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Parametric studies of cable bolts using a modified Short Encapsulation Pull-out Test

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ABSTRACT: The laboratory short encapsulation pull out test (LSEPT) has been widely accepted as the most efficient method to characterize the mechanical behaviour of cable bolts under axial loading. In this study, a number of LSEPTs was performed on conventional cable bolts including Plain SuperStrand and TG cable bolts using the improved pull out test design. The effects of several parameters including the uniaxial compressive strength (UCS) of confining medium and grout and the borehole diameter on the mechanical behaviour of both cable bolts were investigated. Analysis of Variance (ANOVA) was employed to quantify the contribution of these parameters on the responses including peak and residual loads and initial stiffness. ANOVA revealed that UCS of confining medium and grout is the key contributing factor to the mechanical behaviour of Plain SuperStrand cable bolt. Also, it was demonstrated that the borehole diameter had a negligible impact on the overall behaviour of TG cable bolt while the peak load of SuperStrand cable bolt was increased due to an increase in the diameter of borehole. Finally, from a comparative analysis, it was confirmed that TG cable bolt exhibits a higher load carrying capacity than Plain SuperStrand cable bolt.

INTRODUCTION

Cable bolts, as well as rock bolts, have been increasingly used for strata reinforcement in underground coal mines over the past few decades (Aziz et al., 2016; Aziz et al., 2015; Ghadimi et al., 2015; Hyett et al., 1995; Jalalifar and Aziz, 2010; Jalalifar et al., 2006; Li et al., 2017; Li et al., 2016). The types of cable bolts which are currently used in the mining industry can be classified into two main categories, namely conventional and modified (Li et al., 2017). The former is made of several plain steel strands (e.g. plain strand cable bolts) while the latter has different forms of deformed structure such as bulb, nutcage or birdcage.

A number of researchers have investigated the effect of different parameters on the performance of conventional cable bolts in service (Chen and Mitri, 2005; Goris, 1991; Hyett et al., 1995; Reichert, 1991; Stillborg, 1984). The peak load of the load-displacement performance of plain strand cable bolts in pull-out tests was found to increase with encapsulation length (Chen and Mitri, 2005; Goris, 1991; Hassani et al., 1992; Hyett et al., 1992; Stillborg, 1984). Goris (1991), Reichert (1991), and Stillborg (1984) demonstrated that an increase in compressive strength of the grout used to embed the cable bolt lead to an increase in peak shear strength of the plain strand cable bolt at the grout to cable bolt interface. The effect of grout strength on the initial stiffness was inconclusive as on the one hand, Stillborg (1984) reported that the initial stiffness increased with grout compressive strength while Reichert (1991) reported no meaningful correlation between these two parameters. Rajaie (1990), Chen and Mitri (2005) and Mosse-Robinson and Sharrock (2010) concluded that borehole diameter

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has a negligible effect on the peak load and initial stiffness of load-displacement behaviour of plain strand cable bolts.

In this study, two types of conventional cable bolts including Plain SuperStrand and TG cable bolts were investigated. The LSEPT facilities and testing procedures can be referred to the study by Li et al. (2018b) as seen in Figure . The advantage of such a testing design is that the rotation of the cable bolt steel strands could be restricted during the pull out of the cable bolt through using the locking key and locking nut (seen in Figure) that can prevent the relative spinning movement of anchor tube, bearing plate and sample holder tube. Such a device can hence leads to a more realistic reflection of the field testing conditions. The details of ANOVA can be reffered to the study by Li et al. (2018a). The effects of a range of parameters including confining medium strength, grout strength and borehole diameter on the performance of both cable bolts were investigated. Finally, an extensive statistical Analysis of Variance (ANOVA) was performed to identify the most influential parameter affecting the performance of the two cable bolts.

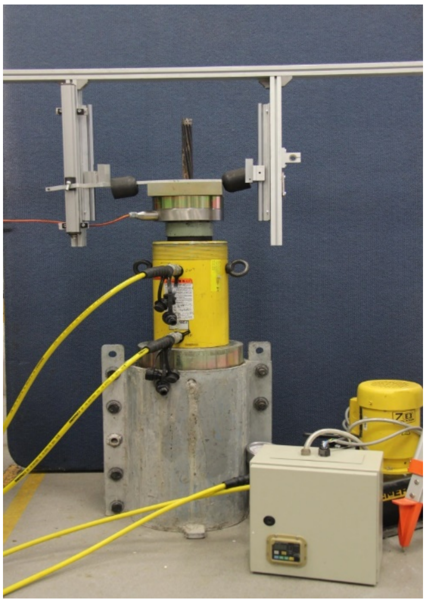

Figure 1: Pull-out test facility

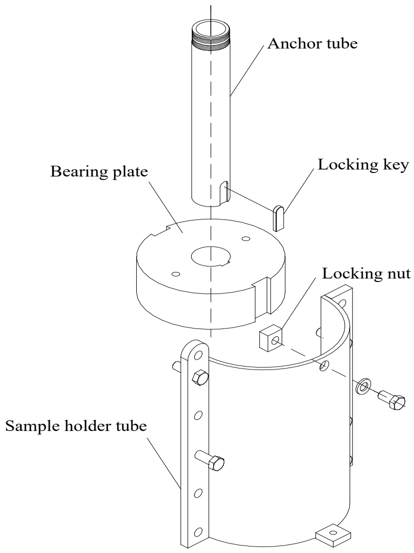

Figure 2: Concept design of anti-rotation devices

PLAIN SUPERSTRAND CABLE BOLTS

Experimental design

The confining medium compressive strength and borehole diameter were nominated as the parameters for the investigation of the Plain SuperStrand cable bolt. The experimental program design is shown in Table 1. It should be noted that three replication tests were conducted under each testing condition.

Table 1: Experimental design for Plain SuperStrand cable bolt

Testing condition	Compressive strength of confining medium (MPa)	Compressive strength of grout (MPa)	Borehole diameter (mm)	Replications
1	64	71	27	3
2	64	71	37	3
3	11	71	27	3
4	11	71	37	3

Test results

Both the peak and residual loads increased with compressive strength of the confining medium (see Table 2). It is noted that the increase in confining medium compressive strength from 11 MPa to 64 MPa led to 50% increase in the peak and residual loads of the Plain SuperStrand cable bolt.

Table 2: Effect of compressive strength of confining medium on the peak and residual loads of Plain SuperStrand cable bolt tested at 27 mm borehole diameter

Variables	Number of tests	Mean load (kN)	Standard deviation (kN)	Coefficient of variation
Peak load obtained from the test with strong confining medium	3	97	2.5	2.6
Residual load obtained from the test with strong confining		86	11.1	12.9
Peak load obtained from the test with weak confining medium	3	63	9.5	14.9
Residual load obtained from the test with weak confining medium		60	4	6.7

With the 10 mm increase in borehole diameter it was observed that the peak and residual loads increased regardless of the type of confining medium. The combined effect of borehole diameter and compressive strength of confining medium on peak load of Plain SuperStrand cable bolts are illustrated in Figure . In addition, Figure shows that a 10 mm increase in borehole diameter led to an increase in the initial stiffness and residual load. This might in part be due to the significant difference in mechanical properties of resin grout compared to that of the confining medium.

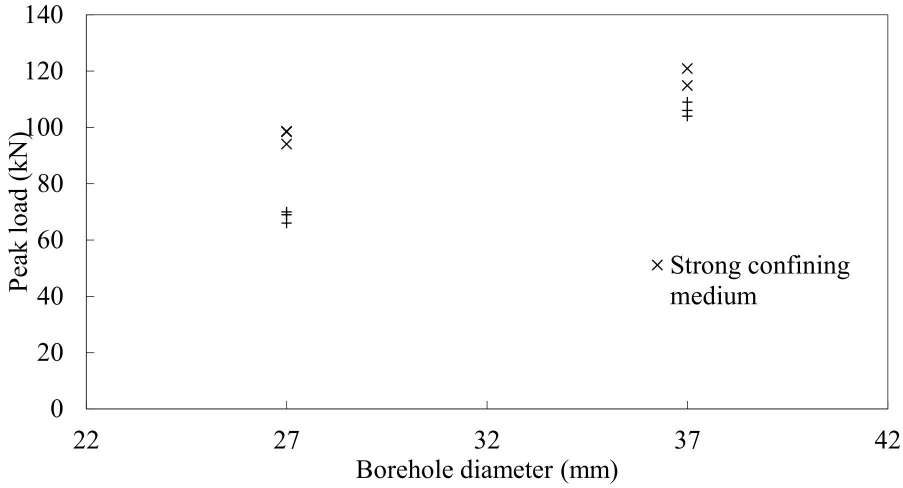

Figure 3: Effect of borehole diameter on peak load of Plain SuperStrand cable bolts

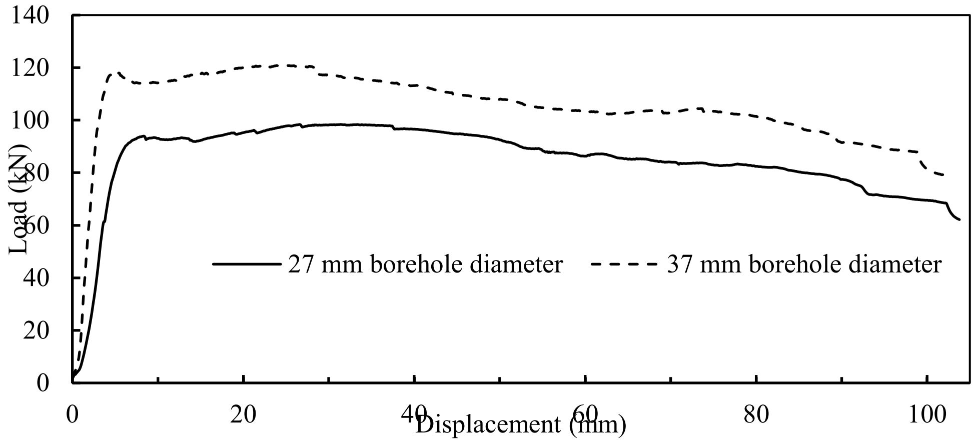

Figure 4: Examples of load-displacement curves resulted from pull-out test on Plain SuperStrand cable bolts with strong confining medium to assess the effect of borehole diameter on its performance

Analysis of variance (ANOVA) for plain SuperStrand cable bolt test results

The contribution of each parameter (confining medium compressive strength and borehole diameter) to the variation in each response (peak load and initial stiffness) was weighted and the results are shown in Table **3** and Table 4. As a result, the borehole diameter was found to be the most influential factor to peak load of the performance of Plain SuperStrand cable bolt in pull-out tests. This is attributed to the significant difference between the confining medium and resin grout leading to the great variation in the confinement when changing the borehole diameter.

On the contrary, the compressive strength of the confining medium was revealed to be the most influential factor to the initial stiffness of the performance of Plain SuperStrand cable bolt. This is related to the greater stiffness of the confining medium resulted from the higher compressive strength. It is hypothesized that the stiffness of the confining medium has the direct effect on the initial stiffness of the Plain SuperStrand cable bolt.

Table 3: Summary of ANOVA for peak load of Plain SuperStrand cable bolt

Source	Sum of square	Degree of freedom	Mean square	F value	Contribution weighting (%)
Confining medium compressive strength	2436.75	1	2436.75	30.62	41%
Borehole diameter	3570.75	1	3570.75	44.87	59%

Table 4: Summary of ANOVA for initial stiffness of Plain SuperStrand cable bolt

Source	Sum of square	Degree of freedom	Mean square	F value	Contribution weighting (%)
Confining medium compressive strength	114.083	1	114.083	2.56	97%
Borehole diameter	4.083	1	4.083	0.09	3%

TG CABLE BOLTS

Experimental Design

The grout compressive strength and borehole diameter were nominated as the parameters for the investigation of the TG cable bolt. The experimental program design is shown in **Table 5**. It should be noted that three replication tests were conducted under each testing condition.

Table 5: Experimental design for TG cable bolt

Testing condition	Compressive strength of confining medium (MPa)	Compressive strength of grout (MPa)	Borehole diameter (mm)	Replications
1	11	80	42	3
2	11	62	42	3
3	11	80	52	3
4	11	62	52	3

Test results

The means of the peak load and initial stiffness of the performance of TG cable bolts in pull-out tests were summarised in Table 6 with the corresponding CV values. It shows that the 18 MPa increase in the grout compressive strength led to approximately 50 KN increase in the peak load. Such behaviour is associated with the higher shear strength of the stronger grout leading to the higher resistance against the axial displacement of the cable bolt.

Table 6: Results obtained from pull-out tests on TG cable bolts

Experiment Condition	Borehole diameter (mm)	Grout compressive strength (MPa)	Mean peak load (KN)	CV (%)	Mean initial stiffness (kN/mm)	CV (%)
1	42	80	293	0.0	78.5	8.6
2	42	62	232	11.2	75.1	2.5
3	52	80	262	6.1	85.0	4.8
4	52	62	216	8.1	74.0	3.4

By contrast, Figure shows that the borehole diameter has negligible effect on the full load-displacement performance of TG cable bolt despite of some minor deviations during the large displacement. Such an effect might be attributed to the mechanical properties of the confining medium and grout.

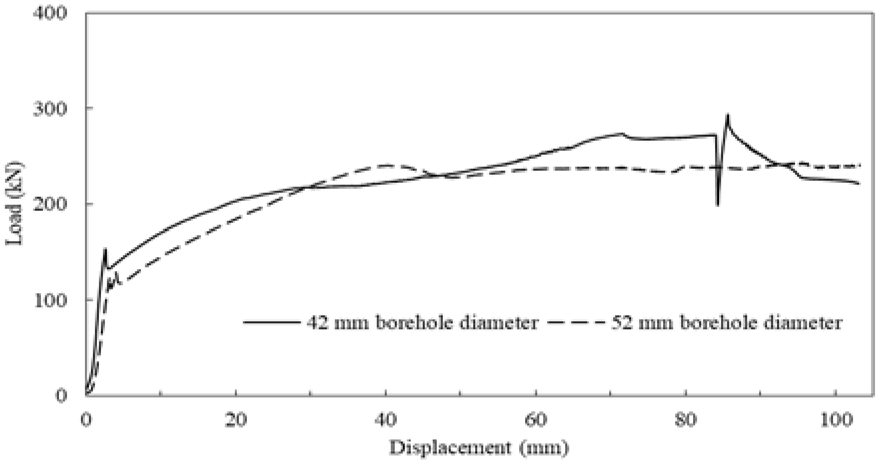

Figure 5: Example of full load-displacement performance of TG cable bolt with grout compressive strength of 80 MPa

Analysis of variance (ANOVA) for TG cable bolt test results

The contribution of each parameter (grout compressive strength and borehole diameter) to the variation in each response (peak load and initial stiffness) was weighted and the results are shown in Tables 7 and 8. As a result, the grout compressive strength was found to be the most influential factor to peak load and initial stiffness of the performance of TG cable bolt in pull-out tests. On the contrary, the overall performance of TG cable bolt was insensitive to the borehole diameter in which 10 mm change had negligible effect on either the peak load or the initial stiffness. Such a finding might be attributed to the mechanical properties of the confining medium and grout.

Table 7: Summary of ANOVA for peak load of TG cable bolt

Source	Sum of square	Degree of freedom	Mean square	F value	Weighting contribution (%)
Borehole diameter	1633.3	1	1633.3	5.24	15
Grout UCS	8748	1	8748	28.06	83
Residual	161.3	1	161.3	0.52	2

Table 8: Summary of ANOVA for initial stiffness of TG cable bolt

Source	Sum of square	Degree of freedom	Mean square	F value	Weighting contribution (%)
Borehole diameter	21.87	1	21.87	1.22	10
Grout UCS	156.963	1	156.963	8.75	71
Residual	42.563	1	42.563	2.37	19

CONCLUSIONS

Extensive parametric studies on the performance of Plain SuperStrand and TG cable bolts were conducted followed by in-depth analysis of the experimental result using ANOVA technique. It was found that the confining medium strength is the most influential parameter to the initial stiffness of Plain SuperStrand by contrast to borehole diameter as the most influential variable to the peak load. For TG cable bolts, grout strength has a more significant effect on the peak load and initial stiffness of the cable bolt than borehole diameter.

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