Quantification of stope fracture zone behaviour in deep level gold mines

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Synopsis

This paper presents an overview of work carried out by the CSIR Division of Mining Technology and formerly by the Chamber of Mines Research Organization (COMRO) to quantify the behaviour of the stope fracture zone near deep level gold mine stopes. The motivation for this work is first reviewed in the context of the unsatisfactory status of current mine layout design criteria. Numerical methods to represent failure processes are reviewed briefly. Specific studies of microfracture processes are described as well as physical modelling experiments that can yield insights into deformation mechanisms. Modelling of stope scale deformation mechanisms are presented and considerations relating to elastodynamic modelling of the rock mass are described. The implications of this understanding in relation to prospects for active fracture zone 'engineering' are outlined and finally, the directions of future research work are proposed.

Introduction

The present paper sets out to review the work carried out by the CSIR Division of Mining Technology which has been directed towards establishing a fundamental understanding of rockmass behaviour in deep level South African gold mines. The work was formerly carried out by the Chamber of Mines Research Organization (COMRO) and is currently sponsored through the Safety in Mines Research Advisory Committee (SIMRAC), constituted by the South African Department of Mineral and Energy Affairs. (The specific SIMRAC projects described in this paper are 'Rock Mass Behaviour' (GAP029, 1992–1995) and the current project 'Deep Gold Mine Fracture Zone Behaviour' (GAP332, 1996–1998).

Extensive research is being undertaken world-wide by the international rock mechanics fraternity into fundamental aspects of rock failure. Notable efforts include the detailed experimental observations of fracture processes near a circular experimental tunnel driven in the Canadian Shield (Martin[1]) and fundamental studies of the mechanics of fracture and fracture propagation undertaken in a number of research institutions such as the Earth Sciences Division of the Lawrence Berkeley Laboratory, University of California (Myer *et. al.*[2]), the Fracture Group, Cornell University (Ingraffea[3]), the Rock Mechanics Institute at the University of Oklahoma (Germanovich *et. al.*[4]) and the CSIRO organization in Australia. Allied research work in the fields of hydrofracture propagation, earthquake studies and structural geology have also provided fundamental insights into rock failure processes at all scales. The work reported in the present paper is directed specifically towards gaining an understanding of fracture processes occurring near excavations in deep level South African gold mines. Where appropriate, references are made to related international research investigations but no attempt is made to review the general literature on rock fracture mechanics. Some general reviews of this topic are given by Myer *et. al.*[2], Atkinson[5], Cook[6], Roegiers[7] and Rossmanith[8].

Most of the gold produced in South Africa is mined at depths ranging between one and three kilometres generally from sedimentary tabular deposits in hard, brittle rock formations. Over the past fifty years, the major technical difficulties associated with these deep level mining operations have centred on the occurrence of rockbursts and rockfalls and the accompanying horrific toll of injuries and fatalities suffered by the workforce. The problem of rockbursts has been recognised for decades and is most clearly outlined in the seminal document 'Rock Mechanics Applied to the Study of Rockbursts' by Cook, Hoek, Pretorius, Ortlepp and Salamon which was published in 1966 as a monograph by the South African Institute of Mining and Metallurgy[9]. This monograph presents both

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the nature of the problem and the main design methodology proposed at that stage, based on concepts of energy release in the rockmass. Impetus was given to this approach by Salamon[10] who described a then novel technique termed the 'face element principle' for the analysis of arbitrarily shaped tabular openings in an elastic medium. This method, which is allied to an approach suggested previously for the analysis of coal mining problems in Britain (Hackett[11]), allowed stress distributions around openings to be computed and, in addition, permitted the design engineer to determine the so-called energy release rate (ERR, Cook[12]) at the edges of the openings. The energy release rate is equivalent mathematically to the crack extension force G of fracture mechanics but has a number of subtle attributes that were not clearly understood in its initial application to mining problems. The main difficulty, subsequently explained by Salamon[13], lies in the fact that the rockmass is assumed to behave as a linear elastic material with infinite strength. In these circumstances it can be demonstrated that the energy balance associated with the mining of small increments of elastic material is such that the work done by the applied loading forces is equal to the sum of the strain energy in the mined volume of material and the strain energy change in the surrounding rockmass. This implies that there is no obvious connection between the released energy and potential seismic motions when an analysis is based on the assumption of a perfectly elastic material. In order to relate seismic activity more directly to rockburst phenomena, Ryder[14] proposed the use of the so-called 'excess shear stress' concept (ESS) in which the energy release can be related to the stress drop on a suddenly slipping fault plane. The ESS level can be interpreted explicitly as a source of potentially damaging seismic energy. Unfortunately, the ESS concept has proved to be problematic in its application to mine design problems mainly due to imprecise knowledge of the underground stress state at any given time and also due to uncertainty regarding the most appropriate material properties to assign to a given fault plane or, indeed, the assumption that the fault structure can be represented adequately as a flat slip surface. It must also be remembered that the kinetic energy release associated with a given stress drop is only approximately estimated by the ESS measure. Effects of slip overshoot and seismic attenuation are unquantified.

It is apparent that the assumption of particular design criteria, for example the ERR and ESS concepts, can dictate major mine layout decisions such as the choice between longwall and scattered mining methods, the use of stability pillars and the use of backfill material. If the design criteria are ill-founded, the safety and economic consequences of sub-optimal layout planning are enormous. In practice, the uncertainty surrounding the use of 'standard' mine design criteria necessitates that practical layout design is based on previous mining experience and site-specific judgements. It is, however, unsatisfactory to base major strategic design decisions too strongly on empirical considerations. The South African mining industry has recognised the need to understand the fundamental mechanisms of rock failure near underground workings and has supported fundamental research into the nature of rockmass behaviour. In carrying out this research work a compromise must be struck between a detailed enquiry into the fundamental nature of the physics of rock failure and the need to provide useful guidelines to the mining industry to solve current and potential mine design problems. It should be clearly stated that a fundamental understanding of the basic nature of brittle material failure has been the subject of intense local and international research for many decades, possibly with Griffith's work[15] still underpinning many current concepts of failure. The literature on brittle material fracture processes and fracture mechanics is vast; the work edited by Liebowitz 'Fracture: An advanced treatise'[16] runs to seven volumes and covers the subject as far as 1968. The implication is that considerable care must be taken to define the appropriate depth and scope of a fundamental enquiry into the nature of brittle rock fracture. The following sections present highlights of results that have been achieved in the research carried out to date and give some indication of proposed lines of enquiry for the future.

Methods of failure analysis and modelling

The interpretation of brittle failure mechanisms and the representation of these mechanisms in computer codes presents a number of difficulties. A well-defined method of analysis has evolved for the treatment of the non-linear behaviour of metal deformations and is embodied in current theories of plastic flow. The use of these plasticity models for representing rock failure processes is usually inappropriate. In addition, the incorporation of so-called strain softening behaviour to represent brittle cohesion breaking can result in the initiation of shear bands that are not observed in practice or in physical models (Kuijpers and Napier[17]) and the assignment of parameters to these models is not well defined. Alternatively, it is possible to develop continuum models of material damage that represent the progressive degradation of material stiffness as failure proceeds. Continuum damage models do not depend on plasticity flow rules but require the evolutionary tracking of the material stiffness degradation according to the applied load path and the postulated evolution rules (Sellers[18]).

Yet another approach is to represent the material as a collection of pre-defined grains or randomly packed spherical or elliptical particles and to track the interactions between the grains or particles as fracture progresses. These methods were to a large extent pioneered by Cundall in his universal distinct element code UDEC[19] and his work on the simulation of particle assemblies[20,21]. Other approaches rely on the construction of 'cellular automata' (Wilson *et. al.*[22]) and so-called 'percolation' models (Blair and Cook[23]). All of these models strive to recognise the underlying random nature of fracture initiation and the consequent self-organising processes of coalescence that lead to overall failure localisation patterns.

If it is accepted that initial failure can be represented by small strain dislocations in the medium, then it is also possible to represent material defects explicitly as cracks by means of the displacement discontinuity boundary element method (Crouch and Starfield[24]). The small strain assumption permits multiple interacting crack assemblies to be analysed very conveniently without having to maintain explicit lists of particle positions and also permits a straightforward treatment of crack opening and sliding behaviour.

The simulation of fracture growth can be effected in two ways. In the first method, explicit growth sites are defined at specified positions in the material. These sites represent positions from which flaws can be initiated and can be located at random points in the initially unfractured parts of the medium or on the boundaries or extremities of pre-existing cracks. Fractures are propagated by adding displacement discontinuity elements to a selected subset of the available sites. The orientations of the additional elements are chosen according to specified growth rules. The determination of this orientation is an explicit part of the solution process. Once the elements are added, the entire problem is solved to determine the sliding and/ or opening interactions between each discontinuity element. All potential growth sites are again reviewed and new growth increments are generated. This sequence is repeated until no further growth is possible. The numerical procedure has been implemented in a computer code DIGS (Discontinuity Interaction and Growth Simulation) described by Napier[25] and by Napier and Hildyard[26].

A second variation of the fracture growth simulation procedure is to specify a random population of potential cracks which are again selectively activated according to specified failure criteria. The activated cracks are, however, constrained to occupy pre-defined spatial positions. This form of the DIGS code has proved to be useful for the simulation of microfracture processes that arise within or around grains and allows the inherent irregularity of an actual rock fabric to be represented to some degree. This in turn allows investigations of fracture coalescence and self-organising localisation mechanisms to be studied.

The accuracy of small strain dislocations to represent fracturing is sometimes affected by the shape functions that are used to describe the discontinuity values in each crack element and run time efficiency may be poor when many thousands of elements are to be modelled. These difficulties are the subject of ongoing research and some progress has been made in finding efficient solution techniques for large-scale problems (Peirce and Napier[27]). The use of the displacement discontinuity method to represent a propagating pattern of fractures has been used in mining problems by Sun *et.al.*[28], in problems of hydraulic fracturing (Vandamme and Curran[29], Cleary[30]) and in applications to geological problems (Thomas and Pollard[31]).

Microfracture processes

Fracture formation in a homogeneous material subjected to direct tension can be related to the breaking of atomic bonds ahead of the advancing fracture[32-34]. However, in geotechnical applications microcracks generated under compressive stress states are observed to be extensile in nature and follow the direction of maximum compression[35]. In the absence of a direct tensile stress, alternative mechanisms such as grain splitting due to local stress concentrations[2], different grain and matrix properties, locked-in initial stresses[36], spherical or cylindrical pores[37] and sliding on pre-existing flaws[38] have been proposed to explain extension fracturing. Numerical simulations of rock granular structure were carried out by Handley[39] using the discrete element code UDEC and showed that brittle strain softening behaviour can be reproduced with a small sample comprising convex polygons. In addition, a series of fracture growth simulations using the boundary element program DIGS[40] have demonstrated that extension cracks can grow in the region between cavities, as well as from pore surfaces. At higher load levels, the microcracks interact and coalesce to form macro-extension fractures or shear bands which ultimately result in failure[41]. The formation of these shear bands can be described by linked echelon combinations of sliding crack structures[42,43]. In all these cases it is assumed that fracturing is initiated as a stable growth process in which the loading rate and the fracture growth rate is small as defined by Bieniawski[44].

In order to investigate the influence of micro-fracture mechanisms on the macroscopic fracture pattern and stress–strain response, triaxial extension tests were modelled in plane strain using the DIGS program to analyse granular structures represented by convex Voronoi polygons and including initiation points for discrete fractures[45]. The samples were loaded 'hydrostatically' in plane strain to a confinement of 600 MPa and then one component of the confining stress was reduced until the specimen failed. In this paper σ_1 is used to designate the major principal stress component with compressive stress values assumed to be positive. The model results (Figure 1) show a high density of intragranular fracturing, sub-parallel to the maximum principal stress σ_1, with several transgranular fractures visible. The density of intergranular fracturing in the models is lower than was noted in actual tests on siliceous quartzite by Briggs and Vieler[46] and localised failure is not observed. In the triaxial extension test experiments micro-fractures in the quartz grains tend to be aligned parallel to the major principal stress direction. Fractures are observed to grow from small sharp micaceous spikes or as protrusions, overgrowths on the mica that penetrate into the adjacent quartz (Figure 2). This is probably due to the sharpness of the apex, the weakness of the cohesion between the quartz and the mica and some plastic deformation of the mica which causes tensile stresses adjacent to the granule. Discrete fractures are formed under a compressive stress state in the manner of a Brazilian test[45], when tensile stresses are developed in the centre of a grain, and by the sliding flaw mechanism, when shearing along a grain boundary can lead

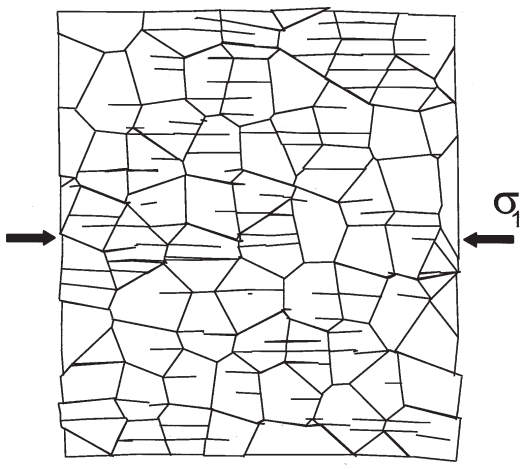

Figure 1—Simulated fracture patterns in triaxial extension test

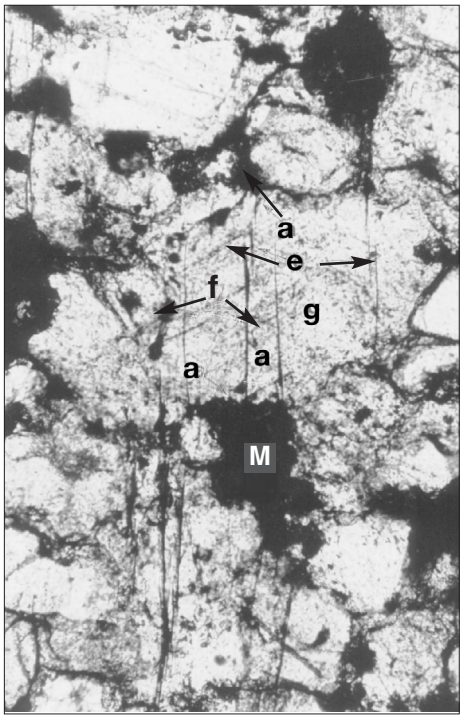

Figure 2—Observed fracture patterns in triaxial extension test. Fractures (f) grow from the sharp apices (a) on the margins of the chlorite mica (M, black grains). They tend to grow across the quartz grains (g), often from opposite sides as successive en-echelon fracture pairs (e)

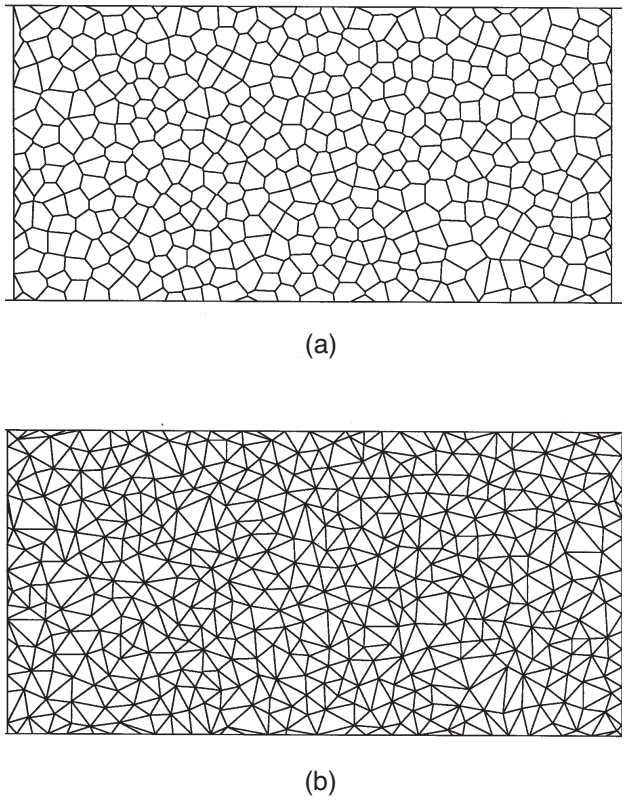

Figure 3—Examples of (a) Voronoi and (b) Delaunay tessellation patterns

to growth of fractures from the ends of the sheared element. It was found[45] that the inclusion of intragranular fracturing is necessary for the overall axial stress–strain curves to compare with the experimental results.

A series of numerical experiments were performed using the DIGS program to study the fracture mechanisms induced in random Voronoi and Delaunay tessellation patterns (Figure 3) with the aim of relating the macroscopic behaviour of the samples to the micro-structure of granular materials such as rock or concrete[47]. In these experiments, incremental displacements were applied in a sequence of steps to the surface of a rectangular block to simulate compression tests. Initial studies were performed by allowing any facet of a grain to activate when the stress state exceeded the Mohr Coulomb failure criterion. The crack density in the Voronoi samples under uniaxial loading is observed to increase with a finer mesh. The fracture pattern resulting from an intermediate density test is shown in Figure 4a. The major fracture trend is aligned in the loading direction. More fractures are generated by the Delaunay triangulation than the rounded Voronoi tessellation for the same number of geometric centres and rapid load shedding and strong dilatancy occurred after fracture initiation in uniaxial loading. Figure 4b suggests failure by the wedging open of diamond shaped regions that force cracks to propagate in the axial direction.

An alternative procedure is to allow fracturing to initiate in an incremental, 'weakest link', fashion by evaluating the stress tensor at each possible failure site and then mobilising only the most favourable site according to a specified criterion. In an unconfined loading test on a Voronoi

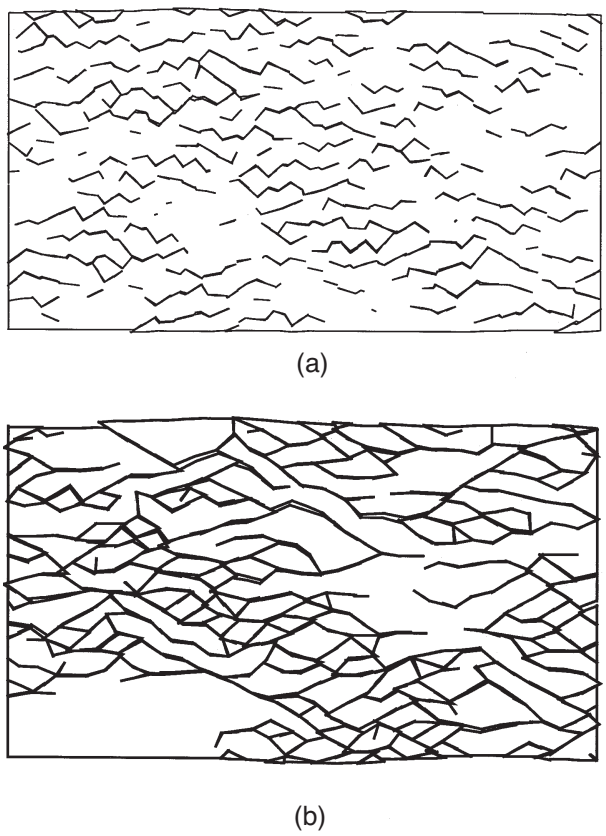

Figure 4—Parallel activation of fractures in uniaxial loading (a) Voronoi tessellation and (b) Delaunay tessellation

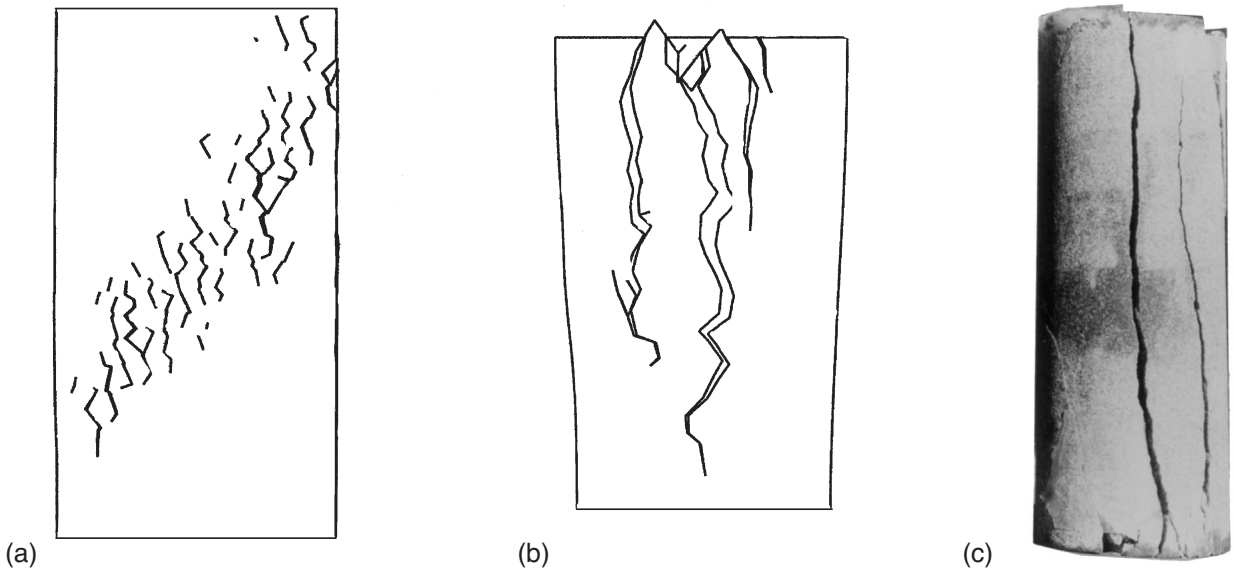

Figure 5—Activation of fractures in uniaxial loading (a) Shear band mechanism developing in a Voronoi assembly. (b) Axial splitting using Delaunay grains (c) Photograph of axial splitting in an unconfined compression test

assembly it is observed that failure initiates near one corner of the sample and then progresses across the sample forming a shear band mechanism[48] (Figure 5a). Continuation of the fracture activation results in a distributed pattern which approaches the one observed in the simultaneous activation approach (Figure 4a). The failure pattern using a Delaunay triangulation (Figure 5b) and Voronoi samples with an angular grain structure correspond to the axial splitting mode observed in experiments (Figure 5c). Therefore, it appears that the shape of the material grains affects not only the load shedding characteristics of the material but also the failure mode. Angular grains allow the transition from extension to en-echelon shear fracturing with confinement to be modelled whilst rounded grain shapes promote inherent shear banding even under uniaxial conditions.

A new fracture initiation procedure has been developed in which a percentage of the facets of the Voronoi tessellation are considered to be weak grain boundaries and each can slip whenever its shear strength is exceeded. Intragranular fracture paths are specified through the geometric centres of the Voronoi polygons and these elements are only permitted to fracture when there is direct tension normal to the fracture. In both compression and extension test simulations[49], the intergranular fracturing is initially distributed throughout the sample and then localises at higher load levels (Figure 6). The macroscopic stress–strain response and the dimensions and the angle of the localised zone are found to depend on the number of flaws within the sample. This suggests that the tessellation approach can provide a convenient means of modelling macroscopic fracture mechanisms for specific rock types by specifying the size and density of microflaws and by selecting appropriate microscopic fracture processes. For practical purposes it is necessary to relate the material-dependent microfailure processes to the behaviour of the rock mass at the stope scale. Future

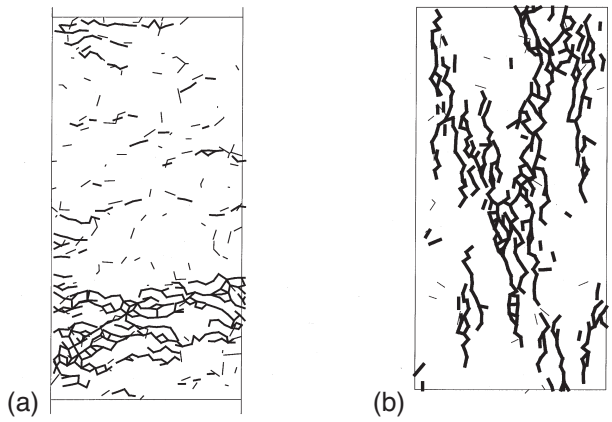

Figure 6—Fracture patterns in Voronoi sample with intergranular fractures and weak grain boundaries under (a) extension , and b) uniaxial compression loading

research will therefore be focused on representing macroscale behaviour by synthesising the microscale deformation mechanisms in the form of equivalent damage models that can be used to investigate fracture patterns formed around stopes in various geotechnical environments.

Physical modelling

Improving the understanding of rock behaviour and developing better numerical models are interactive processes and the two need to be continually checked and validated against one another. Physical information obtained *in situ* is preferred to facilitate this interaction but, in many cases, this is difficult to interpret because of complexities involved in describing the rock mass structure and determining the local stress state. Testing of models under controlled conditions in the laboratory offers an alternative option for initial calibration and validation of numerical models and constitutive laws, and for studying the mechanisms of fracture initiation and growth.

Experiments to understand the effect of parting planes on the initiation and propagation of extensional fractures, commonly observed around mine stopes were carried out on Brazilian test specimens containing pre-existing fractures at various angles to the loaded diameter[50]. When slip occurs on the interface, the stress state is perturbed causing different fracture patterns to those observed in specimens with no slip. It was observed that progressive slip on the interface reduces the amount of stored energy and the recorded stress drop magnitudes. Modelling of the experiments using the DIGS program produced similar fracture patterns, as shown in Figures 7a and 7b, and revealed that local asperities on a sliding interface can form points for fracture nucleation.

Figure 7a—Fracturing in a Brazilian test with an inclined interface

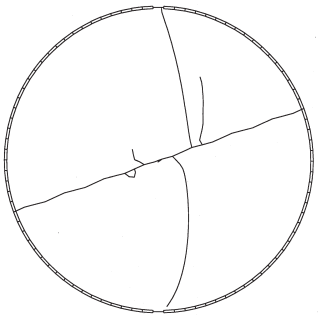

Figure 7b—The resulting fracture pattern modelling the experiment using DIGS

Physical modelling studies have been conducted also, to examine the effects of layering on the initiation of fractures near an opening. In one series of experiments, fifteen layers of synthetic brittle material (plaster of Paris and cement mixtures) were cut and stacked on top of one another to form a composite layered structure. One or two parallel-sided openings were emplaced in the layers and the structure was loaded both in the direction normal to the layering and in the direction parallel to the layering and perpendicular to the axis of the opening. It was found that extension fractures were induced to form at the layer interfaces and the initial orientation of these fractures could be predicted successfully using the fracture growth facilities of the DIGS computer code[51]. Further experiments using glass layers proved to be more difficult to interpret due to suspected point-loading effects which were exaggerated in the higher modulus glass material.

More recently, a triaxial test cell has been constructed which can allow approximately plane strain tests to be conducted. The test ring can accommodate 80 or 100 mm cubic samples which may be subjected to confining pressure levels of up to 10 MPa. The geometry of the samples used and the schematic diagram of the test rig is shown in Figures 8a and 8b. The models were made from blocks of quartzite, the properties of which are listed in Table I. The geometry modelled resembles a rib pillar, as shown in Figure 8b, with the pillar width and height machined to 10mm and 1mm respectively. The loading direction through the 'pillar' is shown in Figure 8b. Stearic acid was applied to all sides of the specimen in order to reduce friction between the sides of the specimen and the confining platens.

The fracture pattern obtained under 9 MPa confinement is shown in Figure 9a. The vertical stress acting on the pillar at the point of failure was recorded to be about 550 MPa. The depth of the failure wedge beneath the pillar is about twice the width of the pillar. This is unlike axisymmetric tests carried out previously where cone depth is similar to the punch width. This illustrates also the need to retain geometric similarity if model tests are to be used to infer the behaviour of large scale pillar structures.

The numerical modelling of the physical tests using DIGS gave similar results to those observed in the physical modelling. The same boundary conditions as those in the physical tests (9 MPa confinement and 550 MPa axial stress) were used. The overall resemblance of the numerical modelling results to that of physical tests could be achieved by introducing two shear and several tensile seed points

Table I

Crack and material properties of quartzite used for the DIGS model

Crack and Material Properties	Properties obtained from laboratory tests	Modified M (shear type of fracture)	Modified N (tensile type of fracture)
Unmobilized cohesion (MPa)	36	35.1	45
Unmobilized friction angle (°)	51	35	51
Mobilized dilation angle (°)	–	0	0
Mobilized cohesion (MPa)	–	0	0
Mobilized friction angle (°)	–	32	35
Reverse dilation angle	–	0	0
Tension cutoff (MPa)	35	30	10
Young's modulus (MPa)	68	68	68
Poisson's ratio	0.17	0.17	0.17

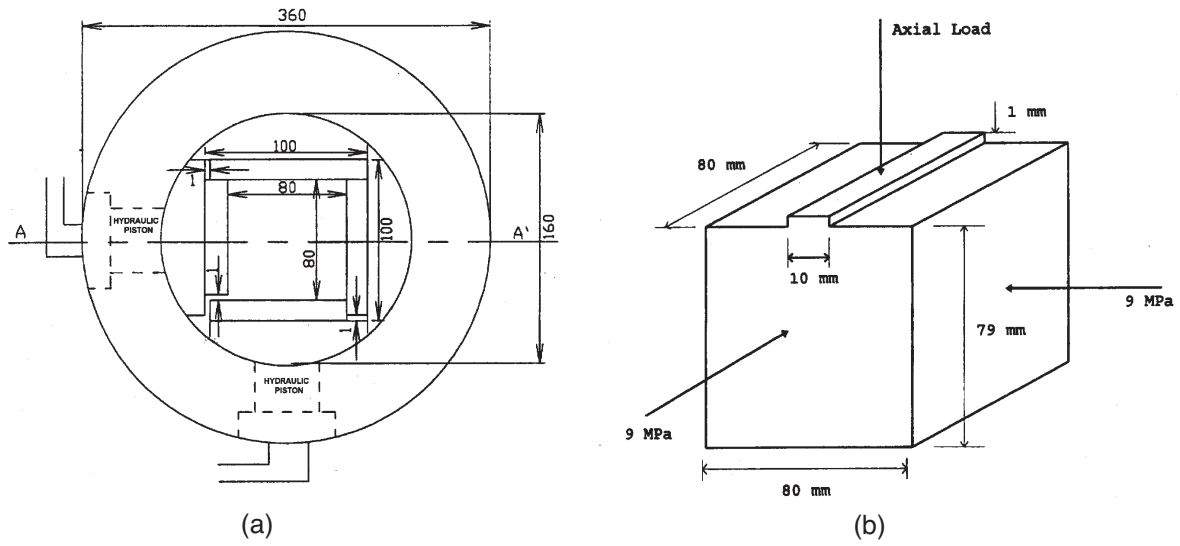

Figure 8—The triaxial test frame (a) and a typical test specimen (b)

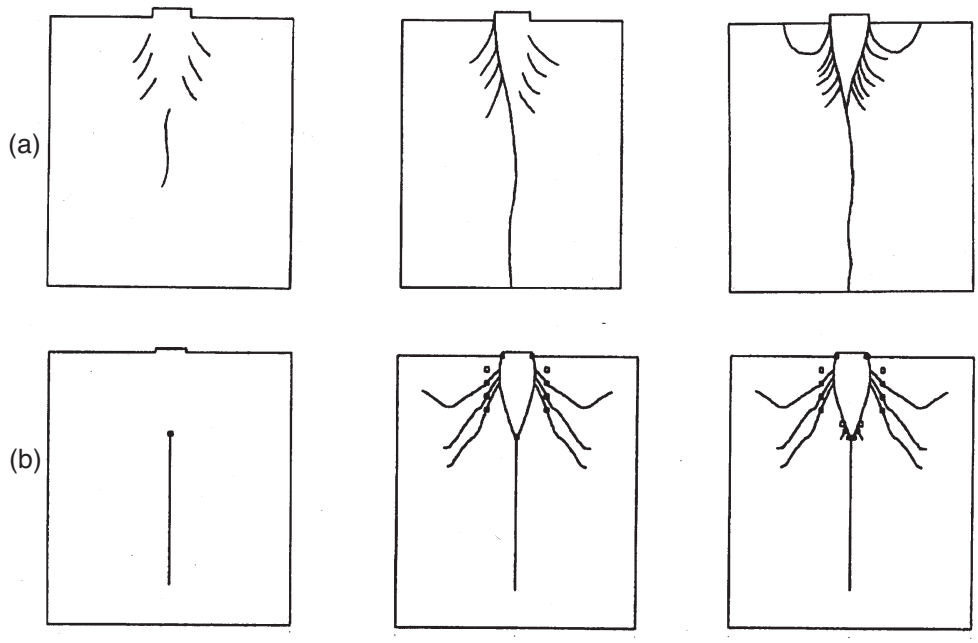

Figure 9—Physical (a) and numerical (b) modelling results for a strip punch test

around the potential cone zone. Also, some of the material properties had to be modified (Table I) to obtain the fracture pattern given in Figure 9b. The wedge under the pillar could be initiated by inserting two shear points at the edges of the pillar and additional tensile failure sites in the middle of the sample. While these fractures are growing, additional tensile fractures were initiated adjacent to the wedge with the uppermost fractures intersecting the free surface of the sample. These results show that the explicit modelling of fracture growth is feasible, but also show that the modelling procedure is somewhat contrived in having to both emplace appropriate growth sites at specific positions, and in having to define the growth modes that are to occur. Work is presently under way to develop more robust growth models that will not require pre-judgements concerning the fracture positions or the likely fracture modes.

Stope scale deformations

The identification of deformation mechanisms near the edges of deep gold mine stopes in South Africa has been the subject of considerable research [52-60]. Regular fracture patterns are often observed but in many cases these patterns become difficult to interpret in different geotechnical regions and in some cases may be prone to misinterpretation in distinguishing the difference between pre-existing joints and mining induced fractures. When interpreting the sequence and orientation of fracturing around stopes it is apparent that the primitive stress condition, the incremental nature of mining, the rock properties and the existence of geological features such as bedding planes or joint structures can influence the fracture patterns. Assumptions must be made regarding the extent to which stope blasting and other elastodynamic stress waves control the growth of fractures.

Some attempts to model the evolution of the fracture zone have been made using the computer code DIGS[25,26]. These studies have illustrated the potential role of parting planes in the evolution of extension fractures but were confined to one or two mining steps. An alternative to this approach is to allow the problem space to be covered by a random mesh of potential fractures and then to select the particular elements of the mesh that will fail according to the given stress field and prescribed failure criteria. Once this selection is made, the mutual interaction between the active mesh elements are solved using a special iterative method[27] and the fracture zone deformation and pattern can be determined. This procedure can be repeated for a number of mining steps to simulate the progressive evolution of the fracture zone. Figure 10a shows the results of a simulation of twenty-five equal mining steps of two metres in a narrow stope, marked S–S, approximated as a slit with an infinitesimal stope width. The rock mass is assumed to be homogeneous and the stope is mined from left to right showing a progressive mobilisation of the fracture zone. In this case the initial primitive stress was assumed to be 60MPa perpendicular to the stope horizon and 30MPa parallel to the stope. The rock strength was assigned a cohesion of 15MPa and an internal friction angle of 45 degrees. The strength of any crack in direct tension was set to 7MPa. After failure, each mobilised element was assumed to have zero cohesion and a sliding friction angle of 30 degrees. It is interesting to note from Figure 10a that the fracture zone appears to reach a maximum extent of about ten metres in both the hangingwall and the footwall and that damage continues to accumulate at the stationary (left hand) side of the stope. The fracture pattern is similar to some of the conceptual models of fracturing proposed by Leeman[60].

An entirely different fracture pattern emerges if parting planes are introduced parallel to the stope plane. Figure 10b shows the case where six parting planes are introduced, three in the hangingwall and three in the footwall. (The parting planes are marked P–P.) The separation between each layer is four metres. In this case the parting planes were assumed to be easily mobilised and to have a sliding friction angle of 10 degrees. It is clear from Figure 10b that the partings tend to promote concentrated fracturing close to the stope and that the density of fracturing decreases in each band away from the stope horizon.

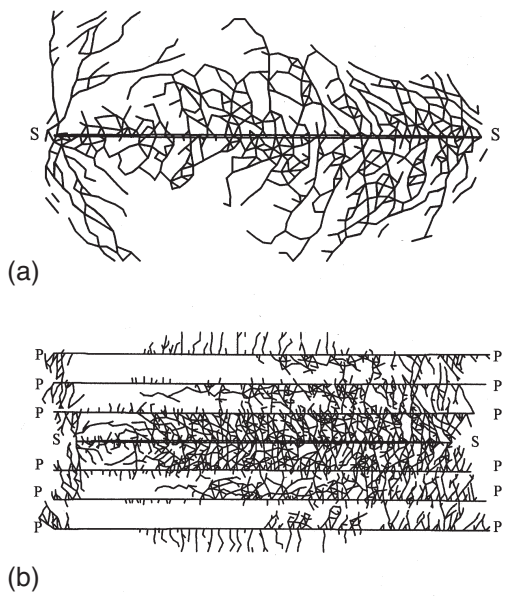

Figure 10—Simulation of fracture patterns around a 1 metre wide stope using a multipole version of DIGS (a) homogeneous rockmass (b) rockmass with bedding planes

In the simulation without parting planes, shown in Figure 10a, the random mesh comprised approximately 7000 elements and in the second case shown in Figure 10b, the mesh comprised about 14000 elements. The solution of these large-scale problems was carried out on a DEC workstation equipped with 256 Megabytes of main memory and the run times were approximately eighteen hours and forty-one hours respectively. The solution was effected using a special adaptation of the displacement discontinuity technique, termed the 'multipole' method, developed by Peirce and Napier[27]. The advantages of the multipole method can be emphasised by noting that the simulation comprising 14000 elements would have required about fifty times as much memory (12,5 Gigabytes) when using a conventional boundary element analysis and, at best, a fifty-fold increase in the run time. In spite of these advantages, considerable effort is needed to characterise the fracture zone stability of different mining configurations in different geotechnical settings. This will enable traditional design criteria to be re-assessed and the implications of off-reef deformations and generalised energy release considerations can be reviewed. This forms part of the current research effort that is directed towards the development of a realistic fracture zone simulation tool. An essential component of this development is the investigation of constitutive models that can reflect both elastodynamic movements and slower creep-like deformations over periods of hours or days as well as equivalent damage representations of multiple fracture clusters[61].

The slower creep-like deformations were largely neglected in past analyses owing to the difficulty of understanding these effects and incorporating them in models. Malan[62] used a viscoelastic approach to model the time-dependent closure behaviour of tabular excavations after blasting. A good fit between this model and measured stope closure was obtained. However, a disadvantage of this approach is that it cannot predict failure and the time-dependent extension of the failed zone surrounding the stope. The creep rate of some excavations is much larger than data available from creep experiments on intact rock. Therefore, it is generally accepted that the creep deformations are governed mainly by the rheological properties of discontinuities and the interaction of these discontinuities in the fracture zone. Modelling of this zone will lead to a better understanding of the time-dependent energy dissipation and the possible link between creep-like rock behaviour and seismicity.

A first attempt to model the formation of the time-dependent fracture zone was made by developing viscoplastic discontinuity elements for DIGS. These discontinuities are immobilised below a certain yield stress. If the shear stress exceeds this yield stress, the discontinuity behaves viscoplastically. The rate of change of shear movement on the discontinuity is assumed to be proportional to the magnitude

of the excess shear stress. As described previously, stope modelling was undertaken by covering the problem space by a random mesh of potential viscoplastic discontinuities and then selecting the particular elements of the mesh that will fail according to the given stress field and prescribed failure criteria. Because of the viscous behaviour of the fractures, the complete fracture zone does not form immediately after blasting but is established as a gradual time-dependent process. The majority of the fractures, however, form within a short period after blasting. This is in agreement with experimental observations and seismic data where most of the increased microseismicity decreases after blasting to some background level within three or four hours. Further modelling to investigate the rate of face advance has indicated that the volume of stope closure decreases as the time increment between successive steps reduces. This also agrees with experimental stope behaviour where it is unwise to leave faces standing because of increased closure and deterioration of rock conditions.

If off-reef deformations are modelled explicitly, then the maximum kinetic energy release may be estimated (Napier[63]). This energy is calculated as the difference between available energy and the energy dissipated due to work done against support or frictional sliding on discontinuities. When calculating the energy dissipated for different face advance rates in the viscoplastic model, it is found that less energy is dissipated on the discontinuities as the time increment between blasts decreases. Therefore, more kinetic energy is released at the higher face advance rates (smaller time increments between blasts) as illustrated in Figure 11. This situation is assumed to be hazardous as it is preferable to have as much energy as possible released in a non-violent manner. However, further work is necessary to verify the particular viscous constitutive law and calibrate the models against underground observations. It must be emphasised that no statements can as yet be made concerning the desirability of a particular face advance rate policy.

Elastodynamics

Elastodynamic movements in the rockmass and the effects on simplified mining geometries, have been studied through applications of both boundary element and finite difference techniques.

The first approach is to use the boundary element method to represent the effect of dynamic slip and opening motions on dislocations in an isotropic medium. In this case influence functions based on Stokes' fundamental solution for a time-varying point force in an infinite medium, are computed for displacement discontinuity elements which are used to define cracks, faults or stopes at arbitrary orientations. This method for the solution of two-dimensional plane strain problems is embodied in the computer code TWO4D developed by Siebrits[64]. Two drawbacks have been encountered in the use of boundary element elastodynamics. It is found that in some cases problems of numerical instability in particle motions can occur, resulting in unusable results following a number of time steps. The cause of these instabilities is related to the shape functions that are used to represent the spatial variation of crack opening and slip movements within each boundary element. Constant or linear variation shapes induce stress singularities near the element edges which can result in uncontrolled resonance being induced between elements. This problem can be controlled but will not be discussed in this paper[65]. A further problem encountered in the application of elastodynamic boundary element methods is the necessity to retain a back-history of solution values for all time steps that are to be analysed. This immediately removes one of the traditional advantages associated with the boundary element technique, which is to reduce the problem space dimensionality. Consequently, storage requirements are proportional to one time dimension plus the total number of element surface dimensions. At present it seems that the boundary element method can be useful for small-scale problems in which arbitrarily oriented crack geometries occur and may provide opportunities to study

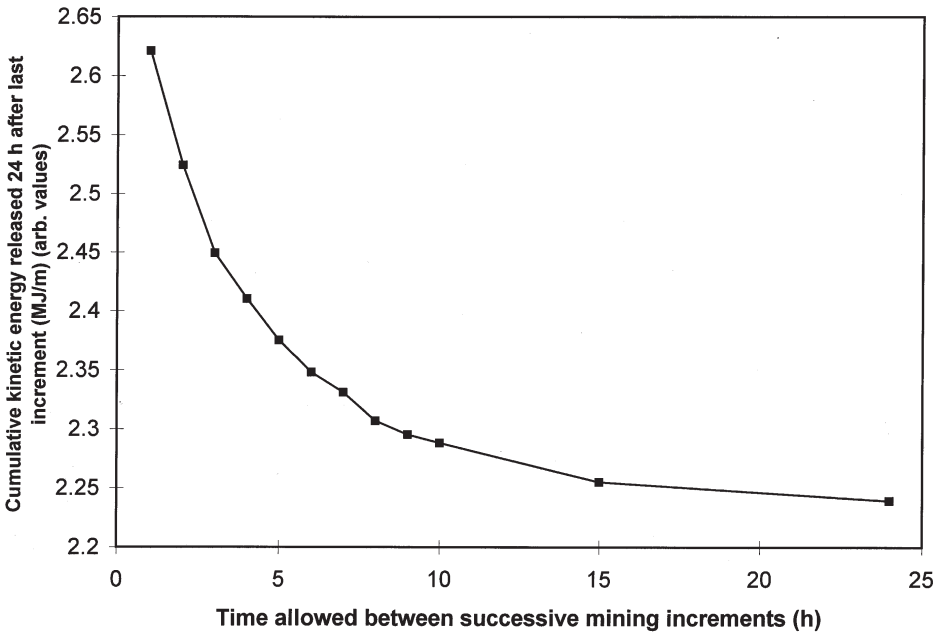

Figure 11—Kinetic energy released at different rates of mining (arbitrary values)

dynamic fracture growth phenomena. It is unclear at present whether the method will be useful for large-scale stope movement studies.

The second approach uses an explicit finite difference method to solve the differential equations describing the propagation of elastodynamic waves, and is encoded in the computer program WAVE[66,67]. This program allows studies in both two and three dimensions on a regular cartesian grid. Important features are that it is multi-material; it allows explicit discontinuities to be modelled, which may represent stope, fault or crack behaviour; and stope mining layouts can be represented in three-dimensional models. The most important characteristic of WAVE is that it is extremely memory- and speed-efficient due to the regular grid and the use of a staggered mesh, in both space and time, which requires fewer grid-points and memory for the same accuracy than grid-schemes whose variables are co-incident (Table II). Accuracy can be additionally improved through the use of higher order spatial differencing. The major limitation is that features, including discontinuities, must be aligned to a cartesian grid. In spite of this limitation WAVE has proved to be a useful tool due to its accuracy and efficiency.

WAVE and TWO4D have been applied in analysing a number of simplified mining problems. One such application was to consider the importance of backfill in the dynamic behaviour of stopes[68]. This study investigated a model with a vertical shear source ahead of an advancing stope, and compared the overall dynamic motions in the stope as well as the convergence and ride responses near the face, for filled and unfilled stopes. The differences due to backfill were small if a homogenous elastic rock mass was assumed. The presence of the fracture zone was then represented crudely either with a single open parting plane in the stope hangingwall or with a zone of softer elastic material surrounding the stope. In these cases more significant effects due to backfill were observed, including a reduction in both the duration of the dynamic activity and in the peak particle velocities in the vicinity of the stope. This compared qualitatively with conclusions reached from underground seismic measurements, although no attempt was made to carry out a quantitative comparison with actual seismic data.

Comparisons were made between the far-field peak particle velocities produced by a model of Mohr-Coulomb fault slip in WAVE, and those predicted by the analytical fault rupture model of Brune[69] and the empirical relationship established by McGarr[70]. The fault rupture logic allowed either an instantaneous loss of cohesion, or a degradation of cohesion as a function of the amount of fault slip (slip-weakening)[71]. Velocities calculated by the three-dimensional WAVE model with instantaneous fault rupture compared well with the analytical solution of Brune[69]. With an appropriate rate of slip-weakening, the peak particle velocities of the three-dimensional WAVE model correlated closely with the seismological field data of McGarr[70]. Modelling the fault slip in WAVE with a two-dimensional plane–strain assumption was shown to under-estimate wave attenuation and hence over-estimate the far-field peak particle velocities as compared with the relationships of Brune and McGarr[71].

In order to demonstrate some of the special consequences of elastodynamic behaviour, a stope-fault model was investigated wherein the waves generated by an initial slip event trigger a much larger event. The two-dimensional model considered is shown in Figure 12, and represents mining parallel to the fault. The dip is 20 degrees and the fault is at 90 degrees to the reef plane, with a 40m throw. The left-hand stope of the 96m span was mined to within 4m of the fault. The effects of a number of different positions of the right-hand stope were considered (no stope, or the distance from the fault ranging from 40m down to 12m). The dip was represented by a rotation in the applied stress field, so that the stope and fault were aligned with WAVE's orthogonal mesh.

An elastic analysis of this model showed interesting trends in excess shear stress (ESS). There are two lobes of

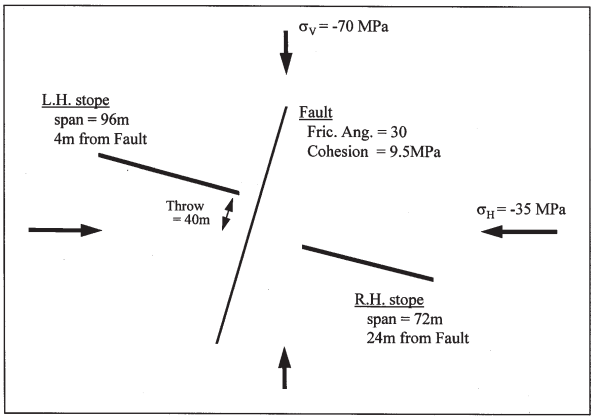

Figure 12—Geometry for WAVE model with triggered fault slip

Table II

Maximum model size for WAVE based on available memory, and projected run-times for a simple model

	2D MODELS			3D MODELS		
Memory	**N***	**N_1****	**t*****	**N***	**N_1***	**t*****
1Mb	10,333	100	7 sec	6,200	17	2 sec
4 Mb	140,333	373	7 min	84,200	42	1 min
16 Mb	660,333	811	1.1 hrs	396,200	72	9 min
64 Mb	2.7 mil	1654	10 hrs	1.6 mil	117	1 hr

*** N = Total Elements**
**** N1 = Elements in one dimension**
*****t = Run-time on a 120 MHz Pentium PC**

ESS which intersect the fault—a larger upper lobe and smaller lower lobe. For closer positions of the right-hand stope, the upper lobe becomes smaller and less intense, while the lower lobe becomes more intense. At some position, conditions in the lower area are more conducive to slip than those in the upper area, and slip on the lower area can trigger a second, larger event.

A particular case is shown where the right-hand stope is 28 metres from the fault, with a fault friction angle of 30 degrees and the fault cohesion is 9,5MPa. An initial static stress state was calculated, which will cause slip to initiate in the lower section of the fault, but not in the upper. The model was then allowed to slip dynamically. Figure 13 contains snapshots of particle velocity contours at 4 different times, showing how the energy propagates from the initial slip event in the lower ESS lobe. In the second and third snapshots one can distinguish the separate P and S wavefronts. Once the shear wavefront reaches the upper ESS lobe, slip is triggered—in the upper section of the fault.

A static analysis was performed by damping out the wave motion from the initial slip event, and by considering the final equilibrium state after stress redistribution. In this case, the second event is not triggered–in fact this stress redistribution slightly decreases the upper ESS lobe, making the second event less likely. In this particular model the static condition itself was close to failure, and there is a fairly narrow band of conditions under which the triggering occurs. However, the importance of this work is to show that there may be underlying dynamic mechanisms which are not predicted directly by static analyses.

Elastodynamic back analysis studies have also been carried out on actual seismic events. One such analysis using a three-dimensional finite element code, ABAQUS, modelled the dynamic slip on a stresses fault[72]. A broad correspondence with the first arrival times and amplitudes of the measured waveforms could be obtained by adjusting the fault friction angle as a function of time. An analysis using WAVE compared measured waveforms at a pillar site with numerical waveforms generated for different model geometries[73]. This allowed conclusions to be reached on the position of total stope closure in the region near the pillar, with consequent indirect inference of the average pillar stress at the site.

Physical models representing simple mining-type geometries have been investigated through photodynamic experiments. Photographs of the resulting fringe patterns were analysed theoretically, and back-analysed with WAVE to validate the accuracy of the elastodynamic models[74]. The physical models consisted of a slot-shaped opening ('stope') in the centre of a thin composite plate made from photo-elastic materials. The wave patterns emanating from a blast source in the bulk material were investigated for three geometries: a stope in a homogenous medium; a stope with surrounding soft material and a bonded interface with the bulk material; and a stope with surrounding soft material but with a non-cohesive interface with the bulk material. The conclusions were that WAVE accurately modelled the diffraction, refraction, transmission and reflection of stress waves in these models.

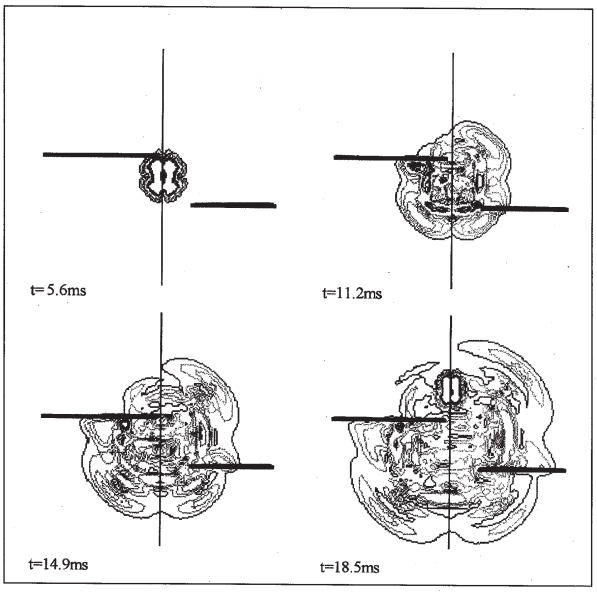

Figure 13—Snapshots of particle velocity contours showing the wave propagation from the initial event triggering a second event

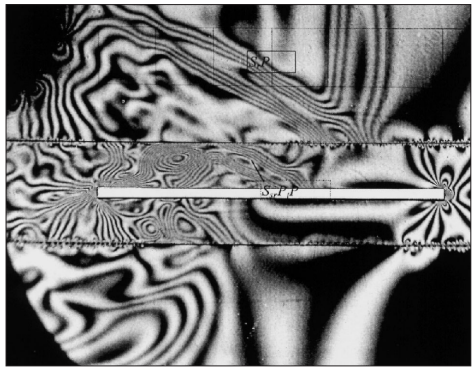

Figure 14—Photograph of isochromatic contours in the physical model of a stope with non-cohesive parting plane, and softened fracture zone, 93 μs after the blast

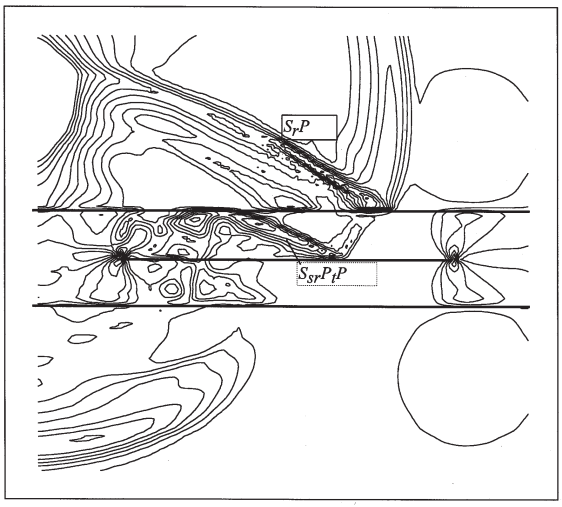

Figure 15—Contours of maximum shear stress in the WAVE model of a stope with non-cohesive parting plane, and softened fracture zone, 93 μs after the blast

The experimental and WAVE isochromatic fringe patterns are presented at a time 93 μs after the blast, for the case of the unbonded interface in Figures 14 and 15. Both the experimental and the WAVE results show a strong shear wave reflection from the interface (S_rP), a reflection of the transmitted P-wave at the stope ($S_{Sr}P_tP$), and a high density of reflected waves within the hangingwall beam.

Further dynamic photo-elastic experiments were performed to study the effects of high angle fractures in the vicinity of the stope. The emphasis in these studies is on the wave interaction with fractures, and the growth of pre-existing fractures under dynamic stress loading. These experiments were modelled using TWO4D and WAVE, although there was no attempt to model the fracture extension. A comparison between the experiment and the WAVE results at a time of 169 μsec is shown in Figure 16. All cracks were approximated as having a vertical orientation in the WAVE model, leading to errors in the orientations and positions of some of the wave-fronts. Nevertheless, transmission and reflection in the WAVE model corresponds closely with the experiment. A number of WAVE models were investigated, each with different crack conditions. The crack conditions considered were open cracks (no contact), closed cracks with a linear stiffness, cracks with a slip law, and initially closed cracks with a contact law allowing opening under tension. Although many models could be matched for some time-step, it was found that in order for the experiment to be matched over a number of time steps, the contact law was the most important crack characteristic that had to be adjusted to match the experimental observations.

Fracture zone engineering and future research directions

An important aspect of excavation design is to control the incidence of adverse fracturing to improve the stability of the opening. Low angled-fractures and other discontinuities can break the hangingwall into semi-detached keyblocks which enhance the possibility of falls of ground. In addition, stress transfer onto the face can cause sudden and, generally, unpredictable failure of the face. Strategies have in the past been proposed to de-stress the face[75] and currently efforts are being made to research and develop techniques for the preconditioning of stope faces[76]. A fundamental insight into the deformation mechanisms that arise near the stope face and a quantitative understanding of the interaction of blast-induced elastodynamic waves and gas-driven stress loading with existing fracturing, is necessary to enable these and other strategies to be used to the greatest effect.

As described in a previous section, the time-dependent nature of deformation in the fracture zone has been largely ignored in the past development of numerical models but has been emphasised in the seismic monitoring of deep gold mine rock behaviour[61] and has more recently been highlighted in studies of stope face preconditioning[76]. One strategy which may also be useful to control the stability of the fracture zone is the rate of stope face advance. The speed of extraction, combined with an appropriate viscous constitutive law, should provide some guidance as to how to determine safe values of extraction rate and better control of the fracture zone. Current research into this topic suggests that the speed of fracture zone development is not only dependent on material properties, but also on the mining rate. Different face advance rates can alter the stress concentrations near the stope face. If strategies such as preconditioning are used to shift the peak stresses away from the face area, it is also necessary to choose the optimal interaction between the de-stressing cycles, the production blast cycles and the time dependent relaxation of fracture zone discontinuities. Before optimum face advance rates can be determined, further work is necessary to confirm the use of particular viscous laws, to implement these laws in computer models and to calibrate these models against underground observations.

A second strategy that would allow some control to be exercised over the behaviour of the stope fracture zone is the interaction of stope production blasting with the pre-existing stress field in the formation of mining-induced fractures. It has been established from the fracture geometry and fracto-graphic observations (the structures on the fracture surfaces) that a high proportion of the 'bow-wave' fractures in the walls of tunnels that have been excavated in conditions of high stress, are due to the combination of this high field stress and the superimposed transient blast stresses[77]. The significant effect of this combined influence of the blast and the field stress in causing the growth of 'blast assisted stress fractures' is to increase greatly the fracture penetration and

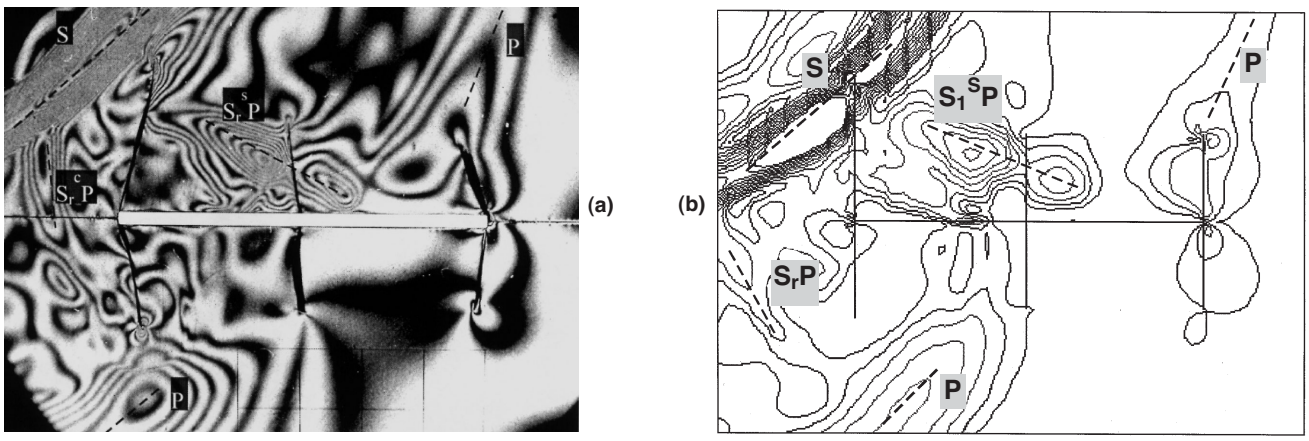

Figure 16—Comparison between (a) the physical model of a stope with high-angle fractures, and (b) the WAVE model, 167 μs after the blast

severity in the stope hangingwall. Exposures due to falls of ground have revealed fracture penetrations from 0,5m to 1m which commonly extend until a weakly cohesive bedding plane or similar discontinuity is encountered. These fractures can act to reduce the stope hangingwall stability.

Some of the observed fracture patterns in stopes and tunnels can be interpreted using small-scale blasting experiments in PMMA blocks, loaded in a biaxial stress field. Fractures are observed to grow preferentially in the direction of the applied maximum stress and to curve into alignment with the plane of the major and the intermediate principal stress components. Numerical modelling, using the DIGS computer program, has been applied to reproduce, in two dimensions, the axi-radial growth of fractures from a pressurised shot-hole in a high vertical stress. The fracture growth is controlled by computing the elastostatic stress field ahead of the current crack front and then advancing the front in the growth direction indicated by a specified growth rule. Although this is a quasi-static approach to the growth of fractures, it is able to replicate the observed fracture patterns around pressurised shot-holes fairly well (Figure 17). Additional work is being carried out to study the propagation of blast-induced gas-driven fractures in large PMMA blocks and to develop suitable models of the gas flow and heat transfer effects as the fracture front expands.

From these considerations it seems that future research should focus on several interrelated topics. In the first instance, it is necessary to study wave transmission behaviour in the stope fracture zone in order to understand the stability of the fracture zone when it is subjected to seismic excitations. Existing representations of the fracture zone have been crude approximations using either a small number of discrete fractures, or the assumption that the fracture zone can be modelled as a low modulus elastic region. Methods to study general fracture orientations, which are not currently possible in WAVE, will be needed and techniques to represent fractured rock as an equivalent

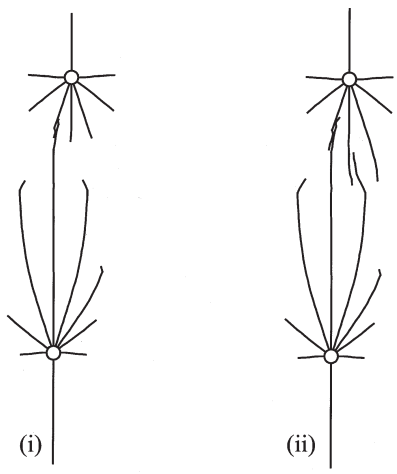

Figure 17a—A DIGS fracture growth model showing two stages of fracture growth during the sequential blasting of two shot-holes:
i) shortly after the second (upper) hole has detonated and
ii) later when the fractures from the first hole have been captured by the stress field from the second hole and drawn towards it. The maximum stress is vertical

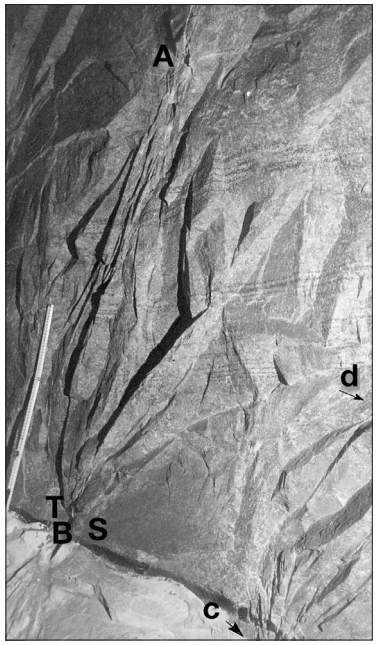

Figure 17b—Photograph showing the same phenomenon in the wall of a tunnel. Axi-radial fractures (parallel to the shot-hole axis and radial to it) grow parallel to the maximum compressive stress (arrow), from the top (T) and bottom of the shot holes. Growth from the sides of the holes (S) is suppressed by this stress. Fractures from one shot hole (A) tend to be 'captured' and extended towards a subsequent adjacent hole (B). Fractures from hole C (out of view, below) are drawn round a curve towards D (out of view, right)

damaged material will be investigated. It is also planned to study both the physical processes of dynamic fracture growth and the numerical modelling of dynamic fracture propagation and dynamic motions of fractured material. Efforts will be directed towards the development of a suitable fracture zone analysis tool that can draw on the physical understanding of both wave propagation and blast-assisted fracturing and effects of creep-like relaxation on discontinuities. This will allow mining rate simulations to be conducted to explore seismic recurrence cycles in relation to different geotechnical environments. This would provide a direct tool to assist studies of expected seismic hazards and to assess mining strategies in different geological environments. Such a fracture zone simulator would supplement traditional methods for mine layout design. Although the future research directions are focused specifically on investigations of deep gold mine fracture zone behaviour, the work will draw, where possible, on advances that are made in allied fields of earthquake mechanisms, seismology and rock fracture mechanics.

Conclusions

The quality and effectiveness of deep level gold mine rock mechanics design is determined by the degree to which rock failure mechanisms can be predicted and the extent to which these can be controlled by effective engineering strategies. Fundamental research into rock mass and fracture zone behaviour in the vicinity of deep level excavations has been conducted in the following areas.

- Fundamental progress has been made in characterising the nature of rock fracturing with specific reference to the nucleation and coalescence of splitting fractures and the nature of fracture localisation under conditions of compressive confinement. Additional work is required to synthesise this information into useful constitutive rules that can be used in numerical modelling procedures.
- Investigation of fracture mechanisms have been supported by an extensive programme of laboratory and physical modelling. This forms an essential adjunct to the development and calibration of numerical models of fracture processes.
- The representation of fracturing at the stope scale and the understanding of stope fracture zone formation has been addressed using special purpose computer codes. These have been developed to allow explicit large-scale fracture and damage simulations to be performed in order to interpret and predict expected underground behaviour. Of particular importance is the initiation of studies of the mechanisms of creep-like deformations that occur in the stope fracture zone in order to be able to represent the effect of face advance rate on the intensity and recurrence frequency of seismic activity.
- Considerable effort has been directed towards constructing numerical methods that can allow elasto-dynamic movements in the rockmass to be modelled. These computer models provide a platform for studies of seismic source mechanisms, surface particle velocity amplification, interaction of seismic activity with stopes and effects of backfill on the expected dynamic motions in stopes. High speed photographic experiments have also been carried out which have allowed numerical results to be checked against the observed elasto-dynamic movements in photoelastic plates.
- Initial steps have been taken in moving towards the goal of fracture zone 'engineering' by carrying out experimental studies of the interaction of blast-driven fractures with the ambient stress field. This experimental work has been supplemented by the development of numerical models of gas-driven fracturing. If sufficient understanding of the interaction between stope blasting activity and the growth of mining-induced fractures is gained, it is possible to envisage controlling the intensity of fractures ahead of the stope face. In addition to this, the understanding of energy release processes in relation to the relaxation time for discontinuity creep movements in the fracture zone, can allow realistic assessments of seismic recurrence to be carried out. Effective models of the stope fracture zone should also enable estimates to be made of the effectiveness of various support units or layout options such as the use of backfill. These possibilities provide additional alternatives to standard design procedures.

Acknowledgements

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Wits University initiates drive to attract scholars to metallurgy*

Professor Sylvana Luyckx (right) of the School of Process and Materials Engineering at Wits University with science teacher Marjorie Redshaw of Johannesburg's Kingsmead College at the University's stand at MinQuiz, Mintek's schools' science quiz

'South Africa will need at least 160 metallurgists a year by the end of the century. At present our universities are graduating only 12 metallurgists a year.'

This statement from Professor Sylvana Luyckx of the School of Process and Materials Engineering at the University of the Witwatersrand gives some idea of the gravity of the problem facing this country which is, ironically, among world leaders in the discipline.

Professor Luyckx is a driving force behind Wits University's efforts to attract young people to a career in metallurgy. The School of Process and Materials Engineering recently launched a competition inviting scholars to enter metallurgy projects in a special interests category in the Young Scientists Expo '97 to be held later this year.

A number of these projects will be selected for the Expo '97 national finals and winners will be invited to visit the School of Process and Materials Engineering at Wits University. There they will see metallurgy in practice and be made aware of the many bursaries available for studies in this field.

MinQuiz

The School of Process and Materials Engineering also recently participated in the Johannesburg-leg of the 10th annual Minquiz competition. Professors and post-graduate students from the School were on hand to answer questions from the more than 100 students who attended and Professor Hurman Eric and Dr Lesley Cornish each gave a talk to the 85 teachers present.

Minquiz, a competition for scholars sponsored each year by Mintek, specialists in mineral and metallurgical technology, is aimed at encouraging metallurgy as a career choice.

The competition, run simultaneously by Mintek at ten venues around the country, involves teams of scholars competing for cash prizes for their schools. The top team from each region goes on to participate in a two-day national finals competition.

The winning school in the national finals receives two bursaries, with the second, third and fourth placed teams being awarded one bursary each. ◆

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