1972) and (b) McLaskey et al. (2014), (c) intact rock rupture tests

In summary, the analogues of these laboratory tests to the earthquakes are incorporated in the following aspects:

- (i). the slip nucleation can be observed to initiate firstly at a small section (or small volume) of the final rupture fault plane;
- (ii). massive strain energy release can be identified as the tests approach the mechanical slip instabilities; and before that,
- (iii). acceleration on the growth (or termed as unstable growth) of slip nucleation section (or slip nucleation volume) can occur;
- (iv). the slip behavior is highly influenced by the asperity system along the fault.

In the following, the author will elucidate these 4 aspects by illustrating some previous laboratory studies together with their crucial findings.

2.2.1 Laboratory stick-slip mechanism—an analogue of natural earthquake mechanism

The theory of earthquake mechanism describes “an earthquake is the result of strain release caused by sudden shearing motion along a fault” (Brace and Byerlee, 1966). This concept has been proposed for over 100 years (Reid, 1910). Dating back to some over 60 years ago, Brace and Byerlee (1966) have suggested that the “jerky” motions on stress curve (see Figure 2.2 for illustration) when geological materials are compressed to failure under tri-axial conditions can represent earthquakes. In the original interpretation of their experiments, a laboratory earthquake might be represented as one of the many small stress drops on the loading curves.

In Figure 2.2, the specimen configurations and stress-displacement curves of the tests conducted by Brace and Byerlee (1966) are presented. This figure is drawn after Brace and

Byerlee (1966), where the upper parts of the subfigures are specimen configurations, and their corresponding lower parts are the typical stress-displacement curves for the axial direction. The cylindrical core samples are under axial stress, σ_1 , and confining pressure, σ_2 . The subfigures 2.2(a) and 2.2(b) stand for the test conditions where specimens are without precut plane, and with precut plane, respectively. In Figure 2.1(a), the dashed red line indicates the future failure plane which are initiated from the intact rock material through a continuous laboratory loading process; and in Figure 2.1(b), the precut plane, which is indicated by a solid red line, is prepared before the start of experimental loading. The drops on stress-displacement curves of two subfigures are drawn by dashed line. It is because according to Brace and Byerlee (1966), the exact shape of the curves at those dynamic stress drops are unknown, although this “unknown statement” was given at a time where limited experimental knowledge and technologies are available. In the original research of Brace and Byerlee (1966), it is also emphasized that the stiffness of the loading frame plays an important role on the exact shape of the stress-displacement curves on this type of tests.

Figure 2.2 specimen configurations and jerky motions on stress-displacement curves for cylindrical core samples under tri-axial stress (after Brace and Byerlee (1966))

Those jerky motions in present days are regarded as laboratory stick-slips among seismologists. Before a mature laboratory acoustic emission monitoring technology is available, Brace and Byerlee (1966)'s work is interesting. It is because they have concluded that the drops of global axial stress are the releasing of a small portion of the total stress of fault core, with an assumption such that these drops are also the signs of strain energy release

of that fault core. To some extent, the amplitudes of those stress drops “does not depend solely on the material (Brace and Byerlee, 1966)”; the stiffness of the loading frame can drastically change the amplitudes of these stress drops. Thus, the amount of energy release of each global stress drop was unknown in their study (Brace and Byerlee, 1966). The laboratory evidence of the phenomenon that “slip nucleation from a comparative small volume” comes from the later studies (Lockner and Byerlee, 1991; Lockner et al., 1991; Reches and Lockner, 1994) after the mechanical interpretations on the stress-displacement curves obtained by Brace and Byerlee (1966).

2.2.2 Slip nucleation at small section (or small volume) of the final rupture fault plane

Lockner and Byerlee (1975) (or Byerlee and Lockner (1975)) have developed a system that can couple a real time multi-channel AE monitoring and AE source location into the tri-axial compression configuration. By analyzing the AE source location result from a tri-axial core sample rupture test (height = 190.5 mm, diameter = 76.2 mm according Lockner et al. (1991)), Lockner et al. (1991) have reported that the slip nucleation volume is within a 3 cm³ volume “with no preceding development of an embryonic fault zone” (Reches and Lockner, 1994) (see Figure 2.3 (a), which is drawn based on the Figure 12 of Reches and Lockner (1994)).

As illustrated in Figure 2.3 (a), the time and volume of slip nucleation in a core sample can be judged by the means of containment spheres of AE events (Reches and Lockner (1994)). The term “containment sphere” of N consecutive AE events was defined as the average distance of these N AE events to their geometrical center which was calculated by separately averaging the three coordinates of those N AE events. An obvious drop on the volume of containment sphere indicates the time of slip nucleation, which is indicated by a red star mark on the curve of Figure 2.3(a). This subfigure is drawn according the Figure 12

of Reches and Lockner (1994). The original data presented in Reches and Lockner (1994) has been resized and presented in the upper insert of this subfigure. In the original presentation (Reches and Lockner (1994)), the unit for the horizontal axis (time axis) was second, and the unit for the vertical axial (axis for containment sphere volume) was cm^3 . This may possibly be different with some later experiments. It is because the testing time of Lockner and Byerlee (1975); Lockner et al. (1991) can last for days or even weeks, and the sizes of the specimens used by different researchers are different.

Figure 2.3 slip nucleation at small volume or small section. (a) for core sample (after Reches and Lockner (1994)), and (b) and (c) for precut fault (after Ohnaka and Kuwahara (1990))

In addition to the rupture tests on intact rock cores, in an experimental study of the shear-sliding along an diagonally cut through rectangular rock block (Ohnaka and Kuwahara, 1990) (see Figure 2.3 (b)), the formation zone of slip nucleation has also been found to initiate from a small section (see Figure 2.3 (c), which is reproduced from Figure 10 of Ohnaka and Kuwahara (1990)).

As illustrated in Figure 2.3 (b) and (c), the experimental configuration used in Ohnaka and Kuwahara (1990) is a rock block with diagonal precut plane. In Figure 2.3 (b), this diagonal precut plane is indicated by a red thicker line. Strain gauge sensors are mounted along the precut plane. The numbers beside these sensors indicate the channel numbering for the signals presented in subfigure 2.3 (c). Figure 2.3 (c) is reproduced from Figure 10 of Ohnaka and Kuwahara (1990), which was served as an example of a series of shear stress and slip displacement records along the precut fault in the zone of unstable, dynamic rupture propagation. In the left half of Figure 2.3 (c), two dashed lines crossing the signals from channel 1 to channel 6 were indicating the time of peak shear stress (left one), and the time shear stress had just dropped to its residual value (right one). In the right half of Figure 2.3 (c), the displacement and slip velocity records at the position of different strain gauge sensors were presented. From this subfigure, a clear growth on the length of slip section at the moment of rupture propagation can be observed—the slip velocities of channel 1 to channel 6 subsequently jumped to a high value, indicating the starting moment of slip at different locations; while at the moment the location of channel 6 begins to slip, the velocity of channel 1 had not recovered to its pre-slip level; this phenomenon indicates the growth of the slip section in the experiment.

One fact that differentiates those above mentioned core sample tests in this section (Section 2.2.2) and other engineering rock mechanics core sample tests should be emphasized. The total testing time of these above mentioned core sample tests, i.e. Byerlee and Lockner (1975); Lockner and Byerlee (1975); Lockner et al. (1991); Reches and Lockner (1994), can last for days or even weeks. This length of testing time is several orders larger than the range in ISRM suggested method (Bieniawski and Bernede, 1979) or ASTM standard (ASTM, 2017) for determining the rock compressive strength. Because of this slow test procedure, the

detail phenomena during the transition from intact rock to final slip state can be much more clearly observed. Indeed, many present laboratory tests adopting ISRM suggested method or ASTM standard are unable to observe the transition stages from slip nucleation to final slip rupture failure in great details, due to the short testing time.

2.2.3 Massive strain energy release as the tests approaches the mechanical slip instabilities

The massive strain energy release always accompanies with the global stress drops no matter that the tests are conducted on intact rock or sliding rock surfaces. For intact rock tests, a vast of publications have reported the rise of AE energy as an AE parametric change when the tests approach the failure. Unlike the transition from slip nucleation to unstable slip, this phenomenon can be observed without a prolonged testing time. Several studies have documented much detailed AE phenomena i.e. Lei et al. (2000a); Lockner and Byerlee (1991); Lockner et al. (1991); Reches and Lockner (1994); Zang et al. (1998); Zang et al. (2000). Based on the results of the tests on these studies, when the tests approach the global stress drops, the number of AE source locations, and the released AE energy will both increase (Figure 2.4 (a) and (b)). These AE phenomena are the direct evidence of the massive strain energy release accompanying with the global stress drop.

Figure 2.4 (a) is the experimental result reported by Lei et al. (2000a). As illustrated in the upper part of this subfigure, as the differential stress approaches the final drop, the AE rate has displayed a drastic rise. The upper part has presented the whole testing time, where the details on the transient rise of AE activity may be difficult to be observed. In the lower part of subfigure (a), a section of the total testing time has been enlarged. Its temporal location in the upper part to the overall testing time has been indicated, which helps the reader to understand this comparatively transient phenomenon with the overall test.

Another experimental example which proves the massive energy release when the tests

approach the mechanical slip instabilities comes from Zang et al. (1998). It is illustrated in Figure 2.4(b), which is reproduced from the subfigures (a) and (c) of the Figure 3 in Zang et al. (1998). A rise of AE activity as the global loading approaches the final drop can also be observed through this subfigure (b), which is similar to that of Lei et al. (2000a). In the tests of Zang et al. (1998), both symmetric and asymmetric loading have been attempted. The symmetric loading is identical to the loading configuration of standard triaxial loading test. The insert of the lower part in Figure 2.4 (b) displays the configuration of asymmetric loading—the lower surface of the core specimen is fully contacted with the loading platen, while for the upper surface of the core, only 80% of the upper surface is contacted with the loading platen. The contacted areas of the upper and lower surfaces of the specimen are represented by green lines and green color, respectively. Both symmetric and asymmetric loading conditions have displayed a drastic rise of AE activity as the global loading approaching the final drops.

Figure 2.4 experimental examples of massive energy release when the tests approach the mechanical slip instabilities in intact rock. (a) Lei et al. (2000a), and (b) after Zang et al. (1998)

For the tests conducted on sliding frictional rock surfaces, the number of AE is affected by the surface roughness of the saw-cut through plane as well as the sensitivity of the AE monitoring system. However, it still can observe the rise of amplitudes for the AE signals at the moment of global stress drops (McLaskey et al., 2014) and the rise of AE event numbers when the test approaches the slips (Thompson et al., 2005) (see Figure 2.5). Figure 2.5 (a) presents the experimental result of Thompson et al. (2005), which is reproduced from the subfigure (a) of the Figure 1 in Thompson et al. (2005). The loading configuration used by Thompson et al. (2005) is presented in Figure 2.5 (b). The precut plane is indicated by a red line and its roughness has been controlled by a gritting procedure. As illustrated in Figure 2.5 (a), the sudden rises on accumulated AE curve always accompanies the moments when the global deviate stress approaches the drops. This coincident phenomenon in AE activity and global stress is similar with the phenomenon of intact rock tests, which has already been

presented in Figure 2.4 (a) and (b).

Figure 2.5 experimental example of massive energy release when the tests approach the mechanical slip instabilities in sample with precut plane. (a) Thompson et al. (2005), and (b) test configuration

It is worthy to mention that, Lei et al. (2003); Lei et al. (2004) have also documented the detailed AE behaviors of the rupture tests for core samples containing natural healed joints. Similar energy release behavior has been observed. This testing configuration can be regarded as the transition type in between the testing configurations of intact rock rupture and slip on contacting rock surfaces. However, it needs to note that there is a distinctive difference between the AE behaviors of laboratory stick-slips and field earthquakes. “Laboratory rock fracture is dominated by a large number of foreshocks, where seismicity in the Earth’s crust is characterized by an abundance of aftershock” (Davidsen et al., 2007; Main, 2000). This will be visited again in Chapter 5 when I interpret my test results.

2.2.4 Unstable growth of slip nucleation section

When the tests approach the mechanical stress drops, which usually suggests the

specimen of intact rock fails, or the frictional rock surfaces start to slip. There is a transition between quasi-static fault nucleation to dynamic rupture, or slip. For the aspect of observing this unstable growth, Reches and Lockner (1994) have analyzed the change of AE event density for the sequential AE events. They found a drastic drop on containment sphere volume (see Figure 2.3 (a)) would occur just before the moment of fault propagation. They suggest this phenomenon indicates that, the stage of fault nucleation is separated from unstable fault propagation stages. Similarly, a drastic growth of slip section length can also be found for block slip test (Ohnaka and Kuwahara, 1990).

2.2.5 Slip behavior is highly influenced by the asperity system along the fault

To study the influence of asperity system along the fault, Sammonds and Ohnaka (1998) have conducted sliding tests along saw-cut through planes with distinctively different roughness. The roughness of the planes can be controlled through comprehensive grit procedures (Figure 2.6). The tests have been conducted under an identical loading stress and displacement rate so that the influence of surface roughness can be compared. It is reported that “maximum amplitudes of AE events during stable sliding are strongly dependent on the surface roughness, smooth-ground surfaces giving smaller maximum AE amplitudes”. The b-value of Gutenberg-Richter law ($N = 10^{a-bM}$, where N is the events with magnitude larger than M) is also found to be correlated with the specimens’ surface roughness, which will be further described in next section (Section 2.3).

As illustrated in Figure 2.6, which is reproduced from Figure 3 of Sammonds and Ohnaka (1998), the influence of the asperity system along the fault is reflected in the form of the amplitude-frequency distribution of the AE events. The labels #60 and #600 are indicating the data of rough and smooth surfaces, respectively. The numbers are the designations of the grits which Sammonds and Ohnaka (1998) have used to control the surface roughness. This figure shows the AE frequency-amplitude distributions of rough and smooth surfaces are distinctively different, where the rough surface is more likely to produce large amplitude AE

events.

Figure 2.6 AE frequency-amplitude distributions of rough and smooth surfaces (Sammonds and Ohnaka (1998))

The experiments of Sammonds and Ohnaka (1998), which were conducted on sliding surfaces with controlled roughness, showed the AE releases is highly influenced by the asperity system along the fault. Another study have compared the AE behaviors between laboratory induced “natural” fault and saw-cut through “smooth” fault (Thompson et al., 2009). It has showed that, the AE behaviors between laboratory induced “natural” fault and the saw-cut through fault are different (Figure 2.7).

As illustrated in Figure 2.7, the smooth fault plane was created by a cut through plane (red line) on the core specimen which is illustrated on the left. The natural fault plane was created in the loading procedure. Thompson et al. (2009) have documented the differences of released AEs during the stick-slips on the two different faults; and reported that the AE

number released from a “natural” fault was much greater than a smooth fault. It was stated by Thompson et al. (2009) that thousands of AE can be located along the natural fault plane, while less than a hundred AE can occur along the smooth fault plane. The post-mortem exam of the specimens also indicated that, the fault asperity of the natural fault was much more complex than smooth fault. Thus, this post-mortem exam has highlighted the influence of the fault asperity on its laboratory analogue of seismic release behaviors.

Figure 2.7 experimental configurations of Thompson et al. (2009) (a) with precut fault, and (b) with “natural” fault

2.3 Some improvements of recent studies

There are limitations for the laboratory investigations of intact rock rupture and sliding tests on frictional contacting rock surfaces. For the intact rock rupture tests, one of the major limitations is in the transition between fault nucleation and unstable fault rupture. It has difficulties to control this transition in most experiments, because the unstable rupture can occur in a very short time. As suggested by the self-organized criticality theory, at the self-organized criticality state, there is no length scale of the rupture, and ruptures can take place at all scales where the only limit of these ruptures is the physical boundary of the mass/system at self-organized criticality state (Bak and Tang, 1989). Thus, it is not surprising for the experimental researchers to notice the difficulties to observe the phenomena within this transition, to some extent only by chance. In order to make a detailed AE documentation of the slip behavior after slip nucleation, in some studies, AE feedback control was used (Lockner et al., 1992; Lockner et al., 1991; Stanchits et al., 2009; Stanchits et al., 2011; Stanchits et al., 2006). This experimental procedure allows the axial loading piston to be reversely travelled. Thus, the temporal AE statistical feature(s) of a faulting sequence may not be maintained. For the sliding tests on frictional contacting rock surfaces, one of the major limitations is that, it is difficult to achieve real earthquake slip rate by the sandwich type sliding (Figure 2.1 (a)) or the sliding along the diagonally precut plane (Figure 2.1(b)). In addition, another major limitation of this type of tests is that the prepared surfaces may lose the randomness feature of its along-fault asperity system. Some recent studies have attempted to address these limitations and some meaningful discoveries have been obtained.

In some publications which are published within one decade, cylinders samples were pretreated with saw-cut guides (see Figure 2.8) (Goebel et al., 2012; Goebel et al., 2015; Goebel et al., 2013; Kwiatek et al., 2014b). The original purpose of this treatment appears to guide the shear fault to develop within a predesigned plane. However, the tests are reported to be able to generate multiple stick-slips, with only a constant axial displacement loading rate. After some improvements such as the “fault locking” procedure (Charalampidou et al., 2014) and placing Teflon sheets as infilling into the saw-cut guiders (Goebel et al., 2015), the

multiple stick-slips along a laboratory generated fault can successfully be generated, and well AE documented stick-slips can be identified in the following constant axial displacement loading.

As illustrated in Figure 2.8, a specimen with precut guides is presented in subfigure (a). The precut guides are indicated as two red short sections at two sides of the specimen. The future failure plane is indicated by dotted red line and the faulting zone is indicated by the ellipse. As the specimen is loaded by a slow and constant displacement, multiple stick-slips can be generated. With those stick-slips, the b-value systematically drops and recovers which is presented in Figure 2.8(b). This subfigure (b) is reproduced from the Figure 1 of Goebel et al. (2013). From the reported results of these tests, the b-value of Gutenberg-Richter law has been reported always approaching 1 as the test approaches the slips, and will recover to its pre-slip level after the slips (Goebel et al. (2013)) (Figure 2.8 (b)). Goebel et al. (2013) suggest this change of b-value is the consequence from the periodic stress changes over many seismic cycles; the amount of b-value increase indicates the extent of the corresponding stress drop, and b-value variation can be used to approximate the stress state on a fault.

In addition to the systematical b-value variation, periodical and systematical changes on the AE moment tensor components have also been reported over many stick-slip circles (Kwiatek et al. (2014b)) (Figure 2.8 (c)). An example of this variation has presented in Figure 2.8(c). This subfigure (c) is reproduced from the subfigure (d) of the Figure 2 in Kwiatek et al. (2014b). The ISO/CLVD/DC represent for the isotropic, compensated linear vector dipole, and double-couple, respectively. The time of slip onset is marked as inverted triangle at the top of the plot. Six lines of each AE moment tensor components are drawn based on the AE data of six stress drop circles. Rough surface sample refers the fault plane was created through the experimental loading process. Kwiatek et al. (2014b) have interpreted the changes on AE moment tensor components as the result of the periodically rotations in fault plane parameters; this periodical rotation is related to the existence of shear-enhanced compaction or extension in the seismic source.

The evolution of fractal dimension of the loading created faults has been reported to be

obvious in the first two or three successive stick-slip circles (Goebel et al. (2015)). However, as the evolution of fault fractal dimension has not been primarily addressed by the result interpretation of my tests in Chapter 5, the physical meaning of this aspect will not be described extensively in this literature review Chapter.

Figure 2.8 (a) specimen configuration with precut guides. (b) b-value variation (Goebel et al. (2013)) and (c) variation of AE moment tensor components with stick-slips (Kwiatek et al. (2014b))

Considering the facts that the cylinder samples are prepared with 60-degree inclined

saw-cut notches and the laboratory fault is created under triaxial compression tests (Goebel et al., 2012; Goebel et al., 2015; Goebel et al., 2013) (Figure 2.8 (a)), this type of test is in between the typical intact rock rupture tests and the typical frictional slip tests, as (i) the fault is created from intact rock and (ii) multiple successive slips can occur along the failure planes which are predetermined along the plane of saw-cut notches.

In Section 2.2.3, it was stated that the testing configuration of Lei et al. (2003); Lei et al. (2004) can be viewed as the transition type in between the testing configuration of intact rock rupture and slip on contacting rock surfaces. However, note that it is by chance to obtain the core samples containing natural healed joints. Moreover, as the available experimental data is limited for samples containing natural healed joints, it is difficult to use a holistic pre-test evaluation/classification system for characterizing the natural healed joint. Thus, although the test on the core sample containing natural healed joint may provide a best approximation of the natural fault behavior in the laboratory, essentially it has not solved the limitation in intact rock rupture tests.

For the sliding tests on frictional contacting rock surfaces, recent studies have adopted a rotary ring settings (see Figure 2.9) (Di Toro et al., 2004; Han et al., 2010; Mizoguchi et al., 2006; Passelègue et al., 2016; Reches and Lockner, 2010; Yund et al., 1990). This setting solves the limitation of classical sandwich type slip tests in that the real earthquake slip rate can be achieved in the slip blocks. The reported results provide insightful knowledge about the mechanisms of gouge forming, gouge powder increasing, powder lubrication, slip-weakening, and gauge powder rheology, etc., suggesting fundamental changes can take place on the gauge layer of the fault plane during earthquakes. As a result, more earthquake mechanisms and the slip mechanism can be investigated through one type of experimental configuration. For instance, the powder lubrication mechanism has already been reported in previous laboratory tests of this type (Reches and Lockner, 2010), and possibly more other mechanisms can also be quantitatively investigated through this experimental configuration.

Figure 2.9 (a) experimental configuration of rotational ring test, (b) example of half rotary rock ring (upper-left) and post mortem powder of different scales (Reches and Lockner, 2010). An video example of this type of test can be found in <http://www.youtube.com/watch?v=YTfwJ3Elw5s>

From a much broader perspective of laboratory and field earthquake analogue, the experimental configurations mentioned in this Chapter are attempting to simulate the fault behavior at one predetermined specific setting, including intact rock rupture tests, stick-slip tests on cylindrical rock with saw-cut, rotational slip tests on hollow rock rings, sandwich type sliding tests or the sliding tests on the diagonally precut plane. Each of those specific settings may only be the analogue of one aspect of the natural fault and simulate the fault behavior to limited extent; alternatively it is also possible that those specific settings may only best approximate the fault condition at one of the many specific evolution stages of the natural fault. A natural inquiry for a much more comprehensive understanding on the experimental results of these types of tests, especially for the rock rupture type tests, is to understand the transition from the fault creation on intact rock material to the fault slip along the well-formed fault. This aspect is one of the primary foci that the current research plans to contribute to.

2.4 Previous applications and associated limitations of prismatic specimens with preexisting flaw(s)

At the last section before the summary of this Chapter, I would shortly review the previous tests on prismatic specimens containing preexisting artificial inclusions. This kind of tests has been conducted for over 50 years since the work of Lajtai (1969, 1971, 1974). In the original work of Lajtai (1969) (Figure 2.10), the preexisting flaws have been created in the specimens of molded water and plaster mixture. At that time, the loading method is the direct shear, which is different with the later tests on prismatic specimens.

In Figure 2.10, (a) the test configuration of Lajtai (1969) has been presented. A block of rock-like material contains two pre-existing flaws (drawn as red sections in two sides of the block) and a comparatively intact rock bridge between them. The block was subject to normal stress σ_n and the rock bridge was subject to shear stress which was induced by a pair of forces F_1 and F_2 . The lower insert of subfigure (a) is the photo of the loading frame provided by Lajtai (1969), which is reproduced from Figure 10 of Lajtai (1969). Figure 2.10 (b) is the photos on the post-mortem specimens after shearing tests, provided by Lajtai (1969). This subfigure (b) is reproduced from the Figure 16 of Lajtai (1969).

Figure 2.10 (a) direct shear test configuration, after Lajtai (1969), and (b) post-mortem photos (Lajtai (1969))

Later, Lajtai (1971, 1974) have also conducted series of tests on specimens containing single inclusion (Figure 2.11). One of his purposes is to investigate the Griffith's theory in brittle rock-like material. In these tests, the loading has been monotonically applied to the specimens and the orientations of the elongated inclusions on the specimens are inclined with the loading.

In Figure 2.11 (a), a schematic drawing of the single pre-existing flaw and the fracture development paths during loading test has been reproduced from Figure 13 of Lajtai (1971). In comparison, schematic drawing of single inclusions of different shapes and the fracture development paths during loading test is presented in Figure 2.11 (b). This subfigure (b) is reproduced from the subfigure (a) of Figure 8 in Lajtai (1974). Figure 2.11 (c) is the photos of the post-mortem specimens provided by Lajtai (1971), which is reproduced from the Figure

Figure 2.11 experimental schematic draws of (a) single pre-existing flaw (Lajtai (1971)), and (b) single inclusion of different shapes (Lajtai (1974)), and (c) the photos of the post-mortem specimens (Lajtai (1971))

After Lajtai (1969, 1971, 1974), many researchers have adopted this loading setup, rather than the direct shear, for the fracture coalescence tests on rock and rock-like materials (to list a few from the long list, Bobet and Einstein (1998); Shen et al. (1995); Wong and Einstein (2009a, 2009b)). The so-called fracture coalescence in those tests refers to the fracture behaviors that link the bridging area between two elongated inclusions (pre-existing flaws) (Figure 2.12). The elongated inclusions are designed to be in overall inclined directions to the maximum stress. As the loading applied, a shear displacement tendency will be induced along the bridging area. As a result, the configuration for the rock bridging area is the analogue of the configuration of Lajtai (1969) (Figure 2.10 (a)). In both configurations, shear stress can be created along the rock bridge.

In Figure 2.12, an example configuration of the prismatic specimen containing a pair of

pre-existing flaws for fracture coalescence tests has been presented. The maximum loading direction is parallel to the long edge of the specimen. Some tests are conducted under biaxial loading conditions while others are conducted under uniaxial loading condition. The two preexisting flaws are symmetrically located to the planar center of the specimen. The length of the pre-existing flaws, the inclination of the pre-existing flaws, and the length and the inclination angle of the bridging section between the inner tips of the flaws are changed in previous studies, creating a series of specimens containing different pre-existing flaw settings.

Figure 2.12 illustration of the prismatic specimen containing a pair of pre-existing flaws for fracture coalescence tests

Although many experimental tests have been conducted in specimens containing pre-existing flaw(s), unfortunately most of these tests primarily focus on the investigation of the mechanical behaviors, such as, the stress of fracture initiation, fracture type classification, etc. (for specimens containing single inclusion), or the so-called fracture coalescence patterns (for specimens containing multiple inclusions), as well as the strength of the specimens. Only very recently, a well AE documented post-peak fracture process has become available (Wong and Xiong (2018)) for the single flaw contained specimens for this type of tests. Based on the author's limited knowledge, the well documented AE and optical observations for the post-stress-peak domain in fracture coalescence test are rare. Thus, the discoveries in the experimental results reported by Wong and Xiong (2018) are very helpful, as compared with a vast number of previous studies.

Additionally, there are many previous studies that suggest the preexisting flaw does not grow in its own planes and does not propagate in the direction of the maximum shear stress; in contrast, tensile wing-cracks develop at the tips of the preexisting flaw and they propagate along a curve toward the axis of maximum compression (Germanovich et al. (1995)). The propagation of the secondary shear crack along the direction of the pre-existing flaw only can be observed, after the first/primary fracture has a considerable propagation (Ingraffea and Heuze (1980)) (Figure 2.13 (a)). Note that Wong and Xiong (2018) have shown the fractures in the white patch format propagate along the direction of maximum shear stress (in tests of 60° and 70° inclined preexisting flaws), without any considerable propagation of the first tensile cracks (Figure 2.13 (b)).

This contrast can be further clarified in Figure 2.13. The left side of Figure 2.13 (a) is a schematic drawing for illustrating the concepts of first fracture and secondary fracture. On its right side, the original photo provided by Ingraffea and Heuze (1980) has been reproduced. This photo on the right side is reproduced from the subfigure (a) of the Figure 2 in Ingraffea and Heuze (1980). The letters "A" and "B" are indicating the path where first fracture has propagated, while the letter "C" indicates the path of secondary fracture. In Figure 2.13 (b),

screenshots of the experimental results reported by Wong and Xiong (2018) have been presented. These screenshots are obtained from the identical video sources which were used by the Figures 19 (b) and 17 (b) of Wong and Xiong (2018). Specimens containing a single pre-existing flaw were uniaxially loaded. In both cases, flaw inclined 60-degree to the loading direction for the left screenshot, and flaw inclined 70-degree to the loading direction for the right screenshot, the evidence of first fracture propagation appears very weak and even almost non-distinguishable. The white patches at the places where the first fractures should be at are of ultra-small size; and appear to be unchanged until a considerable propagation of the white patches at the places for the secondary fractures. A more important feature of the tests reported by Wong and Xiong (2018) is that most of the important changes in the fracture process zones have happened in post-peak domain.

Figure 2.13 (a) schematic draw of first fracture and secondary fracture (on the left), and photo on the specimen (on the right) (Ingraffea and Heuze (1980)). (b) weak and non-distinguishable first fracture propagation (generated from the same raw data used by Wong and Xiong (2018))

Considering the above mentioned facts, it is possible that the post-peak behavior of the fracture coalescence tests is more important than the mechanical interpretation focusing on fracture initiation and coalescence to understand the real field scale phenomena. This post-peak behavior can be refereed as the analogue of the fault evolution in the post-stress-peak domain. Its evolution appears to be of some universal features regardless of the change of preexisting flaw distance and angle. Using different geometrical settings of the pre-existing flaws are favored by the traditional studies of fracture coalescence tests. However, if the existence of these universal features can be well approved, it would be of high necessity to re-define the terminology “fracture coalescence”. Furthermore, it is believed the theoretical structure of self-organized criticality theory (Bak and Tang, 1989) is more promising in describing this post-peak evolution, rather than the theoretical structure of classical fracture mechanics theory. The analyses of Chapter 6 are out of this believing. In Chapter 6, an example of the data analyses without any consideration focusing the pre-peak to peak stress mechanical behavior has been presented. The work in that Chapter incorporates the above mentioned idea into the experimental interpretation of pre-flawed specimens and showcases the power of the data analyses method of that Chapter.

2.5 Summary of this Chapter

This Chapter aims to provide the necessary background knowledge for the experimental data analyses and experimental result interpretations made in the following Chapters. Especially, this knowledge will primarily be referred to the experimental result interpretations of Chapter 5. First, two concentrations of the laboratory investigations on earthquake mechanisms are existed. They are rooted in the concepts of friction and rupture, respectively. Both types of tests have displayed analogue features of natural earthquakes. There are four analogue features which these tests have displayed. These analogue features have been summarized at the start of Section 2.2. Examples of these four analogue features have further been given through Sections 2.2.1 to 2.2.5.

In Section 2.3, some recent experimental advancements and discoveries on the rock rupture tests and frictional slip tests have been reviewed. As the rupture tests will create a fault on the intact rock material and the frictional slip test is conducted on contacting rock surfaces, they are inherently different. Each type of tests may only best approximate and simulate the fault behavior in one aspect. Regarding the recent experiment advancement on the rupture type tests, multiple stick-slips can be observed within one continuous laboratory process. As those multiple stick-slips are out of rupture type tests, the laboratory fault creation process has also involved in this one continuous laboratory process. The fault created through laboratory loading process is inherently of randomness for its asperity system. This type of laboratory fault represents a very interesting laboratory analogue of a field scale fault. A natural inquiry for a much more comprehensive understanding on the experimental results of these types of tests is to understand the transition from the fault creation on intact rock material to the fault slip along the well-formed fault. Therefore, efforts of this thesis will be devoted into generating an laboratory process where the laboratory fault creation process from intact rock material can be extensively observed with multiple observation methods, and simultaneously the rupture or/and slip mechanism(s) of earthquake can occur within this one continuous laboratory process.

In Section 2.4, a short review on the previous experimental configurations on

experiments conducted on pre-flawed specimens has been given. It is because, this type of tests can create shear type failure along the two coplanar pre-existing flaws, and simultaneously multiple observations such as optical and AE observations can be obtained together with the mechanical measurements. However, no extensive literature review on the achievements of this type of tests has been given in Section 2.4, because the foci of previous researches on this type of tests are distinctively different with the foci of the present thesis.

Hopefully, through the literature of this Chapter, the background knowledge for understanding the interpretations on the experimental results in Chapter 4, Chapter 5, and Chapter 6 has been properly addressed.

Chapter 3 Experimental procedure and data analyses methods

This Chapter combines a section of “Methodology and experimental setup” of “Wong and Xiong (2018), Journal of Geophysical Research: Solid Earth, A Method for Multiscale Interpretation of Fracture Processes in Carrara Marble Specimen Containing a Single Flaw Under Uniaxial Compression”, and a section of “Experimental procedure and data analyses” of “Xiong and Lin (under preparation), Laboratory-scale instabilities within a progressive shear-sliding failure”.

3.1 Specimen preparation and testing approach

The specimens for the experiments conducted for this PhD thesis are prepared on Carrara Marble. The material used for testing, Carrara Marble, is well homogenous and consists of small size grains (ranged from 50 to 300 μm) (Cheng et al., 2015). For the tests on specimens containing a single pre-existing flaw, five specimens of different flaw inclination angles against the uniaxial loading direction are prepared. One of the primary purposes of conducting these tests on specimens containing single flaw is to verify the observations of different systems. More descriptions of the experimental observations and discoveries on the rock fracture process will be described in Chapter 4 . For the observation of the progressive shear-sliding failure, two specimens are prepared. All the specimens are prepared from the prismatic Carrara Marble blocks of size 152 mm $\times$ 82 mm $\times$ 32 mm.

The pre-existing flaws are cut out by waterjet. They are approximately 13 mm. For the specimens containing a single pre-existing flaw, the flaws are cut out in the middle of the specimens. The flaw inclination angle, β , lies in the range from 90° to 30° inclined against the horizontal direction (see Figure 3.1 (a)). For specimens containing a pair of coplanar pre-existing flaws, the flaws are inclined 60° to the horizontal direction, and gaped 26 mm, symmetry to the middle of the specimens (see Figure 3.1 (b)). All surfaces of the specimen are grinded to reduce the end friction and to achieve a good and equivalent condition of AE sensor coupling. The water jet cutting procedure and the following surface grinding would introduce slight differences on the specimens' geometry. Detailed measurement on the

specimens' geometry has been made before conducting each test. The results are listed in Table 3.1 (a).

Figure 3.1 Illustrations of specimens and sensor array configurations and locations of calibration points for (a) specimens containing a single flaw (after Wong and Xiong (2018)), and (b) specimens containing coplanar flaws (after Xiong and Lin (under preparation))

Table 3.1. (after Wong and Xiong (2018) and Xiong and Lin (under preparation)) a. geometrical parameters of the specimens. b. loading procedure. c. parameters used for the AE data acquisition system. And d. high-speed camera settings

a. Geometry of the specimens

Tests	Height	Width	Thickness	Flaw length	Ligament L	Aperture
Single flaw tests						
$\beta = 90^{\circ+}$	151.5	75.4	31.0	~ 13 mm	Not applicable	1.80/2.40*
$\beta = 70^{\circ+}$	151.4	78.9	31.7	~ 13 mm	Not applicable	1.60/2.30*
$\beta = 60^{\circ+}$	151.4	78.9	31.1	~ 13 mm	Not applicable	1.70/2.40*
$\beta = 45^{\circ+}$	151.0	78.8	31.6	~ 13 mm	Not applicable	1.70/2.34*
$\beta = 30^{\circ+}$	151.2	78.3	29.8	~ 13 mm	Not applicable	1.74/2.36*
Double coplanar flaw tests						
60-1	151.94	80.24	29.78	13.18	25.80	1.28
60-2	151.26	79.80	29.80	14.10	25.74	1.28
* F and B in the parentheses stand for aperture measured in the Front, and Back of the specimen, respectively.						
+ The flaw inclination angle β is measured from the horizontal direction as shown in Figure 3.1 (a).						

b. Loading procedure

Loading stages	Stage 1	Stage 2''	Stage 3
Load range	3 kN – 50 kN	50 kN – 100kN or 50 kN – 70kN	70 kN – failure
Loading rate	0.1 kN/s	0.002 mm/s	0.0001 mm/s
'' the end loading stresses of stage 2 are different for single flawed specimens and double flawed specimens			

c. AE data acquisition parameter

Parameter name	Threshold type	Threshold	HDT**	HLT**	Sampling rate	Preamplifier gain	Parameter name
Value	Floating	39 dB+5	600 μ s	300 μ s	3 MHz	40 dB	Value
Sensor operation range				125 kHz-750 kHz			
Sensor resonant frequency				300 kHz (in V/ μ bar reference unit)			
** HDT = Hit Definition Time, HLT = Hit Lockout Time.							

d. high-speed camera setting

Frames-per-second	Resolution	Storage	Lasting time
10,000	352 $\times$ 600	15 GB	7.28 s

AE signals are monitored by 16 NANO-30 sensors (with resonant frequency 300 kHz in V/ μ bar, and 8 mm diameter), and registered into a 16 channel MICRO-II system manufactured by Physical Acoustic Corporation. Each AE data acquisition channel has a 2/4/6 preamplifiers, which is set to 40 dB gain value for the tests. All the sensors are attached onto the specimen by Loctite superglue, which provides stable and constant contact between the sensors and the specimens. No other couplant has been used. Before the loading test, pencil lead break, pencil scratching, and no-axial-force-applied piston up-and-down movement are repeatedly conducted to determine the data acquisition parameters such as threshold, HDT (Hit Definition Time), and HLT (Hit Lockout Time) etc. The ideal signal-to-noise ratio of the AE waveform data acquisition under the present setting is 2. It is because the data acquisition parameters are in-situ determined which gives a 33 dB threshold for filtering out all noises during the no-axial-force-applied piston up-and-down movement. To raise the threshold for 6 dB ideally settles a signal-to-noise ratio of 2 for the AE waveform data acquisition during the tests. This ideal signal-to-noise ratio cannot always be maintained during the tests. Therefore more signal pre-conditioning treatments are applied in the data analyses, which will be described in Section 3.2. Details of the present data acquisition parameters, and sensor and pre-amplifier information are listed in Table 3.1 (c). A further explanation about the influences of these parameters on data acquisition is provided in Appendix I.

A camcorder (Sony HDR-XR150) is used to log the normal speed video during the test, and a high-speed camera (VRI-V310-16G-M) is to record the high-speed video when the dynamic rupture occurs. The frame rate and resolution of the high-speed camera system are set to be 10,000 frames-per-second, and 352×600 pixels, respectively (see Table 3.1 (d)). With the 15 GB storage capacity of the high-speed camera, a high-speed camera video footage lasting 7.28 seconds can be recorded with the present setting.

Uniaxial compression test is conducted in MTS-815 loading frame. To facilitate the test, 3 loading stages are used in the present study. The first and second loading stages loaded the axial force to 100 kN (for specimens containing a single pre-existing flaw) or 70 kN (for specimens containing a pair of coplanar pre-existing flaws) in a fast manner (See Table 3.1

(b)). The 3rd loading stage is controlled using 0.0001 mm/s ($\dot{\epsilon} = 6.6 \times 10^{-7}$) displacement rate. This rate is in the range of the strain rates (in the range of $\dot{\epsilon} \approx 10^{-6}/s - 10^{-8}/s$) adopted by most AE monitoring experiments under triaxial compression (e.g. Goebel (2013); Goebel et al. (2012); Goebel et al. (2015); Goebel et al. (2013); Kwiatek et al. (2014b); Lei (2003); Lei et al. (2000a); Lei et al. (2003); Lei et al. (2000b); Lockner and Byerlee (1975); Lockner et al. (1991); Stanchits et al. (2009); Stanchits et al. (2006); Zang et al. (1998); Zang et al. (2000)). The axial forces and axial displacements are recorded by a 250 kN (1.25 kN accuracy) force transducer and a pair of embedded LVDTs (0.01 mm accuracy), respectively. The maximum adjustment rate of the axial piston valve is 1024 Hz/second. This rate allows an accurate adjustment of the axial force loading especially at the post-peak loading. Two folded plastic adhesive tapes with silicon grease lubrication between the folds are placed on the top and bottom of the specimens. Silicon grease lubrication is also provided between the platens and the tapes, and between the tapes and the specimen. This treatment is to reduce the end friction between the specimen and platens. In addition, it can significantly reduce the influences of outside noise. Before the start of the test, the specimen is pre-loaded with 3 kN axial force for 20 minutes. This pre-loading slowly expels the extra silicon grease out from the gaps to minimize influences on the subsequent displacement measurement. A summary about the experimental setups can be found in Table 3.1.

The AE sensors are in-situ relatively calibrated after they are glued onto the specimen surface. Network sensor calibration (Davi et al., 2013) and energized piezoelectric source (Xiong and Wong, 2017) are used for calibration. The details of the calibration process are presented in Appendix II. This calibration has two purposes. Firstly, it provides a location error estimation. Secondly, the first peaks of the received waveforms are used to calibrate the local/coupling effect of the sensors. For the tests on specimens containing a single pre-existing flaw, it is reported that an initial 3-D mean error of 4.2 mm, and an initial mean error of 1.9 mm in the thickness direction of the specimens within the central dash-line confined rectangular area in Figure 3.1(a) can be achieved (much detailed explanations can be found in Wong and Xiong (2018)). As similar to the calibration procedure of Wong and Xiong (2018), for the tests on specimens containing a pair of coplanar pre-existing flaws, an

initial position error of less than 2 mm can be achieved for AE source locations along the fault-forming-path, and overall the initial mean position error in the center area of the specimen is within 4.5 mm. Detailed information about the sensor array configuration and the positions of the calibration points has been presented in Figure 3.1 (b). Taking into account the aperture of the calibration sensor, the PICO sensor, the present estimation on the source location accuracy is conservative—lower source location error (high source location accuracy) could be achieved in the practice for point source locations. Taking into account the grain size and the sensor configuration, the source-to-sensor paths of the fault forming zone are approximately equal to or over 100 times the sources' characteristic sizes. This fact is beneficial for the reliability of the SiGMA moment tensor inversion, which will be described in Section 3.2.

In the beginning of the experiment, MTS loading system, AE monitoring system, and camcorder acquisition system are triggered simultaneously where maximum time lapse is 0.4s approximately among these systems. A photo of the systems used in the tests has been provided in Figure 3.2.

Figure 3.2 Assembly of the (1) acoustic emission system, (2) camcorder, (3) high-speed camera, (4) MTS loading frame, and (5) light sources, edited based on a same photo that used by Wong and Xiong (2018)

3.2 Data analyses methods

The data analyses for AE signals involved pre-analyses filtering, source location determination, moment tensor inversion, relative AE moment release rate estimation, and b-value estimation.

For the pre-analysis filtering, the individual AE signals have been filtered according to their pre-and-post-onset amplitude features, and their certainty level of the onset time which is determined by a conjugated Akaike's information criterion (Wong and Xiong, 2018). The mathematics expression of this pre-analysis filtering is expressed in equation (3.1)

$$\begin{cases} T_{AIC} > T_{threshold} \\ 10\sigma_{avg} > Amp \\ DD > 0.05 \end{cases} \quad (3.1)$$

where, T_{AIC} , $T_{threshold}$, σ_{avg} , “ Amp ”, and “ DD ” stand for the onset time determined by the Akaike Information Criterion (T_{AIC}), the time at the first threshold crossing ($T_{threshold}$), the average signal level of the selected section from the pre-onset time (σ_{avg}), the peak amplitude of the waveform (“ Amp ”), and the DD parameter (“ DD ”) based on a conjugated AIC model for estimating the accuracy of the auto-picked onset time (Carpinteri et al., 2012b), respectively. The number of sampling points for calculating the DD value, and the sampling points for calculating the average signal level of the selected section prior to the onset time are 50, and 10, respectively.

After the signal filtering, the onset time determined by AIC of the AE waveforms are used to seek source locations. Their corresponding first P-wave amplitudes are used to calculate the time-independent moment tensors of the sources. In the process of seeking source locations, the optimization function between the observed onset time and the calculated onset time (equation (3.2)) will be minimized.

$$\varepsilon = \frac{1}{n} \sum_{i=1}^n abs(T_{obs} - T_{cal})_i \quad (3.2)$$

where T_{obs} and T_{cal} are the observed and calculated sensor onset time, respectively.

Downhill simplex algorithm has been used for AE source location. The out-of-specimen source locations are discarded. As the algorithm iterates, the initial guess points of source location will shrink to a point where outputs the minimal residual (ε) between the observed time and calculated time.

SiGMA (3D) moment tensor inversion (Ohno and Ohtsu, 2010; Ohtsu, 1998) has been used in meso-scale AE event crack type classification. In this method, the relationship between the observed AE amplitudes and the source moment is expressed as equation (3.3),

$$A(x) = Cs \frac{R_e(t,r)}{R} r_p M_{pq} r_q \quad (3.3)$$

where $A(x)$ is the observed amplitude; Cs is the magnitude of the sensor response including material constants, which is obtained through in-situ sensor calibration (Appendix II); R is the distance from the source to the sensor; r_p and r_q are the directional cosine; and M_{pq} is the moment tensor of the source. $R_e(t,r)$ is the reflection coefficient which is expressed as equation (3.4) (Ohtsu, 1995),

$$R_e(t,r) = \frac{2k^2 a [k^2 - 2(1-a^2)]}{[k^2 - 2(1-a^2)]^2 + 4a(1-a^2)\sqrt{k^2 - 1 + a^2}} \quad (3.4)$$

where t represents the orientation vector of sensor sensitivity which is assumed to be the normal vector of a sensor; $k = v_p/v_s$ is the ratio of P-wave velocity and S-wave velocity; a is the scalar product of vectors r and t .

Once the moment tensor of an AE event is obtained, the eigen-values and eigen-vectors of the moment can be solved. The moment tensor decomposition procedure is accomplished by equation (3.5) (Ohtsu, 1995),

$$\begin{cases} \frac{e_1}{e_1} = X + Y + Z \\ \frac{e_2}{e_1} = 0 - 0.5Y + Z \\ \frac{e_3}{e_1} = -X - 0.5Y + Z \end{cases} \quad (3.5)$$

where e_1 , e_2 , and e_3 are the maximum, intermediate, and minimum eigen-values, respectively; X , Y , and Z are the shear component, deviatoric component, and hydrostatic component of the source moment, respectively. The cracking motion vector (l) and the normal vector of the crack surfaces (n) can be obtained by equation (3.6),

$$\begin{cases} \text{normalized}(e_1) = \text{normalized}(l + n) \\ \text{normalized}(e_2) = \text{normalized}(l \times n) \\ \text{normalized}(e_3) = \text{normalized}(l - n) \end{cases} \quad (3.6)$$

Because of the “open” pre-existing flaw, some first peaks are inevitably distorted if their source-to-sensor paths are intercepted by the flaw. Signals whose source-to-sensor paths have been truncated by the pre-existing flaw will not be used in this moment tensor inversion. A step of logic algorithm is implemented into the AE analysis program to judge whether the source-to-sensor path is intercepted by the pre-existing flaw (see Appendix III). Once a signal is found to be of this condition, it will be rejected from the moment tensor inversion of the corresponding source. The moment tensors of those sources having over 6 signals whose source-to-sensor paths have not been intercepted by the pre-existing flaw will be inverted.

The P-wave velocity and S-wave velocity required for this moment tensor inversion are measured by a PROCEQ ultrasonic tester together with the calibration process prior to each compression test (see Appendix IV).

The relative AE moment release is estimated as (equation (3.7)):

$$M_{relative} = \frac{1}{n} \sum_{i=1}^n \sqrt{(R_i C s_i A_i(x))^2} \quad (3.7)$$

where $M_{relative}$ is the relative AE moment of an AE event, n is the number of AE signals attributed to that relative AE moment estimation, R_i is length of the source-to-sensor path, $C s_i$ is relative calibration coefficient, and $A_i(x)$ is amplitude of the first peak.

The b-value is estimated by maximum likelihood method (equation (3.8)):

$$b = \log_{10} e / (\overline{M^*} - M_{min}^*) \quad (3.8)$$

where $\overline{M}^*$ and M_{min}^* are the average and minimal moment magnitudes, respectively, which are converted from $M^* = \frac{2}{3}[\log_{10} M_{relative} - C]$. For simplicity, C is equal to zero in the following data analysis

The signal filters, AIC onset time determination and auto-picking of the first peaks, source location, intercepted signal rejection, moment tensor inversion and decomposition procedure, relative moment magnitude estimation, and b-value calculation used in the present Chapter are implemented in a suite of in-house MATLAB programs.

Chapter 4 Multiscale interpretation of fracture processes in Carrara Marble specimen containing a single flaw under uniaxial compression

This Chapter primarily follows the main content of “Wong and Xiong (2018), Journal of Geophysical Research: Solid Earth, “A Method for Multiscale Interpretation of Fracture Processes in Carrara Marble Specimen Containing a Single Flaw Under Uniaxial Compression”.

4.1 Introduction

The experimental tests on rock and rock-like specimens containing a single pre-existing flaw have been extensively conducted by different researchers. However, its fracture process has not yet been fully understood. In most of these previous experimental studies on rock/rock-like specimens containing a single flaw (Huang et al., 1990; Ingraffea and Heuze, 1980; Lajtai, 1974; Li et al., 2005; Petit and Barquins, 1988), the major focuses were the identification of macro-scale crack patterns and cracking paths, and cracking type classifications. Only limited knowledge about the connection between the micro-scale crack accumulation and the macro-scale fracture process has been obtained.

The fracture process zone in rock is normally much larger than that in metals or fine-grained ceramics (Nolen-Hoeksema and Gordon, 1987). However, presently, the relationship between the micro-scale fracture accumulation and the macro-scale cracking in rock and rock-like materials remains unclear. A number of laboratory studies focusing on micro-scale observation of specimens containing pre-existing flaw(s) have been conducted. Zhao et al. (1993) conducted real-time SEM observation on a marble plate (20 mm × 10 mm × 2.5 mm) containing a 45-degree inclined pre-existing flaw (0.6 mm center hole diameter, 7.2 mm flaw length, aperture not mentioned) under loading. In their study, they concluded that the observed micro-cracks were mostly tensile in nature; cracks with detectable traces of shear slippage were very few. Wong and Einstein (2009b) conducted micro-observation on

specimens containing double pre-existing flaws. According to their observation, a series of en-echelon micro-fractures developed along the future fracture coalescing path between two pre-existing flaws prior to the macro-scale fracture coalescence. Each individual micro-fracture in that series of en-echelon fractures was generally parallel to the loading direction. Such orientation suggested that they were tensile fractures. Cheng et al. (2016) conducted micro-observation on specimens containing en-echelon artificially created pre-existing flaws by fluorescent dye impregnation method. According to their observation, the micro-crack density in the tensile stress zone was significantly higher than that of the shear stress zone throughout most of applied stress levels. Only at the stress very close to rock specimen failure, the micro-crack density in shear zone significantly increased. Among these research studies, the major difficulties to establish the link between micro-scale fracture process and macro-scale cracking by micro-scale observation are (1) the field of view was of limited size and scale, (2) the observations were discontinuously obtained in most cases and, (3) in most cases, the loading tests had to be paused half-way for conducting the observation. Regardless of the pre-existing flaw types (single, double, en-echelon), the possible explanation for the small number of shear slippages in micro-scale (or lower micro-crack density in shear stress zone) is that shear cracking can only appear in a comparatively very narrow time window which is very close to the ultimate macro-scale specimen failure. The scale-up process associated with the rapid expansion of fracture process zone into macro-scale cracking was still not comprehensively observed and studied in laboratory tests.

This Chapter of the thesis aims to extend the presently available experimental observations on the fracture process of specimens containing a single pre-existing flaw. The present study takes advantages of the combination of (1) 16 channel AE system, (2) camcorder and high-speed camera, (3) mechanical loading frame. The AE data, camcorder video recording, and loading force-displacement record are synchronized. In the meso-scale, the fracture process is analyzed by AE source location and moment tensor inversion techniques. In the macro-scale, the cracking types are classified based on the camcorder video recording and high-speed camera recording. By comparing camcorder video recording with AE source location and moment tensor inversion results, it is the first time the

continuous picture on the white patch extension (see the support document of the present Chapter for the detailed description of the white patch) and the accumulation-and-clustering of different types of cracks in meso-scale can be obtained in such type of test. The moment tensors of the AE sources provide insightful knowledge on the sub-scale fracture process. The rapid shifts on the sub-scale cracking types can help better distinguish much subtle and fundamental meso-scale changes in fracture process/scale-up stages than the traditional AE analysis solely based on AE hit rate, AE event rate, and energy release rate. The phenomena such as white patch initiation and widening, brightening dot appearance, wrapped section appearance (explanation/description of these phenomena can be found in the support document of the present Chapter), are the first time found to be attributed to specific meso-scale AE crack type changes. New understanding on the role of stress drop on the development of fracture process zone has also been obtained.

One of the major foci of this Chapter is to verify the observation capability of the proposed methods. The test results reveal that the AE source location closely matches the paths of white patches. Additionally, various new phenomena (possibly new stages) in the fracture process are observed. The distributions of the moment-frequency of AE sources also display distinctive features for different time sections. From rock engineering's perspective, the interest in laboratory tests on specimens containing a single pre-existing flaw is initiated by simulating the geometry of joints, flaws, or tectonic scale faults embedded in a rock mass. From geophysicists' perspective, recent effort has been made to bridge the gap between the AE produced during small-scale laboratory experiments and larger-scale man-made and natural earthquakes (Goodfellow and Young, 2014). The present experimental method together with the corresponding data analysis can enrich the understanding on both above-mentioned disciplines.

4.2 Experimental results of the individual observation systems

The experimental results are from the specimens containing a single pre-existing flaw (see Table 3.1(a)). The experimental results of optical observation system, the AE system, and the MTS mechanical test system will be presented separately in this section. The comparison of the results among these 3 systems will be discussed for each test in Section 4.3.

4.2.1 Optical observation results (macro-scale)

Optical recordings provided by the camcorder and the high-speed camera are used to characterize the macro-scale cracking behavior of the specimens. The crack classification follows Wong and Einstein (2009a), which contains three types of tensile crack, three types of shear crack and one type of mixed shear-tensile crack (Figure 4.1). In this classification, not only the crack inclination angle with the axial loading direction, but also the motions of the two crack surfaces at the cracking moment are used to characterize the crack type. The observation results of the present study are analyzed and listed in Table 4.1.

Figure 4.1. Crack type classification, re-drawn after Wong and Einstein (2009a)

Table 4.1 Macro-scale crack type classification

Flaw inclination angle (β)	Crack types						
	Type 1 tensile	Type 2 tensile	Type 3 tensile	Mixed tensile-shear	Type 1 shear	Type 2 shear	Type 3 shear
Close to 90		C*			C		
70	C	C*				C	
60	C	C*			C		
45	W.P.	C*	W.P.	C	C		
30	W.P.	C*	C		C		C

W.P. = White Patch developed; C = Crack of the respective type developed; * = First open crack.

The flaw inclination angle (β) is to the horizontal direction (refer to Figure 3.1(a)).

The above crack classification results are generally comparable with the results presented by Wong and Einstein (2009a). Some differences between them may be attributed to the subjectivity of distinguishing a crack opening from the formed white patches.

4.2.2 Mechanical results

The mechanical stress and strain versus time curves are plotted in Figures 4.2 (a) to (e). The stress is calculated from the axial force divided by the specimen's top/bottom area. The strain is calculated from axial displacement divided by the specimen height. In these Figures, all the specimens have a post-peak stage lasting from several minutes to almost twenty minutes. In several tests ($\beta = 70^\circ, 60^\circ, 45^\circ, 30^\circ$), the stress drops of the post-peak stages have one or several interceptions of local stress build-up or local stress-hold (the stress level is neither obviously increasing nor decreasing for a period). Tracing back to the video recordings, the timing of these stress drops after the stress-hold or local stress build-up are always accompanied by the formation of a new white patch, an obvious extension of the white patch, and/or the crack opening of some white patches.

Figure 4.2 Stress, strain vs time curves for (a) $\beta = 90^\circ$, (b) $\beta = 70^\circ$, (c) $\beta = 60^\circ$, (d) $\beta = 45^\circ$, and (e) $\beta = 30^\circ$. The flaw inclination angle β is measured from the horizontal direction as shown in Figure 3.1(a).

4.2.3 AE source location and moment tensor inversion results

The AE source location results are firstly plotted into histograms (bins of 500) against time (Figure 4.3). Later, the experimental time is separated into different time sections based

on the changes in these AE event histograms (changes from rising trend to falling trend, or falling trend to rising trend). The AE source locations and the moment tensor inversion results of different time sections are presented separately. The analysis is combined with the stress and strain versus time curves, and the camcorder recording. For instance, around the separating points of these time sections, the extension of white patches or macro-cracks opening, and the local stress drop or stress-holding, appear along some sequences. This will be discussed further in the next section. The division of these time sections is subjective to certain extent because of the bin number used in the histograms. However, this subjectivity is negligible as compared with the much longer test duration. The crack type classification is based on the moment tensor decomposition result. Relative AE moment is calculated directly from the moment tensors based on equation (4.1). This calculation was used for interpreting the seismic moment by Zhu and Ben-Zion (2013).

$$M = \sqrt{\frac{M_{ij}M_{ij}}{2}} \quad (4.1)$$

Figure 4.3 Histogram plots of the AE source location for all tests

The time sections are divided according to the histogram changes for each test and the corresponding number of source locations (in parentheses) are listed in Table 4.2. The sources for each time section and the corresponding cracking motions and cracking planes of the sources are presented separately in Figures 4.5 to 4.9. The presentation of the cracking motion and cracking normal (see the illustration in Figure 4.4(e)) followed the convention of Ohno and Ohtsu (2010). Figure 4.4 (a) to (c) illustrate the elements used to represent the

different crack types – tensile (blue), shear (red), and mixed-mode (green) crack, respectively. The selected classification thresholds are, $\frac{X}{X+Y+Z} > 0.6$ for the shear crack; $0.4 < \frac{X}{X+Y+Z} < 0.6$ for the mixed-mode crack; and $\frac{X}{X+Y+Z} < 0.4$ for the tensile crack, respectively (Ohtsu, 1995). The pre-existing flaws for all tests are presented along with the AE source locations and moment tensor inversion results as a solid line shown in Figure 4.4 (d). The definitions of crack normal and crack motion are presented in Figure 4.4 (e). The screenshots of the camcorder videos at the end points of the time sections, and the high-speed camera image(s) at the final cracking moment are supplemented below the source location pictures. The temporal evolutions of AE crack type ratios are calculated according to the AE crack type classification using the above-mentioned thresholds. AE crack type ratio is defined as the number of events of a certain crack type included by the moving averaging window (50 events in the present study) divided by the total event number included in that moving averaging window.

Figure 4.4. Illustration of 3 crack types presentations, (a) tensile crack, (b) shear crack, (c) mixed-mode crack, (d) pre-existing flaw (color figure online), (e) crack normal and crack motion

Table 4.2. Divided time sections and corresponding number of source locations (in parentheses)

β (°)	Section1	Section2	Section3	Section4	Section5	Section6	Section7
90	0-550s (675)	550-4300s (165)	4300-4565s (86)	4565-end (856)			
70	0-3430s (176)	3430-3530s (996)	3530-3615s (817)	3615-3665s (460)	3665-end (415)		
60	0-3070s (242)	3070-3370s (471)	3370-3420s (440)	3420-3470s (658)	3470-end (626)		
45	0-2650s (359)	2650-3025s (1050)	3025-3100s (442)	3100-3830s (174)	3830-4060s (160)	4060-4120s (231)	4120-end (169)
30	0-2650s (228)	2650-2740s (376)	2740-3040s (221)	3040-3190s (180)	3190-3550s (101)	3550-end (82)	

Figures 4.5 to 4.9 show the source location and moment tensor inversion results of each test, together with the corresponding video screenshots at the end of each time section. A preliminary comparison between the AE clustering results and the video screenshots reveals that the extension of the macro-scale cracks is normally accompanied by the formation of AE clusters. For the first fracture propagation (the first time when the fracture initiates and propagates towards the top and bottom specimen boundaries), the center lines of the AE clusters closely match the cracking paths/ white patches. After the propagating fracture reach the specimen boundaries, the AE source locations appear scattered for the later stages (time sections). A further discussion on source locations for each test will be provided in the following section. For the $\beta = 30^\circ$ test, one sensor prematurely detaches from the specimen. The signals obtained by this sensor (sensor 3) after its detachment are excluded from the source location analysis.

Figure 4.5 (Top) AE source locations and moment tensor inversion results of each time section. (Bottom) corresponding screenshots for $\beta = 90^\circ$ test

Figure 4.6 (Top) AE source locations and moment tensor inversion results of each time section. (Bottom) corresponding screenshots for $\beta = 70^\circ$ test

Figure 4.7 (Top) AE source locations and moment tensor inversion results of each time section. (Bottom) corresponding screenshots for $\beta = 60^\circ$ test

Figure 4.8 (Top) AE source locations and moment tensor inversion results of each time section. (Bottom) corresponding screenshots for $\beta = 45^\circ$ test

Figure 4.9 (Top) AE source locations and moment tensor inversion results of each time section. (Bottom) corresponding screenshots for $\beta = 30^\circ$ test

4.2.4 Temporal evolutions of AE crack type ratios and relative AE moment-frequency distributions

The temporal evolutions of crack type ratios of $\beta = 90^\circ$, 70° , 60° , 45° , and 30° tests are shown in Figures 4.10 (a), 4.11 (a), 4.12 (a), 4.13 (a), and 4.14 (a), respectively. These ratios are based on moving average of 50 events for better elucidating the changes along the testing time. Figures 4.10 (b), 4.11 (b), 4.12 (b), 4.13 (b), and 4.14 (b) present the relative AE moments of each test against time in a linear-log plot. The AE moment of each individual source is calculated by equation (4.1). In these Figures, the large moment events always occur at a time of high AE event concentration. The relative AE moment-frequency distributions of different time sections are shown in a log-log plot in Figures 4.10 (b), 4.11 (b), 4.12 (b), 4.13 (b), and 4.14 (b). For different flaw inclination angles, the evolutions of the

crack type ratios are different. The changes on the crack type ratio curves seem to be related to the appearance of the white patches, or/and white patch extension, or crack opening as observed in the camcorder video recordings. In sub-Figures (c) of Figures 4.10 to 4.14, the inclinations (slopes) of the curves for each time section are remarkably different. A brief discussion of this issue will be provided in Section 4.4.

Figure 4.10 (a) AE classified crack type, (b) relative AE moment, and (c) relative AE moment-frequency distribution for $\beta = 90^\circ$ test

Figure 4.11 (a) AE classified crack type, (b) relative AE moment, and (c) relative AE moment-frequency distribution for $\beta = 70^\circ$ test

Figure 4.12 (a) AE classified crack type, (b) relative AE moment, and (c) relative AE moment-frequency distribution for $\beta = 60^\circ$ test

Figure 4.13 (a) AE classified crack type, (b) relative AE moment, and (c) relative AE moment-frequency distribution for $\beta = 45^\circ$ test

Figure 4.14 (a) AE classified crack type, (b) relative AE moment, and (c) relative AE moment-frequency distribution for $\beta = 30^\circ$ test

4.3 Cross comparison among the results provided by different systems

Since the MTS loading system, the AE system, and the camcorder are triggered simultaneously, comparisons between the observed results from different systems are possible. In the following sub-sections, different sets of results from each individual test will be compared as follows. First, the three crack type ratios and the stress curve versus the same time line are plotted on the same graph. Second, the changing points on crack type ratios are identified. Third, the changing points on crack type ratios and the separation points between time sections are indicated and labelled in the plots. The changing points on crack type ratios (named as CTC_i for crack type changing point at *i* second in the following description) are indicated by star marks along the crack type ratio curves. Each crack type changing point has been labelled with a number, and the corresponding time of the crack type changing point has been indicated by a legend beside the plots. The time sections are indicated and labelled by “Si” (*i* stands for the number of time section) at the top of plots accompanied with vertical blue dashed-dotted lines separating these time sections (named as Sec *i-j* for the separation point between *i* and *j* time sections in the following description). Forth, check the camcorder video recordings for the corresponding time periods.

To avoid the influence of the time lapse between different systems, namely, the camcorder, the AE system, and the MTS loading system, the resolution for picking the changing points is selected to be 5 seconds. This selection is over 10 times the estimated time lapse between different systems (0.4 seconds). As such, the related phenomena on different systems can be correlated temporally. In most identified changing points, camcorder screenshots are provided for better illustration. The discussion and conclusions based on the experimental results in Section 3, and those cross comparisons in Section 4 will be presented in Section 5. In the following sub-sections, the phenomena of $\beta = 70^\circ$ test will be described in detail as an illustration of the cross-system comparison. The detailed descriptions on other tests are not provided due to the limitation of space here. The results of the cross-system comparison for all tests will be summarized in Table 4.3.

4.3.1 Comparison on $\beta = 70^\circ$ test

The AE source location and moment tensor inversion analysis of this test is divided into 5 time sections based on the AE event histogram (table 4.2). Because the remarkable (i) changes of AE crack type ratios, (ii) changes of AE histogram, (iii) stress non-linearity, (iv) white patch extension and crack opening all occur late during the entire course of loading, the plot from 3200s until the end is enlarged for a clearer illustration (Figure 4.15 (a)). The description and analysis below focus on the final stage of loading.

As observed in the camcorder recording, at crack type changing point 3290 s (will be referred to as CTC3290 thereafter, labelled as 1 in Figure 4.15 (a)), the white patches of horse tail trajectory (type II in Figure 3) initiate from the two flaw tips (Figure 4.15 (b)). The stress curve fluctuates slightly around and after CTC3290 (approximately from 3290s to 3330s, see Figure 4.15 (a)). This fluctuation is larger than the measurement error of the force transducer ($1.25 \text{ kN} \approx 0.5 \text{ MPa}$). However, the fluctuation range is small when compared with the contemporary axial stress. From CTC3290 to CTC3445 (labelled as 2 in Figure 4.15 (a)), the ratio of shear crack generally declines, while as observed in the camcorder recording, the white patches become longer (Figure 4.15 (b)). Just 15 seconds prior to CTC3445, the AE event histogram begins to rise at Sec 1-2 (vertical blue line between S1 and S2 in Figure 4.15 (a), see also in Table 4.2 and Figure 5 (b)). From CTC3445 to CTC3480 (labelled as 3 in Figure 4.15 (a)), the ratio of shear crack rises, while the white patches extend slightly, becoming wider and much longer (Figure 4.15 (b)). At CTC3480 (labelled as 3 in Figure 4.15 (a)), the length of the white patches becomes comparable to or longer than the length of the pre-existing flaw.

From CTC 3480 to CTC 3565 (labelled as 4 in Figure 4.15 (a)), the crack type ratios shift significantly. During this period, the white patches remarkably extend towards the upper and lower specimen boundaries at approximately 70° inclination (Figure 4.15 (b)). The first peak of AE event histogram (vertical blue line between S2 and S3 in Figure 4.15 (a), see also in Table 4.2 and Figure 5 (b)) is close to the mid-point between CTC3480 and CTC3565. The time of Sec 2-3 (vertical blue line between S2 and S3 in Figure 4.15 (a)) is coincident with

the peak of stress. From CTC 3565 to CTC 3595 (labelled as 5 in Figure 4.15 (a)), the ratio of shear crack declines again. At CTC3595, the white patches reach specimen boundaries (Figure 4.15 (b)), while an inflection point on the stress curve appears coincidentally at CTC3595.

From CTC3595 to CTC3605 (labelled as 6 in Figure 4.15 (a)) a short rise-and-drop for the ratio of shear crack occurs. At CTC3605, a new vertical white patch subtly appears at a distance away from the horse tail white patch of the upper part of the specimen (Figure 4.15 (b)). At the same time, the secondary tensile wing (type I in Figure 3) white patch also subtly appears at the upper part of the specimen.

From CTC3605 to CTC3640 (labelled as 7 in Figure 4.15 (a)), the ratio of shear crack rises again, while all the white patches become wider (Figure 4.15 (b)). Some sections of the white patches become wrapped inward or outward as shown in the screenshot at CTC3640 (Figure 4.15 (b)). Around 10 seconds after CTC3605, the AE event histogram begins to rise at Sec 3-4 (vertical blue line between S3 and S4 in Figure 4.15 (a), see also in Table 4.2 and Figure 5 (b)). The ratio of shear crack enters another abrupt phase again from CTC3640 to CTC3675 (labelled as 8 in Figure 4.15 (a)), while the screenshot at CTC 3675 is very similar to the screenshot at CTC3640 (Figure 4.15 (b)). Some brightening dots occur sparsely along the path of the white patches/cracks within this short period. The second peak of AE event histogram (Sec 4-5, vertical blue line between S4 and S5 in Figure 4.15 (a), see also in Table 4.2 and Figure 5 (b)) occurs between CTC3640 and CTC3675. Within this period, the stress firstly undergoes a sharp drop, which then becomes stable for a while and begins to build up again. The peak of this local stress build-up appears coincident with CTC3675 (Figure 4.15 (a)).

From CTC3675 to CTC3750 (labelled as 9 in Figure 4.15 (a)), as observed in the camcorder recording the frequency of brightening dots appearance firstly rises, and then decreases; wrapped sections gradually occur along the white patches and replace the brightening dots (can be partially revealed by Figure 4.15 (b)). The inflection point on the stress curve within this period (Figure 4.15 (a)) appears to be corresponding to the transition

point that the appearance of wrapped sections becomes the dominant phenomenon of the fracture processes instead of the appearance of brightening dots.

From CTC3750 to CTC3810 (labelled as 10 in Figure 4.15 (a)), as observed in the camcorder recording, some rock materials detach from some severely wrapped sections and the wrapped sections enlarge (Figure 4.15 (b)). Some wrapped sections begin to connect with each other. From CTC3810 to CTC3910 (labelled as 11 in Figure 4.15 (a)), the ratio of shear crack rises again, while no significant change in camcorder recording within this period is observed. As the test approaches the end, the ratio of shear crack declines again after CTC3910, showing a preferential development of tensile cracks prior to the final rupture.

Figure 4.15 $\beta = 70^\circ$ (a) Stress, and AE crack type ratios plot (only plotted from 3200s to end of the test). Changing points of AE crack type ratios are labelled as 1 – 11 in the plot. The i -th time sections (in Table 4.2), which are separated by vertical dashed-dotted lines, are labelled as S_i (blue letters) at the top of the plot. (b) camcorder screenshot (enlarged as necessary) at AE crack type changing points (labeled with its time of occurrence)

4.3.2 Comparison on $\beta = 90^\circ, 60^\circ, 45^\circ, 30^\circ$ tests

As stated in the previous part of this section, detailed description on $\beta = 90^\circ, 60^\circ, 45^\circ, 30^\circ$ tests will not be provided in the present Chapter due to the space limit. Only the corresponding Figures for cross comparison are presented below (Figures 4.16-4.19).

Figure 4.16 $\beta = 90^\circ$ (a) Stress, and AE crack type ratios plot (only plotted from 3000s to end of the test). Changing points of AE crack type ratios are labelled as 1 – 3 in the plot. The i -th time sections (in Table 4.2), which are separated by vertical dashed-dotted lines, are labelled as S_i (blue letters) at the top of the plot. (b) camcorder screenshot (enlarged as necessary) at AE crack type changing points (labeled with its time of occurrence)

Figure 4.17 $\beta = 60^\circ$ (a) Stress, and AE crack type ratios plot (only plotted from 2000s to end of the test for the top plot, and from 3250s to end of the test for the bottom enlarged plot). Changing points of AE crack type ratios are labelled as 1 – 15 in the plots. The i-th time sections (in Table 4.2), which are separated by vertical dashed-dotted lines, are labelled as S_i (blue letters) at the top of each plot. (b) camcorder screenshot (enlarged as necessary) at AE crack type changing points (labeled with its time of occurrence)

Figure 4.18 $\beta = 45^\circ$ (a) Stress, and AE crack type ratios plot (only plotted from 2000s to end of the test for the top plot, and from 2400s to 3400s of the test for the bottom left enlarged plot, and from 3900s to end of the test for the bottom right enlarged plot). Changing points of AE crack type ratios are labelled as 1 – 14 in the plots. The i -th time sections (in Table 4.2), which are separated by vertical dashed-dotted lines, are labelled as S_i (blue letters) at the top of each plot. (b) camcorder screenshot (enlarged as necessary) at AE crack type changing points (labeled with its time of occurrence)

Figure 4.19 $\beta = 30^\circ$ (a) Stress, and AE crack type ratios plot (only plotted from 2000s to end of the test for the top plot, and from 2600s to 3350s of the test for the bottom enlarged plot). Changing points of AE crack type ratios are labelled as 1 – 12 in the plots. The i-th time sections (in Table 4.2), which are separated by vertical dashed-dotted lines, are labelled as S_i (blue letters) at the top of each plot. (b) camcorder screenshot (enlarged as necessary) at AE crack type changing points (labeled with its time of occurrence)

Table 4.3 Comparison on $\beta = 90^\circ, 70^\circ, 60^\circ, 45^\circ, 30^\circ$ tests

Inclination angle β	Inc-W.P.	W.P. > Flaw	σ peak	1st R.B.	1st Abt phase	Other phenomena
90	$\uparrow$ CTC3920	CTC3920 $\downarrow$ 4425	CTC4460	Sec3/4-end, W.P. ext (sig) $\rightarrow$ final rupture, Sec3/4 AE rise (4565),		
70	$\uparrow$ CTC3290, H.T.	CTC3445 $\uparrow$ 3480	1 st (global) = Sec2/3 AE peak (3530), 2 nd = CTC3675	H.T.R.B. at $\downarrow$ CTC3595 = σ_{in} (De $\downarrow$)	CTC3480-3565, H.T. ext (sig, 70 $^\circ$),	$\downarrow$ CTC3605, T.W., New V.W.P. (sub)-away-H.T.; CTC3605 $\uparrow$ 3640, all W.P. wid, W.S.-on-H.T.; CTC3640-3675 (2 nd Abt phase), B-dots-on-H.T., CTC3675 = 2 nd σ peak; CTC3675 $\uparrow$ 3750, σ_{in} (De $\downarrow$) = W.S.»B-dots; CTC3750 $\downarrow$ 3810, Rock $\downarrow\downarrow$, W.S.-coa;
60	$\uparrow$ CTC2525, H.T.	CTC3215 $\uparrow$ 3315	CTC3315	H.T.R.B. at $\uparrow$ CTC3405	CTC3315-3385, H.T. ext (sig), Inc-T.W., B-dots-on-H.T., Sec2/3 AE peak (3370) = σ_{in} (Ac $\downarrow$), CTC3385 = σ_{in} (De $\downarrow$)	CTC2930 $\uparrow$ 3095 H.T.ext&wid; CTC3385 $\uparrow$ 3405 all W.P. wid, B-dot-mig-H.T.; CTC3405 $\downarrow$ 3430, lo-T.W.(sub), New P.W.P.(sub)-away-H.T.; CTC3430 $\uparrow$ 3440, T.W. and New P.W.P. wid (sig); CTC3440 $\downarrow$ 3460 $\uparrow$ 3480 (2 nd Abt phase), B-dots $\uparrow$, up-T.W.-con-New P.W.P., CTC3460 = σ_{in} (Ac $\downarrow$) = W.S.»B-dots, CTC3460 = σ_{in} (De $\downarrow$); CTC3480 $\downarrow$ 3490 $\uparrow$ 3495 $\downarrow$ 3515, W.S.-coa, Rock $\downarrow\downarrow$, T.W.R.B.;
45	$\downarrow$ CTC2130 T.W.(sub), H.T., A.W.	CTC2410 $\downarrow$ 2925, H.T.>flaw	1 st (global) = CTC2985 ; 2 nd = Sec4/5 AE rise (3830);	CTC2985-3045 (Abt phase), H.T. R.B. at CTC3045, Sec2/3 AE peak (3025) = σ_{in} (Ac $\downarrow$), CTC3045 = σ_{in} ($\downarrow\uparrow$)		CTC3045 $\downarrow$ 3085, B-dots-on-H.T.; CTC3215 $\downarrow$ 3380, W.S.»B-dots, CTC3215 = $\sigma\downarrow$ (small); CTC3380 $\uparrow$ 3925, Damaged zones appeared in corners, W.S.-coa, Rock $\downarrow\downarrow$, Sec4/5 AE rise (3830) = σ peak; CTC3925 $\downarrow$ 4055, cracks opened in macro-scale, CTC4055 = Sec5/6 AE rise = σ_{in} (Ac $\downarrow$); CTC4055 $\uparrow$ 4110 (2 nd Abt phase), W.S.s were fully opened from flaw to boundary, Damaged zones were much developed; Sec6/7 AE peak (4120) = σ_{in} (Ac $\downarrow$); CTC4135 $\uparrow$ 4165, $\sigma\downarrow$, Distances between two surfaces of the open cracks increased slowly; CTC4165 $\downarrow$ end, no dynamic rupture
30	T.W.(sub), H.T., A.W. appeared before the end of 2 nd loading stage	CTC2695 = σ peak, H.T. > flaw, A.W. > flaw	1 st = CTC2695 ; 2 nd (global) = CTC3175 ; 3 rd = CTC3620	CTC2805 $\uparrow$ 3070 , A.W.R.B., A.W.&H.T. wid	CTC2695-2765, A.W. ext (sig), CTC2695 = σ_{in} ($\uparrow\downarrow$), CTC2765 = σ_{in} ($\downarrow\uparrow$)	CTC3070 $\downarrow$ 3110, B-dots-on-H.T.&A.W.; Sec4/5(3190) $\uparrow$ 3275, B-dots $\uparrow$ (sig)-mig-A.W. CTC3175 = 2 nd σ peak; CTC3175-Sec4/5 (3190, 2 nd Abt phase), $\sigma\downarrow$ sharply; CTC3275 $\uparrow$ 3310, W.S.»B-dots; CTC3310 $\downarrow$ 3470, W.S.-coa & subsidiary B-dots-on-A.W.; CTC3620 = 3 rd σ peak, W.S.s were fully opened from flaw to boundary; CTC3620 $\uparrow$ 3680, $\sigma\downarrow$ sharply, opened sections on two A.W. enlarged significantly, up-H.T.R.B. at $\uparrow$ CTC3680;

“Inc-W.P.” = Incipient initiation of White Patch

“W.P. > Flaw” = the length of White Patch exceeds the length of the pre-existing Flaw

“ σ peak” = time of local stress peaks

“1st R.B.” = first White Patch reaches the specimen boundary

“Abt phase” = Abrupt changing phase in crack type ratio curves

“ $\uparrow$ CTC3920” = Shear crack ratio rises to the time of CTC3920

“CTC3920 $\downarrow$ 4425” = from CTC3920 to CTC4425, the shear crack ratio declines

“=” = the time of two phenomena on the two sides of the equal are coincident

“W.P. ext/wid (sig,70°) $\rightarrow$ final rupture” = White Patch extends/widens (significantly, at approximate 70 °inclination) and led to the final rupture

“Sec3/4 AE rise (4565)” = time section separation 3-4, the AE histogram begin to rise at (4565s)

“up/lo-T.W.(sub)/H.T./A.W.” = the White Patch of Tensile Wing(subtly)/Horse Tail/Anti-Wing appears at upper/lower part

“ σ_{in} (De/Ac $\downarrow$ / $\uparrow$ $\downarrow$)” = inflection point on the stress curve which is characterized as the start of (Deceleration/Acceleration of the overall stress decline trend)/ or which is characterized as the point (where stress changes from rise to drop).

“New V/P.W.P.(sub)-away-H.T.” = a New Vertical/Parallel White Patch (subtly) appears at a distance away from the Horse Tail White Patch

“W.S.-on-H.T.” = Wrapped Section appears on Horse Tail

“B-dots (spa) -on/mig-H.T.” = Brightening dots (sparsely appears) are on/migrating along Horse Tail

“W.S.»B-dots” = Wrapped Sections replace Brightening dots at the places of Brightening dots

“W.S.-coa” = Wrapped Sections are coalescing

“Rock $\downarrow\downarrow$ ” = Rock material detaches from some severely wrapped sections

“&” = and

“CTC3440 $\uparrow$ 3460 $\downarrow$ 3480 (2nd Abt phase)” = the shear crack type ratio rises from CTC3440 to CTC3460, and then declines from CTC3460 to CTC 3480, (characterized as the second abrupt phase with many fluctuations along the overall rising and declining trends)

“B-dots↑” = frequency of Brightening dots appearance increases

“up-T.W.-con-New P.W.P.” = Tensile Wing White Patch at the upper part connects to the
New Parallel White Patch

“ $\sigma\downarrow$ (small)” = a (small) stress drop

4.4 Discussion on the experimental result of single flaw tests

4.4.1 Mechanical stress drops, perturbations and inflection points on stress curves and corresponding meso-scale AE crack type changes

From the mechanical perspective, new evidence of the correlations between the accumulation of micro-meso-scale cracks and the macro-scale stress behavior (such as local stress peaks, sharp stress drops, the inflection points on stress curves, etc.) are found. In all 5 tests (Figures 4.15 (a), 4.16 (a), 4.17 (a), 4.18 (a), and 4.19 (a), and Table 4.3), the stress changes are coincident with AE crack type ratio changes and/or AE histogram changes (for instance, in $\beta = 70^\circ$ test, the time of first stress peak is coincident with the separation point between time section 2 and time section 3 (AE peak at 3530s), CTC3595 is coincident with a stress inflection point characterized as stress drop deceleration, and the second stress peak is coincident with CTC3675). As the changes in stress curves are believed to be the macro-scale phenomena caused by the sub-scale crack accumulations, this sequence further evidently suggests the close correlation between macro-scale stress changes and the shifting of sub-scale AE fracture mechanism.

Besides the major changes in stress curves, the proposed method is advantageous to the discovery of the subtle changes on stress and fracture process. Some subtle stress changes/perturbations, such as the stress perturbation around and after CTC3290 in $\beta = 70^\circ$ test (Figure 4.15 (a)), the small drop at CTC3215 in $\beta = 45^\circ$ test, etc., are also identified by the crack type changes. These small stress changes, which are much smaller than the major stress changes in the stress curves, indicate the transitions of plausible new stages in the fracture processes when they are characterized by AE crack type changes. For $\beta = 70^\circ$ test, CTC3290 suggests the decline of the influence of the pre-existing flaw, and the dominance of the initiated fracture in subsequent fracture extension. The physics of the fracture initiation from an open pre-existing flaw is obviously different from the fracture extension from the initiated fracture. For $\beta = 45^\circ$ test, brightening dots vividly appear before CTC3215, while this phenomenon diminishes and is replaced by the phenomenon of wrapped section

appearance after CTC3215. The physics of these two phenomena are different. However, without the aid of AE moment tensor analyses, these small changes in stress are most likely indiscernible.

Tracing back to the camcorder recordings at the time of the inflection points on stress curves (which are identified by the aid of meso-scale AE crack type change points), the following two features are observed. (i) The plausible acceleration/deceleration transitions of the white patch extensions/widening are all coincident with some crack type changing points in all 5 tests; (ii) Some much subtle changes in the white patches, such as the appearance/disappearance of the brightening dots, the appearance of wrapped sections, detachment of rock materials from the wrapped sections, etc. are also coincident with some crack type changing points in all 5 tests. These subtle changes will in most cases leave no trace on the stress curves and AE event histograms.

4.4.2 Cross comparison between optical observable changes on fracture process and meso-scale AE crack type changes

The correlation between the meso-scale AE shear crack inclination and the white patch extension/development possibly offers a new understanding on the white patch appearance and the fracture process. In previous literature, white patch is regarded as a direct optical phenomenon on the fracture process zone (Wong and Einstein, 2009b). The understanding on the mechanism of the micro-scale fracture accumulation in the white patch development process is limited. According to the present experimental results, white patches are obviously widened in shear crack rising periods for $\beta = 90^\circ$, 70° , 60° tests (the period from CTC4460 to the separation between time section 3 and time section 4 (AE rise at 4565s) for $\beta = 90^\circ$; the length of white patch exceeds the length of pre-existing flaw in the ratio-of-shear-crack-rising period from CTC3445 to CTC3480 for $\beta = 70^\circ$; the length of white patch exceeds the length of pre-existing flaw in the ratio-of-shear-crack-rising period from CTC3215 to CTC3315 for

$\beta = 60^\circ$). The new white patches formed in $\beta = 70^\circ$, 60° tests also become obviously widened in shear crack rising periods.

For $\beta = 70^\circ$, the new white patch incipiently initiates within the period from CTC3595 to CTC3605, where the ratio of shear crack firstly rises and then declines; the new white patch obviously develops within the period from CTC3605 to CTC3640, where the ratio of shear crack is in a rising trend.

For $\beta = 60^\circ$ test, new white patch incipiently initiates within the period from CTC3405 to CTC3430, where the ratio of shear crack is in a declining trend; the new white patch obviously develops within the period from CTC3430 to CTC3440, where the ratio of shear crack is in a rising trend.

These phenomena suggest that the widening of white patch may be accompanied by the increase of shear crack ratio in micro-scale. In previous literature, it is known that the propagation of shear crack may consist of multiple secondary cracks along its path (Petit and Barquins, 1988). The present experimental results provide further insights on the process of white patch development. As shear cracks will have more subsidiary cracks along their path, thus having wider process zone. The increase of shear crack components in micro-scale may lead to the macro-scale white patch widening. For the new white patches appeared in $\beta = 70^\circ$, 60° tests, regardless of the inclination angles, the nature of these white patches is a combination of tensile cracks and shear cracks in the micro-scale.

For $\beta = 45^\circ$, 30° tests, the white patch becomes longer than the pre-existing flaw within the periods when the shear crack ratio declines (from CTC2410 to CTC2925 for $\beta = 45^\circ$ test, and from CTC2130 to CTC2695 for $\beta = 30^\circ$ test). However, the camcorder recording of these two tests reveals that, for $\beta = 45^\circ$ test the horse tail propagation direction has curved towards the vertical from CTC2410 to CTC2925; and for $\beta = 30^\circ$ test the dominant fracture propagation is anti-wing white patches, whose macro-scale cracking is interpreted as tensile. These two phenomena show the agreement between macro-scale optical observation and the micro-scale AE moment tensor interpretation.

For $\beta = 45^\circ$ test, the agreement on micro-scale moment tensor interpretation and macro-scale phenomena is also observed after the cracks become fully opened. In that test, from CTC4135 to CTC4165, the distances between two surfaces of the open cracks increase slowly, while the ratio of micro-scale shear crack rises in that period. The stress drop in that period is much slower than that in its previous period. This phenomenon can be explained by the following reason. As the macro-scale crack opens, the specimen is split into two major rock columns supporting the axial loading individually. The ratio of micro-scale shear crack will rise within these two rock columns instead of the tensile opening along the opened macro-scale tensile crack.

In contrast with the previous macro-scale interpretations based on the high-speed video examination (Wong and Einstein, 2009a), which classified a crack into shear or tensile mostly by observing its rupture dynamics, the micro-scale interpretation suggests the existence of both micro-scale shear and tensile components during the formation of a macro-scale crack. However, the micro-scale tensile components are in rising trends during the crack formation which are interpreted as tensile in macro-scale. Meanwhile, for the cracks which are interpreted as mixed mode or shear in macro-scale, the micro-scale shear components are in rising trends during the crack formation.

One interesting issue is that the SiGMA moment tensor inversion has also been applied in concrete tests (Ohtsu et al., 2007) for identifying the different meso-scale crack mechanisms. For concrete, different crack mechanisms can also be identified by AE parametric analysis (Aggelis, 2011). According to Ohtsu et al. (2007), the macro-crack in concrete is also found to consist of different meso-scale crack components; and Ohtsu et al. (2007) attribute the cause of different meso-scale crack components to the zigzag cracking path. However, one must notice that, the physics of the different crack mechanisms in concrete is distinctively different from those in rocks.

4.4.3 New phenomena observed under the aid of multi-scale comparison

The brightening dots and wrapped sections begin to appear after the first stress drop and the white patches have reached the specimen boundary (the period from CTC3315 to CTC3385 of $\beta = 60^\circ$ test is the only exception, while even for that test, the frequency of brightening dots appearance after the white patch has reached the specimen boundary is obviously higher than the frequency of brightening dots appearance before the white patch reaches boundary), where the AE event activities remain active. The transition times from solely white patches extension to the appearance of these phenomena along the formed white patches/cracks are coincident with certain crack type changes. This correlation suggests new stages in the fracture process. Previous literature seldom reports the phenomenon of brightening dots. It is believed that a necessary condition for the appearance of such local brightening grain is the large displacement along the two fracture surfaces. Under this condition, mineral grains will be greatly crushed, thus enhancing grain splitting. Some reflective granular facets will be exposed towards the observer (camcorder), which give a shiny appearance in the loading process. This phenomenon suggests a transition of the physics within the fracture process zone. Literature of loading tests in Carrara Marble (Cheng, 2015; Cheng and Wong, 2018; Cheng et al., 2016) reported that the intergranular cracks (grain de-bonding along grain boundaries) dominate at early loading stages; while the percentage of transgranular cracks rises only at later loading stages. It is reasonable to suggest that, the thin white patch extension is primarily dominated by grain de-bonding. Meanwhile, as the displacement along two fracture surfaces reaches a sufficiently high level, granular crushing will replace the grain de-bonding as the dominant mechanism for fracture process. Later, in all tests, the wrapped sections occur along the white patch (fracture process zone) after the appearance of brightening dots. It also suggests a transition of grain crushing to a larger scale cracking process, which is characterized by the rock fragment detachment from the white patch/crack paths.

4.4.4 New understanding on the role of stress drop (stress release) period in the development of fracture process zone

The AE source location and moment tensor inversion technique have been successfully used to characterize the extension of fracture process zones (Carvalho and Labuz, 2002; Li and Einstein, 2017; Zang et al., 1996; Zang et al., 1998; Zang et al., 2000; Zietlow and Labuz, 1998). The present experimental observation combining optical observation and AE moment tensor interpretation suggests that besides the forward fracture propagation, much more complex fracture processes may continue to operate within the fracture process zones.

The majorities of the AE events in the clusters of different tests (also corresponding to the peaks in AE event histograms) occur in the stress drop periods (Labeled as Sec i - j in Figures 4.15 (a), 4.16 (a), 4.17 (a), 4.18 (a), and 4.19 (a)). In these periods, substantial observable extension/widening of the white patches occur. This phenomenon manifests the continual development of fracture process zone in the stress drop period, whereas previous research may have failed to observe this once the applied force was designed to be monotonically increasing in their loading procedure or a very high displacement rate was designed. This phenomenon also further evidences the existence of the critical thresholds for the crack coalescence at the sub-scales. Similar threshold concepts had been reported in literature. For intact rock core sample, there was a threshold between stable/unstable micro-crack growth (Hoek and Martin, 2014). For the fracture coalescence test, thresholds between stable micro-crack growth, micro-crack coalescence, and macro-crack initiation were proposed by Moradian et al. (2015). These two kinds of thresholds (for intact rock core, or for specimens containing double pre-existing flaws) were both suggested based on the identification of the change of AE hit rate or the combination of changes in AE hit rate and energy release rate. Additionally, in the present study, the stress drops and the white patch extensions are closely accompanied by the changes in crack type ratio curves. This phenomenon suggests that the changes in crack type ratio curves may also be useful for identifying these sub-scale thresholds. In addition, the certain crack type changes before stress drops are also influenced by the β angle.

4.4.5 Implication of limitations on AE source location analysis

Comparing the camcorder video recordings with the AE source location results, the first white patch is observed to develop well before the appearance of any AE clusters. The only exception is $\beta = 30^\circ$ test, where a small cluster of AE sources occurs when the first white patch appears. This phenomenon supports the speculation that some micro-scale cracking events have not been picked up by the AE array. The AE clusters and white patch paths match closely before the white patches reach the specimen boundaries in all 5 tests (Figures 4.5 to 4.9). These matchings gradually disappear after the first white patches reach the specimen boundaries and become open. Afterwards, the AE source locations become scattered. It is expectable that after the major cracks have developed, the micro-scale crack development may migrate to the remaining parts of the specimens as these parts will be under greater stress after the first white patches/cracks have developed. Another possible explanation to this scattered AE source location may be the influences of the fracture formation and opening on the accuracy of AE source locations. This speculation is coincident with the fact that the initial error estimations reported in research on intact samples are smaller than that of research on pre-flawed samples. Generally, larger initial error estimations for specimens containing pre-existing natural fault (Thompson et al., 2009) and saw-cut fault (McLaskey et al., 2014) were made as compared with those (initial error estimation) for intact rock specimens (Graham et al., 2010; Lockner et al., 1991; Stanchits et al., 2009; Zang et al., 1996; Zang et al., 1998; Zang et al., 2000). In the intact rock specimens, error estimations smaller than 3 mm could be achieved, while much larger error estimations were expected for the tests on specimens containing natural/saw-cut pre-existing flaws.

4.4.6 Issues on the selection of meso-scale AE crack type thresholds

The presently adopted AE crack type classification thresholds are, $\frac{x}{x+y+z} > 0.6$ for shear crack, $0.4 < \frac{x}{x+y+z} < 0.6$ for mixed mode crack, and $\frac{x}{x+y+z} < 0.4$ for tensile crack. The selection of the thresholds in classifying the crack types is subjective to some extent. For instance, Charalampidou et al. (2014) discussed the influence of shifting the thresholds. Different values of thresholds were also proposed by Ohtsu (1991, 1995). However, because the ratios of mixed mode cracks are comparatively small, the influence of shifting the thresholds will not be significant. Moreover, different selections will not affect the time of the changing points on the crack type ratio curves. In the initial loading stages, the crack type ratio curves are perturbed much greater than in the following stages. This may be attributed to two reasons. First, the different loading rates will have influenced the source feature at the initial loading stages. Second, the small AE event numbers in initial stages exaggerate the random perturbation effect. However, the in-depth investigation of loading rate influence is out of the scope of the present Chapter.

4.4.7 Moment-frequency distribution of relative AE moment

Among the results of relative AE moment-frequency distributions, the distribution appears to satisfy a log-log relationship. This is understandable under the rationale of Gutenberg-Richter (G-R) law considering that the moment can be converted into moment magnitude by $\frac{2}{3}[\log_{10} M_{AE} - C]$, where C is a constant which does not affect the shape of curves if one considers that the M_{AE} are relative values.

Kwiatek et al. (2014b) used a different method to calculate the moment magnitude for the laboratory scale obtained AE moments. In their calculation, the AE moment magnitude was calculated as,

$$M_{AE} = \log_{10} \left(\frac{1}{n} \sum_{i=1}^n (A_i R_i)^2 \right)^{0.5}$$

where A_i and R_i were the first P-wave amplitudes and source to sensor distances.

Since in the present study, the AE moment-frequency displays a linear relationship in the log-log coordinate, and both the calculation of the present study and the above equation are based on the first P-wave amplitude, the result of the above calculation would also likely produce a suitable AE moment magnitude-frequency relationship under the rationale of the G-R law. Other estimations of the AE moment magnitude also exist, for instance, in Zang et al. (1998),

$$M_{AE} = \log_{10} \left(\frac{1}{n} \sum_{i=1}^n \left(A_{imax} \frac{R_i}{10} \right)^2 \right)^{0.5}$$

The above was used for estimating the amplitude of focal magnitude. To the best of the authors' knowledge, there is no decisive conclusion of which calculation gives the best estimation. Some researchers checked the open source seismic data by statistical methods (Costa et al., 2016; Tsai et al., 2015), and argued that the favor of simplicity of the G-R law may suffer the problem of information loss and the Zipf-Mandelbrot distribution may potentially be a better summary for the earthquake magnitude-frequency distribution.

The truncations or turning angles of the relative AE moment-frequency curves may be attributed to two factors. First, in the small AE moment domain, some micro-scale AE cannot be registered by the system. In Cheng (2015) observation of granular scale micro-cracks on specimens containing en-echelon flaws, the results were presented in terms of micro-crack densities of shear stress zone and tensile stress zone. In the present study, the crack type ratio for 0% to 90% stress range is not comparable with Cheng's (2015) micro-crack densities in shear stress zone and tensile stress zone. Although the tests of Cheng (2015) were also conducted in prismatic Carrara Marble specimens, the expected similarity between the ratios of AE micro-crack types and the micro-crack densities in the shear stress zone and tensile stress zone under fluorescent dye observation is not observed. Second, for the large AE

moment domain, as the micro-meso-scale fractures are scaled up by coalescing and connecting neighboring fractures, the scale of the source may become comparable with the scale of the source-to-sensor paths. This fact undermines the theoretical foundation of laboratory scale AE source location and moment tensor inversion. Therefore, at both the ultra-small domain and ultra-large domain, the relative AE moment-frequency curves always have turning/truncated points in the log-log plots.

Many questions still remain unanswered in the laboratory scale observed relative AE moments. The above-mentioned factors suggest the necessity of further research and discussion on the laboratory scale AE activities regarding the G-R law. However, a thorough discussion of this issue exceeds the scope of the present Chapter.

4.5 Conclusions on experiments containing single pre-existing flaw

The present Chapter presents a method of multi-scale multi-system observation and interpretation on the fracture process on specimens containing a single pre-existing flaw. The results manifest its capability to reveal the new phenomena in the fracture process of uniaxial compression tests on specimens containing a single flaw. Comparing with the previous research, the major discoveries and new understanding on the fracture process on specimens containing a single pre-existing flaw can be summarized in follow.

In the aspect of mechanical analysis, in addition to the major stress drops, the proposed method successfully identifies the subtle stress perturbations and inflection points on stress curves through the aid of coincident substantial meso-scale AE crack type ratio change. These subtle changes used to be neglected if without the aid of sub-scale AE crack type information.

The correlation between macro-meso-scale interpretations on the crack type can be summarized in two aspects. In $\beta = 90^\circ, 70^\circ, 60^\circ$ tests, the prominent widening and extension of the white patches occur in the meso-scale AE shear crack rising period; in $\beta = 45^\circ, 30^\circ$ tests, the prominent extension of the white patches occur in the meso-scale AE shear crack declining period. In macro-scale, the cracks of $\beta = 90^\circ, 70^\circ, 60^\circ$ tests are shear or mixed mode; the cracks in $\beta = 45^\circ, 30^\circ$ tests are tensile. In meso-scale, shear, tensile, and mixed mode cracks are all present in the development process of fractures regardless these fractures are interpreted as shear, tensile, or mixed mode in macro-scale. However, the micro-scale tensile components are in rising trends during the formation of macro-cracks which are interpreted as tensile in macro-scale. Meanwhile for the cracks which are interpreted as mixed mode or shear in macro-scale, the micro-scale shear components are in rising trends in the formation of such cracks.

The coincidence of certain meso-scale AE crack type changes and the phenomena of brightening dot migration, and the subsequent appearance of wrapped sections appear to be new stages which should be included in the fracture process. However, as they occur in the domain after the first stress drop, they are not easily picked up in previous research.

According to the AE histograms on the stress drop period, the stress drop period may play a more important role in the fracture process as compared with previous understanding. In previous studies on the fracture process of specimens containing a single pre-existing flaw, this continual development of fracture process zone in the stress drop period, whereas previous research may have failed to observe this once the applied force was designed to be monotonically increasing in their loading procedure or a very high displacement rate was designed.

The scattering of AE source locations after the first white patches have reached the specimen boundary suggests a shift of stress concentration to the remaining parts of the specimens after the white patches have reached the specimen boundary. Meanwhile, such scattering may also be attributed to the recently formed fracture which affect the accuracy of source location.

The moment-frequency distribution of the AE moment obtained in the present study displays a log-log relationship, which is understandable under the rationale of Gutenberg-Richter (G-R) law considering that the moment can be converted into moment magnitude by $\frac{2}{3}[\log_{10} M_{AE} - C]$.

4.6 Support documents for experiments on specimens containing single flaw—white patch, brightening dots, and wrapped sections

White patch refers to the development of whitish phenomenon associated with the fracture process zone on the specimen surface. This term has been thoroughly used in previous research focusing on the fracture process in Carrara Marble specimens (i.e. Bruno (2016); Cheng (2015); Cheng and Wong (2018); Cheng et al. (2016) Moradian et al. (2015) et al., 2015; Wong and Einstein (2009a, 2009b)). According to the micro-observation (SEM) (Wong and Einstein, 2009b), the white patches are associated with the extensive development of micro-cracks in the fracture process zone. An example of this whitish phenomenon is shown in Figure 4.20(a).

The phenomena of brightening dots and wrapped section are illustrated in Figure 4.20(b) and 4.20(c), respectively. In Figure 4.20(b), several large brightening dots appeared along the white patches (fracture process zones) are indicated by the red arrows. In the later fracture process, more brightening dots will appear along the fractures. The brightening dots at some places will disappear while almost at the same time new brightening dots will appear at other places. The brightening dots thus appear to migrate along the fractures. In Figure 4.20(c), the red ellipse encloses a wrapped section which has partially opened. The two lower green circles enclose two sections with severe tortuosity. In the later fracture process, the fracture sections at these two places will conspicuously wrap inward or outward. This tortuosity may be related to some higher level of stress concentration as the open sections of the fracture in most of time firstly appear at these locations. As the fracture process continues, the wrapped sections spread out along the fractures, connecting to each other one by one, and finally forming a continuous open macro-scale fracture.

Figure 4.20 Illustration of (a) white patch, (b) brightening dots, and (c) wrapped sections

Chapter 5 Stick-slip, fracture creation, and laboratory-scale instabilities within a progressive shear-sliding failure

This Chapter primarily follows the main content of “Xiong and Lin (under preparation), Laboratory-scale instabilities within a progressive shear-sliding failure”.

5.1 Introduction

Stick-slip, one type of mechanical instabilities in the laboratory scale rock mechanics experiments, provides a fundamental assistance to improve understanding of the physical processes during an earthquake (Brace and Byerlee, 1966; Thompson et al., 2009). One of the methods to induce a laboratory stick-slip is the shear-type sliding along a plane of shear stress, which can be achieved by tri-axial compression on core specimens (Goebel et al., 2015; Goebel et al., 2013; Kwiitek et al., 2014b; Thompson et al., 2005, 2009). They include the healed failure plane (Charalampidou et al., 2014; Lei et al., 2003; Lei et al., 2004), the smooth faulted plane (sawcut through plane) (Thompson et al., 2005), and the “natural” fault plane by sawcut notches (Goebel et al., 2012; Goebel et al., 2015) as well as AE feedback control (Lockner et al., 1991; Thompson et al., 2009). The observed phenomena in these stick-slip experiments, including the rise of acoustic emission (AE) rate and the drop of b-value, have been reported as evidences of a good analogue to tectonic-scale earthquakes, in particular when the slips are approached in the experiments (Goebel et al., 2013; Thompson et al., 2009).

However, there are fundamental differences between those stick-slip experiments, although they look similar. For example, the AE phenomena of the stick-slips in the sawcut plane (Goebel, 2013; Thompson et al., 2005) are distinctively different from the AE phenomena in the quasi-nucleation to slip-rupture process along the failure plane created from an intact rock material (Lockner et al., 1991; Thompson et al., 2009). The differences are the consequences from the different physical processes between the sawcut plane and the “naturally” faulted plane (Thompson et al., 2009). In particular, when the fault is induced

from an intact rock material, there must be a transition between the creation of fault from an intact rock material and the actual fault slip (e.g. Goebel et al. (2012); Goebel et al. (2015); Lockner et al. (1991); Thompson et al. (2009)). However, fault creation and fault slip release energy during the experiment, so that both can induce mechanical instabilities in the laboratory. As a result, it is highly possible to regard them as stick-slips, if there are no more decisive evidences to distinguish the fault creation from its following slip. More importantly, for triaxial experiments, one of the limitations is the difficulty to have direct optical measurements on specimen surface. Without the help of optical information, e.g., direct observation of the evolution of fault plane, only AE and mechanical phenomena cannot provide decisive evidences to identify fault creation and its slip. Thus, very little knowledge about this transition is available in the literature currently.

In the laboratory, the induced “natural” fault from an intact rock material inherently represents a different but very interesting laboratory analogue of a field scale fault, as compared to the sawcut fault, which results in a great interest for seismic research to understand mechanical instabilities during the fault processes. Thus, this study selected uniaxial compression experiment to investigate the mechanical instabilities caused by a induced fault, because (i) uniaxial compression can be used to generate a shear-sliding failure (i.e., creation of a fault) along two coplanar pre-existing flaws on a prismatic specimen (Nguyen et al., 2011; Shen et al., 1995), (ii) uniaxial compression has a convenient application of optical and AE observations, which enables the experiment to provide more detailed optical information about the mechanical instabilities including the transition between fault creation and slip. It needs to note that the shear-sliding failure from uniaxial compression has long been regarded as a type of laboratory analogue to field scale shear failure. However, only very recently complex AE phenomena and optical observations of fracture process were reported for uniaxial compression on pre-flawed prismatic specimens when the load passed the peak (Wong and Xiong, 2018).

In the study, three successive mechanical instabilities have been generated in a progressive shear-sliding failure under uniaxial compression. With these instabilities as a temporal sequence, the fault “naturally” develops in a spatial procedure that forms along two

artificial coplanar pre-existing flaws step by step. Note that mechanical instability is a phenomenon, i.e., it observes the fast mechanical stress drops and the corresponding rise-and-drop circles of AE activities periodically in the experiment. Thus, AE observations from these instabilities all display strong periodical features over these instabilities including periodical changes of AE activities, ratios of AE crack types, and b-values. These phenomena are similar to laboratory stick-slip experiments (Goebel et al., 2012; Goebel et al., 2015; Kwiatek et al., 2014b; Thompson et al., 2009), which clearly demonstrates the challenges to identify the fault creation from its slip.

However, detailed analysis based on the combination of optical and AE observations present a different picture. There are two groups based on the optical observations, one is fault development including fault initiation, its widening, and macro-scale crack and gouge powder occurrence during the first and second instabilities; the other is fault slip because frictional shear-sliding movements along a gouge filled fault have been clearly captured by the high-speed video during the third instability. Interestingly, the different features also can be found for fault creation and its slip from careful AE analyses, so that they can be separated into fault development and fault slip as well. In one word, this study identifies creation of a macro-scale fracture (i.e., the fault) on intact rock material from the fault slip in three mechanical instabilities, which helps to improve the understanding of the analogue relationship between laboratory scale and tectonic scale faults, and the mechanism of fault slip as well.

5.2 Periodical features of AE activities during the mechanical instabilities

The experimental results presented in this Chapter are from specimen 60-1 (see Table 3.1(a)). Based on these experimental results, a series of parameters are presented in Figure 5.1(a-c) to demonstrate their changes with respect to the loading time during the mechanical instabilities, including the axial stress, AE event histogram, AE moment release rate, b-value, and crack type ratios. For the convenience of analyses, only the activities with respect to loading time (i.e., 3800 - 4400s) are presented, because they already cover all instabilities and the corresponding non-linear stress behaviors as well.

One thing should be mentioned is that a picture displaying the whole testing time may induce great inconvenience for the data analyses and interpretation. It is because, (i) first, one of the primary foci of the thesis is the phenomena in the post-peak domain; (ii) second, in previous Chapter (Chapter 4), it is clear that to present the whole testing time will also involve the information of the first two fast loading stages, which will occupy a great span of the plots; and (iii) third, to present the whole testing time will condense the key information in the post-peak domain into great concentration and will induce difficulties in displaying and indicating the post-peak phenomena. In test 60-1, no much information in the testing time before 3800s is necessary to be presented. Therefore, it is proper to only present the plots within the loading time from 3800s to 4400s. To present the whole testing time in one plot will make the plot appear as the plots in Figures 4.2 and 4.3. This approach of Figure presentation even has not been used in the following analyses and illustrations of the post-peak phenomena in Chapter 4, i.e. from Figure 4.15 to Figure 4.19.

In the study, a mechanical instability is identified temporally by AE event activities, i.e., it starts when amounts of AE event start to increase, and ends when amounts of AE event drop to a minimum value in an AE activity cycle. The reason is that the period characterized by AE event activities covers: (i) the fast stress drop that is the most important feature of a laboratory stick-slip experiment; (ii) the periodical strain energy release that is well accepted

as the evidence of laboratory scale analogue to field scale periodical seismology activities. Note that the mechanical instability can be clearly identified from AE even histogram, such that its beginning is when the histogram begins to rise, and its end is when the histogram drops to the valley. Figure 5.1(a) clearly demonstrates three individual mechanical instabilities.

In Figure 5.1(a), a correlation is clearly observed for three peaks of AE event histogram and AE moment release and the onsets of fast stress drops for three mechanical instabilities. In other words, when the fast stress drops initiates with respect to the instability, the AE events numbers and AE moment release also immediately start to reduce. Note that a small stress drop is also identified with an AE activity circle before the peak, which is believed as a preparation for the following instabilities. The periodical changes in b-value have been presented in Figure 5.1(b). This b-value curve is obtained based on a moving window of 200 events (standard error $\approx \frac{b}{\sqrt{200}}$ according to Lei et al. (2000b) and Lei (2003)). Similarly, when the fast stress drop initiates for corresponding instability, the drastic drops of b-value are also observed. Interestingly, the b-value will drop to a minimum value within the range of 0.9~1 for corresponding instability, which is a typical value for the seismic active regions (Shearer, 2009). For first and second instabilities, the b-value slowly recovers after the stress drop. In particular, after first instability, the b-value almost recovers to its previous value, i.e., 1.6 approximately, just before the second fast stress drop. For the third instability, the b-value only has a small recovery. The differences of the b-value changes between the first two and third instabilities suggest different physical processes, because from the general perspective the changes of b-value indicate a systematical smoothing of the fault strength distribution in its drop and the re-adjustment of stresses around along-fault asperities (Lei, 2003). In addition, it appears that the largest differences in b-values during the first and second instabilities are proportional to the magnitudes of their fast stress drops. However, this proportional relationship does not maintain in the third instability. This phenomenon also provides a support for the different physical processes in three instabilities.

Figure 5.1. (a) AE event histogram, relative AE moment release rate, and axial stress vs. the loading time, where the three mechanical instabilities are clearly demonstrated in the AE activities; (b) b-value and axial stress vs. the loading time; (c) AE crack type ratios, and axial stress vs. the loading time, where the ratios of different AE crack types are represented by different lines (see shear crack type as red dash line; tensile crack type as blue dot line; mixed-mode crack type as green plus line).

The ratios of meso-scale AE crack types also display the periodical features during three mechanical instabilities, as shown in Figure 5.1(c). Essentially, the changes on AE crack types are the consequences of the changes among AE moment tensor components, which are believed to be related to the shear-enhanced compaction or extension in the seismic source after each fast slip (Kwiatk et al., 2014b).

For better illustration, the enlarged figures for the ratios are presented in Figure 5.2, with respect to the small stress drop before the peak and three mechanical instabilities. All those

curves are obtained by a moving window of 50 event (Wong and Xiong, 2018). Before the instabilities, AE events of shear crack type occupies approximately 80% of total AE events, and even after these instabilities, the ratio of shear AE crack type still maintain the value of about 50%. Thus, detail information about the ratio of shear AE crack type is presented in Figure 5.2(b-d) for periodical features, i.e., the cycle of drop-rise-and-drops during three instabilities. These features are: (i) the first drop in the ratio of shear AE crack type begins a little earlier (i.e., 20-30s) before the global stress curve starts to change; (ii) when the global stress starts to drop slightly, the ratio rises again; and (iii) interestingly, the last drop in the ratio is observed to well match to the global stress drop. Again, from a general perspective the systematical drop-rise-and-drop in shear AE crack type in the instabilities can also be considered due to the existence of shear-enhanced compaction (Kwiatek et al., 2014b). However, optical and AE analyses in this study will demonstrate that the three instabilities are actually related to different physical processes. Thus, it is possible for this drop-rise-and-drop in shear AE crack type to represent a universal physical essence during rock fracture process regardless the physical processes, which presents an interesting topic for future research.

Figure 5.2. Systematical changes of AE crack type ratios along with axial stress drops for (a) pre-peak small stress drop, (b) first instability, (c) second instability, (d) third instability. Vertical dashed lines in (a-d) indicate starts and ends of mechanical instabilities. Different AE crack types are represented by different lines (see shear crack type as red dash line; tensile crack type as blue dot line; mixed-mode crack type as green plus line)

The observations in global AE activities, including AE moment energy release, b-value, and AE crack type changes, show similar features to previous stick-slips experiments (i.e. Goebel et al. (2013); Kwiatek et al. (2014b); Thompson et al. (2009)). However, the detailed analyses about the AE parameters and the optical observations of the three instabilities will reveal the differences between experimental results in the present study and reported results from previous publications. With the helps from optical measurements, the present study presents a relatively complete procedure about fault development and its slip, so that a deeper understanding about laboratory analogue of the earthquake mechanism can be obtained.

5.3 Fault- development and its slip in the progressive shear-sliding failure

According to the above-mentioned definition of instabilities, the progressive shear-sliding failure can be divided into four stages based on the axial stress and AE event histogram (see Figure 5.1(a)). These four stages include one stage in the pre-peak loading and three stages with respect to the three instabilities from the peak to post-peak.

5.3.1 Stage 1–Fault initiation or incipient fracture creation

This stage refers to the stage of fault initiation or incipient fracture creation. It is due to the observed phenomena, i.e., several sparsely distributed dots of white patches occur in the region between two pre-existing flaws at the end of this stage. More interestingly, the width of region with the dots of white patches is so small that it almost can be regarded as a line connecting two pre-existing flaws (Figure 5.3). This line represents the core region for fault initiation because the fault will eventually develop along it.

Generally, the beginning and end of this stage can be determined in the first cycle of rise and down on the AE histogram. It covers the time from 3790s to 4005s. Its end is when external stress reaches 99.4% of peak before the peak. A small stress drop has been observed in this stage, and then the global axial stress continues increasing to the peak (Figure 5.3).

Figure 5.3. Crucial changes of fault initiation stage. Labels 1 and 2 on stress curve indicate the moments of the two screenshots on its right side. As similar to Figure 5.1, the AE source locations of red, blue, and green are for shear, tensile, and mixed-mode AE crack types.

The crucial changes in this stage are shown as camcorder images and AE event locations in Figure 5.3, where their corresponding times are marked on the left axis of this figure. When two incipient white patches occur at the inner tips of the flaws, the external stress starts to drop, and simultaneously AE histogram and moment release also start to drop, as shown in label 1 in Figure 5.3. However, AE and optical observations indicate the fracture processes of this stage are primarily related to the development of external-fractures that initiate from the outer tips of two preexisting flaws (Figure 5.3). For example, during this stage the spatial AE source locations are primarily clustered around the areas of two outer tips of pre-existing flaws, and only very a few AE events are identified in the plane between two preexisting flaws. At the end of this stage (4005s), one external-fracture from upper outer tip even propagates to the specimen boundary from optical observation. It needs to note that the off-fault fractures are also observed to initiate from the inner tips of preexisting flaws, when the end of this stage is approached.

Thus, the fault development during this stage can be summarized as: (i) very a few AE events are located in the plane between two preexisting flaws, but the optical observation of the white patches suggests that the area may already be occupied by some inelastic deformation zones (Cheng and Wong, 2018; Wong and Einstein, 2009b; Wong and Xiong, 2018). Wong and Xiong (2018) provided an interpretation possibly it is more sensitive for the camcorder to detect the inelastic material deformation than the AE recording, due to the fact that the observation of white patch is earlier than AE cluster; (ii) the amounts of AE events and associated moment releases start to drop when the white patches begin to initiate at two inner flaw tips.

5.3.2 Stage 2—Instability 1, extension and connection of the white patches, initiated fault widening

This stage refers to the stage of extension and connection of the white patches (i.e., continuation of fault initiation), and initiated fault widening. The most crucial change of the core region for the fault in this stage is the sudden widening of connected white patch when the external stress starts to drop in this instability. Note that the occurrence of continuous white patch indicates the rock material starts to be weakened.

Similarly, instability 1 starts at 4005s and ends at 4120s based on AE activity. During this instability, the global stress gradually increases to its peak, and then suddenly drops to about 95.47% of post-peak stress. After this sudden drop, the stress becomes temporally stabilized. The crucial changes in this stage are shown in Figure 5.4, and similarly they are marked in the left axis.

Figure 5.4. Crucial changes of instability 1. Labels 3 and 4 on stress curve indicate the moments of the two screenshots on its right side. The AE source locations are presented by the same convention of Figure 5.3

In instability 1 (Figure 5.4), the white patches already extend from the inner notch tips of two pre-existing flaws gradually, and start to connect together. As shown in Figure 5.4, at the time of 4066s (i.e., label 3), a white patch line is observed to connect two inner tips eventually. It represents a fundamental moment for fault initiation because this white patch line can be regarded as the initiated fault. When this initial fault is identified, the global stress starts to experience a fast drop in this instability till at the time of 4085s (i.e., label 4). During the period, the fault development has significantly speeded up, i.e., the initiated fault experiences a sudden widening so that it can be more clearly identified at 4085s (Figure 5.4).

Indeed, the external-fractures keep developing during this instability. For example, the AE source locations are still primarily clustered around two outer tips of preexisting flaws, which suggests the developments of external-fractures are still main concentration of fracture processes in this stage. However, more AE source locations are observed in the plane between two preexisting flaws (see Figure 5.4 middle-right insert, and Figure 5.13(b)). It indicates the materials inside the core region for fault initiation starts to experience a severe

damage, which not only confirms the optical observations but also suggests the foundation of future slip for the initiated fault has been laid in this stage.

One interesting AE phenomenon should be noticed for instability 1. Before the AE activity reaches its peak, the amounts of AE events and associated moment releases have experienced a gradual increase and then a fast drop. The rise of AE activity is obviously slower than the decrease of AE activity (see the right-upper insert of Figure 5.4). This phenomenon is similar to the AE activity in the testing of an intact rock (e.g. Lei et al. (2000a); Zang et al. (1996); Zang et al. (1998)).

More importantly, a brightening zone is detected along the fault plane during initiated fault widening. This zone occurs in a sudden and drastic way, i.e., less than 5 second, which is just about 1% of the total testing time (see the last 6 photos of Figure 5.5, photo-7 to photo-11). Detailed information of this drastic change has been shown in Figure 5.5. The photos presented in Figure 5.5 are from 4065s to 4076s, sampled in a per-second based. They show the development of the core region, after the onset of the fast stress drop in this instability. The major changes occur primarily at the last 5 seconds (last 6 photos of Figure 5.5, photo-7 to photo-11). According to Wong and Xiong (2018), the observation of brightening grains on the surface of Carrara marble may be related to the local shear displacements within the fracture process zone, which causes the reflective grain surfaces of Carrara marble split and rotate towards the light source. (see the brightening dots and brightening zone in Figure 5.5)

Figure 5.5. Sudden and drastic widening of the white patch along the core region of the fault during the fast stress drop of instability 1

5.3.3 Stage 3—Instability 2, a fully-developed fault

In this stage, a macro-scale crack can be identified in the end of this instability, which suggests that the initiated fault reaches its fully-developed state and is ready for its final stage, i.e., the slip. This macro-scale crack, filled with thin gouge layer of marble powder, is formed between two pre-existing flaws after the fast stress drop in this instability. Then the global stress again stabilizes temporally, and further shear failure also temporally stops. Instability 2

starts at 4120s and ends at 4245s. During the time, the global stress gradually decreases (to approximately 4175s to 4180s), and then it follows a drastic fast stress drop (Figure 5.6). At the end of this instability, the global stress drops to 79.36% of its peak stress.

Figure 5.6. Crucial changes of instability 2. Label 5 on stress curve indicate the moment of the two screenshots on its right side. The AE source locations are presented by the same convention of Figure 5.3 and 5.4

The crucial changes in this stage are shown in Figure 5.6. For example, a macro-scale crack filled with thin gouge layer can be identified at time of 4183s (i.e., label 5). The macro-scale crack is overall in a zig-zag shape, clearly illuminating itself by a brightening line within the white patch zone (shown in Figure 5.6). A close examination of this brightening line indicates it is caused by the light reflection from marble powder gouge. There are inwardly or outwardly warped sections on the two sides of the macro-scale crack, e.g., some dimmer sections are identified along the macro-scale crack (Figure 5.6). These dimmer sections are actually the deeply indented parts of the macro-scale crack where light cannot be efficiently reflected towards the camera recorder. In addition, two off-fault cracks

have also significantly developed during instability 2.

The AE source locations of instability 2 are primarily concentrated on the center region, even covering the pre-existing flaws (see Figure 5.6 left insert and Figure 5.13(c)). It indicates that most energy releases in instability 2 are due to the fault development, although they may also involve the development of off-fault fractures. Note that the substantially fewer AE events are detected in the core region of fault during the instability 3 following current instability, which indicates the energy to create a macro-scale crack in core region have been mostly released in instability 2. With the complementary information from optical observations, it is reasonable to regard the fault as fully-developed after the end of instability 2. Again, when the AE activity reaches its peak in instability 2, the amounts of AE events and associated moment releases have experienced a gradual increase and then a fast drop. Also, the rise of AE activity is obviously slower than the processes of AE activity decrease (see the left-upper insert of Figure 5.6).

Figure 5.7 shows a series of photos during the fast stress drop in instability 2. They cover the period of less than three seconds, where the global axial stress drops from 67 to 61.5 MPa. From photo-1 to photo-4 of Figure 5.7, a thin brightening line propagates from the upper inner tip towards the lower inner tip. At photo-5, the upper part of the fault becomes curved. Vague but distinguishable dimmer sections begin to occur. Those phenomena indicate that the formed macro-scale crack is slightly curved in the upper part of the fault. From photo-6 to photo-12, the macro-scale crack progressively connects the two inner tips. From photo-6 to photo-8, the macro-scale crack continuously involves much more local tortuosity. Simultaneously, the brightening line within the white patch zone becomes much thicker and brighter. From photo-8 or photo-9, a fracture bifurcation has occurred at the lower part of the fault.

local stress severities (Wong and Xiong, 2018), whereas the global driving force (axial stress) undergoes a fast and accelerating drop. Based on previous experiments, these observed phenomena also suggest that the fault reaches its fully-developed state in instability 2 (Wong and Xiong, 2018).

5.3.4 Stage 4–Instability 3, fault slip

This instability, i.e., instability 3, is regarded as the actual stick-slip because (i) a fully-developed fault has occurred after the instability 2; (ii) a continuous frictional sliding movement has been observed along the fault, with vivid gouge powder growth and falling by the high-speed video when the final rupture is reached.

As shown in Figure 5.8(a), the stress drop of instability 3 is gradual (from 4275 - 4312s), and brightening dots vividly migrate surrounding the severely warped fault plane. Then a fault is observed with a thicker gouge and deeper warped sections (Figure 5.8(a)). The final fault slip can be characterized by optical observations from the camcorder and high-speed camera. The first is the camcorder recording. The crucial features in this stage have been presented in Figure 5.8 (a) with AE histogram, AE moment release rate, AE source location, and etc. Figure 5.8(b) shows a comparison between the fully-developed fault (i.e., a macro-crack formed in end of instability 2, 4183s of label 5 in Figure 5.6) and the slipped fault (i.e., 4312s of label 6 in Figure 5.8). The core region clearly becomes wider at the end of instability 3 than instability 2. Brightening grains and brightening zones spread outwardly. The brightening line in the middle of the core region becomes much thicker and brighter. These changes indicate that a much thicker gouge layer has developed before the final sliding can be captured by the high-speed camera. The dimmer sections along the fault become much larger, and spatially they are more continuous, which indicates the expansion of the severer warped and greatly indented sections. It appears that this thicker and more continuous gouge layer can act as a lubrication for the fault slip, because marble powders are continuously observed to be generated from the sliding fault during the final slip. This phenomenon can be

more clearly captured by the high-speed camera (Figure 5.8(c)).

The second of optical observations is the high-speed video recording. Under high-speed video, frictional shear-sliding movements are continuously identified during last several thousand μs at the final rupture, and the massive marble powders are increasingly produced along the fault plane (Figure 5.8(c)). Note that the generation of marble powder can serve as an evidence of shear movement, and the opening of the external fractures has also become larger (as indicated with legend on Figure 5.8(c—3)). Indeed, a clear and continuous shear-sliding movement can be observed in high-speed video. Some powders are even ejected out and fall from the fault during (‘during’ is under the perspective of high-speed video) the final rupture. The falling powders can cast the shadows on specimen surface, which results in the dimmer grey dots on the static screenshot (Figure 5.8(c—3)).

Figure 5.8. Instability 3 – fault slip. (a) Crucial changes of instability 3. Label 6 on stress curve indicates the moments of the screenshot on its right side. The AE source locations are presented by the same convention of Figure 5.3, 5.4 and 5.6; (b) Comparison between digital images at 4183s (instability 2) and 4312s (instability 3); (c) fault sliding under high-speed image and moment release behavior of three instabilities in the lower-right insert

A small amount of AE source locations is identified inside the core region between two preexisting flaws in instability 3 (Figure 5.8(a)), which indicates the energy release is insignificant in the fault plane. As a consequence, it is highly possible that the fully-developed fault is already cohesionless after the instability 2.

Three distinctive differences in mechanical and AE features can be observed between the final and the previous two instabilities, which actually reveal their different physical processes. Firstly, (1) the stress drop of instability 3 is gradual and in a continuous manner,

while the fast stress drops of instabilities 1 and 2 are sudden and drastic. (2) The second difference is their AE event activity. For instability 3, the AE event activity rises quickly to a comparatively high level (see Figure 5.8(a)), and this high value is maintained for a considerably long period. For instability 1 and 2, their AE event activity rises progressively and then decreases drastically after their peaks, where overall their rising processes is longer than their decreasing processes. The highest level value in instability 3 is only about half of instability 1 and 2, but the decreasing process from the AE peak is obviously longer in instability 3 than in instability 1 and 2. The observations show that AE activity of instability 3 is very similar to the seismic features of natural fault zone after large earthquake, while instabilities 1 and 2 are similar to the AE feature of intact rock failure experiments. (3) Third and most interestingly, in moment scale, the difference between the AE moment release peak and its maximum post-peak moment release of instability 3 is 1.15 (in the range between 1.1-1.2), but they are 0.95 and 1.06 for instabilities 1 and 2, as Figure 5.8(c—4) (or Figure 5.14). The Bath's law was firstly proposed in 1965 as an empirical relation, which describes the relationship between the main earthquake and its aftershocks (Bath, 1965; Helmstetter and Sornette, 2003). Empirical experiences demonstrate the average difference in magnitude is 1.2 between a main-shock and its largest aftershock, regardless of the main-shock magnitude (Helmstetter and Sornette, 2003). Thus, this moment scale difference in instability 3 obeys the Bath's law, and obviously, there are no observations about the Bath's law for the instabilities 1 and 2.

5.3.5 Summary of experimental results

In the study, three mechanical instabilities have been observed when a laboratory created fault experiences from fault development to its final slip. This progressive shear-sliding failure can be divided into four stages:

- (1) Stage 1 refers to fault initiation or incipient fracture creation. The primary optical feature of this stage is the occurrence of several sparsely distributed white patches

along the fault core.

- (2) Stage 2 refers to the extension and connection of the white patches (i.e., fault development), and initiated fault widening. It mainly includes the instability 1. The primary change of the fault core in this stage is the great extension and connection of the white patches along it, indicating the initiated fault core begins to weaken.
- (3) Stage 3 refers to the fully-developed state of the fault. It mainly includes instability 2. The primary change of the fault in this stage is the occurrence of a zig-zag shape macro-scale crack that is filled with thin gouge of marble powder.
- (4) Stage 4 refers to the actual stick-slip. It mainly includes instability 3. The primary optical feature of this stage is the occurrence of continuous frictional shear-sliding movements along a well-formed and gouge filled fault. Marble powder can also be massively created within those continuous frictional shear-sliding movements. Within the movements, the behaviors of stress drop and AE features are distinctively different than instabilities 1 and 2.

In the following sections, the discoveries and understanding from the present study will be discussed.

5.4 Discussions on the experimental result of double flaw test 60-1

Stick-slips in the laboratory scale rock mechanics experiments have been extensively conducted to understand earthquake mechanisms under various types of experimental setups. One fundamental and critical issue of those experiments is the analogue relationship between the laboratory scale and tectonic scale faults. The induced fault from an intact rock material inherently represents a different but very interesting laboratory analogue of the natural fault as compared to other laboratory scale faults such as the sawcut fault, which helps to provide essential information for seismic research. However, the challenge to study this type of induced fault is to identify the fault creation and its slip from mechanical instabilities, and of course, their transition when the fault is formed and ready to slip. It is simply because both release energy and induce the instabilities so that it is easy to mix two physical processes together.

The present study presents AE and optical observations of an induced fault from intact rock material, i.e., a progressive shear-sliding failure. The experiment can be divided into several stages based on the periodical AE and mechanical behaviors, mainly containing three mechanical instabilities. These stages clearly show the induced fault experiences from incipient fault creation to the frictional slip along the well-formed fault. With the help of optical observations and the AE and mechanical recordings, the transition from fault creation to fault slip has been characterized: the instability 2 — creation of a macro-scale crack. The discussions include: (1) several key optical features have been observed within mechanical instabilities, which provide novel understandings for the laboratory stick-slip (see sections 5.4.1 and 5.4.2); (2) an interesting issue is discussed, i.e. the differences in AE and mechanical behaviors for fault creation and fault slip as two physical processes (see section 5.4.3).

5.4.1 Key features of a well-formed fault and its transition from fault creation—macro-scale crack, powder gouge, zig-zag shape and asperities, and their implications for previous understandings from laboratory stick-slips experiments

Several analogue features between laboratory scale and field scale faults are optically observed during the transition from fault creation to fault slip. They are important to interpret the fault slip mechanism, because the “naturally” induced laboratory scale fault provides fundamental information on understanding the behaviors of field scale fault for its natural, random, and complex asperity system.

In summary, five important phenomena with respect to the transition between fault creation and its slip have been observed in the present experiment. The first one is shape change of the macro-scale crack after it is created in instability 2. The crack starts from a thin white brightening line, and then, it fast evolves into a zig-zag shape within just one second. The second is the occurrence of a marble powder gouge layer almost simultaneously with the macro-scale crack. The third is the systematical migration of brightening dots (within 1-2 or several seconds) just prior to the creation of macro-scale crack. The fourth is the observation of sub-millimeter shear displacement during the development of macro-scale crack and the marble powder gouge layer. Note that the uniaxial displacement is 0.76 mm (less than 1.0 mm) at the end of the test, and thus it is reasonable to consider the shear displacement to be within sub-millimeter scale along the fault. The fifth is the progressive widening of the fault influenced zone (displayed as white patch) surrounding the macro-scale crack from instability 2 to instability 3.

The above-mentioned five features, not only demonstrate the analogue between laboratory scale and field scale faults, but also display a much clearer picture about the development of laboratory scale fault, especially its transition from intact rock material to well-formed fault. Firstly, a thin and straight brightening line occurs at the upper inner tip during the onset of the macro-scale crack (instability 2), suggesting the initiation of the

macro-scale fracture is influenced by the stress concentration between the two flaws, because the location of macro-scale fracture is close to the flaw tip in the beginning (see left of Figure 5.9). This phenomenon is observed during a periodical AE release, which provides more fundamental information on the rock fracturing process. It is believed the large-scale imperfections during rock fracture process can induce more triggered AE events in front of them (Davidsen et al., 2017). This conclusion is drawn from the relationships of triggering-triggered AE events which is based on “the violation of null hypothesis of Gutenberg-Richter law” (Davidsen et al., 2017) without optical information on the changes of the fracture/fault. Thus, it implies that the predicted location of triggered AE should be exactly at the location where the thin and straight brightening line takes place firstly. However, based on present experiment, it appears that the white patch widening of the incipient fault in instability 1 has successively escaped the AE monitoring, because fewer AE events have been detected in the patch during instability 1 (see middle and right of Figure 5.9). It suggests that the incipient stage of fault creation may not be detected by an AE monitoring system. Hence, the triggering-triggered AE events are possible to occur in the channel of pre-developed white patch, i.e., pre-damaged rock material. This observation provides an alternative explanation for the existence of the triggered AE events in the presence of large-scale imperfections during rock fracture process.

Figure 5.9. The macro-crack location, the white patch channel and its associated AE locations in instability 1

Secondly, the macro-scale fracture evolves into a zig-zag shape within just a few seconds or even less than one second. In this transient evolvment, however, the phenomenon suggests this newly created fracture may influence the local stress field significantly during the fracture process, so that a straight thin brightening line changes into a zig-zag shape crack with a thin gouge quickly. In addition, this change optically indicates that the transition involves formation of the fault asperities, and provides a picture about the evolvment and formation of a complex asperity system.

Thirdly, the observation of brightening dots migration (see Figure 5.10) suggests the grain splitting and crushing shortly prior to the transition, which presents an important assumption for this transition, i.e., it is highly possible for the transition to be influenced by the individual grains. If this assumption is true, the mechanical instabilities and the fault slips will become highly unpredictable (or can be predicted only if comprehensive information of all grains is available), which exactly agrees with the conclusion of state-of-criticality (SOC) modeling simulation results (Bak and Tang, 1989).

Figure 5.10. Brightening dots migration, which is believed to be caused by the grain splitting and crushing; In the end of brightening dots migration, the boundary of some dots will become dimmer, and then dimmer sections are filled with gouge marble powders after the macro crack forms

Fourthly, considering the sub-millimeter shear displacement, the marble powder gouge of this fault may primarily come from the crushing of grains and local asperities, rather than the long-distance shear frictional grinding. Possibly, this local crushing process have already started, i.e., 1 or 2 seconds earlier than the brightening dots migration — a process of local stress severities transferring (Wong and Xiong, 2018).

Finally, the macro-scale crack is always surrounded by a much larger fracture process zone (see Figure 5.8 (b) or Figure 5.11). This process zone (highlighted by the white patch) becomes brighter and wider progressively from instability 2 to instability 3. It optically implies the possible influence of off-fault damage (the damage orthogonal to the fault plane) on the fault development and fault slip. This phenomenon also provides useful information to interpret experimental results from previous stick-slip tests. Based on previous experimental results, the AE clusters surrounding the laboratory fault induced by pre-cut notches are usually wider than the AE clusters around a sawcut plane (Goebel, 2013). It is also reported that, the fractal dimension of AEs is always larger than 2 for the fault by pre-cut notches; while AE fractal dimension of AEs is between 1.48 and 1.82 for the sawcut plane, even when the different levels of pre-defined roughness have been prepared on the sawcut planes

(Goebel et al., 2015). For the fractal dimension larger than value of 2, the physical interpretation is that the fractal feature of the fault occupies a three-dimensional space. In other words, it is highly possible that the development of off-fault (orthogonal to fault plane) is fundamentally involved in the stick-slip experiment for the laboratory fault induced by pre-cut notches. This interpretation on previous stick-slip tests is also supported by the optically progressive widening of the process zone (fault influenced zone) in present test.

Figure 5.11. Illustration for extending and changing of the outer boundary of the white patch zone from instability 2 to instability 3

5.4.2 Key features of the stick-slip—gouge growth in the fault sliding, and their implications to field and laboratory observations

The creation of marble powder is a typical feature of shear failure. After the fast stress drop of instability 2, a thin gouge layer can be observed along the newly created fault, where the marble powder gouge may mainly come from the crushing of local grains. Because the overall slip distance of the present test is limited for final slip, the growth of marble powder during the final slip may also involve the crushing of local asperities, which are the consequence of the zig-zag shape fault development.

The gouge layer can be observed in the fault of different scales (Di Toro et al., 2004; Mizoguchi et al., 2006; Passelègue et al., 2016; Reches, 1999; Reches and Lockner, 2010; Wilson et al., 2005). For the laboratory scale fault, it has been reported that the thin gouge can be identified within the several millimeters slip distance when slip rate of the fault approaches the actual seismic slip velocity (Di Toro et al., 2004; Mizoguchi et al., 2006; Passelègue et al., 2016; Reches and Lockner, 2010). For field scale fault, it has been reported that mature gouge material can be found on newly created fault where its rupture source location is at a previous “unfaulted quartzitic layer” (Wilson et al., 2005). In the present test, however, experimental results strongly suggest that the occurrence of the gouge powder material is a part of the fracture initiation, due to the observed phenomena, e.g., the sub-millimeter shear displacement along the fault, and the almost simultaneous occurrence of a macro-scale crack and a thin gouge layer. More interestingly, it is possible that the beginning of gouge powder creation can even be slightly earlier than the formation of macro-scale crack, based on the assumption that brightening dots migration is caused by the splitting and crushing of local marble grains. This explanation can also be regarded as an evidence to support the unexpected experimental results reported by Wilson et al. (2005). According to Wilson et al. (2005), the fractal feature of the gouge material from a newly ruptured fault can be as “mature” as the fractal feature of the gouge material from a fault of

millions years old (Wilson et al., 2005). It is important to emphasize that the gouge material within a fault of millions of years supposes to experience thousands of stick-slips already, while the material within a newly ruptured fault probably has experienced only one slip ideally. Based on the present experimental results, the gouge material is primarily from grain splitting and crushing, and has already been created before the first stick-slip, and the other slips following the first one do not change the gouge materials fundamentally. Thus, the gouge material in a newly ruptured fault is as “mature” as a fault of millions years old, and its role is like the lubricant when a fault slip is activated (Di Toro et al., 2004; Passelègue et al., 2016; Reches and Lockner, 2010). In the present experiment, this lubrication effect has been evidenced as the rolling and falling of the gouge marble powder in instability 3.

5.4.3 Reveals of different physical processes—comprehensive understanding on AE and optical observations for fault creation and fault slip

On the base of the detailed mechanical, AE, and optical observations of a progressive shear-sliding failure along two pre-existing flaws, two different physical processes can be identified in the present study. This progressive failure can be divided into two main stages: fault development and fault slip. For the former, it is to create a fault/fracture from intact rock material; for the latter, it is a frictional slip of this fault along a fault plane. Experimental results provide evidences on two different physical processes:

Firstly, the optical observation is the direct and solid evidence: (i) it indicates that there is no macro-scale crack until the end of fast stress drop in instability 2; (ii) a clear shear-sliding movement with marble powder creation and falling has been captured by the high-speed video in instability 3.

Secondly, the AE measurements, including the AE activity and the spatial AE events distribution, also display distinctive different features between fault creation and fault slip, although they share some similarities in the periodical AE features. For the AE activity, it is

well known that “laboratory rock fracture is dominated by a large number of foreshocks, where seismicity in the Earth’s crust is characterized by an abundance of aftershock” (Davidsen et al., 2007; Main, 2000). The laboratory AE activity of intact rock tests experiences a progressive rise of AE events, and a sudden and drastic drop after the final failure (Lei et al., 2000a; Zang et al., 1996; Zang et al., 1998), whereas the decaying of seismic activity after the main shock is obviously slower than the rise of foreshocks.

In the present study, the AE activity of instability 1 and 2 shows the characteristics of a progressive increasing of AE events number, and its sudden and drastic drop (see Figure 5.12(a)). This is similar to the AE activity from the experiments of intact rock. For the instability 3, the post-peak decaying of the AE activity is prolonged (see Figure 5.12 (a)). Its decaying process is obviously longer and slower than its rise, and more interestingly, its rise is characterized by a sudden jump to a high level of AE activity. Thus, it appears that the feature of AE activity in instability 3 shares more similarities with the seismic activities. Note that the macro-crack is observed to occur only after the fast stress drop of instability 2, which actually is an evidence that the fault is created from the intact rock. Indeed, the AE activities of the present test can also be divided into “foreshock” and “aftershock” types, because they are the consequence from different physical processes.

Figure 5.12 (a) comparison of AE activities between foreshock type and aftershock type, (b) moment release behaviors of two different physical processes: fault creation and fault slip

AE distribution along the fault plane in instabilities 1 and 2 has progressively developed to be denser, and it even has occupied a larger off-fault area as well. In instability 3, the distribution becomes sparsely distributed. It is well-known that most of the strain energy is consumed for the fracture initiation in rock (Reches, 1999). Thus, it is reasonable to observe the fewer and more sparsely distributed AE events for instability 3, because the fracture has been fully-developed after the fast stress drop of instability 2. Note that these sparsely distributed AE events may be the results from the incidental breakage of the asperities along the zig-zag fault as well as the off-fault damage in the preparation of successive fault slip.

Thirdly, the stress drops of three instabilities are different (see Figure 5.12 (a)). For instabilities 1 and 2, the stress drops are drastic and sudden due to creation of a fracture in brittle rock mass, which is known to be a violent process with massive strain energy release. For the instability 3, the stress drop is progressive, so that it agrees with the conceptual modeling of the earthquake along a well-formed fault, where earthquake nucleation occurs by breaking the fault resistance at some local asperities and then accelerates when the final earthquake reaches its fast slip.

Fourthly, there is another interesting phenomenon observed in AE measurements, which also provides an experimental support on the difference of physical processes for fault development and fault slip. The moment release behaviors of these three instabilities also evolve towards the typical behaviors of a well-formed fault (Figure 5.12(b) or Figure 5.14). For instability 1 and 2, the moment release behaviors disobey the Bath's law; for instability 3, they support the Bath's law. Bath's law demonstrates a relationship between the individual main-shock and the maximum individual aftershock, which helps to interpret the differences in the moment release behavior of three instabilities. Thus, it is believed Bath's law can be used as a bridge for laboratory scale and field scale observations by the scaling effect and the self-similarity during rock fracture process. Indeed, it is rare to have such an analogue that documents Bath's law for stick-slip experiments between laboratory and field (McLaskey and Kilgore, 2013; McLaskey et al., 2014; Thompson et al., 2005). However, the optical observation has demonstrated the stages of fault creation and fault slip, the difference in their moment release behaviors possibly suggests: (i) the Bath's law is a phenomenon only for seismic activity of a well-developed fault; (ii) on the contrary, for a fault in development, such phenomenon is hardly expected for its aftershocks.

5.4.4 Inspiration of present experimental data analyses from previous studies and issues related to geometrical settings

The data analyses of the current study is primarily inspired by previous stick-slip tests, especially those whose laboratory shear fault is “naturally” formed on intact rock material through pre-cut notches (Goebel et al., 2015; Goebel et al., 2013; Kwiitek et al., 2014b) as well as AE feedback control (Lockner et al., 1991; Thompson et al., 2009). Indeed, although differences in geometrical settings exist, the fault forming and slip process of the present study are operating along the co-planar pre-existing flaws, which is similar with the condition of previous stick-slip experiments with sawcut notches (Goebel et al., 2015; Goebel et al., 2013; Kwiitek et al., 2014b). On the other hand, similar geometrical settings of 2-D

embedded flaws in prismatic rock mass have been extensively used by previous researchers (Nguyen et al., 2011; Shen et al., 1995) for investigating the relationships between the induced fracture patterns and the pre-peak-to-peak stress behavior. Unfortunately however, I have failed to find a research among a large number of studies using such type of prismatic specimens and embedded flaws which has placed its primary focus on the analyses of post-stress-peak evolution stages of the shear fracture along two pre-existing flaws. None the less to say any literature can elucidate the analogue between post-stress-peak evolution and seismic activities.

Another interesting geometrical phenomenon is the development of the off-fault cracks in the present test, which has also been found in one triaxial stick-slip test whose laboratory fault is formed through AE feedback control (Thompson et al., 2009) (see Figure 5(b) of Thompson et al. (2009) or Figure 5.15). To the authors' understanding, the off-fault fractures in both previous (i.e. Thompson et al. (2009)) and the present studies are a kind of rupture barriers ("barrier" is following Aki (1979, 1984)). Their development is prior to the final shear-slip and has generated observable AE events. However, this kind of barriers is not on-fault, which is different with the traditional understanding of the rupture barriers. Interestingly, in Thompson et al. (2009), although there is no direct real-time optical observation on their testing sample, the development of the off-fault fractures is considered as a necessary step before the successive stick-slip. Alternative transitions of the AE processes between on-fault and off-fault fractures have been documented by Thompson et al. (2009) as an evidence for supporting this argument.

5.5 Conclusion on the experimental investigation of double flaw test

The study systematically monitors the processes of fault development, and captures the final fault slip along the well-formed fault in a specimen with coplanar pre-existing flaws under uniaxial compression. With helps from AE and optical techniques, a series of observed phenomena including three successive mechanical instabilities are identified from the experiment. The phenomena can be categorized as: (i) fault development involves fault initiation, initiated fault widening – instability 1, fully-developed fault – instability 2; (ii) fault slip, i.e., stick-slip, mainly includes frictional shear-sliding movements of the fault – instability 3. The observations involve important components, i.e., migration of brightening grains as indication of transferring process of local stress severity, the transient creation and evolvement of the macro-scale crack as the fully-developed fault, and the creation and growth of marble powder gouge layer in the fault as well as the growth of the fault influenced zone. Of course, the optical and AE measurements provide a solid foundation to interpret the processes of this laboratory-scale fault and its final slip. For example, AE features associated with fault development are similar to AE measurements from intact rock, while AE features with fault slip are more similar to the features of natural fault zone. It needs to emphasize that the Bath's law is supported by the moment release behavior of fault slip — instability 3, while it is not supported by fault development — instabilities 1 and 2.

In summary, the study is not only helpful for a further understanding of the nature of earthquake, but also enriches the laboratory methods and understandings for investigating the stick-slips mechanism of earthquakes.

5.6 Support documents of double flaw test 60-1

Figure 5.13. Source locations of (a) fault initiation, (b) initiated fault widening, (c) fully-developed fault, and (d) actual fault slip. Presentation of source locations follows the convention of Wong and Xiong (2018). Screenshots of camcorder recording (for (a), (b), and (c)) and screenshot of high-speed video recording (for (d)) at ends of all periods are supplemented in lower row

Figure 5.14 peaks of moment release rate at and after the fast stress drops of three instabilities.

Correspondingly, $\log_{10^{1.5}}(76.3923/2.8092) = 0.9563$, $\log_{10^{1.5}}(55.7884/1.4174) = 1.0634$, $\log_{10^{1.5}}(31.8836/0.6068) = 1.1462$, respectively

Figure 5.15. (a) Illustration of off-fault fractures by post-mortem exam and the alternative transitions of AE activity on on-fault and off-fault fractures, edited after the Figure 5(b) of Thompson et al. (2009), (b) schematic draw illustration of the off-fault fracture in present test

Chapter 6 Cascading non-local triggering in rock fracture process

This Chapter primarily follows the content of “Xiong and Wang and Hampton (under preparation), non-local triggering in rock fracture process”.

6.1 Summary and highlights of this Chapter

The experiments of Chapter 4 (Wong and Xiong, 2018), which can be served as the first time that quantitative and continuous AE and optical observations on the post-peak fracture evolution has been obtained in the uniaxial compression tests on specimens with single preexisting flaw, provide a unique chance for analyzing the AE and fracture phenomena in post-peak rock fracture dynamics. Phenomena of this domain are absolutely out of criticality state as the stress peak has passed in post-peak loading. In this Chapter, the analysis will go to the topological structures of the AEs released from the rock fracture under symmetry/quasi-symmetry extensions, following the methodology of time-space-magnitude earthquake clustering analysis. The experiments have combined the latest in-situ calibration technique (Davi et al., 2013; Xiong and Wong, 2017); and the analyses take the advantages of the AE system and advanced AE data analyses techniques. The accuracy of the spatial-magnitude information for the AEs can be tremendously improved. For instance, empirical calibration can inherently create an error of 6 dB (100% error) (McLaskey et al., 2014); on the contrary, the in-situ calibration can reduce the error into lesser than 17% (Xiong and Wong, 2017). Thanks for the quality of the experimental data and data analyses, a unique chance of analyzing the rock fracture dynamics into great detail has appeared.

In the following work, evidences for the existence of event-event triggering, and swarm-like topology feature of the AEs have been recovered. Dominant AE trees have been identified, where their topological roots must locate after the peak stress or the close-to-peak stress perturbation has already completed. Moment magnitude of the roots can be lower than the mean and median moment magnitude of all AEs. The spatial AE migration along the

root-to-leaf paths indicates the existence of long-range/non-local triggering cascades, which can transversally migrate through the fracture/fault and can only be limited by the physical boundary of the specimens. These features exactly fit for the prediction of the self-organized criticality (SOC) theory (Bak and Tang, 1989). More interestingly, the statistical features of the non-local triggering-triggered AE event pairs suggest laboratory non-local triggering phenomenon has been substantially facilitated by the preexisting large-scale imperfection. These evidences unveil the mechanism of long-distance triggering phenomena, which suggests that large earthquakes in far away distance can be virtually correlated. As a result, the discoveries of this Chapter can provide a better understanding on the spatial event-event triggering dynamics between long-distance gaped but essentially correlated earthquakes.

6.2 Introduction

Recent evidence has confirmed that a large magnitude earthquake can possibly trigger subsequent earthquakes even in geologically remote regions (Gomberg et al., 2001; Hill et al., 1993; O'Malley et al., 2018; Parsons et al., 2008; Shan et al., 2013). Such a spatially non-local triggering phenomenon greatly aggravates the difficulty in predicting earthquakes. Although intuitively this ought to be a result of the stress field change along the fault system, the exact details of the triggering dynamics, such as when and how the non-local triggering process takes place, are still field-experimentally elusive to date, primarily due to the inaccessibility of in-situ measurement and characterization. While the laboratory acoustic emission (AE) test is a widely used method that can successfully detect the energy release events during the rock fracture process, only in very recent the triggering phenomenon in rock fracture under the existence of large-scale imperfections has been uncovered (Davidsen et al., 2017). Thanks to the scale invariance property of the earthquake dynamics as interpreted by the self-organized criticality (SOC) theory (Bak and Tang, 1989; Sornette, 2006), similar statistical laws of AE events are found to hold universally for both field and laboratory experiments (Baro et al., 2013; Corral, 2003; Davidsen et al., 2007), giving much credence to the investigation of triggering dynamics based on AE events. A careful analysis of AE signals from laboratory rock mechanics tests is performed in Davidsen et al. (2017), where the authors convincingly show that in a triaxial compression setting, no AE signal can be identified as a triggering event in the sense of statistical significance for intact rock, and only in flawed rock can triggering be prominently present. This amazing result quantitatively highlights the decisive role of flaws (reminiscent of a well-developed and highly lubricated section of the fault system) in influencing the rock fracture process. Also, it showcases the great power of the methodology developed in that reference (Davidsen et al., 2017) in mining AE signals' information.

In the same vein, while with a different focus on the dynamics of non-local triggering that is crucial in developing a global scale failure of flawed rock, analyses of this Chapter will further extract the spatiotemporal information of triggering from AE signals in

experiments of symmetry extending fracture that is induced by an inclined open preexisting flaw (Wong and Xiong, 2018), with the inclination angles lying in the range of possible laboratory slip nucleation plane in intact rock (Lockner et al., 1991; Reches, 1999; Reches and Lockner, 1994). These experiments have combined the latest in-situ calibration technique (Davi et al., 2013; Xiong and Wong, 2017) into the tests therefore convinced a high accuracy of the AE magnitude information, and have been reported as the first time that quantitative and continuous AE and optical observations on the post-peak fracture evolvement of single flawed specimens under uniaxial compression has been obtained. Thus they provide a unique chance to investigate the rock fracture dynamics into great details. It unveils at a high precision level the complete dynamical fracture process as pinpointed by a network of triggering-triggered events. By inspecting the growth of the network, in particular of its dominant trees, it readily finds besides the gradual local expansion, there exists a sudden increase in network range, signaling the creation of a non-local connection that cascading links otherwise spatially segregated nodes, which turns out to be the emergence of fracture-transverse non-local triggering. This is direct evidence for the existence of non-local triggering. Moreover, in different damage stages as characterized by the AE event frequency, it observes distinct patterns of (non-local) triggering as demonstrated by the spatial migration routes of nodes in the topologically connected structure. In the first stage, the damage is incremental, and the network slowly grows in both number of nodes and range. When the local damage is accumulated to its first extreme, by the SOC theory, the redistribution of stress causes a large number of AE events, and the first non-local, flaw-traversing triggering events can be observed. However, the rock as a whole does not fail, and lesser non-local triggering can be observed after the burst of energy release, though at both ends of the flaw more nodes are continuously added to the network in a non-interacting manner. As the experiment proceeds, the rock will come to the final critical stage of failure, which leads to a more intense and durable energy releasing process. More non-local triggering events are found, and more importantly, some of them hop between two ends of the flaw, conducting and amplifying stress perturbations at two ends in a chain-reaction way. Eventually, the triggering cascades spread to the boundary of the rock, leading to its global failure.

In all cases, it is noted that rather than emerging randomly in position and orientation, non-local triggering events are occurring near two ends of the preset flaw with a great statistical significance and the links connecting two nodes of triggering-triggered events are under statistical sense spatially aligned with the flaw correspondingly. It is thus plausible to argue that the emergence of non-local triggering relies on two factors. The first is a strong enough energy releasing process; and the second is the existence of a flaw, which, as a friction-free section along its direction, provides a pathway of non-local interactions. Laboratory rock mechanics tests focusing on the slip phenomena are widely accepted as an analogy for investigating the earthquake mechanism (Brace and Byerlee, 1966; Goebel et al., 2012; Goebel et al., 2015; Goebel et al., 2013; Kwiitek et al., 2014b; Lockner et al., 1991; Thompson et al., 2005, 2009). Taking the flawed rock as an idealized minimal model of fault system, where a fully-developed and well gouge lubricated fault section (e.g. the creeping aseismic zone of a fault system) has been sandwiched by the newly extending fault sections, one might imagine that when the main shock energy level is high, and regions connected by a fault system to the main shock location are themselves in a state close to the onset of SOC, then the aftershocks are highly probable due to non-local triggering facilitated by the complex network of subsurface fractures whose span can reach some tens of kilometers. The work in this Chapter thus sheds new light on the understanding of triggered earthquakes in remote regions. Also, by establishing the correspondence between triggering dynamics and network structure, the work provides a feasible way to systematically and multi-dimensionally capture information from AE signals beyond several empirical power laws, and it is hoped that such analysis of triggering dynamics could boost the relevant research in understanding the analogue of rock fracturing processes between laboratory and tectonic scales.

6.3 Results

6.3.1 Network triggering

Rock mechanics test

Our rock mechanics tests are conducted on prismatic Carrara Marble specimens ($151.4 \times 78.9 \times 30.4$ (30.4 ± 0.3) mm³). For each specimen, an open elongated preexisting flaw (length ≈ 13 mm, length/width > 7) is created by waterjet before the loading test. The flaw inclination angles are in between 60° and 70° to the horizontal direction, conforming to the modeling prediction of the slip nucleation plane from intact rock (Lockner et al., 1991; Reches, 1999; Reches and Lockner, 1994). The loading rate is set as a constant 0.0001 mm/s after transient stages to ensure a reliable observation of the complete failure process, during which the AE events are recorded. Detailed experimental procedures can be found in Chapter 4.

Probability density function

The probability density function (PDF) of the inter-event time ratio $p(R)$ is used to detect the existence of triggering. Define the i th ratio $R_i \equiv \Delta t_{i+1} / (\Delta t_{i+1} + \Delta t_i)$, where Δt_i is the time interval between the i th and $(i-1)$ th AE events. This ratio statistic has been successfully used to show the existence of triggering in triaxial tests of rock cores containing large-scale imperfections (Davidsen et al., 2017), and the connection between near-field and far-field earthquakes (van der Elst and Brodsky, 2010). In case that the event process is Poisson and without triggering, $p(R)$ is uniformly distributed on $[0, 1]$. While in our experiment one can observe peaks near 0 and 1, which are strong evidence against this assumption and are the manifestation of triggering and anti-clustering, respectively (Davidsen et al., 2017). In Figure 6.1(a), $p(R)$ is calculated for AE events from time $t = 1000$ s till the first AE peak (till the

stress peak for its upper insert). The triggering phenomenon as indicated by a peak at close to zero is not obvious for the PDF based on all AE events, but it becomes pronounced for the magnitude-conditioned AE events, consistent with the result in Davidsen et al. (2017). The peak at 0.975 and 0.725 shows the tendency of anti-clustering; this relaxation is analogue to the Omori-Utsu law for describing aftershock relaxation in seismology (Davidsen et al., 2015).

Event-event triggering

Event-event triggering cascades are determined using a well-established and widely accepted method in seismology (Davidsen et al., 2017; Gu et al., 2013; Moradpour et al., 2014; Zaliapin and Ben-Zion, 2013a; Zaliapin et al., 2008), in which the key idea is to find the condition under which the null hypothesis that the event distribution obeys the Gutenberg-Richter (GR) law can be rejected. To find the trigger, if any, of a given AE event j , it calculates $n_{kj} = l_{kj}^* \times \tau_{kj}^* \equiv (r_{kj}^{Df} \times 10^{-bm_k/2}) \times (t_{kj} \times 10^{-bm_k/2})$ for each of its preceding event k , where l_{kj}^* and τ_{kj}^* are the normalized spatial and time distances between events k and j ; m_k is event k 's moment magnitude; Df , b are the correlation fractal dimension of the AE events, and b-value of the G-R law, respectively, which can be estimated directly from the statistical features of AEs (see the support document of this Chapter for details). Then it defines the i th event that satisfies $n_{ij}^* = \min_k n_{kj}$ as the most probable trigger of event j . A very low value of n_{ij}^* indicates the existence of real event-event triggering. In this work, a threshold $n_{th} = 8$ is selected by observing the distribution of shuffled (randomized) AE data in the normalized space-time plane (Davidsen et al., 2017) (please see the support document of this Chapter for details). In Figure 6.1(b), the density contour of n^* is plotted, and it is noted that a considerable amount of n^* for the complete AE data set is below n_{th} (represented by the red line), similar to the result in Davidsen et al. (2017) for the core samples with large-scale imperfections. For $n_{ij}^* < n_{th}$, event i is believed

to trigger event j , and they are considered to be two topologically connected nodes (with the spatial link from event i to event j) in a network of triggering. While for $n_{ij}^* > n_{th}$, it is concluded that there is no triggering in the sense of statistical significance, and the two events are not included in the topologically connected structure. By doing so, what can be obtained is the growth history of a network that conceptually describes the “geometry” feature of the triggering dynamics in rock fracture. As shown in Figure 6.1(c) the network consists of several isolated trees, in each of which the temporally earliest node is defined as the “root”, and nodes without any outgoing link are “leaves”. This AE network displays swarm-like feature, which is the analogue feature of the real seismic swarm (Zaliapin and Ben-Zion, 2013a, b). Among these trees, a dominant one is observed, which includes an overwhelming proportion of triggering events and is plotted in lower-right insert of Figure 6.2(a). Its temporal evolution of structure reflects the most important aspects of the fracture process of rock.

Figure 6.1 (a) PDF of interevent time ratio for specimen containing 60° preexisting flaw based on the AE events from after 1000 s to first AE histogram peak, or from after 1000 s to stress peak (upper insert). (b) density distribution of event-event connections for specimen of 60° preexisting flaw, and specimen of 70° preexisting flaw (lower insert). (c) node number vs. average leaf depth $\langle d \rangle_f$ for specimen of 60° preexisting flaw, and specimen of 70° preexisting flaw (upper insert)

6.3.2 Patterns of non-local triggering

The existence of non-local triggering is most obviously seen through the drastic structural change of the dominant tree when the first non-local triggering occurs. In Figure 6.2(a) (also its lower-right insert), one plots the maximal and minimal values of nodes' coordinates in the direction of flaw (denoted $y'_{\max}$ and $y'_{\min}$ respectively) versus time. They are, up to a length factor, almost symmetric about the line $y(t) = y_{\text{root}}$ with y_{root} being

the root's coordinate in this direction. The imperfect symmetry seems to interestingly imply that the flaw helps the downward triggering pass through it to an otherwise unreachable region. Note at the time (≈ 3370 s) when the first peak of AE events appears, both $y_{\max}$ and $y_{\min}$ undergo a sudden increase, however, the downward penetration is much deeper than the upward. It is also important to notice that, many of the non-local triggering of all AEs (Figure 6.2(d)), especially the first several ones (Figure 6.8), are concentrating aligned with the flaw direction and the connected nodes are spatially close to the two ends of the flaw (Figure 6.2(b) and its insert). It thus seems reasonable to suggest the flaw has induced a pathway for the downward triggering pass through it to an otherwise unreachable region.

The asymmetric extension in opposite direction is ascribed to the facilitating effect of the flaw. However, the peaks of non-local triggering occurs slightly earlier than the peaks of massive AE releases (Figure 6.2(d) middle insert), implying an amazing picture that those non-local events are amplifying the stress perturbations at two ends and appears as the precursor of the much more massive energy releases (see support document and Figure 6.10 for more details). It is also interesting to notice that the magnitude distribution of non-local triggering events is obviously larger than the overall AEs in most of magnitude span (Figure 6.2(c)), indicating a magnitude dependence of this non-local triggering. Additionally, all those above mentioned phenomena happen in post-peak domain, thus the rock fracture is of criticality state; also the ultimate spatial extension of the dominant tree appears to be only limited by the specimen boundary, which exactly fit for the SOC prediction.

Figure 6.2 (a) Y' projection of the events included in the dominant tree for specimen of 60° preexisting flaw and (lower-right insert) spatial span of the topological structure of dominant tree (b) spatial distribution and its (right insert) Y projection distribution of triggering and triggered events (c) frequency magnitude distributions of non-local triggering and triggered events and all AE events (d) frequency of inclination angles of the connections between non-local triggering and triggered events and (middle insert) temporal correlations between non-local triggering peaks and AE event peaks

Furthermore, a closer look at the dominant tree structure helps to uncover distinct (non-local) triggering patterns that are crucial to the fracturing process of rock. In particular, along the root-to-leave paths, the spatial migration of triggering events can be depicted. They are summarized in Figure 6.3. Four typical paths observed in branches of the dominant tree: (i) the path is strictly constrained within one lobe of the flaw (Figure 6.3(a)), (ii) the path crosses the preexisting flaw and later migrates back to its original lobe (Figure 6.3(b)), (iii) the path crosses the flaw, and does not return to its original lobe (Figure 6.3(c)), and (iv) the

path crosses the flaw and then moves back-and-forward for multiple times (Figure 6.3(d)). Also shown in Figure 6.3 is the plot of the counts of AE events versus time. The times of the crossing migrations can occur at or around the AE peaks. For example, the migration from the 17th node to the 18th in Figure 6.3(b) takes place at $t = 3374.6$ s, and that from the 32nd node to the 33rd in Figure 6.3(d) happens at $t = 3374.8$ s. Both are close to the first peak. The migration from the 48th node to the 49th in Figure 6.3(d) occurs when $t = 3451.9$ s, which is almost the time for the second AE peak.

Figure 6.3 Within the dominant tree of specimen containing 60 °preexisting flaw, examples of (a) spatially non-crossing root-to-leave path, (b) spatially crossed and returned root-to-leave path, (c) spatially crossed and not returned root-to-leave path, and (d) a root-to-leave path spatially transversal the whole fracture length in a chain reaction like manner. The titles of these figures are indicating the number sequences of the root and leaves among all AE events. Sizes of all circles for the events are proportional to their magnitudes. Two events in (a) are indicated with their relative moment magnitudes for aiding the understanding of the relationship between circle size and moment scale. Also in (a), the 1st-8th events are filled with red color, indicating the local accumulation of damage around the root at the onset of first SOC state. Lower inserts of these figures are the Y projections of the events along these paths versus time, and AE histogram. These inserts help to understand the temporal relationship between crossing migration and AE activity

6.3.2 Physical scenario of non-local triggering dynamics in rock fracture

Based on the observations above, one can establish a physical scenario as to the triggering dynamics in rock fracture. In the initial stage of damage accumulation, the tree grows gradually around the root, without any non-local connection to the other end of the flaw (see Figure 6.8 for more details). As the loading process continues and the rock arrives at the onset of the SOC state, the first peak of AE events is seen. A burst of energy releasing causes not only local but also non-local triggering events in the rock. The local triggering events stay at the same one lobe of the flaw, while non-local events spatially cross the flaw. Both local and non-local events display a cascading triggering chain from root towards specimen boundaries. After this period of energy dissipation, the system reaches a quasi-equilibrium state with the AE events at an inactive level, and fewer triggering identified. This implies the sequential displacement adjustment along the whole fracture length in the previous burst of AE events. Nonetheless, the damage is still being accumulated in this stage in a somewhat mild manner where AEs in the Poisson family continuously growth. As the rock approaches its final state of failure, another process of stronger and more durable energy releasing lead to another round of triggering cascades, in which more non-local triggering events are observed in two senses: first, there are more triggering-triggered events passing through the flaw (see Figure 6.2(d) middle insert); second, more paths can cross the flaw and then back for more than once. Since the non-local triggering events have a larger magnitude distribution, and intuitively they represent consecutive long-distance strong energy releasing events, one can know that along the flaw direction, there exist frequent and intense damage processes that lead to the formation of a fracture traversing the whole rock specimen. The AEs within this damage processes, especially those corresponding to the “back and forth” type of non-local triggering, are connected by a cascading chain, and will further amplifying the stress perturbation between two ends of the fracture, suggesting a comprehensive but interesting picture for the remote earthquake triggering process. The interpretations of the non-local triggering physical process in this Chapter, although are primarily based on statistical analyses, have further validated by the optical observations on the white patch/fracture extensions and evolvments which have been reported in Chapter 4 (please see

support document in section 6.5.6 and 6.5.8 for further explanations).

6.4 Discussion and conclusion

This Chapter uses the well-established and widely accepted method in seismology (Davidsen et al., 2017; Gu et al., 2013; Moradpour et al., 2014; Zaliapin and Ben-Zion, 2013a; Zaliapin et al., 2008) to investigate the acoustic emissions of fracture undergoing symmetry/quasi-symmetry extension. Following Davidsen et al. (2017), it proves the existence of event-event triggering in our tests. This Chapter further investigates the spatial AE migration along the topological root-to-leaf paths. This investigation proves the existence of correlation between long-distance events. This experimental observation supplements the previous understandings on the triggering cascade of rock failure (Kun et al., 2014).

6.4.1 Typicality of the results

The nonlocal cascading triggering is realized by three patterns of the spatial migration paths. All types of the mentioned above spatial migration patterns are not unicorn examples. For type 1 path (Figure 6.3(a)), one can find several root-to-leaf paths who share short tree trunk and have long tails of separated branch-to-leaves paths. For type two to four paths (Figure 6.3(b-d)), bifurcated long tails of separated branch-to-leave paths also exist for the part after crossing migration. Those crossing migration/non-local triggering patterns can also be found in other non-dominant trees.

6.4.2 Robustness of the results

As illustrated in Figure 6.3, multiple paths for the AE cascade to spatially migrate to the symmetry fault lobe/wing (and/or return) exist. At least three downward migration paths are identified even one has only picked several root-to-leaf paths for illustration, and within only this dominant tree. All the mentioned above topology path types still exist event one changes Df to a value obviously larger than the value estimated from the AE spatial distribution of present test (i.e. $Df = 1.78$, which is approximately 17% larger than the average estimation,

see Figure 6.6).

6.4.3 Roots

An interesting discovery of the dominant tree is the temporal location and moment magnitude of its root. The temporal location of the root (3332.7s) is just after the stress peak and long before the onset of the first fast stress drop (see Fig. 6.7 in support document); and its relative moment magnitude (≈ -0.69) is obviously below the averaged (≈ -0.55) and mean value (≈ -0.57) of the moment magnitudes of all AE events. These facts exactly fit for the picture that the SOC model has described—a small perturbation at seemly random place of the extending fault can trigger the cascading events in a chain reaction like manner (Bak and Tang, 1989), and the only limit of this cascading expansion is the physical boundary (Bak and Tang, 1989). In tectonic scale fault undergoing extension, devastating earthquakes may initiate from a small breakthrough of the fault strength weakening (Reches and Lockner, 2010). Some recent field scale observations have highlighted the temporal correlations between ultra-small scale emissions and earthquakes, suggesting the precursors of earthquakes can even be generated from millimeter scale ruptures (Carpinteri and Borla, 2017, 2019). Laboratory evidences supporting this hypothesis can also be found as well (Carpinteri et al., 2012a). In the global scale, the Earth's crust system has evolved into an equilibrium criticality stage under the explanation of SOC modeling (Bak and Tang, 1989). Under the explanation of this theory, specific prediction of devastating earthquake is virtually no hope (Bak and Tang, 1989). However, alternatively, the present analyses have depicted a comprehensive picture on the connections between remote events when the fracture is under equilibrium criticality state, and the evolutionary features of the fracture exactly fit for the SOC theory; the remote triggering criteria, although can depend on the local damage conditions which may scale down to a hardly measurable size, still displays a statistical dependence on the inclination angle of the open flaw (which can be viewed as the analogue of the fully-developed and well gouge lubricated fault section such as the creeping aseismic

section of a fault system) and the dependence on larger triggering energy for most of magnitude span. These discoveries absolutely intrigue the investigations of remotely triggered earthquakes into a novel direction—i.e. the correlation between remote triggering and the creeping or deformation of the aseismic region.

6.4.4 Non-local triggering and stress peak; length issue

The spatially crossing migration between two lobes/wings of the extending fracture can only exist after the stress peak (This can be proved by using only pre-stress-peak AE events to build the topology structures). While immediately after the stress peak (even within the period of global stress perturbation around the peak), a tree displaying spatial migration transversal the whole fracture length has appeared (see Figure 6.8 in support document, provided by Wong and Xiong (2018) that the length of the extending fracture in its optical white patch appearance has just exceeded the length of the preexisting flaw at the moment of stress peak, and exactly matches the spatial span of that tree plotted in Figure 6.8). These facts indicate the fracture process will be much self-organized once the fracture length exceeds a certain length away from the large-scale imperfection. As in both Chapter 4 and Chapter 5 experimental results suggest the existence of post-stress-peak fracture evolution stages, the present analysis connects this suggestion with SOC process by providing experimental phenomena exactly fit the picture described by the prediction of SOC theory. However, those facts also suggest the event-event triggering may be even stronger after the fracture process zone extended away the large-scale imperfection. Those facts also extend the conclusion of Davidsen et al. (2017), which states that “the PDF of triggered events may decrease with the distance to notches”; and additionally, triggering phenomenon would be more prevailing when the fracture process zone has extended to a distance away the large-scale imperfection.

6.4.5 Natural mechanism

According to the present analysis, the role of large-scale imperfection may have facilitated the fracture process evolves into the equilibrium criticality stage following exactly the way of SOC modeling. The transversal root-to-leaf path can only exist after the stress peak. Correspondingly, the reduction of the global driving force appears like the result of this SOC process. The topology feature of spatially fracture-transversal migration is rather an inherent feature of the SOC process, and the limit of its expansion is the specimen's physical boundary. Additionally, the dominant AE tree is triggered by a small perturbation at a seemingly random place. All the features displayed in the present analyses exactly fit for the prediction of the SOC modeling. Therefore, the works in the present Chapter post the stepping-forward evidences and demands to universally and integrated combine the theoretical prediction and the experimental observations. Besides the presented correlations between experiments and modeling, the matching between the optical observed length of fracture process zones and the spatial non-local triggering span (the span of the crossing migration tree), in plus with the recent field observations (Carpinteri and Borla, 2017, 2019), absolutely point towards a much universal understanding on rock fracture and tectonic scale earthquakes.

However, the experimental results show that only in specimens with large-scale imperfection, can this evolution process exactly follows the SOC theory. No comparable evolution process has been reported in intact rock tests, and the existence of triggering in intact rock is still hardly found in statistical sense (Davidsen et al., 2017). Therefore, for the Earth's crust system, it is still unknown which fact has tuned its evolution process (Bak and Tang, 1989), which is playing the analogue role of the large-scale imperfection in the present experiments.

6.5 support documents—methodology and supplementary evidences of the analyses in Chapter 6

6.5.1 Extracting the AE information—the source to regenerate the data and its relation with the data in the support document of Wong and Xiong (2018)

The experiments discussed in this Chapter is identical with the experiments of $\beta = 70^\circ$ test and $\beta = 60^\circ$ test in Chapter 4, which are reported by Wong and Xiong (2018). However, the AE data used in this Chapter are regenerated from the analyses on the raw data of those experiments. The primary differences between the AE data of this Chapter and the AE data reported in the support documents of Wong and Xiong (2018) are the AE number and its moment amplitude estimation.

First, in Chapter 4, the moment of the AE events are estimated through the following expression,

$$M = \sqrt{\frac{M_{ij}M_{ij}}{2}}$$

Later, this AE moment will be converted into AE moment amplitude through the expression used in Chapter 4, Chapter 5 and this Chapter (i.e. $M^* = \frac{2}{3}[\log_{10} M_{relative} - C]$). However, in this Chapter, the calculation of the relative AE moment in the first step is identical with the calculation used in Chapter 5 (i.e. $M_{relative} = \frac{1}{n} \sum_{i=1}^n \sqrt{(R_i C s_i A_i(x))^2}$). This is because, in Chapter 4, the purpose of calculating the moment magnitude is to get a rough idea about the magnitude-frequency distributions of the AEs. It is easy to directly calculate the AE moment out of the AE moment tensor since the moment tensor is already available in the previous data analyses steps of Chapter 4. However, essentially, the AE moment magnitude (or the AE moment) in Chapter 4 is the “two-steps” approximation of the AE moment. The first-step approximation is the calculation of the AE moment tensor, which has been completed through the SiGMA moment tensor inversion process. The second-step approximation is the AE

moment calculation equation, $M = \sqrt{\frac{M_{ij}M_{ij}}{2}}$. This “two-steps” approximation includes more sources of errors and is of higher possibility to produce larger errors in the estimation of the AE moment than the calculation used in Chapter 5 and this Chapter. The calculation used in Chapter 5 and this Chapter is “one-step” approximation of the AE moment, where the AE moment is directly estimated from the amplitudes of the first peaks.

Second, in Chapter 4, only the AE events which can successfully produce moment tensors are extensively analyzed and are used in the source location plots. Therefore, for those source locations whose qualified waveform signals are less than 6, they are not reported in the support document of Wong and Xiong (2018). The data which is publicly available in the support document of Wong and Xiong (2018) is absolutely enough for completing the analyses of Chapter 4 and enough for reaching the conclusions of that Chapter. However, they are not the ideal data for the much detailed AE data analyses of this Chapter. In this Chapter, more AE events have been re-discovered and the magnitude of completeness has been greatly extended downwardly, which are rightfully helpful for extending the AE data analyses into much greater details. The data in the support document of Wong and Xiong (2018) is not suggested to be used in the similar data analyses of this Chapter, although I have not made this attempt yet.

6.5.2 Data shuffling and determination on the existence/non-existence of event-event triggering

The data shuffling process of this Chapter follows Davidsen et al. (2017), where the time, spatial location, and magnitude information of the AE events are shuffled independently. The new data set is of randomness in nature, thus statistically no triggering should exist in the shuffled data set. By observing the distribution of the shuffled data set in the normalized space-time plane, the threshold for dividing the existence and non-existence of triggering phenomenon can be determined. To avoid the bias of the data shuffling, multiple times of

data shuffling can be conducted. The following Figure 6.4 represents an example of this shuffled data set. The lighter color represents higher data density. A threshold of $n = 8$ is fairly enough (over two orders lower than the yellow center of the cluster) for filtering out AEs having no triggering relationship. In the data analyses process of this Chapter, over 100 times of data shuffling experiments have been conducted for each test and 10 of them have been stored with full data set.

Figure 6.4. Distribution of randomized AE data in normalized spatial (l^*_{i-to-j}) and time (τ^*_{i-to-j}) space

6.5.3 Magnitude-frequency distribution and magnitude of completeness

The parameter b-value of the AE data set for the analyses of this Chapter can be estimated through the statistical feature of the AE magnitude-frequency distribution. The following Figure 6.5 gives an example of obtaining this parameter for $\beta = 60^\circ$ test. A threshold of AE data completeness at $M_{\text{threshold}} = -0.6$ is fairly enough to distinguish the threshold magnitude on the magnitude-frequency distribution where above it the distribution obeys the power law distribution (the G-R law). The AE data set produces $b = 1.3155$ according to the maximum likelihood estimation, $b = \log_{10} e / (\overline{M^*} - M^*_{\min})$, where $\overline{M^*}$ and $M^*_{\min}$ are the average and minimal moment magnitudes respectively. To testify the sensitivity of the results to this parameter, in the parallel analyses the global average b-value, $b = 1$, has been used. Identical phenomena can be discovered again under $b = 1$, but for some AEs the network built under this condition will produce different node-to-node topological connections. Beyond the magnitude of completeness, the existence of triggering and anti-clustering becomes pronounced statistically (see Figure 6.1(a)), which in turn proves the correctness of the magnitude of completeness.

Figure 6.5. AE relative magnitude-frequency distribution

6.5.4 Determination of fractal dimension

The fractal dimension of AE clusters, Df , can be estimated through the spatial distribution feature of the AEs. Figure 6.6 presents an example of how this parameter can be determined. As the fracture/fault is undergoing symmetry/quasi-symmetry extension, the AE events are divided into two clusters, and the clusters' centers are obtained using k-mean algorithm. The distribution of AE density from 12 mm to 42 mm (± 3 mm) to the cluster's center in this figure display typical power law distribution which ideally fit the definition of AE fractal dimension, $\mu(R < r_i) = A_h r_i^{Df}$, where μ is the density, and r_i is the distance. Taking the data set from 12 mm to 42 mm ± 3 mm out, the Df can be obtained through the linear regression of $\log \mu = constant + Df \cdot \log r_i$. Results are listed in the upper-right insert table. Other regression methods can also be used. The selection of linear regression is just for simplicity. Although the linear regression used here is not the ideal regression method

for the power law type relation, however, it is believed that it will not generate significant larger statistic error than the other regression methods. Additionally, the stability of the data analyses results have been verified by increasing the Df value into a much larger one, which has been discussed in section 6.4.2 “robustness of the results”.

Figure 6.6 Density distribution of AE event to the AE cluster center, and the linear regression results for Df (upper-right insert)

6.5.5 Temporal location of the roots for the dominant trees

In Figure 6.7, an example of the temporal location for the root of the dominant tree has been plotted together with the stress curve and AE event histogram. This example comes from $\beta = 60^\circ$ test. More information about the time sections of the rises and drops of AE event histogram can be found in Table 4.2 (or table 3 of Wong and Xiong (2018)). Stress peak is located at 3306s to 3323s. The axial force data at these two points are quite close, and from 3306 to 3323 the axial force data has perturbed around 181 kN. The range of this perturbation

is certainly smaller than the uncertainty of the axial force measurement (see Chapter 3, it is 1.25 kN accuracy, 0.5% of the maximum measurement capacity). Axial stress before and after that range goes down monotonically as the time moves away from that perturbation stage. While the temporal location for the root of the dominant tree, 3332.7s, is fairly after this stress perturbation stage. For the $\beta = 70^\circ$ test, three dominant trees can be identified (see Figure 6.1(c)). Similarly, all of the temporal locations for the roots of these dominant trees must be after the axial stress has entered the peak perturbation stage (or the pre-peak stress perturbation has already completed).

Figure 6.7 AE event histogram and peak stress

6.5.6 Phenomenon of sudden spatial tree size growth in post-peak

The sudden spatial tree size growth when the axial loading just entrances the post-peak domain can be further elucidated and visualized through the following method.

First, a network which includes only the AEs released in the pre-peak to peak loading domain can be built. Excepting the single node family, the spatial features of all trees within this network can be displayed by plotting the nodes of all individual trees on the X-Y plane. Thus, one can visualize the existence or non-existence of non-local triggering in the pre-peak to peak loading domain as well as the spatial spans of all trees.

Second, another network can also be built using the AEs from pre-peak loading to first AE peak. The time of the first AE peak is just slightly after the moment of stress peak. Repeating the work in the first step, the sudden spatial tree size growth can be clearly seen through the comparison between the results of the first step and second step.

An example of these analyses has been presented in Figure 6.8. This example is from a tree whose root is the 330th AE. The plot is from the second step, where AEs from pre-peak loading to the first AE peak have been used to build the network. This tree, rooted at 330, is with 13 events, 5 leaves, and averaged leaf depth $\langle d \rangle_f = 3.4$. Clearly, it has already displayed the spatial crossing migration when the axial loading has just passed its peak loading. Another tree, rooted at 338, with 16 events 5 leaves, and $\langle d \rangle_f = 5.8$, has also displayed the spatial crossing migration, but weaker than tree 330. On the contrary, at pre-stress-peak stage the largest tree will not have more than 4 events. For the network built in the first step, checking all trees with 3 or more than 3 events, no spatial crossing migration exist. Another interesting phenomenon should be mentioned is, according to Chapter 4 (also according to Wong and Xiong (2018)), the optical length of the white patch fracture process zone has just exceeded the length of the pre-existing flaw at the moment the stress peak has just passed. This again highlights the correlation between the spatial tree growth and the fracture process zone. As the consequence of the crossing migration phenomenon, interactions between the fracture process zones at two ends of the flaw have proved to be existed. Statistic evidences

prove that the crossing migration of the AEs is facilitated by the flaw; and the non-local triggering process further amplifies the stress perturbations at two ends, leading to the massive AE releases to its peak (Figure 6.2(d) middle insert).

Figure 6.8 Appearance of a tree that has spatially migrated across the open section (the flaw). The network of this tree includes only the AEs from pre-peak loading to the temporal location immediately after the stress has entranced the peak perturbation period

6.5.7 Features for the AE clusters of dominant trees

For the other dominant trees, i.e. the three dominant trees in $\beta = 70^\circ$ test, it is easy to prove the existence of the crossing migration by plotting out their Y axis projection versus time. Example of this plot has been presented in Figure 6.9. More than proving the existence of non-local triggering, for the red tree, two red dots can be found in pre-peak loading (but after one pre-peak stress perturbation). This agrees with the small and random perturbation assumption of the SOC modeling, which has been much more extensively discussed in section 6.4.3 “roots”. Also, it is easy to find in Figure 6.9 that, the crossing migration of these dominant trees must be after the stress has entranced the peak perturbation stage. The first peak concentration of the red tree is also prior to the first AE peak (Figure S 6.6 lower-right insert), which is similar with the temporal correlation between the peaks of non-local triggering events and the peaks of AE events (displayed in Figure 6.2(d) middle insert). Identical analyses have been conducted for both $\beta = 60^\circ$ test and $\beta = 70^\circ$ test. All the conclusions presented in this Chapter can be verified, although in some places example from only $\beta = 60^\circ$ test have been presented, which is just for simplicity consideration. Identical phenomena can be found in both tests.

Figure 6.9 Y projections of AE events of three dominant clusters (left Y axis) for specimen containing 70° preexisting flaw versus time, and stress (right Y axis) versus time. Three dominant trees are represented by dots of red, blue, and green, respectively. Lower insert is the Y projections of the AE events of these three dominant clusters (left Y axis) and AE histogram (right Y axis) versus time

6.5.8 Non-local triggering—amplifying the stress perturbation and as precursor of the much more massive energy releases

More specifications of the relationship between the peaks on non-local triggering events and the peaks on all AE releases have been depicted on Figure 6.10, which is an enlarged one of Figure 6.2(d) middle insert. There are two peaks on non-local triggering events which are closely prior to the peaks of all AE releases, which has been indicated on Figure 6.10. These two peaks are temporally closely prior to the following AE peaks, seems as if they are the

precursors of the following much more massive energy releases. The stress perturbations at two ends of the extending fracture process zones absolutely have been amplified by these peaks of non-local triggering. It is because the following massive AE energy releases are simultaneous with the onset of comparatively faster stress drops (the inflection points on stress curve as described in Chapter 4) and simultaneous with the optically more aggressive extensions and changes on the fracture process zones (Wong and Xiong, 2018). Within those aggressive extensions of fracture process zones, phenomena of brightening dots migration and occurrence of wrapped sections can also be observed (Wong and Xiong, 2018), serving as the indications of stress severity transferring process. These optical phenomena have further confirmed the influence of non-local triggering on amplifying the stress perturbations.

More interestingly, it is known that the first peak is close to the stress peak. Therefore, considering the fact that at the moment of first AE peak all non-local triggering AEs are spatially close to the two ends of the flaw (Figure 6.8), the temporal information of the first non-local triggering peak in Figure 6.10 seems to agree with the conclusion of Davidsen et al. (2017) in that “triggered events may decrease with the distance to notches”, as in Davidsen et al. (2017) only AEs from pre-peak loading to peak loading has been used in analyses. What Davidsen et al. (2017) have not analyzed is the features of the AEs in the following multiple stick-slips of their experiments, which in their experiments are after the onset of the first stress drop. This partially explains the different observations between this Chapter and Davidsen et al. (2017). Amazingly, the post-peak phenomena evolvement of the present experiment exactly follows the prediction of SOC modeling.

One peak of non-local triggering is closely after the first AE peak. However, no massive AE energy release (another AE peak) is closely following. The temporal location of this non-local triggering peak is within the relaxation stage after the first AE peak. This special phenomenon may contain some information of the relaxation stage which appears to be the analogue of the behavior of aftershocks.

Figure 6.10 More specifications on the non-local triggering as precursor of more massive AE release based on Figure 6.2(d) middle insert

Chapter 7 Discussion, conclusions, and suggestions of future work

7.1 Process of finding the post-peak analogue phenomena of seismic activity in uniaxial compression tests on pre-flawed specimens

At the beginning of conducting the experimental tests which are reported in this thesis (Chapter 4), the aim was just to investigate the AE behaviors of the fracture process on the single flawed specimens under compression. The research perspective at that moment was quite close to that of Lajtai (1969) in some over 50 years ago—out of the perspective of the classical Griffith's fracture mechanics theory. But the discovery on the analogue laboratory seismic releases in the post-peak loading of uniaxial compression tests on specimens containing flaw(s) was coincident and unexpected.

It was thought that, the fracture propagation can release AEs, and through the moment tensor inversion on the AE signals released from the fracture propagation, more information about the fracture process of single flawed specimens can be obtained. Comparing to the previous publications on the experimental investigations of the fracture process on pre-flawed specimens under compression, the only adaption of my tests was the loading rate. A displacement loading rate which is within the range adopted by most AE experiments (e.g. Goebel (2013); Goebel et al. (2012); Goebel et al. (2015); Goebel et al. (2013); Kwiatek et al. (2014b); Lei (2003); Lei et al. (2000a); Lei et al. (2003); Lei et al. (2000b); Lockner and Byerlee (1975); Lockner et al. (1991); Stanchits et al. (2009); Stanchits et al. (2006); Zang et al. (1998); Zang et al. (2000)) has been used in my tests. The thought was simple—to answer a question whether the fracture propagation from the single pre-existing flaw can be correlated with the releases of any typical meso-scale AE crack type as it was correlated with the pre-peak stress levels in many previous researches of this kind.

However, the information obtained from these tests on single flawed specimens is ways beyond the original expectation. Besides the attempts in correlating the fracture process with

typical meso-scale AE crack types, the most astonishing phenomenon is, most of the AE phenomena can only occur in the post-stress-peak loading domain. The interpretations of these phenomena have already exceeded the scope of most of the interpretation methodologies which are applied to interpret the pre-peak to peak mechanical behaviors of previous experimental studies on single flawed specimens under compression. On the contrary, for the incipient fracture process zone extension, which can primarily happen in pre-peak loading, the extension of those incipient fracture process zones in the format of white patch usually escape the monitoring of AE source locations.

After a careful check on the loading rates used in previous publications of this kind, it is really rare that only one of them has been found to have adopted the slow loading rate which is comparable to the present tests. That only one publication (i.e. Nguyen et al. (2011)) uses Digital Image Correlation in investigating the fracture process on specimens containing multiple pre-existing flaws. However, no post-peak phenomenon has been reported in that publication (Nguyen et al., 2011). Additionally, in present tests the optical observations prove that several types of the appearance changes on the fracture process zones could happen when the loading has entered the post-peak loading domain. These changes are proved to be correlated with the changes on the meso-scale AE crack type curves. For instance, the widening of the white patch for macro-scale shear cracks may be accompanied by the increase of shear crack ratio in meso-scale; the vivid migration of brightening dots are in most of times correlated with the abrupt phase of crack type changes; etc. These facts are the undeniable evidences that, the post-peak evolvement of the fracture process zone exists. However, in the work of Chapter 4, still a great amount of effort has been devoted to find the correlation between the meso-scale crack type changes and the fracture propagation. The post-peak fracture process zone evolvement still draws limited attention in the publication of Wong and Xiong (2018), although the demand for an alternative physical description for the fracture process on pre-flawed specimens has already emerged.

In the tests on specimens containing double pre-existing flaws, the white patch fracture process zone between flaws can clearly be truncated by the flaws. The alternative explanation on the periodical AE releases, which attributes the periodical AE releases to the fracture

propagation instead of fracture post-peak evolvement, can be rejected. Therefore, clearly, the post-peak evolvement stages of the fracture process zone have been discovered. Instead of the fracture propagation towards one direction causes the periodical AE releases, the evolvement of the fracture process zone in the post-peak domain causes the periodical AE releases. The forming of the fracture process zone in the form of white patch has been completed in pre-peak to peak loading. It is of high possibility that the forming of the white patch zone can escape the AE monitoring according to the experimental observations.

Additionally, detailed data analyses on the experimental results of Chapter 4 have been conducted and reported in Chapter 6. The spatial and temporal features of the AE network almost exactly fit for the predictions of SOC theory. Those features can only display in post-peak domain. Thus the fracture process zone (or the specimen as a whole) is of criticality state. These experiments and data analyses further highlight the importance of the post-peak fracture evolvement. Indeed, the terminology of “fracture propagation” has not been used in Chapter 5 and Chapter 6. It is must have a second consideration about whether to weight the “fracture propagation” over the “fracture evolvement” in understanding the analogue post-stress-peak seismic release is proper.

Along the experimental investigations which lead to the discovery of the post-peak fracture evolvments on pre-flawed specimens and the novel data analyses on these laboratory analogue seismic releases (the AE releases) in the post-peak loading domain, plenty of new understandings are obtained on the fracture process in pre-flawed specimens as well as on the earthquake mechanisms. They are summarized in Section 7.2.

7.2 Conclusions on the experimental results and data analyses of the tests presented in this thesis

(i) Uniaxial compression tests on specimens containing a single pre-existing flaw have been conducted with the observations of multiple systems, i.e. AE system, normal and high-speed optical observation systems, mechanical loading and stress-displacement measurement system. It is the first time that the continuous picture on the white patch extension and the accumulation and clustering of different types of cracks in meso-scale can be obtained in such type of test.

(ii) In the correlation between the macro-scale optical observations and meso-scale AE interpretations on the fracture process, many optical macro-scale changes on the fracture process zone are correlated with the changes on the meso-scale AE crack types. For instance, the widening of the white patch for macro-scale shear cracks may be accompanied by the increase of shear crack ratio in meso-scale; the vivid migration of brightening dots are in most of times correlated with the abrupt phase of crack type changes.

(iii) Additionally, the incipient forming of the fracture process zone in the pre-peak loading in both types of tests, i.e. tests on specimens containing a single pre-existing flaw and tests on specimens containing a pair of coplanar flaws, can usually escape the AE monitoring. The facts in (ii) and (iii) prove that the post-peak evolvement of the fracture process zone exists.

(iv) Successive mechanical instabilities can be generated in peak to post-peak loading domain of a test on specimen containing a pair of pre-existing flaws. Along these mechanical instabilities, the experiment combines the process of creating a laboratory fault on intact rock material and the process of frictional slip along a well-formed laboratory fault together into one continuous laboratory process.

(v) In the post-peak fracture evolvement of the test which has generated three successive mechanical instabilities, the physical processes of this evolvement can be divided into fault

creation and fault slip. Distinctive different features are displayed in these two physical processes in AE, mechanical, and optical aspects.

(vi) Analogue features of the real natural fault have occurred in the laboratory fault. For instance, the creation of powder gouge layer, the zig-zag shape of the laboratory fault and the asperities having natural randomness.

(vii) Progressive widening of the well-formed fault and massive creation of the marble powder can be observed for fault slip. The AE behavior features, i.e. the rise-and-drop feature of AE event amount and the feature of AE moment release rate, also evolve towards the features of a natural fault as the physical process shifts from fault creation to fault slip.

(viii) A well-established data analysis method in seismology has been applied to investigate the acoustic emissions of fracture undergoing symmetry/quasi-symmetry extension.

(ix) Non-local triggering phenomenon has been proved to be existed in the rock fracture process. Statistically, the non-local triggering can be facilitated by the pre-existing flaw.

(x) Post-peak AE temporal and spatial features within the rock fracture process exactly fit for the theoretical predictions of SOC theory when large-scale imperfection is existed.

(xi) Peaks of non-local triggering are closely prior to the AE peaks, while simultaneously the whole system is under post-peak criticality. Those occurrence of non-local triggering amplifies the stress perturbations at the ends of large-scale imperfection and could be a precursor of the oncoming massive energy releases.

7.3 limitations of the experimental scale results on uniaxial compression tests

The present tests are all conducted under uniaxial compression loading, which is partially attributed to the limited availability of experimental equipment. Under my understanding and my perspective, the limitations are primarily on three aspects, which I will further elucidate in the follows.

- First, limitation which is fundamentally rooted on the focus

The first and the most fundamental limitation is rooted on the focus of the present thesis. The focus of this thesis is rooted on the laboratory analogue(s) of large-scale natural seismicity. In reality, however, according to the experimental results almost all of these analogues can only be observed in post-stress-peak rock fracture evolvement; and it is, out of the best knowledge of the author, almost the first time the post-peak fracture evolvement phenomena have been treated as the primary focus of these so-called “common type” uniaxial rock mechanics tests—the uniaxial compression tests on pre-flawed specimens. Therefore the experimental results and the corresponding data analysis can provide very little information on the mechanical understanding of pre-flawed specimens. On the contrary, the mechanical understandings, such as, strength, fracture patterns, etc., are the focus of many engineering rock mechanics applications (i.e. Bobet and Einstein (1998); Moradian et al. (2015); Wong and Einstein (2009a); Wong and Einstein (2009c)).

Indeed, for the success of experimental observation on the post-stress-peak phenomenon, many of the mechanical considerations have been simplified and on purposely overlooked, for instance, the selection of co-planar pre-flaws, and the usage of only one rock type for all the tests. The author has also on purposely not followed the previously common experimental data analysis procedures as well as conclusions on analyzing the strength of pre-flawed specimens and their failure patterns. However, even under such simplifications, once the post-stress-peak evolvement can be experimentally observed (Wong and Xiong, 2018), the subsequent complexity is way over the author’s original expectation. This surprise holds true

throughout all tests conducted on single flaw specimens as well as on double flaw specimens.

According to Reches and Lockner (1994), the shear slip nucleation could be of an angle between 20-30 degree deviated from the maximum stress direction. In the uniaxial loading condition, it is a failure plane of an inclination angle between 60-70 degree to the horizontal direction. If one focuses on the phenomena in experiments of coplanar double flaw specimens where their coplanar flaws are of this angle, the induced failure plane bridging the pre-existing flaws will also be of this angle. From a mechanical and determinism perspective, if two specimens are of identical pre-flaws—identical flaw inclination angle, flaw gapping distance, flaw aperture, flaw length, etc., their mechanical strength and the failure pattern of these specimens under identical loading protocol should be convergent. However, the experimental results point towards a contradictory conclusion against this perspective.

For instance, in the tests, two different variations of rock fracture process can occur among the tests of identical setting. The FPZ can either be forged first and evolve later as a whole system (see Figure 7.1(b)), or the FPZs from two inner flaw tips are escaping each other and their connection can immediately lead to rock fracture rupture (see Figure 7.1(a)). While again, the author must emphasis, this category classification is based on the displayed post-stress-peak evolvement of rock fracture. Categories proposed by previous literature of this kind of tests appear not applicable to categorize my test results. Therefore, out of my limited knowledge, I can only give such a very preliminary category classification as shown in Figure 7.1. A more interesting thing is, by summarizing the results of multiple tests, the ratios of both categories are only approximately 40%. While for the rest approximately 40% tests, they should belong to the intermediate stage—the in-situ optical observation suggests that the FPZ is forged first and later evolves as a whole, however once epoxy is used to impregnate the FPZ, a sine shape damage zone can occur.

Figure 7.1 illustration of two post-stress-peak based rock fracture behavior

There is an implicit experimental design consideration on this thesis, by on purposely using the special pre-flaw structure to truncate a fracture section. Once the mechanical behavior in the post-stress-peak domain can be more complicate than a directly drop down, and the FPZ in between the two coplanar flaws can optically be observed and whose forge is prior this complicate post-stress-peak mechanical changes, the subsequent post-stress-peak mechanical changes must be attributed to the inherent rock fracture evolvement other than the

classical fracture mechanics' understanding which may suggest that the fracture propagation should primarily control the specimen's mechanical behavior.

Indeed, it touches one fundamental issue of fracture mechanics and its application in the analysis of rock mass behavior. According to the available experimental results of fracture mechanics, for two approaching shear fractures in the nominal brittle materials they should tend to avoid each other instead of linking each other directly. Even if it is commonly known that the FPZ in rock is ways larger than that in metals or fine-grained ceramics (Nolen-Hoeksema and Gordon, 1987), there are hardly any experimental literature where the rock FPZ has firstly damaged the whole region between two inner flaw tips, forges, and later evolves as a whole system.

In Chapter 6, I have introduced the SOC theory for the AE data analysis. This theory shares great similar presumptions with the chaos theory. Indeed, the observed experimental result exactly fits for the description of the chaos theory—a butterfly flapping its wings in the Amazon can influence a typhoon in the Pacific Ocean (Boeing, 2016). Here, a small perturbation (the root of the dominant tree) occurs at a seemly random place, can trigger a series of cascading damages which traverse the whole rock specimen and lead to the final specimen rupture. One cannot know exactly which “butterfly” causes the cascading chain-reactions; however, once this butterfly event has changed its feature, e.g. its magnitude, or its place, a whole rock fracture evolvement series will likely to be changed. If one applies this concept into the analysis on the post-peak mechanical behavior of double flaw tests, once the post-stress-peak fracture evolvement begin to occur and gradually become the dominating factor for the specimen's global post-peak mechanical behavior, we definitely should not expect the convergent experimental results.

A further investigation on these experimental results is suggesting a primarily understanding on the correlation between the post-peak fracture evolvement and the final specimen rupture—the controlling factor appears to be a kind of micro-scale feature, a feature that affects the time sequence of the fracture development in on-fault or off-fault directions (further illustration can also be found in section 7.4.2). Consequently, where is the boundary

for applying the different disciplines in the interpretation of the experimental rock fracture behavior? To what extent, it should be explained by fracture mechanics; and to what extent, it should not? For this question, till now, the author do not have a clear answer.

- Second, confining pressure

Experimental results from literature on double flaw specimens suggest that a bi-axial loading condition can induce different rock fracture patterns than uniaxial loading do (Bobet and Einstein, 1998). For instance, a general tendency on the influence of bi-axial stress is the growth of secondary tensile fractures on the off-fault direction can be inhibited. Although the authors of the above research (i.e. Bobet and Einstein (1998)) acknowledged that, experimental results of pre-flawed specimens are material dependent, and test dependent (i.e. the loading dependent, and even the experimental equipment dependent), which can make the cross comparison among different experimental results difficult, their results are out of identical material preparation, and identical loading machine. As such, the tendency on the influence of bi-axial stress should be convincible for the interpretation of pre-stress-peak to stress-peak mechanical behavior. The case dependency nature, as well as the small experimental number where this thesis has presented, have further weakened the possibility of drawing any in-depth mechanical understanding on the pre-stress-peak rock fracture behavior.

For the post-stress-peak fracture evolvement and the analogue of seismicity which is the focus of this thesis, the author had hoped similar analogue feature(s) can be found through the experiments using the loading protocol adopted by many previous researches. For testifying this, the author has conducted a parallel experimental test whose flaw geometry and material are identical to that of the test in Chapter 4 but the so-called “common practice” of loading protocol has been used. The comprehensive comparison of the analogues out of different loading protocols will be presented in section 7.4.2. The author had hoped similar analogue can be found. Unfortunately, according to the experimental result, there is no evidence to support that the similar analogue of the tectonic-scale earthquake activity still can exist when this so-called common practice of loading protocol has been adopted.

As such, the author should have a caution on believing that the general tendency of the influence of bi-axial stress on inhibiting the growth of secondary tensile fractures can be still valid for the post-stress-peak rock fracture evolution under slow loading tests. However, even if out of the fundamental pursuit for the laboratory-scale analogue of natural tectonic-scale phenomena, it is very meaningful for conducting tests under bi-axial loading. It is because, by changing the bi-axial stress, we can observe the rock fracture evolution under a series of different normal stress to shear stress ratio. Without that, as the present tests which are conducted under uniaxial loading, the normal stress to shear stress ratio can mostly be determined by the inclination angle of the coplanar pre-existing flaws. The normal stress to shear stress ratio is widely believed as a controlling factor for influencing the fault evolution, especially for influencing the alteration of the asperities along the fault (Scholz, 2002). It is also impossible for on purposely changing the normal stress to shear stress ratio for the different stages of rock fracture evolution under uniaxial loading condition. However, it is an important aspect on rock fracture evolution.

From the perspective of natural tectonic-scale phenomena, the in-situ stress condition along or near a fault region can be altered due to multiple causes, such as, large earthquake rupture (Parsons et al., 2008), nuclear explosion (Hong et al., 2016), natural energy exploitation activities (Zeng et al., 2015), as well as long term geo-chemistry processes (Bahesti, 2014; Varre et al., 2015). The in-situ stress can also change by time due to several inherent mechanical processes of fault zone, such as creeping of aseismic section(s) (Rubin et al., 1999), etc. As such, it is really a pity as well as a limitation of the present thesis that no test under bi-axial loading has ever been conducted.

- Third material usage

The testing material, Carrara marble, is only one of the rock materials. The selection of this material is out of several empirical considerations. It has a good balance among its mechanical and AE related physics properties. For instance, it has homogeneous wave velocity field, homogeneous initial undamaged status, comparatively significant change on its optical appearance once a region has been occupied by damages, and comparatively not too

small strain energy releases in rock fracture. This delicate balance indeed has significantly contributed to the success of the experimental observation. For instance, granite may have a stronger energy release in its fracture, but when a FPZ is initially forming the optical changes on its colorful and texture surface can hardly be observed through naked eyes—most literature would use microscope for this observation; other soft rock materials may just not have enough energy release for a comprehensive AE monitoring.

The other rock materials, especially those rocks that are plenty in the fault region, should be of further research interesting. More importantly, when one considers the two facts that (i) the phase transfer in rock crystal would be stress dependent (Schubnel et al., 2017) as well as the morphology transfer in rock fracture would be shear velocity dependent (Di Toro et al., 2004; Reches and Lockner, 2010) for different kind of rocks, and (ii) the Carrara marble is comparatively a meta-stable rock, the present conclusion drawn from the experimental results of the uniaxial compression tests on a kind of meta-stable rock would be of limited representative for the complexity of the great Mother Nature.

However, one should bear in mind, it is almost the first kind among the so-called “common type” uniaxial rock mechanics compression tests on pre-flawed specimens that complex post-stress-peak evolvement has displayed with a great analogue of the natural seismicity. At this stage, we should ask ourselves, shall we simplify the experimental setting so that the complex coupled-together different mechanisms in rock fracture evolvement can be separately distinguished out? This strategy will be at a sacrifice on the approximation of the experimental setting to the complexity of the great Mother Nature. Or shall we sacrifice the chance of separating the coupled-together mechanisms, and make the approximation of experimental setting best to the complexity of the Mother Nature? It can always be a dilemma for the research strategy of the experiments, especially for those investigations on some newly observed phenomena.

7.4 Future works and some preliminary results

The phenomena in the post-peak domain of compression tests on pre-flawed specimens have occurred, been investigated, and been analyzed in this thesis. Together with the novel understandings this thesis have stated, conflicts between the interpretations of the present thesis and the interpretations of previous experimental investigations on the compression tests on pre-flawed specimens have also occurred. Those conflicts also intrigue certain questions for future researches.

(i) First, it appears that by only adopting a slow displacement loading rate, the post-peak fracture evolvement can occur. On the contrary of this seemingly simple fact, what deeper mechanism(s) can be found in explaining the different fracture processes on pre-flawed specimens under slow loading rate and fast loading rate?

(ii) Second, periodical AE releases are observed in a test which originally should belong to rock rupture type test (the 60-1 test in Chapter 5). It is classified as the rupture type test as a laboratory fault has been created on intact rock material. What mechanism has temporally stopped the rock rupture?

The SOC theory predicts that the energy release state is of no inherent scale limitation and the only limit is the physical boundary. On field, the reality that stops the earthquake rupture would be referred as the rupture barriers. In laboratory, do the analogues of the rupture barriers rather than the specimen boundary exist? What are the mechanisms behind the stopping and reactivation of the periodical laboratory massive energy releases?

(iii) Third, since the previous fracture coalescence interpretations primarily focus the phenomena in pre-peak to peak loading domain, how should we comprehensively understand the relation between the white patch patterns formed in pre-peak loading and their following post-peak evolvement?

In the following sections, these questions will be further discussed. Together with the discussions, some preliminary results containing the possible answers to those questions will

also be presented. Those results will be included in some of my future publications addressing different issues.

7.4.1 Existence and non-existence of the Poisson process in laboratory rock fracture process

To address the first question, what deeper mechanism(s) can be found in explaining the different fracture processes on pre-flawed specimens under slow loading rate and fast loading rate? The most straightforward method is to repeat the experiments with fast loading rate and compare the experimental results with that of slow loading. To make this comparison, experiments of fast loading has been conducted on specimen containing a single flaw. This time, the loading procedure exactly follows that of Wong and Einstein (2009c). Following the similar data analyses procedure of Chapter 6, it is found that the AEs of Poisson process have predominantly occurred for the slow loading test. On the contrary, the AEs of Poisson process have almost disappeared in the fast loading test (see Figure 7.1). This phenomenon has been illustrated in Figure 7.1. The AE feature of fast loading test is displayed on the left of Figure 7.1; while the AE feature of slow loading test is displayed on the right of Figure 7.1.

The disappearance of the AEs of Poisson process has already proved that the AE statistical feature of the fast loading tests is not a good analogue of natural seismic activity, as the seismic events of Poisson process can in most of times occur in natural fault zone. The preliminary post-mortem exam on these specimens suggests much wider fracture process zone can be formed under slow loading. To find more comprehensive information on the fracture process zones, micro-observations on these fracture process zones are undergoing. Efforts are devoted on finding the connections and physical interpretations between the existence/non-existence of the Poisson process and the difference on the fracture process zones.

Figure 7.2 Illustration for the disappearing of Poisson Process AEs in faster loading test

7.4.2 Off-fault rupture barriers and rupture types for laboratory fault

The second natural question is whether analogues of the rupture barriers rather than the specimen boundary exist? How these rupture barriers have influenced the stopping and reactivation of the periodical laboratory massive energy releases? To address this question, more tests on specimens containing a pair of coplanar pre-existing flaws have been conducted, and further data analyses on these experimental results have been made. One of the primary features for the data analyses at this time is the usage of the concept of containment spheres following Reches and Lockner (1994). The sudden drop on the radius of the containment spheres can indicate the temporal location of fracture nucleation. Tracing the migration of the AE cluster after the temporal location of the fracture nucleation point, a clearer picture on the development sequence between the on-fault fracture and off-fault fracture can be obtained. By comparing the rupture models and the positions of the first fracture nucleation which are indicated by the sudden drop of the radius of containment spheres, the analyses suggest that the sequence of the on-fault fracture evolvement and the off-fault fracture development are the key issue to determine the laboratory fault rupture model.

Takes one test conducted on specimen containing a pair of pre-existing flaws, which are

70° inclined against the horizontal direction, as an example. The illustration has been displayed in Figure 7.2. The first fracture nucleation position is off-fault (see Figure 7.2 (a) and (b)). Optical observation (Figure 7.2 (d)) of this test has indicated an otherwise sequence of the on-fault and off-fault fracture developments, which is judged by the first occurrence of the white patches. Considering the AE is an indication of energy release, the location of first fracture nucleation which is indicated by the AEs analyses should have obvious energy releases. Revising the optically observed fracture development sequence (white patch) under this energy consideration, universal explanation on the different post-peak fracture evolvement models can be achieved.

Figure 7.3. Illustration of find the on-fault/off-fault fracture development sequence (a) plot of containment spheres, (b) first fracture nucleation location, (c) development of on-fault fracture unveiled by AE observation, (d) optical fracture development sequence

The analyses should focus on the tests creating fault whose inclination to the maximum stress direction is within the theoretical predicted range of natural sliding fault (Reches and Lockner, 1994). Different models of post-peak fracture evolution can occur in different tests on specimens having identical geometrical setting for pre-flaws. This fact rejects the hypothesis that geometrical setting can predominately control the whole rock fracture process on pre-flawed specimens. It is due to the existence of post-peak fracture evolution process. The post-peak fracture evolution is self-organized, and shows dependence on some factors which have not been considered before.

7.4.3 Re-evaluation of the fracture coalescence pattern classifications and a comprehensive understanding on the relations between the pre-peak patterns of the fracture process zones and the following post-peak phenomena

To address the third question, how to comprehensively understand the relation between the patterns formed in pre-peak loading and their following post-peak evolution, systematical experiments on specimens of different geometrical settings of the pre-existing flaws should be conducted. A summary of those tests conducted by the author has been provided in Table 7.1. To comprehensively understand the fracture process zones whose initial patterns are primarily formed in pre-peak to first peak loading and the following fracture evolution, a novel experimental data interpretation method is proposed. Continuous effort is devoted to the micro-observations on the post-mortem specimens. Some preliminary results are,

(i) some previous different fracture coalescence categories need to be unified. To divide them into different categories is due to the different completeness levels of the post-peak fracture evolution in different tests of previous publications;

(ii) scale-invariant phenomena can be found in the post-peak fracture evolution, for instance, the serpentine scale-up of the fracture process zone and the forming of interlocking

structures through different means;

(iii) stable structures, for instance, the stiff parallelogram, can always induce much greater massive strain energy releases, which indicate the oncoming of greater disasters.

Hopefully, this work can provide a more comprehensive understanding on the previous experimental results and the newly discovered post-peak evolvement. This investigations will also be beneficial for a comprehensive understanding on the experimental results on specimens containing artificially prepared en-echelon flaws (Cheng, 2015; Cheng and Wong, 2018; Cheng et al., 2016; Cheng et al., 2015). It is because, it is possible that, although the loading rate of those studies is still comparatively faster than the loading rate used in the present thesis, local interlocking or local stiff structure would have occurred among some pairs of the artificial en-echelon flaws.

Table 7.1 Variation of geometrical parameters of the specimens

$\alpha \backslash \beta^*$	70	60	45	30
150	α -150- β -70	α -150- β -60	α -150- β -45	α -150- β -30
120	α -120- β -70	α -120- β -60	α -120- β -45	α -120- β -30
90	α -90- β -70	α -90- β -60	α -90- β -45	α -90- β -30
70	α -70- β -70 $\times 2^{**}$			
60	α -60- β -70	α -60- β -60 $\times 2$	α -60- β -45	α -60- β -30
45			α -45- β -45 $\times 2$	
30	α -30- β -70	α -30- β -60	α -30- β -45	α -30- β -30
0	α -0- β -70	α -0- β -60	α -0- β -45	α -0- β -30
-30	α -(-30)- β -70	α -(-30)- β -60	α -(-30)- β -45	α -(-30)- β -30
<p>* β = flaw inclination angle, α = bridging angle between two closest flaw tips. Both angles are measured from horizontal direction.</p> <p>** $\times 2$ indicates the test has been duplicated. In later section, they will be referred as, α-i-β-j-1, and α-i-β-j-2, respectively.</p> <p>This table only summarized the tests conducted on the specimens whose bridging distance is equal to the flaw length.</p>				

References

- Aggelis, D.G., 2011. Classification of Cracking Mode in Concrete by Acoustic Emission Parameters. *Mechanics Research Communications* 38, 153-157.
- Aki, K., 1979. Characterization of barriers on an earthquake fault. *Journal of Geophysical Research* 84, 6140.
- Aki, K., 1984. Asperities, barriers, characteristic earthquakes and strong motion prediction. *Journal of Geophysical Research: Solid Earth* 89, 5867-5872.
- ASTM, 2017. Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures.
- Båth, M., 1965. Lateral inhomogeneities of the upper mantle. *tectonophysics* 2, 483-514.
- Bahesti, F., 2014. Integrated Basin Analysis and Geomechanics Study of Lower Baong Shale for Preliminary Shale Gas Prospectivity in the North Sumatra Basin.
- Bak, P., Tang, C., 1989. Earthquakes as a self-organized critical phenomenon. *Journal of Geophysical Research: Solid Earth* 94, 15635-15637.
- Baro, J., Corral, A., Illa, X., Planes, A., K, E., Salje, H., Schranz, W., Soto-Parra, E.D., Vives, E., 2013. Statistical similarity between the compression of a porous material and earthquakes. *Physical Review Letters* 110, 088702.
- Bieniawski, Z.T., Bernede, M.J., 1979. Suggested methods for determining the uniaxial compressive strength and deformability of rock materials: Part 1. Suggested method for determining deformability of rock materials in uniaxial compression. *INTERNATIONAL JOURNAL OF ROCK MECHANICS AND MINING SCIENCES & GEOMECHANICS ABSTRACTS* 16, 138-140.
- Bobet, A., Einstein, H., 1998. Fracture coalescence in rock-type materials under uniaxial and biaxial compression. *International Journal of Rock Mechanics and Mining Sciences* 35, 863-888.
- Boeing, G., 2016. Visual Analysis of Nonlinear Dynamical Systems: Chaos, Fractals, Self-Similarity and the Limits of Prediction. *Systems* 4, 37.
- Brace, W.F., Byerlee, J.D., 1966. Stick-Slip as a Mechanism for Earthquakes. *Science*, 153, 990-992.
- Byerlee, J.D., Lockner, D.A., 1975. Acoustic Emission During Fluid Injection in Rock, in: Hardy, H.R.J., Leighton, F.W. (Eds.), *First conference on acoustic emission/microseismic activity in geologic structures and materials*, Pennsylvania State University, U.S., pp. 87-98.
- Carpinteri, A., Borla, O., 2017. Fracto-emissions as seismic precursors. *Engineering Fracture Mechanics* 177, 239-250.
- Carpinteri, A., Borla, O., 2019. Acoustic, electromagnetic, and neutron emissions as seismic precursors: The lunar periodicity of low-magnitude seismic swarms. *Engineering Fracture Mechanics* 210, 29-41.
- Carpinteri, A., Lacidogna, G., Manuello, A., Borla, O., 2012a. Piezonuclear Fission Reactions in Rocks: Evidences from Microchemical Analysis, Neutron Emission, and Geological Transformation. *Rock Mech Rock Eng* 45, 445-459.
- Carpinteri, A., Xu, J., Lacidogna, G., Manuello, A., 2012b. Reliable onset time determination and source location of acoustic emissions in concrete structures. *Cement and concrete composites* 34, 529-537.
- Carvalho, F.C.S., Labuz, J.F., 2002. Moment tensors of acoustic emissions in shear faulting under plane-strain compression. *Tectonophysics* 356(2002), 199-211.
- Charalampidou, E.-M., Stanchits, S., Kwiatek, G., Dresen, G., 2014. Brittle failure and fracture reactivation in

sandstone by fluid injection. *European Journal of Environmental and Civil Engineering* 19, 564-579.

Cheng, Y., 2015. Studies on the Formation of Faults from en-echelon Fractures in Carrara Marble, School of Civil and Environmental Engineering. Nanyang Technological University.

Cheng, Y., Wong, L.N.Y., 2018. Microscopic Characterization of Tensile and Shear Fracturing in Progressive Failure in Marble. *Journal of Geophysical Research: Solid Earth* 123, 204-225.

Cheng, Y., Wong, L.N.Y., Maruvanchery, V., 2016. Transgranular Crack Nucleation in Carrara Marble of Brittle Failure. *Rock Mech Rock Eng* 49, 3069-3082.

Cheng, Y., Wong, L.N.Y., Zou, C.J., 2015. Experimental study on the formation of faults from en-echelon fractures in Carrara Marble. *Engineering Geology* 195, 312-326.

Corral, A., 2003. Local distributions and rate fluctuations in a unified scaling law for earthquakes. *Phys Rev E Stat Nonlin Soft Matter Phys* 68, 035102.

Costa, L.S., Lenzi, E.K., Mendes, R.S., Ribeiro, H.V., 2016. Extensive characterization of seismic laws in acoustic emissions of crumpled plastic sheets. *EPL (Europhysics Letters)* 114, 59002.

da Silva, B.M.G., 2016. fracturing processes and induced seismicity due to the hydraulic fracturing of rocks, Civil and Environmental Engineering. Massachusetts Institute of Technology.

Davi, R., Vavryčuk, V., Charalampidou, E.-M., Kwiatek, G., 2013. Network sensor calibration for retrieving accurate moment tensors of acoustic emissions. *International Journal of Rock Mechanics and Mining Sciences* 62, 59-67.

Davidson, J., Gu, C., Baiesi, M., 2015. Generalized Omori – Utsu law for aftershock sequences in southern California. *Geophys J Int* 201, 965-978.

Davidson, J., Kwiatek, G., Charalampidou, E.M., Goebel, T., Stanchits, S., Ruck, M., Dresen, G., 2017. Triggering Processes in Rock Fracture. *Phys Rev Lett* 119, 068501.

Davidson, J., Stanchits, S., Dresen, G., 2007. Scaling and universality in rock fracture. *Phys Rev Lett* 98, 125502.

Di Toro, G., Goldsby, D.L., Tullis, T.E., 2004. Friction falls towards zero in quartz rock as slip velocity approaches seismic rates. *Nature* 427, 436-438.

Dieterich, J.H., 1972. Time-dependent friction in rocks. *Journal of Geophysical Research* 77, 3690-3697.

Dieterich, J.H., 1979. Modeling of rock friction: 1. Experimental results and constitutive equations. *Journal of Geophysical Research* 84, 2161.

Dieterich, J.H., 1981. Potential for geophysical experiments in large scale tests. *Geophys Res Lett* 8, 653-656.

Germanovich, L.N., Ring, L.M., Carter, B.J., Ingraffea, A.R., dyskin, A.V., Ustinov, K.B., 1995. Simulation of crack growth and interaction in compression, in: Toshio, F. (Ed.), 8th ISRM congress, Tokyo Japan.

Goebel, T.H.W., 2013. Microseismicity, Fault Structure, and the Seismic Cycle: Insights from Laboratory Stick-slip Experiments. University of Southern California.

Goebel, T.H.W., Becker, T.W., Schorlemmer, D., Stanchits, S., Sammis, C., Rybacki, E., Dresen, G., 2012. Identifying fault heterogeneity through mapping spatial anomalies in acoustic emission statistics. *Journal of Geophysical Research: Solid Earth* (1978–2012) 117.

Goebel, T.H.W., Sammis, C.G., Becker, T.W., Dresen, G., Schorlemmer, D., 2015. A Comparison of Seismicity Characteristics and Fault Structure Between Stick–Slip Experiments and Nature. *Pure and Applied Geophysics* 172, 2247-2264.

Goebel, T.H.W., Schorlemmer, D., Becker, T.W., Dresen, G., Sammis, C.G., 2013. Acoustic emissions document stress changes over many seismic cycles in stick-slip experiments. *Geophys Res Lett* 40, 2049-2054.

Gomberg, J., Reasenber, P.A., Bodin, P., Harris, R.A., 2001. Earthquake triggering by seismic waves following the Landers and Hector Mine earthquakes. *Nature* 411, 462-466.

Goodfellow, S.D., Young, R.P., 2014. A laboratory acoustic emission experiment under in situ conditions.

Geophys Res Lett 41, 3422-3430.

Graham, C.C., Stanchits, S., Main, I.G., Dresen, G., 2010. Comparison of polarity and moment tensor inversion methods for source analysis of acoustic emission data. *International Journal of Rock Mechanics and Mining Sciences* 47, 161-169.

Gu, C., Schumann, A.Y., Baiesi, M., Davidsen, J., 2013. Triggering cascades and statistical properties of aftershocks. *Journal of Geophysical Research: Solid Earth* 118, 4278-4295.

Han, R., Hirose, T., Shimamoto, T., 2010. Strong velocity weakening and powder lubrication of simulated carbonate faults at seismic slip rates. *Journal of Geophysical Research* 115.

Helmstetter, A., Sornette, D., 2003. Båth's law derived from the Gutenberg - Richter law and from aftershock properties. *Geophys Res Lett* 30, 2069.

Hill, D.P., Reasenber, P.A., Michael, A., Arabaz, W.J., Beroza, G., Brumbaugh, D., Brune, J.N., Castro, R., Davis, S., dePolo, D., Ellsworth, W.L., Gombert, J., Harmsen, S., House, L., Jackson, S.M., Johnston, M.J.S., Jones, L., Keller, R., Malong, S., Munguia, L., Nava, S., Pechmann, J.C., Sanford, A., Simpson, R.W., Smith, R.B., Stark, M., Stickney, M., Vidal, A., Walter, S., Wong, V., Zollweg, J., 1993. Seismicity Remotely Triggered by the Magnitude 7.3 Landers, California, Earthquake. *Science* 260, 1617-1623.

Hoek, E., Martin, C.D., 2014. Fracture initiation and propagation in intact rock – A review. *Journal of Rock Mechanics and Geotechnical Engineering* 6, 287-300.

Hong, T.K., Choi, E., Park, S., Shin, J.S., 2016. Prediction of ground motion and dynamic stress change in Baekdusan (Changbaishan) volcano caused by a North Korean nuclear explosion. *Sci Rep* 6, 21477.

Huang, J., Chen, G., Zhao, Y., Wang, R., 1990. An experimental study of the strain field development prior to failure of a marble plate under compression. *Tectonophysics* 175, 269-284.

Ingraffea, A.R., Heuze, F.E., 1980. Finite element models for rock fracture mechanics. *International Journal for Numerical and Analytical Methods in Geomechanics* 4, 25-43.

Karner, S.L., Marone, C., Evans, B., 1997. Laboratory study of fault healing and lithification in simulated fault gouge under hydrothermal conditions. *Tectonophysics* 277, 41-55.

Kun, F., Varaga, I., Lennartz-Sassinek, S., Main, I.G., 2014. Rupture Cascades in a Discrete Element Model of a Porous Sedimentary Rock. *Physical Review Letters* 112, 065501.

Kwiatek, G., Charalampidou, E.-M., Dresen, G., Stanchits, S., 2014a. An improved method for seismic moment tensor inversion of acoustic emissions through assessment of sensor coupling and sensitivity to incidence angle. *International Journal of Rock Mechanics and Mining Sciences* 65, 153-161.

Kwiatek, G., Goebel, T.H.W., Dresen, G., 2014b. Seismic moment tensor and b value variations over successive seismic cycles in laboratory stick-slip experiments. *Geophys Res Lett* 41, 5838-5846.

Lajtai, E.Z., 1969. Shear strength of weakness planes in rock, *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*. Elsevier, pp. 499-515.

Lajtai, E.Z., 1971. A theoretical and experimental evaluation of the Griffith theory of brittle fracture. *Tectonophysics* 11, 129-156.

Lajtai, E.Z., 1974. Brittle fracture in compression. *International Journal of Fracture* 10, 525-536.

Lei, X., 2003. How do asperities fracture? An experimental study of unbroken asperities. *Earth and Planetary Science Letters* 213, 347-359.

Lei, X., Kusunose, K., Rao, M.V.M.S., Nishizawa, O., Satoh, T., 2000a. Quasi-static fault growth and cracking in homogeneous brittle rock under triaxial compression using acoustic emission monitoring. *Journal of Geophysical Research: Solid Earth* 105, 6127-6139.

Lei, X., Kusunose, K., Satoh, T., Nishizawa, O., 2003. The hierarchical rupture process of a fault: an experimental study. *Phys Earth Planet In* 137, 213-228.

- Lei, X., Masuda, K., Nishizawa, O., Jouniaux, L., Liu, L., Ma, W., Satoh, T., Kusunose, K., 2004. Detailed analysis of acoustic emission activity during catastrophic fracture of faults in rock. *Journal of Structural Geology* 26, 247-258.
- Lei, X.L., Kusunose, K., Nishizawa, O., Cho, A., Satoh, T., 2000b. On the spatio-temporal distribution of acoustic emissions in two granitic rocks under triaxial compression: The role of pre-existing cracks. *Geophys Res Lett* 27, 1997-2000.
- Li, B.Q., Einstein, H.H., 2017. Comparison of Visual and Acoustic Emission Observations in a Four Point Bending Experiment on Barre Granite. *Rock Mech Rock Eng.*
- Li, Y., Chen, L., Wang, Y., 2005. Experimental research on pre-cracked marble under compression. *International Journal of Solids and Structures* 42, 2505-2516.
- Lockner, D., Byerlee, J., Kuksenko, V., Ponomarev, A., Sidorin, A., 1992. Observations of quasistatic fault growth from acoustic emissions. *International Geophysics* 51, 3-31.
- Lockner, D.A., Byerlee, J.D., 1975. Acoustic Emission and Fault Location in Rocks, in: Hardy, H.R.J., Leighton, F.W. (Eds.), *First conference on acoustic emission/microseismic activity in geologic structures and materials*, Pennsylvania State University, U.S., pp. 99-107.
- Lockner, D.A., Byerlee, J.D., 1991. Precursory AE patterns Leading to Rock Fracture, in: Hardy, H.R.J. (Ed.), *Fifth conference on acoustic emission/microseismic activity in geologic structures and materials*, Pennsylvania State University, U.S., pp. 45-58.
- Lockner, D.A., Byerlee, J.D., Kuksenko, V., Ponomarev, A., Sidorin, A., 1991. Quasi-Static Fault Growth and Shear Fracture Energy in Granite. *Nature* 350, 39-42.
- Main, I.G., 2000. A damage mechanics model for power-law creep and earthquake aftershock and foreshock sequences. *Geophys J Int* 142, 151-161.
- Marone, C., 1998. the effect of loading rate on static friction and the rate of fault healing during the earthquake cycle. *Nature* 391, 69-72.
- McLaskey, G.C., Glaser, S.D., 2011. Micromechanics of asperity rupture during laboratory stick slip experiments. *Geophys Res Lett* 38.
- McLaskey, G.C., Kilgore, B.D., 2013. Foreshocks during the nucleation of stick-slip instability. *Journal of Geophysical Research: Solid Earth* 118, 2982-2997.
- McLaskey, G.C., Kilgore, B.D., Lockner, D.A., Beeler, N.M., 2014. Laboratory Generated M -6 Earthquakes. *Pure and Applied Geophysics* 171, 2601-2615.
- Mizoguchi, K., Hirose, T., Shimamoto, T., Fukuyama, E., 2006. Moisture-related weakening and strengthening of a fault activated at seismic slip rates. *Geophys Res Lett* 33.
- Moradian, Z., Einstein, H.H., Ballivy, G., 2015. Detection of Cracking Levels in Brittle Rocks by Parametric Analysis of the Acoustic Emission Signals. *Rock Mech Rock Eng.*
- Moradpour, J., Hainzl, S., Davidsen, J., 2014. Nontrivial decay of aftershock density with distance in Southern California. *Journal of Geophysical Research: Solid Earth* 119, 5518-5535.
- Nguyen, T.L., Hall, S.A., Vacher, P., Viggiani, G., 2011. Fracture mechanisms in soft rock: Identification and quantification of evolving displacement discontinuities by extended digital image correlation. *Tectonophysics* 503, 117-128.
- Nolen-Hoeksema, R., Gordon, R., 1987. Optical detection of crack patterns in the opening-mode fracture of marble, *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*. Elsevier, pp. 135-144.
- O'Malley, R.T., Mondal, D., Goldfinger, C., Behrenfeld, M.J., 2018. Evidence of Systematic Triggering at Teleseismic Distances Following Large Earthquakes. *Sci Rep* 8, 11611.

Ohnaka, M., Kuwahara, Y., 1990. Characteristic features of local breakdown near a crack-tip in the transition zone from nucleation to unstable rupture during stick-slip shear failure. *Tectonophysics* 175, 197-220.

Ohnaka, M., Mogi, K., 1982. Frequency characteristics of acoustic emission in rocks under uniaxial compression and its relation to the fracturing process to failure. *Journal of Geophysical Research: Solid Earth* (1978–2012) 87, 3873-3884.

Ohno, K., Ohtsu, M., 2010. Crack classification in concrete based on acoustic emission. *Construction and Building Materials* 24, 2339-2346.

Ohtsu, M., 1991. Simplified moment tensor analysis and unified decomposition of acoustic emission source: Application to in situ hydrofracturing test. *Journal of Geophysical Research* 96, 6211.

Ohtsu, M., 1995. Acoustic-Emission Theory for Moment Tensor Analysis. *Res Nondestruct Eval* 6, 169-184.

Ohtsu, M., 1998. Basics of acoustic emission and applications to concrete engineering. *Journal of the Society of Materials Science, Japan* 47, 131-140.

Ohtsu, M., Isoda, T., Tomoda, Y., 2007. Acoustic Emission Techniques Standardized for Concrete Structures. *Journal of Acoustic Emission* 25, 21-32.

Okubo, P.G., Dieterich, J.H., 1984. Effects of physical fault properties on frictional instabilities produced on simulated faults. *Journal of Geophysical Research: Solid Earth* 89, 5817-5827.

Parsons, T., Ji, C., Kirby, E., 2008. Stress changes from the 2008 Wenchuan earthquake and increased hazard in the Sichuan basin. *Nature* 454, 509-510.

Passelègue, F.X., Spagnuolo, E., Violay, M., Nielsen, S., Di Toro, G., Schubnel, A., 2016. Frictional evolution, acoustic emissions activity, and off-fault damage in simulated faults sheared at seismic slip rates. *Journal of Geophysical Research: Solid Earth* 121, 7490-7513.

Petit, J.P., Barquins, M., 1988. Can natural faults propagate under mode II conditions? *Tectonics* 7, 1243-1256.

PhysicalAcousticCorporation, 2001. AEWinTM SOFTWARE Installation, Operation and User's Reference Manual, SAMOS AE SYSTEM USER'S MANUAL, 4 ed. MISTRAS Group, Inc., Products&Systems Division. Princeton Junction, New Jersey, USA.

PhysicalAcousticCorporation, 2011a. Model Nano30.

PhysicalAcousticCorporation, 2011b. Model PICO.

Reches, Z.e., 1999. Mechanisms of slip nucleation during earthquakes. *Earth and Planetary Science Letters* 170 (1999), 475-486.

Reches, Z.e., Lockner, D.A., 1994. Nucleation and growth of faults in brittle rocks. *Journal of Geophysical Research: Solid Earth* 99, 18159-18173.

Reches, Z.e., Lockner, D.A., 2010. Fault weakening and earthquake instability by powder lubrication. *Nature* 467, 452-455.

Reid, H.F., 1910. The California Earthquake of April 18, 1906; Volume II, the Mechanics of the Earthquake, Report of the State Earthquake Investigation Commission.

Rubin, A.M., Gillard, D., Got, J.-L., 1999. Streaks of microearthquakes along creeping faults. *Nature* 400, 635-641.

Sammonds, P., Ohnaka, M., 1998. Evolution of microseismicity during frictional sliding. *Geophys Res Lett* 25, 699-702.

Scholz, C.H., 2002. *The Mechanics of Earthquakes and Faulting*. Cambridge University Press, Cambridge.

Schubnel, a., Brunet, F., Hilairret, N., Gasc, J., Wang, Y., Green, H.W.I., 2017. Deep-Focus Earthquake Analogs Recorded at High Pressure & Temperature in Lab. *Science* 341, 1377-1380.

Shan, B., Xiong, X., Zheng, Y., Jin, B., Liu, C., Xie, Z., Hsu, H., 2013. Stress changes on major faults caused by 2013 Lushan earthquake and its relationship with 2008 Wenchuan earthquake. *Science China Earth Sciences* 56,

1169-1176.

Shearer, P.M., 2009. Introduction to Seismology, second edition ed. Cambridge University Press.

Shen, B., Stephansson, O., Einstein, H.H., Ghahreman, B., 1995. Coalescence of fractures under shear stresses in experiments. *Journal of Geophysical Research: Solid Earth* 100, 5975-5990.

Sornette, D., 2006. Critical Phenomena in Natural Sciences, 2nd ed. Springer, Berlin.

Stanchits, S., Fortin, J., Gueguen, Y., Dresen, G., 2009. Initiation and Propagation of Compaction Bands in Dry and Wet Bentheim Sandstone. *Pure and Applied Geophysics* 166, 843-868.

Stanchits, S., Mayr, S., Shapiro, S., Dresen, G., 2011. Fracturing of porous rock induced by fluid injection. *Tectonophysics* 503, 129-145.

Stanchits, S., Vinciguerra, S., Dresen, G., 2006. Ultrasonic Velocities, Acoustic Emission Characteristics and Crack Damage of Basalt and Granite. *Pure and Applied Geophysics* 163, 975-994.

Thompson, B.D., Young, R.P., Lockner, D.A., 2005. Observations of premonitory acoustic emission and slip nucleation during a stick slip experiment in smooth faulted Westerly granite. *Geophys Res Lett* 32.

Thompson, B.D., Young, R.P., Lockner, D.A., 2009. Premonitory acoustic emissions and stick-slip in natural and smooth-faulted Westerly granite. *Journal of Geophysical Research* 114.

Tsai, S.-T., Chang, C.-D., Chang, C.-H., Tsai, M.-X., Hsu, N.-J., Hong, T.-M., 2015. Power-law ansatz in complex systems: Excessive loss of information. *Physical Review E* 92, 062925.

van der Elst, N.J., Brodsky, E.E., 2010. Connecting near-field and far-field earthquake triggering to dynamic strain. *Journal of Geophysical Research* 115.

Varre, S.B.K., Siriwardane, H.J., Gondle, R.K., Bromhal, G.S., Chandrasekar, V., Sams, N., 2015. Influence of geochemical processes on the geomechanical response of the overburden due to CO₂ storage in saline aquifers. *International Journal of Greenhouse Gas Control* 42, 138-156.

Wilson, B., Dewers, T., Reches, Z., Brune, J., 2005. Particle size and energetics of gouge from earthquake rupture zones. *Nature* 434, 749-752.

Wong, L., Einstein, H., 2009a. Crack coalescence in molded gypsum and Carrara marble: part 1. Macroscopic observations and interpretation. *Rock Mech Rock Eng* 42, 475-511.

Wong, L., Einstein, H., 2009b. Crack coalescence in molded gypsum and Carrara marble: part 2—microscopic observations and interpretation. *Rock Mech Rock Eng* 42, 513-545.

Wong, L.N.Y., Einstein, H.H., 2009c. Systematic evaluation of cracking behavior in specimens containing single flaws under uniaxial compression. *International Journal of Rock Mechanics and Mining Sciences* 46, 239-249.

Wong, L.N.Y., Xiong, Q., 2018. A Method for Multiscale Interpretation of Fracture Processes in Carrara Marble Specimen Containing a Single Flaw Under Uniaxial Compression. *Journal of Geophysical Research: Solid Earth*.

Xiong, Q., Wong, L., 2017. Comparison of three source types for calibrating AE sensors used in fracture coalescence tests, 51st US Rock Mechanics/Geomechanics Symposium, San Francisco, California, U.S.A.

Yund, R.A., Blanpied, M.L., Tullis, T.E., Weeks, J.D., 1990. Amorphous material in high strain experimental fault gouges. *Journal of Geophysical Research* 95, 15589.

Zaliapin, I., Ben-Zion, Y., 2013a. Earthquake clusters in southern California I: Identification and stability. *Journal of Geophysical Research: Solid Earth* 118, 2847-2864.

Zaliapin, I., Ben-Zion, Y., 2013b. Earthquake clusters in southern California II: Classification and relation to physical properties of the crust. *Journal of Geophysical Research: Solid Earth* 118, 2865-2877.

Zaliapin, I., Gabrielov, A., Keilis-Borok, V., Wong, H., 2008. Clustering analysis of seismicity and aftershock identification. *Phys Rev Lett* 101, 018501.

Zang, A., Wagner, C.F., Dresen, G., 1996. Acoustic emission, microstructure, and damage model of dry and wet sandstone stressed to failure. *J Geophys Res-Sol Ea* 101, 17507-17521.

- Zang, A., Wagner, F., Stanchits, S., Dresen, G., Andresen, R., Haidekker, M., 1998. Source analysis of acoustic emissions in Aue granite cores under symmetric and asymmetric compressive loads. *Geophys J Int* 135, 1113-1130.
- Zang, A., Wagner, F., Stanchits, S., Janssen, C., Dresen, G., 2000. Fracture process zone in granite. *Journal of Geophysical Research* 105, 23651.
- Zeng, Y.-J., Zhang, X., Zhang, B.-P., 2015. Stress redistribution in multi-stage hydraulic fracturing of horizontal wells in shales. *Petroleum Science* 12, 628-635.
- Zhao, Y.-h., Huang, J.-f., Wang, R., 1993. Real-time SEM observations of the microfracturing process in rock during a compression test, *International journal of rock mechanics and mining sciences & geomechanics abstracts*. Elsevier, pp. 643-652.
- Zhu, L., Ben-Zion, Y., 2013. Parametrization of general seismic potency and moment tensors for source inversion of seismic waveform data. *Geophys J Int* 194, 839-843.
- Zietlow, W.K., Labuz, J.F., 1998. Measurement of the intrinsic process zone in rock using acoustic emission. *International Journal of Rock Mechanics and Mining Sciences* 35, 291-299.

Appendix

Appendix I influence of the AE data acquisition parameters on waveform picking

(this section of the appendix is reproduced from the Appendix A2 of Wong and Xiong (2018))

The data acquisition setup used for the tests of this PhD thesis is hit-based streaming. The continuous-based streaming is not selected because it is uneconomical for the present experimental tests. For the hit-based streaming, a waveform can be recorded according to parameters of threshold, HDT, and HLT (see section 3.1). The operating principle is shown in Figure 4.20. A waveform will be separately recorded once the following conditions are satisfied, (1) it crosses the threshold, (2) it has a time at its pre-threshold-crossing section that is without any threshold-crossing and longer than the HDT, and (3) its time gap between the first threshold-crossing and the end of the previous waveform in the same channel is larger than the HLT.

Figure A1. Illustration of the AE data acquisition parameters, reproduced from the Figure A2 of Wong and Xiong (2018)

The floating type threshold (see Table 3.1 (c)) means when the signal level is higher than the threshold, the threshold will shift to the value of initial threshold plus floating value (PhysicalAcousticCorporation, 2001) . Here a 5 dB floating value has been used.

Appendix II procedure of in-situ relative calibration

(this section of the appendix is edited based on the Appendix A3 of Wong and Xiong (2018))

The present calibration method is based on the evaluation of the sources for relative calibration focused on the first peak amplitudes in Xiong and Wong (2017). It is conducted in two steps.

In the first step, a PICO sensor (its aperture is smaller than that of NANO-30 for better calibration) manufactured by PAC with 200-750 kHz operating frequency and 550 kHz resonant frequency in V/ μ bar unit) is used to transmit elastic waves at the fixed points (blue dots in Figure 3.1 (a) and (b)). These points are designed in a way such that the signal-to-sensors paths for several pairs of sensors with identical distance and incident/takeoff angles can be produced. Assuming that all the sensors can only have normal direction movement and response, the directionality of the PICO sensor can be negligible. Therefore, the PICO sensor will generate an elastic wave with planar-isotropic amplitude. When the PICO sensor is energized, a single polar rectangular pulse of 125V and 1.0 μ s duration is given to the sensor. The selection of the pulse duration is to maximize the sensor's vibration according to the reported sensor's resonant frequency in the PAC manual of PICO sensor (PhysicalAcousticCorporation, 2011b). As the NANO-30 sensors have recorded the elastic waves generated from the PICO sensor at the calibration points (the fixed points) from 1 to 5 subsequently, the NANO-30 sensors having identical signal-to-sensor paths (identical distance and incident/takeoff angles) to a specific calibration point can display their strength of sensor response by their output waveforms. As such, their in-situ relative sensor response can be determined. This first step can greatly increase the overdetermine condition of the non-linear regression in step two.

In the second step, sensors 1 to 16 are energized sequentially by a single polar rectangular pulse of 125V and 1.7 μ s duration. The selection of the pulse duration is to maximize the sensor's vibration according to the reported sensor's resonant frequency based on the PAC manual of Nano-30 sensor (PhysicalAcousticCorporation, 2011a). When one

particular sensor is energized, the remaining 15 sensors will be triggered by the elastic wave transmitted by that energized sensor. The network sensor calibration method (Davi et. al., 2013) is used to extract the relative site-effect values of the sensors. In this method, an empirical equation is used to describe the relation between the received AE amplitude and the energized PZT sensor source.

$$A_{ij} = \frac{1}{r} \exp(-a\alpha^b \beta^b) S_i S_j \quad (A1)$$

where A_{ij} is the resulted sensor output when sensors i and j play as transmitting and receiving sensors, respectively; r is the distance between sensor i and j ; α and β are the incidence and takeoff angles of the transmitting and receiving sensors; S_i and S_j are the coefficients of the local effect (site effect); a and b are constants in this model.

Because of the presence of a pre-existing flaws, the waveform will be distorted once the signal-to-sensor path has been truncated by the pre-existing flaws. As such, the number of sensor pairs that can be input into equation (A1) is greatly reduced. However, with the relative value obtained from step 1, the overdetermined condition of the sensor network will be greatly increased. Therefore, based on the sensors' coordinates and normal directions information, the received signal is sufficient to calibrate all 16 sensors used in the test.

Appendix III Algorithm on judging whether the source-to-sensor path were intercepted by the pre-existing flaw or not

(this section of the appendix is reproduced from the Appendix A6 of Wong and Xiong (2018))

The source-to-sensor path and the open pre-existing flaw can be viewed as two sections on X-Y plane (because the pre-existing flaws cut through the specimens' thickness). Assume the source-to-sensor path is section “ $\overline{ab}$ ” and the open pre-existing flaw is section “ $\overline{cd}$ ”. As Figure A2 illustrates, mathematically, for a point in the left-hand side of a vector, the cross product of these two vectors ($\overrightarrow{ab} \times \overrightarrow{ad}$) shall be positive; for a point in the right-hand side of a vector, the cross product of these two vectors ($\overrightarrow{ab} \times \overrightarrow{ac}$) shall be negative. If one section is intercepted by the other section, the two points of this section shall be on two sides (left-hand side and right-hand side) of the other section. Therefore, to judge whether the two sections are intersected or not, one has (equation (A2)),

$$\begin{cases} \text{crossproduct}(\overrightarrow{ab}, \overrightarrow{ac}) \times \text{crossproduct}(\overrightarrow{ab}, \overrightarrow{ad}) < 0 \\ \text{crossproduct}(\overrightarrow{cd}, \overrightarrow{ca}) \times \text{crossproduct}(\overrightarrow{cd}, \overrightarrow{cb}) < 0 \end{cases} \quad (\text{A2})$$

The cross product of $\vec{ab}$ and $\vec{ac}$ is negative, while the cross product of $\vec{ab}$ and $\vec{ad}$ is positive. So the product of these two cross products is negative.

Figure A2. Illustration of the logic algorithm on judging whether the source-to-sensor path is intercepted by the pre-existing flaw or not, reproduced from the Figure A5 of Wong and Xiong (2018)

Appendix IV measurement of P-wave and S-wave velocity

The measurement of the P-wave velocity and S-wave velocity is conducted by the PROCEQ ultrasonic tester and two PICO sensors on the rock specimen before the loading test. When the P-wave measurement is conducted, the two PICO sensors are attached onto the side faces depicted in Figure A3(a). Multiple single dipole rectangular pulses with $1.0\ \mu\text{s}$ duration are given to one of the two sensors. The other sensor will receive the signal from that energized sensor. As the primary vibration direction of PICO sensor is the normal direction of the sensor, this arrangement maximizes the P-wave transmission and receiving.

Figure A3. (a) and (b) measurement of P-wave and S-wave velocity, reproduced from the Figure A4 of Wong and Xiong (2018).

When S-wave measurement is conducted, the two PICO sensors are attached onto the front face as depicted in Figure A3(b). Again, multiple single dipole rectangular pulses with 1.0 μ s duration are given to one of the two sensors. The other sensor will receive the signal from that energized sensor. This arrangement maximizes the S-wave transmission and receiving.

Before each measurement, the time difference reported between the wave transmission sensor and the receiver is calibrated by a standard manufactured polymer core provided by PROCEQ. As the length and the wave velocity of the polymer core are known, any error on the electric system in reporting the time difference between the transmitter and the receiver can be calibrated before the P-wave velocity and S-wave velocity measurements.