Fundamental principles of an effective reinforcing roof bolting strategy in horizontally layered roof strata and three areas of potential improvement

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FUNDAMENTAL PRINCIPLES OF AN EFFECTIVE REINFORCING ROOF BOLTING STRATEGY IN HORIZONTALLY LAYERED ROOF STRATA AND THREE AREAS OF POTENTIAL IMPROVEMENT

Russell Frith\textsuperscript{1}, Guy Reed\textsuperscript{2} and Martin McKinnon

\textbf{ABSTRACT:} It is arguable that the development of reinforcing roof bolting systems has largely stagnated in recent times primarily due to the prevailing industry view that few, if any further improvements can be made to the current state of the art. On the contrary, this paper will contend that reinforcing roof bolting systems can be further refined by considering both the specific manner by which horizontally bedded roof strata loses its natural self-supporting ability and the specific means by which reinforcing roof bolts act to promote or retain this natural self-supporting ability.

The Australian coal industry’s seeming insistence on minimising bolt-hole diameter to maximise load transfer and targeting full-encapsulation by any means has led to a significant, albeit unintended consequence in terms of overall roof bolting effectiveness, namely the promotion of increased resin-pressures during bolt installation and the associated potential for the opening up of bedding planes that may otherwise remain closed during the bolt installation process. Given that the natural self-supporting ability of roof strata is strongly linked to whether bedding planes remain open or closed, it stands to reason that minimising resin pressures should be of significant benefit. Three issues are primarily focused on three key issues that relate directly to the function of the roof bolting system itself, namely: (i) the importance of proper resin mixing in the context of maximising load transfer strength and stiffness, (ii) the importance of minimising resin pressures developed during bolt installation and (iii) the importance of maximising the effectiveness of the available bolt pre-tension.

The logic being that if: the reliability of resin mixing with varying hole diameter is substantially improved, if resin pressures generated during bolt installation are substantially reduced, if the length of the bolted interval directly influenced by high resin pressures generated during bolt installation is substantially reduced, and if roof bolt pre-tension levels are increased, why wouldn't individual roof bolt effectiveness and thus roof reinforcement improve?

The potential benefits to the mining industry of improving the individual effectiveness of each installed roof bolt, even by relatively small incremental amounts, should be of interest to all mine operators and is an important topic for discussion amongst the mining community.

\textbf{INTRODUCTION}

The installation of primary roof bolting as part of the roadway development operation is the most obvious “pro-active” strata control process that is available to mining operations. The extent by which primary roof support is installed suitably close to the development face and is geotechnically fit for purpose, sets in place the conditions, good or bad, that will ultimately determine such operational outcomes as triggering of the TARP, subsequent roof deterioration and/or instability and the need or not for high density and expensive secondary or remedial support measures. However in an overall industry context, the effectiveness of primary roof support has received far less attention in more recent times as compared to such areas as geotechnical characterisation, geotechnical design and operational strata management. This paper re-visits the subject area by examining three technical

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areas whereby substantial improvements can potentially be made based on the published findings of a range of research studies and specific testing data.

The development of reinforcing roof bolting in underground coal mining, which is the mainstay of safe and efficient mining, has reached a point whereby the design and set-up of the bolting system can be further refined by considering the manner by which the roof strata loses its own self-supporting ability, reinforcement being the promotion or retention of natural self-supporting ability within the host rock mass. By understanding both the de-stabilising mechanisms within the roof strata itself and the various influences that primary roof bolts have on those mechanisms, the set-up of each installed roof bolt can be optimised to achieve the highest level of individual roof bolt effectiveness. The potential benefits to the mining industry of such an outcome as compared to using less effective bolting systems should be self-evident and requires no further discussion.

Without digressing into a detailed history of roof bolting development over the past 40 to 50 years, it is contended that an optimum roof bolting system needs to incorporate measures that address at least eight fundamental principles of roof reinforcement:

1. The position of bolt installation with respect to the development face (i.e. cut-out distance)
2. Use of an appropriate bolt length and a geotechnically suitable bolt pattern
3. Minimising resin pressure developed during bolt installation in an attempt to minimise any adverse effects on the roof strata within the bolted interval
4. Ensuring proper resin mixing when generating the bond between the bolt and surrounding strata
5. Utilising a resin system with properties that act to promote increased load transfer strength and most importantly, load transfer stiffness
6. Maximising the effectiveness of the bolt pre-tension generated via nut tightening at bolt installation
7. Protecting persons in the mine from any roof material that may detach between bolts
8. Applying an on-going operational process to both correctly install ground support as well as manage and control the inherent uncertainties in the stabilisation of a naturally formed engineering material

Applying these eight fundamental principles leads to various insights as to how a reinforcing roof bolting strategy can be best-optimised, this paper considers in varying detail three issues that relate directly to the set-up of the roof bolting system itself, namely:

(i) proper resin mixing in the context of maximising load transfer strength and stiffness
(ii) the importance of minimising resin pressures developed during bolt installation
(iii) maximising the magnitude and effectiveness of the bolt pre-tension developed at installation

The discussion around each of these aspects will be based on an analysis of how the primary source of self-supporting ability in layered roof strata is retained, how such natural roof stability is lost and the various interactions between installed roof bolts and the occurrence of de-stabilising mechanisms.

**SELF-SUPPORTING ABILITY IN LAYERED ROOF STRATA**

Figure 1 illustrates a simplified representation of the three fundamental sources of roadway roof stability in a layered and jointed rock mass under the action of some level of horizontal stress (UNSW 2010). The three stabilising mechanisms are (i) cohesion between bedding planes, (ii) horizontal stress acting to prevent shear slip along sub-vertical jointing within the roof strata and (iii) some form of “suspension” type support to hold-up a roof mass that does not contain the natural stabilising benefits of (i) and (ii). Without at least one of these mechanisms in place, a major roadway roof fall is an inevitable consequence.
On the assumption that utilising a suspension roof control strategy is not a preferred approach in high production underground coal mining, the critical importance of preventing horizontal separations occurring within the roof strata is self-evident. Firstly the opening up of bedding planes directly causes the loss of bedding plane cohesion (stabilising mechanism (i)) and if sufficient closely-spaced bedding planes open up, it can lead to the *en masse* buckling of the roof strata and an associated reduction in horizontal stress levels (stabilising mechanism (ii)), as explained in detail in Colwell and Frith (2010 and 2012).

A real-world demonstration as to the significance of bedding plane condition to the self-supporting ability of layered roof strata is found in Figure 2, which is derived from the US extended cut database (Mark, 1999) used to evaluate roadway roof stability without roof bolts installed. The two-axes represent the varying compressive strength or UCS of the roof material (x-axis) and bedding cohesion within the roof (y-axis) for each of the database case histories, the estimation of the latter being part of the underground method for determining the Coal Mine Roof Rating (CMRR) as was used in the Mark,(1999) study.

The key feature of Figure 2 is the line or boundary that best separates the “always stable” from the “never stable” cases, as this provides an indication of the relative importance of the UCS of the roof material, as compared to bedding plane cohesion within the roof, to either the retention or loss of natural roof stability (self-supporting ability).

A “by-eye” discriminant line/zone (in blue) is shown in Figure 2 and it is clear that it only “discriminates” between stable and unstable cases according to varying bedding plane cohesion – i.e. lower cohesion (greater than ≈ 3) is linked to “never stable” cases and higher cohesion (less than ≈ 3)
to “always stable” cases. Furthermore the “always stable” cases cover the full UCS range from low to high meaning that UCS is not a reliable predictor of natural roof stability (as described in detail by Frith and Colwell, 2006).

The point to be made from Figure 2 is that the roof almost certainly loses its natural stability or self-supporting ability in line with the opening of bedding planes (termed “delamination”). It logically follows that the higher the level of delamination within the bolted interval, the higher the level of installed roof support that will be required to maintain adequate levels of roof stability (all other factors being equal). Bolted roof reinforcement should therefore be primarily focused on preventing bedding planes opening-up within the bolted interval, with minimising the degree of bedding separation once they are open being a second-order, albeit still relevant, consideration.

The set-up of a reinforcing roof bolting system will be further considered based on the concept that retaining the self-supporting ability of the roof strata is primarily based around preventing bedding planes opening up within the bolted interval, but accepting that if they do open up it is nonetheless beneficial to minimise the level of separation that occurs.

**RESIN MIXING AND MAXIMISING LOAD TRANSFER PROPERTIES**

The entire subject of maximising the load transfer properties of resin-encapsulated roof bolts has been widely researched based largely on both *in situ* short encapsulation pull-tests and laboratory based pull tests and/or push tests. The general outcome of this work, in Australia at least, was that in order to maximise load-transfer strength and stiffness, the roof bolting system should be fully encapsulated and that the annulus between the bolt and surrounding strata should be as small as possible. When considered in isolation, the logic behind maximising load transfer makes logical sense and remains the current norm in the Australian coal mining industry. However, work from New Zealand, published by Campbell and Mould (2003) as well as Pastars and McGregor (2005), found that there was a fundamental problem with the 15:1 ratio (mastic to catalyst) resins systems that were almost universally used in the Australian coal industry at that time, namely they were prone to poor resin-mixing towards the top end of the bolt and also reduced load-transfer due to “gloving” of the bolt via large pieces of plastic film corrupting the integrity of the resin bond between the bolt and the surrounding strata. A combination of both poor resin mixing and gloving was found to give very low load transfer properties, the existence of which is “hidden” from view during normal mining operations and cannot be easily audited or directly monitored. No practical solution was found from this work to overcome these problems using an industry standard 15:1 resin system.

The idea that load transfer is maximised by minimising the annulus between the bolt and surrounding strata was brought into question by the work of Hagan and Weckert (2004). Lab-based pull-testing using a “mix and pour” resin system rather than a “spun through” resin as used in actual bolt installations, showed no discernible difference in load transfer properties, neither strength nor stiffness, for hole diameter variations between 28 mm and 30 mm (see Figure 3). This finding is directly contrary to what had been published in the past (see Figure 4 after Fabjanczyk and Tarrant, 1992), which in hindsight has almost certainly driven the industry practice of using the smallest possible bolt hole diameter (as low as 26.5 mm).
Figure 3: Load v displacement data for roof bolt pull-testing using Mix and Pour resin (Hagan and Weckert, 2004)

Figure 4: Effect of hole diameter on load transfer (from Fabjanczyk and Tarrant, 1992)

The logical conclusion that can be drawn from these independent areas of research is that the effectiveness of resin mixing within a 15:1 resin system is highly dependent upon minimising the hole diameter, this then leading to the common finding with in situ short encapsulation pull test studies, that load transfer increases as a direct function of decreasing hole diameter.
This theory was put to the test as part of ACARP Project C21023 (McTyer, 2015) whereby it was conclusively shown that resin mixing effectiveness for 15:1 resins substantially reduced with an increasing hole diameter from 28 mm to 30 mm, whereas there was little or no such reduction when using a US-style 2:1 resin system (the interested reader is directed to the full project report for the detailed findings). Figure 5 illustrates why this is likely to be the case via a simple cross-section of the bolt hole and the relative cross-section areas and locations of the bolt, mastic and catalyst sections.

From this it is inevitably concluded that the Australian coal industry's seeming insistence on minimising bolt hole diameter to maximise load transfer, is almost certainly a direct function of resin mixing limitations of 15:1 resin systems according to increasing hole diameter. As will become apparent in the next section of the paper, the use of the smallest possible roof bolt hole has a significant, albeit unintended consequence in terms of overall roof bolting effectiveness, namely the promotion of increased resin-pressures during bolt installation, the associated potential for the opening up of bedding planes near the bolt hole and resin losses into the roof strata as a direct consequence.

**RESIN PRESSURE DEVELOPMENT DURING BOLT INSTALLATION**

The entire issue of resin pressure development during bolt installation and its significance for roof reinforcement can be considered based on a combination of:

- resin pressure measurements made during bolt installations by several researchers,
- a theoretical treatment of the key parameters that influence the development of resin pressures,
- common fracture patterns observed within the bolted interval,
- Griffith Crack Theory, and
- published test data showing the clear links between less than theoretical bolt encapsulation being achieved with various changes made to the bolting set-up (e.g. resin volume used and varying hole diameter).

Comments will also be included pertaining to a recently published technical paper (Purcell *et al.*, 2016) which purported to significantly diminish the significance of resin pressures generated during bolt installation to roadway roof stability using a series of technical arguments and roof bolt installation testing results that are judged to contain several fundamental oversights.

An early indication of the significance of resin pressures developed during roof bolt installation is found in Pettibone (1987) whereby the fracturing of 31 MPa concrete blocks is reported as a direct...
result of roof bolt installation. The significance to roadway roof stability was not directly considered at this time, but the link was made between roof bolt installation and potential fracturing of the host material.

Compton and Oyler (2005) reported resin pressure measurements (Figure 6) during installation, albeit without spinning during installation, of a 1.2 m long x 5/8 inch roof bolt in a 1 inch (25.4 mm) steel pipe resulting in a 4.7 mm thick annulus (which is equivalent to a 21.7 mm core diameter roof bolt as used in Australia being installed in a 31.1 mm diameter hole). At an insertion rate of 128 mm/second (equivalent to a 1.2 m bolt being fully inserted to the back of the hole in 9.5 seconds – see Figure 6), the maximum pressure measured is in the order of 6000 psi (or 41.4 MPa) at the top of the hole, which is of a greater magnitude than the setting pressure for longwall shields.

Whilst the bolt installation method used is fundamentally different from that used in Australia whereby spinning of the resin starts at the base rather than top of the hole, the results reported by Compton and Oyler (2005) provide an indication of the potential resin pressure magnitudes that can be generated (they report a maximum measured pressure of 68 MPa) using the available power of a hydraulic roof bolting rig.

![Figure 6: Hydraulic pressures generated at four locations in a 1 inch pipe during roof bolt installation (5/8 inch bolt) – Compton and Oyler (2005)](image)

A combination of very high resin pressures being measured during roof bolt installation and the observation of blocks of strong host material being fractured as a direct consequence, leads to the inevitable conclusion that resin pressures are indeed significant and have the potential ability to “hydro-fracture” the roof strata, particularly in the upper portion of the bolt where the highest pressures are generated during bolt installation. The logical questions that follow from this recognition are:

(i) Does the action of such resin pressure potentially detract from overall roof stability?
(ii) If the answer to (i) is “yes”, which roof types are most affected by such action?
(iii) What are the controls of resin pressure generation and can they be implemented in practice to minimise or even eliminate any negative impact on roof stability whilst not compromising other key reinforcing aspects of the bolting system?

The answer to (i) can be found by reference to observed or inferred fracture patterns within the bolted interval of mine roadways combined with the previously justified statement that the self-supporting ability of roof strata is primarily retained by preventing or at least minimising loss of bedding plane cohesion within the roof strata.
Figure 7 shows a roof fall cavity (with extruded resin “pancakes” clearly evident at the top of the fall profile) and an associated borescope observation plot of the location and distribution of open fractures in the roof strata. The installed roof bolts were 2.1 m long and were designed to be fully encapsulated using 1200 mm long resin cartridges in a hole drilled with a 27 mm bit. The presence of more intense roof fracturing in the upper section of the bolted interval is clearly evident in the borescope data. The geotechnical reasoning for such fracturing is not obvious, however the action of resin pressure forcing resin into the roof strata and so opening up bedding planes can be reasonably inferred from the available evidence.

Figure 8 shows a series of sonic-probe roof extensometers from an ACARP Project field trial at Tower Colliery with the condition of the upper section of the bolted interval being consistently fractured as compared to the overlying strata, to the extent that the bolt length in use can be reasonably identified from the extensometer plots.

In contrast, Figure 9 contains a series of aged sonic probe roof extensometer plots linked to roof bolt installations via hand-held compressed air roof bolters, which logically have a far lower ability to generate high resin pressure during bolt installation. The change in roof fracturing in the upper section of the bolted interval as compared to Figure 8 is self-evident, the potential implication being that far less roof fracturing is present in the section of the bolted interval where maximum resin pressure is generated.

Figure 7: Roof fall cavity and bolted interval fracture pattern from an adjacent borescope hole

Figure 8: Sonic probe extensometer data from ACARP project C3032 (ACIRL 1995)
In terms of the answer to question (i), if the natural self-supporting ability of roof strata is strongly linked to whether bedding planes remain open or closed (Figure 2) but resin pressures during bolt installation act to initiate and/or aggravate the propagation of open fractures within the upper section of the bolted interval via pumping resin along such fractures, then it stands to reason that roadway roof stability is negatively impacted as compared to such fracture development not occurring.

In terms of which roof or strata types are most likely or easily affected by the influence of resin pressures, this can be considered by applying the various principles of hydro-fracturing, as was used by Purcell et al (2016) in their commentary on the subject.

Fracture development from a borehole is based on the hydraulic pressure being applied being able to overcome two distinct resistive forces to fracture development – 1) The stress acting across the plane of fracture development; 2) The cohesion (intact tensile strength) of the rock mass again across the fracture plane. As a result of 1, fracture development from a vertical borehole typically propagates perpendicular to the lower of the two relevant horizontal stress magnitudes as this represents the lowest possible resistance of the in situ stresses to fracture propagation. The relevant equation governing fracture propagation as quoted by Purcell et al, (2016) from Amadei and Stephansson (1997) is as follows:

\[
\sigma_1 = 3\sigma_2 + S - P_i - P_o = 3\sigma_2 - P_r \tag{1}
\]

where:  
\(\sigma_1\) = major principal stress  
\(\sigma_2\) = intermediate principal stress  
\(S\) = tensile strength of the rock perpendicular to the fracture direction  
\(P_i\) = crack initiation pressure  
\(P_o\) = pore pressure  
\(P_r\) = crack re-opening pressure

Using Equation 1 (which was specifically developed for predicting crack initiation and re-opening pressures for vertical cracks in a vertical borehole as part of hydro-fracturing stress measurement), Purcell et al (2016) apply a basic model for the in situ major and minor horizontal stresses in underground coal mines which in combination with what they state to be a moderate tensile strength for coal measures rock (5 MPa), results in the required crack initiation and re-opening pressures for a range of cover depths as shown in Figure 10.
Crack initiation pressures ranging from almost nothing to 50 MPa are predicted and these are used by Purcell et al (2016) to conclude that crack initiation pressures in coal measures strata are both highly variable and require site specific consideration in terms of stress conditions and rock parameters before applying roof bolting systems that include resin pressure reduction measures.

The analysis conducted and presented by Purcell et al (2016) is fully agreed with in terms of crack initiation pressures required to fracture solid rock material around a vertical borehole in virgin conditions whereby the \textit{in situ} major and minor horizontal stresses act across the borehole plane. However, the analysis significantly over-predicts crack initiation pressures in the immediate roof of a mine roadway on the basis of the following:

i. Crack initiation develops perpendicular to the minimum applied stress. In the case of the bolted interval above a mine roadway, the minimum stress is inevitably vertical due to the presence of the underlying roadway void, hence the fracture propagation is likely to be horizontal – as illustrated in Figure 11 from Mills and Jeffrey (2002).

ii. The magnitude of the vertical stress within the bolted interval of a mine roadway is inevitably substantially less than the \textit{in situ} vertical stress or either of the principal horizontal stresses.
due to the existence of the underlying roadway void which acts as a very efficient vertical stress reliever. Therefore the confining stress ($\sigma_2$ in Equation 1) to be overcome during roof bolt installation is likely to be far lower than indicated by the analyses of Purcell et al (2016). The same logic was applied by Mills and Jeffrey (2002) in their analyses for hydro-fracturing the spanning conglomerate unit above longwall panels at Moonee Colliery for the purpose of windblast mitigation and control.

iii. The weakest horizontal planes in the roof of a mine roadway are inevitably bedding planes and contacts, which have a tensile strength in the vertical direction substantially less than 5 MPa (as assumed in Figure 10). Frith (2012) reports the tensile strength of bedding planes in both sandstone and carbonaceous material as found from direct tensile testing of core samples. In all cases, average values were less than 0.5 MPa and even for solid sandstone, the tensile strength was found to be just over 2 MPa. Therefore, the assumption in the Purcell et al 2016 analysis that a 5 MPa tensile strength represents “moderate” strength rock, is judged to be a significant over-statement and certainly, is an order of magnitude higher than the tensile strength across horizontal bedding planes, this being the more relevant consideration in terms of the stability of a bolted mine roof.

For weak bedding planes/contacts within the bolted interval, typical crack initiation pressures in the order of 3 MPa and less are estimated to be far more realistic, such values being (a) depth independent due to the very low vertical stresses acting within the bolted interval being almost entirely determined by the formation of the underlying roadway void and (b) at the low end of resin pressures that have been measured in surface and in situ bolt installation testing, including those reported by Purcell et al (2016).

One further aspect in regards to resin pressures driving the development of bedding plane separations in the roof needs to be considered, namely the short time period (of only a few seconds) that high resin pressures are able to act. Griffith Crack Theory states that the highest stress is required to start the propagation of a crack, but once initiated the stress required to further propagate it decreases as a function of the length of the crack. Therefore, in the example of resin pressures causing bedding plane separations in the roof of a roadway, it may be that the main significance of resin pressure is simply to commence the propagation of a fracture that would have not otherwise started under the action of horizontal stress alone, but once started the horizontal stress is then able to drive its further propagation unassisted.

In terms of the controls on resin pressure development, if the problem is considered as a piston being pushed into a closed void space full of resin, resin pressure will develop if the rate of resin volume escaping past the piston is less than the volumetric compression of the resin ahead of the piston. Therefore it is necessary to consider both the rate of piston insertion (roof bolt insertion rate in this instance) and the various factors that act to restrict the escaping of resin back past the piston (the roof bolt in this case). It is self-evident that slowing down the rate of roof bolt insertion into the bolt hole will tend to reduce the development of resin pressures ahead of the bolt, as this allows more time for resin to escape past the bolt. The data in Figure 6 relates to an insertion rate of 128 mm/second and the test data shown in Figure 12 (developed in conjunction with DSI) was typically associated with a bolt insertion rate of 150 mm/second.
Figure 12: Resin pressure measurements for varying hole diameters and resin volumes

Rate of bolt insertion is also a relevant consideration in terms of resin mixing as if the rate of insertion is too slow (say 100 mm/second), for a 1200 mm or 1400 mm long resin cartridge as commonly used by industry for full encapsulating a 1.8 m or 2.1 m long bolt, the bolt will not reach the back of the bolt hole and be spun sufficiently (according to suppliers specifications) to ensure adequate mixing in the top section of the bolt without over-spinning the resin in the bottom section of the bolt.

Reducing the rate of bolt insertion is an obvious method for lowering resin pressures developed during bolt installation, as implied in the test work reported by Purcell et al (2016) who conduct their testing at an insertion rate of 100 mm/second and report lower resin pressures than other published test data including Figure 12. However it is almost certainly inconsistent with resin mixing needs along the full length of the roof bolt. Therefore other remedies are required to reduce resin pressure development, which leads to the various reasons why resin is restricted from flowing along the annulus around the roof bolt during insertion.

Figure 12 contains typical results from a series of roof bolt installations under controlled conditions conducted by the authors and DSI. The first point to make in regards to this type of testing is that it is vital to use a closed system so that resin cannot escape by means other than back past the bolt being inserted, this ensuring that the maximum possible resin pressure is measured. Similar testing conducted in situ for example, is prone to resin bleed off through any openings in the roof strata, particularly in friable roof types such as coal/claystone sequences, and will inevitably return lower resin pressures than would be the case in a closed system. Such testing is judged to be meaningless if the roof bolting system design objective is to minimise resin pressures so as to prevent the development of open fractures in the roof in the first instance. This is assessed to be a major oversight of the in situ testing reported by Purcell et al (2016) and fully explains the very low measured resin pressures which are used in isolation to then discredit the significance of resin pressures and their potential detrimental influence on roof instability.

Figure 12 demonstrates the significance of two key drivers of resin pressure development during bolt installation:

i. resin pressures decreases as a direct function of increasing bolt hole diameter (i.e. annulus thickness around the bolt)
ii. resin pressures decrease as a direct function of using less resin as evidenced by the pressure development curve associated with the use of a 440 mm long resin cartridge as compared to 1000 mm.

Two further logical drivers of resin pressure during roof bolt installation are the viscosity of the resin and the extent to which the rotation of the roof bolt during installation acts to ‘pump’ the resin back up the hole thereby further restricting its flow past the bolt.

With regard to any pumping action of the spinning roof bolt, it is noted that the early roof bolt patents included a specific innovation whereby the deformed profile was designed to push resin back up the hole during spinning in, as opposed to having it pump resin out of the hole. Therefore the idea that a spinning roof bolt acts to prevent resin flowing along the annulus during installation has been a roof bolt design characteristic since their first use in the mining industry. This pumping action can be readily eliminated by either the use of a smooth bar or preferably, a neutral deformed profile such as a herringbone pattern, which neither pushes resin back up the hole nor pumps it out of the hole. The general relationship between the efficiency of a pump and minimising the clearance between the impellor (in this case the roof bolt) and casing (in this case the bolt hole wall) is also noted in the context of the annulus thickness around the bolt.

A link between increasing resin pressure and increased roof fracturing via resin being forced into the surrounding roof strata, can be reliably inferred from various known changes in bolt encapsulation according to either increasing the bolt hole diameter or volume of resin used, both having previously been inferred to influence resin pressure development.

Figure 13 is taken from Craig (2012) and it is clear that for a 1200 mm resin length, the lower bolt hole diameters result in the encapsulation achieved being less than 100% of the theoretical value, this only being achieved at a hole diameter of 28 mm. Other published research studies mirror this general outcome.

![Figure 13: Resin loss by drill bit diameter (Craig, 2012)](image)

Figure 14 shows variations in what is termed as “Encapsulation Ratio” for varying resin cartridge lengths from 1.8 m long bolt installations in a friable coal roof. For a 28 mm diameter hole, a 21.7 mm diameter bar and a 25 mm diameter resin cartridge, for every 1 mm of resin cartridge length, 1.8 mm of bolt encapsulation should theoretically be achieved if no resin is lost from the hole and the hole diameter is accurate. In other words, if there is no resin loss the Encapsulation Ratio should be 1.8. The data in Figure 14 shows that for resin lengths up to 700 mm, the measured Encapsulation Ratio is just below the theoretical maximum of 1.8, the likely reason for this being the actual hole diameter being slightly greater than the assumed hole diameter (drill bit diameter) of 28 mm. However, for resin lengths > 700 mm, the Encapsulation Ratio incrementally reduces such that for a resin length of 1200 mm, the encapsulation length achieved (960 mm) is actually less than that achieved with 600 mm of resin (1080 mm). Logically, this effect is being driven by ever-increasing resin pressures during installation due to increasing resin volumes, thereby driving ever greater resin losses into the surrounding strata.
The data and arguments presented in this section of the paper lead to the inevitable conclusion that resin pressures developed during roof bolt installation are sufficiently high in the top section of the bolted interval to both initiate and further propagate roof fracturing and associated resin loss. In bedded roof conditions whereby preventing such fracturing occurring is a primary objective of reinforcing roof bolts, this is a judged to be a real and legitimate stability concern. Industry focus on achieving full encapsulation for long bolts (> 1.8 m long) in the smallest possible hole is logically aggravating this effect, which is largely hidden from view during operations. Fortunately, there are some obvious controls for resin pressure development that can be modified to substantially reduce this potentially deleterious effect.

ROOF BOLT PRE-TENSIONING

Pre-tensioning generates an axial tensile force in the bolt and a compressive force against the roof at the plate, without the need for roof movement or more importantly bedding plane separation, the latter being the principal driver of roof beam breakdown. This is why it is referred to as an “active” force as compared to the “reactive” force generated by load transfer. A tensile axial load due to pre-tensioning will be developed along whatever bolt length is able to be freely stretched at the time of nut tightening.

Figure 15: Roof extensometer data – applied roof bolt pre-tension two to three tonnes

The effectiveness of the applied pre-tension in reinforcing the initial 0.5 m or so of roof and the significance of doing so, is clearly illustrated in Figures 15 and 16, these being sonic probe extensometer data from Teralba Colliery in the mid 1990’s when increasing roof bolt pre-tension was first being operationally evaluated in industry. Figure 15 shows data related to low levels of applied pre-tension, the salient points being (a) the presence of delamination throughout the entire bolted interval (2 m for 2.1 m long bolts) and (b) the associated time dependent roof behaviour whereby equilibrium is not easily being achieved and displacement levels would undoubtedly trigger a
Development TARP in today's industry. Comparing Figure 15 to Figure 16 which is related to a significantly higher level of applied pre-tension, it is clear that the initial 0.5 m of roof strata contains no obvious delamination, total roof displacement is substantially reduced and the time-dependent trend is far more stable. When it is also noted that the height of roof fracturing in both instances is identical and that in neither case are the 2.1 m roof bolts anchored securely into more stable overlying strata, the significant stabilising effect of generating beam action in the initial 0.5 m or so of roof by preventing delamination using the action of the applied pre-tension, is self-evident.

If it is accepted that the condition of the initial 0.5 m or so of roof strata is a key roof reinforcement consideration, it raises the question as to whether it is best reinforced via pre-tension or load transfer, the latter by definition requiring full encapsulation to be achieved whereas the former can potentially be achieved without the roof bolt necessarily being fully encapsulated.

It is contended that the critical aspect of utilising roof bolt pre-tension for roof reinforcing purposes is that it modifies the “end condition” of the roof strata between roof bolts from “pinned” to “clamped”, clamped-end beams being 4 times as stable as pinned-end beams (all other factors being equal). This is potentially highly relevant in friable roof types whereby the dominant mechanism driving roof instability is roof deterioration between bolts (guttering and buckling) which can eventually lead to instability across the full roadway width if not adequately controlled.

The concept of different roof beam end conditions is schematically illustrated in Figure 17 whereby a pinned roof beam via full encapsulation and minimal pre-tension effect is compared to a clamped beam developed using pre-tension and a bolt free length that is equivalent in length to a beam thickness that can assist in stabilising the full width roof span. The different roof displacement profiles shown between bolts (u-curve for pinned and double s-curve for clamped) is entirely dictated by the end condition of the beam as defined by the installed roof bolts.
Utilising the applied pre-tension to best possible effect requires that at least three requirements are met:

i. That the pre-tension generated from nut tightening is as high as possible.

ii. That the roof bolt plate is able to (a) accommodate the applied pre-tension levels and (b) preferably at least the yield load of the bolt without itself going into yield.

iii. That the resin anchor above the intended roof interval of bolt pre-tension is able to (a) allow the pre-tension level to be generated by nut tightening and (b) again allows at least the yield strength of the bolt to be generated as a result of any subsequent roof delamination below the resin anchor.

iv. Only points (i) and (ii) will be considered in more detail in this paper.

In terms of the level of pre-tension generated due to nut tightening, the key issues are (a) the applied torque and (b) the thread system, the latter determining the efficiency of the torque to pre-load conversion and must also remain stable under the dynamic loading and associated heating during nut tightening.

Current day hydraulic bolting rigs commonly use two-speed motors whereby “high rpm-low torque” is used for drilling and “low rpm-high torque” for nut tightening. This makes best use of the available hydraulic power for these two significantly different functions.

Attempting to maximise both the efficiency of torque to load conversion and thread stability during tightening is actually counter-productive as the former increases but the latter decreases as thread pitch reduces. Roof bolts generally use a 3 mm thread pitch (standard M24 thread) which is about as low as pitch can go without thread stripping being inevitable during nut tightening.

Test work evaluating pre-tension achieved as a function thread pitch (Figure 18) for a hydraulic rig generating in the order of 400 N.m (300 ft.lbs) torque, indicated that the combination of a 3 mm pitch and a 1.25 D nut did not always allow the maximum possible pre-tension level to be achieved, whereas at 5 mm and above, it did. The solution to this, without decreasing the applied torque, is to either (a) increase the nut length so as to reduce thread contact pressures thereby making the thread more stable or (b) increase the pitch to at least 5 mm.

As a general statement, with a suitably designed thread system modern hydraulic roof bolting rigs that stall at around 400 N.m (300 ft.l) should be able to reliably generate 12 to 15 tonnes pre-tension due to nut tightening. This is a significant roof bolting attribute that has yet to be fully exploited by industry.

The strength of the head plate is a roof bolt system component that received little attention following the industry move to full encapsulation, the plate being seen as relatively unimportant part of the bolting system as a direct consequence. However in any roof bolting system that uses pre-tension for
reinforcing purposes but may not always achieve full encapsulation, the head plate is in fact a vital component of the system.

![Figure 19: Load test arrangement for testing of steel domed washer plate (British Standards, 2007)](image)

The British Standard on strata reinforcement support system components used in coal mines (British Standards 2007) states that a roof bolt plate “shall flatten under a load of 50% to 70% of the nominal breaking load of the bar...” and “allow pull through of the rockbolt, nut and conical seat assembly under a load of 70% to 95% of the nominal breaking load of the bar”. In other words, the plate should be in yield at an applied load as low as 17 tonnes (50%) for a 34 tonne bar (X grade steel) and allow system failure at an applied load as low as 24 tonnes (70%) for a 34 tonne bar. The underlying intent is presumably to protect the rockbolt from tensile failure by limiting the strength of the plate. The direct consequence of this is that the plate loses its elastic stiffness (system stiffness being the key reinforcement consideration) at quite low levels of applied load, which is less than ideal.

The other major problem is that plate testing, as defined in the same British Standard, is undertaken as per the arrangement shown in Figure 19. This is a highly idealised test set-up using a flat surface against the plate. Whilst this may allow representative comparisons between different plate designs, it inevitably provides optimistic plate strength values as compared to when used in an undulating and uneven roof environment. Therefore the stated plate design criteria listed previously that are based on the test arrangement shown in Figure 19, will in fact result in in situ plate performance at even lower levels than those specified.

Current standard roof bolt plates are understood to have an ultimate strength rating (or collapse loading) in the order of 24 tonnes, which is exactly 70% of the ultimate strength of an X grade bar. Whether this is directly linked to the British Standard is not known, however it confirms that there is potential, via a stronger head plate, to generate and utilise higher bolt loads within the immediate roof strata as compared to the current situation.

In contrast, the basic load transfer mechanism is shown in Figure 20, the main point being that for axial bolt load to be generated due to bed separation, stable resin anchorages are required both above and below the bed separation. It is therefore instructive to consider the extent by which this reinforcing mechanism is able to work within the initial 600 mm of roof as this will provide further guidance as to the true imperative of achieving full encapsulation to the head of the bolt.
Ignoring any contribution from the roof bolt plate, the preferred requirement of the resin anchorage system is to allow at least the yield strength (24 tonnes for an X grade bolt) and ideally the full axial strength of the bolt to be developed via bedding separation effects. For a 600 mm thick immediate roof beam, if it is assumed (for the sake of illustration) that bedding separation occurs at the mid-point of the beam, the resin anchorage above the separation is the majority of the bolt length, but below the anchor it logically can be no more than 300 mm in length. Therefore the question posed is whether a 300 mm long resin anchor, particularly in weak roof strata, has the ability to develop 24 tonnes, if not 30 tonnes of axial bolt load?

A 300 m long resin anchor is the same as that used for short encapsulation pull testing, the objective of using a short anchorage being to evaluate the resin bond rather than the strength of the bolt. This in itself is indicative that it is unlikely that a 300 mm long resin anchor will reliably allow the yield strength of an X grade roof bolt to be developed. Short-encapsulation pull out test results in weak types roof commonly indicate pull-out strengths in the range of 10 to 12 tonnes depending upon resin type and its associated characteristics.

Therefore, load transfer reinforcement within the immediate 600 mm of roof is unlikely to be able to develop more than about half of the yield strength of an X grade bolt. Further illustrations of this are provided in Figure 21 (Gale, 1991) and Figure 22 (Gale and Matthews, 1993) whereby it is clear that the axial loads being developed incrementally reduce towards the top and bottom of the bolt. More importantly, in Figure 22 the roof displacement profile is also shown (based on sonic probe extensometry) which indicates that even though axial bolt load reduces towards the bottom of the bolt, the roof strata nonetheless contains a significant amount of delamination as low as the as-cut roof line. In other words, whilst the driver of axial bolt load generation via load transfer is present throughout the entire bolted interval, the load magnitude being developed in the initial 1 m or so of roof is clearly being limited by some influence.
Other points of note in regards to the use of load transfer for reinforcing the immediate roof strata are:

(a) By definition, load transfer requires bedding planes to open up in order to develop axial bolt load. However, the opening up of bedding planes is also the main driver for beam breakdown and associated roof instability (as previously justified). In other words, the required mechanism of load transfer is directly contrary to the primary roof reinforcing objective, namely preventing the opening up of bedding planes in the first instance.

(b) Whilst this has never been researched, the role of the plate in supplementing load transfer in the immediate roof is not clear-cut. The loading mechanism for the plate largely relies on relative movement between the strata and the bolt, whereas load transfer attempts to minimise such relative movement. The second graph in Figure 22 clearly shows the bolt in yield above 1 m into the roof, but zero axial bolt load at the plate, meaning that the plate is presumably providing no direct contribution to overall load transfer.

(c) The base of the bolt is the most likely location for “sliming” of the hole wall due to drilling through any overlying clay bands along the bolt length. This effect is rarely captured in short encapsulation pull testing, but is known to significantly reduce load transfer strengths from those generated without hole sliming.

With all of these considerations to-hand, it is concluded that whilst load transfer has the proven ability to develop the full axial strength of an X grade bolt in its mid-section, it is significantly limited in the lower section which is where the first potentially stabilising roof beam is located. Given the importance of this beam to overall roof stability, this is a less than optimum reinforcing outcome.
Figure 23: Schematic illustration of step-wise development of roof softening with increasing roof displacement

Figure 24: Field Data – roof softening progression with displacement (Gale et al., 1992)

The recognition that the maximum potential axial loading of a roof bolt via load transfer is typically limited to the middle portion of the bolt length, is also at odds with the known “step-wise” progression of roof movement and associated softening starting at the roof line and incrementally moving up into the roof (see Figure 23, which is a general illustration of the data presented in Gale et al., 1992 – see Figure 24). The logic here is that if the immediate roof can be reinforced as a stabilising beam such that its vertical movement is restricted, it will then act to limit the upwards progression of roof softening. This is also beneficial as the higher into the roof that roof softening progresses, the less stable the roof overall and therefore, the higher the level (length and density) of long tendon roof support required to control the roof.

It is concluded that with a suitably designed nut and appropriately rated roof bolt plate, reinforcement of the immediate roof “beam” is best facilitated by the application of bolt pre-tension so as to prevent bed separations, rather than load transfer which relies upon bed separations opening up. Furthermore, the inclusion of a defined bolt “free-length” to ensure that pre-tension is applied over a requisite roof “beam” thickness, is judged to be beneficial when the potential for increased roof fracturing in the upper section of the bolted interval due to the use of larger resin volumes to achieve full encapsulation, is also considered.

SUMMARY

The paper has attempted to demonstrate in selected technical areas that the Australian coal industry’s general belief that current primary roof bolting systems are fully optimised with little scope for further improvement, is significantly in error. Furthermore, substantial improvements in reinforcing
effectiveness can potentially be realised to benefit mining operations if geotechnical engineers and mine operators are prepared to embrace such a possibility.

To put the above statement into a more practical context, it is useful to pose the following questions to industry:

- Why wouldn’t roof reinforcement improve if the reliability of resin mixing with varying hole diameter is substantially improved?
- Why wouldn’t roof reinforcement improve if gloving of the resin cartridge film is minimised?
- Why wouldn’t roof reinforcement improve if resin pressures generated during bolt installation are substantially reduced?
- Why wouldn’t roof reinforcement improve if the length of the bolted interval directly influenced by high resin pressures generated during bolt installation is substantially reduced?
- Why wouldn’t roof reinforcement improve if roof bolt pre-tension levels are increased?
- Why wouldn’t roof reinforcement improve if roof bolt pre-tension is reliably applied across a section of immediate roof strata that is sufficiently thick to be able to substantially and positively influence overall roof stability?
- Why wouldn’t roof reinforcement improve if the load-capacity of the head plate is increased so that a greater proportion of the available roof bolt strength is mobilised?
- Why wouldn’t roof reinforcement improve if load transfer stiffness is substantially improved via the use of a modified resin system?

Mine Advice in conjunction with DSI have taken the view that there is substantial benefit to be realised if roof bolting systems are improved in each of these technical areas. DSI’s PEAK Resin Bolting system using a “partially” rather than “fully” encapsulated bolt, is the first significant industry initiative that has incorporated all of these various research findings in a more “balanced” overall bolt set-up. It has found full commercial use at several mines and has allowed a number of substantial operational improvements to be realised (e.g. Hart, 2014) without any negative strata control implications. However, that is another story for another time.

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