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GEOTECHNICAL ASSESSMENT OF POLYMERIC MATERIALS AS SKIN REINFORCEMENT IN UNDERGROUND MINES

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ABSTRACT: Current advances in roof support automation require a fast and effective skin reinforcement of underground mine roadways. To satisfy these needs a strong and tough fibre reinforced polymeric alternative is emerging as a logical substitute to the old steel mesh support system. Differences between steel mesh and polymer skin behaviour are investigated. Computational models are utilised to compare these two skin support systems with a view to optimising the performance needed for effective roadway skin reinforcement. In particular, development of a strong and resistant shell that minimises movement along the fractured rock and coal surfaces found between the roof bolt anchors is recommended. A strong surface adhesion and the strength of a reinforced polymer skin can provide the necessary toughening mechanism required to enhance roadway surface support by forming a reinforced polymer/rock surface layer. The fractured rock mass in its undisturbed phase is relatively stiff while confinement stresses exist. However, any dilation that occurs due to displacement along the rough surfaces of the fractured rock causes strata softening, bulking and movement into the mine opening. The polymer skin can provide active resistance to any movement along the fractured rock surface as soon as any movement begins to occur. Even partial de-bonding of the polymer from the rock surface may not significantly disturb this mechanism.

INTRODUCTION

Steel mesh has been used successfully for many years to control friable roof conditions and prevent loose roof and rib material from caving into the roadway. To increase the speed of development rates of underground roadways, automation of the mining process is required. Despite its extensive use, the installation of steel mesh is difficult to automate and many other products have been trialled to take its place. Ideally, the properties of these new products should be similar or better than those of the steel mesh. Most of the Thin Spray-on Liners (TSL) trialled in the mines are weak with slow curing times, and the plastic mesh currently used to support the coal ribs is relatively weak, therefore neither material can seriously compete with steel mesh.

Currently, manually handled steel mesh is still the most widely used product to control friable strata in underground mines, however the automation process requires a suitable product that can replace the steel mesh. Now such a polymer product that cures in seconds and forms an instantaneous strata binder that surpasses the properties of steel mesh is under development at the University of Wollongong.

STRATA REINFORCEMENT SYSTEMS

It is impossible to prevent formation of mining induced fractures, however it is possible to successfully control fractured ground. The fractured rock mass in its undisturbed phase is relatively stiff while confinement stresses exist, however the loss in ground confinement results in strata softening, bulking and strata movement into the mine opening. In general, mining induced fracture surfaces are of an irregular nature and excessive shear displacements along such fractures cause significant strata dilation and therefore excessive convergence into the mine opening. It is common knowledge that reduction of strata movement is desirable for ground stability and therefore 'active' strata reinforcement is essential to minimise fracture displacements.

Historically, wooden props, sprags and arches provided passive roof and rib support that allowed large roof and rib displacements to occur before active resistance to movement was achieved. Such passive systems could not provide effective strata control and large amounts of support were required to control severe ground conditions resulting in slow mining advance and expensive labour intensive support systems that would not be suitable for today's modern high production mines.

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Effective strata reinforcement systems evolved over time with fully encapsulated high capacity steel bolts currently used as the primary reinforcing support, while high capacity cable bolting systems are used as the secondary reinforcement of severely deformed ground. It is essential that good reinforcement must be of a high capacity and stiffness to provide significant resistance to minute fracture movement whether in shear or dilation. Today's reinforcement systems ensure high strata confinement characteristics, low ground movement and superior ground stability in adverse conditions.

Although the success of steel bolts in ground reinforcement is undisputable, skin reinforcement of the mine roadways has not yet been optimised. Steel mesh has proven successful for the control of friable roof conditions but as with the wooden props its role is purely passive in nature. The steel mesh does not provide reinforcement to the strata and is exclusively used to prevent loose material from caving into the roadway.

THE ROLE OF STEEL MESH IN ROADWAY SUPPORT

Steel mesh is normally installed in mine roadways, tunnels and other underground openings where poor strata conditions prevail. Integrated together with the steel bolt reinforcement, the main role of steel mesh is to provide passive confinement to the fragmented rock surface that would normally fall out into the opening. In severe cases the steel mesh can prevent gradual degradation of loose material between the rock anchors where excessive cavities may form and affect the integrity of strata reinforcement.

To investigate properties of steel mesh, numerous testing programs have been undertaken (Tannant (1995), Thompson (2004), Villaescusa (1999) and our team) to quantify steel mesh properties and demonstrate the role of steel mesh in the civil and mining industries. The square or rectangular rock bolting pattern and the alignment of steel mesh wire have a significant influence on the load distribution in mesh. A typical steel mesh consists of 4-5 mm diameter drawn steel wire generally welded in a square or rectangular pattern. When loaded, steel mesh is stiffer in the direction parallel to the wire strands indicating that the row of bolt anchors installed parallel to the mesh wire strands would share most of the strata loads located in line between the bolts. The strata loads experienced elsewhere along the mesh may result in large displacements with some load distributed further away from the point of load application, depending on the bolt anchor pattern.

EXPERIMENTAL MEASUREMENT OF STEEL MESH BEHAVIOUR

The results of tests conducted to date indicate that steel mesh behaviour is complex and requires comprehensive tests and numerical modelling to predict its behaviour. A steel mesh deformation test, designed to allow calibration of the numerical models, is shown in Figure 1, while the ABAQUS computational modelling results for the same load are shown in Figure 2. While the general values of the experimental and model displacements are similar, the experimentally measured displacements were affected by the loading system.

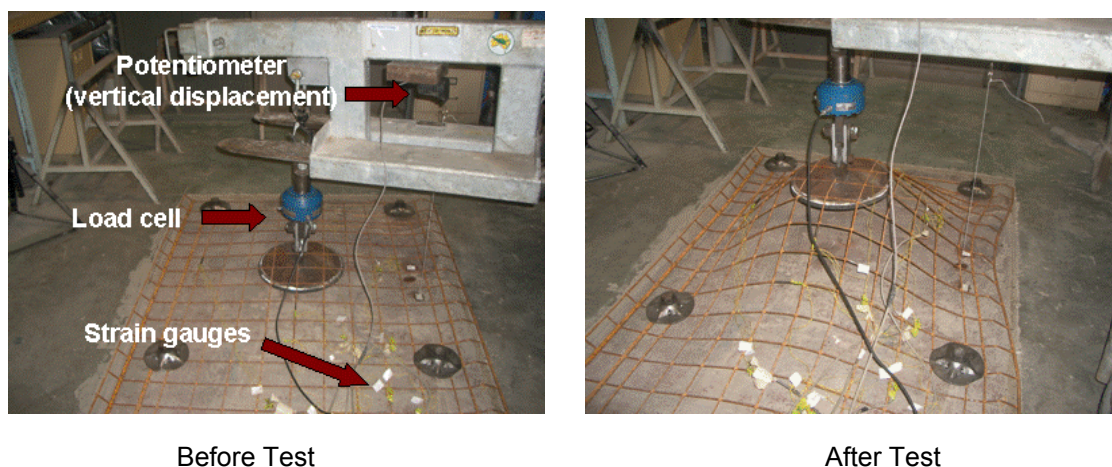
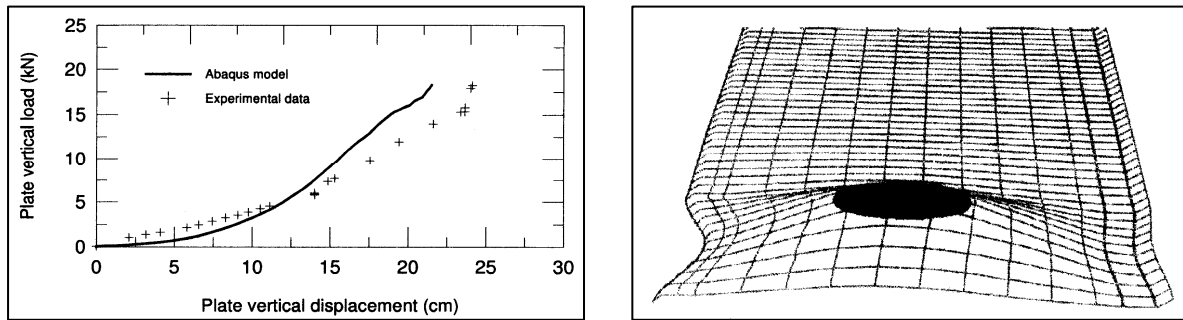


Figure 1 - Deformation Testing of Steel Mesh



Numerical Model

Experimental Data vs Numerical Model

Figure 2 - Numerical Modelling of Mesh Deformation

Both experimental results and numerical modelling involving stretching steel mesh at 45° to the steel strands (Figures 3 and 4) indicate that the mesh can deform easily, accepting strains of approximately 80% before mesh failure occurs. Apart from low stiffness, the ultimate strength of steel mesh welds loaded at 45° to the wire strands is approximately 40% of the wire strand tensile strength. The diamond pattern experienced more than 60% strain at approximately 50MPa when the welds connecting the mesh strands began to deform. The weakened steel wire, now aligned at a lower angle to the “stretch” direction, loaded quickly with welds failing at approximately 220MPa. Note that the typical tensile strength of steel wire is usually more than 500MPa. As expected, the welds joining the steel wire are weaker than the wire itself and can significantly reduce the ultimate mesh capacity if loaded in directions other than the wire strand direction.

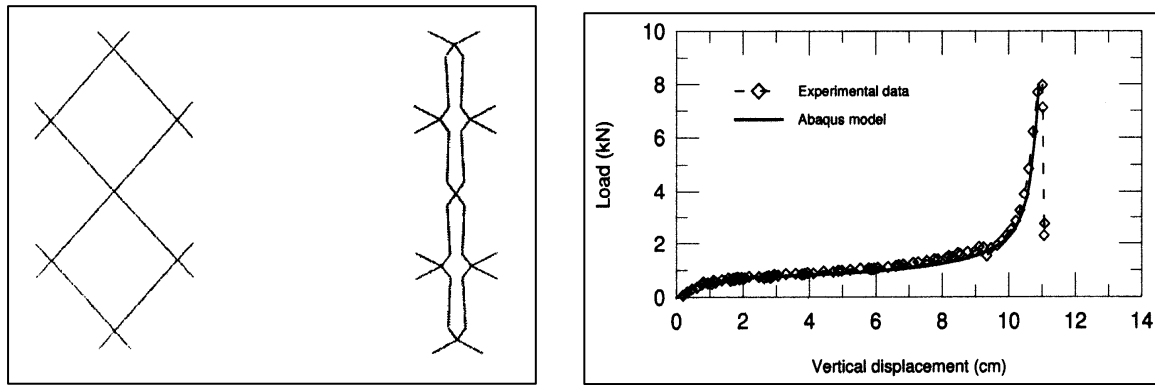


Before Test

After Test

Figure 3 - Steel Mesh “Diamond” Tensile Strength Test

Higher loads can always be expected along the wire strands that directly stretch between two adjacent bolts. These strands are often overloaded and can fail at low deflections. The subsequent loads applied elsewhere within the diagonal area would be expected to produce higher permanent mesh deformation at lower loads. If a mesh failure occurs in line between the bolts, diagonal displacements would follow and the progressive mesh failure would occur wire by wire with mesh deformations similar to those observed in the test described in Figures 3 and 4.



Model of 45° Tensile Test

Experimental Data vs Numerical Model

Figure 4 - Numerical Modelling of "Diamond" Tensile Test

ROCK FRACTURE MECHANISMS IN UNDERGROUND ROADWAYS

Mining induced fractures occur ahead of the roadway face where the stresses are high. These fractures gradually grow, forming a typical fractured roof as illustrated in Figure 5. The fractures develop in response to the elevated compressive stresses that intercept the stress relief towards the mine opening. In other words, while stresses may concentrate across the mine opening, reduction in stress occurs towards the mine opening. Bending of bedded strata that typically occurs in the vicinity of mine openings will result in failure along the weak bedding planes. It is impossible to prevent the development of mining induced fractures, however it is possible to minimise their displacement.

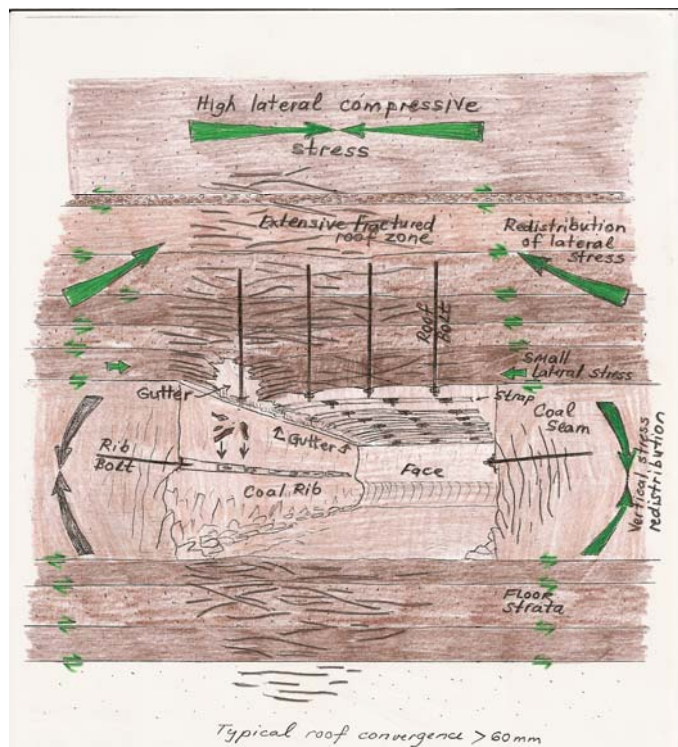


Figure 5 - Typical roof conditions in a mine roadway requiring steel mesh application

In strain softened strata, gradual displacements reduce the virgin compressive stress until equilibrium is reached where the remnant compressive stresses that remain within the strata provide enough confinement to arrest any further movement along the fractures. If the strata are severely broken and the confining stresses are totally dissipated, strata will lose self supporting capability and disintegrate. In particular, large displacements tend to occur when the fractured rock mass is stress free. For this

reason even a small confining stress may be enough to arrest significant rock displacements and falls of "loose" rock material. Just prior to a fall, accelerated fracture displacements and fragment rotations may occur that will "unlock" the rock structure and eventually cause the yielded rock zone to fall. Inadequately supported roadway skin can slowly deteriorate and affect the ground stability between the bolts as illustrated in Figure 6. Ideally, it is the function of the reinforcing members, such as the rock bolt together with the appropriate skin reinforcement, to prevent the last phase of rock de-fragmentation and thus improve integrity of the fractured rock zones.

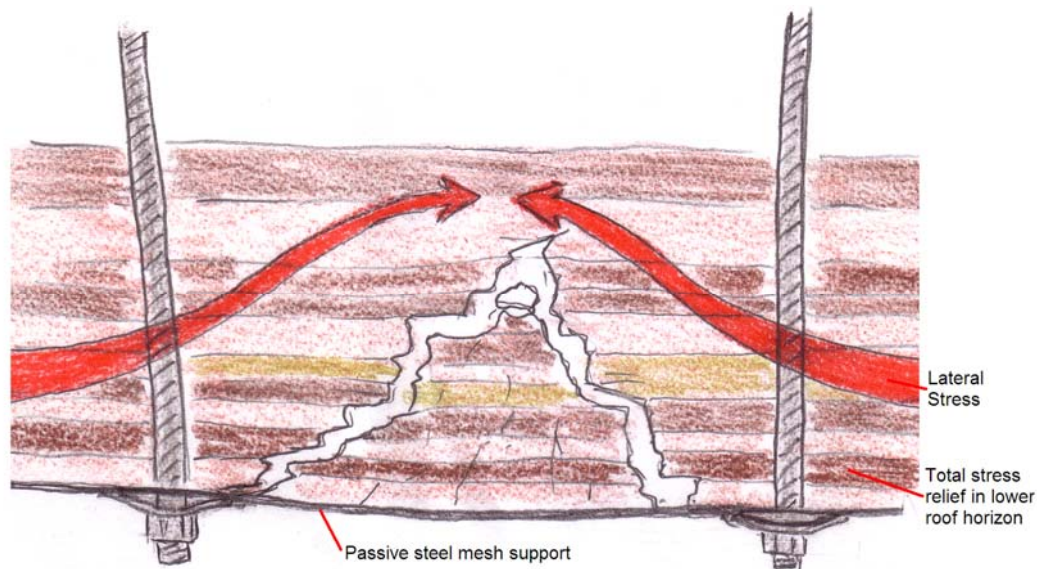


Figure 6 - Partial Roof Failure Between Bolts Affecting Roof Stability

COMPARISON OF THE POLYMER SKIN REINFORCEMENT AND STEEL MESH SUPPORT

The fundamental difference between the polymer skin and the steel mesh support is similar to the difference between a point anchor and a fully encapsulated bolt system. A fully encapsulated bolt provides immediate resistance to any fracture movement via its continuous anchorage to the surrounding strata while the point anchor bolt needs to stretch significantly over its entire length to provide comparable strata confinement. In a similar manner the reinforced polymer skin bonded to the strata surface provides immediate resistance to any crack movement that occurs at the strata surface while the steel mesh will support the strata only after significant roof deformation occurs. The reinforced polymer skin adhesion to the strata provides an additional active reinforcing mechanism to compliment the fully encapsulated bolt reinforcement system and contribute to the overall stability of strata adjacent to the mine roadway.

To investigate the polymer skin reinforcing capabilities, several numerical models were constructed to test the roof response to displacement of fractures in the failed roof. The models were designed to simulate fracture behaviour with dilation and displacement parallel and perpendicular to the fractures. The numerical simulations were done with and without the polymer skin reinforcement.

During the fracture movement two distinct displacement mechanisms occur:

- (i) fracture displacement along its length (shearing); and
- (ii) fracture dilation perpendicular to the fracture plane due to fracture irregularities.

The mechanism of fracture movement can be seen in Figure 7 with combined fracture displacements parallel to the fracture plane and the influence of the fracture asperities on fracture dilation. Other fracture opening mechanisms are also common during strata bending or tension.

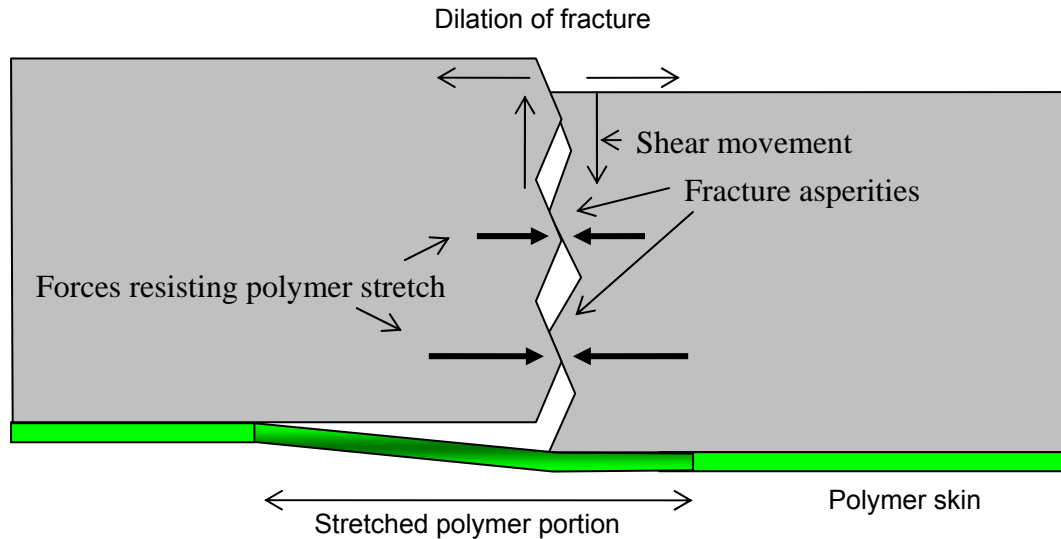


Figure 7 - Shearing and dilation mechanisms of fracture surface

To quantify the influence of both fracture shearing and dilation mechanisms and study the response of polymer skin to these movements, fracture dilation was studied separately to fracture shearing. In the first model shown in Figure 8 the fracture at the rock skin surface was parted perpendicular to the surface with the polymer bond to imitate the effect of fracture dilation (without fracture shearing) that usually occurs during shearing along the fracture plane. Typical fracture dilation is in the order of a few millimetres depending upon the roughness of the fracture surface and the fracture displacement. The numerical model was set up to simulate dilation of a single fracture oriented perpendicular to the polymer layer and the stress response within the strata was studied. The polymer skin was bonded to the rock surface and fracture dilation simulated. In response to the fracture dilation the polymer skin de-bonded in the immediate vicinity of the crack but the strong adhesion to the rock kept the polymer skin anchored a short distance from the crack opening. Opposing the fracture opening, the stretched polymer induced a compressive stress within the rock. The test can be observed in Figure 9.

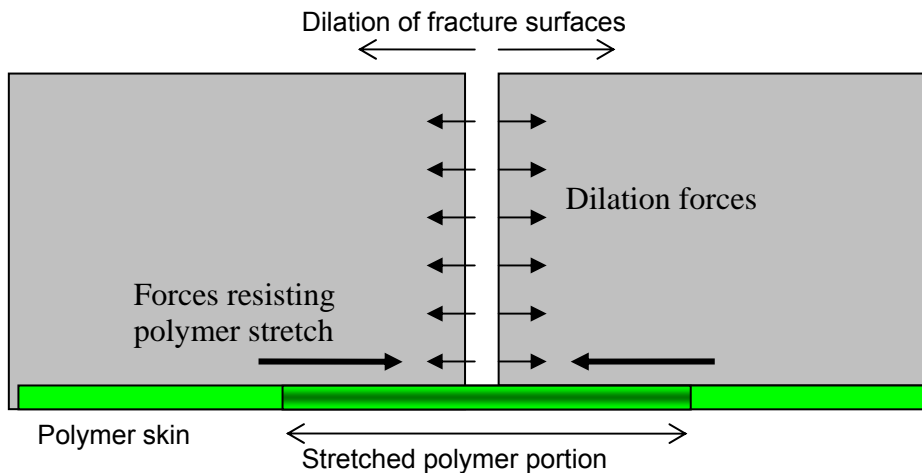


Figure 8 - Dilation mechanism parting the fracture surface

The stress contours shown in Figure 9 clearly show a significant compressive stress normal to the fracture that occurred in response to 2mm of fracture dilation.

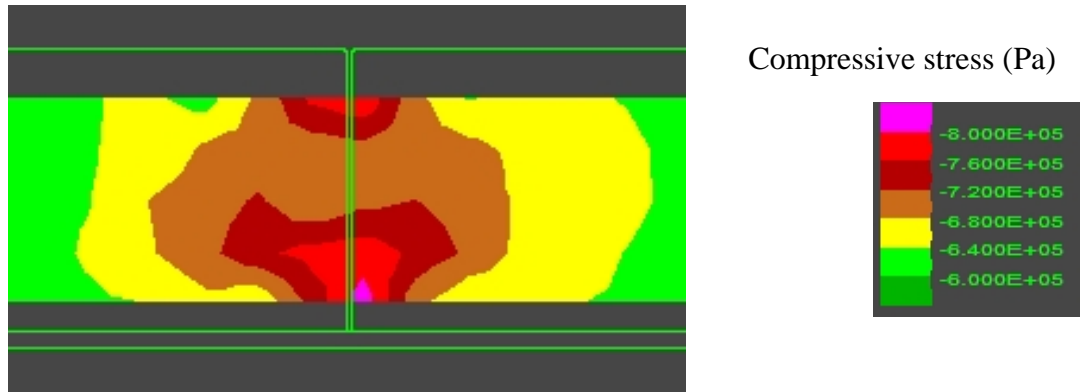


Figure 9 - Effect of fracture dilation on lateral stress across the fractured surface

The magnitudes of stress that develop within the lower roof depend on:

- (i) fracture displacement,
- (ii) polymer bonding properties,
- (iii) polymer stiffness, and
- (iv) polymer thickness.

Further research is underway to quantify the de-bonding length for various values of polymer adhesion and thus determine the total normal fracture loads for a given fracture displacement.

In the second model (Figure 10) a completely smooth vertical fracture was gradually displaced and the polymer skin response observed. During the vertical shearing, strata movement parted the polymer skin away from the rock surface, de-bonding a short section of the polymer/rock interface. The polymer was thus forced to stretch across the fracture as the distance from the bonded anchorage on each side increased. The reaction force at the skin anchorage induced a small compressive stress within the rock across the fracture area, as shown by contours in Figure 11. It is the fracture dilation that in this case produced larger stress across the fractured surface. It must be pointed out that the fracture shearing and dilation are not separate events but occur together and therefore the polymer induced compressive stresses across the fracture shown in Figures 9 and 11 would combine together.

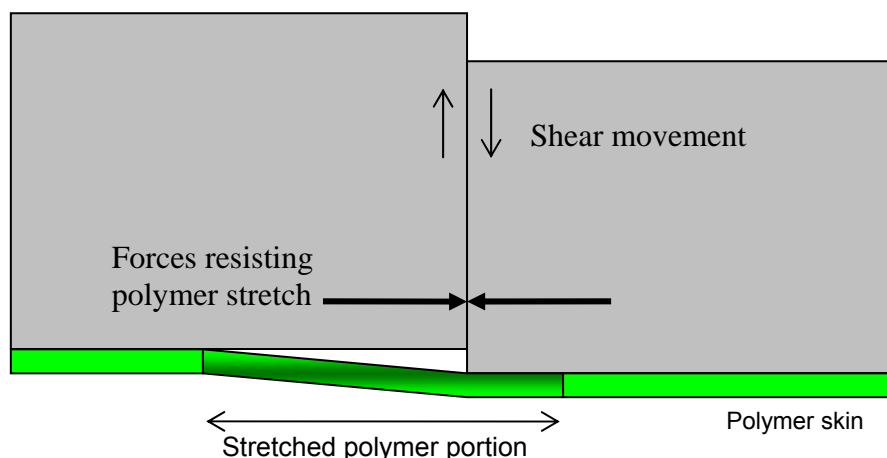


Figure 10 - Shearing mechanism along the fracture surface

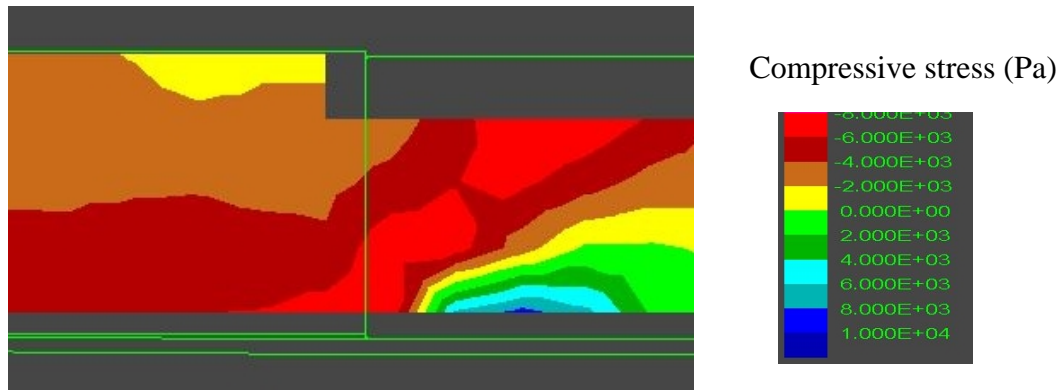


Figure 11 - Effect of fracture shearing on lateral stress across the fractured surface

CONCLUSION

The above investigations indicate that the reinforced polymer may provide a strata skin reinforcement system superior to the currently used steel mesh. Benefits of the polymer skin can come from the ability to adhere well to rock/coal surfaces and provide resistance to strata displacements and fracture opening. The adhesion is not negligible and would have a positive influence on the overall roof support. The reinforced polymer skin is fundamentally a different type of support to the passive steel mesh, providing active resistance to any movement as soon as movement begins to occur. The partial de-bonding of the polymer from the rock surface during fracture movement is unavoidable and may not significantly disturb the polymer reinforcing capabilities. Severe roof movement that may occur in heavily loaded roadways may eventually de-bond the polymer from the fractured rock mass. However, the tough nature of the polymer mesh will further resist the severe strata displacements in a manner similar to that of steel mesh, while the polymer fibre yielding mechanism will give an audible warning reminiscent of the sound made during yield of the old wooden prop system.

Further benefits of the polymer skin include automated application where continuous or intermittent applications of polymer skin of various thickness and patterns are possible. The polymer skin can be applied on the roof and rib strata close to the working face or as required. The fully automated fast setting polymer application can be incorporated together with the automated bolting system with the aim to speed up roadway development and remove mine personnel from the working face area.

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