Fracturing around highly stressed excavations in brittle rock

by J. Kuijpers*

Synopsis

Failure and fracturing are often regarded as synonymous. While this is obviously true in an environment dominated by tensile stresses, it is still not clear how failure and macro fracturing are related in a compressive stress environment. Excavations at great depths are typically subjected to compressive stresses only. The fracturing observed around such excavations is therefore commonly assumed to be induced by such compressive stresses. The physics of such a phenomenon have unfortunately never been explained properly, so that the formation of these so-called extension fractures still remains a mystery. As the presence of fractures is an important factor affecting the stability of underground excavations, it is of practical relevance to understand their formation. In this paper, a possible explanation is proposed. It is argued that fracturing in a compressive stress environment is a secondary effect. Primary failure, in the form of micro fracturing and associated damage is assumed to precede the major fracture processes. The fractures are thus generated in *response* to material failure and may not directly be the *cause* of failure. The implications for material response and behaviour are discussed.

Keywords: micro fracturing, macro fracturing, extension fractures, failure, compressive stresses, damage, excavations.

Introduction

The presence of parallel fractures around highly stressed excavations in brittle rock is a common phenomenon. Such fractures are generated near the face of the excavation and propagate towards the excavation, thus forming layers of rock around the excavation. Previous investigations[1,2] indicated that these fractures are not necessarily generated by excessive blasting or any other external forces which may induce tensile stresses. The formation of these fractures is believed to be associated with the presence of excessive (compressive) stresses around the excavation.

If this is accepted, an obvious question needs to be addressed, namely: how do fractures form in an environment in which all stresses are compressive? The formation of shear fractures, or rather shear zones, can readily be explained under such circumstances. However, these structures are *not* considered here. The fractures under consideration are so-called extension fractures, which form in a plane perpendicular to the minor principal stress. These extension fractures do not exhibit any sign of shear damage or deformation, immediately after their formation, and have thus been subjected to opening (extension) only.

Three basic mechanisms for the formation of extension fractures in a compressive environment have been suggested in the past.

➤ In the first one the fracture opening is assumed to be caused by strain rather than stress. A critical extension strain is proposed as failure and fracture criterion[3]. While such a mechanism is simple and therefore attractive, it fails to address the physics of the problem. The formation of a fracture must be associated with energy release; if fracture opening takes place against the action of a compressive stress, the opposite is happening, namely the generation of energy. This appears to be implausible.

➤ The second mechanism is related to the actual shape of the fracture tip. Gramberg[4] proposes a 'notch with ellipse', whereby clamping stresses around the ellipse effectively induce tensile stresses at the nearby fracture tip. Fracture formation is assumed to take place by a transformation process in which the relatively narrow cusp-shaped tip rapidly changes into an ellipse which is orders of magnitude wider than the fracture tip. Gramberg[4] explains that the fracture tip occurs at an atomic scale and that the widening is possible due to the relaxation of atomic bonding stresses. This proposed mechanism is not based on any evidence in the form of fracture

* *Miningtek, CSIR, Johannesburg, S.A.*

tip observations and appears to be driven by the assumption that tensile fracturing can propagate from a single flaw in all compressive stress environment.
- The third mechanism is based on the concept of sliding cracks, originally developed by Brace and Bombalakis[5] and Fairhurst and Cook[6]. This mechanism operates at a micro scale and macro fracture formation is assumed to result from a coalescence process of micro fractures. Kemeny and Cook[7] and Meyer *et al.*[8] analysed the coalescence of micro fractures by assuming collinear interaction of wing cracks developing from such sliding cracks. Closer examination[9] showed, however, that coalescence is not feasible in such a way and that coalescence is in fact only possible if the sliding cracks are positioned along a line which is inclined with respect to the direction of the major principal stress. The macro fracture, resulting from this coalescence process, should thus be interpreted as a shear fracture and not as an extension fracture.

From the above it is clear that the proposed mechanisms cannot satisfactorily explain the observed phenomenon of extension fracturing in a globally compressive stress field. A common feature of the first two proposals is that they seek to explain extension fracturing in a linear elastic medium. It is, however, clear from typical stress-strain relationships in compressive strength tests that some form of yield and/or degradation occurs before brittle failure and macro fracturing is initiated. Such yield and/or degradation is associated with micro fracture growth in most brittle rocks. In the third proposal the micro fracture growth is explicitly incorporated, but only the interaction between individual micro cracks is considered as relevant to the formation of macro fractures.

Adopting a more conventional approach, with the notion that micro fracturing can have a profound effect on material stiffness and deformation, it can be demonstrated that the global stress distribution can be affected in such a way that tensile stresses are induced in an initially compressive environment. A similar process in fact takes place at the micro scale and is responsible for the initiation and growth of micro cracks. The micro scale is, however, only of concern with respect to its influence on larger scales, in terms of the formation of macro (extension) fractures. Of main importance, therefore, is a realistic representation of the influence of collective micro fracturing. This influence can ultimately manifest itself in a stress redistribution at larger scales, provided that the distribution of micro fracturing is non-uniform; a homogeneous density and intensity of micro fracturing would obviously only result in uniform material softening without affecting the stress distribution.

Effect of micro fracturing on global stress distribution

The condition of non-uniform distribution of micro fracturing and associated damage is easily satisfied in most applications. Even in the most strictly controlled laboratory experiments, a uniform distribution of global stress can hardly be enforced. Boundary effects typically restrain or promote the horizontal expansion of vertically compressed specimens in such a way that global stresses are not uniformly distributed. The induced micro fracturing therefore also assumes a non-uniform distribution. In more practical applications, where global stress concentrations are common, non-uniform micro fracture and associated damage distribution will be the norm, rather than the exception.

Figure 1 shows the distribution of tensile stresses in a vertically loaded model. The vertical boundaries are not restrained, while the horizontal boundaries are restrained in both horizontal and vertical directions. The vertical displacement of these boundaries is prescribed by a uniform

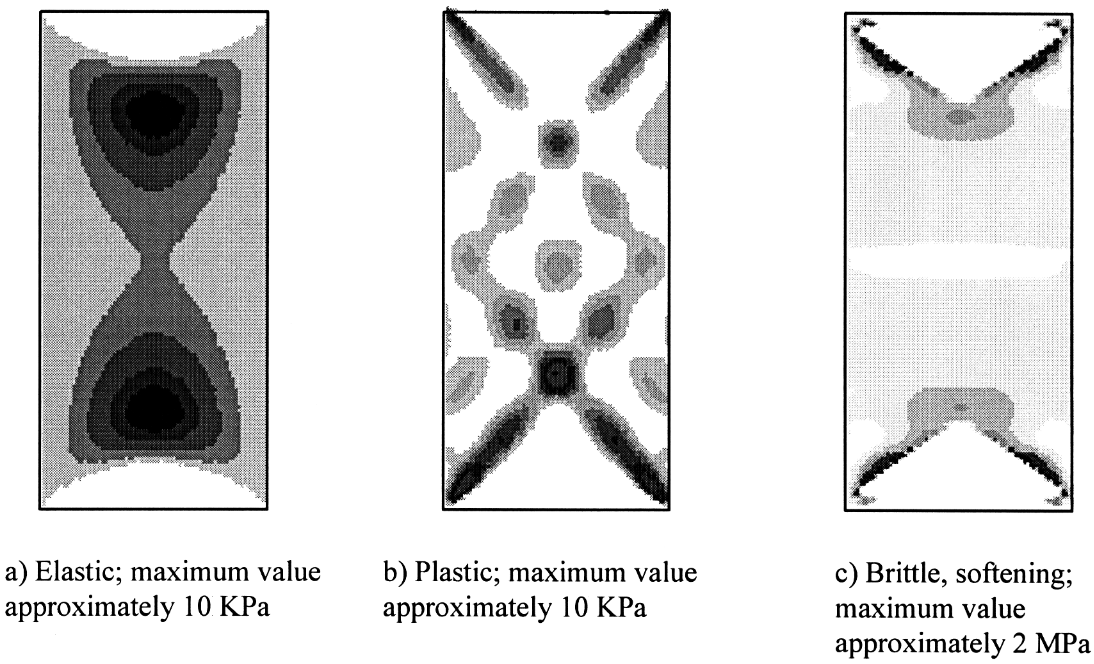

Figure 1—Distribution of tensile stresses in specimens subjected to a vertical load of approximately 10 MPa; the results are from numerical simulations with FLAC. (Maximum values are shown in black; compression in white)

value and no horizontal deformation is allowed. The model represents a typical uni-axial loading test in which rock specimens are evaluated. In an attempt to represent the effect of micro fracturing, a plasticity type model has been used. Both perfect plastic behaviour as well as strain hardening and strain softening (brittle) can be simulated.

Although it is arguable that the effects of micro fracturing are directly represented in a plasticity model, some useful observations can be derived from Figure 1. The results from the elastic model in Figure 1a show the presence of maximum tensile stresses in the core of the specimen. This would suggest that if fracturing were to initiate at this stage, it would have to split the specimen in two equal portions. Subsequently, maximum tensile stresses will occur in the centre line of these halves, resulting in splitting, etc. It is, however, difficult to envisage how such relative low tensile stress values (1/1000 of the compressive stress) could lead to fracturing. Local stresses may obviously reach higher values as stress concentrations, caused by micro defects, may be associated with relatively high tensile stress levels. In that case fracturing may initiate anywhere within the specimen and the global stress distribution is of little relevance. Figure 1a represents conditions for perfectly brittle fracturing and associated failure. It is clear, however, that even the smallest amount of horizontal confinement will suppress the tensile stresses and the associated large scale fracturing in this case.

Figure 1b shows the results of a numerical simulation in which the material is assumed to behave perfectly plasticly. As can be observed, the distribution of tensile stresses is affected by the associated inelastic deformations. The magnitude of the tensile stresses are still relatively low and cannot be expected to lead to macro fracturing. In Figure 1c, the material strength is reduced in relation to the magnitude of inelastic shear deformation. (so-called strain softening). As a consequence, relatively large tensile stresses are induced, which may well be expected to result in macro fracturing. The model suggests that fracturing takes place in response to preceding material damage and associated degradation.

Conventionally, the formation of fracturing is explained from an initially (linear) elastic stress distribution. In the following, a previous analysis of fracturing in a laboratory experiment will be critically discussed in order to obtain a better insight in the processes involved. In an attempt to simulate observed fracturing with a numerical model, Napier[10] used results from a physical model, published by Ozbay and Ryder[11]. The model consisted of blocks of norite and quartzite, which were cut in such a way that two narrow slots, separated by a pillar in the middle, were created (Figure 2). The blocks were compressed in both the horizontal and vertical direction until failure occurred.

The resulting load deformation relations are shown in Figure 3, while Figure 4 represents a typically observed fracture pattern. These fractures could only be viewed after the tests, as the specimens were concealed during the test by a bi-axial frame, which was used to confine the specimens. No out of plane confinement was applied and thus out of plane stresses were absent.

Figure 4 shows clearly that the regions above and below the pillars have not been subjected to fracturing. Ozbay and Ryder[11] comment that 'the pillar foundations did not fail completely in the sense that the regions above and below the pillar remained intact'. This can, however, not be reconciled with the results depicted in Figure 3 which demonstrate

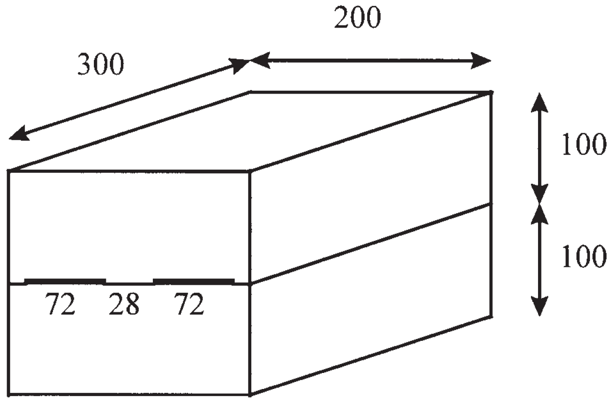

Figure 2—Geometry of the laboratory specimens tested by Ozbay and Ryder[11] (Dimensions are in millimetres)

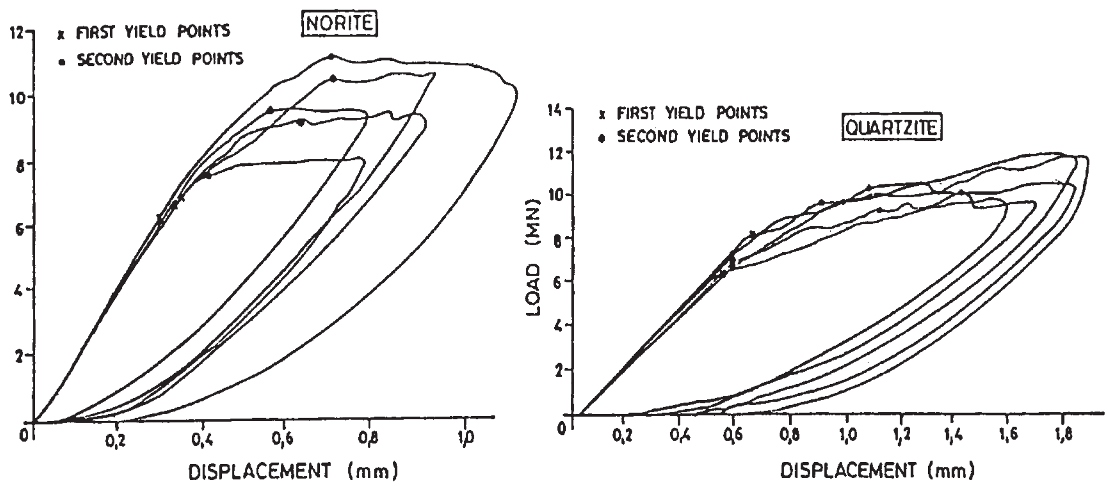

Figure 3—Overall load-deformation relationships of the specimens tested by Ozbay and Ryder[11]

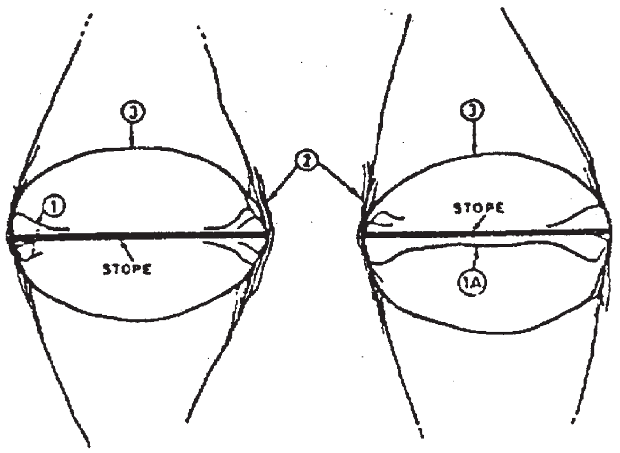

Figure 4—Schematic representation of the fracture pattern observed from vertical sections taken from the bi-axially tested specimens

clearly that either the pillars or the pillar foundations must have been yielding. Although it is typically assumed that the failure of brittle rock is directly caused by fracturing, these results suggest that the observed fracturing cannot be related to the observed specimen yielding. This conclusion has a direct implication to current interpretation of brittle failure and fracturing and will be discussed in more detail.

Napier[10] used displacement discontinuities to simulate fracture initiation and growth numerically. The selection of a propagation path is based on the evaluation of field points at a fixed radius around the end of a discontinuity. Two different fracture growth criteria are considered, namely one which is based on a maximum allowable tensile stress across the radial direction and one which is based on a maximum allowable shear stress along the radial direction. Inelastic and/or-non linear deformation can only take place within the discontinuities. The material is otherwise treated as a linear elastic continuum. Figure 5 shows some of the results obtained from these numerical simulations.

The results of the numerical models suggest that shear fracturing has taken place in the laboratory tests. Only the shear (S) type fractures appear to coincide with the steep fractures observed in these tests and from this it could be concluded that a shear fracture criterion is required in order to obtain realistic results. However, the potential for tensile fracture formation has not been completely assessed yet. In the numerical experiments initial cracks are used in order to represent the shear and compressive damage around the abutments. The discontinuities located at the edges of the horizontal slot are assumed to offer frictional resistance only, as no cohesive and tensile strength is allowed. As a consequence, stress concentrations which exceed the threshold for fracturing by far, develop at the tip of these 'initial cracks' The effect of such excessive stresses is investigated in the following.

A numerical experiment, similar to the one described by Napier[10], has been used to demonstrate the effect of stress concentrations at the initial crack tips on the propagation of subsequent tensile fractures. Two extremes are being compared, namely the case in which the initial cracks do not have a cohesive and tensile strength (fractures numbered 1) and the case in which the cohesive and tensile strength are continuously adjusted in such a way that the tensile stress near the fracture tip just exceeds the threshold for fracture growth (fractures numbered 2). Figure 6 shows the results for both extremes in the case of a 2:1 stress ratio and a 4:1 ratio.

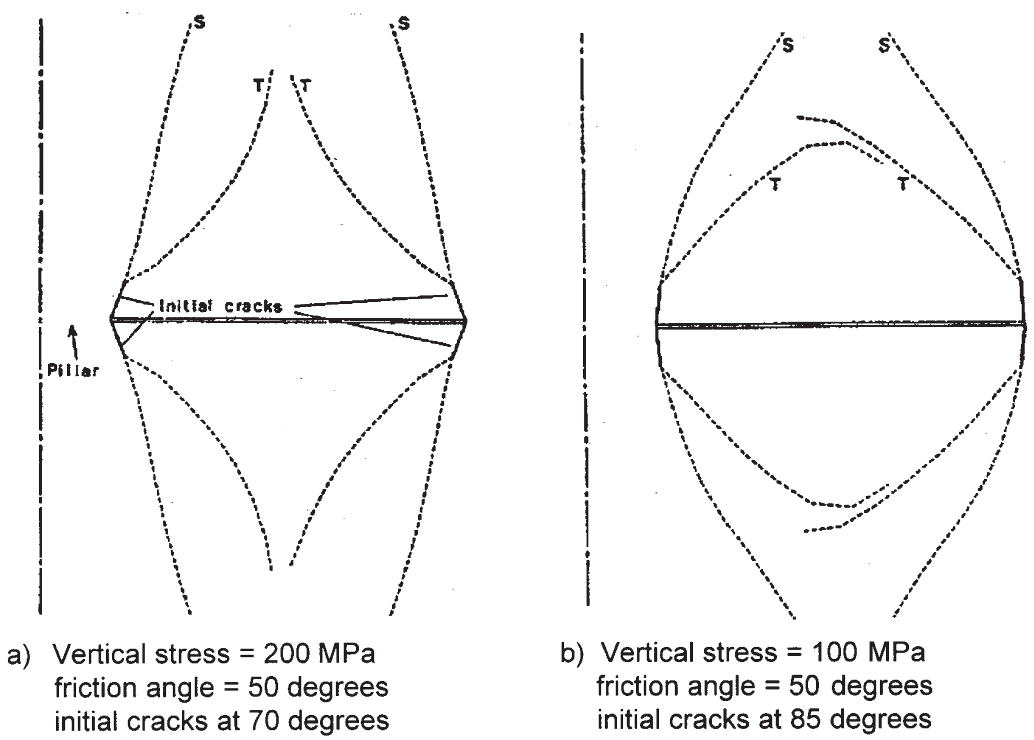

Figure 5—Propagation of tension (T) and shear (S) cracks from starter discontinuities located at the abutments of a horizontal slot. Horizontal confinement = 50 MPa. (after Napier[10])

It is clear from Figure 6 that the fracture pattern is quite sensitive with respect to the details of the driving mechanism. Figure 6 demonstrates how tensile fractures can assume a much steeper orientation if the driving shear stresses are not excessive. This appears to be a realistic limitation as a fracture can be expected to initiate as soon as a critical tensile stress is available. Any stresses in excess of the critical levels would lead to an unrealistic stress distribution.

The observed fracture geometry can thus closely be matched by the simulated tensile fractures. While this is a satisfactorily result, it should be emphasized that the observed relationship between the load and the deformation cannot be explained by the mere presence of these fractures. This may be illustrated by comparing a non-fractured model with that of a fractured model. Numerical results indicate a reduction of around 30% in stiffness in a specimen with a fracture geometry similar to the observed ones. Some in plane fracturing has also been observed, but this only affected the immediate areas near the front and the back of the specimens.

If the observed yielding behaviour cannot directly be associated with explicit macro fracturing, then a potential alternative cause may be found in plastic material deformation. In order to investigate this alternative, numerical analyses with the Finite Difference Code FLAC have been carried out. The same specimen geometry has been simulated, but in this case is has been assumed that shear failure takes place according to a Mohr-Coulomb failure criterion. The results, which are shown in Figure 7, indicate a relationship between load and deformation which is in good agreement with the observed behaviour (Figure 3). The distribution of failure propagates from the abutments across the pillars, while the core of the pillars remain intact. The stress redistribution, associated with the inelastic deformations within the failure zone, indicates an increased potential for tensile failure (= fracturing) at locations which would otherwise not be subjected to tensile stresses. Such a mechanism, or a similar one, may explain fracture formation in a medium which is subjected to compressive stresses.

The concept of primary material damage taking place on a micro scale is often used in the context of brittle failure under compressive stress conditions. Damage mechanics offer constitutive laws for material behaviour. However, the formation of macro fractures is normally associated with some form of a coalescence process between micro fractures[7]. Closer examination of proposed coalescence processes shows, however, that the formation of tensile fracturing under compressive stress conditions is not possible[9]. The effect of micro fracturing on the global stress distribution may offer a more realistic mechanism for the formation of macro fractures in a compressive environment.

Relevance to fracturing around underground excavations

The fracturing of brittle rock around highly stressed excavations is still poorly understood and can therefore not be represented in an adequate fashion. Fracturing in a typical tunnel sidewall at great depth occurs in the form of slabs which intersect the tunnel wall at very small angles. These fractures are believed to have initiated at or near the tunnel face, irrespective of the excavation technique. Elastic analyses do not indicate the presence of tensile stresses, and the formation of these fractures thus remains a mystery. If the effects of micro fracturing and associated damage are, however, taken into consideration, the induction of tensile stresses and associated fracture formation become a possibility as has been demonstrated previously.

Macro fracturing under these conditions is therefore a secondary process which takes place in response to primary failure in the form of micro fracturing. In an attempt to represent the effects of micro fracturing in this paper, use has been made of a plasticity formulation. More appropriate models can most likely be formulated if these micro damage processes are analysed in more detail and for various rock types. The aspect of fracture formation under compressive stress conditions has been addressed, but the effect of macro fracturing on global material behaviour is probably of more practical importance.

The (residual) strength of a fractured material is an essential parameter affecting the stability and support requirements of the associated excavations. The strength of a series of parallel slabs, compressed in the plane of these slabs, cannot easily be formulated. In essence such slabs will be prone to buckling, and slenderness and boundary

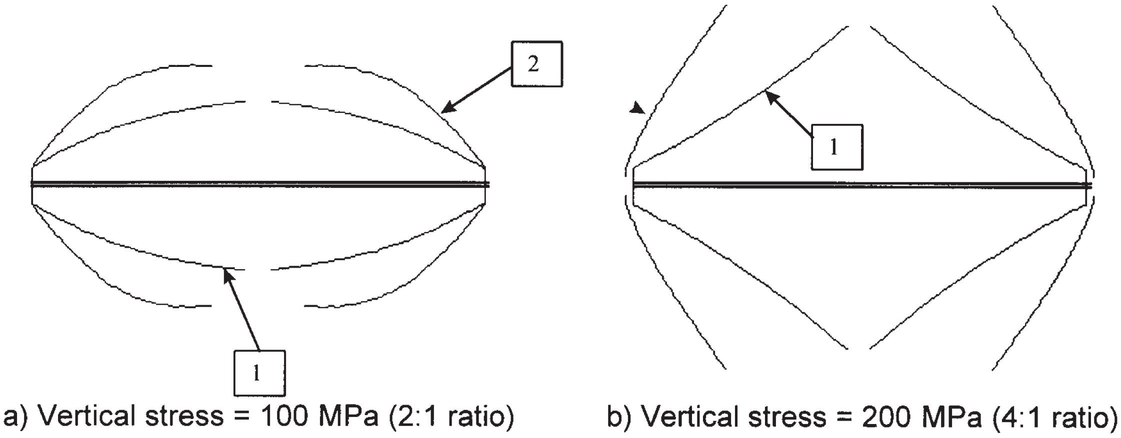

Figure 6—Resulting fracture patterns from numerical simulations; horizontal confining stress = 50 MPa

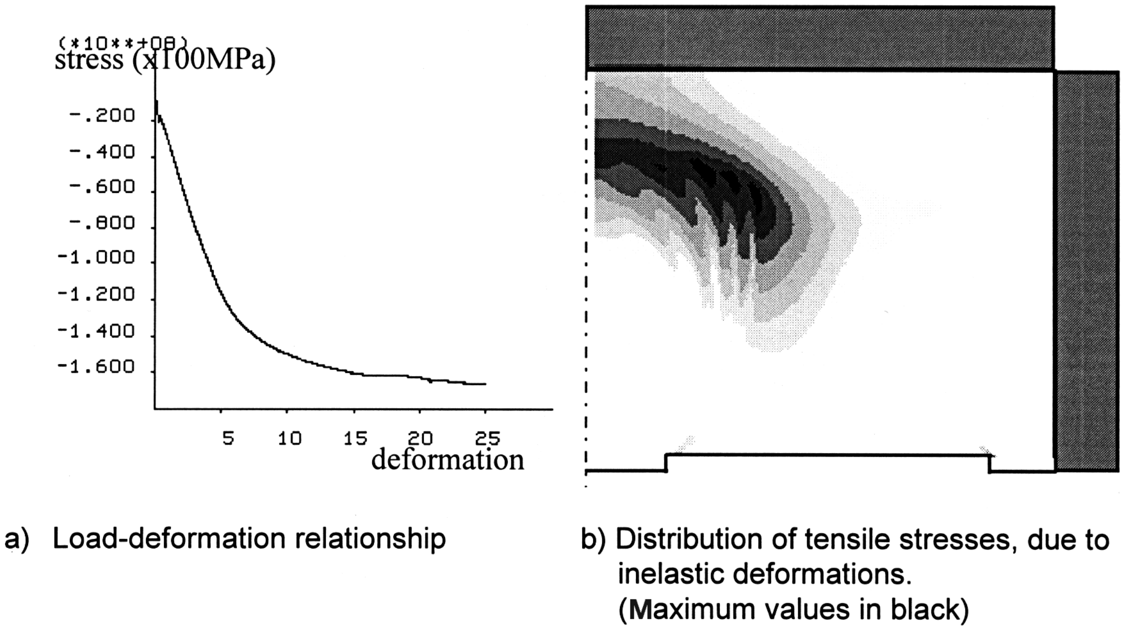

Figure 7—Results of a numerical simulation in which the rock is represented as perfectly plastic material (FLAC)

conditions will determine the strength to a large extent. It is known[12] that harder, more brittle rocks are more densely fractured than softer, more ductile rocks. This may be associated with the fracture toughness of the material.

It has been suggested (but never demonstrated) that higher stresses lead to more intense fracturing as well. If true, this reinforces the concept that fracturing is a secondary process in a compressive stress environment. If fracturing would be a primary failure process, leading to immediate material failure, it would be impossible to increase the stresses in the fractured material. The fact that it is possible to increase the stresses, and in such a way increase the density of fracturing, indicates that fracture formation cannot directly be associated with material failure under these conditions. Ultimately fracturing will contribute to material failure, but rather indirectly, by processes such as buckling and even shearing. Unfortunately, such post-fracturing behaviour has not been analysed in any detail yet and no practical information is available.

Currently, the extent of fracturing around a tunnel in highly stressed brittle rock is estimated by comparing the acting stress with the Uniaxial Compressive Strength of the associated rock. Deformations taking place within the fractured rock can be estimated by assuming a certain value for dilation in a continuum approach. However, as the fracturing creates a discontinuous material, a more realistic representation may be required. Numerical models allowing for the simulation of a fragmented, blocky medium are available. In order to obtain meaningful results it is of importance that the results of such models are calibrated against relevant data. These data must include the correct fracture geometry, stress changes and the associated deformations. The author is not aware of any attempt to represent the behaviour of an excavation in such a way. If support systems are to be designed in a more efficient manner, it is essential that a realistic representation of fracturing and fracture zone behaviour becomes available.

Conclusions

No realistic representation of fracturing in a compressive stress environment is yet available. The design of support systems in highly stressed excavations, has for this reason, no fundamental basis. The assessment of stability conditions and requirements is at best based on previous experience in equivalent conditions.

In this paper, the formation of so-called extension fractures has been explained from the presence of induced tensile stresses. Such a mechanism allows for a realistic representation of fracturing and its effects on material behaviour. Extension fracturing is assumed to be preceded by a micro damage process which, in turn, affects the global stress distribution in such a way that tensile stresses can be generated.

Examples of a potential representation of the micro damage processes have been presented. This was merely an initial attempt and more work is required in order to calibrate these processes for various materials. The behaviour of fractured rock needs to be analysed in much more detail in order to calibrate associated models. Finally, data regarding the detailed fracture geometry and its response to stresses is required from *in situ* excavations.

Once the proposed model has been sufficiently calibrated according to these recommendations, a realistic design tool will be available.

Acknowledgement

The work described in this paper is partly derived from research work sponsored by the Deepmine programme. Permission to publish the results is gratefully acknowledged.

References

1. Stacey, T.R. and De Jongh, C.L. Stress fracturing around a deep-level bored

tunnel. *Journal of the South African Institute of Mining and Metallurgy*. 1977, pp. 124–133.

2. MORE O'FERRALL, R.C. and BRINCH, G.H. An approach to the design of tunnels for ultra-deep mining in the Klerksdorp district. *Proceedings of the SANGORM symposium on rock mechanics in the design of tunnels*. 1983.
3. STACEY, T.R. A simple extension strain criterion for fracture of brittle rock. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr*., vol. 18, 1981. pp. 469–474.
4. GRAMBERG, J. *A non-conventional view on rock mechanics and fracture mechanics*. Rotterdam, Balkema. 1989.
5. BRACE, W.F. and BOMBALAKIS, E.G. A note on brittle crack growth in compression. *Journal of Geophysical Research*, vol. 68, no. 12, 1963. pp. 3709–3713.
6. FAIRHURST, C. and COOK, N.G.W. The phenomenon of rock splitting parallel to the direction of maximum compression in the neighbourhood of a surface. *Proc. First Congr. Int. Soc. Rock. Mech*. 1966.
7. KEMENY, J.M. and COOK, N.G.W. Crack models for the failure of rock under compression. *Proc. 2nd Int. Conf. Const. Laws for Eng. Mat*., vol. 2, 1987. pp. 879–887.
8. MEYER, L.R., KEMENY, J.M., ZHENG, Z., SUAREZ, R., EWY, R.T., and COOK, N.G.W. Extensile cracking in porous rock under differential compressive stress. *Appl. Mech. Review*, vol. 45, no. 8. 1992.
9. KUIJPERS, J.S. Identification of inelastic deformation mechanisms around deep level mining stopes and their application to improvements of mining techniques. PhD thesis, University of the Witwatersrand. 1998.
10. NAPIER, J.A.L. Modelling of fracturing near deep level gold mine excavations using a displacement discontinuity method. *Proc. Int. Conf. Mech. of Jointed and Faulted Rock*. 1990. pp. 709–715.
11. OZBAY, M.U. and RYDER, J.A. Investigations into foundation failure mechanisms of hard rock squat rib pillars. *Int. Symp. Rock Mech. & Rock Physics at great depth*. Pau. 1989.
12. WAGNER, H. Some considerations concerning the support of tunnels. *SANGORM symposium on rock mechanics in the design of tunnels*, 1983. ◆

Researchers expand commercial interests in South Africa*

Transferring applied research to South Africa's mining sector took a huge leap forward recently with the expansion of JKTech's consulting and software agency in Cape Town.

JKTech is the commercial division of the University of Queensland's Julius Kruttschnitt Mineral Research Centre, and has been formally represented in Southern Africa by University of Cape Town research engineer Dr Malcolm Powell since 1997.

Dr Powell said demand during the past twelve months from the South African minerals sector for JKTech products and services had grown to the point where expansion of the local agency has become necessary.

'The industry believes we are filling a gap for a service that hasn't previously existed in this country,' he said.

'We represent JKTech on all of their simulation software, and we are also the exclusive South African agent for the software simulators JKSimMet and JKMBal.'

He said mineral processing simulators were still relatively new to South Africa with only a few operations using the more recent versions of JKSimMet.

'JKSimMet is heavy duty software used to design and optimize mineral processing plants,' Dr Powell said.

'The challenge with using Australian-designed simulators is their application to local South African data.'

He explained that data from comminution research conducted by UCT's Mineral Processing Research Unit had been fed into the software to simulate typical South African process plant conditions.

'At the moment the industry is standing by waiting for the release of JKSimFloat, which will be the first flotation simulator to be marketed through a South African agency,' Dr Powell said.

'This simulator will represent a combined applied research effort between UCT and the JKMRC as joint developers.'

Part of the planned expansion of the agency includes the appointment of minerals industry consultant Mr Vic Hills who will be responsible for marketing and management of JKTech's simulation software in southern Africa.

Dr Powell said additional technical support staff would be required as the agency expands.

According to MPRU research coordinator Mr Martin Harris, many South African mining houses haven't had people on the ground to do optimization and design work.

'With company research units being down-sized there will be a greater demand for local consultants such as Malcolm Powell and Vic Hills to conduct this work.'

Anticipating steady growth for the agency, Mr Harris and UCT colleagues Professors Cyril O'Connor and Gerald Nurick, have started planning the formation of an official technology transfer division of the UCT's Mineral Processing Research Unit.

He said the MPRU commercial division would be based along similar lines to the highly successful JKMRC-JKTech model in Australia, and would evolve from the existing JKTech agency operated by Vic Hills and Malcolm Powell.

'We will have our own independent consulting research organization extending from UCT's MPRU with close links to JKTech in Australia.'

Mr Harris said JKTech's major contribution to the establishment of an equivalent MPRU commercial division would be in the provision of supporting technical advice and product information.

'It's important for Universities and the Departments within them to foster these kind of commercial activities,' he said.

'It means we can keep academics within the university system without losing them to industry where they may cease to conduct fundamental research, which we can otherwise feed through a unit of this type.'

To give the new MPRU commercial division its best possible start, UCT will partially underwrite its development for the first twelve months, commencing in 2001. ◆

* Contact: CVic Hills, JKTech (South Africa),
Tel: +27 21 650 4528,
e-mail: vhills@eng.uct.ac.za

Ties strengthen as students travel both ways*

Undergraduate students, Clive Robertson and Geoff Mphahlele are the first Chemical Engineering students to take advantage of the link between the University of British Columbia (UBC) and UCT. They will be completing the final semester of their degrees at UBC. The link was set up by the International Academic Programmes and the exchange has been co-ordinated by Quinton Redcliffe of IAPO, UCT.

The students will be working on a research project supervised by Prof Janusz Laskowski and co-ordinated by Dr Dee Bradshaw of the UCT Depressant Research Facility to further the understanding of the behaviour of polymeric depressants in flotation. The relationship between the two universities follows several visits by Prof Janusz Laskowski to UCT and a reciprocal visit by Dr. Dee Bradshaw to UBC culminating in collaborative research projects being set up. In 1999 Foskor sponsored joint work and a programme is presently underway sponsored by the chemical company, Akzo Nobel in Holland.

Travelling in the reverse direction, two UBC Mineral Processing students, Graham Lamson and Tad Cowie have been doing their practical training in South Africa at Eastern Platinum, a Lonplats platinum mine in North West Province. They joined researchers from the University of Cape Towns' Mineral Processing Research Unit (MPRU) and the Julius Kruttschnitt Mineral Research Centre (JKMRC), University of Queensland, Australia, where they were involved in an extensive campaign to test a state-of-the-art flotation pilot plant, the Floatability Characterization Test Rig, or FCTR, for use as a process modelling and optimization tool. The FCTR has been developed as part of an international collaborative research project, the P9 project, which is co-ordinated by the Australian Minerals Industry Research Association (AMIRA), and sponsored by 40 mining companies from all over the world, including 15 South African Companies. The project is managed by Professor JP Franzidis of the JKMRC, with Martin Harris of the MPRU managing the activities in South Africa. ◆

** Issued by: Coral Heath, Department of Chemical Engineering, UCT, cheath@chemeng.uct.ac.za*