AN EXPERIMENTAL INVESTIGATION ON CABLE REINFORCEMENT

By

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ABSTRACT

The paper presents the results of a series of pull out tests performed on roof reinforcement systems currently being adopted in mines in Australia: 7mm wire, dividing bar, 15.2mm strand cable, and birdcage cable. The study also investigated the load deformation characteristics and the various design parameters controlling the effectiveness of a cable-grout system. Suggestions for continued work are highlighted.

INTRODUCTION

The use of steel bolts in the strata control of underground coal mines is continually changing with the advent of new technology. In longwall mining, the problems of roof instability along the coal face have been significantly reduced with advanced designs and high load bearing capacities of the powered supports currently in use in Australia. Instability problems of gate roads or roadways however remain largely unabated although a number of effective geological measures (see Schaller and Davida, 1985. Gale and Fabjanczyk, 1986) has been devised to improve strata stability. These measures include:

(i) Fully grouted bolts (2.1 - 2.7 m) placed directly at the faces driven, and at intersections.

(ii) Grout chock-bags for secondary support in areas under high abutment load, and

(iii) The use of cable bolts, which is under intensive field and laboratory studies at many research organisations in Australia.

It can be recalled that the use of cable reinforcement in Australia has only gained wide acceptance in cut-and-fill mining in the mid-seventies (Fuller, 1984). The main advantages of cable bolting can be listed as:

(i) Cable bolting can reinforce a rock mass like steel in a reinforced concrete beam. Cable bolting is thus most effective in layered rock when the rock material is strong in a small scale but is weak as a rock mass due to "plains" weak zones (Lappalainen et al., 1984).

(ii) Cable bolting is economical, by way of low cost per reinforcement effect, and

(iii) Cable bolting is by far the more flexible reinforcement system with bolt length ranging from 1-80m in metalliferous mines, and 1-10m in coal mines.

This paper presents the results of a laboratory investigation initiated and made in collaboration with the CSIRO, Division of Geomechanics on the performance and load deformation characteristics of four types of tendons: 7mm steel wire, Dividing bar, 12.5mm strand cable, and birdcage cable (Table 1). For reviews of previous work on cable supports, most of which were in metalliferous mining applications, readers are referred to published reports by Fuller and Cox (1975). Fuller (1981, 1983, 1984). Stheeman (1982) and Fabjanczyk (1982).

PULL-OUT TESTS ON 7MM BENT WIRE

TEST ARRANGEMENT

The main objective of this test series is to investigate the influence of different bend amplitudes on the load transfer characteristics of 7mm steel wires. This work was originally carried out and reported by Fuller and Cox (1977). Single tests were performed on 7mm diameter bent wires randomly selected from one batch and allowed to rust. The wavelength of the bends was fixed, by a three point load frame, at approximately 100mm (Figure 1). The wires were grozoted into galvanized steel tubes of 50mm nominal bore and 3.6mm wall thickness to the required embedment length. The threads on one end of the steel tube and the holder were specially designed and machined for the

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93
TABLE 1. THE STRAND PROPERTIES

<table>
<thead>
<tr>
<th>Type of strand</th>
<th>Cross-section Area (mm²)</th>
<th>Apparent modulus of elasticity</th>
<th>Ultimate Strength (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birdcage strand</td>
<td>282.7</td>
<td>180-200</td>
<td>350-400</td>
</tr>
<tr>
<td>(5mm destranded</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>strand) 10-wire</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>strand 45mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel wire</td>
<td>38.5</td>
<td>193</td>
<td>70</td>
</tr>
<tr>
<td>= 7mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 wire strand</td>
<td>97.5</td>
<td>193</td>
<td>184</td>
</tr>
<tr>
<td>cable = 12.5mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pre stressing wire.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dividing Bar</td>
<td>314</td>
<td>193</td>
<td>341</td>
</tr>
<tr>
<td>20 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 1 BENT WIRE BEFORE GROUTING

Experiments (Figure 2), and the strength of the holders and the threads were tested before cement grout was poured into the tube. In this series, the grout has a water cement ratio of 0.45 : 1.0.

All the tests were carried out after the cement grout was allowed to cure for twelve days.

The testing machine used in the series was a servo-controlled (electro-hydraulic) INSTRON machine (Series 8000). It is recalled that a servo-controlled testing machine can be viewed simply as a device that varies the applied force such that a feedback parameter, i.e., an experimental output, may coincide with a prescribed function of time. The feedback parameter may be the output from a load transducer or it may be the differential displacements of two points within a test specimen.

Electrical transducers were used to record both force and displacement. Experimental data was automatically printed and plotted by an INSTRON series 8000 control console.

In the tests, the rate of deformation was set initially at 0.05mm per second, and increased to 0.1mm and 0.5mm per second afterwards. The electrical outputs from the transducers together with load were recorded as a function of time.

RESULTS

The force displacement curves in Figure 3 show typical load deformation characteristics of bent wire tested in this study. Compared with similar tests on straight wires, the results depicted in Figure 3 show that load deformation curves for bent wires have a gentle rise in

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94
resistance to a second peak (B) after an initial sharp peak (A) was attained. At low deformation, prior to the first peak (A), the load deformation curves for all wires (Figure 4) show a non-linear and hyperbolic-type characteristic similar to that given by Fuller (1984). The initial peak (A) occurs at almost the same yield load, whereas the secondary peak (B) increases proportionately with increased bend amplitudes, and takes place at about 26mm of wire slippage and deformation.

The effect of change in embedment length for bent wires with similar amplitudes is shown in Figure 5. By increasing the amplitude of the bent wires, 0.5mm to 3mm, the embedment length required to produce the same maximum load resistance is reduced. It is also of interest to note that after pull-out tests, all the original bends were eliminated.

This indicates that the wires in the tests underwent extensive plastic deformation, with the first peak characterizing bond adhesion and the second peak, frictional resistance. It was commonly observed that a thin layer of grout adhered to the wire in spots after pull-out tests.

Load transfer across the steel-grout interface increased by more than threefold from tests with straight wire to tests with bent wire configurations (Figure 3). The peak load of bent wire approaches the ultimate tensile strength of straight wire (70 kN) when the bend amplitude is equal to 8.5mm (Table 2) and embedment length is 500mm. Displacements of 26mm in magnitude were apparent prior to development of the peak tensile strength in the reinforcement system. Such displacements are normally undesirable in practice.

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**FIGURE 2** GALVANIZED STEEL TUBE AND HOLDERS

**FIGURE 3** RESULTS FOR LARGE DISPLACEMENTS OF WIRES HAVING DIFFERENT BEND AMPLITUDES

**TEST ARRANGEMENT**

Reinforcement bars of the type used in concrete technology were cut to lengths of 370mm and 570mm. The bars were grooved into steel tubes of 43mm nominal bore and 3.6mm wall thickness (Figure 6) using polyester resin. The pull-out test was performed using an Avery testing machine, and electrical outputs from the transducers together with load were recorded as a function of time. Figure 7(a) is a diagrammatic
TABLE 2. SUMMARY OF RESULTS FOR BENT WIRE REINFORCEMENT EXPERIMENTS

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Embedment Length (mm)</th>
<th>Peak Load (kN)</th>
<th>Peak Load per Unit Embedment Length (kg/100mm)</th>
<th>Average Group Unconfined Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
<td>3</td>
<td>33.5</td>
<td>16.75</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>3</td>
<td>54.5</td>
<td>18.17</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.5</td>
<td>38</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>1.0</td>
<td>45</td>
<td>11.25</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>1.5</td>
<td>64.0</td>
<td>13.62</td>
</tr>
<tr>
<td>High</td>
<td>400</td>
<td>straight</td>
<td>13.5</td>
<td>3.38</td>
</tr>
<tr>
<td>Tensile</td>
<td>500</td>
<td>straight</td>
<td>15.5</td>
<td>3.1</td>
</tr>
<tr>
<td>Steel</td>
<td>500</td>
<td>1.5</td>
<td>52.5</td>
<td>10.5</td>
</tr>
<tr>
<td>Wire</td>
<td>500</td>
<td>5</td>
<td>64.5</td>
<td>12.9</td>
</tr>
<tr>
<td>7mm</td>
<td>500</td>
<td>8.5</td>
<td>70</td>
<td>14</td>
</tr>
</tbody>
</table>

FIGURE 4 RESULTS OF PULL OUT OF 7mm WIRES WITH DIFFERENT EMBEDMENT LENGTHS AND AMPLITUDES

sketch of pull-out test arrangement for a diviag bar in this series. Only two specimens were tested.

RESULTS

Figures 8 and 9 give the force displacement curves for the two specimens. The two curves showed in general identical trend. The specimens with 500 mm embedment length however revealed a higher stiffness than that with 360 mm embedment. Test observations also revealed that the tube started to yield at point A (11.4 tonnes). Point C in Figure 6, and point D in Figure 9 correspond to the ultimate strength of the bars (34 tonnes or 340 kN). Unconfined compressive strength tests on the resin grout used in this series showed a relatively high strength, 86 MPa, and an average modulus of 6.7 GPa. It is apparent that load transfer by a diviag bar is higher than plain wire and bonding resistance can be mobilized to full capacity with short embedment. It is cautioned however that the results in this series might be inaccurate due to the crushing of the pipe by the jaw of the Avery machine. A modification of the test arrangement involving the insertion of a plug on the bottom of the steel tube is aimed at preventing the jaw from crushing the pipe (Figure 7b).
FIGURE 6 DIVIDAG BAR SPECIMEN READY TO BE TESTED

FIGURE 7a TEST CONFIGURATION FOR DIVIDAG BAR

7-WIRE STRAND CABLE

TEST ARRANGEMENT

This test series was performed to investigate the load deformation behaviour of 7-wire prestressed strand cable under pull-out loads. The diameter of the cable is 12.0mm and the ultimate strength and modulus are 184 kN and 193 GPa, respectively. Reinforced cables were grouted into galvanized steel tubes of 50mm bore and 3.6mm wall thickness. The internal walls of the tubes were grooved to increase bonding between grouts and the walls.

INSTRON testing machine was used for this series and the test configuration is similar to that in series 1 (Figure 10). (Figure 10 shows a pulled out 7-strand cable). The

FIGURE 7b MODIFIED TEST CONFIGURATION FOR DIVIDAG BAR EXPERIMENT

complete force displacement curves were automatically plotted by the INSTRON 8000 control console.

In this series both cement and resin grouts were used and the grouts were tested subsequently for strength.

RESULTS

Figure 11 gives the results of the three pull-out tests of this series using cement grout. Curves 1 and 3 in Figure 11 were obtained from the same loading rate of 0.05mm/s at peak load and 0.1mm/s in the post-peak range. For test 2, loading was maintained at a constant rate of 0.1mm/s.

The test specimens failed at resin and wall...
Interface at very low loads. The observed failure modes suggest that the poor adhesion between the resin and galvanized steel walls could be the main factor contributing to failures, and such are not representative.

**BIRD-CAGE CABLES**

**TEST ARRANGEMENT**

The experiments involved the pulling-out of 10 destranded strand bird-cage cables enclosed in cement and resin grouts. Bird-cage cables have been used recently in strata roof reinforcement at Appin Colliery.

The bird-cage cables (Figure 12) were cut into 760mm and 1080mm lengths, and grouted into 50mm nominal bore and 12.7mm wall thickness. The interior walls of the steel tubes were grooved to improve bonding between grouts and walls (Figure 13). In addition to pull-out tests performed on the INSTRON machine, unconfined compression tests and triaxial tests were carried out on cylindrical specimens made up by the grouts used in pull-out tests.

**RESULTS**

Figure 14 shows the force-displacement curves

**FIGURE 8 PULL OUT OF 20mm 'DIVIDAG BAR'**

**FIGURE 9 PULL OUT OF 20mm 'DIVIDAG BAR'**

**FIGURE 10 INSTRON TESTING MACHINE WITH SPECIMEN OF SERIES III EXPERIMENTS**

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for large displacements of bird-cage split-tube pull-out tests.

Curves 1, 2 and 3 of Figure 14 show that, for the same embedment length, a higher load transfer can be achieved by using grout with a higher stiffness and higher uniaxial strength.

Curves 2 and 3 show that an initial peak resistance is followed by a secondary peak, similar to the series 1 results with bent wires, and the magnitude of the secondary peak is dependent on grout strength. Table 3 shows a summary of results including the relationship of grout properties to pull out characteristics.

**SUMMARY OF RESULTS**

In this study a system of pull-out experimental instrumentation has been developed to obtain basic information on the bond characteristics of tendon systems. The success of the experimental instrumentation has been proved by laboratory pull-out tests.

From the results obtained in this study, it can be concluded that:

1) The wires bent into cyclic form and grouted in cement grout exhibit greater load transfer and stiffness than equivalent straight wires. This improvement in load transfer continued for considerable displacements.

The results also indicated that the tensile strength of the wire is unaffected up to a threshold pattern of 0.6m amplitude x 100mm he wavelength.

[Diagram of pull-out test results]

**FIGURE 11** PULL OUT OF PRESTRESSING T-WIRE STRAND (12.5mm )

[Image of birdcage cable]

**FIGURE 12** 10 STRAND BIRDCAGE CABLE
(2) The results of dividag bar pull-out tests showed excellent load transfer on the steel-grout interface. This could be due to the coarse thread on the bar, and it was observed also that load transfer of dividing reinforcement can achieve maximum capacity with 300-500m embedment.

(3) The bird-cage pull-out tests have shown that the capacity and stiffness of the system are dependent on the grout strength and modulus of elasticity of the grout. The deformation of the bird cage within the grout when subjected to a tensile force is complex. The major load transfer mechanism at small displacements is deduced to be wire straightening and crushing of the grout in the birdcage "antinodes". At longer displacement the antinode is pulled into the grout wedge at the node of the birdcage, this wedging action gives the secondary peaks on the load displacement curves in Figure 14.
TABLE 3 BIRDCAGE STRAND CHARACTERISTICS

<table>
<thead>
<tr>
<th>Embedment Length</th>
<th>Graft Type</th>
<th>UCS (MPa)</th>
<th>E (GPa)</th>
<th>UTS (kN)</th>
<th>'Stiffness (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>380</td>
<td>RESIN</td>
<td>324.2</td>
<td>5</td>
<td>131.7</td>
<td></td>
</tr>
<tr>
<td>380</td>
<td>RESIN</td>
<td>170.5</td>
<td>3</td>
<td>75.6</td>
<td></td>
</tr>
<tr>
<td>380</td>
<td>CEMENT</td>
<td>253.4</td>
<td>10</td>
<td>155.5</td>
<td></td>
</tr>
<tr>
<td>540</td>
<td>RESIN</td>
<td>387.2</td>
<td>5</td>
<td>(96.9)*</td>
<td></td>
</tr>
</tbody>
</table>

*Figure uncorrected for additional pipe deformation.

CONCLUSIONS

The comparison of performance of the four Tendon types investigated shows the wide variation of load transfer capacities between tendon types and grout properties.

The tendon type used most frequently within coal mines is now the birdbcage strand, with its ability for long lengths to be placed in areas with low headroom.

As part of an AMIRA sponsored project the CSIRO is investigating the application of cable bolting to roof reinforcement in coal mines. The work on the load transfer characteristics of the tendons is part of this investigation.

In order to provide design criteria for cable bolting the load transfer behaviour of the cable system has to be obtained, and the parameters influencing its behaviour determined. The initial tests discussed here were to prove the testing system and obtain values on the systems which have been used in mines to date. The tests have shown the correlation between grout strength and stiffness and load transfer behaviour.

A further series of tests to be carried out in collaboration with Wollongong University are designed to further investigate the load transfer in tension and in shear of the birdbcage tendon system with a wide variety of grout types.

These tests will independently investigate the influence of grout stiffness and strength on the birdbcage tendon behaviour.

With the optimisation of the load transfer behaviour the roof reinforcement capabilities of the cable can be increased (Gale 1986).

The design of cable bolting patterns although still empirical can be improved if the failure mechanism of the roof strata can be determined and the appropriate reinforcing action of the cable array selected.

ACKNOWLEDGEMENTS

The support for this study by the Mining Research Centre (University of Wollongong) is gratefully acknowledged.

The authors are indebted to Dr. W. Gale of the CSIRO, Division of Geomechanics for their helpful suggestions in the course of this work, and Mr. D. Tague for his valuable technical advice.

REFERENCES


