DESIGN AND TESTING OF A RATED FLEXIBLE MEMBRANE STOPPING

Verne Mutton [1], Naj Aziz [2] and Robert Hawker [3]

ABSTRACT: The introduction of flexible explosion rated stoppings has become an item of interest to many supply, contract and mining companies in the last few years. These ventilation devices are characterized by the fixing of various fabrics with direct bolt attachments to the mine roadway perimeter. They are often rated through design calculations rather than practical assessment of the system for load carrying capacity. These design calculations are often based on the tensile capacity of the fabrics and assume full distribution of load over the entire cloth surface which is impossible to achieve in practice. The potential limitations that may exist with flexible stopping systems through Minova Australia's experience in the development of its Flexi-Stop ventilation stopping is described.

INTRODUCTION

During the course of underground coal mining, it sometimes becomes necessary to install stoppings to separate the air paths in the mine. In order to fulfill this function efficiently, the stopping must have minimal leakage over its intended life. Underground mining imposes a variety of conditions on the stopping such as fluctuations in ventilation pressure, changes in the boundary conditions due to movement of strata, impoundment of water and changes in atmospheric humidity. Stoppings have been constructed of either cementitious based products including cement based shotcrete, Gypsum plaster, ash bricks and stoppings consisting of props, wooden battens and plasterboard. Stoppings can be damaged by strata convergence and are often difficult to repair in order to minimize leakage. Severe damage often necessitates complete replacement which is difficult when personnel inbye require ventilation air. Many of these stoppings are required to possess an explosion rating. Legislation introduced in Queensland in 1993 required that stoppings be able to withstand pressures of 14 kPa (2 psi) and 35 kPa (5 psi) under the guidelines of the Queensland Department of Mines and Energy's "Approved Standard for Ventilation Control Devices". Some mines in New South Wales have adopted the same standards for stopping installation.

Minimization of leakage through the coal ribs is also an important issue that sometimes requires treatment with strata injection and effective bolt support. Strata support in cut-throughs has not been as rigorously treated as gateroad support for economic reasons and this has often affected the long-term performance of stoppings in terms of structural integrity and air leakage. However, rib support has become part of the stopping design system in recent years. Minimization of strain softening in the roadway will help in the performance of any stopping design.

The flexible stopping concept allows for strata convergence and has many advantages over a conventional rigid stopping. Depending on the design, it can be installed temporarily and can be unbolted and hung to the roof if renewed access for men and materials becomes necessary. The Flexi-Stop design can be installed where high ventilation pressure differentials exist. It is possible to transport many stopping kits in a conventional materials pod whereas other rigid designs require large material weights and volumes with a greater component of manual handling. Depending on the design, these stoppings offer productivity gains to the contractor or mine installing them with potentially up to three being installed per shift.

In 2002, Minova Australia embarked on a test program of flexible stopping designs that was based on evaluation of the response to both static and dynamic pressure testing. Initially static testing of various cloths

[1] Senior Mining Engineer, Minova Australia Pty Ltd
[2] Associate Professor of Mining Engineering, University of Wollongong
[3] Product Manager, Minova Australia Pty Ltd

was undertaken at the School of Civil, Mining and Environmental Engineering, University of Wollongong (UOW). This research program evaluated the static load response of a stopping design. Results from this testing gave confidence to undertake dynamic pressure evaluation at the National Institute of Occupational Safety and Health's testing facility at Lake Lynn Experimental Mine (LLEM), PA during November, 2003. These stoppings were designed to resist an explosion pressure of 14 kPa (2 psi) and 35 kPa (5 psi) and were evaluated in a range of pressures from 19.6 to 42.7 kPa (2.8 to 6.1 psi).

These research programs focus on the ability of particular stopping designs to maintain their structural integrity whilst being subject to a specific methane or methane and coal dust explosion. A series of controlled explosions of successively increasing magnitude provided data that can be used to optimize future seal designs in terms of strength and the economics related to material usage and installation times.

The installation methods, static load results and the explosion test results associated with the Flexi-Stop flexible stoppings are presented in this report. Measurements of stopping response to both static and dynamic load are summarized in tabular format.

STATIC LOAD TEST PROGRAM

Static load testing of the stopping system was conducted in three separate programs. This testing series documented the static load results achieved on four fabric types referred to in this paper as Fabric A, Fabric B, Fabric C and Fabric D. The aim of the test series was to achieve a static load equivalent to 14 kPa (2psi).

Each static load test was conducted by fixing the fabrics inside a purpose built steel frame manufactured from "I" beams. The internal dimensions of this steel frame were 4.0m x 2.7m with the steel frame designed for a maximum static load capacity of 19.6 kPa (2.8 psi), which is equivalent to 21.5t.

The frame was located in a horizontal position above the lab floor and supported using a combination of concrete blocks and steel props 1m from floor level.

The fabric loading was carried out using a 70t capacity hydraulic jack mounted at the centre of the load frame. The ram was powered by a Rexroth 630 ATO pressure pack with the applied load monitored by an Interface Model 24/HL load cell. Figure 1 details the frame assembly and load testing position.

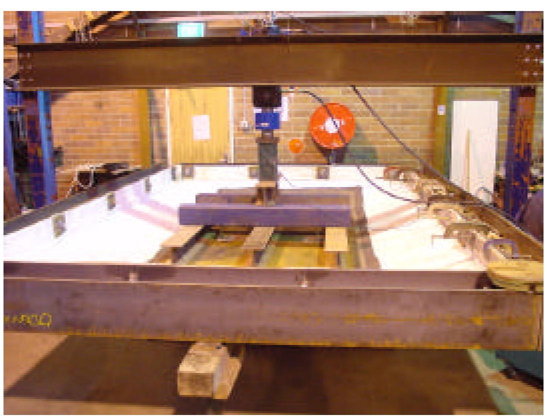

Fig 1 - View of the testing frame with Fabric A attached.

The first test program involved the static load testing of Fabric A and Fabric B. Fabric A was a white PVC non-woven fabric of thickness 0.45mm and tensile strengths documented as 40 kN/m. Fabric B was a green canvas type fabric of thickness 0.65mm with no documented strength characteristics. Both fabrics were fixed to the steel frame by wrapping the periphery of the fabrics around 150mm wide wire mesh (aperture size 50mm x 75mm) then bolting to the steel frame using 150mm square steel plates and 20mm diameter bolts. In addition to this, plywood and G clamps were used to further distribute load of the cloth around the frame perimeter. Figure 1. shows Fabric A loaded into the test frame.

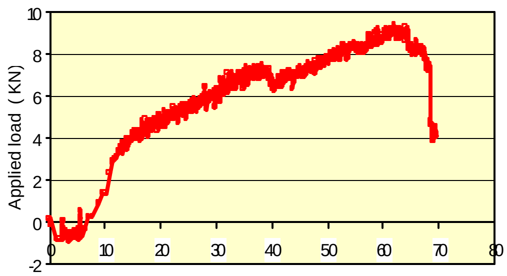

Fig 2 - Hydraulic jack load vs ram displacement

Loading of Fabric A commenced with the placement of 1112.10 kg of weights. It was evident during the placement of these weights that the fabric was unevenly loaded. This uneven tension was further evident during loading via the hydraulic ram, which eventually led to failure of the fabric at a total load of 2032 kg, which was well short of the desired load needed to achieve 14 kPa (2psi). Figure 2 shows the Hydraulic jack load vs the ram displacement. Fabric B also exhibited uneven loading with failure occurring during placement of the weights at 661kg.

Both Fabrics exhibited failure at the anchor plate zones located in the central positions on the long span section. This failure was due to point loading of the fabrics at these points and characterized by initial puncturing of the fabric then tear propagation of the fabric around the plate zones. Figure 3. shows the failure of Fabric A around plate zones.

Fig 3 - Fabric A failure at plate zones

It was evident from the first test program two issues needed to be addressed for a 2psi load rating to be achieved. The first of these was the effect of uneven load distribution concentrated around the plate zone. This effect was hoped to be overcome through either a more efficient load transfer system or higher tensile strength fabric. The second consideration was tear propagation of the fabric once puncturing of the cloth had occurred.

As a consequence of the results achieved during the first test program Fabric C was selected for the second test program. Fabric C was a composite fabric consisting of a high tensile strength geogrid backed by a non woven fibrous mat. The tensile strength of Fabric C was 26.5 kN/m. No tear strength data was available but it was thought the composite nature of the fabric would offer improved tear propogation resistance.

Fabric C was again fixed in the same method as Fabrics A and B however a thin sprayable liner (TSL) Tekflex was used to seal the fabric around the perimeter. It was anticipated that the TSL would be later used as the sealant for Fabric C thus the reason for its inclusion in the load test.

Uneven loading was again seen during placement of the weights at a value of 1050kg. This weight was actually increased during the loading test due to the addition of spacers placed between the hydraulic jack and the loading frame. Spacers were required during the ram loading due the vertical displacement of the fabric exceeding the jack pistons stroke length. The final weight of 1089.5kg was added before applied ram load.

Several stages of failure were evident during the test program including tearing of the TSL, snapping of the geogrid around the plate zones and tearing of the fibrous mat around the plate zones. A total load of 7900kg was achieved during the test with a vertical displacement of 300mm. Figure 4. shows the three failure events seen during the test. Figure 5 shows the hydraulic jack load vs the ram displacement for the test program 2.

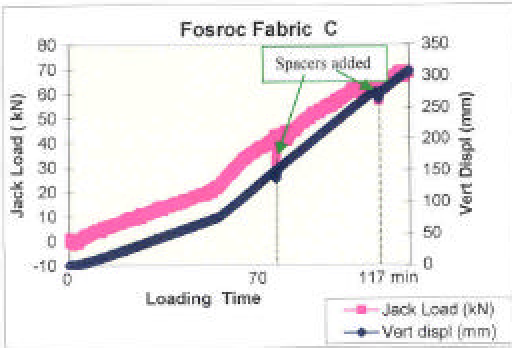

Fig 4 – Jack load and FFC sagging versus loading time

Fig 5 – 280mm laterial width of the torn felt around the central plate @ 68 kN load (total applied load – 0.795t)

Although a significant improvement in load had been achieved the result was still well short of the required 15.5T needed for 2psi. To overcome point loading at the plate zones, across the short span, a different fixing system was required and a higher strength single component fabric.

Test program 3 involved the testing of both these items with Fabric D selected for the test work. Fabric D was a PVC coated ultrahigh tensile strength woven fabric with weight of 2kg/m, thickness of 1.7mm and tensile strength of 200kN/m. Initial in-house testing by fixing Fabric D in a steel slot structure indicated that even distribution of load could be more effectively achieved. Figure 6 and Figure 7 detail the test work and slot method used to achieve loads of 7000kg/m. Based on this result it was thought that over the 4m length of the loading frame a load near 28t could be achieved and would give greater confidence to undertake further testing at UOW.

Fig 6 - In house testing of fixing system and Fabric D

Fig 7 - Slot fixing system

The final test program involved fixing fabric D using the slot system along the 4m length of the testing frame and bolting the cloth using square steel plates with rubber washers along the 2.7m lengths. This test program was completed in two sections due to early failure of the slot fixing system in the first section. Adjustments were made to the steel grade of the slot and the method used to hold the fabric in the slot. Section 2 involved loading of fabric D with the same method as for the previous fabrics tested with the addition of sand to further distribute load. After placement of the initial 2226kg of weight it was evident the load was more evenly distributed along the 4m length. During testing additional gussets were added to bond the slot to the test frame and stop bending of the slots. Further timber posts were also added to support the test frame as buckling of the 4m length was beginning to occur. A maximum load of 20.371 t was applied to the cloth, equivalent to 2.71psi and near to the 2.8psi static load capacity of the test frame. Figure 8 details the Hydraulic jack loads and vertical displacement of Fabric D during the section 2 tests. Figure 9 details Fabric D fixed in the test frame during loading and Figure 10 shows the tests frame buckling under load.

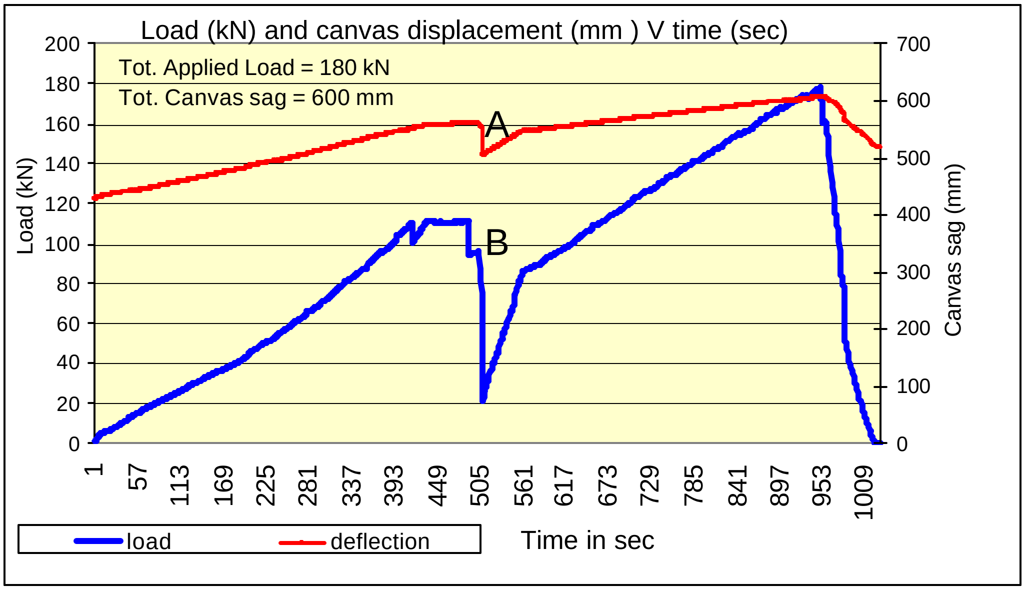

Fig 8 - Hydraulic jack load vs vertical displacement for Fabric D

Fig 9 - Fabric D load distribution in slot

Fig 10 - Buckling of the test frame under load

EXPERIMENTAL MINE AND TEST PROCEDURES

LLEM is one of the world's foremost laboratories in conducting large-scale explosion testing of seals and stoppings and the test area is designed to withstand explosion pressures up to ~700 kPa (~100 psi). Figure 11 shows an expanded view of the stopping test area in the multiple-entry section of LLEM.

Two Flexi-Stop stoppings were constructed in cut-throughs 6 and 7 between B- and C- drifts. There were already seals in the first three cut-throughs from the simulated face and concrete block stoppings in cut-throughs 4 and 5. Before each explosion test a hydraulically operated, track mounted, concrete and steel bulkhead was positioned across E-drift to contain the explosion pressures in C-drift.

Four full-scale explosion tests were conducted in LLEM C-drift in November, 2003. These gas explosions were designed to provide an increasingly higher pressure pulse on the stopping designs during each subsequent test.

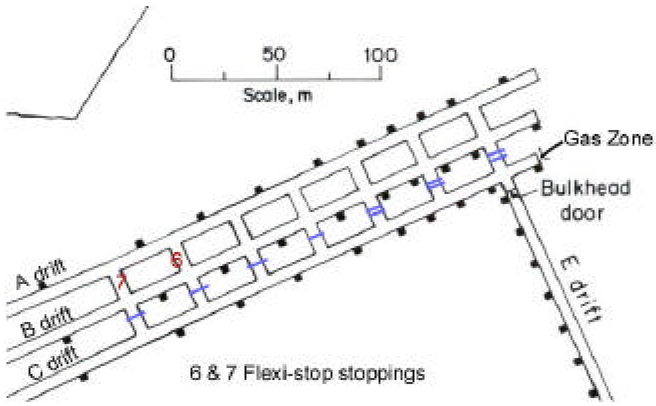

Fig 11 – LLEM Layout

The Flexi-Stop flexible stopping designs were located in cut-through 6 at 167.6 metres and cut-through 7 at 197.8 metres from the face of C-drift. Refer to Figure 11 for details.

For first two tests (test 459# and 460#) a clear plastic diaphragm blocking off C-drift contained the natural gas and air mixture within a 3 m deep by 3.7 m wide ignition zone (~27m^3). For the last two tests (tests # 461 and # 462), the methane-air ignition zone was extended out to 8.2 m from the face forming a gas volume of ~78.3 m^3. A circulation fan inside the ignition zone ensured uniform mixing of the methane-air mixture before the explosions were set off. For tests 460# and 462#, the circulation fan remained operating during the ignition process to provide turbulence and more rapid flame development. The electric match, used as the ignition source, was placed either mid-width within the zone and 0.9 m outbye the face near the door (test # 459) or at mid-height and mid-width near the face (tests 459# - 461#). Double point ignition (one electric match near the center of the face and one located near the right inbye corner) was used during test # 462. Pressures generated were lower when ignition was further outbye the face because the explosion would vent outward as it burned towards the face

As the explosions travel towards the stoppings down C-drift the static pressure was measured at a transducer ~ 4 metres from the face.

INSTRUMENTATION

Each drift has ten environmentally controlled data-gathering stations inset in the rib wall. Each data-gathering station houses a strain gauge pressure transducer that is perpendicular to the entry length (and explosion gas flow) and therefore measures the static pressure generated by the explosion. Pressure transducers were located on the C-drift rib at locations 152.7, 182.3 and 230.7 metres from the face near the Flexi-Stop locations. Most of the pressure transducers were rated at 0-100 psia, with 0-5 V output, infinite resolution, and response time less than 1 ms. A few 0-50 psia transducers were also used.

Although the pressure transducers measured absolute pressure, the local atmospheric baseline pressure was subtracted from the outputted data traces, so that they were gauge pressure values. For some of the explosion tests, the static pressure pulses exerted on each stopping were measured by interpolation of the data from the two nearest C-drift pressure transducers, one inbye and the other outbye the crosscut position. Additional pressure transducers were installed on the C-drift (explosion side) side of the stopping in crosscuts 6 and 7. These transducers were suspended approximately 0.45 m from the mine roof and were located about 0.3 m in front of each stopping. These transducers were positioned perpendicular to the stoppings. The pressure data recorded by these transducers measured the total pressure (combination of static and dynamic pressures) generated on the stoppings during each of the explosion tests. A similar transducer was also mounted from the mine roof ~ 3.3 m behind each stopping on the non-explosion side (B-drift). These B-drift transducers were positioned parallel to the stopping or perpendicular to the explosion path thereby recording only the static pressures caused by any gas flow or air displacement.

The data gathered during the explosion tests were relayed from each of the data-gathering stations to an underground instrument room off C-drift and then to an outside control building.

A high-speed, 64-channel, PC-based computer data acquisition system (DAS) was used to collect and analyze the data.

This system collected the sensor data at a rate of 1,500 samples /s over a 5 s period. The data was then processed using LabView software and presented in graphic and tabular format. The reported data were averaged over 10 ms (15 point smoothing). This PC data analysis system allows the data traces to be expanded in time and pressure (or other sensor value) so that the peak values can be read and recorded precisely. Figure 12 shows a pressure sensor mounted on the C-drift side of the Flex-Stop stopping in cut-through 7.

Fig 12 – Pressure Transducer

CONSTRUCTION OF STOPPINGS

Two flexible stopping designs were constructed in cut-throughs 6 and 7 between B and C drifts at LLEM. These stoppings were designed to withstand overpressures of 14 kPa (2 psi) and 35 kPa (5 psi), the higher pressure stopping being installed in cut-through 6 and the lightweight design likewise in cut-through 7. The stopping in cut-through 6 was located ~ 1.7 metres towards C drift as measured from the center of the cut-through; the cut-through 7 stopping was located ~ 2.4 metres towards C-drift.

Alternatively, the crosscut 6 stopping was located approximately 4.7m into the crosscut as measured from the explosion side entry (C-drift); the crosscut 7 stopping was approximately 3.8m into the crosscut. Crosscut 6 had an average height of 2.17m and width of 5.25m (as measured between the rib slot positions); crosscut 7 had an average height of 2.24m and width of 5.12m.

In October 2003 contractors had shotcreted roof to floor rib slots into both stopping sites using the dry application process. These slots were of 20 mm in width and 200 mm in depth. The roof section of each site had been smoothed with shotcrete. The floor of the roadways was a pad of reinforced concrete laid onto a gravel base overlying the limestone. Figure 13 shows the B-drift side of cut-through 6 stopping cloth being wedged into the shotcreted slot.

Figure 13 – Rib Strengthening

The cloth used in each stopping was Fabric D as tested at UOW. The cloth was pre-cut to an appropriate size depending on the dimensions of the opening being used. Each stopping was pre-assembled on the floor. The sewn edges of the cloth forming the roof and the floor formed a loop into which was inserted a steel pipe. The cloth along with the inserted pipes was fed into the slotted RHS steel sections intended to hold the roof and floor sections of each stopping. Each RHS section (top and bottom) had 6 evenly spaced pipes welded to provide a means to anchor the RHS section to the mine roof and floor using 25 mm diameter by 660 mm length resin bolts.

These bolts were embedded 560 mm into 35 mm diameter drill holes and were fully encapsulated. The roof to floor span of the cloth was intentionally oversized so as not to create a pretensioned surface. The cloth material was anchored to each rib by inserting it into the slot and hammering in wooden wedges at regular intervals. Refer to Figure 13. Minova's thin sprayable liner, Tekflex, was then spray applied to the entire stopping periphery. The equipment used for the spraying consisted of a mixer, pump, hoses and a 40 cfm compressor to supply air to the spray nozzle, all in a self contained module.

Following the first explosion test (# 359), 4 (for cut-through 7) and 5 (for cut-through 6) equally spaced 25 mm diameter by 400 mm length resin bolts were installed through the cloth material and into each rib (embedded 300 mm) on the C-drift side of the rib slots. Figure 14 shows the finished stopping in cut-through 6 and Figure 15 shows the finished stopping in cut-through 7. Note the curve in the roof profile of cut-through 7 shown in Figure 15.

Fig 14 – Finished stopping cut-through 6

Fig 15 – Finished stopping cut-through 7

The stoppings were constructed under conditions analogous to those encountered in an underground coalmine. Because the concrete floor slab in each cut-through had been laid on gravel its stiffness would influence the ability of the stoppings to resist the explosion loads. The under floor aggregate was removed under each bolt hole and replaced with a slurry of gunite. The underground air temperature during the test period was around 11.1^{o}C (52^{o} F) and relative humidity in the range 76-90%.

EXPLOSION TEST RESULTS

A summary of the four explosion test pressures is presented in Table 1, which lists total pressures measured on the C-drift side of both stoppings. Please note that this data is indicative only pending the finalization of a report by NIOSH.

During the first test (# 459) a total pressure of 21 kPa (3 psi) was measured at the sensor immediately in front of the cut-through 6 stopping and 19.6 kPa (2.8 psi) at cut-through 7 stopping. There was little or no damage to the stopping with roof beams and rib slots completely intact.

As mentioned previously rib bolts and square washers were installed in both stoppings before test # 460. During this test a total pressure of 28 kPa (4.0 psi) was measured at the sensor immediately in front of the cut-through 6 stopping and 28.3 kPa (3.9 psi) at the same location in front of the stopping in cut-through 7. On some of the bolts the cloth sheared on three sides of the bolt plates. The rib slots essentially held the stopping rib sections of each stopping in place. The stoppings were essentially intact with no damage to the roof and floor beams and rib slots.

Test #461 resulted in total pressures of 25.9 kPa (3.7 psi) and 25.1 kPa (3.6 psi) on the stoppings in cut-through 6 and 7 respectively. There appeared no further additional damage to either of the stoppings from that observed after test #460.

Test 462# resulted in total pressures of 42.7 kPa (6.1 psi) and 37.8 kPa (5.4 psi) on the stoppings in cut-throughs 6 and 7 respectively. The stopping in cut-through 7 failed when the slot in the roof RHS opened up under the high tension loads on the cloth, letting the cloth go in the central roof portion. This was not an unexpected result for a 14 kPa designed stopping.

The stopping in cut-through 6 failed after the central bolts holding the RHS beam bent and snapped dislodging the upper portion of the stopping.

In all tests the cloth remained intact where it was held within the rib slots. The RHS beams comprising the 35 kPa stopping design did not release the cloth from their slots during the four explosion tests.

Table 1 – Summary of four explosion test pressures conducted at LLEM

Total Pressure kPa (psi)	# 459	# 460	# 461	# 462
Cut-through 6	21.0 (3.0)	28 (4.0)	25.9 (3.7)	42.7 (6.1)
Cut-through 7	19.6 (2.8)	27. 3 (3.9)	25.1(3.6)	37.8 (5.4)

CONCLUSION

Explosion resistant stoppings such as those evaluated in this paper provide protection for coal mine personnel and assets by isolating them from the effects of an explosion that might occur within the workings.

The primary objective was to develop and test a flexible stopping system that would satisfy the requirements of the Queensland Department of Natural Resources and Mines "Approved Standard for Ventilation Control Devices" and to satisfy the requirements of "Coal Mining Safety and Health Regulation 2001, Qld".

The results achieved in both the static test program and the explosion test program have provided confidence to Minova Australia that the Flexi-Stop system satisfies the legislative requirements. The results provide the opportunity of testing to further improve and optimize the Flexi-Stop stopping designs.

Initial testing has shown that even with the use of high tensile and tear resistant cloths point load failure will still occur when steel bolts and plates are used as the fixing medium. To optimize the load bearing capacity of any stopping system using cloth, it is necessary to develop a fixing system that enables the superimposed loads to be more evenly distributed through the cloth. The RHS beam and internal pipe arrangement developed (patent pending) as part of the flexi-stop system has proven to evenly distribute load on the cloth between the roof and floor and has made 2 and 5psi stoppings possible.

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