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Investigations Into Premature Rock Bolt Failures in the Australian Coal Mining Industry

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INVESTIGATIONS INTO PREMATURE ROCK BOLT FAILURES IN THE AUSTRALIAN COAL MINING INDUSTRY

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ABSTRACT: An ACARP project was initiated in 1999 to address the observed phenomenon of premature failure of rock bolts in a number of Australian coal mines, and with a particular focus on the problem of Stress Corrosion Cracking (SCC) in rock bolts. This paper briefly outlines the findings of this study.

INTRODUCTION

SCC is a progressive fracture mechanism which can occur in different metals. It is not a new phenomenon and has been found in Bronze age swords, and in brass ammunition used in India in the last century. However, the effect of SCC on rock bolt failures has only been recognised in recent years.

STRESS CORROSION CRACKING

SCC occurs by the slow progressive growth of stress corrosion cracks under the joint action of stress and a corrosive environment affecting susceptible alloys. Eventually one of the cracks will reach a critical length at which the remaining section can no longer carry the load and final instantaneous overload failure then occurs. The stress corrosion cracks act as very sharp stress concentrators so that even small stress corrosion cracks can cause bolts to fail at below their design strength. An example of SCC cracks in a rock bolt is shown in Figure 1.

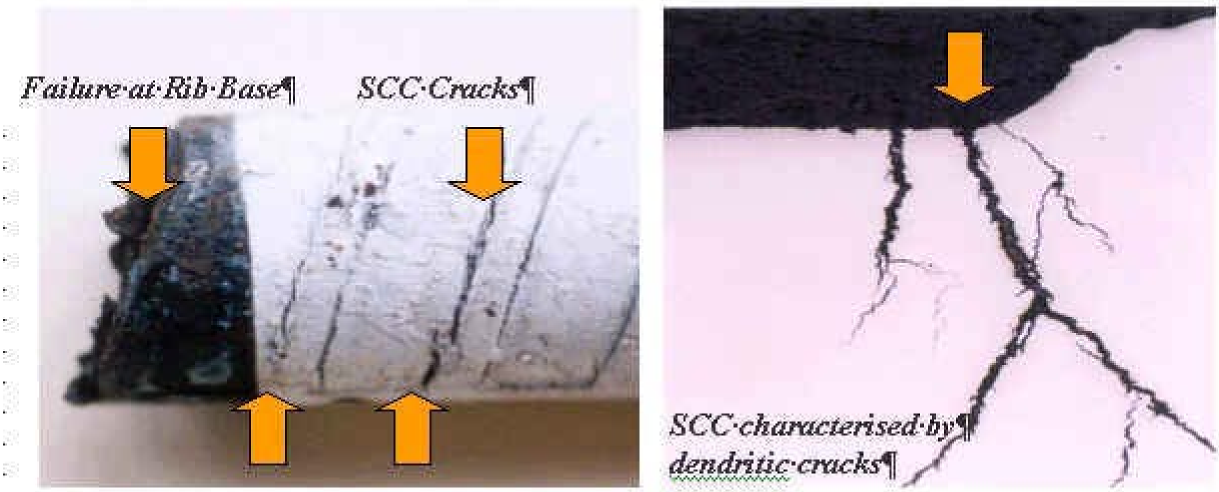

FIG. 1 - SCC Cracking in a Rock Bolt

SCC is not restricted to old bolts – some recently installed bolts have been found to fail under SCC conditions. It appears to be more prevalent where:

- Clay bands are intersected by the bolts
- Thick coal roof sections are present

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- High tensile steel bolts are used
- There is some groundwater present in the strata
- There is limited shearing within the strata inducing bending in the bolts
- Bacterial 'bug' corrosion of steel underground may be active, promoting corrosion of existing flaws within the steel.

Examples of SCC brittle failures in rock bolts are shown in Figure 2.

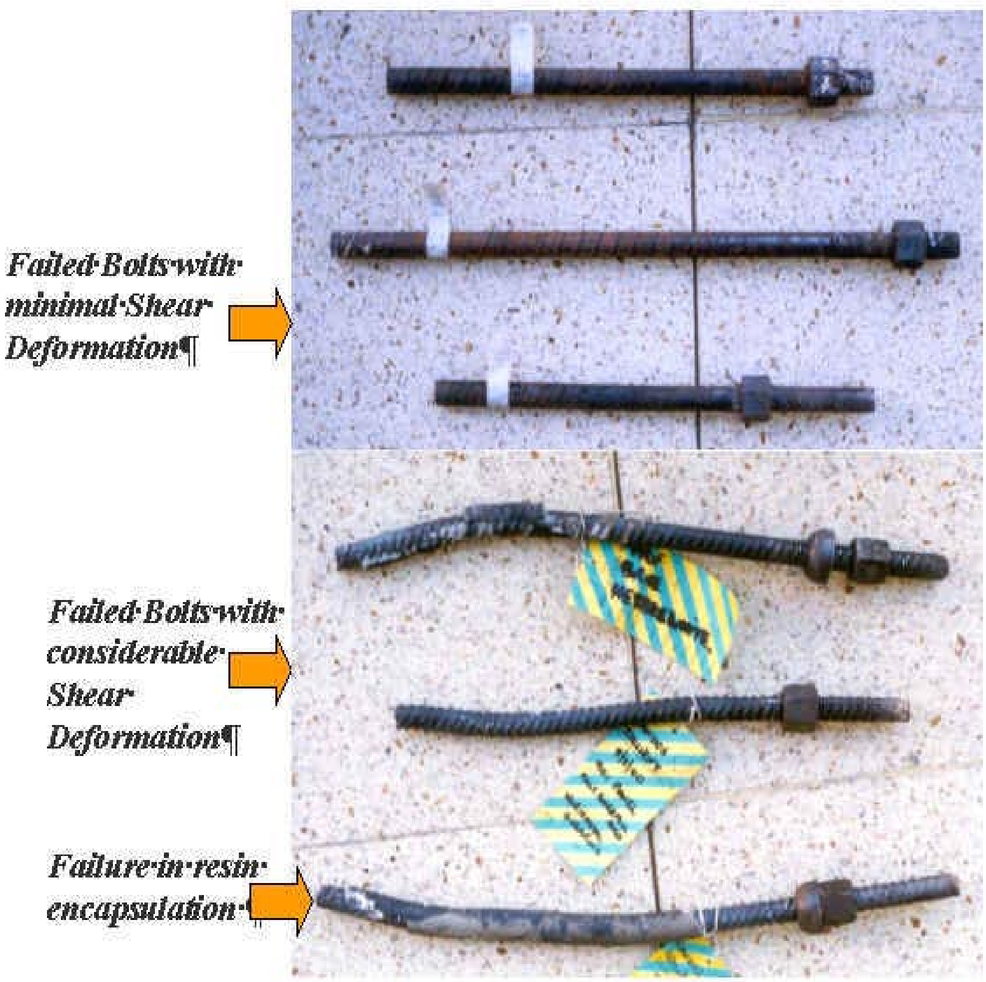

FIG. 2 - SCC Brittle Failures of Rock Bolts

Results of the Study

The current project has surveyed the industry and found that the problem, although not identified in all mines, is more than just an isolated problem. It is not confined to just one coal seam where particular corrosive conditions apply or to all areas of that seam. It is not confined to one manufacturer or steel supplier.

The data collected during this project does indicate that there are still significant problems in defining the scale of prematurely fractured bolts in coal mines. The causes of the uncertainty can be summarised as:

- Lack of a consistent, or formal reporting system for the identification of incidents of broken bolts.
- The results of any survey of premature bolt failures is limited because only bolts that fail outside the encapsulated length of the bolt and are free to fall out or significantly displace out of the roof are identified.
- To date the only means of identifying bolts that fail in the encapsulated section is through inspection of fall cavities.

- Even in areas of high broken bolt frequency no broken bolts were identified in high deformation roofs. With the exception of failure of the collar of the bolt – bolts may be locked into the roof by shear action.
- Identification of the steel source is not possible without recourse to metallurgical analysis even for bolts with similar profiles.

There were at least four main types of premature bolt failure identified as part of this study. These were:

a. traditional stress corrosion cracking failures caused by corrosion cracks or pits propagating until ultimate brittle failure occurs as shown in Figure 1;
b. brittle failures within the encapsulated section of the bolt without any visible corrosion see bottom bolt in Figure 2;
c. existing cracks or pits in the steel which propagate and are the trigger mechanism for ultimate failure as shown in Figure 3;
d. failures within the threaded section of the bolt typically across the root diameter of the thread as shown in the right hand holt of Figure 4).

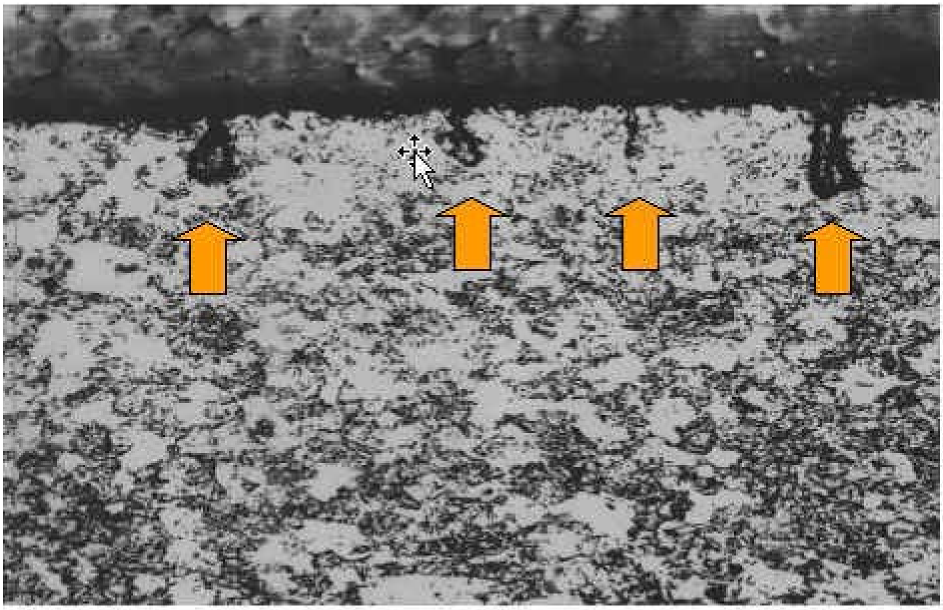

FIG. 3 - Corrosion Pitting on the bolt surface – may also be an incipient failure point for rock bolts.

Metallurgical Characteristics of the Failed Bolts

Most failed bolts that were recovered from the mines were substantially straight, see Figure 2, but this is considered to be simply caused by biased sampling because straight bolts are less likely to be locked into the roof. In fact, some shear loading mechanism is probably required to explain bolt failures, below the level of encapsulation, with very low tensile collar loads.

Fracture depth in bolts varied from <1mm to over 40% of the surface area of the bolt (as shown in Figure 5 below).

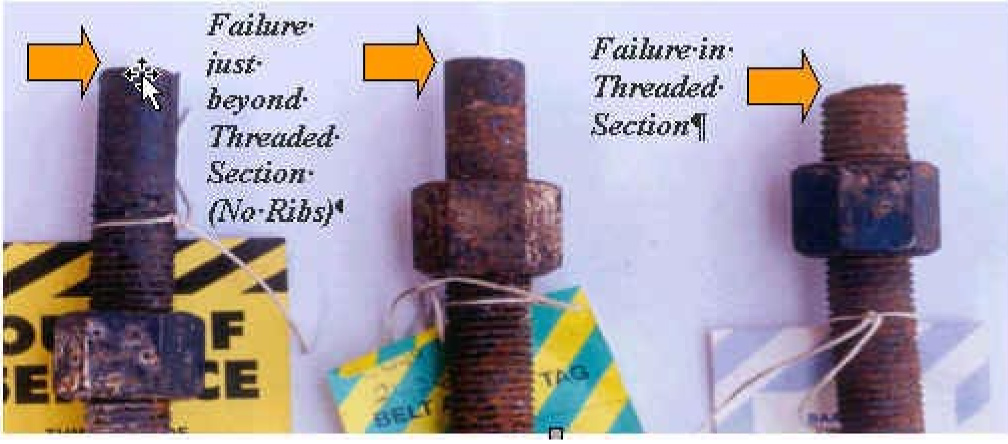

FIG. 4 - SCC Brittle failures of Rock Bolts near the collar – *the two bolts on the left have failed through the bar-peeled or swaged section of the bolt, whereas the bolt on the right has failed through the root diameter of the thread.*

FIG. 5 - SCC Failure Surfaces – *the bolt on the left has a large surface crack before ultimate failure, whereas the bolt on the right has only a very small surface crack that initiated failure.*

METALLURGICAL CHARACTERISTICS OF THE FAILED BOLTS

A series of metallurgical tests have been applied extensively to the sampled bolts to identify metallurgical characteristics of the failed bolts and the nature of the corrosion. These point to steels with a low fracture toughness as particularly susceptible to this type of problem, and related brittle fracture in the vicinity of the threaded section of the bolt (toughness is a measure of the energy required for fracture).

The latest developments of higher fracture toughness steels in Australia has produced variable fracture toughness results as measured by the Charpy test. This may be due in part to actual variability in the steels but also the inability of the Charpy test to adequately measure fracture toughness on quench and tempered or accelerated cooled steels. Alternative indicators of fracture toughness for rock bolts should be considered (eg bending tests or drop tests).

Anecdotal evidence and the latest use of higher fracture toughness steels by mines, indicates that higher fracture toughness steels are less susceptible to premature failure than steels with low fracture toughness. Tempcored steels, accelerated-cooled steels and micro-alloyed steels in particular, appear to reduce the incidence of premature failures. However, the level of fracture toughness required to prevent premature bolt failures requires further investigation. The tensile, elongation and charpy values for various rock bolt steels are shown in Figure 6 below.

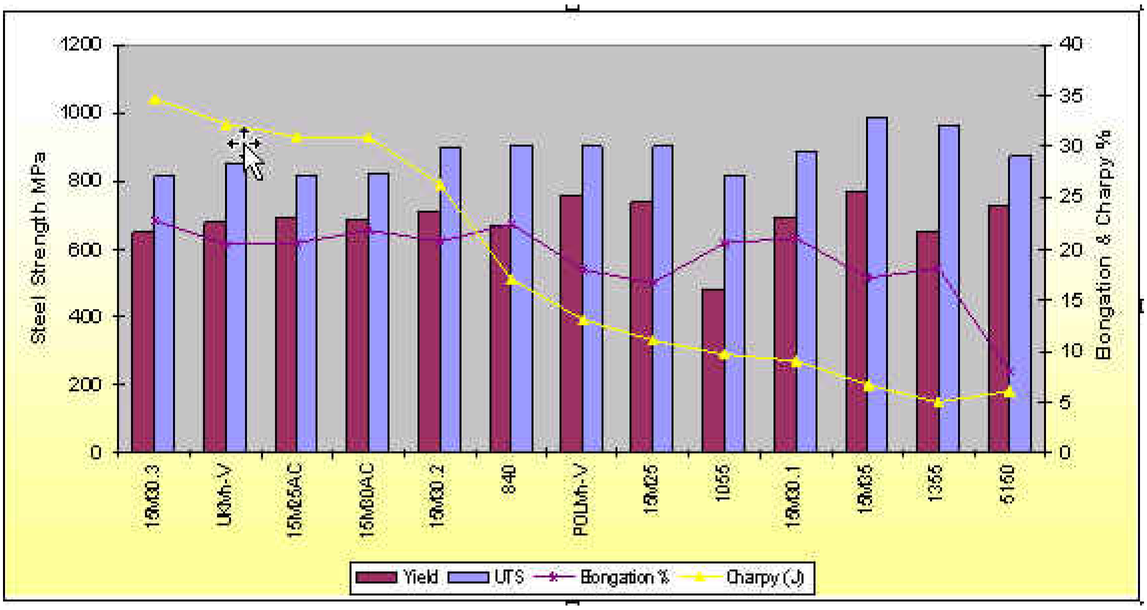

FIG. 6 - Comparison of Tensile Strength, Elongation and Charpy values for various rock bolt steels

In addition to identifying that the problem of premature bolt failure due to SCC is occurring in a number of mines in both NSW and Queensland, the current project has accessed a considerable database of similar problems from the UK coal industry over the past ten years or more. Furthermore, it appears that SCC is also surfacing as a significant problem in a number of Australian metalliferous mines. In such cases, the prevalent use of point anchored bolts results in an even more severe problem due to 100% loss of capability on failure. A research project has recently been initiated in Western Australia into this problem in the metalliferous sector and agreement has been reached for collaboration through future information exchange.

SUMMARY OF THE FINDINGS

The problem has now been identified in 9 different collieries throughout NSW and Queensland. Samples of broken bolts have been collected from at least 5 of these mines for detailed metallurgical testing. Because of the sporadic occurrence of premature bolt failure and the low level of record keeping within the mines, only a limited sample is available for the current database. At this stage, only bolts which have fallen to the ground are normally recognised as premature failures. To date there has been no method of identifying broken bolts which have failed within the encapsulated portion of the bolt or are restrained in the roof by strata shear.

Approximately 50 different bolts were analysed as part of this study. These included AVH, AXR, X, HPC, Threadbar, Wriggle and Tempcored bolts. The testing program included crack detection through magnetic particle inspection; spectrographic analysis for chemical composition; toughness and impact testing using the Charpy test; plus micro-structural analysis of bolt steels. Additionally, confidential data available for use in the overall database was obtained from mines where a further 50 bolts failed.

Arising from this work has come a clear indication that the steel toughness is a critical factor in this type of failure, with lower toughness values being more prone to SCC failure – at least in certain mine environments. The majority of the failed bolts examined had very low Charpy impact values (4–7 Joules). There is a definite need to develop a much simpler and cheaper test for toughness, to enable an improved 'quality control' process to be employed by the industry.

It is also apparent that the SCC problem is almost entirely confined to the high tensile strength bolts, as opposed to mild steel – by virtue of the metallurgy involved. It is noted that the failed bolts examined all contained 0.4% - 0.6% carbon, but they were of a number of different chemical types, including manganese steels, chrome steels and micro-alloyed steels.

A further aspect of the database work involved detailed underground investigation in at least one mine where the problem was widespread, in order to assess any features of the mine environment, or the age or type of bolts which were more prone to SCC failure. This confirmed that the presence of a mildly corrosive groundwater will encourage SCC to develop. The existence of clay or tuffaceous bands within the bolting horizon appears to be one of the contributors to an SCC-prone environment.

A further feature of the site database development was a small-scale investigation into bacterial corrosion – iron and sulphur eating bacteria present in the mine environment, which corrode steel. This investigation was additional to the original project objectives, and was only conducted at a very low level, on a restricted sample, but it did confirm that these bacteria were prevalent at least in the one mine investigated.

The database also identified a number of bolt failures occurring in the threaded region of the bolts – apparently due to simple brittle failure in tension. This was observed as particularly relevant to bolts used for hanging loads such as belt structure, monorails and the like. This type of failure was not part of the original project, but is considered a significant issue, which warrants further investigation.

NON-DESTRUCTIVE BOLT INTEGRITY TESTING

It was recognised from the outset that the database obtained from broken bolts found on the floor of mine roadways may only be a small part of the problem. The type of failures being identified could just as easily be occurring within the grouted horizon. This would leave partially or totally failed bolts grouted into the roof, providing the potential for an extremely hazardous situation of roof instability developing, with little or no warning to operators. It was recognised that there was a need for a non-destructive device to be available to the industry to be able to check bolt integrity on a routine basis.

Several potential devices, or prototype developments, were identified and investigated as part of the current project. These included developments from the USA, Sweden, UK, and Germany. The most promising of the techniques, that was also the furthest developed, and already suitable for routine use in coal mines (with respect to cost and approvals) was an ultrasonic device developed by Deutsche Montan Technologie (DMT) in Germany. Discussions were initiated with DMT to enable trialling of the device in Australia. The German results, to date, have been very promising with this device, at least for detecting total bolt failure, and identifying the horizon where such failure has occurred.

DMT agreed to work with the ACARP project team to conduct further evaluations for application in Australian conditions. The first part of this agreement was a small test program in the DMT laboratories of similar types of bolts to those used in Australia. This testing yielded promising results. A more complete laboratory and field testing program of the DMT device should be pursued as part of any future investigations.

CONCLUSIONS

The current project has effectively characterised the problem and focused on some of the key metallurgical and environmental conditions under which the problem has to date been detected. A real concern is that the database, to date, only consists of bolts that have failed below the grouted horizon and dropped out onto the floor. Because of the nature of the problem, there is a very real likelihood that -under the right conditions - some bolts are failing within the grouted horizon but remaining in the roof (at least two examples of broken bolts exposed in falls has indicated premature failure of bolts within the encapsulated section of the bolt). These give the appearance of a competent bolt, but one which may in fact be failed, in situ, and be effectively only offering a greatly reduced bolt length. The safety implications of this problem are considerable, and warrant priority future investigation.

The critical issues that should be addressed in the future, by the industry, include the following:

- Comprehensive field evaluation of the DMT developed ultrasonic NDT bolt testing device, to both prove the device for routine industry use, and further quantify the extent of the in situ bolt integrity problem.
- Further development of metallurgical and corrosion surface test procedures and database expansion – in particular, to develop and test a simplified steel 'toughness' test.
- Investigation and documentation of the properties of new steel products in the marketplace.
- Investigation of the extent of potential bacterial 'bug' corrosion of bolt steel and possible remedial actions.

- Documentation of the extent of brittle failure of bolts in threaded sections, especially with regard to bolts used for hanging structure, such as monorails.
- Provision to the industry of guidelines for minimizing SCC problems, including bolt and steel traceability.
- Introduction of an Australian standard for rock bolts. In particular, a minimum toughness level should be specified. This Standard should be based on the results of the key recommendations of this report, and include input from steel manufacturers, bolt producers and bolt users.

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