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Double Shear Testing of Cable Bolts with No Concrete Face Contacts

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Abstract

A new series of double shear tests were carried out using a newly modified double shear apparatus which prevented contacts between concrete block surfaces during shearing. 13 double shear tests were carried out using 21 mm diameter 19 (9 x 9 x 1) seal construction wire strand cable (also called Superstrand cable), Plain SUMO, Indented SUMO, Spiral MW9 and Plain MW10 cable bolts. These cables were tested subjected to different pretension loads. Concrete blocks with Uniaxial Compressive Strength (UCS) of 40 MPa and Stratabinder grout were used for all the tests to maintain test consistency. The results show that the peak shear load and the corresponding shear displacement decrease by increasing the pretension load of the tested cable. The Ultimate tensile strength, lay length, number of wires and cable bolt surface profile type (plain and spiral/indented) are important factors in total shear strength of the cable bolt.

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Keywords: Cable bolt; double shear test; pretension; cable debonding

1. Introduction

Mining in Australia is one of the safest industries but there are still some fatal accidents. The number of deaths was 10, 13 and 13 in 2013, 2014 and 2015 respectively [1]. The current emphasis is to towards zero fatality Therefore, one of the greatest concerns to designers and engineers during and after excavation is the stability of

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underground excavations and surface mining slopes. It is important for designers to understand and have views on various forms of instability and the mechanisms of failures and associated conditions to support the unstable surfaces by installing various types of cable bolts for effective ground stabilization.

The application of cable bolts as a secondary support system is a growing trend in underground coal mines worldwide [2].The first type of cable bolts used in mines consisted of seven high tensile strength and pre-stressed wires, which were arranged in the strand with plastic spacers. The plain strand cable bolts with poor load transfer properties due to smooth and straight profile wires were initially introduced to mines, as a temporary means of rock reinforcement. Over the years, a number of modifications has been introduced to the plain strand cable, such as strand surface profiling and indentations [3], double plain strand [4], epoxy-coated strand [5], fiberglass cable bolt [6], birdcage strand [7], bulbed strand [8], and nutcage strand cable bolts [9]. These various types of cable bolt have been incorporated to improve the load transfer capacity as permanent ground reinforcement.

While the Australian mines use a variety of cables to suit ground condition, the trend, in recent years in both Canada and in the USA has been to down size the cable dimensions to less than 20 mm diameter. According to Tadolini [10], the most popular cables used in the USA are15 mm (0.6 inch) diameter strand (30 t capacity) and 18 mm (0.7 inch) diameter strand (nominal 40 t). They are both 7 wire strand (King-wire and 6 outer wrap wires). There are very few high strength strand cable bolts sold in the US or Canada, because of cost. In 2016, 1.32 million of 15.25 mm (0.6 in) diameter cable bolts and 25,000 of 18 mm (0.7 in) cable bolts were sold in the US.

Axial, shear or the combination of axial and shear failure are different mechanisms of failure of cable bolts. A combination of both axial and shear failures typically occurs in situ. Strength characteristics of cable bolts are important factors in the axial failure of cable bolt in comparison with the strength of grout and rock mass [11]. When the strength of cable bolt is lower than the optimum required support, the cable bolt fails. The amount of shear in the bolt-grout surface is higher than the grout-rock surface because of smaller effective area. Pull out and shear tests (single and double shear tests) are the known methods of evaluating the performance of cable bolts. Pull testing has been conducted over the years by researchers to determine tensile failure and load transfer capacity of cable bolts and rock bolts [12–24].

Fifteen single shear tests using various concrete grades, three steel sizes and four different angles for stirrup were conducted by Dulacska [25] to assess bolt action in cracked concretes. Stillborg [26] conducted a series of single shear tests to determine the shear behaviour of fully grouted cable bolts. It was found that when the angle of cable bolt to the joint surface is 45° compared with 90°, the shear resistance of the grouted cable bolt was significantly higher. Also, the maximum of shear resistance in the cable bolt occurred at 10 mm of shear displacement. Four modes of failure of a fully grouted cable bolt were reported by Thomas [22] and include; failure at cable to grout interface, failure through grout column, failure at grout to rock interface and failure through rock around borehole wall. The first two failure modes are not common while the third and fourth failure modes are common; however, the cable bolt failure is the most common mode. Goris et al. [27] conducted a series of direct shear tests on 15.25 mm (0.6 in) diameter cable bolts with 26 mm hole diameter using concrete blocks with 69 MPa strength and the joint surface area of 0.078 m^2. The result from the single shear test was higher than the double shear test for the same type of cable bolt.

Craig and Aziz [28] conducted a series of double shear tests on 28 mm TG hollow strand cable bolt. Cable bolts are under tensile and shear load in mines because of the roof deformation loads; therefore, two tests were conducted to investigate the shear behaviour of cable bolts in different displacement limitation and initial pretension loads. Developed in 2007, the Jennmar TG cable is a 630 kN (63 t) post grouted cable bolt with 9 wire strand (each element is 7 mm in diameter), which surrounds a 14 mm hollow steel core tube. The initial pretension loads of cable bolts were 50 kN (5 t) and 90 kN (9 t) respectively. Shear Tests were carried out using a 50 MPa concrete blocks. The shear displacement for the first test was limited to 50 mm, with the vertical shear load reaching 900 kN, the pretension load increasing to 238 kN and with no cable bolt failure. The cable failed in the second test at 60 mm shear displacement. The cable shear failure load was 1354 kN with the cable axial load reaching 385 kN. It was observed that the majority of strand wires failed in tension and there were some in the combination of shear and tensile failures. Aziz et al. [29] investigated the performance of 19 wire 21.8 mm diameter of plain and spirally profiled Hilti cable bolts subjected to double shear tests. The result for the plain cable bolt was higher than the spiral cable bolt because of reduction in the strength of spiral cable. The result of the double shear test was also compared with the single shear test recommended by British Standard [30]. It was found that the single shear test underestimated the shear strength of 21.7 mm, 19 wire (9 x 9 x 1) cable bolt Rasekh et al. [31] studied the contact surface area of the concrete joints during shearing. It was observed that the contact surface area can vary between 70–90% of the total surface area. Aziz et al. [32] proposed a mathematical model to determine the peak shear load of the pre-tensioned fully grouted cable bolts subjected to double shear test using the combination of Mohr-Coulomb Criterion and Fourier Series scheme. This model was extended by Aziz et al. [33] to determine the peak shear load when concrete blocks were not in contact with each other. Rasekh et al. [34] compared the experimental test results with the mathematical models to determine their accuracy in simulating experimental studies. Rasekh et al. [35] used the Energy Balance theory and Fourier series concept to simulate the shear performance of cable bolts subjected to double shear tests in elastic, strain softening and failure stages. Further study on the shear behaviour of various cable bolts under double shear tests without joints in contact with each other is the subject of this paper.

2. Sample preparation, test apparatus and experimental plan

Each double shear test required three cement-mortar concrete blocks to create the double jointed apparatus. The outer two blocks were 300 mm cubes and the middle block was a 300 mm x 300 mm x 450 mm rectangular prism. The 25 mm thick steel shear boxes, without the top plates, were greased on the inner edges and used as mould. Four greased wooden boards with a central 50 mm diameter hole were placed at either end and between each steel mould. A 42 mm cylindrical rod was inserted lengthways through the centre of the mould to replicate the drilled borehole. A twin core 3 mm diameter electrical wire was wrapped around the steel rod to emulate the rifling effect expected in underground cable bolt installation as shown in Fig. 1a.

Concrete was made with a Portland cement mixture, with sand and aggregate, to obtain a uniaxial compressive strength (UCS) of 40 MPa (verified by UCS testing on a 100 mm diameter cylindrical sample from each concrete batch). The concrete was then poured into the mould and vibrated to remove air bubbles and ensure homogeneity. To assist with later grouting a length of plastic conduit, 15 mm diameter, was pressed into the wet concrete in the centre of each block until it was resting against the steel rod. Once the concrete had set the steel rod was gently tapped out, followed by pulling out of the electrical wire. The vertical plastic conduits were also removed leaving vertical hole prints as shown in Fig. 1b. After 24 hours blocks were removed from the mould, covered in a damp cloth and set aside to cure for 30 days. During the double shear assembling, two 60 t load cells were used to monitor axial load build up on the cable bolt during shearing process. Two sets of barrel and wedge assembly were used to retain the cable bolt in tension. After pre-tensioning the cable bolt, Stratabinder HS, was injected through vertical holes from the top of the concrete blocks to encapsulate the cable bolt. To protect the load cells from being contaminated by the grout, quad seals were used around the cable in both sides. The test was conducted seven days later.

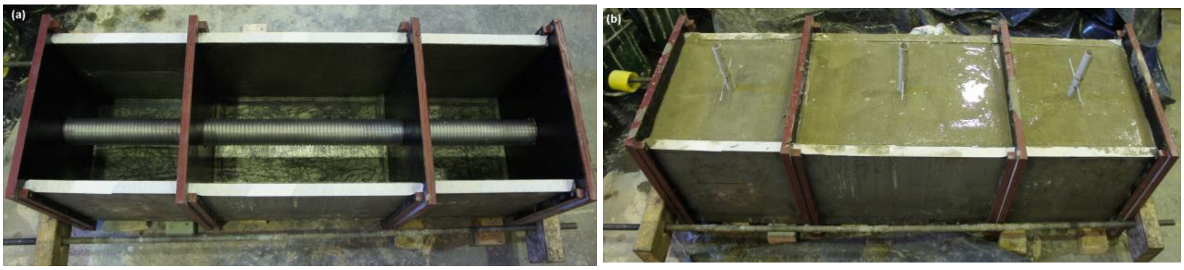

Fig. 1. Concrete blocks casting assembly and vertical holes printed on top of the concrete blocks for grout injection.

A modified double shear apparatus (MKIII) was used to remove the friction between concrete block joint surfaces during shearing process and to determine the pure shear strength of cable bolts. Two open box steel channel braces (U brace), mounted axially on each side of the double shear apparatus assembly and connected to two end plates with dimension of 500 x 340 x 30 mm^3 was employed to prevent the concrete joint faces of the concrete blocks coming in contact with each other. During shearing the load was transferred from the U sections to the end plates thus avoiding the friction between shearing blocks (Fig. 2). The 500 t machine in the laboratory of University of Wollongong was used to perform double shear tests. The rate of shear displacement was set by the digital controller at 1 mm/min. The shear load was applied to the sample using a hydraulic jack located on top of the instrument. The middle concrete block was moved in the vertical direction. The amount of shear and normal load and shear displacement were recorded by a data taker.

Fig. 2. Double shear assembly without friction between concrete blocks.

Thirteen double shear tests were conducted using five different types of cable bolts as shown in Table 1, showing the number of wire strands, cable bolt diameter, typical strand yield strength, lay length and elongation at strand failure. 40 MPa concrete blocks were used as host medium.

Table 1. Cable bolt properties

Cable bolt type	Wire Strand No.	Dia. (mm)	Cable geometry	Typical Strand Yield Strength (kN)	Typical strand breaking load (kN)	Lay length (mm)	Elongation at strand failure (%)
Plain SUMO	9	28	Bulbed	568	635	400	5–7
ID- SUMO	9	28	Bulbed	568	635	400	5–7
Plain 19 wire(9 x 9 x 1)*	19	21.7	No bulb	–	590	300	–
Plain MW10	10	31	No bulb	–	687	600	5–6
Spiral MW9	9	31	No bulb	–	608	600	5–6

* 19 wire (9 x 9 x 1) twin layer seal construction cable strand.

3. Test results and discussions

Table 2 shows the result of conducted tests including peak shear load and the corresponding shear displacement. This provides a good comparison with regard to cable bolt type (surface profile type, lay length and ultimate tensile strength) and pretension load. Plain SUMO with 0 t pretension load, Plain MW10 with 0 t pretension load and Spiral MW9 with 0 t pretension load did not reach their peak shear load in 100 mm of shear displacement. This table shows the percentages of shear strength of each cable bolt to its Ultimate Tensile Strength (UTS). The average is about 67%, which shows that the shear strength of a cable bolt is approximately 65% of its UTS value as expected based also on the theoretical calculation.

Table 2. Test results.

Test No.	Cable	Cable Dia. (mm)	Hole Dia. (mm)	Pre-Tension (kN)	Peak Shear Load (kN)	Shear Displacement at Peak Shear Load (mm)	Shear Strength/UTS (%)
1	Plain 19 wire (9 x 9 x 1)	21.7	30	0	884	76.8	74.9
2	Plain 19 wire (9 x 9 x 1)	21.7	30	0	761	98.8	64.5
3	Plain 19 wire (9 x 9 x 1)	21.7	30	100	738	92.3	62.5
4	Plain 19 wire (9 x 9 x 1)	21.7	30	160	774	86	65.6
5	Plain SUMO	28	42	0	886*	100	69.8
6	Plain SUMO	28	42	150	852	88.2	67.1
7	ID-SUMO	28	42	0	815	93.4	64.2
8	ID-SUMO	28	42	150	767	85.7	60.4
9	Plain MW10	31	42	0	878*	105	63.9
10	Plain MW10	31	42	150	923	88.5	67.2
11	Spiral MW9	31	42	0	939*	105	77.2
12	Spiral MW9	31	42	75	907	89.7	74.6
13	Spiral MW9	31	42	150	837	88.5	68.8

* The shown value is not peak shear load because the cable did not break. Stratabinder grout was used to install the cables in 40 MPa concrete.

3.1. Effects of pretension load

Fig. 3 shows the effect of pretension load on the peak shear load of various cable bolts. It was observed that the peak shear load decreases by increasing the pretension load of all the five types of tested cable bolts. The exception to the trend was the peak shear load for Plain MW10 as the cable bolt did not reach its peak shear load at 0 t pretension load. Moreover, the shear displacement at peak shear load decreased by increasing the pretension load. Further tests are planned for MW10 cable bolt. Also note that the four plain 19 wire cable bolt results are arranged in two groups (tests 1 and 4 in one group and tests 2 and 3 in another). This is because of different techniques were used to stop grout leaking out of the blocks during cable bolt installation process.

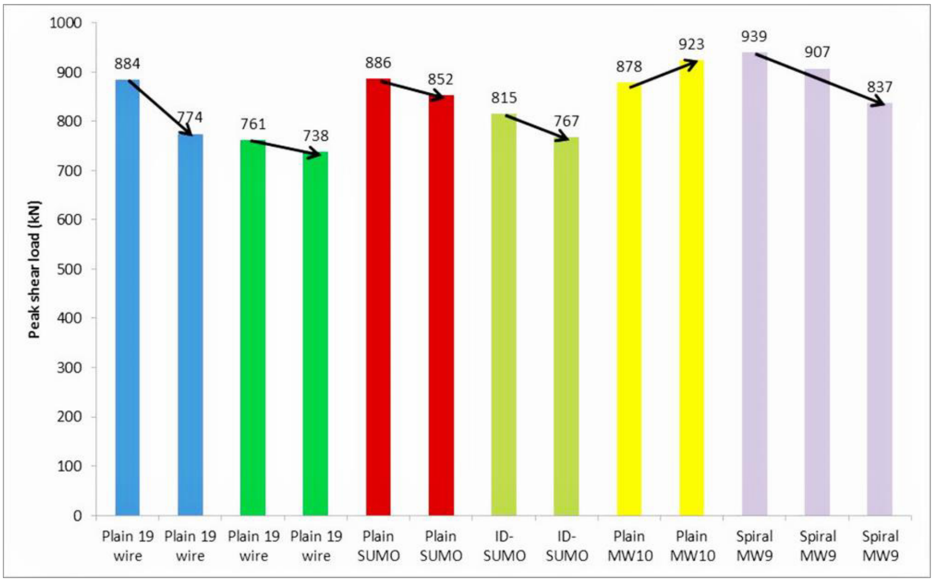

Fig. 3. Effect of pretension load on peak shear load.

3.2. Effect of cable type

Figs. 4 and 5 show the comparison between peak shear loads of different types of cable bolts subjected to 0 and 15 t pretension loads. The result shows that Plain MW10 had the highest peak shear load at 15 t pretension loads. The comparison in 0 t pretension load was difficult with other tested cables because the plain SUMO, spiral MW9 and plain MW10 did not fail in 100 mm of shear displacement. The higher shear strength of plain MW10 was due to the cable strand having ten wires instead of nine wires of SUMO and MW9 cable bolts. Other features of MW10 cable include high tensile strength of 70 t, greater wire lay length of 600 mm and plain cable surface profile type.

3.3. Cable bolt's mode of failure

Figs. 6 and 7 show the failure angle and modes of failure in MW10 cable bolt. The cable bolt failed completely on one side. As Fig. 7 shows, the failure in the cable bolt was observed to be a combination of both shear and tensile failure.

3.4. Cable bolt's deflection

Fig. 8 shows the extent of concrete deformation zone around the bent section of the sheared cable surrounding sheared joint planes. The level of deflection at the hinge point is clearly evident from the extent of deformation shown in Fig. 8. Result from Table 3 illustrates that the extent of concrete deformation in various tests which ranges between 65 mm and 110 mm with an average of 85 mm. The amount of cable bending was more than three times of its diameter.

3.5. Equipment modification

It is clear from this study that, due to the addition of braces on the double shear testing apparatus; the results of cables in shearing were found to be more consistent with past studies where the influence of joint surfaces occurred. However, the concrete deformation at hinge points is excessive, which leads to the cracking of concrete blocks. One way of achieving comparative shear failure values of cables, in both the single and double shear tests, would require shearing the cables in concrete blocks of similar confinement. Fig. 9 shows the new version of the double shear apparatus which will allow equal confinement to be applied to the host medium. Such confinement will allow identical torqueing of the concrete medium irrespective of the testing technique. Thus the applied confinement loads will be similar to tests conducted in single shearing as well in cable pull tests carried out by Chen et al. [23, 24], and Mackenzie et al. [36].

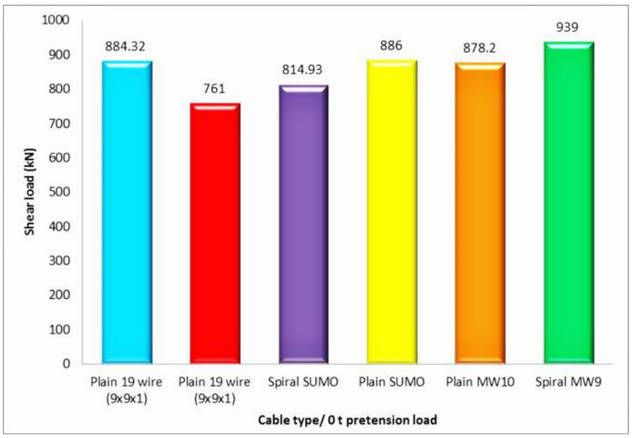

Fig. 4. Peak shear loads of different types of cable bolts subjected to 0 t pretension load.

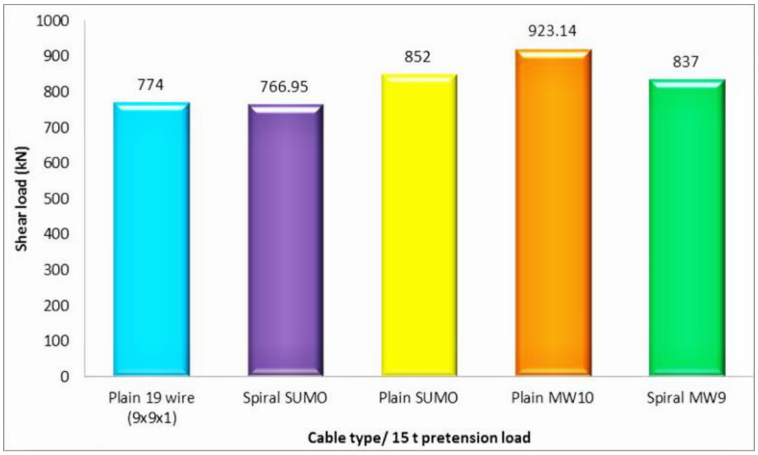

Fig. 5. Peak shear loads of different types of cable bolts subjected to 15 t pretension load.

Fig. 6. Failure angle of cable bolt.

Fig. 7. Tensile and shear failure of cable bolt.

Fig. 8. Zone of concrete deformation due to cable bending in shear.

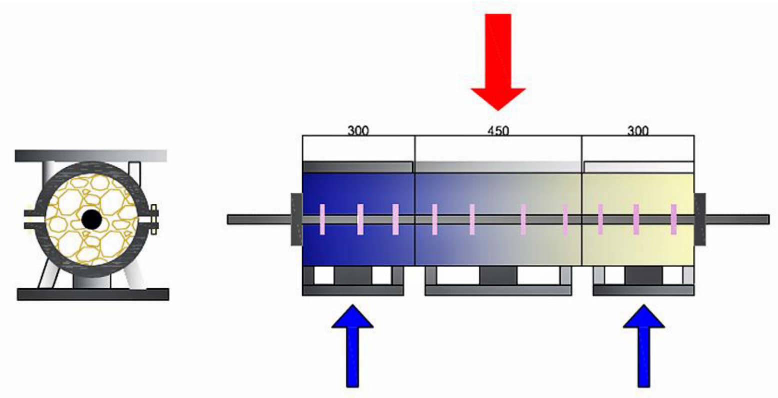

Fig. 9. Double shear apparatus MKIV.

Table 3. Comparison between cable bolts deflection and diameter.

Test No.	Cable	Pre-tension (kN)	Dia. (mm)	Extent of concrete deformation (mm)	$(\frac{\text{Cable bolt deflection}}{\text{Diameter}})$
1	Plain 19 wire (9 x 9 x 1)	0	21.8	65	2.98
2	Plain 19 wire (9 x 9 x 1)	0	21.8	70	3.21
3	Plain 19 wire (9 x 9 x 1)	100	21.8	60	2.75
4	Plain 19 wire (9 x 9 x 1)	160	21.8	85	3.90
5	Plain SUMO	0	28	90	3.21
6	Plain SUMO	150	28	110	3.93
7	ID-SUMO	0	28	95	3.39
8	ID-SUMO	150	28	75	2.68
9	Plain MW10	0	31	100	3.23
10	Plain MW10	150	31	105	3.38
11	Spiral MW9	0	31	90	2.90
12	Spiral MW9	75	31	90	2.90
13	Spiral MW9	150	31	105	3.39

4. Conclusions

The shear performance of pre-tensioned fully grouted cable bolts were studied by conducting a series of experimental double shear tests on five different types of cable bolts without contacts of concrete blocks surfaces to determine their pure shear strength. The following conclusions are drawn from this investigation:

- The plain cable bolt provides higher shear strength irrespective of the cable type.
- The shear load and shear displacement at peak shear load decreases by increasing the pretension load.
- The shear strength of each cable bolt was 67% on average of its Ultimate Tensile Strength.
- The double shear tests should be modified to permit the application of confinement load to the host medium. The availability and consistency of the concrete confinement would enable comparative tests to be carried out on tendons irrespective of the shear apparatus types as long as other factors and parameters remain the same.

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