Acoustic emission and digital image correlation for damage evolution in brittle rocks under time-dependent tensile loading

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Abstract. Time-dependent rock deformation is considered to precede dynamic failure in many rock-engineering projects and natural geohazards. In order to understand long-term performance of brittle rocks, we gather mechanical load, strain, acoustic emission (AE) and digital image correlation (DIC) data to describe the evolution of damage and cracking in response to tensile loading during multi-stage relaxation experiments on inverted single edge notch bending (iSENB) specimens. The source locations of the AEs correspond to a process zone ahead and around the notch indicating the evolution of the microcracks. The results showed that the cracks first start aseismically under subcritical growth until 10mm from the tip of the notch and then they grow seismically by showing seismic signals in the form of acoustic emissions. It was observed that the process zone obtained by DIC is smaller than the cloud of the AE locations. This can be partially because DIC only shows surface deformation and partially because of the errors associated with the AE source locations such as ignoring anisotropic velocity, sampling rate, sensor locations, etc. Moment tensor analyses of the AE signals showed that both tensile and shear cracks are involved in the micro-scale although in the macroscopic scale the damage process is mostly considered as tensile. The results showed that microcracks start as tensile, and then continue as shear, especially at the end of the crack where the specimen experiences compression loading.

1. Introduction
Rocks subjected to constant load, or constant displacement boundary conditions can be observed to deform slowly and eventually fail at stress levels less than otherwise expected from short-term strength tests (Amitrano and Helmstetter, 2006). Similarly, rock mass failures commonly don’t occur immediately after a forcing event (e.g. excavation or intense precipitation), but instead may occur months or years after the disturbance, indicating failure is partly controlled by a gradual decrease in rock strength. Understanding progressive rock deformation, and in particular the transition from sub-critical to critical fracture velocities, is therefore important to predict the onset of dynamic and catastrophic failure associated with landslides, earthquakes, and volcanic eruptions (Brantut et al., 2013). Understanding this process can also provide important insight into the integrity of underground mines and excavations, the long-term storage of hazardous wastes, effective recovery of hydrocarbon and geothermal energy resources with controllable induced seismicity, and last but not least safe and economic CO2 sequestration [Brantut et al., 2013]. United Nations Educational, Scientific and Cultural Organization (UNESCO) has recently emphasized our current lack of knowledge in this area, and “Understanding Slow Deformation before Dynamic Failure” has been suggested as one of the two
priority research areas within the Natural Hazards theme of its International Year of Planet Earth (Ventura et al., 2009, Brantut et al., 2013).

Over the last decades, researchers have studied the time-dependent or long-term performance of rocks by creep testing and rheological modeling. As a result, numerous rheological models have been developed to describe long-term behavior of sub-critically loaded rocks. However, the traditional models which are mainly based on the evolution of strain with time, fail to capture the full range of behavior from elastic deformation at the beginning of loading, viscous deformation in primary and secondary creep and especially plastic deformation as cracking progresses toward dynamic failure during tertiary creep. This is, in part, due to the lack of reliable experimental data for validating the models.

Within the Griffith-Irwin framework of the linear elastic fracture mechanics (LEFM), ruptures will propagate only when the strain energy release rate is larger than surface energy in a vacuum. However, most near-surface fractures take place in a chemically interactive environment subjected to sub-critical loading (e.g. surface water, moisture, temperature) and grow at rates several orders of magnitude than otherwise expected for critical crack growth (usually >10-6 m/s vs. 103 m/s). This phenomenon can include elements of subcritical, slow, aseismic, stable, quasi-static, or kinetic crack growth (Atkinson, 1982, 1984; Atkinson and Meredith, 1987). Subcritical crack growth (SCG) is suggested to be the key process controlling the rate of strength degradation in near-surface brittle rocks under relatively stable environmental conditions. Several competing micro-mechanisms could be responsible for SCG. Nevertheless, the overwhelming body of experimental evidence suggests that the growth of pre-existing cracks and flaws by stress corrosion is the dominant mechanism of SCG in the progressive failure of near-surface brittle rocks (Brantut et al., 2013; Atkinson, 1982, 1984; Atkinson and Meredith, 1987).

Gaining new physical insights into the manner in which SCG progresses to dynamic failure is important for understanding the evolution of instability in engineering projects and the assessment of the precursory phase of natural hazards. Despite significant progress, there is still a lack of understanding of SCG, notably the transition phase, due to the lack of quantitative analysis of progressive rock failures in a broad range of near-surface environmental conditions. In this paper, AE monitoring and DIC are coupled with traditional mechanical measurements in order to provide new insights into spatiotemporal micro-crack evolution, fracture mode, and aseismic/seismic transition during SCG in brittle rocks.

2. Experimental Setup and Methodology

2.1. Sample preparation and properties

The inverted single edge notch bending (iSENB) samples were prepared with dimension of 400 × 91 × 91 mm (length × height × depth). A notch with 10 mm depth and 3 mm width was cut orthogonally across the center of each sample. The specimens were sourced from a fine-grain granite block from Herrnholz quarry in Germany. The physical and mechanical properties of the tested rocks are presented in table 1.

| Properties         | Unit   | Value       |
|--------------------|--------|-------------|
| Grain size range   | mm     | 0.3 – 1     |
| Density            | g/cm³  | 2624.4 ± 3.5|
| P-wave Velocity    | m/s    | 3996 ± 98   |
| UCS                | MPa    | 142.35 ± 11.20|
| Tensile Strength   | MPa    | 13.58       |
| Young's Modulus    | GPa    | 30.59       |
| Poisson's Ratio    | -      | 0.28        |
2.2. Loading setup

Our new rock physics and mechanics lab at ETH Zurich (www.rpml.ethz.ch) includes dual loading frames designed to conduct thermo-hydro-seismo-mechanical observation of progressive strength degradation of hard rock samples loaded under either uniaxial compression or induced tension during inverted single edge notch bending configurations. Our new creep testing frames are capable of maintaining a load of 100 kN (in iSENB configuration) for up to 100 days. Customized components allow the software to maintain (or cycle) stress or strain, temperature (from -20° to 150° C, ± 0.1° C) and humidity (from 20 % to 90%, ± 2.5%) using an environmental chamber surrounding the loaded laboratory sample (Li, et al., 2019). Figure 1 shows an iSENB specimen instrumented with 16 AE sensors, and an extensometer that measures the crack mouth opening displacement (CMOD) during testing.

Figure 1. An inverted single edge notch-bending (iSENB) specimen during multi-stage relaxation testing.

To ensure consistency of experimental results, several tests with similar configurations were performed under room environmental conditions (23°C, 70% humidity). Initially, four short-term experiments (5 – 50 minutes) were conducted on four specimens (1a – 01, 02, 03, 06 – 31) to obtain the peak load (Fm). The results were similar for the four experiments, with Fm consistently around 14.5kN (figure 2a), suggesting a (theoretical) average fracture toughness of 1.82 MPa m1/2. Based on the measured peak load Fm, two tests with four – hour staged loading levels (F1, F2, ... Fm) were undertaken on two specimens (1a – 04, 07 – 31). The loading protocol for the multi-stage stress relaxation-bending test on the latter two specimens is as follows:

a) Load each specimen to 0.12 kN (around 1% of estimated peak load) at a rate of 0.004 kN/s and then maintain the load for around 16 hours (to allow the sample and sensors to settle in the configuration).

b) Load specimen to 6 kN (around 40% of estimated peak load) with a load point (piston) displacement rate of 1μm/s.

c) Maintain the displacement so that the specimen experiences stress relaxation for 1800 s.

d) Increase the load by 10% of the estimated peak load by load point displacement control at a rate of 1μm/s.

e) Repeat steps c) and d) until the target load reaches 95% the peak.

f) Maintain the displacement so that the specimen undergoes stress relaxation until failure. The load and CMOD of an iSENB sample 1a – 07 – 31 under this staged increase loading are shown in figure 2b.
Figure 2. a) Load-time data from six iSEN tests under short-term loading (samples 1a–01, 02, 03, 06–31) and four-hour staged loading (1a–04), and b) load and crack mouth opening displacement for one iSEN test on sample 1a–07–31 under multi-stage stress relaxation loading.

2.3. Digital image correlation (DIC) setup
Digital image correlation was undertaken using images taken on a Sony Alpha A7RII digital camera with standard zoom lens mounted to the loading frame. The camera was set to time lapse mode, with full resolution (42 MP) images taken every 20 seconds during the duration of the test. Image correlation was undertaken using Ncorr for Matlab, with frames referenced to a source image near the end of the 1% loading period. The resolution of images at the sample was around 0.01 mm/px, and displacements were analyzed using a subset radius of 30 px, providing a maximum resolution of observed displacements similar to the minimum grain size.

2.4. Acoustic Emission (AE) setup
For AE monitoring of the damage processes, three types of sensors were used: KRNBB-PC point contact broadband sensors from 100-2500 kHz, PAC resonant sensors with frequency range of 35-65 kHz, and GmuG resonant sensors with frequency range of 300-1000 kHz. Though KRNBB-PC sensors are around an order of magnitude less sensitive than GmuG sensors, still useful as they have a broadband frequency range and therefore can provide information on radiated energy. A combination of broadband and resonant sensors will work in an associated manner during our subsequent experiments, where broadband sensors will be used for the analysis of source properties like energy budget and resonant sensors with higher sensitivity will be used for picking small events and then doing AE location. Some text.

3. Subcritical Crack Growth in single edge notch bending specimen

3.1. Time-series analysis
By using time-series analysis of the AE data Moradian et al. (2016) have shown that the number of AE hits is related to the number of cracks, and the AE energy is related to magnitude of the cracking event. Other researchers such as Lei and Satoh (2007) have employed triaxial compression tests and analysed the statistical properties of the AE signals. They found that for the intermediate-term prediction of time-to-failure, the decreasing b-value and increasing AE energy rate are suggested to be meaningful indicators of transition between SCG and catastrophic failure. Figure 3 shows the time-series analysis of the AE signals performed on the experiments. The results show that the resonant sensors, with higher sensitivity, could detect more signals and showed that crack numbers increase logarithmically after the 4th staged loading (95% of the estimated peak load), while most signals from KRNBB-PC sensor were recorded very close to the failure or even completely after the failure.
3.2. Spatiotemporal micro-crack evolution

Visual observations of the cracking processes provide the intuitive insights into time-dependent tensile failure of the specimens. Slow or subcritical crack growth can be detected by using high-resolution photography with low frame rate while for dynamic failure high-speed photography is needed. Digital image correlation (DIC) is used to evaluate the photography data (Rastogi and Hack, 2012; Lin et al., 2019a; Li and Einstein, 2017; Dutler et al., 2018; Koivisto et al., 2016; Molnár and Gravouil, 2017) for both displacement and strain fields.

Figure 4 details calculated horizontal surface displacements for six intervals during the final creep phase of an iSENB test (1a – 07 – 31). Times are described with respect to the final failure. The six intervals are also marked in figure 3b. Figure 5 presents the calculated relative strain field change in the final image of our second creep test (1a – 07 – 31) approximately 20 sec prior to dynamic failure.

The development of microcracks can be detected with AE event source locations. The Aikake information criterion (AIC) (Maeda 1985) was used to pick arrival times of the events the same way as discussed by Li et al (2019). Source locations were calculated using an isotropic velocity model of 4000 m/s and minimization of the residuals, in order to estimate the formation and growth of microcracks in granite. The 2D AE locations (figure 6 and 7a) show that most microcracks distributed within an apparent zone of nearly 4 cm width during the last relaxation stage, and extend approximately 40 mm beyond the crack tip in the final seconds of the test (approx. 20 mm below the sample surface).

The first AE event (blue dot) happens 10mm under the notch. This indicates that that cracks start aseismically under subcritical growth from the tip of the notch and then they grow seismically after propagating for almost 10mm.
Figure 4. Surface displacements in horizontal direction (+, right, - left) at six moments before failure for the experiment presented in figure 2b. The six intervals are also marked in figure 3b.

Figure 5. Surface strain of sample 1a – 07 – 31 approximately 20 sec prior to dynamic failure.

Finally, source mechanisms of microcracks were determined using moment tensor inversion of the AE waveforms. The simplified moment tensor analysis (SiGMA) (Grosse and Ohtsu 2008) is performed by analyzing the amplitudes of the first motions. Events with a double couple (DC) component greater than 60% are considered shear, less than 40% as tensile and the rest as mixed. The evolution of the tensile and shear cracks during the last relaxation stage of an iSEN test is presented in figure 7b. The results show that tensile cracks happen first and then shear cracks are mobilized too but the end of the cracking where the specimen experiences compression loading is mostly happening under shear.
4. Conclusions
In this study inverted single edge notch bending (iSENB) specimens were subjected to tensile loading, and the AE signals were detected using resonant and wideband AE sensors. Digital image correlation (DIC) and a mechanical crack mouth opening displacement sensor were used to observe the evolution of the subcritical and critical crack growth during the creep process: The following conclusions can be drawn:

1- The source locations of the AEs start showing off after 10 mm from the notch tip. This indicates that cracks start aseismically under subcritical growth from the tip of the notch and grow seismically only when the opening displacement rate increases at the end of the experiment.

2- The 2D AE locations show that most microcracks are distributed within an apparent zone of nearly 4 cm width during the last relaxation stage, and extend from the crack tip 4 cm down into the sample.
3- Surface strain of the last frame from DIC results reveals a small process zone comparing to the cloud of the AE events. This is because DIC shows only surface cracks while many of the microcracks can happen in the specimen volume.

4- Moment tensor analyses of the AE signals showed that both tensile and shear cracks are involved in the micro-scale although the macroscopic processes is considered as tensile. The results showed that microcracks start as tensile, then both tensile and shear cracking happen and finally microcracks continue as shear, especially at the end of the crack where the specimen experience compression loading.

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