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Back-calculation of failure stress of rockbolts affected by Stress Corrosion Cracking in underground coal mines

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1. Introduction

Stress Corrosion Cracking (SCC) is a failure mechanism which has been observed to result in the catastrophic failure of rockbolts in Australian underground coal mines over the past 20 years.[1,2] SCC is a failure mechanism that results in crack growth orthogonal to the direction of applied load when a material is exposed to an appropriate corrosive environment. SCC of rockbolts has been a relatively active area of research in Australia,[3–6] as well as internationally,[7,8] with a number of laboratory based experimental programs having been carried out to examine the issue.

SCC has also been an issue for the high pressure pipeline industry since the 1970's.[9–11] However SCC was not identified in underground coal mines until the mid 1990's when failures were observed in the UK.[12,13] By the late 1990's an incidence of SCC was reported in an underground coal mine in New South Wales (NSW), Australia.[1] SCC of rockbolts has subsequently been identified at a number of underground coal mines throughout Australia,[2,14] and more globally in mines in China.[8] This shows that the phenomenon of rockbolt SCC is a pervasive issue, with the propensity to affect rockbolts in a wide range of mining conditions. Understanding the initiation and failure conditions for SCC in rockbolts is important for engineers as it allows for planning and remediation measures to be taken in advance, improving safety and ground control outcomes, and consequently, productivity.

A characteristic SCC failure surface in a rockbolt is presented in Fig. 1. In Fig. 1, the area of crack growth can be seen as the dark thumbnail shaped region in the top-right quadrant of the failure surface. The silver speckled region in the remainder of the rockbolt's fracture surface has occurred by brittle overload once the SCC crack had grown to the critical size. A small amount of material can be seen missing in the bottom-left quadrant of the rockbolt and is due to secondary corrosion of the specimen.

It is hypothesised that a critical stress threshold, below which SCC will not occur, exists for rockbolts as it does for many other materials. Many attempts have been made to identify and quantify this threshold - most notably it has suggested that this threshold lies at the upper limits of the rockbolt's ultimate strength.[3] However, other research studies suggest that such a high threshold is unlikely due to there being very little observable deformation on rockbolt ancillaries (such as bolt plates) in recorded *in-situ* failures.[1,15] This paper, therefore, proposes a novel approach for determining the stress conditions experienced by a rockbolt at failure.

When an elasto-plastic material is placed under load, it will experience deformation. Initially, this deformation is elastic in nature and obeys Hookes Law - this elastic behaviour will continue until the material reaches its limit of proportionality, also called the ‘yield point’. Once the material has exceeded this proportional limit, it will begin to behave plastically.[16] This means that any further deformation experienced by the material beyond this point will be permanent and irrevocable. However, the amount of elastic deformation experienced by the material is recovered during unloading. If the recovery of elastic deformation is plotted on a stress-strain curve, it is observed to obey the elastic proportionality of the material. If the material is then reloaded, the stress-strain plot will follow the same unloading path before strain hardening resumes at the point of unloading.[16] This process is known as ‘elastic recovery’ and is described schematically in Fig. 2, which shows an idealised stress-strain plot for mild steel.

Since SCC causes the failure of a material at below its ultimate strength, it will have likely failed at some point during the strain hardening process, and as such, will have experienced some amount of

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Fig. 1. Photograph of an SCC failure surface on a rockbolt recovered from an underground coal mine in NSW, Australia.

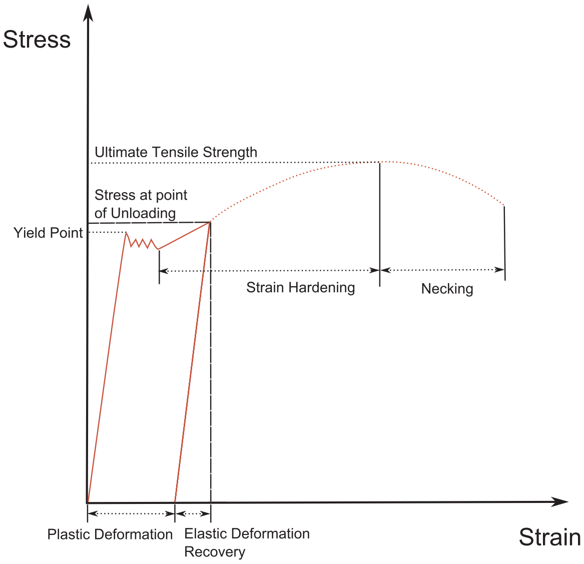

Fig. 2. Illustration of the behaviour of elastic deformation recovery during unloading.[16]

plastic deformation. This paper proposes to estimate the load experienced by a rockbolt at the time of its failure through an examination and comparison of the rib-spacing of rockbolts that failed *in-situ* with that of an unstressed rockbolt of the same type. Through this comparison, the amount of plastic deformation experienced by a broken rockbolt can be determined. The stress at failure can then be calculated by extrapolating the amount of plastic deformation along the gradient of elasticity to find the intersection point with a known stress-strain curve. This will give an indication of the stress experienced by a rockbolt at the time of failure.

2. Sampling of SCC affected rockbolts

To carry out this analysis, 50 specimens were selected from a collection of over 200 broken rockbolts found to have failed due to SCC *in-situ* at a number of underground coal mines throughout Australia. The rockbolts that comprise this collection is limited to specimens which were found to have fallen out of the roof, and were lying on the ground. A set of sampling criteria were used to select appropriate rockbolt specimens. Rockbolts only passed the sampling criteria if:

- the rockbolt showed signs of SCC attack;
- the rib profile of the rockbolt matched that of the datum rockbolt (HSAC 840, X-Grade rockbolt);
- the rockbolt was 'clean' and had not undergone excessive amounts of secondary corrosion; and,
- the rockbolt did not exhibit excessive amounts of lateral deformation around the point of failure which may indicate a component of shear loading as opposed to pure axial loading.

A number of rockbolts that were excluded from the study are compared to an appropriate rockbolt in Fig. 3.

These selection criteria were used to exclude rockbolts that may have introduced error from a number of sources. Rockbolts were selected on the basis that an unobstructed measurement could be made of the rib spacing. Rockbolts with excessive secondary corrosion were omitted as they generally had damaged rib profiles and may have experienced unusual loading conditions while in service. HSAC 840 rockbolt rib profiles were selected as they represent the largest proportion of rockbolts in service in Australia and thus, provide an appropriate datum on which to base this methodology.[2]

It was highlight by that collecting rockbolts which were found to have fallen from roof may introduce a sampling bias, as rockbolts that failed within the resin column, or that were locked into the roof by strata shear, are omitted from the sample.[2] There are two encapsulation conditions experienced by rockbolts *in-situ*: either there can be strata separation below the resin column, or within the resin column, as shown pictorially in Fig. 4.

In Fig. 4(a), any loading generated by strata separation will cause uniform stress and deformation along the length of the rockbolt. If the rockbolt should then fail by mechanical overload or SCC, the rockbolt will be free to fall from the roof. In the event of strata shear, the rockbolt is likely to be locked in the roof, or will exhibit obvious signs or lateral deformation. The uniform deformation caused by scenario (a) will thus provide useful specimens for this analysis.

In Fig. 4(b), the strata separation will cause localised stress and deformation to the rockbolt as the resin column will prevent load propagating along the length of the rockbolt.[17] This makes rockbolts from scenario (b) less desirable specimens for this analysis. Rockbolts that failed in scenario (b) will likely remain in the roof as the resin column below the separation plane will act to retain them in the roof. Therefore, the proposed sampling bias[2] may in fact benefit this analysis by removing undesirable rockbolts from the sample.

3. Measurement and analysis methods

It is important to note that the rib profile on rockbolts is not of uniform spacing. This is because mass manufacturing techniques introduce slight deviations in spacing from rib to rib. To overcome this, numerous measurements were required in order to quantify the average rib spacing of a rockbolt. This average was then used for the analysis.

Measurements of the rib spacing were carried out with the use of a hand held Scale Loupe with a 7-times magnification. The increments on the scale loupe were etched to a resolution of 0.1 mm. The scale loupe was held against the surface of the spine of the rockbolt and the spacing between the rib profiles was measured as shown in Fig. 5. This measurement point was chosen because it presented the observer with two distinct points from which to measure adjoining rib profiles. The spine of the rockbolt also presented the observer with a straight edge to align

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