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Preliminary Studies of Class II Brittle Rock Behaviour

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SUMMARY A lateral servo-controlled uniaxial compression test technique for rock core is described. Complete load-deformation data from tests on Mount Isa rocks is discussed. The interpretation of Class II brittle behaviour is complex, and some preliminary studies are presented to encourage further debate.

1 INTRODUCTION

Brittle rock behaviour has long been recognized and studied, and the concepts of "stiff" testing techniques for obtaining complete load-deformation behaviour are well established (Hoek and Brown, 1980). Typical laboratory uniaxial compression tests for rock core are shown on Figure 1, where two broad classes of behaviour can be identified. The features which distinguish Class II from Class I behaviour can be described semi-empirically by reference to such laboratory data. To generalize the concept of Class II behaviour, and to understand the processes involved, it is more productive to consider the interplay of energies involved in the processes of brittle rock deformation.

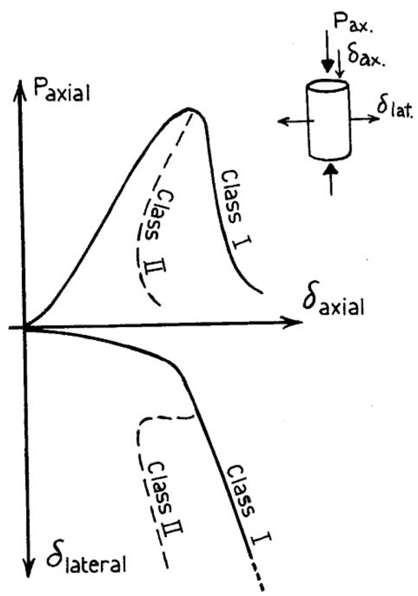

Figure 1 Uniaxial compression test behaviour

Figure 2 shows the difference between Class I and Class II behaviour schematically. The area under the load-deformation curve at any stage of loading represents the work W imparted to the rock sample by the testing apparatus. Some of this work is stored as elastic strain energy (E) while the remainder (P) is absorbed by inelastic processes such as fracture growth and internal friction.

Prior to peak strength, the imparted energy is essentially elastic, and the peak value E_p represents the maximum energy which can be so stored. Class I postpeak yielding is strain-weakening but requires additional external energy ΔW_I to be imparted to the rock for continued deformation. Class II postpeak yielding is also strain-weakening, but the stored elastic energy is greater than the work F required to fragment the rock to the stage of collapse. Class II yield can be controlled only by extracting energy ΔW_{II} from the rock to absorb the excess stored energy, otherwise violent uncontrolled failure results.

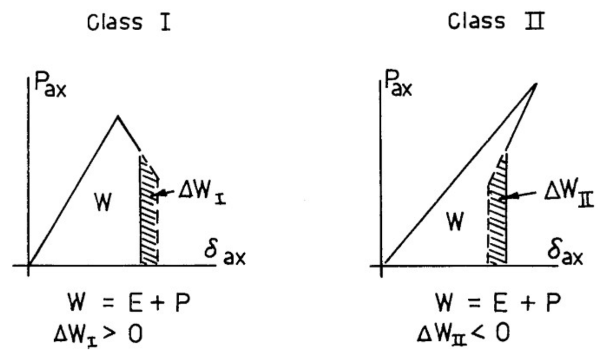

Figure 2 Class I and Class II energy increments

While there is considerable experience with brittleness phenomena in simple laboratory tests, it is by no means easy to transfer these concepts of energy flow to a larger scale, generalized rock mass. A principal problem of brittle rock mechanics is the prediction of unstable energy release, or "rockburst". Most engineering situations involve stress paths of unloading, which are not equivalent to the typical laboratory compression test.

It is the purpose of this paper to indicate an approach, based upon observations from uniaxial compression tests, general enough to be utilized in prediction of typical brittle instabilities. Whether or not this approach is satisfactory will depend to a large extent on experience gained when it is applied to engineering problems.

2 DERIVATION OF ENERGY COMPONENTS FROM U.C.S. TESTS

At any stage of any loading test, an unload-reload cycle is, in principle, very useful for distinguishing elastic and plastic components of energy imparted to the rock. Figure 3 shows (ideally) how the elastic and plastic energy components may be distinguished for both Class I and Class II conditions. In practice it is quite difficult to achieve control of Class II yielding, and the distinction between yielding with local elastic unloading, and overall elastic unloading, is a delicate one.

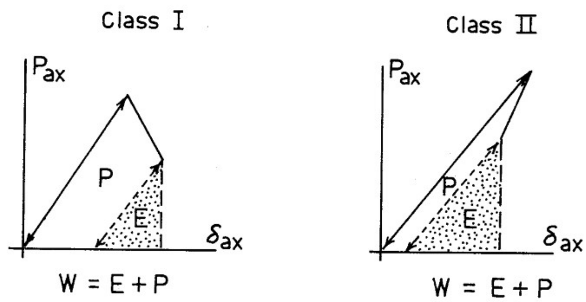

Figure 3 Class I and Class II energy components

A general deformation model requires the establishment of rules governing increments of work, and subdivision into elastic and plastic components. The work components have to be linked to strain or stress variables in an unambiguous manner. Rock samples in uniaxial compression tests have already been subjected to a history of stress relief, which may have induced certain fracture development. It is therefore by no means clear that the U.C.S. test is adequate for providing data for a suitable brittle rock model. Such a situation can only be clarified by further research and discussion.

Despite the obviously non-continuum aspects of macrofracturing, there is a body of experience confirming the validity of strain criteria for brittle fracture development (Stacey, 1981). Strain data from the U.C.S. test may be expressed as principal strain components or in terms of volumetric and shear strain quantities. The latter were used in the present study for purposes of convenience in generalizing the test data. Future work will indicate whether this approach was justified.

3 CLASS II BEHAVIOUR, U.C.S. TESTS

Data were obtained from servo-controlled tests carried out at James Cook University. Since lateral deformations were known to be the most sensitive indicator of yield development, an average radial displacement was used for feedback control. This was compared with a programmed, constant rate of lateral displacement. The average lateral displacement was obtained using three DCDT's, equally spaced around the circumference at mid-height, and an averaging amplifier. This system was generally satisfactory, but its success primarily depended upon the location and sequence of development of macrofractures on the surface of the core. A more satisfactory lateral deformation device has recently been described elsewhere (Attinger and Köppel, 1983).

Chart recorders were used to obtain plots of axial load and lateral displacement as functions of axial displacement during the test. A load cell was used for recording axial load, while axial displacement was obtained from an internal sensor in the load piston. More satisfactory axial displacements were later obtained utilizing external DCDT's mounted parallel to the rock core axis, overcoming some problems caused by hunting and fluctuating levels of piston friction.

With this test configuration experience was required to obtain satisfactory seating of the core and initiation of laterally-controlled loading. A series of cores, representing all major rock types from Mount Isa Mine, were tested with a success rate of about 85% in obtaining satisfactory postpeak data. Unsatisfactory data resulted when cores fractured in a manner which could not be adequately monitored using the 3-point averaging technique.

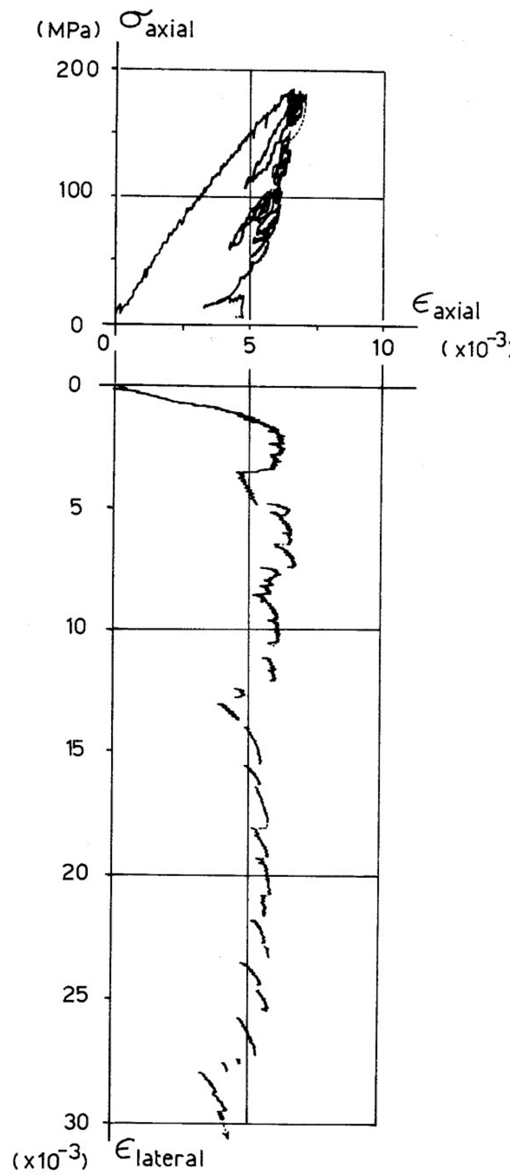

Figure 4 Typical Class II Test Data

Data from a particular test are shown on Figure 4. The prepeak axial load-axial displacement curve shows effects of "hunting" during initial application of load, and there are small-scale irregularities which represent effects of microfracture growth and induced oscillation in the control loop. Of major interest are the unload-reload cycles which arose during postpeak yield, due to the interplay of energies stored in the test system and core with the energy required for fracture development.

The best measurements of prepeak behaviour were obtained using axial displacement controlled tests. The average tangent value of Young's modulus at 50% of peak load was found to be 71.6 GPa (standard deviation 14.1 GPa). Poisson's ratio was determined from the lateral-axial displacement plots using a suitable slope in the range of 0%-70% of maximum load, and was found to be 0.269 (standard deviation 0.070). The unload-reload elastic modulus in the postpeak range was found to be of the same order as the prepeak Young's modulus.

U.C.S. values ranged from 70 MPa to 325 MPa, depending upon the mechanism of fracture development and pre-existence of any weakness planes. An average U.C.S. value of 218 MPa (standard deviation 49 MPa) was obtained.

Recently there has been renewed interest in the use of an extension strain fracture criterion (E.S.F.C.) to describe conditions of brittle fracture in planes perpendicular to the maximum extension strain (Stacey, 1981). Lateral strains of between 70 and 170 microstrain were found to be associated with first evidence of fracturing in the prepeak range of the tests conducted. The lateral extension strain at maximum load was found to vary from 1500 to 4000 microstrain.

4 INTERPRETATION OF CLASS II POSTPEAK YIELDING DATA

Figure 5 is an idealized view of results from imcomplete and complete U.C.S. tests. The superscripts P,I, and U will be used to refer to peak, intermediate postpeak, and ultimate conditions respectively. The linearized curves are a coarse approximation to reality, and because of the unload-reload "hunting" it was thought advisable to consider the two extreme envelopes of postfailure response.

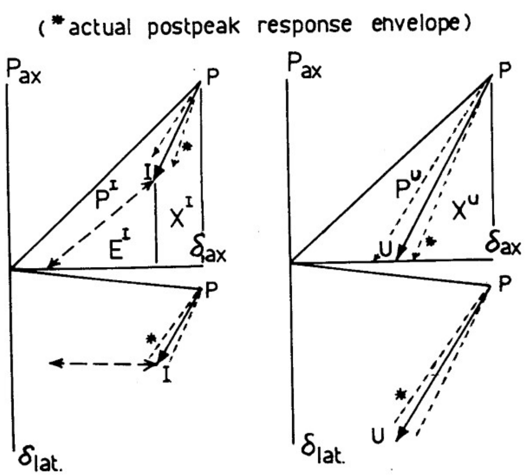

Figure 5 Idealization of Class II Test Data

At an intermediate post peak stage, the energy imparted to the rock is

$$W^I = E^P - X^I \qquad (1)$$

or

$$W^I = P^I + E^I \qquad (2)$$

where W, E, X, P are respectively the total energy, the elastic energy, the energy tranferred to maintain stability, and the energy of fracture.

The lateral and axial deformation data were transformed to enable all energy components to be plotted as functions of volumetric strain ε_{vol}. This leads to curves of the form shown in Figure 6, which are actually bands if the postfailure limiting envelopes are drawn.

The basic concept of stable yield concerns the transferred energy X^u versus the maximum stored energy E^p. An "energy ratio " R was defined as

$$R = \frac{X^u}{E^p} \qquad (3)$$

and because of the "hunting" phenomenon, extreme values Rmax and Rmin were estimated. From the test data, R ranged from a mean minimum of 0.18 to a mean maximum of 0.70.

For the test data, an average value of E^p was calculated to be 332 MJm^{-3}. Using the average limits of R, the energy required to completely fracture a 52 mm diameter core, 120 mm long, would be 25 to 70 J. For equivalent fracture of 1 m^3 of rock, the energy required would be 100 to 272 MJ. Since the stability of the loaded rock is of interest, it may be calculated that the energy transferred outside the 1m^3 volume of yielding rock would be 232 to 60 MJ. In practice, the limits on energy transfer would be much wider since the above calculations are based on average values.

5 GENERALIZED CLASS II ELASTOPLASTIC MODEL

It is assumed that the fundamental energy quantities obtained from interpretation of the U.C.S. test may be generalized. A very loose elastoplastic framework is proposed here. The framework assumes that any increment of strain can be separated into elastic and plastic components. The elastic component may be dealt with using elastic theory. The plastic component has to satisfy two criteria determined by the yield function and flow rule.

The flow rule is obtained experimentally from measurements of instantaneous volumetric and shear strain rates. Plastic strain increments can be derived by assuming (in the absence of better information) coaxiality of principal stress and strain increment axes.

The yield function specifies the relationship between principal stress components. During strain-weakening, strength reduces from peak to ultimate conditions. Experimental data permit the construction of the energy-component versus volumetric strain curve as given in Figure 6. For a given value of volumetric strain, the current values of energy components E, P, X, and W are known. Furthermore, a given change in volumetric strain will give rise to changes in E, P, and X which can be determined. The energy components may be used to determine the associated stress changes from the current stress state. The mathematical elaboration of this process will not be discussed here: it is complex and requires extensive study.

Of fundamental significance is the energy term X. This represents energy which has to be transferred *outside* the volume of rock in question, in order to allow stable yielding of that volume. This represents a stability criterion, in a localized sense, for further yielding. In a global sense, however, there will be volumes of rock undergoing similar

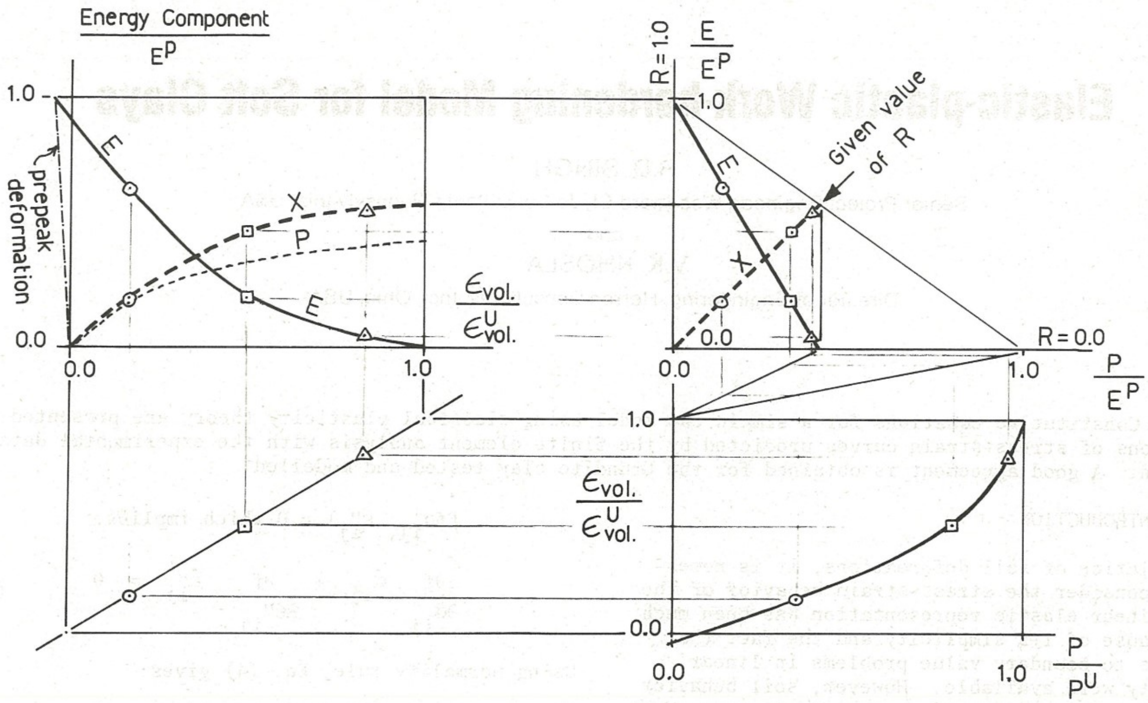

Figure 6 Energy Components versus Volumetric Strain based upon Idealized Class II Test Data

processes. For global equilibrium of a rock structure, there must be a stability criterion on the scale of the structure in order for yielding to remain as a controlled process.

6 SUMMARY AND CONCLUSIONS

Concepts of Class II brittle rock yield have been discussed and some preliminary test data evaluated. The standard U.C.S. test has be to very carefully modified using specialized servo-controlled apparatus in order to obtain Class II postfailure data.

A model framework has been suggested for generalizing Class II behaviour. It is based upon obtaining stress changes from energy components of the rock, assuming a set of basic relationships between strain and energies of fracture, elasticity and stability-transfer. Without mathematical elaboration, it is assumed that this information, together with a flow rule based upon observed, experimental deformations, can be utilized to develop a comprehensive model of Class II response. Using such a model, only the peak and ultimate strength envelopes would need to be defined for a complete description of rock behaviour.

A key issue in Class II response is the stability of yielding. This occurs only in a localized sense when a certain energy per unit volume of rock can be stably transferred to, presumably, surrounding volumes. Such a process is possible because controlled Class II response in U.C.S. tests has been demonstrated. However, in a rock structure the stability of the structure also has to be examined. If a condition develops where the required transfer of energy for local stability cannot be maintained by the structure, then global instability will ensue. In layman's terms, yielding of a rock structure might commence with small-scale brittle "popping" and continue in a *stable* sense throughout the "life" of the structure. This requires that a suitable energy transfer is possible. If the transfer is not possible, then the "popping" will accelerate and become a "rockburst".

The constitutive modelling of the energy transfer process is challenging, and goes beyond current practice in geomechanics modelling. The global stability criterion can, however, be quite readily incorporated into existing computational schemes. The challenge at present is to justify such models by application to rock problems insitu. This will require firstly the mathematical elaboration of concepts similar to those herein, and secondly back analysis. The writer would very much appreciate comments on the approach suggested herein.

7 ACKNOWLEDGEMENT

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8 REFERENCES

ATTINGER, R.O. and KÖPPEL, J. (1983). A new method to measure lateral strain in uniaxial and triaxial compression tests. Rock Mechanics and Rock Engineering, Springer-Verlag, Volume 16, pp.73-78.

HOEK, E. and BROWN, E.T. (1980). Underground Excavations in Rock. London, Institution of Mining and Metallurgy.

STACY, T.R. (1981). A simple Extension Strain Criterion for fracture of brittle rock. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, Pergamon, Volume 18, pp.469-474.