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Innovative approach to strata reinforcement in coal mines with reference to evaluation cable bolts shear strength

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Abstract
There is an increasing need to determine accurately the strength properties of tendons for an effective ground control on mines and underground structures as well as on modelling simulations. The strength properties of cables, used as cable bolts, have been evaluated mainly by their ultimate tensile strength, as this kind of test can be carried out in the field as well as in the laboratory. Only recently, there has been a growing interest in cable bolt failures in shear because of the documented field failure evidence. Accordingly, this paper reports various methods of shear testing of rock bolts and cables using different shear testing rigs, some have been developed by the rock bolting research team at the University of Wollongong. A programme of shear testing of a variety of cable bolts marketed in Australia was undertaken, the results of which were reported and conclusions were drawn. It was concluded that plain cable bolts were de-bonded during shearing when compared to spiral cables under the same testing conditions. In addition, both the single shear and double shear testing methodologies will result in the same outcome if there is no de-bonding, and a proper confinement is applied.

Keywords: *Tendon Technology, Cable Bolt, Shear Testing, Pretension Loads, Concrete Confinement*.

1. Introduction

Cable bolting has been used worldwide as a solution for structural support and in ground reinforcement in civil, mining, tunnelling, and other structure projects. The strength properties of these cables, used as cable bolts, have been evaluated mainly for their ultimate tensile strength, as this kind of testing could be carried out in the field as well as in the laboratory.

Dube (1995) [1] was one of the first researchers who investigated the capacity of fully grouted cable bolts subjected to combined axial and lateral loads. For the past several years, significant knowledge has been gained on the tendon technology (rock bolt and cable bolt) load transfer mechanisms and their strength characterisation mainly by pull testing [2, 3]; however, little is known about the cable bolt shear behaviour since the interest in cable bolt failure in shear has been confined to a small amount of work carried out based on the British Standard of shear testing (BS 7861-part 2, 2009) [4] and the work of [5]; and [6]). Also no credible test results are available from the field, and only pictorial evidence has recently surfaced for both the failed solid rock bolts and cable bolts. Typical signs of sheared tendons recovered from the field and a borehole view shear displacement in rock layers is shown in Figure 1, as reported by [7] and [8].

When a cable bolt is sheared to failure in a soft medium such as soft rock and weak concrete, there is a little chance of the wires in the cable strand failing fully or snap in shear; instead, the strand wires are likely to fail in a combination of tensile and shear. Other influencing factors include grout strength, applied pretension load, testing method, and loading conditions.

Figure 1. Sheared tendons recovered from field and a hole view of sheared rock [7, 8].

2. Methodology of tendon shear testing

Currently, two types of testing rigs are used for shear testing of various tendons; they are Megabolt Integrated Single Shear Test Rig (MISSTR) and Double Shear Test Rig (DSTR). Prior to the construction of MISSTR, all studies in shear testing were carried out in the University of Wollongong DSTR. Figure 2 shows various shear testing rigs used for various studies at the University of Wollongong. Figure 2E shows a new double shear testing rig named as Naj DS rig. Various types of cable bolts tested as parts of this investigation are outlined in [9].

2.1. Single shear test

In order to replicate as closely as possible field conditions for installed cable bolts, the Megabolt Integrated Single Shear Test Rig (MISSTR) shown in Figures 2A and 3 are used to evaluate the behaviour of cable strand in shear [10]. Based on the principle of British Standard 7862-part 2 (2009) [4], the whole length of the 250 mm diameter concrete cylinder used in MISSTR is 3600 mm (1800 mm on each side) with a central hole diameter of 28-55 mm. The diameter of the central axial hole in the concrete is dependent on the diameter of the tested cable bolt.

MISSTR is a horizontally aligned integrated system consisting of a shearing rig and an integrated 120 t capacity compression machine. The 3.6 m long concrete shearing cylinder consists of two sections, each containing 1.8 m long concrete cylinders. The concrete cylinders are covered by steel clamps, which provide confinement during the shearing process. Either a hand pump or a power pack of a suitable capacity applies the hydraulic pressure for the compression machine legs. The pressure in the manifold is monitored with a digital pressure transducer (Type Measure X, range 0-800 Bar) in conjunction with an analogue pressure gauge (0-700 bar). The rate of loading was applied manually, which man no be not always be constant; however, the aim was to apply a constant load at a rate of around 1 mm/min (0.018 mm/s), in line with the BS7861-2 standards. The displacement at the shearing plane was measured using a Linear Variable Differential Transformer (LVDT), as shown in Figure 3. Two other LVDTs were also mounted on the cable ends to enable monitoring of cable de-bonding. A data taker recorder was used to collect the data during the tests.

When preparing two 1800 mm concrete cylinders, two 900 mm cylinders were butt-glued together in a specially built tensioning frame. The cable bolt was then inserted through the centre rifled hole of the concrete cylinder. The cable bolt was pre-tensioned. The whole concrete cylinder loaded frame with cylinder was then tilted for 65 degree, and grout was pumped from the bottom up the hole to remove any air bubbles remaining inside the grout annulus area and to ensure full cable encapsulation. Stratabinder HS grout was used to encapsulate all the tested cables in this programme of study. The strength properties of the grout have been reported by [11] and [12]. Figure 4 shows tilting of the encapsulated and assembled cable bolts to permit effective grout hardening and encapsulation of the cable during the pretension stage.

After the grout was cured, each concrete sample with encapsulated cable bolt was disassembled from the frame and lifted out to be mounted onto the shearing rig. Once the concrete cylinder was correctly placed in the shearing machine, steel clamps were placed around the concrete blocks to provide a confining pressure to the sample. When sheared, one side of 1.8 m of the 3.6 m concrete column remained fixed on the rig, while the other half was subjected to shearing. The applied shear load was recorded in a data taker and the displacement of cable ends, and sheared cable strand wires were monitored by LVDTs, which were all logged by computer. Initially, 16 single shear tests were conducted on the 3.6 m concrete blocks to study the effect of cable type, surface profile type, pre-tension load, birdcage structure, bonding and de-bonding, and failure mode of cable bolts.

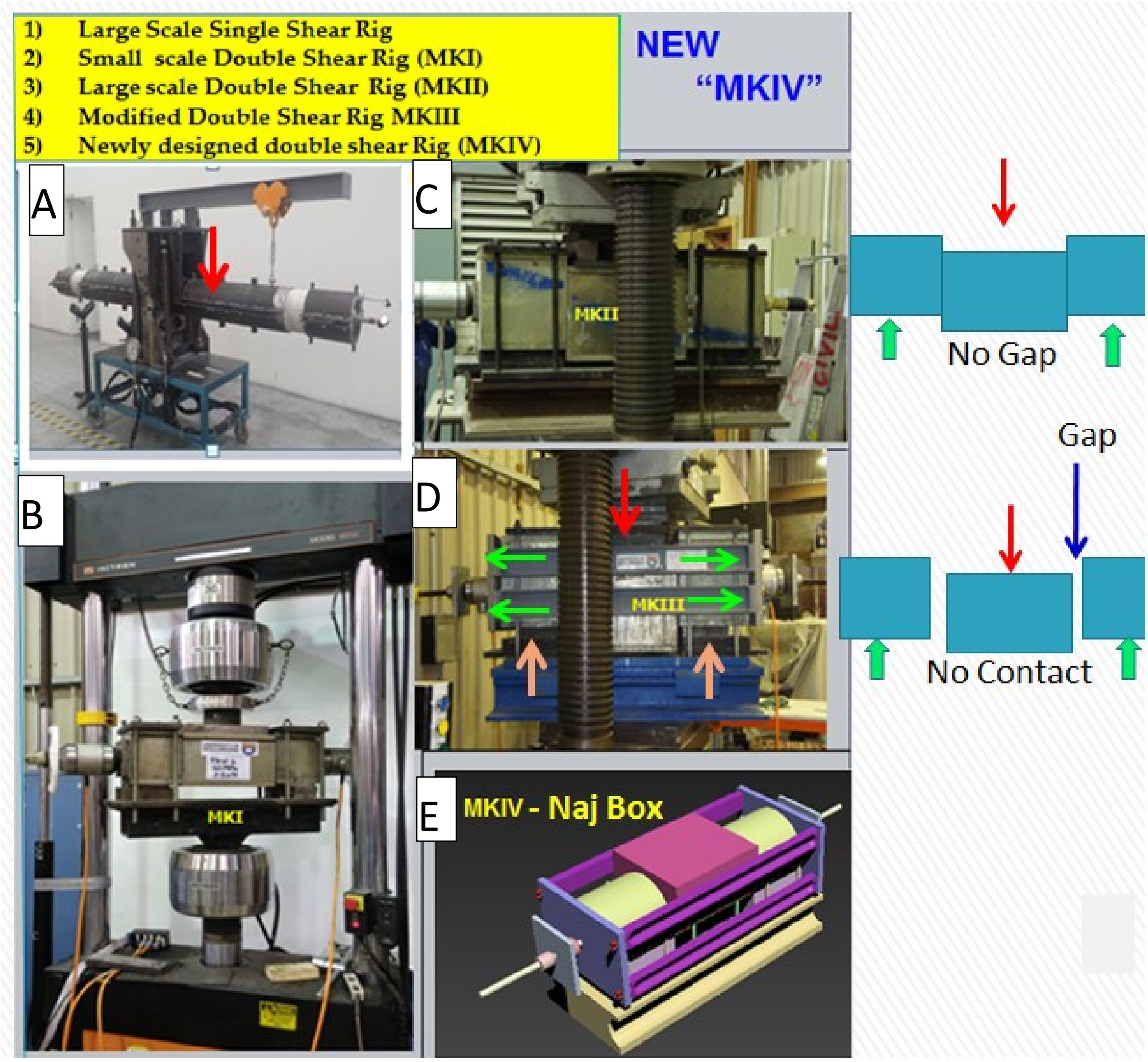


Figure 2. Various types of shear testing equipment at the University of Wollongong. The single shear Megabolt Rig was on load for testing various cable bolts.

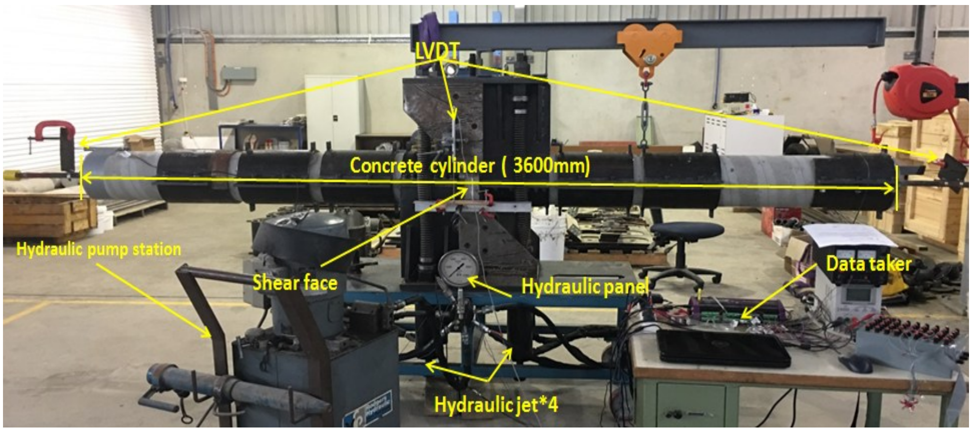


Figure 3. Megabolt integrated single shear rig (MISSTR).

Figure 4. Tilting the pre-tensioned cables in concrete cylinders during the grouting stage.

2.2. Double shear testing method

Two types of double shear testing methods are available for evaluating the shear characteristics of cable bolts (Figure 2): (a) The DSTR-MKII (Figure 2C) with opposing concrete joint faces being in contact with each other, where the resultant shearing force is a combination of the shear failure load and friction force of the sheared host medium faces, (b) A modified DSTR-MKIII (Figure 2D) with opposing concrete joint faces not in contact with each other, and the measured shear resistance force is spent on shearing the cable wires. The level of shear force spent on overcoming the friction force can be determined using the following equation based on the combination of Mohr Coulomb criterion and Fourier series [13].

$$\tau_p = \left(\frac{a_0}{2} + \sum_{n=1}^{3}\left[a_n \cos\left(\frac{2n\pi \frac{T}{2\pi}\cos^{-1}\left[\frac{-4a_2 + \sqrt{16a_2 - 48a_1a_3 + 144a_3^2}}{24a_3}\right]}{T}\right)\right]\right)\tan(\varphi) + c$$

where τ is the shear stress, S is the shear load, C is cohesion, a_n is the Fourier coefficient, n is the number of Fourier coefficients considered to be between 0 and 3, u is the shear displacement, and T is the shearing length. Mirzaghorbanali et al., 2016 [12], verified the proposed equation with the experimental test results. Both the DSTR-MKII and MKIII rigs, as shown in Figure 5, were used in this work. The basic prismatic frames were the same, and consisted of two 300-mm long outer cubic boxes and a 450-mm long middle central cuboid box with 300 × 300 mm^2 cross-sectional area. A conduit wrapped with an 8-mm PVC hose was laid horizontally along the mould to precast a rifled hole through the centre of the concrete blocks. Once the concrete was poured, it was left to set.

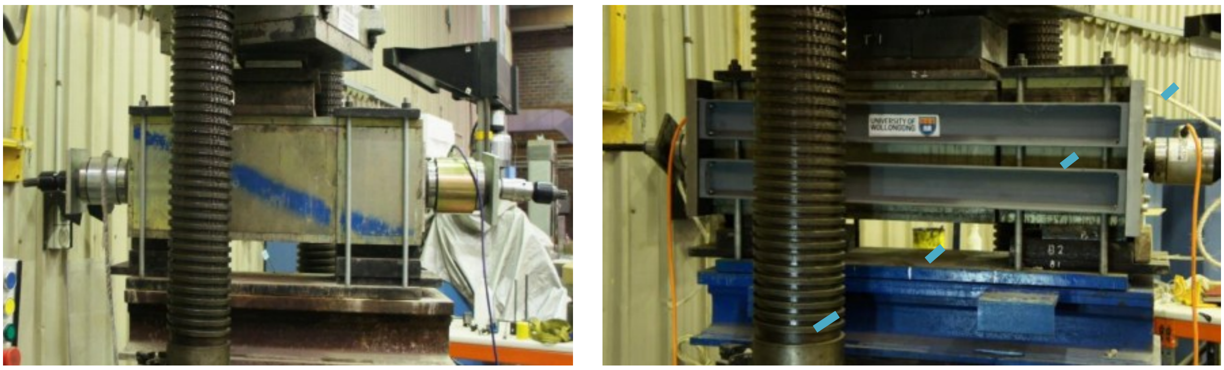
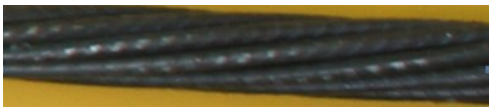


Figure 5. Double shear testing machines with (MKI) [left] and without contact faces (MKII) [right].

Prior to the apparatus being assembled, the hollow central tube of each cable was filled with grout and left to harden prior to encapsulation in the concrete blocks for at least one week. During assembling, three concrete blocks were all mounted on the horizontal steel base frame known as Carrier Base Frame. When assembling the DS apparatus, the blocks were pressed against each other and the cable was pre-tensioned and then grouted, as shown in Figure 2C, while in the MKIII setup, the assembly was held together using a truss system/braces around the double shear assembly, as shown in Figure 2D. The truss system consisted of four 1100 mm long steel braces connected between two 30-mm thick side-steel plates. The brace system impeded the subjecting lateral axial load on the concrete blocks during shearing. When assembled, gaps of almost 5 mm were left between the concrete blocks, and thus the adjacent sheared concrete faces were kept apart eliminating the contact between the sheared faces, and hence, no friction force. Next, the cable bolt was inserted into the central axial hole followed by mounting A 100 t load cell on each protruding side of the cable in the assembled concrete blocks and tensioned to the pre-determined axial pretension load using a "Blue Healer" tensioner. Tensioning of the cable was retained by the barrel and wedge retainers. This was followed by the injection of grout into the central concrete block hole for bolt encapsulation. Grouting of the cable in the concrete block was achieved via 20 mm diameter holes cast on top of each concrete block. Once the cable was pre-tensioned, cement grout mortar was injected into the hole annulus space around the cable strand from the vertically pre-cast radial hole on top of each concrete block. After ten days of grout/resin curing time, the double shear assembly was placed on the carrier base frame consisting of a parallel pair of rail track sections welded to a 30 mm thick steel plate. The outer 300 mm side-cube blocks of the double shear apparatus was mounted on 100 mm steel blocks, leaving the central 450 mm long block free to be vertically sheared down using a 500 t capacity hydraulic universal testing machine at a rate of 1 mm/min for the maximum 100 mm vertical displacement. A hydraulic universal testing machine with a capacity of 500 t is normally used to compress the middle block for shearing the cable strand at a rate of 1 mm/min for the maximum 100 mm vertical displacement.

3. Experimental results and discussion

Figure 6 shows a view of various cables used in this programme of investigation, which are mostly used in Australian mines.



Indented TG-Hollow 28 mm bolt

Garford 15.2 mm bulbed cable bolt

Plain SUMO-Hollow 28mm c/w 35 mm birdcaged cable bolt

Secura-Hollow groutable cable bolt (HGC)

Indented SUMO-Hollow 28mm c/w 35 mm birdcaged cable bolt

MW9S Megastrand (spiral) cable bolt

21.8 mm plain Superstrand 19 wire cable bolt

MW10P Megastrand (plain) cable bolt

21.8 mm indented Superstrand 19 wire cable bolt

Figure 6. Various cable bolts used in Australian mines.

Table 1 shows the peak shear loads and axial forces of SUMO cable bolts with joint faces in contact with each other. The load displacement profiles of both plains and indented cables subjected to axal pre-tesnion loads of 10 t and 15 t are shown in Figures 7. Table 2 and Figure 8 show the test results of load–dislaceent profiles with cables being subected to 0 and 15 t with concrete block joint faces not in contact with each other.

Table 1. Double shear test results of cable bolts with joint faces in contact with each other.

Test NO.	Cable type	Nominal pre-tension (t)	Shear displacement at maximum shear load (mm)	Maximum shear load (kN)	Friction load 30%	Shear load pre-side (kN)
1	Plain	25	58.8	1424	427	499
2	SUMO	10	78.9	1318	395	462
3		25	32.6	829	249	290
4	ID SUMO	10	46.0	933	280	327

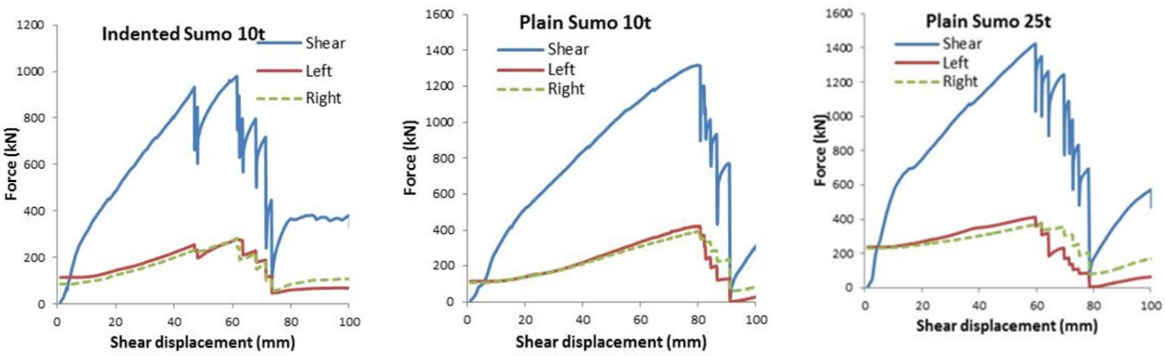


Figure 7. Double shear load-displacement results with concrete joint surface in contact with each other contacts.

Table 2. Double shear load-displacement results with no concrete joint face surface contact.

Test No.	Cable type	Nominal pre-tension (t)	Shear displacement (mm)	Maximum shear force (kN)	Maximum shear force per side (kN)
5	Plain	15	88.2	852	426
6	SUMO	0	105	886	443
7	ID-SUMO	15	85.7	767	384
8		0	93.4	815	406

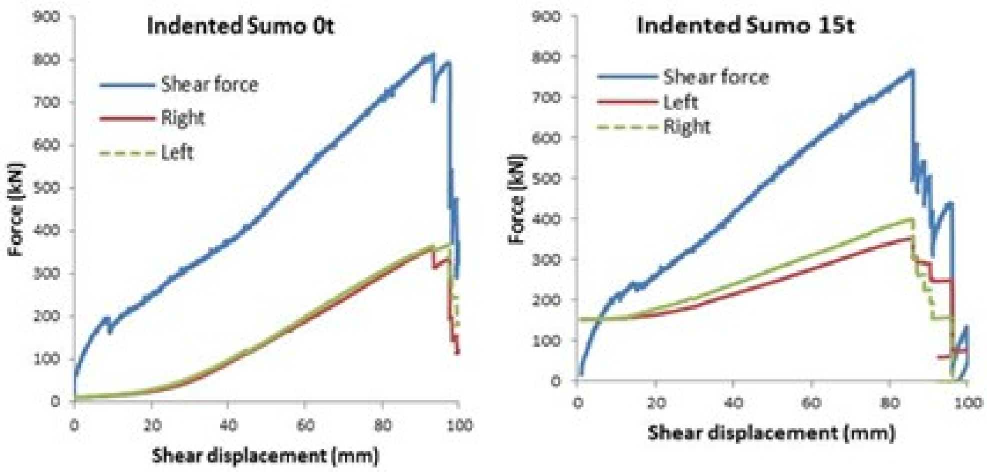


Figure 8. Double shear load-displacement results with concrete joint surfaces not in contact with each other and at different pre-tension loads.

Table 3 shows the results of single shear testing of 16 cables using MISSTR. Most cables were bulbed and one cable type, Minova Secura bolt strand, was made of a combination of five plains and four indented wires.

Plain wire cable bolts were found to have a higher peak shear load compared with the indented cable bolts. Figure 9 shows the cross-section views of both the MW9 Spiral and MW10 Plain wireswith both wires of equal diameters of 7 mm. However, some minor strength reduction may occur due to the rifling or spiralling process during manufacture but no weight loss. Figures 10 (a and b) show the load-displacement profile variations of other manufacture cable strand wires, where up to 10% weight and strength loss can occur during the indentation process.

Table 3. Summary of single shear test results.

Test No.	Product name	Cable Dia. (mm)	UTS (t)	Cable geometry	Pre-tension load (t)	Peak shear load (t)	Shear disp.	Cable de-bonding	Peak shear load/UTS (%)
1	MW 10-P	31	70	Un-bulbed	15	68.34	68.24	Yes	97.6
2	MW 10-P	31	70	6 bulbs	0	63.84	62.57	Yes	91.1
3	MW 10-P	31	70	6 bulbs	15	60.39	56	Yes	86.3
4	MW9-S	31	62	6 bulbs	0	47.73	43.5	No	76.9
5	MW9-S	31	62	6 bulbs	15	43.93	47.4	No	69.9
6	MW9-S	31	62	Un-bulbed	15	49.70	41.73	No	67.3
7	Secura Comb	31	68	6 bulbs	0	64.69	51.8	No	95.2
8	Secura Comb	31	68	6 bulbs	15	55.90	45.9	No	82.2
9	SUMO-P	28	65	6 bulbs	0	55.76	71.8	Yes	86.8
10	SUMO-P	28	65	6 bulbs	15	68.40	78.2	Yes	106.5
11	ID -SUMO	28	63	6 bulbs	0	40.43	44.91	No	73.7
12	ID- SUMO	28	63	6 bulbs	15	32.22	30.9	No	59.4
13	ID-TG	28	60	Un-bulbed	0	44.85	51.3	No	69.8
14	ID- TG	28	60	Un-bulbed	15	36.32	30.87	No	57.6
15	Superstrand-P	21.7	60	Un-bulbed	15	52.40	90.2	Yes	85.7
16	Garford-P	2 *15	2*27	Bulbed	0	44.55	46.8	No	80.9

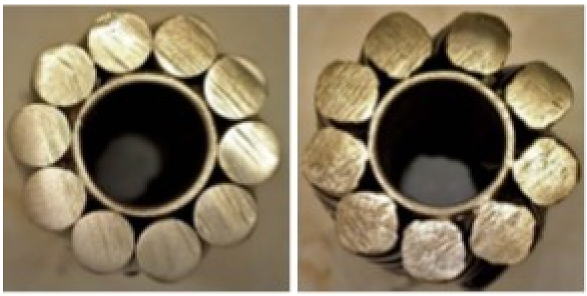


Figure 9. MW10 plain and MW 9 spiral wires with both wires of 7 mm in diameter [10].

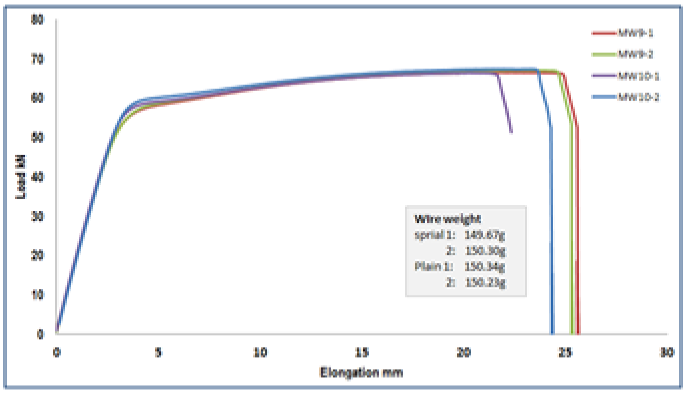


Figure 10 a. Tensile load/elongation profiles of both MW plain and MW indented 7 mm wires of equal lengths.

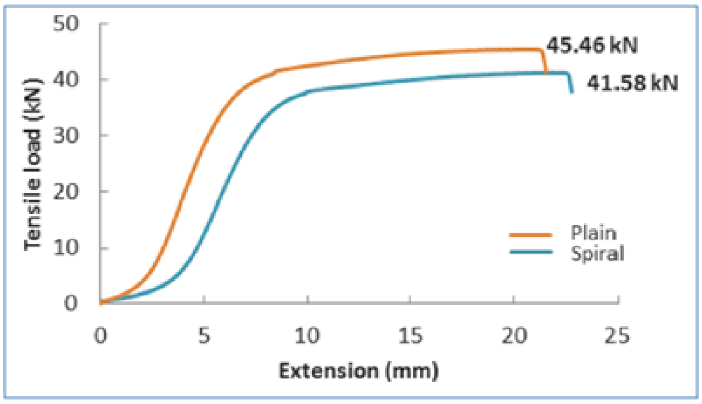


Figure 10 b. Tensile load/elongation profiles of both plain and indented 5.5 mm wires of the 21.7 mm cable bolts [6].

4. Influence of strand wire profiling

In order to study the influence of shear testing methodology on cable strand wire profiling, various cable bolts were tested using both the single and double shear rigs. All tests were carried out in a 40 MPa concrete medium. Both the plain and indented cable bolt strand wire failure profilings in both test methods are pictorially illustrated is Figures 11 and 13. In double shear testing, two types of cable bolts, i.e. the Sumo and Megabolt cable bolts, were considered, while more cable bolts were tested using MISSTR. The focus of attention was to examine the influence of surface profiling and bulbing on cable bolt failure mode and cable strand wire failure modes. In particular, the role of strand wire roughness was evaluated with respect to the cable bolt strand wire failure patterns. Table 4 lists the properties of both the Sumo and Megabolt strand wire cable bolt plains and indented surfaces. The Megabolt cables included MW9 spiral and MW10 plain cables. MW9 is a nine-wire strand cable, while the MW10 strand has 10 wires. The Sumo cable bolts have 9 wire strands. The results of the tested samples are shown in Table 5.

Table 4. Properties of SUMO cable strand and MW cable strand from manufactory.

Cable bolt	Indented SUMO	Plain SUMO	Spiral MW9	Plain MW10
Diameter	28 mm	28 mm	31 mm	31 mm
Capacity	630 kN	650 kN	620 kN	700 kN

Table 5. Shear test results by test methods of SUMO cable bolt.

Method	Double shear test				Single shear test			
Pretension	15 t		0 t		15 t		0 t	
Item	Disp. (mm)	Load (kN) (single face)	Disp. (mm)	Load (kN) (single face)	Disp. (mm)	Load (kN)	Disp. (mm)	Load (kN)
Plain cable	88.2	852 (426)	105	886 (443)	78.2	684	71.8	558
Indented cable	85.7	767 (384)	93.4	815 (408)	30.9	322	44.9	404

5. Profiles of failed wire surface

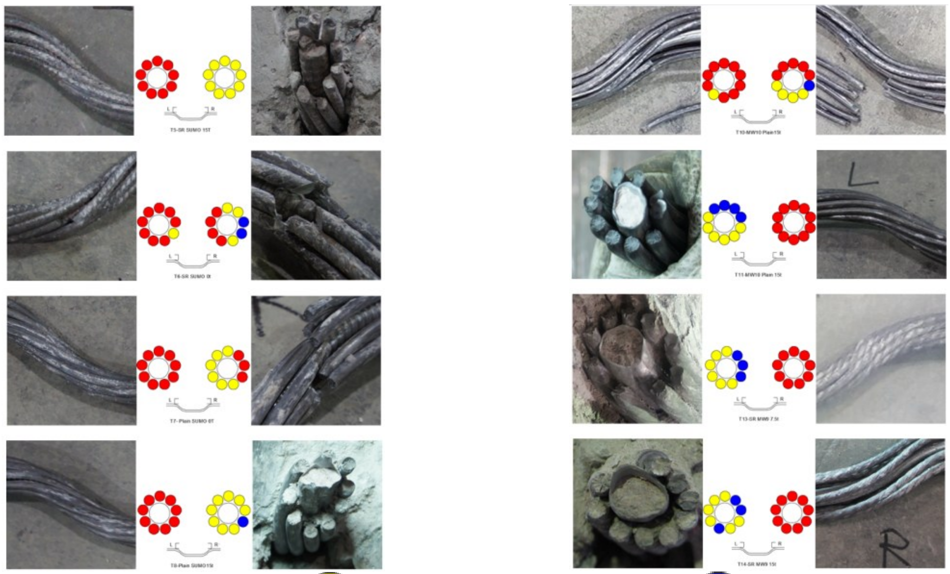
5.1. Double shear tests

Figure 11 shows the profiles of both the SUMO and Megabolt MW9 and MW10 cable bolts tested in double shear rig. Due to the ineffective concrete confinement in rectangular and cubical double shear rigs, the radial and axial cracking of the concrete blocks, as shown in Figure 12, generated conditions that caused increased sheared cable vertical displacement. The increased displacement contributed to significantly higher cable failure loads, a lot greater than that would have occurred with effective confinement and no radial cracks. The radial and axial cracking of the concrete enables the sheared cables to bend excessively along the weak cracked zone, making the cable bent zone to behave as though being pulled apart, leading to failure by pulling rather than shear, and hence, increased failure load. As it can be seen in Figure 11 and profiles of cut strand wires, it is obvious that most wires have failed in tension and in a combination of shear and tension.

5.2. Single shear test

A total of 19 cables were tested, which included six MW10 plains, three MW9 spiral cable bolts, two Sumo plain, and two Sumo indented cable bolts. The applied pre-tension loads to each tested cable are shown in Table 3. The table also lists the additional tested cables that are not considered in this comparative study. Figure 13 shows the typical shear load and vertical profiles of some tested cables using MITSSR.

No axial pretension load profiles can be recorded as each cable is encapsulated in full length, and hence, it may not be necessary to monitor the pre-tension load. However, if the cable is de-bonded, then the cable end movement is monitored by LVDT. Figure 14 shows the wire failure profiles for each cable.



: Un-snapped wires :Snapped wires in tension :Failure in tensile/shear

Figure 11. Strand wire failure profiles in Sumo and Megabolt cables. Both the left and right shear failure faces are shown.

Figure 12. Double shear post-test concrete blocks crack.

6. Comparison of testing results between the single and double shear testing methods

Realistically, the methodology of tendon shear testing should not influence the test outcome as long as various parameters are the same. The factors of particular interest include what follow.

1) Cable end anchorage: In the single shear test, reliance is made on securing the optimum cable length encapsulation in the concrete cylinder. The optimum length of encapsulation was found to vary between the indented surface and plain/smooth wires. In the double shear testing method, the Barrel and Wedge (B & W) system provides a positive anchorage irrespective of the cable strand wire surface. Cable de-bonding in single shear testing may occur if the encapsulated cable length is insufficient, resulting in an increased cable wire failure, mostly in the tension rather than the tensile/shear due to the increased shear load displacement.

2) Competence of concrete medium confinement: A poor medium confinement may result in a premature concrete radial cracking causing a reduction in cable stiffness with a higher shear load travel. The increased cable shear displacement would cause the cable to fail with an increased number of cable wires failing in the tension rather than the tensile/shear. In other words, the cable strand shear failure load will be closer to failure in tension rather than in shear. Thus an effective confinement of the concrete reduces the chances of radial crack occurrence with a less vertical shear travel. This is clearly observed when testing samples in a cylindrical

concrete with effective and high torqued steel clamps. Accordingly, a new double shear rig, known as UOW NAJ DS rig, has been developed, as shown in Figure 2E, and is now undergoing test trials with some positive results. The new rig uses cylindrically-shaped concrete blocks to be confined with steel clamps similar to top single shear testing.

3) All plain wired cables were found to de-bond readily in comparison with the indented and cables with an increased shear displacement with strand wire failure occurring in tensile shear combination.

4) Pure shear in cable wires occurs when the cable is guillotined with wires being squeezed with a lower shear load, as expected from the British Standard teste (BS 7861 part II) [4], and also by the method reported by [14]. In double shear testing, it is impossible to observe cable de-bonding due to the barrel and wedge influence.

5) It should be recognized that a realistic way of evaluating cable de-bonding per encapsulated length can best be determined by pull-out testing and not by shearing. As various tests demonstrated, an excessive displacement of a cable during the shearing process makes it behave as if the strand wires fail in tension rather than in shear. This is demonstrated by the fact that most wires fail in tension with snapped surfaces typically characterised by cone and cup failure, as shown in Figure 8.

6) Bulbing contributes to effective bonding of the cable to the host medium. This is clearly seen in the axially cut concrete section, which clearly demonstrates the effect of bulbing on load transfer interaction between the cable and the rock/concrete medium at the bulbed zone (Figure 15).

7) The rate of shear loading should be at less than 4 mm/min, which will produce consistent results irrespective of the methodology of testing with other factors being the same.

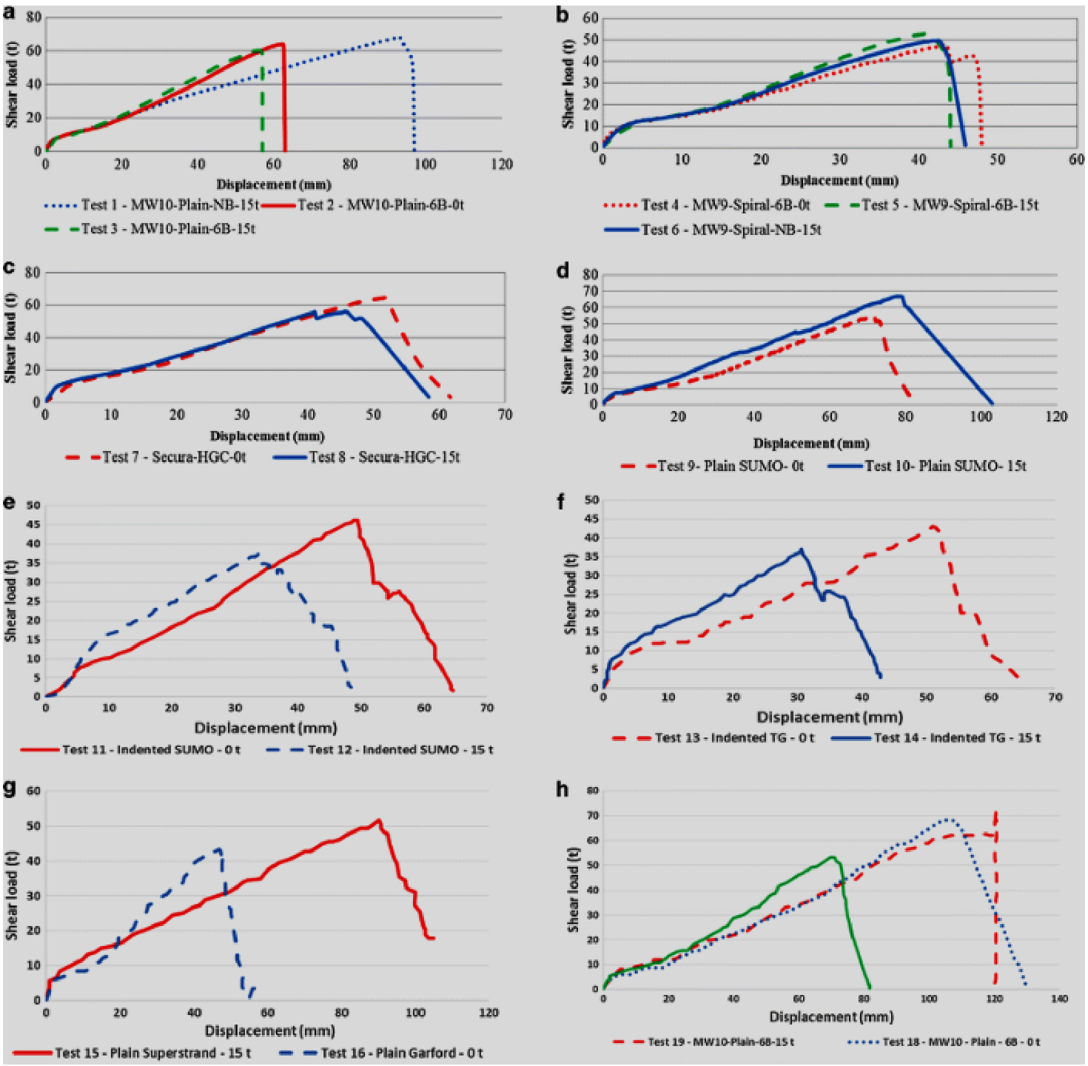


Figure 13. Shear load *vs.* vertical displacement profiles of various tested cables using MISSTR.

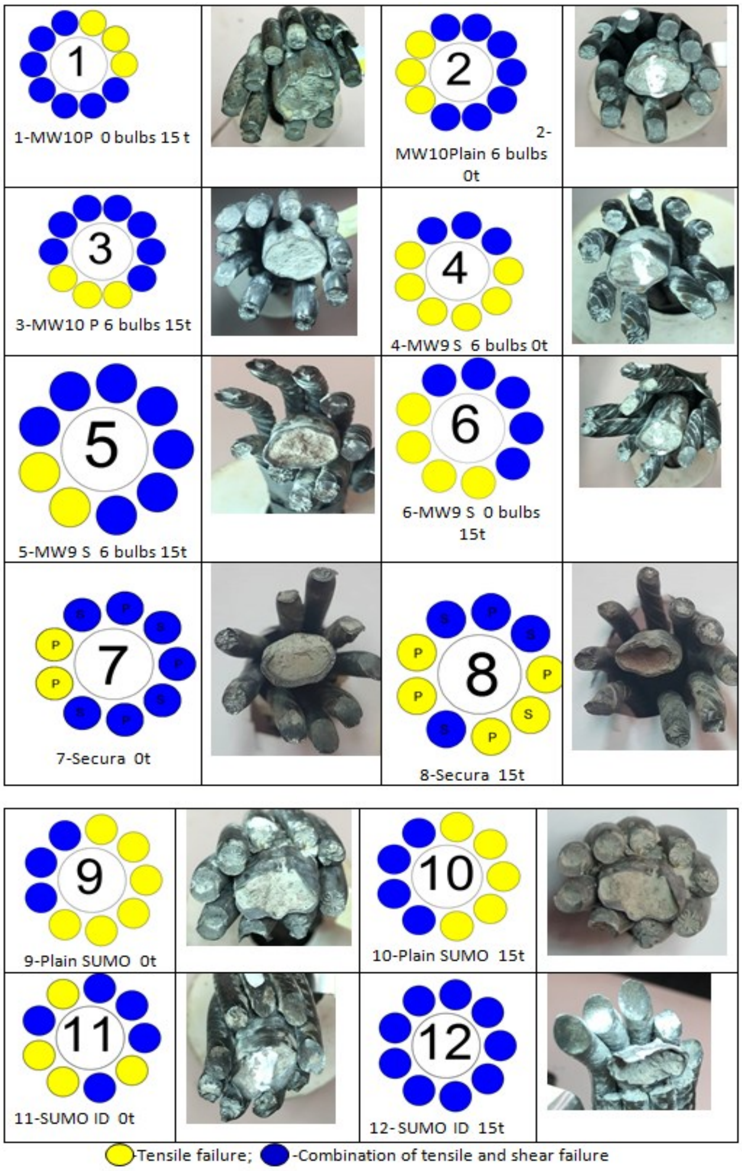


Figure 14. strand wire failure patterns for all tested cables.

Figure 15. Cross-sectional view of de-bonded Plain MW10. Note the extent of wire failure in tension with failed wires surface being mostly in cone and cup.

Figure 16. Bulbed cable strand.

7. Conclusions

- The choice of the method of testing cable bolts in shear is governed by the relevant factors that influence the outcome of the testing, and irrespective of the methodology of testing. An effective medium confinement of the concrete cylinders during shear testing reduces the chances of radial crack occurrence with less vertical shear load travel resulting in cable failures closer to shear rather than failure in tensile.
- Under the same testing conditions, plain cable bolts appear to de-bond much more readily than indented cable bolts when tested in the single shear testing machine with an equal length of encapsulation.
- Pure shearing of cable bolt wires is possible if the cable strand confinement is strong enough so that the cable bolt is sheared in the pseudo-guillotined state with undergoing a minimum bruise.
- Finally, the use of the single shear test rig method is in not appropriate for evaluating true cable de-bonding for a given encapsulation length, rather the pull-out test method should be used.

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رویکردی جدید برای تقویت لایه‌های زغال‌سنگ با توجه به ارزیابی مقاومت برشی پیچ سنگ‌ها

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چکیده:

امروزه نیاز به تعیین دقیق خواص مقاومتی پیچ‌سنگ‌ها برای کنترل مؤثر زمین در معادن و سازه‌های زیرزمینی و نیز شبیه‌سازی مدل‌سازی‌ها افزایش یافته است. خواص مقاومتی کابل‌ها که به عنوان اجزای پیچ‌سنگ استفاده می‌شوند، به طور عمده توسط مقاومت کششی نهایی مورد ارزیابی قرار گرفته است، چرا که این نوع از آزمایش می‌تواند در محل میدانی و آزمایشگاه انجام شود. اخیراً به علت وجود شواهدی از رخداد شکست‌ها، علاقه‌مندی زیادی در بررسی برش پیچ‌سنگ‌ها وجود دارد. بر این اساس، در این پژوهش، روش‌های مختلف آزمایش برش کابل‌ها و پیچ‌سنگ‌ها با استفاده از دستگاه‌های مختلف آزمایش برشی در دانشگاه ولونگونگ استرالیا انجام شد و نتایج آن گزارش شد. نتایج نشان داد که پیچ‌سنگ‌های ساده در شرایط مشابه آزمایش برشی نسبت به پیچ‌سنگ‌های مارپیچی از بین رفته‌اند. علاوه بر این، هر دو روش برش مجزا و برش دوگانه نتایج مشابهی را در صورت عدم وجود پیوند مناسب نشان داد.

کلمات کلیدی: تکنولوژی رشته‌ای، پیچ‌سنگ، آزمایش برش، بارهای پیش تنشی، بتن.
