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PROFILE OF SHEARED CABLE BOLTS STRAND WIRES

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ABSTRACT: For the past several decades cable bolt technology has been used for ground reinforcement in civil, mining and other construction projects. The strength properties of these cables, used as cable bolts, have been evaluated mainly by their ultimate tensile strength as this kind of test could 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 documented field failure evidence. A series of single and double shear tests were carried out to study the extent shear failure of cable bolts in concrete blocks. Tests were made using both single and double shear rigs at the University of Wollongong. Various types of marketed cable bolts were tested using both types of shearing equipment. Various pertinent parameters were examined with direct influence on the failure characteristics of cable bolts were examined. This paper illustrates the strand wires failure profiles in both test methods and with particular focus being directed to the shear failures of both plain and indented cable bolts currently used in Australian mines. The nature of cable failure and the extent of sheared cable displacement affecting the profile of broken strands wires are reported to indicate the way the cable bolt has failed and its failure load.

INTRODUCTION

Cable bolting has been used world-wide 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 test could 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 documented field failure evidence.

For the past several years, a significant knowledge has been gained on tendon load transfer mechanisms and strength characterisation mainly by pull testing (Aziz and Jalalifar, 2005, 2006, Hagan, *et al.*, 2015), however little has been known about the cable bolt shear behaviour, since the interest in cable bolt failure in shear has been confined to small amount of work carried out based on the British Standard of shear testing (BS 7861-part 2, 2009) and the work of Craig and Aziz, 2010, and Aziz, *et al.* 2015a). Also, no credible test results are available from the field and only pictorial evidence has recently been surfaced for both 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 McCowan (2015), and Li (2017)



Figure 1: Sheared tendons recovered from field and a hole view of sheared rock (McCowan, 2015 and Li, 2017)

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When a cable is sheared to failure in a soft medium such as in soft rock and in weak concrete, there is 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 both tensile and shear. Other influencing factors include grout strength, applied pretension load, testing method and loading condition (Aziz, *et al.*, 2017).

This paper examines the shear failure of various cable bolts under different pretension loads using both single and double shear techniques. The extent of shear displacement has been found to play a significant role in the strand wire failure pattern as reported (Aziz, *et al.*, 2017). Particular emphasis is focused on pictorial evaluation of the snapped strand wires.

SHEAR TESTING OF CABLE BOLTS

Methodology

Shear testing of cable bolts has, for several recent years, been undertaken by using both the single and double shear methods. A single shear test method, based on the British Standard BS 7861 Part 2 (2009), was used to determine the shear strength of cable bolts to failure (Aziz and Hawker, 2015). Aziz, (2004) undertook double shear testing of 15.2 mm diameter resin coated, seven wire strand cable bolts to examine the extent of plastic surface damage with respect to increased shearing displacement. Testing of cable bolts to full failure in shear was subsequently carried out in larger double shear machine (DS-MKII) by Aziz and Craig (2010). Further studies on cable bolt load transfer mechanism have since been undertaken with emphasis directed solely on determining the load transfer characteristics with particular reference to evaluating failure profiles of various wires in the strand.

Currently, two types of testing rigs are used for shear testing of various cable bolts, 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 of tendons were undertaken using the University of Wollongong DSTR.

Double shear testing method

Two types of double shear testing methods were available for evaluating the shear characteristics of cable bolts; (a) The DSTR-MKII 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), with opposing concrete joint faces not in contact with each other and the measured shear resistance force is spent on shearing the cable wires. Accordingly, The DSTR-MKIII rig as shown in Figure 2 was used in this study. The DSTR MKIII frame consists of two 300 mm length outer cubic boxes and 450 mm length middle central cuboid box with 300x300 mm² cross-sectional area. A conduit wrapped with 8 mm PVC hose, was laid horizontally along the mould to precast a rifle hole through the centre of concrete blocks. Once the concrete was poured it was left to set.

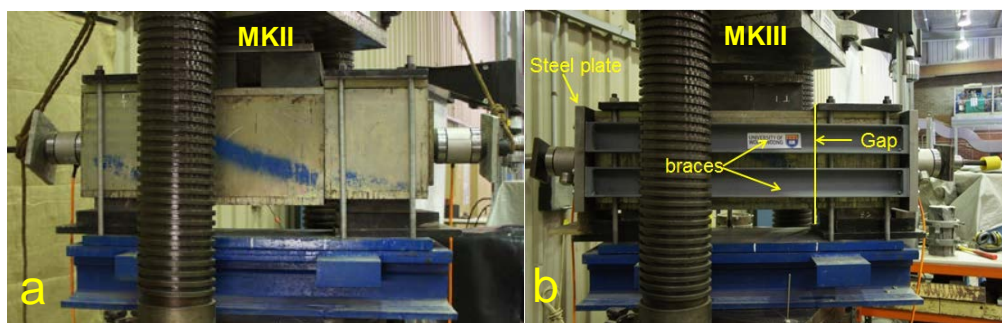


Figure 2: Double shear test rigs (a) MKII and (b) MKIII.

Prior the apparatus being assembled, the hollow central tube of each cable is 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 and held together using a truss system around the double shear assembly as shown in Figure 1 b. The truss system consisted of four 1100 mm length steel braces connected between two 30 mm thickness side steel plates. The brace system impedes subjecting lateral axial load on concrete blocks during shearing. When assembled, gaps of almost 5 mm were left between concrete blocks, thus the adjacent sheared concrete faces are kept apart thus eliminating the contact between the sheared faces and hence no friction force. Next the cable bolt was inserted into the central axial hole and was followed by mounting 100 t load cell on each protruding side of cable in the assembled concrete blocks and tensioned to the predetermined 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 the grout in the central concrete blocks 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 pretensioned, grout mortar was injected the space between central and cable strand from the vertical pre-cast hole in the top of each concrete blocks. After seven days of grout/resin curing time, the double shear assembly was then placed on the carrier base frame consisting of a parallel pair of rail track sections welded to a 35 mm thick steel plate. The outer side 300 mm³ 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 the rate of 1 mm/min for the maximum 100 mm vertical displacement. A hydraulic universal testing machine with a capacity of 500 t was used to compress middle block for shearing cable strand at the rate of 1 mm/min for the maximum 100 mm vertical displacement.

Single shear test

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

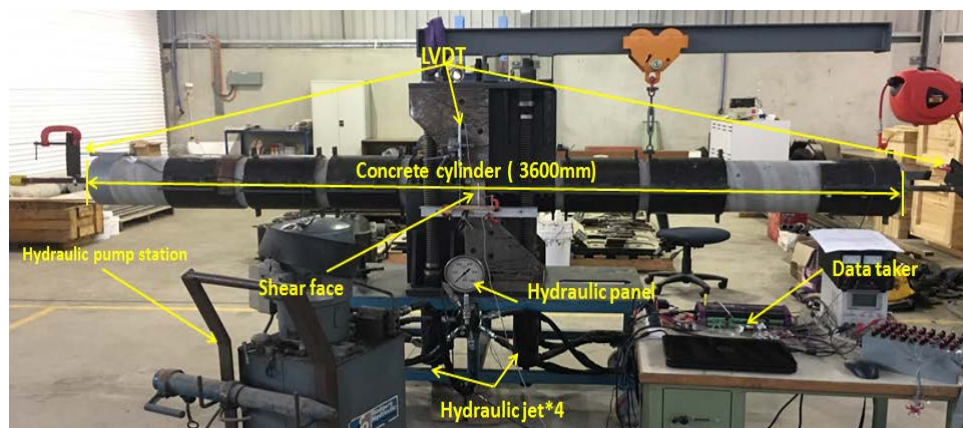


Figure 3: Megabolt integrated single shear rig (MISSTR)

The 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 applied the hydraulic pressure for compression machine legs. The pressure in the manifold was 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 was not constant, however the aim was to apply a constant load at the rate of around 1 mm/min (0.018 mm/sec), in line with BS7861-2 standards. The displacement at the shearing plane

was measured using a Linear Variable Differential Transformer (LVDT) as shown in Figure 3 a. Two other LVDTs were also mounted on the cable ends to enable monitoring of cable debonding. A data taker recorder was used to collect data during the tests.

When preparing, two 1800 mm concrete cylinders glued by two 900 mm cylinders were butted together in a specially built tensioning frame. The cable bolt is 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 the grout was pumped from the bottom up to 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 tested cables in this programme of study. The strength properties of the grout have been reported by Majoor *et al.* (2017), and Mirza, *et al.*, (2016).

After a grout curing period, each concrete sample with encapsulated cable bolt was disassembled from the frame and lifted out to be mounted on to the shearing rig. Once the concrete cylinders was correctly placed in the shearing, steel clamps were placed around the concrete blocks to provide a confining pressure to the sample, this accurately replicating the in situ conditions. When sheared one side of 1.8 m of the 3.6 m concrete column remains fixed on the rig, while the other half is subjected to shearing. Two LVDTs were installed on each end of the cable strand to monitor the point displacement during shearing. The load of shearing face was recorded by data taker and the displacement of cable ends and sheared cable strand wires were monitored by LVDTs, which were all logged by computer.

INFLUENCE OF STRAND WIRE PROFILING

To study the influence of cable strand wire profiling, various cable bolts that are available in the market were tested using both single and double shear rigs. All tests were carried out in a 40 MPa concrete medium. Both plain and indented cable bolt strand wires failure profiling in both test methods are pictorially illustrated in Figures 4 and 6. In double shear testing two types of cable bolts, Sumo and Megabolt cable bolts, were considered, while more cable bolts were tested using the Megabolt single shear test rig. The focus of attention was to examine the influence surface profiling and bulging on cable bolt failure mode and cable strand wires failure modes. In particular the role of strand wires roughness was evaluated with respect to cable bolt strand wires failure pattern. Table 1 lists properties of both Sumo and Megabolt strand wire cable bolts plain and indented surfaces. The Megabolt cables included MW9 spiral and MW10 Plain cables. MW9 is a nine wire strand cable while MW10 Strand has 10 wires. Sumo cable bolts have 9 wire strands. Table 2 shows the comparative shear test results of SUMO cable bolt strand of smooth and indented wires.

Table 1: 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 2: Single and double shear test results of plain and indented SUMO cable bolt strand wires at 0 and 15 t pretension load

method	double shear test (no joints surface contact)				single shear test			
	15t		0t		15t		0t	
pretension	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

Profiles of failed wire surface

Double shear tests: Figure 4 shows the profiles of both SUMO and Megabolt MW9 and MW10 cable bolts tested in double shear rig

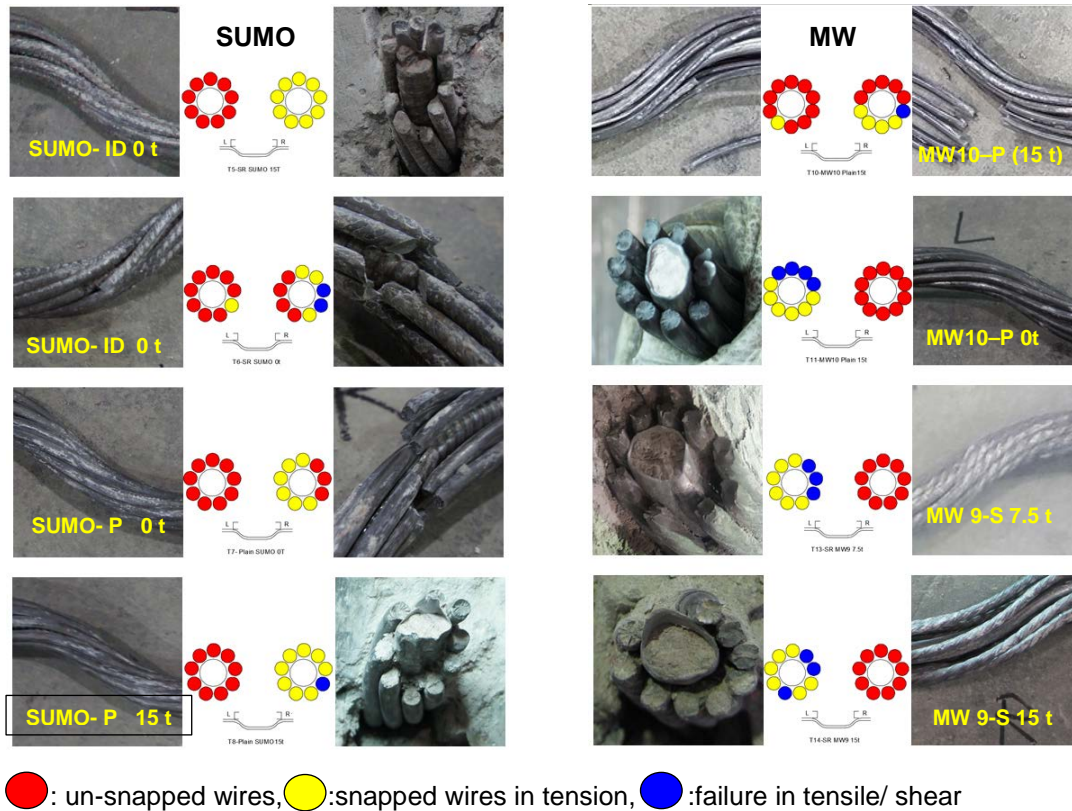


Figure 4: Strand wires failure profiles in Sumo and Megabolt cables tested in DSTR-MKIII Equipment. Both left and right shear failure faces are shown

Because of the ineffective concrete confinement in rectangular and cubical double shear rig, the radial cracking of the concrete blocks, as shown in Figure 5 generated conditions that caused increased sheared cable vertical displacement. The increased displacement contributed to increased cable failure loads, significantly greater than that would have occurred with effective confinement and no radial cracks. The radial cracking of the concrete enables the sheared cables to bend excessively along the weak cracked zone making the cable bent zone behave as though being pulled apart leading to failure by pulling rather than shear and hence increased failure load. As can be seen from Figure 4 and profiles of cut strand wires, it is obvious that most wires have failed in tension and a combination of shear and tension.

Also, unconfined concrete host medium may end up being radially cracked during the shear process, making the cable shear displacement greater, causing the cable to snap or fail as if it is being pulled to failure rather than being sheared and the resulting failure being greater, at around 70%, than would normally be the case.



Figure 5: Double shear post-test concrete blocks crack

Single shear test: A total of 19 cable bolts were tested, which included; (a) nine Meagbolts of six MW10 plain and three MW9 spiral, (b) two SUMO Plain and two SUMO Indented, (c) others. Table 2 lists 16 cable bolts tested at predetermined pretension loads of zero and 15 tonnes. Figure 6 shows the profiles of 12 tested cables tested using MISSTR. The focus in this paper was to compare shear profiles of two types of cable bolts, namely Sumo and Megabolt MW with respect to the type of testing methods (single versus double shear methods).

Table 2: single shear test results of 19 cable bolts.

Test No.	Product Name	Cable Dia. (mm)	UTS (t)	Cable geometry	Pre-tension load (t)	Peak Shear load (t)	Shear disp.	Cable debonding	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

RESULTS AND ANALYSIS

Because of the lack of effective confinement in double shear equipment, the failure profiles of most snapped wires in various cables were mostly in tension, tensile /shear and no failures. No failure often occurred on one side of the double shearing because the individual wires in the strand began to debond causing wires to be pulled out when sheared down further with excessive displacement. As a result the recorded shear strength of the cable was significantly higher than those noted from single shear tests, Hence no realistic conclusions can be made on DS test wires failure.

Also and although no direct comparative analysis can be made between single and double shear methods with respect to cable debonding, nevertheless the cable debonding significance is appreciated when testing cables with long encapsulation length, as in single shear test. This has provided a significant input on the cable bolt performance with regard to cable strand wires failure due to wire surface roughness, cable encapsulation length, debonding and the extent of cable shear displacement at the shear section zone. Plain MW10 was found to be superior in terms of resisting shear load. This is because the increase in number of wires in the strand to ten and had a tensile strength of 70 tonne. From the single shear testing it was found that;

- Plain wired strand cables were debonded for the tested cable encapsulation length of 1.8 m. Some debonded cables did not fail or snap. No debonding occurred in indented cable

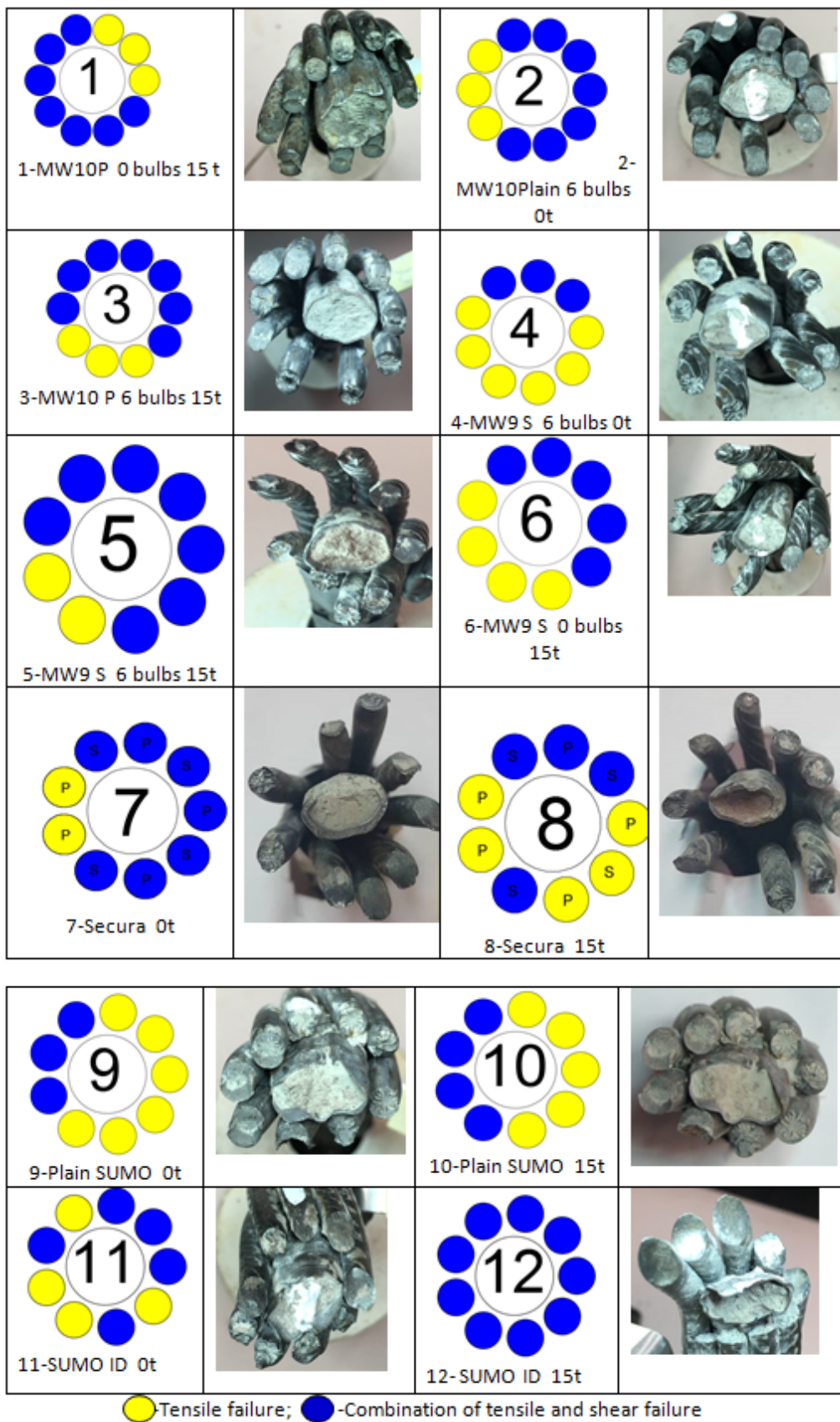


Figure 6: strand wires failure patterns for all tested cables

strand wires for the same length of cable encapsulation. Secura cable with almost 40% spiral wires did not debond.

- The debonded cables, which were mainly plane wired, resulted in an increase in displacement at peak shear load. Where a cable is debonded, the shear displacement of between 60 -120 mm made the shared cable strand section behaves as if it was being pulled apart to failure rather than being sheared. As a result wires tend to fail in tension or a combination of shear and tension with the failure in tension being predominant as can be seen in Figure 7. Thus it is reasonable to suggest that increased displacement has influenced the nature of sheared wires failure in the strand. Generally, wires fail closer to shear/tensile state in comparison to failure in tension.
- Increased cable displacement causes cable wires to fail mostly in tension. The cable failure in tension also occurs in double shear testing as a result of concrete medium cracking axially as shown in Figure 5, thus resulting in excessive bending and stretching of the cable section in the vicinity of joint faces, and shear displacement travel in double shear tests was mostly in excess of 70 mm. Often the failure loads were in excess of the failure loads obtained from single shear testing. Thus the majority of wire failures tend to be in tension failures with a small number of wires failing in a combination of tension and shear.
- No debonding was observed in spiral and indented cable bolts because of the influence of increased interlocking in the cable/grout interface. Accordingly failure modes in the cable bolt wires are the combination of tensile and tensile /shear failures. No strand wire fails in pure shear unless the wire is fully guillotined.
- In general, the failed strand peak shear load was lower with increased pretension load in a bonded condition in shear. Higher pretension load causes the cable to stiffen and fail with lower vertical shear displacement.
- Pure shear in cable wires occurs when the cable is guillotined, with wires being squeezed and with lower shear load as reported by McTyre and Evans (2017). In double shear testing it is impossible to observe cable debonding because of barrel and wedge influence.
- It appears that reducing the rate of loading provided consistent results. It is accepted that the rate of loading of less than 4 mm /min is a reasonable rate for testing.

With single shear testing facility, the preparation of up to six single shear test samples was possible at the same time, hence the grouting of cables was left to cure for a desired cure time and they were all tested over a short time span. All tested samples were fully and effectively confined with steel clamps leading to consistency in results. However, the methodology is laborious and requires heavy lifting gear. Also, prolonging the sample testing duration may allow studies on the influence of host concrete medium and grout age to be investigated effectively without sacrificing any monitoring equipment attached on the prepared samples. This was not the case with the double shear testing method, due to the fixed barrel and wedge anchors; it was only possible to encapsulate one cable at a time with load cells being locked up on the cable's ends. As a result tests were made in shorter grout age of around 10 days.

The next programme of double shear testing will be undertaken in short cylindrical concrete blocks with effective steel clamps that will prevent concrete radial cracking for improved results.

CONCLUSIONS

The rectangular steel clamps on prismatic DSTR cannot provide effective confinement to the concrete medium. Thus, the unconfined concrete host medium may prematurely crack during

the shearing process, with increased shear load displacement, thus causing the cable to fully snap or fail as if it is being pulled to failure rather it is being sheared.

Because of cable debonding, not all debonded plain cable strand wires failed or snapped in single shear testing for the given cable encapsulation length of 1.8 m. Increased displacement influenced the nature of sheared strand wires. Generally wires failed closer to the shear/tensile state in comparison with failure in tension. Increased cable displacement causes cable wires to fail mostly in tension.

In general the failed strand peak shear load was lower with increased pretension load in the un-debonded condition. The peak shear load failure of un-debonded cable was lower with increased pretension load. Higher pretension load causes the cable to stiffen and fail with lower vertical shear displacement.

The use of steel clamps in double shear method with cylindrically shaped concrete would prevent concrete crack radially and may provide a sound way of testing cables for shear similar to single shear tests.



Figure 7: Cross sectional view of Cable bolt Unbulbed, Plain MW10, 15 t pretensioned and debonded. Note the extent of wire failure in tension of Cone and Cup. The failure load of 68.2 t is almost equal the cable axial load capacity of 70 t. The shear load displacement at failure was 68.2 mm.

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