A Laboratory Study on the Capacity of Fully Grouted Cable Bolts Subjected to Combined Axial and Lateral Loads

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INTRODUCTION

Cement grouted 7-wire strands, herein called cable bolts, are ground reinforcing elements widely used in mining and geotechnical engineering. Past research evaluated their performance under axial [1,2, 3, 4 & 5] and direct shear [6 & 7] loading configurations, neither of which are strictly applicable in undergound mining environments. A more general scenario is shown in Figure 1. After creation of an excavation, a reinforced block of rock moves downwards inducing both joint dilation (v) and shear (u). Depending on the bond capacity of the reinforcing system, the cable will either rupture at the joint or debond in the block adjacent to the excavation. The purpose of this research was to evaluate the capacity and the stiffness of fully gouted cable bolts by varying their orientation with respect to the joint displacement.

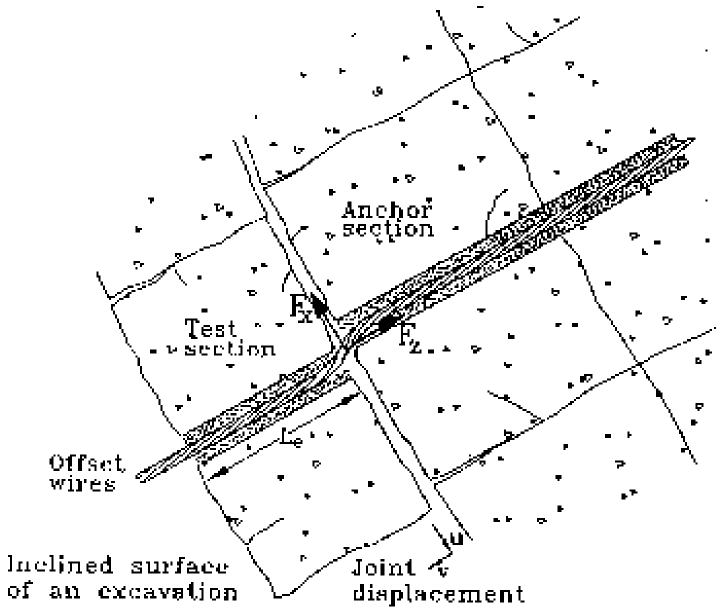
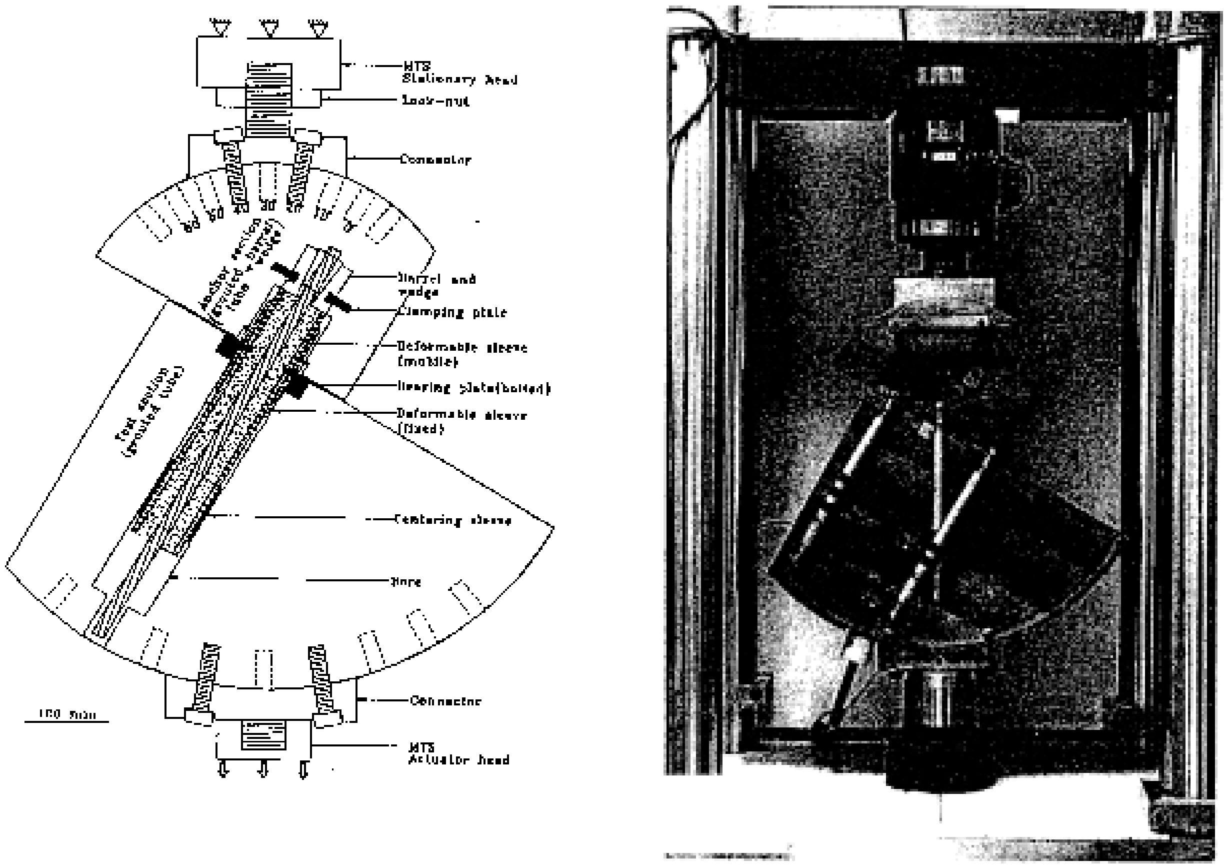


Figure 1 Schematic diagram of the field situation tested. The fundamental assumptions were: (i) the rock remained intact; (ii) joint roughness was discarded; (iii) the cable was oriented perpendicular to the joint; and (iv) translation was applied without block rotation. Bond failure takes place in the test section (adjacent to the excavation) since it has a shorter embedment length (Lẹ) than the anchor section (i.e. deeper in the rock mass).

MILESTONE 1 - DESIGN AND CONSTRUCTION OF THE TESTING APPARATUS

The apparatus shown in Figure 2 was constructed to simulate the *in situ* scenario described above. It consists of two steel plates (100 mm thick) machined in the form of approximate 120° degree arcs with coincident centers but different radii. Their common surfaces can be considered as the joint undergoing combined dilation and shear. They were fastened to the heads of a Materials Testing System (MTS, 500 kN capacity) using circular connectors. The pull angle was varied by rotating the plates on the connectors in increments of 10°: Θ=0° corresponding to axial pull tests; Θ=10° to Θ=60° for inclined pull tests with an increasing component of shear.



(b)

Figure 2 Section (a) and photograph (b) of the testing rig mounted on the MTS for an inclined pull test at Θ=30°.

A pull test sample comprised a cable grouted into two confining tubes (Figure 3). To simulate the block of rock moving into the excavation, the test section was displaced axially by a bearing plate. To reproduce the intact bond deeper in the rock mass, a short anchor section was held fixed with a barrel and wedge.

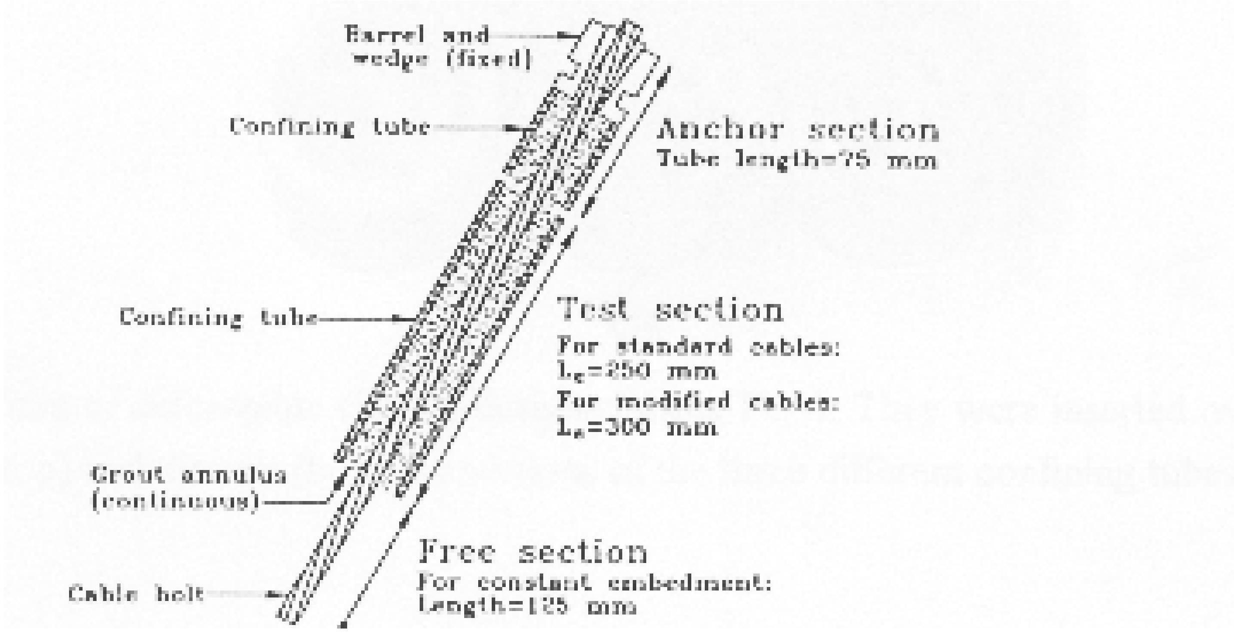
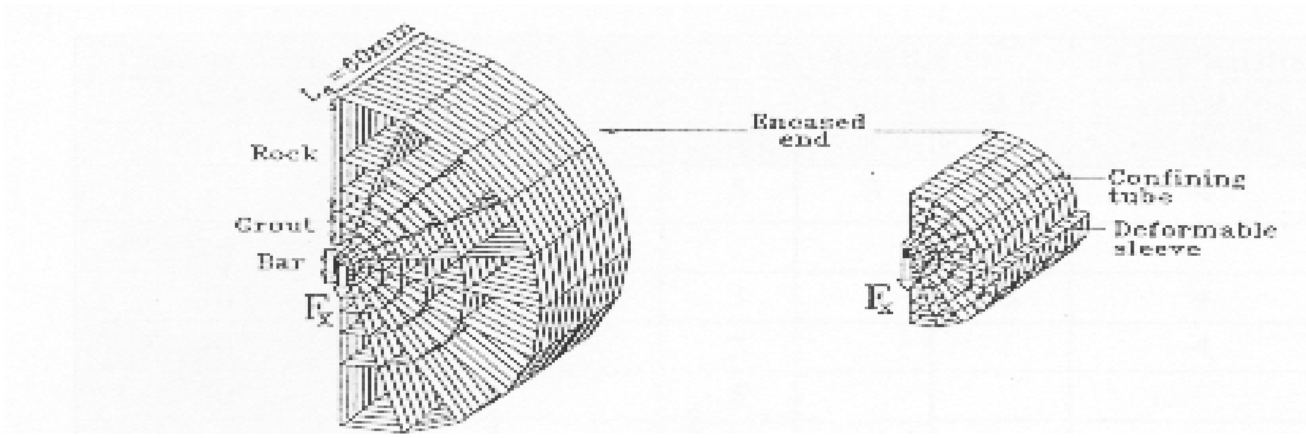


Figure 3 Laboratory sample: identical grout and confinement were used for both sections.

Lateral support was provided by a pair of deforrnable sleeves (Figure 5) inserted over the sample. These were designed using two finite element models (FEM). The first model (Figure 4a) simulated the field condition of a bar grouted in a borehole of radial stiffness equivalent to a given confining tube. Computed deformations of the grout annulus were then matched in another model (Figure 4b), which represented the laboratory condition, by varying the stiffness of the deformible sleeve installed in front of the corresponding confining tube.



(a) (b)

Figure 4 FEM of the field (a) and laboratory (b) conditions. The encased end, the outer periphery of the rock annulus and of the deformable sleeve were held fixed in all directions. Fx= Lateral load.

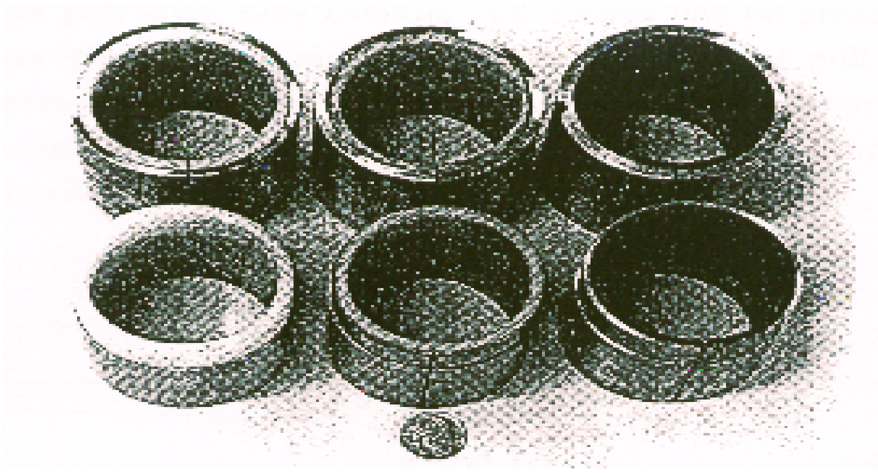


Figure 5 Pairs of deformable sleeves designed using FEM. They were inserted over the anchor (top) and the test (bottom) sections of the three different confining tubes.

MILESTONE 2 - PULL TESTING OF STANDARD CABLE BOLTS

Table 1 shows the pull test programme for standard cable bolts. The following parameters were varied:

i) the radial stiffness of the confining tubes; less stiff from left to right in Table 1,

ii) the grout water cement ratio (*w/c*); good quality (*w/c*=0.3) and poor quality (*w/c*=0.5) grouts,

iii) the strand manufacturer; and most importantly

iv) the orientation of the cable with respect to the applied displacements.

Confinement	St-sched.80		Al-sched.80			Al-sched.40
w/c	0.3	0.5	0.3		0.5	0.3
Strand	A	A	A	B	A	A
0°	4	4	5	3	4	4
20°	2					
30°	4	3	3	4	3	4
40°	4		3			4
50°	4		5			
60°	5	4	5	4 - 3*	4	2

Table 1 Number of pull tests for standard cable bolts. * Tested with steel sleeves instead of defor7nable sleeves. Lė= 250 mm in the test section. St and Al denote steel and aluminum, respectively.

Since Table 1 lists 94 pull tests, only average pull curves will be presented below. Figure 6 plots pull force against total displacement measured in the direction of pull. For tests preformed between 0˚ and 30˚, the stiffness (i.e the slope of the pull curve) was almost unchanged and the ultimate bond strength increased only for the 0.3 *w/c* grout. However, for 40˚ and above, the stiffness decreased and the bond strength increased significantly.

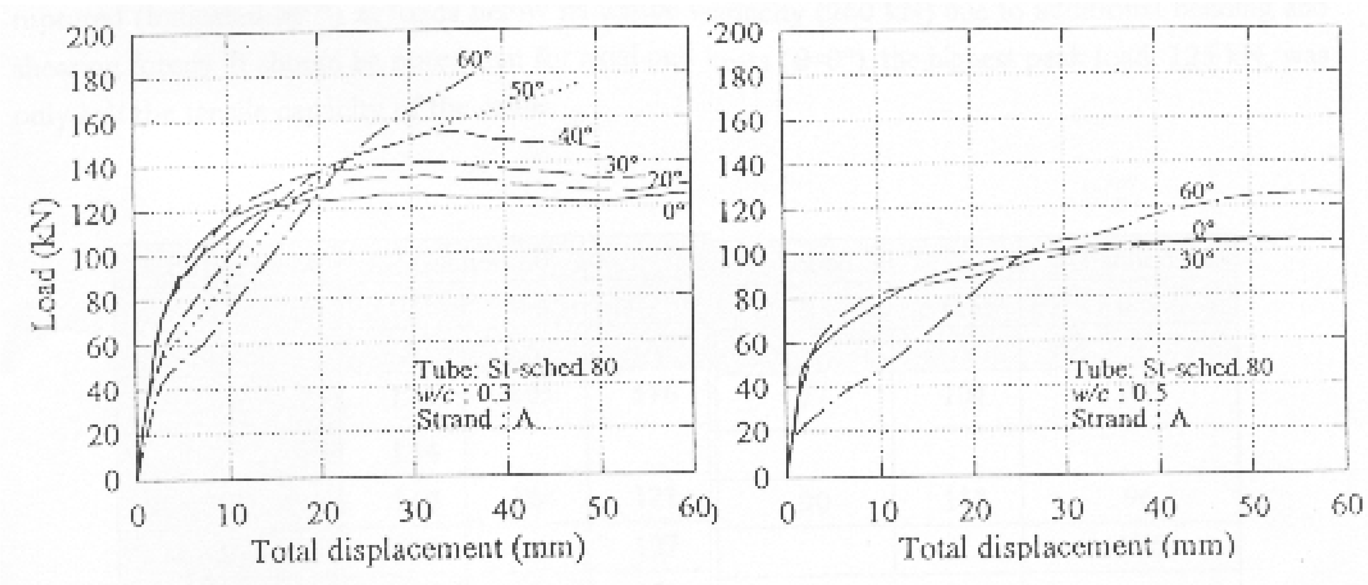


Figure 6 Average pull tests using different grout quality.

Figure 7 shows the pull curves for strands from different manufacturers. It demonstrates that the response from strand A was slightly stiffer and had higher bond strength than that from Strand B. This effect was less pronounced during steeply inclined pull tests (Θ=60°).

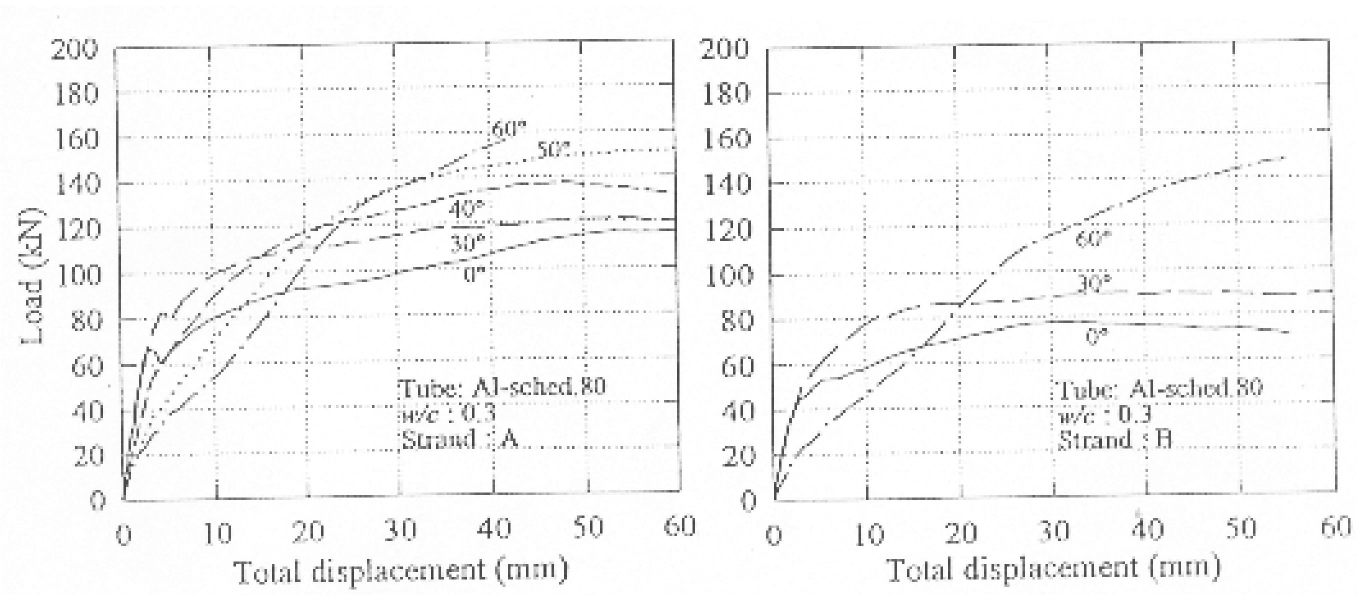


Figure 7 Average pull tests using different Strands.

Table 2 lists the average peak loads for standard cable bolts. Contrary to expectation prior to this research, in all cases peak load increased with pull angle. This effect was most pronounced for stiff confinement and/or good quality grout. For steeply inclined pull tests ($\theta \geq 50°$), the cable ruptured (indicated by *) at loads below it tensile capacity (260 kN) due to additional bending and shearing forces. It should be noted that for axial pull tests ($\theta = 0°$), the highest peak load, 125 kN, was only half the tensile capacity of the cable.

Confinement	St-sched.80		Al-sched.80			Al-sched.40
w/c	0.3	0.5	0.3		0.5	0.3
Strand	A	A	A	B	A	A
0°	125	105	116	77	104	100
20°	134					
30°	140	104	121	90	113	96
40°	154		137			126
50°	175*		152			
60°	182*	125	165*	147*-140*	138	138

Table 2 Peak loads (in kilonewtons) from average pull tests on standard cable bolts.
* Indicates that at least one cable ruptured.

MILESTONE 3 – PULL TESTING OF MODIFIED CABLE BOLTS

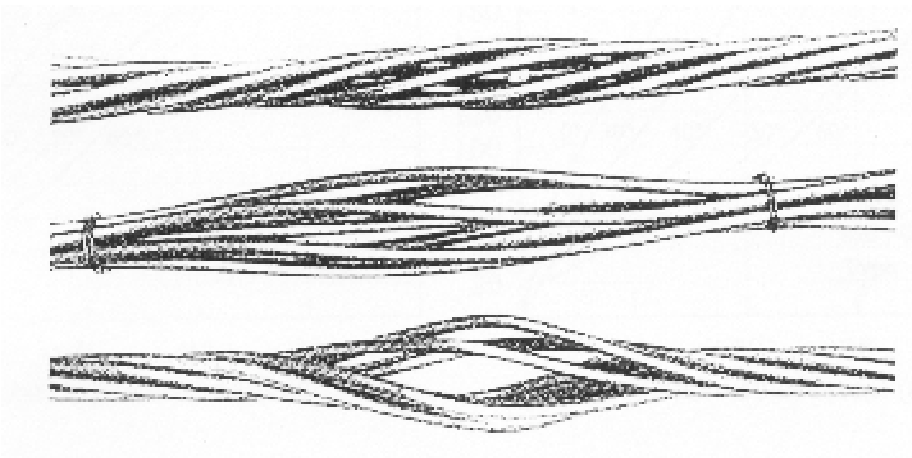


Figure 8 Modified cables: Nutcase(top), Birdcage (middle) and Garford Bulb (bottom)

Figure 8 shows the three types of modified cable tested in this programme. Previous research established that these, when fully grouted, have a high bond capacity which is relatively insensitive to the *w/c* of the grout and the stiffness of the confinement.
Therefore, as outlined in Table 3, the pull angle was the only parameter varied.

Cable Type	Nutcase	Garford Bulb	Birdcage
0°	3	3	3
30°	3	4	3
40°	3	2	3
50°	3	2	3
60°	3	3	3

Table 3 Number of pull tests for modified cable bolts. All tests were performed in A1-sched.80 confining tubes using a 0.4 *w/c* grout. Lė=300mm in the test section.

Average pull curves for Nutcase and Garford Bulb cable are plotted in Figure 9. For axial pull tests (θ=0°), the bond strength was just above 250kN which was roughly double the highest average peak load for standard cable at θ-0° (Table 2) and was close to tensile capacity of the cable itself. Most importantly, the results demonstrate that the stiffness dropped with increased pull angle; the Garford Bulb cable always being slightly softer than the Nutcase cable. Average curves for Birdcage cable were not calculated because their response was too inconsistent (see [8] for dtails).

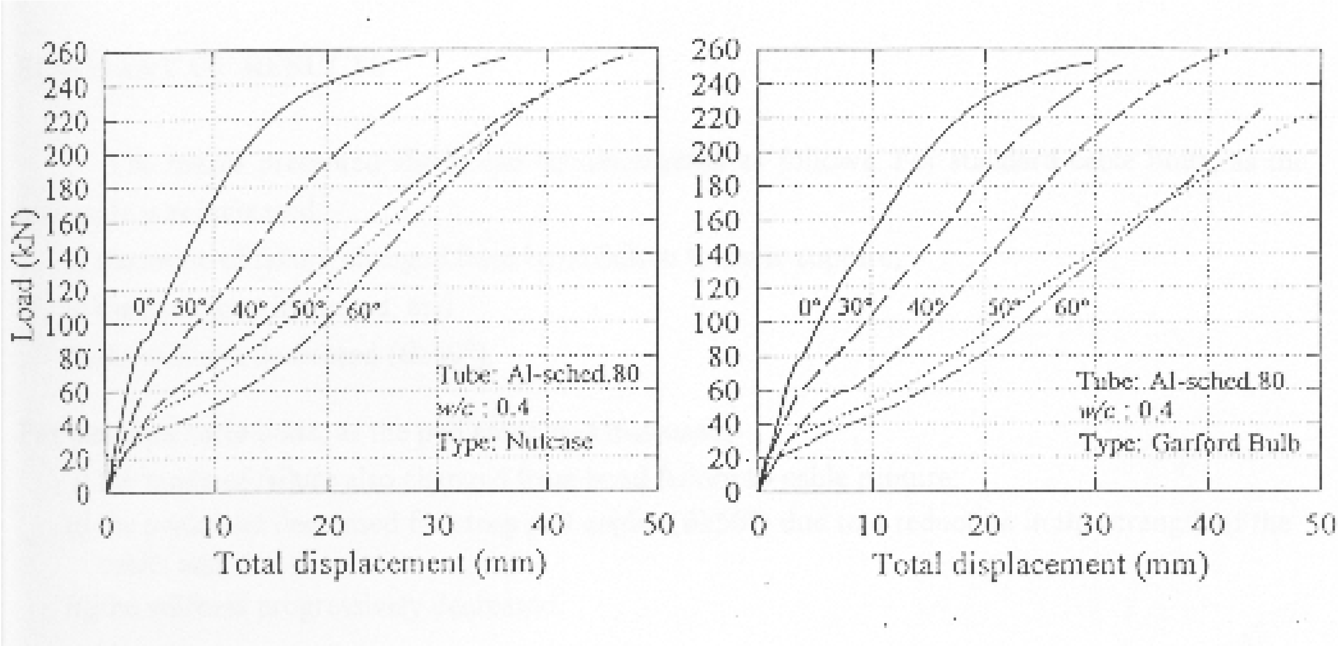


Figure 9. Average pull tests for Nutcase and the Garford Bulb Cable.

As shown in Table 4, the average peak loads were practically the same for tests performed at 0°, 30° and 40°, but dropped slightly for tests performed at 50° and 60°. For all inclined pull tests (θ>0°), the mode of rupture involved rupture of the cable.

Cable Type	Nutcase	Garford Bulb	Birdcage
0°	257	251	-
30°	255*	251*	-
40°	256*	258*	-
50°	243*	223*	-
60°	225*	225*	-

Table 4 Peak loads (in kilonewtons) from average pull tests on modified cable bolts.
* Indicates that at least one cable ruptured.

SUMMARY OF RESULTS

The results presented above can be summarized as follows. For standard cable bolts, as the pull angle was increased;

i) the mode of failure changed from bond failure to cable rupture;

ii) the peak load increased; and

iii) the stiffness decreased (θ≥40°).

For modified cable bolts, as the pull angle was increased;

i) the mode of failure also changed from bond failure to cable rupture;

ii) the peak load decreased for steep pull angles (θ≥50°) due to a reduction in the strength of the cable; and

iii) the stiffness progressively decreased.

Considerations	Standard cables	Modified cables
Mode of failure	0°-50° Bond failure 60° Bond failure/cable rupture	0° Bond failure 30°-60° Cable rupture
Peak load	0°-30° Slight increase 40°-60° Significant increase	0°-40° No change 50°-60° Slight decrease
Stiffness	0°-30° No change 40°-60° Progressive decrease	0°-60° Progressive decrease

Table 5 Summary of results

IMPLICATIONS OF THE RESEARCH

The design of cable bolt patterns (density and spacing) is usually based on well-established geometric considerations accounting for the rock structure (joint frequency and block size). This research will help rock engineers design more effective cable bolt patterns by incorporating additional mechanical considerations such as those presented in Table 5.

Ultimately, the data will be used to derive a constitutive behaviour for cable bolts loaded due to combined axial and lateral displacements. This will be incorporated into the cable bolt element (CABEL) presently under development at Queen's University prior to implementation in numerical models such as Phases, UDEC and FLAC.

Finally, this research was the topic of a Masters thesis [8] which will include all related details.

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