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成果の概要／陳　友晴

今回、京都大学教育研究振興財団の国際会議派遣助成を得て、2009年9月8日～15日まで中華人民共和国四川省成都市で開催された国際会議およびシンポジウム The International Symposium on Geological Engineering Problems in Major Construction Projects in the 7th Asian Regional Conference of IAEG に参加する機会を得た。本会議は、1997年に日本・東京において開催された第１回を皮切りに、概ね２年ごとにアジア各地で開催されており、アジア地域での応用地質学分野の活動や発展にとって重要な役割を担い、各国から多くの参加者を得て地盤災害、気象災害の防災、減災について総合的な情報交換、技術討論を行っている。今回は、学会テクニカルツアーとして昨2008年5月に中国四川省を襲った大地震の震災地現地巡検が予定されていることから、アジア地域のみならず、世界中から参加者が集まった。参加者約250名、30を越える国・地域から参加があったことが報告されている。

シンポジウムは、６つのテーマ（大規模建設プロジェクトにおける地質リスクと地質環境問題、大規模地すべりのメカニズムと管理、活動域内の山岳都市における地質災害とリスク管理、大規模ダム・構造物における基礎問題、地下深部トンネルにおける地質工学的問題と災害、複雑な地質環境地域における地下空間の安定性）と２つの特別テーマ（2008年5月12日四川大地震からの教訓、中国三峡ダムプロジェクトにおける地質工学問題の教訓）に分かれて、講演、討論が行われた。それぞれのテーマでは、キーノートレクチャーを含めて、大変熱のこもった発表と活発な討論が行われた。多くの参加者から、各地域で地質災害から人命と財産を守っているのは自分だという自負、また、それを各地の研究者、技術者に知ってもらい役立てて欲しいという信念、そしてより多くのことを学んでいこうとする熱意のようなものがひしひしと感じられる、和やかな中にも緊張した雰囲気が漂う、大変有意義なシンポジウムであった。

シンポジウムでは、室内試験を用いて基礎岩盤（花崗岩）の疲労劣化プロセスを考察する基礎研究の内容について、発表を行った。当初はポスターでの発表予定であったが、予稿原稿を提出後に口頭発表への変更が認められ、講演、討論と貴重な機会を得ることができたことは、大変嬉しい出来事であった。発表内容は、試験機を用いた花崗岩試験片の圧縮繰り返し載荷試験により発達する内在欠陥であるマイクロクラックについて、破壊まで至らない多数の試験片を作成・観察することにより、その発達過程を明らかにし、劣化のプロセスを検討したものである。試験片の全体的な挙動が比較的安定した状態のときでも、潜在的な欠陥であるマイクロクラックは、確実に成長していることを示すことができ、クラックの伸長と発生によりクラック密度が増加することが、最終的な加速度的な劣化進行に寄与することが示唆された。クラック進展の特徴的な方向性についても議論をした。発表後、基礎的知見の蓄積として、さらなる実験の継続を期待するという激励のコメントと、実用、応用について、さらによく検討を行っていくことが望

ましいという厳しい内容のコメント両方をいただいた。発表時間では討論が終わらず、コーヒーブレイク時にも、さらにゆっくりと討論を続けることができ、今後の研究の遂行に多くの指針を得た。

また、シンポジウム期間中、今まで興味をもっていたが研究のステップとして踏み込めないままでいる分野（内容）の先行する研究者の方々と、直接討論できる機会に恵まれた。短い時間ではあるが、簡単なアドバイスももらうことができたことは、大変貴重な情報となっている。今後、あらためて交流を深めていけるよう期待をし、研究を進めていくことを計画している。

シンポジウム後半では、昨2008年5月の四川大地震の震災地域の巡検ツアーが開催された。無残な爪痕は１年半を経た今なお癒えておらず、地震災害の迫力に圧倒されるばかりであった。ツアーでは、学会主催者の尽力と中国政府の配慮から、通常は立ち入り禁止とされている地域にも、討論のため立ち入りを認められた部分があり、間近で観察することが可能であった。いくつかの重点的な現場では、現地研究者、技術者の解説もあり、室内での討論同様、長時間にわたる密度の濃い討論が行われた。地震後すでに１年以上が経過しているが、震災の状況を自分の目に焼き付けることができ、今後もこれら地質災害の防災、減災のために微力ではあるが貢献できればという思いを新たにすることができた。今後も精力的に研究を継続できればと考えております。

最後になりましたが、今回の国際会議派遣に対し助成をいただきました京都大学教育研究振興財団に厚く御礼申し上げます。会議の参加により、研究者として国際的な人脈を広げられたこと、自己の研究についての多くのコメントをいただけたこと、数多くの有益な情報・知見を得ることができたこと、どれをとっても非常に意義のあるものと感じております。どうもありがとうございました。

Crack growth in granite specimens subjected to cyclic uniaxial loading

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ABSTRACT: In order to examine the fatigue process of granite, a series of Westerly granite specimens were subjected to a cyclic loading test under the uniaxial compression with maximum 140 and 160MPa at room temperature. The development of microcracks within the specimens stressed to different characteristic stages was observed microscopically and their growth patterns were analyzed using image analysis technique. As a result, with increasing loading cycles, the number and the population of microcracks within the specimen increased. At the first stage of loading, many intragranular cracks generated. During the quasi-stable middle stage, many microcracks preferentially elongated parallel to the loading direction and grew into transgranular cracks. With further loading, cracks gradually widened, and some of them grew into intergranular cracks. It was estimated that the generation and growth of these intergranular cracks induced the rock fatigue failure.

1 INRODUCTION

The demand for the long-term safety utilization of rock structures has increased further in recent years. It is known that degradation of rocks or rock masses used in traditional rock structures, i.e., buildings, bridges, traffic tunnels, and mining galleries, occurs by repeated stress changes in their use and operation. For the stability evaluation of many rock structures, it is important to reveal the deterioration characteristics of rocks under repeated stress alternation over the long term.

It is well-known that materials deteriorate by repeated stress change over a prolonged period and then finally reach failure even if the changes are lower than its static breaking strength. This phenomenon is generally termed ‘fatigue’, and happens in many kinds of materials (Suresh 1998). Needless to say, rock is no exception. Many studies on the fatigue characteristics of rocks have been carried out since the 1960's. Most of them stressed rock test specimens cyclically by a loading machine. These primary studies reported that the fatigue life was significantly influenced by the magnitude of the applied maximum stresses (e.g., Burdine 1963, Hardy & Chugh 1970). The strain behavior of rocks during the fatigue process was nearly the same as for other structural materials, such as metals and concrete (e.g., Haimson & Kim 1971). Attempts to estimate the fatigue life were also conducted by many researchers (e.g., Costin & Holcomb 1981). However, the mechanical behavior during the fatigue process has not been clarified.

In many geological engineering problems, granite is one of the most important materials to investigate. In granite, the initiation and the elongation of microcracks play an essential role in the failure process. It is therefore important to analyze the growth of cracks during the fatigue process. In recent years, for example, Åkesson et al. (2004) reported the characteristic microcrack growth pattern in every constituent mineral by the microscopic observation of granite specimens after cyclic loading. However, much remains unknown about the fatigue process of granite, although many studies have been conducted.

In this study, to obtain further insights into the crack development pattern in granite during the fatigue process, microcracks in a series of specimens stressed to different stages by cyclic loading were observed in detail applying the fluorescent approach proposed by Nishiyama & Kusuda (1994). For further examination, microcrack growth patterns were analyzed by the digital image analysis technique.

2 EXPERIMENTAL

2.1 *Sample*

Fine-grained Westerly granite from the USA was chosen for the examination. Many rock tests have been conducted using this rock, and its fundamental characteristics have been accumulated by many researchers (e.g., Tapponnier & Brace 1976, Chen &Wang 1980). The modal composition of the tested samples was about 70% feldspars (including potassium and plagioclase feldspar), 25% quartz, and 5% micas (including biotite and muscovite) and the accessories. The mean grain size was about 0.7mm. The effective porosity of the specimens ranged around 1%.

2.2 *Test condition*

Cylindrical specimens 10 mm in diameter and 20 mm in length, cored orthogonal to the hardway plane (Fig. 1), were subjected to the cyclic loading test under uniaxial conditions at room temperature. The specified maximum stress was 140 and 160MPa (i.e., about 70 and 80% of the estimated uniaxial compressive strength 200MPa), and the minimum one was 0.5MPa. The loading-unloading cycle was 0.1Hz, and the applied load was controlled to change linearly.

2.3 *Monitoring sample behavior*

To monitor the behavior of the specimens during the test, axial and lateral strains, and the load were simultaneously measured every 0.1 second intervals, that is, 100 measurement data for one cycle. The strains were detected by strain gages directly attached to the side surfaces of specimen (Fig. 1).

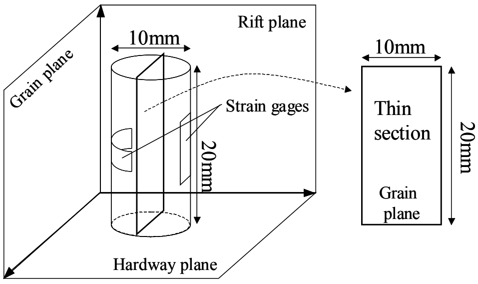

Figure 1. Size and direction of tested cylindrical specimens.

It is a well-known fact that the number of the loading times to reach failure by the cyclic loading test shows some variation (Suresh 1998), and our test was no exception. However, the strain behavior of specimens until failure was nearly the same to all samples. Figure 2 shows the general behavior on the strain of materials during the fatigue failure process. In our test, the lateral strain showed a same pattern; the strains were stable with liner increase at first (Stage 1) and then quasi-stable with gradual increase (Stage 2), and finally the values suddenly increased (Stage 3) and then the sample fractured.

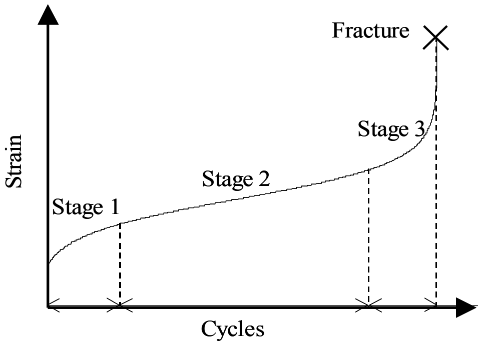

Figure 2. Outline of behavior on the strain of materials during the fatigue failure process.

2.4 *Collecting prefailure specimens for observation*

In order to observe the sequence of the changes occurring within specimens throughout the fatigue failure process, many specimens were tested in the same conditions and retrieved before failure.

In a series of the specimens stressed by 140 MPa, the stage in the fatigue process of the retrieved specimen was decided in consideration of the strain behavior (Fig.3). While in 160 MPa specimen, a total of six specimens, including the intact (i.e., no-loaded) specimen and the fractured specimen, were regarded as a series of the specimens to observe the fatigue failure process (Fig.4). The behavior of four prefailure specimens was nearly the same as those of the fractured specimen.

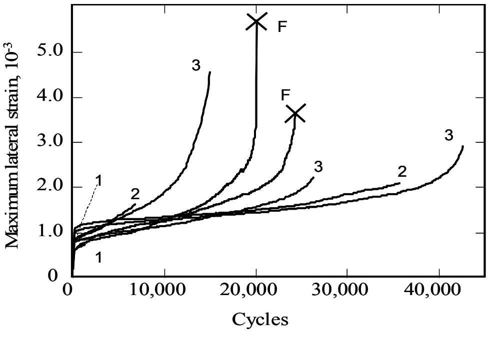

Figure 3. Behavior of maximum lateral strain of selected 140 MPa specimens. Numbers in the figure show the decided stages.

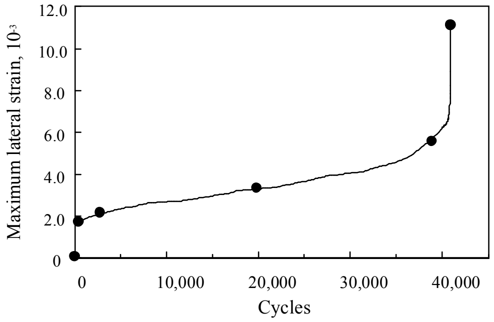

Figure 4. Behavior of maximum lateral strain of tested specimens, and outline of six observed 160 MPa specimens. Real line shows the behavior of fractured specimen.

3 OBSERVATION

3.1 *Microcrack detecting method*

The fluorescent method proposed by Nishiyama & Kusuda (1994) was applied to identify microcracks within the specimens. Microcracks are detected based on a marked difference in brightness under ultraviolet light irradiation, because they are fully filled with acrylic resin mixed with a fluorescent substance in advance. The method provides quick and accurate identification of microcracks with an optical microscope. Thin sections including the axis of the specimen were prepared for the detailed observation (Fig. 1).

3.2 *Overview of the entire section*

First, the crack growth on each entire section was overviewed. As a result, many pre-existing microcracks were already identified in the intact specimen. In the specimen at the first stage of loading cycle, extraordinary marked growth of microcracks was not observed compared with the intact specimen. However, grain boundary cracks widened slightly in several parts and the number of intragranular cracks increased.

In the specimen during the quasi-stable stage (Stage 2), the number of cracks increased significantly compared with the less stressed specimens. Most of these developed cracks were observed in quartz and feldspar grains, and some grew parallel to the loading direction. Cracks further increased and elongated in the specimen at the third stage near the rock failure (Stage 3). In this stage, cracks running parallel to the loading direction, which were estimated to develop around this stage, were dominant, and some of these long cracks cut through more than two grains. These long cracks tended to distribute near the lateral sides of the specimen.

3.3 *Long cracks parallel to the loading direction*

Long cracks which could not be identified in the intact specimen were observed in the tested specimens. Most of these cracks ran parallel to the loading direction. In the later stage, many such cracks grew into transgranular cracks and some cracks elongated to more than about 2mm, cf. mean grain size about 0.7mm, and cut through several grains (Fig. 5). They developed around mica grain in many cases. Long cracks in quartz parts were comparatively straight, while those in feldspar parts sometimes elongated stepwise.

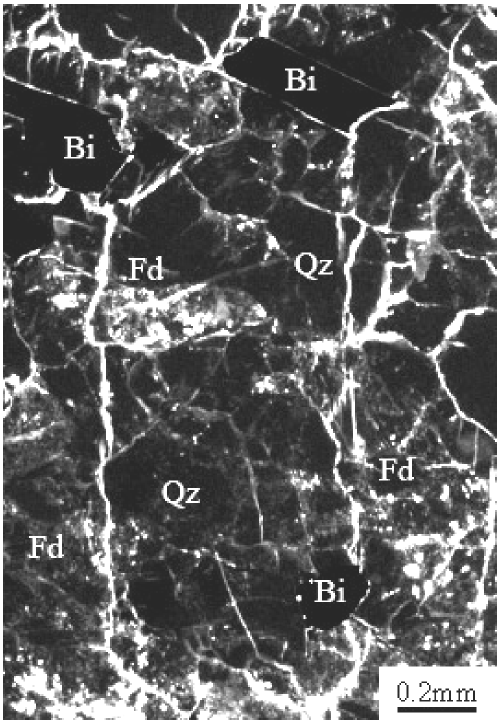

Figure 5. Long cracks observed in the specimen stressed to Stage 3, 140 MPa. White parts are corresponded to cracks. Qz: quartz, Fd: feldspar, Bi: biotite.

3.4 *Microcracks in major constituent minerals*

For further examination, the development of microcracks in each constituent mineral was observed in more detail. In the specimens at Stage 1, slightly larger numbers of short cracks were observed in quartz grains compared with the intact specimen.

Many of these cracks existed within a grain, and the detailed observation found that most of these cracks tended to appear around the boundaries of neighboring mica grains. In the specimens during Stage 2, cracks parallel to the loading direction were observed in quartz grains. These cracks were longer than those observed in the less loaded specimens, and many of them grew into transgranular cracks, and some grew into the intergranular cracks by passing through the grain boundaries.

In feldspar grains, a great number of fine microcracks were observed along the cleavages but they existed only inside the grains, and no clear evidence could be found of marked elongation of these cleavage cracks with increasing loading cycles. In the later stage of loading, two types of crack running parallel to the loading direction were observed: cracks with a relatively long length grown from the grain boundary, and relatively short cracks related to the cleavages.

On the other hand, cracks within biotite or muscovite grains developed little throughout the test, even in the fractured specimen.

4 CRACK ANALYSIS

4.1 *Image analysis*

The features of crack growth pattern were analyzed by applying digital image analysis technique in more detail. Digitalized image files of the reference area at a suitable resolution were captured with a CCD camera attached to an optical microscope, applying the fluorescent approach. Microcracks in the images were automatically extracted following the typical image analysis procedure, i.e. enhancement, smoothing, thresholding, and thinning operations (Kusuda & Nishiyama 1994, Chen et al. 2001). The data on crack width could not be discussed following this procedure because the characteristics of cracks were extracted by the thinning operation. Furthermore, grain boundaries and mineral species of individual grains were identified by typical observations of thin sections.

The number of extracted cracks and the length of each crack were measured. If a crack had some branches, the number was counted as one and its length included the length of branches. To analyze crack growth patterns, two parameters, crack population by length (the sum of crack length per unit area) and average length of crack, were calculated based on the length and the number of cracks.

4.2 *Analytical results and discussion*

4.2.1 *Crack direction*

The crack distribution both in quartz and feldspar grains was analyzed separately. Fine microcracks concerning the cleavages within feldspar grains were excluded from this analysis, because it was estimated that they were rarely influenced to the rock failure. Crack direction was summarized every 20 degrees (Fig. 6). As a result, it was found that the amount of cracks increased gradually with increasing loading cycles and increased drastically immediately before failure. Furthermore, after the later half of Stage 2, crack growth in feldspar was dominant compared with in quartz grains, and especially this tendency was remarkable for the cracks running parallel to the loading direction.

4.2.2 *Crack in quartz grain*

Next, cracks in quartz around mica and cracks in other quartz were analyzed separately. It is because that a different crack growth pattern was observed between quartz grains around mica grains and other quartz grains. As a result, the amount of cracks in quartz around mica increased drastically at the first stage and then it stayed nearly constant until after failure. The average crack length showed no significant change until Stage 2 and elongated distinctly during the later stage. In contrast, in other quartz grains, the tendency was similar to total cracks, of which amount increased gradually with increasing loading cycles and increased drastically at final stage. This indicates that in quartz around mica short cracks firstly appeared and then elongated and conjugated later.

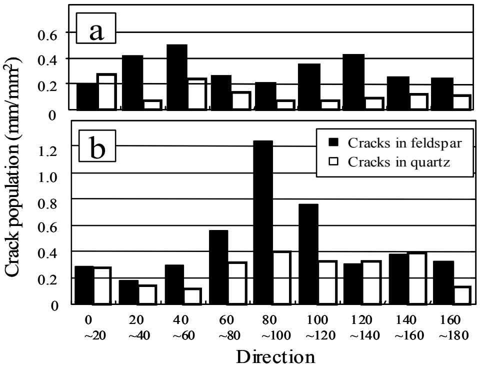

Figure 6. Crack direction in feldspar and quartz grains, 140 MPa specimens. Loading direction corresponds to 90 degree. (a) Intact specimen, (b) specimen stressed to Stage 3.

For more detailed analysis, cracks in quartz grains, which stretched from the boundary of neighboring mica grains, were manually extracted and divided into several ranks by their length. The length 0.3mm, which corresponded to the average grain size of a quartz grain, was chosen for the standard of classification. As a result, the number of cracks less than 0.3mm increased at first but decreased prominently during Stage 2. The number of cracks 0.3-0.6mm long increased distinctly after Stage 2. The number of cracks 0.6-0.9mm long gradually increased until immediately before failure and drastically increased after failure. Cracks over 0.9mm long were not identified until immediately before failure (Fig. 7). It was inferred that the development of cracks over the average grain size led to specimen failure.

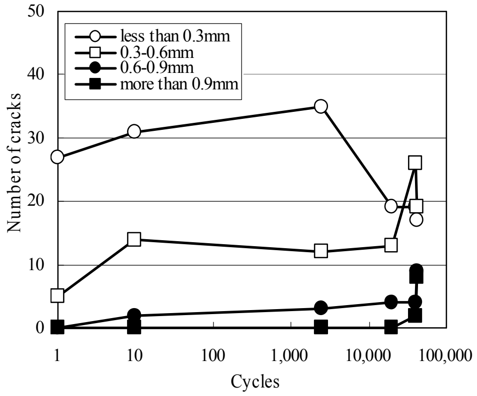

Figure 7. Correlation between cycles and the elongation of cracks in quartz grains, 160 MPa specimens. Reference area is about 25mm^2.

5 CONCLUSIONS

In order to examine the fatigue process of granite, Westerly granite specimens were subjected to a cyclic loading test under the uniaxial compression with maximum 140 and 160MPa at room temperature, and a series of specimens stressed to characteristic stages were retrieved. The development of microcracks in the tested specimens was observed microscopically and their growth patterns were investigated using the image analysis technique.

With increasing loading cycles, the number and the population of microcracks within the specimen increased. At the first stage of loading, many intragranular cracks generated. During the quasi-stable middle stage, many microcracks preferentially elongated parallel to the loading direction and grew into transgranular cracks. With further loading, cracks gradually widened, and some of them elongated and grew into intergranular cracks. It was estimated that the generation and growth of these intergranular cracks induced the rock fatigue failure. The decrease in strength by fatigue was caused by the increase in crack population and preferential orientation of microcracks within the specimen.

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