NEW APPROACHES TO THE DESIGN AND EVALUATION OF MINE STOPPINGS AND SEALS

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ABSTRACT

There are a number of challenges arising from changes to regulations covering ventilation control devices in Queensland. There is a paucity of information on the appropriate selection and use of stopping and seals in mines. Compounding this until recently there was no prospect of the development of a full-scale test facility within Australia. The paper describes recent research undertaken to both develop, evaluate and calibrate a full-scale pressure test facility for ventilation control devices (VCD) within Australia, and examine a number of important aspects of stopping and seal performance, usage, design and application for the coal mining industry.

A review of the safety of coal mining operations after the Moura Number 2 explosion resulted in changes to mining regulations in Queensland. Under the new regulations, ventilation control devices are required to be tested at “an internationally recognised mine testing explosion gallery” to achieve pressure ratings of 14, 35, 70, 140 or 345 kPa. These changes have highlighted the lack of information of the appropriate selection and use of stopping seals in mines and the strategic need for the development of a full-scale test facility within Australia.

A combination of computational fluid dynamics (to model the methane/air explosion through time and space), finite element analysis (to model the structure’s response to the pressure impulse) and measurements from full-scale tests have been used in the project. In practice, it is possible to physically test only one structure full-scale, and then predict its ultimate strength using computer modelling and appropriate data obtained from the testing. The prediction can be then validated/corrected by further, more powerful impulses applied to the structure up to and exceeding its ultimate strength. This project has successfully proved that an Australian explosion test facility can be used in the testing and approval of new mine VCDs. Through a better understanding of the performance of stopping and seals in mines, it will be possible to select the most appropriate seal for a particular application and hence maximise safety and economy outcomes.

INTRODUCTION

There are a number of challenges arising from changes to the regulations covering ventilation control devices in Queensland, Australia. A review of the safety of coal mining operations after the Moura Number 2 Mine explosion resulted in changes to mining regulations in Queensland. Under the new regulations, ventilation control devices are required to be tested at “an internationally recognised mine testing explosion gallery” to achieve pressure ratings of 14, 35, 70, 140 or 345 kPa depending on the purpose of the unit.

The issue becomes more acute with the prospect of the state of New South Wales considering a similar approach. Both the Queensland and NSW coal-mining inspectorates have acknowledged that there is a paucity of information on the appropriate selection and use of stoppings and seals in mines. The aim of this study is to examine a number of important aspects of stopping and seal performance, usage, design and application for the practical coal mine environment.

A major aim of the project was to examine how an existing explosion research gallery might be utilised for full scale explosion type testing at high and low pressures. While a basic test methodology had already been developed for low pressure tests, no high pressure (140 kPa and greater) had been conducted on seals. For both tests computer modelling of the explosion impulses and their effects upon the structures was conducted. Comparisons were made between the predicted and observed results. These results were compared to that found for the same designs tested at an internationally recognised mine testing explosion gallery.

A second major aim was to examine the operational context of the placement of stopping seals in mines and examine the application of engineering principles to design. It was considered important to establish the present views of the industry and manufacturer vendors as to the current practices, appropriateness of these approaches and future direction. Intrinsic to the successful operation of stopping seals is their adequacy as a tool in ventilation engineering. Questions as to the functionality in preventing oxygen ingress, toxic/ combustible gas egress and pressure rating of the device or nearby strata are important.

The study endeavours to give a better understanding of the performance of stoppings and seals in mines and enhance ability to select the most appropriate seal for a particular application and hence maximise safety and economy outcomes over the VCD lifetime. Equally important is an expanded understanding of the device as a structural component within the mine system. What is the confinement load on the stopping or seal over its lifetime? How can they be tied into the seam and surrounding strata to act in concert or interrelate with other structural or support components? Are there other materials for construction worthy of consideration?

A literature review on the stopping and seal practices and approaches used in mining industry was carried out. An overview on the currently available practices and acceptable approaches in the operation of stoppings and seals is described. A study has been undertaken that examines the regulations and compares them with the changing situation in some foreign countries with similar practices and mine layouts. It examines the emerging responses to the regulatory and other changes through an analysis of the results of a comprehensive survey of the operational context of the replace of stopping seals in mines.

OVERVIEW ON SEALS AND STOPPINGS

Background

Success in providing adequate ventilation to the active workings of a mine depends on adequate fan capacities, good primary ventilation air distribution and, when the air reaches the working section, good control and distribution of the face ventilation air. General acceptable practices use various VCDs such as stoppings, seals, overcasts, airlocks and regulators arranged so that air flows in the desired manner at appropriate quantities.

Stoppings, as defined by Hartman et al (1997), are physical barriers erected between intakes, returns or abandoned mine voids to prevent air from mixing. Stoppings are classified according to construction, length of service, and purpose as temporary or permanent. Temporary stoppings are extensively used in areas where frequent adjustment to air directions are necessary. They are moderately airtight and are normally hung in active workings where changes occur rapidly in the mining and ventilation methods. They must be readily movable and are generally reusable. Permanent stoppings, also called bulkheads, are installed in places where a permanent or a long-term control of flow is needed, such as between the main intakes and returns or belt entries. In the past these have been constructed of frame, sheet metal (prefabricated sections), masonry (stone, brick, or concrete block) or “shotctete” sprayed on wire mesh. Because their purpose is to stop airflow for an indefinite period, they must be made airtight by tapping, plastering or caulking and resistant to cracking from blasting concussion or ground movement. Permanent stoppings are also used as fire bulkheads to seal off abandoned workings. Abandoned workings may in time hold toxic or explosive gas mixtures and so these bulkheads must both stop atmospheric mixing and be able to withstand a pressure event. A seal is a special stopping used to isolate abandoned workings and goafs or as fire bulkheads. Seals eliminate the need to ventilate those areas; they may also be used to isolate fire zones or areas susceptible to spontaneous combustion.

US Stopping and Seal Practices and Approaches

In the US prior to the 1990s the normal practice was for stoppings and seals to be built according to the specifications of the Coal Mine Health and Safety Acts of 1969 as given in Title 30, Code of Federal Regulations (CFR). Ordinary seal construction practice was to construct two solid block stoppings about 0.3-0.6 m apart and to fill this void with concrete, earth or sand. Stoppings should be substantially built so that they are airtight and resist the disruptive forces of explosions. All contraction materials for permanent stoppings and seals being used in the US underground coal mines must meet the standards in terms of non-combustibility and have the average flexural strength of “at least 39 pounds per square foot” for three walls. The sealants used must meet the flame-spread index under ASTM E162-87 (Tien, 1996).

An important factor to be considered for any seal design is its impermeability, or its ability to prevent or reduce the exchange of gases from one side of the seal to the other. Measurements of the air leakages across the seals were conducted before and after the explosion tests and compared to Mine Safety and Health Administration (MSHA) established guidelines. These guidelines are as follows: for pressure differentials up to 0.25 kPa, air-leakage through the seal should not exceed 2.8 m^3/min; for pressure differentials over 0.75 kPa, air leakage should be less than 7.1 m^3/min.

Since 1991 MSHA requirements have been that seal design must meet an explosion rating of 140 kPa (20 psi) and in summary be;

- Constructed of solid concrete blocks at least 150 by 200 by 400 mm laid in a transverse pattern with mortar between all joints;
- Hitched into solid ribs to a depth of at least 100 mm and hitched at least 100 mm into the floor;
- At least 400 mm thick. When the thickness of the seal is less than 600 mm and the width is greater than approximately 5 m or the height is greater than approximately 3 m, a pilaster shall be interlocked near the center of the seal. The pilaster shall be at least 400 mm by 800 mm; and
- Coated on all accessible surfaces with flame-retardant material that will minimise leakage.

This standard seal design is illustrated in Figure 1. Alternative methods or materials may be used to create a seal if they can withstand a static horizontal pressure of 140 kPa provided the method of installation and the material used are approved in the ventilation plan. From discussions with a number of longwall mine engineers it appears that in most mines the practice is to construct these seals to isolate old goafs in blocks. A number of adjacent longwall panels within a block are extracted in sequence up to a natural barrier or planned long barrier pillar. All longwalls within the block are isolated by sealing where gateroad entries meet the Mains heading. It is not normal practice to seal individual longwall goafs from adjacent panels ie; cut-throughs along the chain pillars length are not sealed to isolate one goaf from the next. However some western states mines with a consideration for spontaneous combustion propensity eg; Twenty Mile and San Juan, do or are planning to isolate individual goafs by sealing all cut-throughs along the length of the chain pillar. One other company, Jim Walters Resources in Alabama with highly gassy seams also isolates individual goafs for gas management. These are connected with vertical boreholes to the surface with goafs acting as reservoirs for marketing of gas.

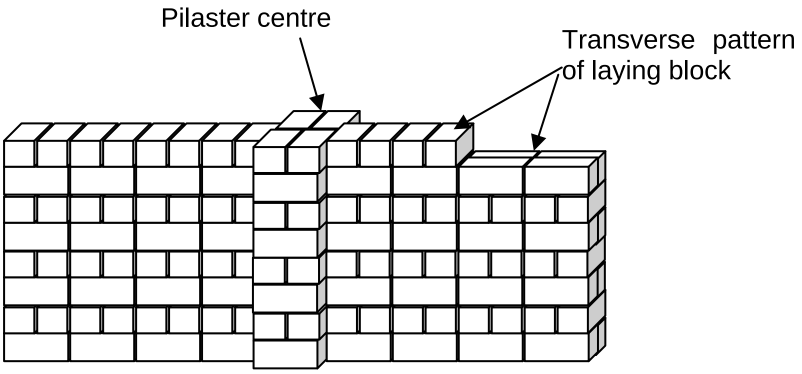

Figure 1. Standard type, solid-concrete-block seal (after Greninger et al, 1991).

Queensland Standards

In Australia, within Queensland according to Standards for Seals and Airlocks 1967 issued by Coal Operations Branch, Safety and Health Division, Queensland Department of Mines and Energy (QDME), four specific elements must be addressed when installing seals. These are;

- design and specification,
- location,
- construction, and
- maintenance and monitoring.

Depending on the purpose or intent of the seal and its location, different design criteria are recommended by QDME. These recommended design criteria are listed in Table 1.

Many countries have pursued research in explosion-resistant structures for underground mining. These include the US, Australia, South Africa, France, Germany, Poland and China. In the US extensive research in the last decade explosion testing of mine seals has been underway. The

Pittsburgh Research Laboratory's (PRL) of the National Institute for Occupational Safety and Health (NIOSH) and MSHA have been jointly investigating the ability of various existing and new seal designs to meet or exceed the requirements of the CFR. Extensive explosion and air leakage tests on alternative seal designs have been conducted at the Lake Lynn Experimental Mine (LLEM), located near Fairchance, PA (Triebsch and Sapko, 1990).

Table 1. Queensland approved standard for ventilation control devices.

Design Criteria	Location	Purpose or Intent
Type A (2 psi) 14 kPa (Recommended)	Limited Life Production Panel	All VCDs installed are to remain "fit for purpose" for the life of the panel and be capable of withstanding an overpressure of 14 kPa.
Type B (5 psi) 35 kPa (Recommended)	Main Roadways	All VCDs constructed as part of the main ventilation system are to remain "fit for purpose" for the life of that area of the mine and always capable of withstanding an overpressure of 35 kPa.
	Sealed Areas	For use in mines where the level of naturally occurring of flammable gas is insufficient to reach the lower explosive limit under any circumstances.
Type C (20 psi) 140 kPa	Sealed Areas	For use in all circumstances not covered by Type B and D seals.
Type D (50 psi) 345 kPa	Sealed Areas	When persons are to remain underground whilst an explosive atmosphere exists in a sealed area and the possibility of spontaneous combustion, incendive spark or some other ignition source could exist.
Type E (10 psi) 70 kPa	Surface Infrastructure	Surface entry stoppings for temporary emergency use and may include - Surface air locks, Main fan housing

Alternative seal designs and types that have been evaluated included (Sapko et al, 1999a):
- Solid concrete block seals;
- Modified solid concrete block seals;
- Bulk cementitious (expanding) seals with various compressive strengths;
- Low density block seals;
- Composite Polymer seals made from block walls that enclose gravel and polyurethane foam;
- Reinforced cementitious seals (using steel mesh) that are anchored to the ribs, roof, and floor with bolts and made with high strength cement with varying curing times.

MSHA over the years has approved various materials and type of construction methods such as solid concrete blocks, Omega 384 blocks, cementatious foams and polymer foams. These seal designs are classified into several categories depending on the similarity of the construction materials used.

QUESTIONNAIRE SURVEY OF SEALS AND STOPPINGS

In order to achieve a better understanding of the type and properties of seals and stoppings currently being marketed and approaches to engineering design of these structures, separate surveys of Australian manufacturers and underground mine seal/stopping usage was undertaken. Fourteen mines and seven manufacturers responded to these surveys.

Mines' Responses

Mines were asked usage pattern of seals and stoppings before 1997 and currently.

Prior to 1997 for belt road segregation, two mines used brattice, two plasterboard, one sheet metal or reinforced cementatious, one mortared block and the rest use nothing. To separate Mains intake or belt from return, four mines used reinforced cementatious, six mortared block and two plasterboard. To separate intake from belt air in panel gateroads, seven mines used plasterboard, two block, two reinforced cementatious and one sheet metal. For final panel seals providing separation from adjacent panel air, four mines used block, three plasterboard, two low density block, and one reinforced cementatious material. For final panel seals providing separation form Mains, four mines used mortared block, two plasterboard, two block, one reinforced cementatious and one composite polymer material. For overcasts applications, nine mines used pre-fabricated steel, two block, one sprayed brattice, and two reinforced cementatious material.

Currently for belt road segregation, two mines use brattice, two reinforced cementatious and two mortared block, one block and the rest of mines use nothing. To separate Mains intake or belt from return, five mines use reinforced cementatious, five mortared block, one composite polymer, one bulk cementatious and one low density block. To separate intake from belt air in panel gateroads, five mines use plasterboard, three block, three reinforced cementatious, one bulk cementatious and one sheet metal. For final panel seals providing separation from adjacent penal air, four mine use reinforced cementatious, three bulk cementatious, two composite polymer, one block and one concrete plug. For final panel seals providing separation form Mains, seven mines use reinforced cementatious and three composite polymer, two bulk cementatious, one concrete plug and one block. For overcasts applications, nine mines use prefabricated steel, two block, one sprayed brattice and two reinforced cementatious.

Only four mines had information about structural properties of their seal products. Half (seven) of the mines have information about stress vs time dependent relationship through the life of their seal or stopping products. Eleven mines indicated face ignition to be the anticipated main source of major pressure disturbance and two mines indicated air blast. seven mines indicated that seals should be designed as both impervious (leakproof) and explosion-proof and six mines indicated design for sealing (leakproof) is most important.

Nine mines consider design should be mainly through structural analysis, Two support physical testing and two indicated both should be considered. When asking views on the Queensland rating code, two mines support this code, three mines consider focus should be on sealing ability, four mines were concerned with the validity of tests required for the rating code and one was concerned with how old stopping should be handled.

Only five mines utilised the concept of pressure balancing sealed areas. Half of the mines have taken account of barometric pressure influences on sealed areas and most of them also monitored sealed areas. In term of views on prohibition on “intake air passing a sealed goaf”, half of mines agreed and the other half disagreed. Nine mines indicate preference to use contractors and only three prefer mine labours for installing VCDs as they have concerns with quality and time vs cost issues.

The load placed on a cut-through stopping or seal can be examined through chain pillar and intersection loading cycle stress analysis. A recently completed ACARP study (Colwell, 1998) examined conditions in this regard, compared US and Australian conditions and undertook site measurements at Central, Crinum, Kenmare, Newstan, West Wallsend and West Cliff collieries. These findings have relevance to the stress placed on a newly formed Longwall panel seal and the subsequent loading history. The in-situ coal strength is taken to be a constant of 6.2 MPa. Mark and Barton (1996) discussed the role, if any, of the laboratory compressive strength of coal specimens in pillar design. They indicated that the strength values obtained in this manner couldn’t be used in a meaningful way in pillar design. This is not to say that the in-situ strength of all US coal is the same. Their study simply concluded that for pillar design purposes uniform coal strength is a better approximation of average pillar strength than one based on laboratory testing. Salamon et al (1996) suggested that the results of University of NSW study support the same conclusion.

The total vertical load transmitted to a chain pillar during the extraction process is a function of some measurable factors and some subjectively determined aspects. These include depth, overburden density, distribution of load between chain pillar, longwall face and adjacent unmined block, position of faceline relative to chain pillar, overburden caving characteristics, spanning characteristics of strata overlying goaf, and roof and floor strength/structure.

Pillars that lie between two longwall panels will experience greatest vertical loading and account for bulk of chain pillars in series of panels. As a longwall laterally approaches and retreats past a chain pillar a dynamic loading cycle is experienced. This incorporates the development load plus the onset of a front abutment load as face approaches pillar. The abutment load increases as face retreats outbye to become a side abutment load - this rises to static maximum.

As the adjacent longwall retreats these chain pillars in the tailgate go through a second dynamic loading cycle. This incorporates development load and first side abutment load plus the onset of a second front abutment load. Second load is estimated as 70 percent of first. Double goafing conditions apply once the second longwall face retreats to a distance sufficiently removed from the pillar. Figures 2 and 3 indicate instrument measuring points and loading pattern on a chain pillar. Stress profiles across the pillar are shown for the initial condition when the pillar forms part of the Main gate access to the Longwall panel and subsequently a panel cycle later when it carries additional load as part of the Tailgate heading.

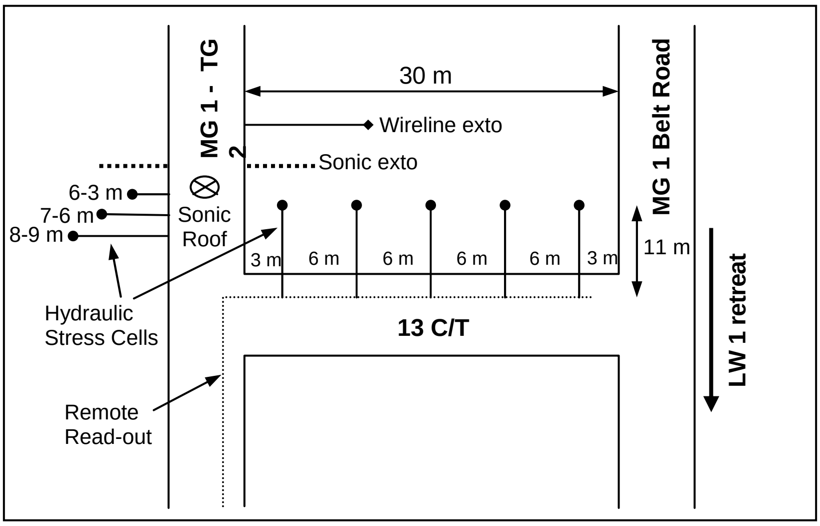

Figure 2. Typical instrumentation layout (30 m wide pillar) (After Colwell, 1998)

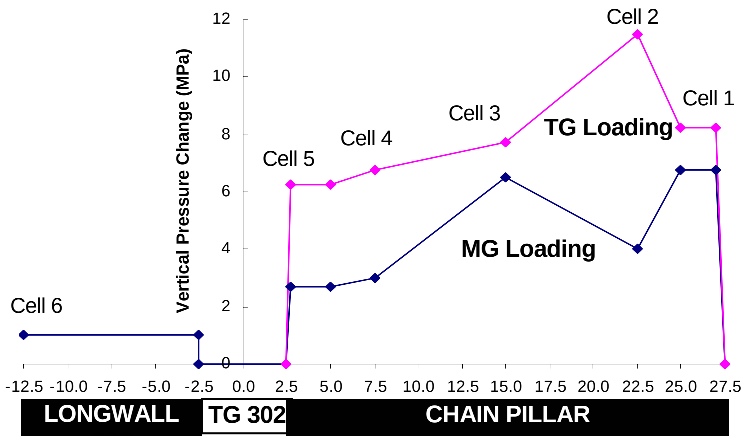

Figure 3. Example of maingate and tailgate loading stress profiles (After Colwell, 1998)

Manufacturers' Responses

A seven page questionnaire was mailed to selected stopping and seals manufacturing companies. All seven stopping and seals manufacturers responded were located in NSW. The majority of the manufacturers are relatively new in business. All manufacturers except one supply products for longwall, room and pillar, gateroad, Mains development and other applications. Average minimum mine opening height to install their seal and stopping products is about 2.0 m with a range varying from 1.2 to 2.7 m and average maximum height is about 4.6 m with variation ranging from 3.0 to 6.0 m.

Four manufacturers have had their seal and stopping products tested at the LLEM facility. Three have had their products tested at the Londonderry TestSafe testing facility, NSW. Two manufacturers also use scaled model testing or engineering model rating for their products. All surveyed can have doors installed in their stopping and claimed no effect on integrity but no test data published. All except one have own (proprietary) approaches to designing for varying height and/or width dimensions of stopping and seal. All manufacturers have products that can be installed alone. Some manufacturers have products can be both stand alone or adjacent to supports. All responding claim that their seals or stoppings are designed to meet at least part of the VCD rating codes.

Five manufacturers claim to use some knowledge of geomechanics considerations in their product design processes. Six respondents claim that products are designed to have the same ability to withstand a force from front and back. Most of the manufacturers except one have information on mine life span of their products before integrity is lost. Most of manufacturers have been involved in sealed area induced inertisation. Five have information on product ability to function adequately after a significant mine pressure event. All except one believe that a seal principally should be designed as both as an impervious membrane and as an explosion barrier. All manufacturers surveyed believe that their products would maintain rib seal as ground load is imposed. Five are aware of some in-mine leakage tests undertaken on seals/stopping by manufactures or others. Most of the manufacturers are aware of some literature or guides on how to undertake accurate in-mine leakage tests and referred to test procedures used by LLEM or TestSafe.

In general most accept that some industry regulations or standards would benefit in terms of safety. One suggested that rating codes should be standardised across Australia. There are some doubts concerning the 14 and 35 kPa stopping standards and how these were determined. A divided view exists on whether design should be principally through design structural analysis or physical destruction testing. One suggested that design should be based on physical destruction tests alone. Another suggested both physical testing and structural analysis for seals but for stoppings structural analysis is sufficient. Two suggested that Australia needs a rating test facility meeting agreed guidelines as LLEM test procedure is considered flawed. About half of the manufacturers prefer products installed by own labour to maintain quality.

PHYSICAL TESTING

A major aim of the project was to examine how an existing explosion research gallery, namely that at TestSafe might be utilised for full scale explosion type testing at high and low pressures. This endeavour can be summarised in a single question - "If one was to test the same seal or stopping at two different test stations, will the results obtained for the explosion resistance be the same?" In order to compare TestSafe to an established test station, identical VCDs were tested at LLEM and TestSafe. The comparison was based upon evaluating the movement, acceleration and ultimate explosion resistance of these devices. In order to simplify the evaluation and to minimise the costs and complexity, the research program was limited to explosion tests on one 40 mm thick stopping and one 325 mm thick seal. These were both steel reinforced shotcrete designs. These structures had been previously tested at LLEM in a research program undertaken by Tecrete Pty Ltd. During this LLEM test program, data was obtained for displacement, acceleration and ultimate explosion resistance for a number of seals and stoppings. With the cooperation of Fosroc Chemfix, the current owner of Tecrete, test structures were installed in the TestSafe Explosions Gallery. These were constructed to the same design and thickness, and using the same materials and construction methods. The major remaining differences between the LLEM and TestSafe tests were the dimensions of the test apertures and the inherent physical differences between the two test stations.

There are some important differences between the two test configurations. The LLEM was once a limestone mine. It was modified to closely simulate the three dimensional configuration of a coal mine Figure 4. illustrates the LLEM test configuration. The test seals are located in crosscuts off "C" drift as shown. Explosive concentrations of methane gas are produced behind a plastic diaphragm in the stub end of "C" drift. Several water filled barrels are placed in the gas volume to induce turbulence and so accelerate the explosion. The explosion travels down the drift past the crosscuts and Data Gathering Stations.

Figures 5 and 6 illustrates the TestSafe Explosion Gallery test configuration. The TestSafe Explosions Gallery was made from several sections of reinforced concrete pipe totalling 50m in length. The internal diameter is 2.7 m and there is a cast in floor reducing the effective maximum height to 2.4 m. It is buried about 1m below ground and has a shell thickness of 150 mm. The explosion overpressure is allowed to vent through a 300 mm diameter hole on the side of the gallery (see Figure 6). It was originally designed for the study of dust and gas explosions, and to test mining equipment under explosion conditions. The test aperture was produced between two 500 mm thick reinforced semicircular concrete walls placed 5.5 m apart as shown in Figures 5 and 6. Figure 7 shows the 325 mm thick Tecrete seal as viewed from the explosion pressure side.

For this test program, Linear Variable Displacement Transformers (LVDT) and an accelerometer were placed at locations on the test wall and the shell of the Gallery in order to measure movement of the structure during explosion tests. Pressure transducers were located near the origin of the explosion and adjacent to the test wall. Transducer locations are given in Figure 6.

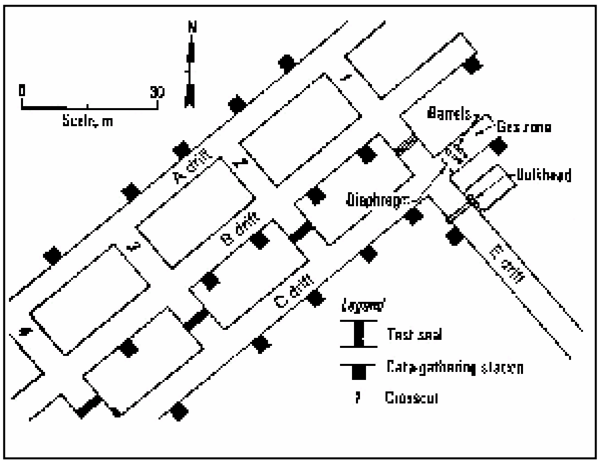

Figure 4. Base plan of LLEM

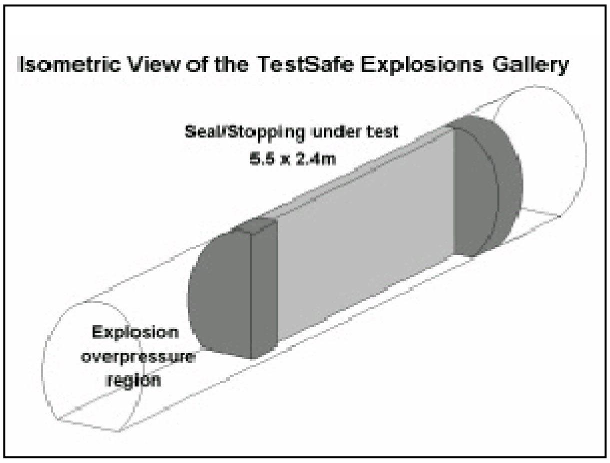

Figure 5. Isometric schematic of the TestSafe explosions gallery.

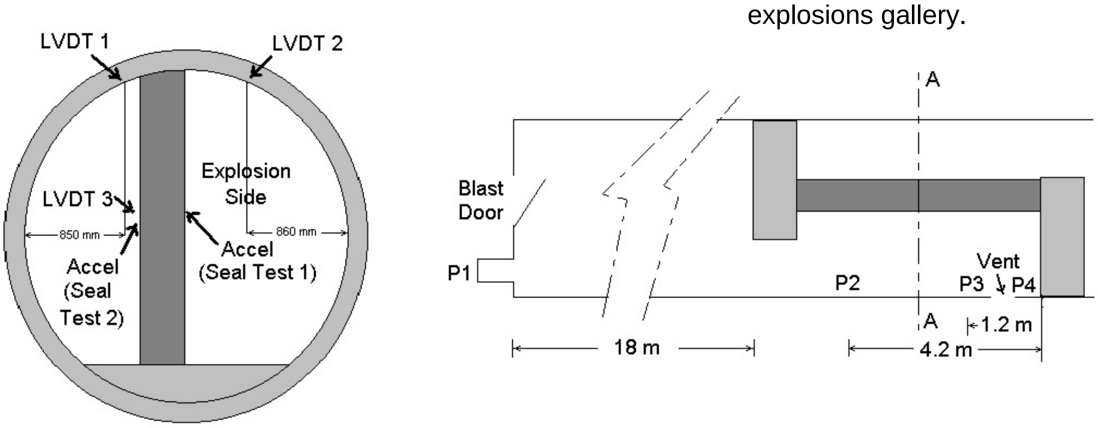

Figure 6. Schematic plan of the TestSafe Explosions Gallery showing pressure transducer locations. Section showing LVDT and accelerometer locations.

Explosion tests on the 40 mm Tecrete stopping involved inflating a thin plastic bag with a known volume of a 10% methane/air mixture. Explosion tests on the 325 mm thick Tecrete seal involved fitting a plastic sheet across the closed end of the gallery enclosing a known volume of air. A weighed quantity of propane was then injected into a recirculation fan over a period of several minutes. These gas mixtures were ignited by electrically initiated 5 kJ chemical detonators. A 9-volt battery connected to a switch was used to fire the igniters and to simultaneously launch a high-speed computer data logging system. The signals from the pressure and movement sensors were collected at a rate of 1000 measurements per second for each channel.

Results of Testing

The 40 mm stopping was tested to destruction. However, a decision was made not to test the 325 mm seal to destruction as it was considered that this might cause damage to the gallery's shell. Examples of the explosion pressure profiles for 135 kPa test both at LLEM and TestSafe are given in Figure 8. The explosion pressures generated at TestSafe are present at the face of the stopping or seal for a much longer period of time than at LLEM. Also, the initial rate of pressure rise is less at TestSafe. The significance of this longer time of exposure and slower onset of the pressure impulse is discussed elsewhere.

However, one difference that was immediately noted was the much greater deflection of the seal at TestSafe when compared to LLEM for the same explosion overpressure. Significant movement of the explosion gallery shell was also observed during the explosion tests on the seal, especially for LVDT 1. This LVDT was located on the low-pressure side of the seal (see Figure 6). A 2 mm expansion in the vertical direction was measured for LVDT 1 for the 135 kPa test (see Figure 9).

Figure 7. Internal view from the explosion side of the 325 mm thick Tecrete Seal.
Note: the curvature of the Gallery shell (right) and the mounting for LVDT No 2.

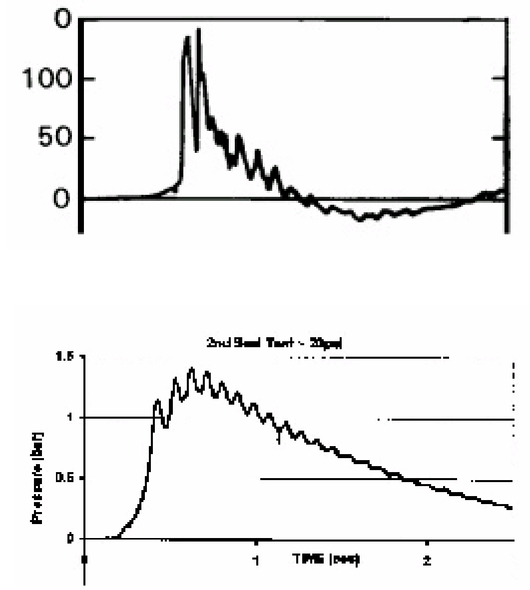

Figure 8. Comparison of the explosion pressure profiles over the first 2.5 seconds resulting from 135 kPa (20psi) tests at LLEM (above) and TestSafe (below).

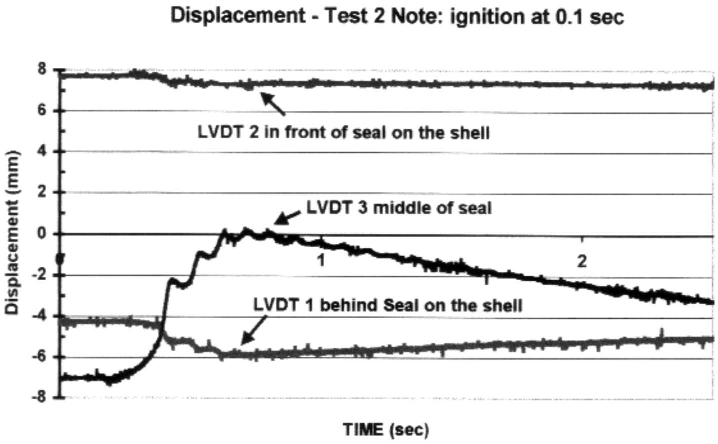

Figure 9. Plot of movement of seal (LVDT 3) and gallery shell (LVDT 1 & 2) during 135 kPa test

These steel re-enforced structures are designed to take advantage of a ridged boundary in order to achieve the desired explosion resistance. These results indicated that there might be insufficient rigidity in the TestSafe gallery shell to achieve explosion resistance ratings comparable to LLEM for these kinds of designs.

Testing Conclusion

The test program was able to produce data that characterised the nature and degree of differences between the TestSafe tests and the LLEM tests. However, it should be understood that these data represents a comparison based upon only one kind of seal/stopping design (steel re-enforced shotcrete). Caution should be taken in extrapolating these differences to other seal/stopping designs. The project has justified the decision by TestSafe to provide a testing service for stoppings but not to undertake testing on high-pressure seals until a proper comparison was made between TestSafe and LLEM. The availability of this limited test service has led to considerable innovation in stopping design and has improved safety levels, economy and compliance throughout the whole industry.

COMPUTER SIMULATIONS

A major aim of the project was to examine how computer modelling of explosion impulses and their effects upon structures could be simulated. This allowed comparisons to be made between the predicted and observed physical test results. The current test configuration used for stoppings and seals may not be the best method of testing these structures particularly when extrapolation of the results to the mine environment is required. Consequently there was a requirement in this project to assess alternative test designs in an attempt to characterise an ideal test design. This alternative test configuration could be substantially different from the present test at TestSafe. The only way of assessing these designs quickly is through simulation of the explosion process within the geometry.

Requirements for a good design include decoupling the test from the environment and simple design to obtain repeatable and reproducible results that can be interpreted. The suitability of alternative monitoring stations can be obtained from the results of simulation. Simulation of existing test facilities is also required as pressure measurements are often not located at the stopping or seal location, making interpretation of results between different test facilities difficult. For example at LLEMM the pressure measurement is located in the main roadway while the stopping or seal is set back in a crosscut. Multiple reflections can occur in this type of situation that increase loadings on the test component compared to the measured static pressure. It is important that these variations in loads are understood in order that a comparison between test facilities can be made.

Simulation of Alternative Test Geometries:

The simulations were based around five different base geometries shown in Table 2. Four variations of base geometry 4 and two variations of base geometry 5 of the TestSafe explosion gallery were simulated in two dimensions using the computational fluid dynamic code, EXPLODE II, developed over the last decade between the Universities of NSW and Wollongong and the TestSafe.

Table 2 Description of the five Base Geometries used for the simulations.

Base Geometry	Comment
1	Current Configuration; closed volume of 24 m length, the test structure is side on to the explosion flow between 18 and 24 m.
2	Existing 50 m explosion gallery open over half of the passage, the test structure is side on to the explosion flow between 43 and 49 m.
3	Extension to 50 m gallery to obtain the full test structure height and width; closed volume with the test structure normal to the explosion flow
4	Extension to 50 m gallery to obtain full height and width; open passage with crosscut containing the test structure. The test structure side on to the explosion flow.
5	Separate structure designed for planar pressure expansion and test structure normal to explosion flow

At least two simulations were carried out for each geometry. The first represented a 2 Bar or 4 Bar pressure pulse of length 10 m in base geometries 1-4 and half the length in base geometry 5. The second simulation was that of a 10 percent methane explosion contained within the first 5m of base geometries 1-4 and throughout base geometry 5.

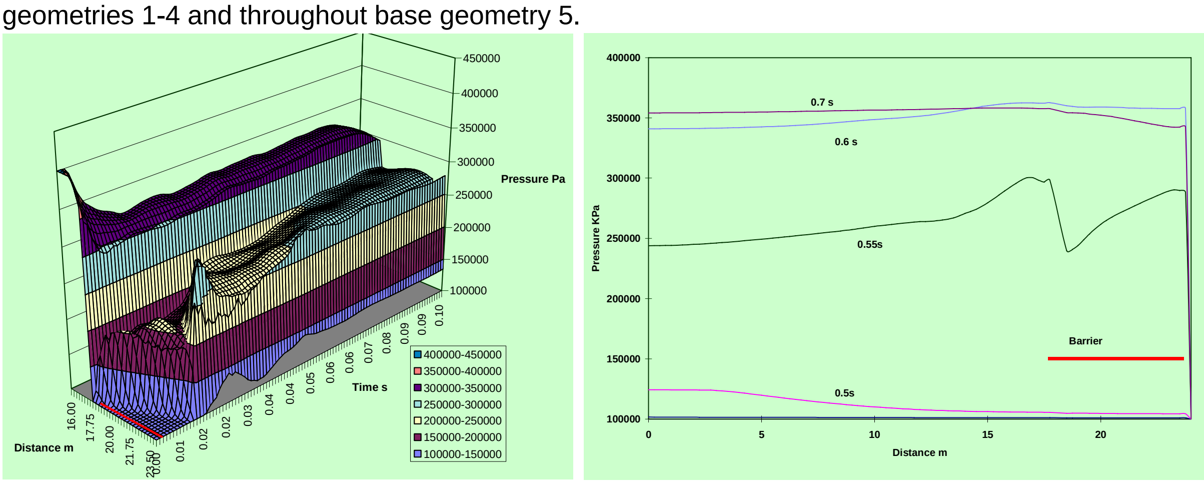

Figure 10. Geometry 1 a) 4 Bar pressure pulse, b) 10% methane/air ignition

The results for Base geometry 1 are shown in Figure 10. Figure 10a is for a 4 Bar pressure pulse over the first 18 m of the geometry. The peak pressure occurs at the barrier region due to pressure piling as the flow rounds the restriction due to the barrier. Figure 10b is a 10 percent methane/air explosion over the first 5 m of the geometry with ignition occurring on the end wall of the gallery. It shows the changes to the pressure profile along the gallery at different times. Note that between 0.5 and 0.6 s after ignition the profile is not flat across the barrier. A variation of the order of 40 percent occurs. The overall pressure response is similar to the previous diagram.

Figure 11 shows the trianguloid structure designed so that as the explosion developed, the pressure front would remain planar rather than curvilinear and so would be expected to give an even loading on the test structure. The diagram shows an even development of the explosion in this facility.

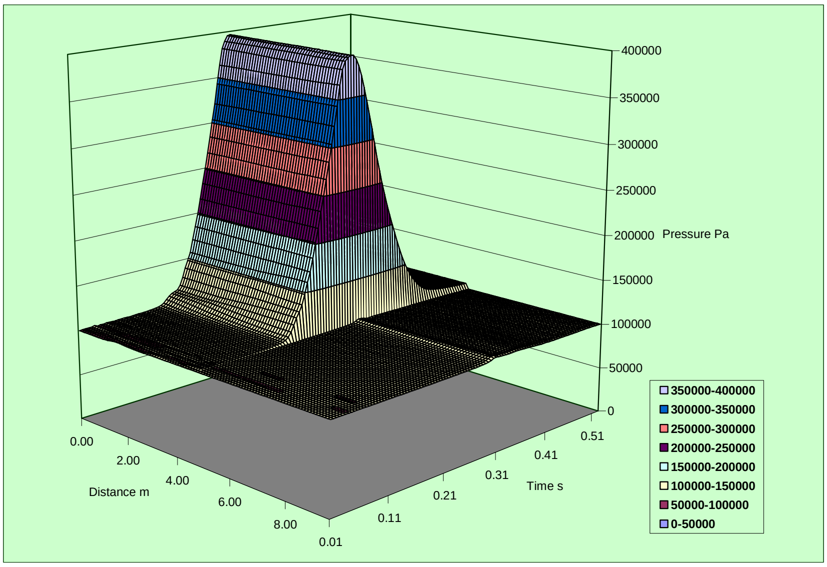

Figure 11. Base geometry 3

Figure 12 shows the peak variation of pressure across the test structure in the nine geometries simulated. The geometries with test structures normal to explosion front had a much lower variation in pressure across the face of the test structure. Typically 2-9 percent as opposed to 25-40 percent when the test structure was side on to the explosion flow.

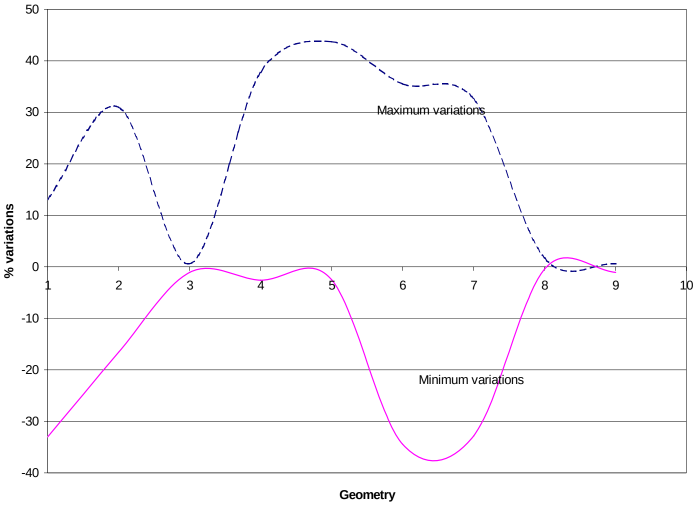

Figure 12. Variation of peak pressures across the test structure for all geometries simulated.

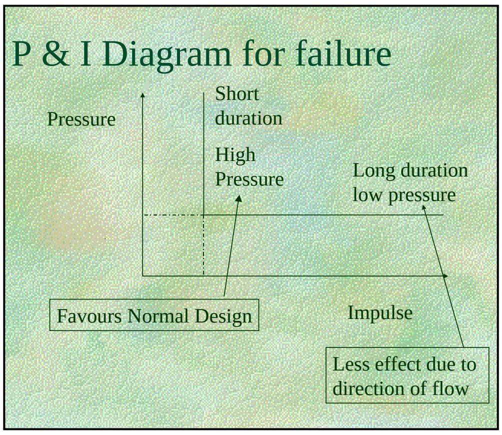

Figure 13. Failure diagram for test structures.

Failure of structures as a function of Peak pressure and Impulse on the structures, occurs between two extremes (Figure 13): long duration slowly rising pressure similar to the conditions for testing low pressure ventilation systems and short duration high peak pressure events characterised by high rates of pressure rise. This is similar to testing of high pressure seals. The former case can be analysed reasonable well in either a normal or side-on configuration. Analysis for the later case may be difficult to interpret if the test structure is side-on to the explosion. Much will depend on the test specimens physical characteristics and whether it is stiff enough to withstand a high pressure transient. It would appear that the current test configuration is suitable for low pressure tests on stoppings but high pressure events should really be tested in a new facility.

STRUCTURAL BEHAVIOUR OF MINE STOPPINGS AND SEALS

Scope and Summary

The principal aim of this research was to investigate the structural behaviour of stoppings and seals subject to explosion loads. The investigation was achieved via the use of non-linear finite element analysis. Attention was focussed on a 325 mm seal and a 40 mm stopping both of reinforced sprayed concrete construction. The analyses have revealed the way these structures carry load and the particular stress conditions leading to failure. It has been confirmed that, while blast loading is of extremely short duration, the response of the structures is essentially static; that is, inertial and damping effects are minor compared with the influence of structural stiffness. The numerical research has enabled a comparison to be made between likely test outcomes at LLEM and TestSafe facilities. Analytical results are directly compared with LLEM test results for the 325 mm seal and are shown to provide reliable predictions.

The principal conclusion from the research is that predictive methods can be used in design of seals and stoppings. Blast testing as the sole criterion for acceptance of the structures is questioned. It is concluded that static testing is likely to be as reliable and that computer analysis is a practical way of including variable conditions of support likely to be found within and between mines.

Finite Element Analysis

Two and three dimensional non-linear finite element analysis was performed. The concrete was modelled as a Mohr Coulomb material with a tension cutoff. Static analysis was performed on 325mm thick reinforced sprayed concrete seal and a 40mm thick reinforced sprayed concrete stopping. The applied pressure was distributed uniformly on the whole face of the wall. These two walls were tested at LLEM and the TestSafe explosion gallery. The analysis allows a study of the wall behaviour in the test facilities. The test results are compared with the numerical analyses.

Structural Response of 325 mm Seals

There are two mechanisms in which the seal is able to resist the applied load - arching and bending. In the arching mechanism a compression arch forms within the thickness of the wall (Figure. 14). This mechanism is very stiff - very little deflection need occur for it to develop. This mechanism imposes compressive stress on the supports. If the seal is wider than it is high, as is the usual case, arching between floor and roof is the principal load transfer mechanism. The arch relies on the supports having sufficient strength to provide high thrust reactions. The strength of the wall in this mechanism is limited by the crushing of the concrete (or the support material) in the high stress regions at the roof and floor. Failure of the wall occurs when the stress in a sufficiently large region of the concrete near the support reaches its crushing strength or if the supporting material crushes. The load / deflection behaviour is linear and failure is expected to be sudden or brittle. The behaviour and response is essentially independent of steel reinforcement in the wall.

The stiffness of the roof and floor supports also is very important. The stress in the concrete is very sensitive to the depth of the arch that can develop, which in turn is dependent on the deflection of the mid-point of the wall. In a 2740 mm high wall (LLEM) just 1.3 mm movement of the roof and floor at the arch supports will result in approximately 6 mm lateral displacement of the mid point of the wall.

In the bending mechanism the applied force is resisted by flexural tension and compression stresses in opposite faces of the wall accompanied by shear as the load is carried to the supports. Reinforcement is required in the tensile face since the tensile strength of concrete is small. This mechanism is considerably less stiff than arching. Compared with the arch, a larger deflection is required before this mechanism is developed. Again, for the usual geometry, the floor and roof provide shear reactions. Provided sufficient shear support (or keying) is available at the roof and floor the capacity of the wall is limited by the amount of tensile reinforcement. Assuming the structure is under-reinforced, the load / deflection behaviour is linear to yield of the reinforcement followed by non-linear ductile response until failure. The capacity of the bending mechanism is typically much less that the capacity of the arching mechanism. If the roof and floor are rigid the arching mechanism develops in preference to the bending mechanism because it is considerably stiffer. If the arching mechanism is lost or cannot develop because of roof and floor deflection - or crushing of the material - the bending mechanism will become dominant.

Figure 15 shows the ultimate capacity of seals for various heights for the bending and arching mechanisms assuming rigid roof and floor supports. This figure assumes the width of the heading is comfortably greater the height. The lower bound line is the pressure at which the peak stress in the concrete at the arch support equals the compressive strength. This pressure represents a lower bound of the strength of the seal since the wall will not collapse until the size of the zone of yielded concrete spreads. The pressure at which the yielded zone is about 5 percent of the width of the wall is shown on the figure.

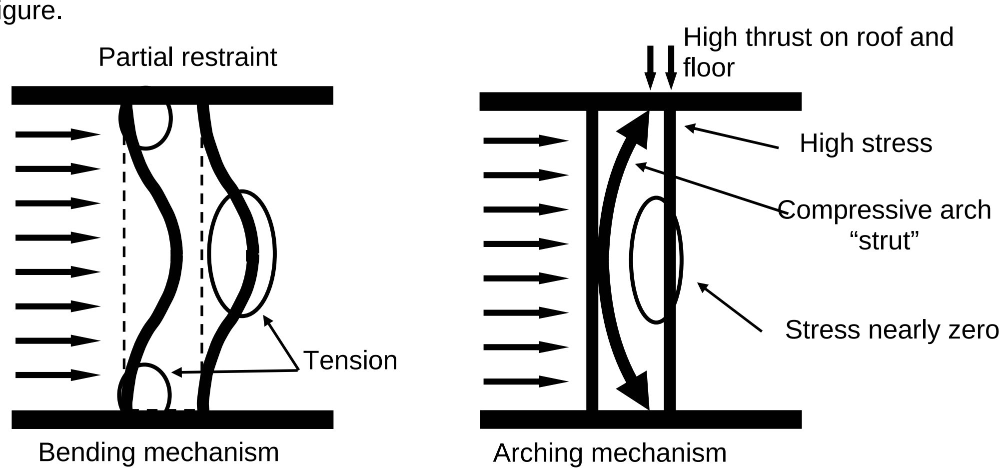

Figure 14. Structural mechanisms for 325 mm seal

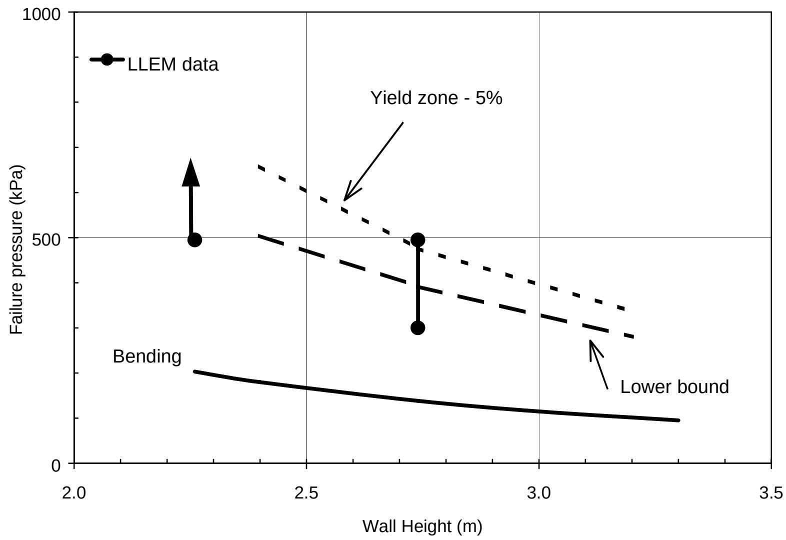

Figure 15. Capacity of 325 mm seal (50 MPa concrete): computed results and LLEM test results

The capacity of the bending mechanism is seen to be about 35 percent of the arching capacity. Test results (LLEM) for 2.74 m and 2.26 m walls are also shown on Figure 15. The lower value indicates the highest pressure that the wall was observed to withstand. The upper value is the measured pressure that caused destruction of the wall. The 2.26 m wall was not tested to destruction. The test walls have clearly withstood pressures greater than the capacity of the bending mechanism indicating that the arching mechanism has occurred occurring in the tested walls. The results of the numerical analysis and the test results agree well. A comparison of the calculated and measured mid height deflection is shown in Table 3. The measured deflection is considerable larger that the finite element prediction. This Finite Element prediction however assumes rigid floor and roof supports. As discussed above about 1.3 mm movement at the floor and roof will result in 6 mm mid-span deflection. The measured value may indicate some deviation at the structure-support interface from the ideal assumptions of the finite element analyses. The magnitude of the deflection confirms arching as the principal method of load transfer to supports.

TestSafe explosion chamber

The explosion chamber at TestSafe is a 2.7 m internal diameter concrete tube with a wall thickness of 150mm and as such the maximum height of the wall that can be constructed is 2.4m. A finite element model of a 325mm seal and the explosion chamber was developed to analyse the effect of these more flexible support conditions. Figure 16 illustrates the arrangement. A static pressure was applied to the wall and the inside face of the test chamber on the left hand side of the wall. The wall was tested up to 140 kPa.

Further numerical analysis indicates that the distortion of the concrete tube will prevent significant arching from occurring in the seal in the test safe explosion chamber. The capacity of a seal in the test safe chamber is likely to be closer to its bending capacity. The development of some thrust in a seal would lead a combined failure mode. The theoretical bending capacity of the test wall is about 160 kPa. The finite element method was not used to predict the ultimate capacity of the seal in the TestSafe apparatus because of uncertainty about the actual physical condition and stiffness of the tube which provides the essential restraint to the seal.

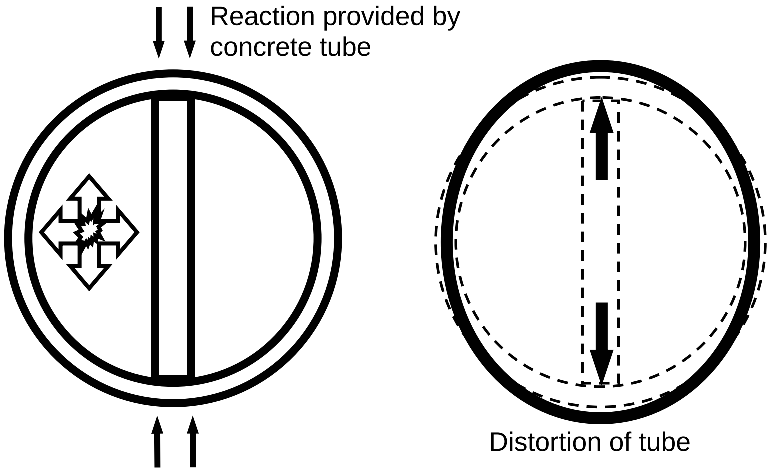

Figure 16. Arrangement of seal in TestSafe explosion gallery

Effect of floor convergence

In an underground situation, floor, roof and wall convergence after construction may add significant compression stress to the seal. The capacity of the seal may therefore be reduced since less pressure will be required to increase the concrete stress to its failure level. Convergence-induced stresses in the seal are affected by creep of the concrete. It is possible that convergence of the roof and floor induce a curvature in the seal. If the convex side of the seal is towards the explosion the ultimate capacity of the seal could be increased. Alternatively, if the concave side is towards the explosion the ultimate capacity will be further reduced. The effects of floor and roof convergence, changes in geometry and material creep can by analysed using finite element methods.

Table 3. Mid-height lateral displacement (mm) at Pressure = 140 kPa

	Measured	Finite element (rigid supports)	Finite element (gallery modelled)
LLEM - height, 2.74m	6.6	0.6	-
TestSafe - height, 2.40m	7.2	0.4	4.9

Soft rock or coal roof

The stiffness and strength of the floor and roof supporting material is important. Finite element analysis can be extended to include the stiffness and strength characteristics of the support material. Analysis of this would indicate whether failure occurs in the supporting material or the concrete wall.

Structural Response of 40 mm Stoppings

There are two possible mechanisms in which the 40 mm stopping is able to resist the applied load - cable action and bending. The 40mm stopping has insufficient depth to develop the arching mechanism described above for the seal. The bending mechanism is the same as for the seal. Deflection occurs as shown in Figure 17. If the deflection is large the change in geometry requires the wall to stretch which results in tensile forces in the stopping. If the material is ductile, sufficient deflection can occur such that a tensile or cable mechanism is developed. The concrete with fine mesh reinforcement spans laterally between the anchored ties. In the cable mechanism the tensile forces in the wall rather than the bending mechanism are more significant in resisting the applied load.

The cable mechanism is stiffer than the bending mechanism. Its stiffness (load/deflection response) increases as the wall deflection increases. Therefore this mechanism is non-linear. This mechanism imposes very large tensile forces at the anchorage points in the roof and floor. It relies on the anchors having sufficient pullout strength. The strength of the wall in this mechanism is limited by the tensile strength of the wall (or the anchors) or the tensile strength at details such as at laps in reinforcement. Failure of the wall occurs when the tensile capacity is exceeded at some location. The capacity in the bending mechanism is typically much less that the capacity of the cable mechanism.

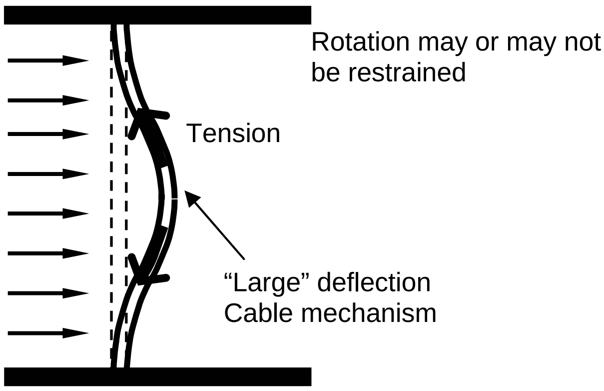

Figure 17. Large deflection cable mechanism

The design of the 40mm stopping consisted of 24mm reinforcing bars lapped near the top and bottom of the wall. This design is difficult to model using conventional models of reinforced concrete. Accurate prediction of the ultimate capacity is not possible with current models. The principal reason for this is that the strength and deformation characteristics at the laps are unknown. These could be obtained by laboratory testing. Observations of test walls (both LLEM and TestSafe) indicate the capacity of this design is limited by the tensile strength of the lapped bars at the laps.

TestSafe explosion chamber

Table 4 gives a comparison of the measured data from LLEM and TestSafe.

Table 4. Measured data 40 mm stopping

	Pressure (kPa)	Mid height displacement (mm)	Capacity (kPa)
LLEM, height 2.10m	23	13.2	23 - 39
Test Safe - height, 2.40m	18	25.5	18 - 23.5

Effect of floor convergence

In an underground situation convergence of the roof and floor induce a curvature in the stopping. Because of the slenderness of the stopping it is unlikely that any significant compressive stress would be induced. The effect of floor convergence is likely to increase the capacity of the cable mechanism.

Structural Behaviour Conclusions

- The response of seals and stoppings to dynamic loading is largely independent of inertial effects. Even though the loading is dynamic and the response of the structure varies with time, the response can be predicted by static analysis.
- Seals and stoppings can be designed using advanced but conventional analysis tools.
- Seals and stoppings could be tested to failure in static tests (either in situ or in laboratory). A laboratory test rig would require careful design to ensure the correct stiffness of support.
- The conditions that might exist on site are likely to vary within a mine and between mines. It follows that an empirical approach to design (ie. design by testing) is not a practical way of ensuring adequacy of stoppings and seals. A better approach is to use occasional testing to verify analyses. Once sufficient confidence has been established, the need to test will reduce.
- As discussed, for the 325mm seal, the test capacity in the TestSafe chamber is expected to be less than that from testing at LLEM.
- A comparison has not been made for the 40mm stopping but test capacity at TestSafe could be expected to be similar to that at LLEM because pressure to cause failure is relatively low.
- Unless site conditions match the test conditions (stiffness and strength of support) there is no guarantee that a test result will indicate the capacity of the wall in situ. This is particularly so for seals which rely on arching.
- The industry should look towards the further development of computer models and static test procedures.

CONCLUSIONS

There is no doubt that the introduction of Queensland regulations has forced attention on the use design and installation of stoppings and seals. Based on the survey results, mines across Australia have improved the quality of stoppings and seals installations in recent years. Australian seal and stopping manufacturers operated in a competitive market and provide the range of products available in the US. US stopping and seal general practice is the same as that being implemented in Queensland in terms of provisions for sealing completed goaf blocks against Mains. However, other US approaches in use of stoppings and seals significantly differ to current Queensland practice.

The physical test program was able to produce data that characterised the nature and degree of differences between the TestSafe tests and the LLEM tests. However, it should be understood that these data represent a comparison based upon only one kind of seal/stopping design (steel re-enforced shotcrete). Caution should be exercised in extrapolating these differences to other seal/stopping designs. The project has justified the decision by TestSafe to provide a testing service for stoppings but not to undertake testing on high-pressure seals until a proper comparison was made between TestSafe and LLEM. The availability of this limited test service has led to considerable innovation in stopping design and has improved levels of safety, economy and compliance throughout the whole industry.

TestSafe has undertaken explosion tests on about ten stoppings over the last 2 years. This testing was provided at less than 15 percent of the cost that it would have been if conducted at LLEM. This has been achieved within the framework of full-scale type tests conducted by an experienced, competent and independent Australian testing authority.

The Structural Behaviour analysis has clearly highlighted the potential benefit in applying known engineering principals to the design of internally steel reinforced shotcrete seals and stoppings. The properties of reinforced concrete are well understood and choosing this type of seal greatly simplified the process of comparing TestSafe to LLEM. However, there are quite a range of designs of seals and stoppings currently in use. Some designs are a complex sandwich of composite materials, others are low density crushable non-reinforced foamed concrete. These designs respond to the pressure load in a more complex way than does the reinforced shotcrete designs tested as part of this project. Faced with this complexity in material properties and design, it is unlikely that full scale explosion type testing can be dispensed with.

The structural behaviour component of this research has shown that internally steel reinforced shotcrete seals can be reliably designed. There are many areas within the coal mining industry where type approval is undertaken on full-scale prototypes before the product can be used underground. Typical of these are personal protective equipment, electrical equipment for hazardous areas and conveyer belting. Full-scale explosion tests on VCDs provide a means by which an independent testing authority can apply a constant and agreed benchmark test for all designs. It is also a process by which a manufacturer's design, construction competency and choice of materials can be assessed in one test.

It needs to be emphasised that the computer simulation explosion modelling was undertaken in two dimensions only and is using highly intense computer generated explosion impulses that cannot be reproduced in reality. They tend to exaggerate possible pressure irregularities but are very useful for diagnostic and qualitative purposes. The modelling shows that simple test geometries produce simple pressure histories that are easy to interpret from a testing point of view.

Overall there have been some significant achievements as a result of this research. This project has led to a greater understanding of the physical requirements for full scale explosion testing of seals and stoppings, the current usage of seals and stoppings in the NSW and Queensland coal mining industry, the context of the current Queensland standards in relation to the US regulatory environment. The project has demonstrated that the expertise exists within Australia to conduct explosion resistance type testing of VCDs, and to undertake research in this field, that the TestSafe explosions gallery can be used to conduct full-scale explosion type testing of low-pressure stoppings and results obtained correlate reasonably well with LLEM, and the potential limitations of the current TestSafe Explosions Gallery for high-pressure tests on seals.

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