LABORATORY TESTING OF STRESS-INDUCED BRITTLE FRACTURE DAMAGE THROUGH INCREMENTAL LOADING

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ABSTRACT

A series of unique laboratory uniaxial compression tests, referred to as incremental damage tests, were performed to measure the degree of stress-induced brittle fracture damage as a function of the applied load. Strain gauge and acoustic emission measurements were combined with elements of monotonic and cyclic loading in an attempt to isolate several stages of brittle fracture development and to quantify the corresponding permanent strain damage. This paper reports the findings for two sets of these tests performed on samples of Lac du Bonnet granite using two distinct load paths.

Results show that measured increases in permanent axial strain correspond to crack development stages that significantly influence the axial component of deformation (i.e. crack closure, crack coalescence and crack damage). Similarly, increases in permanent lateral strain coincide with the crack initiation, secondary cracking and crack coalescence thresholds, crack development thresholds marking the initiation and/or opening of cracks. Results also suggest that in tests where elements of time are considered in the loading process, a significant percentage of brittle fracture damage can occur during periods of constant load. In these tests, measured creep strains were attributed to the continued initiation, propagation and coalescence of cracks due to the slow dissipation of induced strain energy levels.

INTRODUCTION

Failure mechanisms in highly stressed rock are largely controlled by the progressive development of stress-induced brittle microfractures. Numerous laboratory-based studies have been conducted to better understand the nature of these processes, particularly with respect to identifying the different stages of crack development leading to intact rock failure (e.g. Bieniawski, 1967; Martin and Chandler, 1994; Eberhardt et al., 1998). These stages generally include, with increasing compressive load, crack closure, crack initiation, stable crack propagation, crack coalescence and unstable crack propagation.

The initiation of the microfracturing process, termed crack initiation, σ_{ci}, marks the beginning where the intact rock material undergoes irreversible changes to its cohesive fabric. In this sense, the microfracturing process acts to "damage" the material. As the number of propagating microfractures multiply, damage accumulates and measurable decreases in the elastic stiffness and cohesive strength of the rock occur (Martin and Chandler, 1994; Eberhardt et al., 1998; Eberhardt et al., 1999a).

This becomes an important issue in rock engineering design, since design limits may require frequent adjustments to account for significant changes in material behaviour due to near-field stress changes during the excavation process. *In situ* observations at the Underground Research Laboratory (URL) in Manitoba, Canada, suggest that brittle failure can occur at stresses well below the uniaxial compressive strength, σ_{UCS}, of the host rock. In several related studies, Martin and Chandler (1994) and Read et al. (1998) identified a crack damage stress threshold, σ_{cd} ($< \sigma_{UCS}$), approximating the onset of unstable crack propagation, and equated this to the long-term *in situ* strength. Employing such systems requires a comprehensive understanding of the brittle fracture process and its relationship to stress-induced damage.

This paper presents the results from a specialized set of laboratory uniaxial compression tests designed to measure stress-induced brittle fracture damage as a function of the applied load. Referred to as incremental damage tests, efforts were made to better understand and quantify how the progressive accumulation of brittle microfracturing alters material deformation and strength characteristics.

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INCREMENTAL DAMAGE TESTING

Previous studies by Eberhardt et al. (1999a) have shown that damage may be quantified either as a function of continuous stress and strain, as seen in non-cyclic (i.e. 'monotonic') loading tests, or in the form of accumulated permanent strain with increasing damage increments, as seen through cyclic loading tests. In these tests, damage was defined in terms of permanent axial and lateral strain (ω_{ax} and ω_{lat}) as measured using electric resistance strain gauges. By differentiating between the two directional strain measurements, as opposed to combining their values in a calculated volumetric strain, damage could be attributed to either the initiation and opening of cracks, primarily detected through lateral strain measurements, or the closure or shearing of cracks, primarily detected through axial strain measurements (Eberhardt et al., 1998). Strain-based damage mechanisms were further established through correlations with acoustic emission (AE) measurements for which an independent damage parameter was defined (ω_{AE}). For each case, the damage measured over a single load-unload cycle, or damage increment "*i*", was normalized with respect to the total damage measured throughout the test.

A similar methodology was adopted in the testing and analysis performed for this study. Testing was conducted on cylindrical samples of pink Lac du Bonnet granite obtained from the 130 m level (i.e. 130 m below ground surface) of the URL. Samples were prepared for testing according to ASTM standards with 61 mm diameters and 135 mm lengths. Each sample was instrumented with six electric resistance strain gauges (3 axial and 3 lateral at 60° intervals) and four piezoelectric AE transducers (175 kHz resonant frequency). The AE monitoring system consisted of a bandpass filter with a frequency range of 125 kHz to 1 MHz and a pre-amplifier with 40 dB total gain and a dynamic range of 85 dB.

The testing program consisted of two series of uniaxial compression tests differentiated by the load path applied. The first set of tests involved the use of incremental cyclic loads to isolate several stages of crack development and the corresponding change in stress-induced damage. The second set of tests included elements of creep loading to isolate time-dependent fracture characteristics that may be related to the changing state of stress and the added energy available to drive crack propagation. Results from these tests are reported in the following sections.

Incremental Cyclic Load Test

The first of two incremental load paths used involved a series of load-unload cycles for which the maximum load applied increased with each cycle. Test samples were initially loaded up to 40 MPa and then unloaded with each subsequent load cycle increasing by 10 MPa. This process was repeated up to a peak load of 180 MPa, exceeding the crack damage threshold for Lac du Bonnet granite (Figure 1). With each cyclic load increment the permanent strains and the number of acoustic events attributable to the increase in stress over the load interval were recorded.

Measurements of permanent strain damage show that both the axial and lateral strain damage curves increased with increasing damage increments but at different rates (Figure 2). Axial strain damage was seen to increase linearly from the onset of loading, whereas the lateral strain damage did not begin to increase until the approximate crack initiation threshold for Lac du Bonnet granite was reached (approximately 80 MPa as shown in Table 1). The lateral damage curve then increases exponentially at a relatively constant rate. In terms of absolute strain damage, many of the trends observed in the data correspond to threshold values for Lac du Bonnet granite (Table 1) as determined in monotonic loading tests described by Eberhardt et al. (1998). Load intervals over which the rate of permanent lateral strain increased correspond to the crack initiation, secondary cracking and crack coalescence thresholds, i.e. crack thresholds marking the initiation and opening of cracks (Figure 3). Increases in measurements of permanent axial strain coincide with those thresholds which were observed to significantly influence the axial component of deformation, i.e. crack closure, crack coalescence and crack damage (Figure 4).

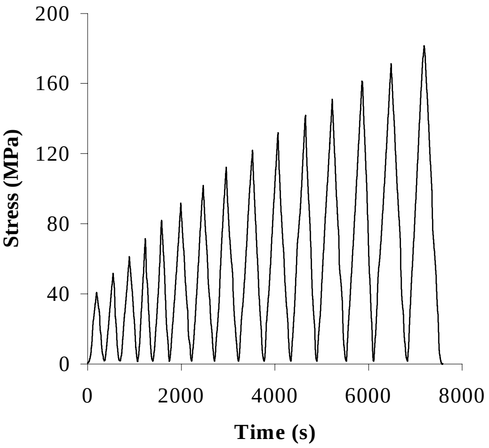

Figure 1 : Load history for incremental damage test using cyclic loading

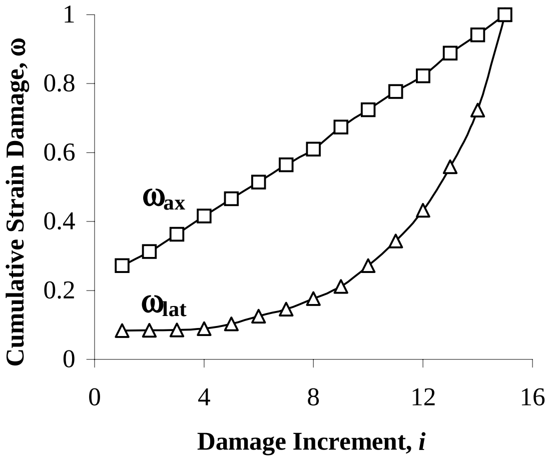

Figure 2 : Cumulative axial and lateral strain damage for an incremental cyclic loading test

Table 1 : Average crack threshold values for Lac du Bonnet granite with standard deviation in parentheses (after Eberhardt et al., 1998)

Threshold Parameter	**Value (MPa)**
Number of Tests	20
Crack Closure, σ_{cc}	47.3 (± 2.7)
Crack Initiation, σ_{ci}	81.5 (± 3.7)
Secondary Cracking, σ_{ci2}	103.9 (± 5.0)
Crack Coalescence, σ_{cs}	132.8 (± 9.0)
Crack Damage, σ_{cd}	156.0 (± 13.2)
Peak Strength, σ_{UCS}	206.9 (± 13.5)

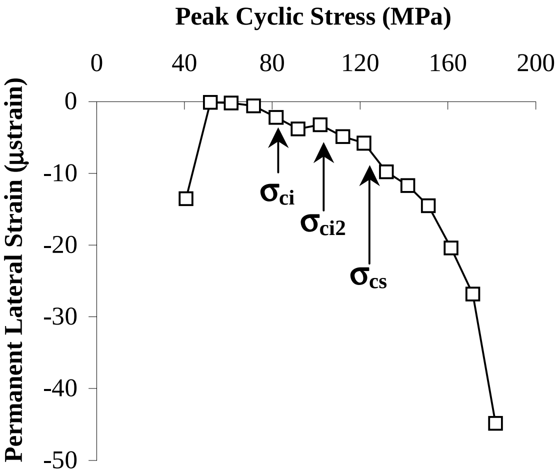

Figure 3 : Absolute permanent lateral strains showing the correlation between lateral strain damage and several crack thresholds

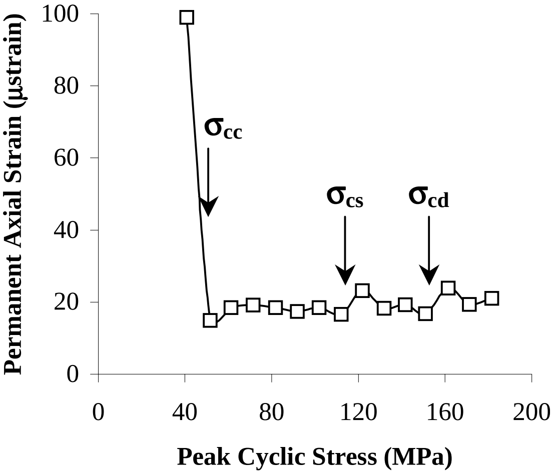

Figure 4 : Absolute permanent axial strains showing the correlation between axial strain damage and several crack thresholds

The acoustic emission data also showed similar trends and correlations with respect to the pre-defined thresholds of crack development (Figure 5). These results suggest that in many ways the Lac du Bonnet granite responded to cyclic incremental loads in the same manner as samples loaded monotonically (see Eberhardt et al., 1998). For example, the volumetric strain curve obtained for the incremental cyclic loading test resembled those derived through monotonic loading tests, showing volumetric strain reversal at approximately 160 MPa (i.e. coinciding with the crack damage thresholds derived through monotonic loading tests; Table 1).

Measured Young's modulus and Poisson ratio values varied with each load cycle but still resembled those obtained through monotonic loading tests. Young's modulus values increased with each damage increment until loads surpassed the secondary cracking threshold (this threshold is described in detail in Eberhardt et al., 1999b). Values then leveled off and remained relatively constant until the crack damage threshold was surpassed at which point the Young's modulus values gradually decreased (Figure 6). These results suggest that for loads between the crack initiation and crack damage thresholds, crack propagation mechanisms did not act to reduce the axial stiffness of the material. These observations concur with Griffith's theory of brittle fracture, wherein crack propagation occurs in a preferential direction parallel to the major principal stress, σ_1, or in the case of uniaxial compression, parallel to axial loading. Accordingly, the opening of cracks perpendicular to axial loading (i.e. perpendicular to their σ_1 propagation direction) should have only a minor effect on the Young's modulus, which is measured parallel to loading. In this sense, increasing Young's modulus values during the initial stages of loading would be expected as existing cracks at oblique angles to the applied load close and the material stiffens. During the latter stages of loading, once the crack damage threshold is surpassed, the unstable propagation and coalescence of existing cracks then contributes a significant non-linear axial strain component as the material softens and Young's modulus values decrease. Poisson ratio values were seen to gradually increase throughout the test as a consequence to non-linearities in the lateral strain component (Figure 6), thus confirming AE analysis showing the initiation and propagation of cracks with each cyclic load increment.

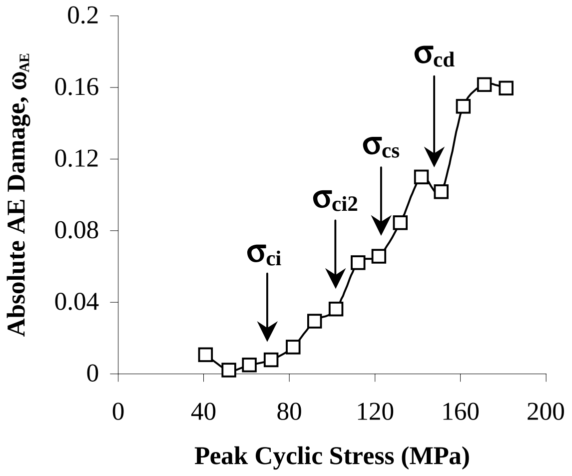

Figure 5 : AE damage correlated to several stages of crack development as determined through monotonic loading tests

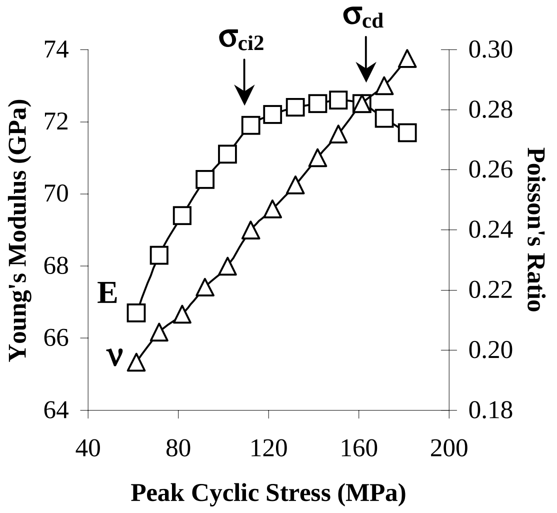

Figure 6 : Change in Young's modulus and Poisson's ratio with each load-unload cycle

Incremental Constant Load Test

The act of applying a load provides energy for the crack initiation and propagation process. By removing the load, the energy supply driving crack propagation is discontinued and the remaining excess energy in the system dissipates through crack propagation processes. However, the dissipation of energy is not instantaneous and some consideration should be given to the effects of time with respect to the loading and unloading process. For example, Farmer (1983) found that the mechanics of deformation in a cyclic loading test are similar to that seen in a creep test except that the cycling process represents a direct energy input which satisfies the conditions for crack propagation much more quickly than the application of a constant load. However, crack propagation can continue under constant loads if the energy in the system exceeds that required for crack propagation (e.g. unstable crack propagation).

A test was therefore designed to determine what effect short time intervals might have on the microfracturing process and the accumulation of damage with increasing stress levels. Analogies may be drawn to the sequencing of an excavation in which stress increases near the excavation face are interrupted by periods of low activity due to development works in the construction process (e.g. drilling of blast holes, installation of rock support, etc.). Testing therefore followed a procedure that incorporated elements of both monotonic and creep loading, whereby test samples were loaded in 10 MPa increments in between which loads were held constant until the level of AE activity showed that crack propagation had ceased (Figure 7).

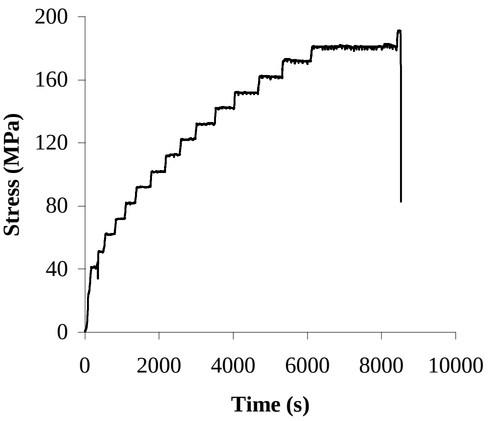

Figure 7 : Load history for incremental damage test using constant loads

Results from this test indicate that a significant amount of brittle microfracturing damage occurred over periods of constant load. This effect was reflected in both measurements of the creep strain and AE activity. However, test results also showed that the overall behaviour of the sample closely followed that seen in monotonic loading tests of Lac du Bonnet granite with the exception that large creep strains were detectable at higher loads. As in the case of the incremental cyclic loading test, volumetric strain reversal occurred at approximately 160 MPa, thus agreeing with crack damage threshold values determined in the monotonic loading tests.

Damage values based on the measured creep strains showed that the accumulation of axial strain damage followed a relatively linear trend, whereas lateral strain damage values increased exponentially (Figure 8). These patterns mirrored those seen in damage curves established for the incremental cyclic loading test (as shown in Figure 2). Similar findings were also made with respect to changes in the Young's modulus and Poisson's ratio, as values for each damage increment followed the same trends as those seen in the incremental cyclic loading tests.

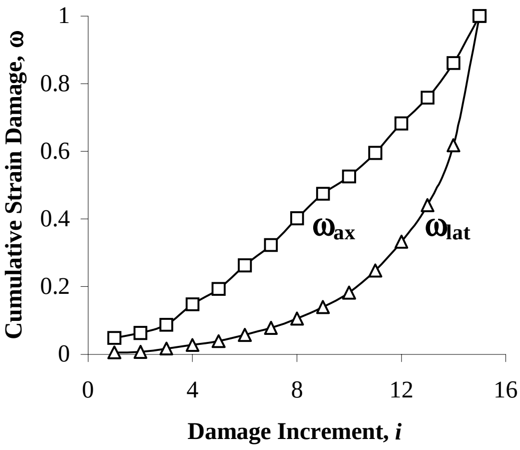

Figure 8 : Cumulative axial and lateral strain damage for an incremental constant load test

Analysis of the recorded AE event counts indicate that a significant proportion of the total events occurred over time intervals where loads were held constant (Figure 9). This confirms strain-based damage observations that suggest that a significant percentage of brittle microfractures were driven by surplus energy stored in the system. Figure 10 depicts the calculated AE event "energy" released with each load level (it should be noted that these values are calculated from peak amplitudes and event durations and are not a direct measure of true energy).

In correlating this response to the thresholds of crack development determined through monotonic loading tests (Table 1), it can be seen that noticeable increases in AE activity and AE event "energy" follow those load intervals in which the different crack thresholds fall. The largest of these increases followed the crack damage threshold, which theoretically marks the beginning of unstable crack propagation (AE activity was detected for over 40 minutes, three times longer than that required for the load intervals following the crack coalescence threshold). AE activity and strain gauge measurements then indicate that the sample eventually reached a short-term stable state. Although this would seem to imply that some uncertainty exists in the use of volumetric strain reversal (by which means the crack damage threshold is determined) as an indicator of unstable crack propagation, the threshold value does appear to provide a good approximation of imminent rock failure.

CONCLUSIONS

A series of specialized uniaxial compression tests were performed in an effort to quantify the different rates of stress-induced brittle damage as a function of the applied stress and several stages of crack development. These tests were designed to incorporate unique loading paths and elements of monotonic and cyclic loading in order to isolate incremental changes in brittle fracture damage.

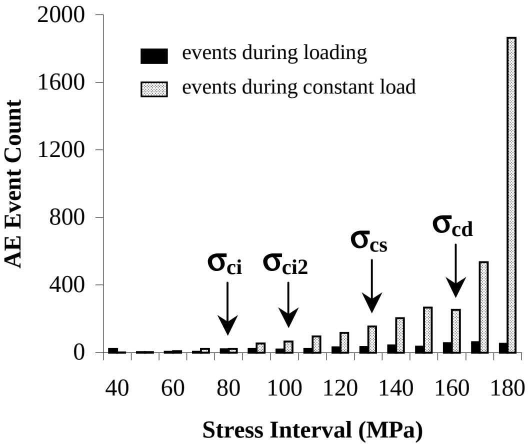

Figure 9 : AE events recorded during loading and constant load intervals

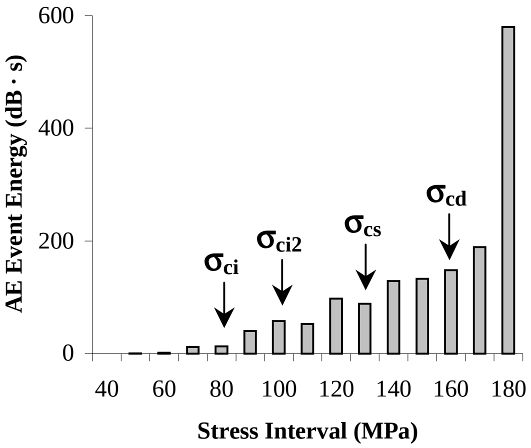

Figure 10 : AE event "energy" as a function of increasing load

Values of axial strain damage were seen to increase linearly with increasing damage increments. Larger increases coincided with the crack closure, crack coalescence and crack damage thresholds (i.e. crack processes that significantly influence the axial component of deformation). Lateral strain damage values increased exponentially, with significant increases occurring at the crack initiation, secondary cracking and crack coalescence thresholds (i.e. crack processes that influence the lateral component of deformation).

Young's modulus and Poisson ratio values varied with increasing damage increments. Young's modulus values increased with each damage increment until loads exceeded the crack damage threshold. Values then gradually decreased. Poisson ratio values were seen to increase with each damage increment thus establishing that new cracks initiated and propagated with each cyclic load increment.

Tests were also devised to isolate time-dependent fracture characteristics that may be related to the changing state of stress and the added energy available to drive crack propagation. Results indicate that a significant percentage of microfracturing damage may occur over periods of constant load as the microfracturing process is fed by energy surpluses in the system. Analysis of creep strains and AE activity suggest that the crack damage threshold provides a reasonable approximation of unstable crack propagation marking imminent rock failure.

REFERENCES

Bieniawski, Z.T. (1967). "Mechanism of brittle rock fracture: Part I - Theory of the fracture process". *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, Vol. 4, pp. 395-406.

Eberhardt, E., Stead, D. and Stimpson, B. (1999a). "Quantifying progressive pre-peak brittle fracture damage in rock during uniaxial compression". *International Journal of Rock Mechanics and Mining Sciences*, Vol. 36, pp. 361-380.

Eberhardt, E., Stead, D., Stimpson, B. and Read, R.S. (1998). "Identifying crack initiation and propagation thresholds in brittle rock". *Canadian Geotechnical Journal*, Vol. 35, pp. 222-233.

Eberhardt, E., Stimpson, B and Stead, D. (1999b). "The influence of mineralogy on the initiation of microfractures in granite". Proceedings 9th International Congress on Rock Mechanics, Paris, August, G. Vouille and P. Berest Eds., Vol. 2, pp.1007-1010.

Farmer, I. (1983). "Engineering Behaviour of Rocks". Chapman and Hall, New York.

Martin, C.D. and Chandler, N.A. (1994). "The progressive fracture of Lac du Bonnet granite". *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, Vol. 31, pp. 643-659.

Read, R.S., Chandler, N.A. and Dzik, E.J. (1998). "*In situ* strength criteria for tunnel design in highly-stressed rock masses". *International Journal of Rock Mechanics and Mining Sciences*, Vol. 35, pp. 261-278.