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BENT BEAM COUPON TESTING FOR THE INVESTIGATION OF STRESS CORROSION CRACKING IN ROCKBOLTS

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ABSTRACT

Coupon testing has been used to investigate stress corrosion cracking (SCC) of rockbolts in a laboratory based experimental program. This program has focused on the use of ASTM G39 three- and four-point bent beam coupon specimens, immersed in an acidified sodium chloride test solution containing hydrogen sulfide. The specimens were loaded to a range of stresses from zero, to just above the materials yield strength. It was found that only specimens above an applied stress of 580MPa failed by means of SCC, showing that rockbolts loaded to near their yield strength may be susceptible to SCC *in-situ*.

KEYWORDS

Stress Corrosion Cracking, Coupon Testing, Rockbolts.

INTRODUCTION

Stress corrosion cracking (SCC) is a failure mechanism that affects material through the growth of hairline cracks when exposed to a corrosive medium while under stress (Jones and Ricker, 1999). SCC has been found to affect rockbolts in the Australian underground coal mining industry and has the capacity to cause the catastrophic failure of ground support systems, potentially leading to falls of ground in underground excavations, injury or death to mine personnel, damage or loss of equipment, and loss of productivity through the loss of roadway access (Crosky *et al*, 2002).

Coupon testing utilises small scale samples that are intended to be indicative of the behaviour exhibited by a material *in-situ* (ASTM G39). The small scale, and usually high surface area to volume ratio of coupon specimens mean that they corrode at faster rate proportional to their mass, greatly reducing testing times. The small scale of the specimens allows them to be more easily prepared and handled, loaning them to mass manufacturing techniques.

A previous study conducted by Vandermaat *et al* (2012b) into the use of three- and four-point coupon testing *in-situ* in an underground coal mine failed to result in SCC of the specimens. This paper serves as a follow up laboratory investigation in order to understand why these specimens did not fail. Previous studies into the SCC in rockbolts carried out by Gamboa and Atrens (2003) determined that rockbolt steel has a critical stress threshold of approximately 90% of the material ultimate tensile strength (800-900MPa). This study will focus on this critical stress threshold as a possible explanation for the lack of failure in the *in-situ* specimens (Vandermaat, 2012b).

METHODS

Design Considerations

The experimental program was carried out in the Controlled Mine Environment (CME) laboratory at UNSW Australia, outlined in Vandermaat *et al* (2012a). The ASTM International G39 bent beam SCC specimen with associated loading jig was used for these experiments. Several standard specimen geometries are described by ASTM International to examine SCC in materials. The ASTM International

G39 Bent Beam test was identified as the most appropriate of all the ASTM International SCC evaluation specimens as it provided the best compromise between realistic sample loading and specimen fidelity. A detailed description of this decision process is highlighted by Vandermaat *et al* (2012b). A number of arrangements are presented in ASTM G39, and both three- and four-point testing designs were considered in this testing program.

The three- and four-point bent beam tests require the use of a thin, tabular specimen which is mounted in a loading jig. Their names are derived from the number of contact points that the loading jig has with test specimen. In both scenarios, the test specimen is loaded as a simply supported beam, with two contact points on each end of the specimen, and either one (three-point) or two (four-point) loading points in the middle. In both cases, load is applied by a central loading screw; turning the screw advances the loading point and applies a force to the specimen. This loading force creates a bending moment and associated tensile stress in the outer radius of the specimen.

In the three-point bending arrangement, the tensile stress on the outer fibres of the specimen ranges from zero at the outer support posts, to a maximum at the centre loading point. In the four-point test, the stress develops from zero at the outer supports, to a maximum between the two inner supports, where the stress is constant. The three- and four-point loading jigs can be seen in

Figure **1** and

Figure **2**.

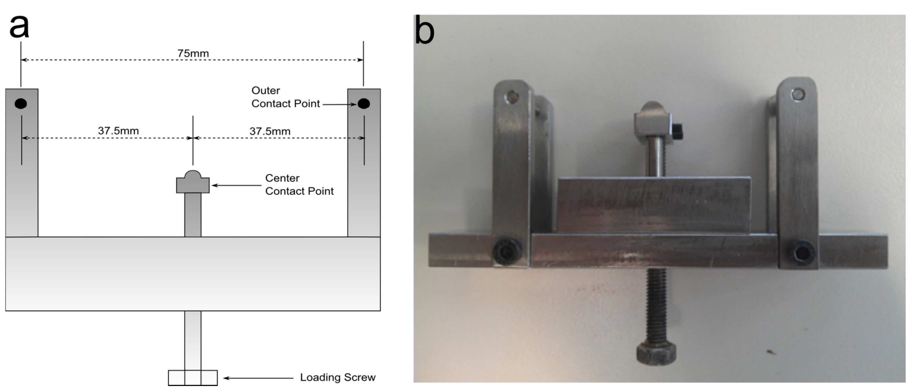

Figure 1: Three-point bending coupon: a) dimensions b) as manufactured.

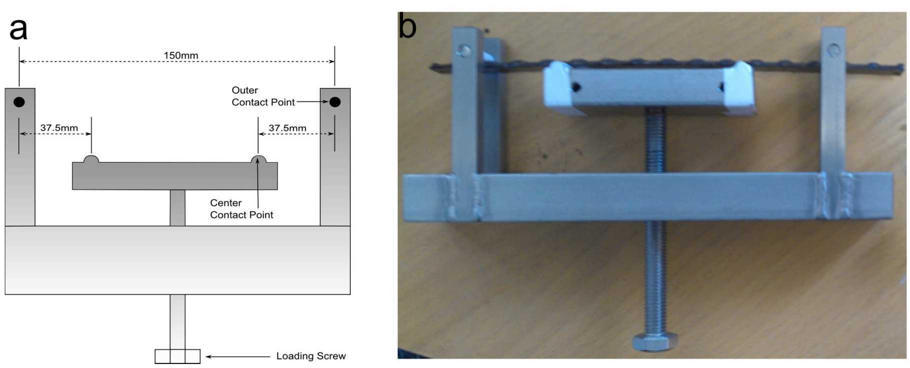

Figure 2: Four-point bending coupon: a) dimensions b) as manufactured (with a coupon specimen).

Sample Preparation

The specimens were prepared by cutting a thin slice from the length of HSAC840 grade rockbolt steel to produce a long, tabular specimen with a rib profile on one side, as shown in

Figure **3**. The samples were then ground flat using a surface grinder. This grade of steel was chosen for its wide use in the underground coal mining industry in Australia (Crosky *et al*, 2002). To prevent any galvanic corrosion between the specimen and the loading jig, the back of the samples were coated with black tar paint. In addition, the contact point of the loading jigs were warped in tape to provide further electrical insulation. Two separate specimen dimensions were required for each of the testing jigs. The sample geometries can be seen in Table 1.

Figure 3: Coupons used in the three- and four-point bend beam coupon testing.

Table 1: Three- and four-point bent beam coupon specimen dimensions.

	Thickness (mm)	Length (mm)
Three-Point Specimen	4	120
Four-Point Specimen	4	200

ASTM G39 recommends the use of polished specimens, however it was decided that the surface effects (such as mill scale and decarburisation) generated through the manufacturing process, were important to the outcome of the experiments. A comparison on the modified sample cross section can be seen in Figure 4. As a result, the equations specified by ASTM G39 for analytically determining the tensile stress in the outer fibre of the specimen had to be recalculated to take into account the curved profile of the specimen. These modified equations are shown in Equations (1) and (2).

$$\sigma_{3point} = \frac{12Edy}{H^2} \tag{1}$$

$$\sigma_{4point} = \frac{24Edy}{2.75H^2} \tag{2}$$

Where:

σ = Stress in the outer fibre (MPa);
E = Young's modulus of the material (230 GPa for rockbolt steel);
d = Distance from the neutral axis to the extreme fibre (mm);
y = Maximum deflection between outer supports (mm); and,
H = Distance between outer supports (mm);

Figure 4: Coupon specimen cross section: a) ASTM G39 suggested specimen b) modified cross section.

Laboratory Testing Program

Laboratory testing was carried out on the three- and four-point coupon specimens to determine the critical stress threshold for SCC in rockbolts. A comparison of the two testing arrangements was also made in this experimental program. Five of each types of sample were prepared and loaded into the loading jigs, as seen in Figure **5**, at a range of deflections summarised in

Table **2** andTable **3**. The deflection points were chosen so that the same range of stress was examined in both the three- and four-point specimens. A range of stresses were chosen to span from zero to just beyond the yield strength of the material.

Once the jigs had been loaded, the specimens were immersed in the acidified sodium chloride (NaCl) solution containing hydrogen sulphide (H_sS) described in Table 4. The specimens were monitored and the time taken for failure to occur was recorded - after 30 days the test was concluded.

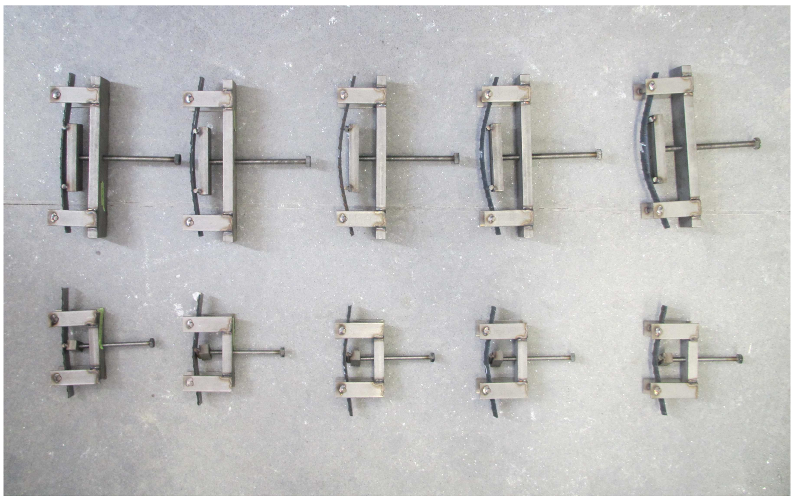

Figure 5: Three- and four-point coupon specimens arranged in loading jigs.

Table 2: Stress placed on three-point specimens.

Three-Point Specimen	Deflection (mm)	Stress (MPa)
1	2	230
2	3	345
3	4	465
4	5	580
5	6	700

Table 3: Stress placed on four-point specimens

Four-Point Specimen	Deflection (mm)	Stress (MPa)
1	4	230
2	6	345
3	8	465
4	10	580
5	12	700

Table 4: Chemical composition of the synthetic test solution.

Solute	Molarity (Mol)	Mass (g)
NaCl	0.62	70
Acetic Acid	0.51	60
NaS	0.013	2
H_2O	-	1570

pH	2.8

RESULTS

Three of the ten test specimens were observed to fail after the 30 day testing period. As seen in Table 5, no specimens loaded to a stress below 580MPa were observed to fail. The three-point failure specimen can be seen in Figure 6,Figure **7** andFigure **8**.

Table 5: Time to failure for the three- and four-point coupon specimens.

Specimen	Time to failure
Three-Point 1	-
Three-Point 2	-
Three-Point 3	-
Three-Point 4	9 day
Three-Point 5	-
Four-Point 1	-
Four-Point 2	-
Four-Point 3	-
Four-Point 4	13 days
Four-Point 5	13 days

Figure 6: SCC failure of three-point specimen. The lack of permanent deformation shows that the specimen has not experience yielding.

Figure 7: Close up view of the three-point SCC failure.

Figure 8: View of the three-point specimen failure surface.

DISCUSSION

The occurrence of specimen failure in specimens loaded up to and above 580MPa indicates that SCC may affect rockbolts loaded at below their yield strength. Furthermore, failures of specimens at these stress levels indicate that SCC in rockbolts is not necessarily a high stress, post yield phenomenon, as suggested by Gamboa and Atrens (2003). In addition, time to failure does not appear to be a function of stress, with both four-point specimens 4 and 5 failing in a similar time frame.

Furthermore, the three- and four-point specimens used in the *in-situ* testing program outlined in Vandermaat *et al*, (2012b) where only loaded to a deflection of 5mm - 580MPa and 290MPa, respectively. This would place these *in-situ* specimens at, or below the observed threshold stress in this aggressive, acidified solution, and may explain why they did not fail. Further *in-situ* testing at higher stress levels and with various other steel chemistries is recommended.

A comparison of the three- and four-point testing arrangement favours the four-point specimens. The three-point specimens are susceptible to crevice corrosion around the side of the inner contact point, which may act to electrochemically 'protect' the highly stressed opposite. Furthermore, the interaction at the loading point interface generates a bi-axial stress state, which may affect the experiment.

The use of other coupon specimen geometries should also be considered for *in-situ* testing. The slotted coupon specimen outlined by Elias *et al* (2013) has also shown to be an effective analogue for investigation rockbolt SCC. The smaller profile of this slotted specimen allows it to be more easily handled and placed *in-situ*. A follow up field investigation should include the use of these specimens.

CONCLUSIONS

The critical stress threshold for rockbolt steel is still yet to be exactly quantified. This experimental program, however, has shown that SCC in rockbolt may not necessarily be a high stress phenomenon, and may affects rockbolts loaded up to, and even below their yield strength. This experimental program has also shown that the stress placed on the original *in-situ* specimens may have been too low to cause SCC failure. Follow up field testing should be carried out at higher stress levels.

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