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Mechanical direct shear tests of cables – combined stress relationships

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MECHANICAL DIRECT SHEAR TESTS OF CABLES – COMBINED STRESS RELATIONSHIPS

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ABSTRACT: Cables have remained an integral part of underground mining in Australia since the 1970s and many of their properties are well-researched. However, no standardised test is generally accepted for shear - an important failure mechanism for cables; therefore, this fundamental property is not fully defined. Further, the uncertainty means the relationship between shear load capacity and axial tensile load (pre-tension) is not completely understood. This paper begins to fill the information gap by reporting the results from a new test method. A simple, replicable and valid mechanical direct (90°) shear test method has been developed, that intentionally departs from existing reported methods, by not embedding the cable. The preliminary results show a clear relationship between peak shear load and pre-tension magnitude, by eliminating the numerous variables associated with embedded shear test methods. The mechanical test method can thus be used to determine the minimum shear performance of cables under repeatable conditions, but also augment existing embedded cable shear research, by providing the baseline mechanical properties of the cable.

INTRODUCTION

Cables have been a part of ground control in Australian underground mining since the early 1970s (Hustrulid 2001). Cables comprise a number of wires (or strands) in a helical formation around a central wire or wires. This arrangement provides both high axial capacity and flexibility. The flexibility is important as it allows for the cable to be long continuous lengths of typically 4 to 11 m, and yet still be installed in the sometimes restrictive roadway heights of coal mines. It has been generally accepted since the 1980s that rock bolts and cables have the primary objective of increasing rock mass stiffness with respect to tensile and shear loads (Gerard 1983). This improvement in rock-mass resistance to tensile and shear forces is a function of a number of mechanical influences, including the use of compression (via bolt or cable tensioning) as well as the transfer of load from the rock mass to the cables.

Cable suppliers provide product specification sheets to end users. This information is comprehensive for the mechanically-derived tensile properties of the cables, including the Ultimate Tensile Strength (UTS), yield load and elongation. These tensile properties are used for ground support design. However, suppliers do not pass on cable shear properties. This information gap exists for two reasons. First, industry does not readily accept any standardised shear test, and second, ground support designers have not generally used cable shear data during the ground support design process. Yet shear properties are important for end users because ground displacement can load cables both in tension and shear.

The two existing methods for generating the combined shear and tensile stresses in cables are single shear plane methods and double shear plane methods. These methods involve embedding the cable in either resin or grout in holes of various annulus. Embedded methods therefore introduce additional test variables over pure mechanical tests. The resulting variability in test results has meant that publicly available test data is highly interpretive when used to compare cables. Further, these test methods are expensive and time consuming resulting in low volumes of test data. It is argued that this lack of comparable shear test data has held back the industry's understanding of how the mechanical properties of cables in shear influences the performance of cables in the field. Field performance of

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cables is an increasingly relevant topic as deeper and more challenging ground conditions become the norm in the Australian coal industry.

To fill this information gap, DSI developed its own mechanical direct shear test method. The method aims to provide end users with benchmark shear properties from a reliable and valid test. It will complement data derived from mechanical tensile test methods. The key point here is that until the mechanical shear properties of a cable are understood, it is difficult to make sense of the results of embedded shear methods, which have introduced additional variables that further affect the results.

The test method deviates from previous test methods because it does not embed the cable. Instead, the method has the cable fed through holes cut into two hardened, tight-fitting steel cylinders. Then, a Universal Test Machine (UTM) shears the cable at the interface between the two cylinders. The UTM allows collection of both load and displacement data. A frame was used to pre-tension the cables to a range of loads. This allows collection of the pre-tension and peak shear-load relationship. The results and relationships between the variables measured were evaluated against existing publicly available cable shear information and discussed for their relevance to the underground coal mining industry.

CURRENT CABLE SHEAR TEST METHODS

Two tests methods that replicate the field performance of cables are commonly used in Australia. The single shear test method has been used by Windsor *et al* (1988), Windsor (1992), and Windsor and Thompson (1993), Fuller and O'Grady (1994), Hagan and Mahony (2006), Rock Mechanics Technology (RMT) (2006) (described in BS 7861-2, 2009), and improved upon by Megabolt Australia (Figure 1 Megabolt 2015). The double shear test is detailed in Aziz *et al* 2003, 2004, 2014, 2015, 2016, and is commonly associated with the University of Wollongong (UOW). Both methods embed the cable in resin or grout, then subject the cable to shear load until the wires either fail, or displacement becomes excessive. Readers are referred to the above for further explanation and information on these methods.

Figure 1: The Megabolt single shear test rig (Megabolt 2015)

These test methods have highlighted several key points on the performance of cables in shear. These include:

The embedded cable single and double shear methods result in the failure of the cables in combination bending and tension (Figure 2). This failure mode is representative of cable shear in coal mine strata. However, it is expected that this failure mode will result in higher shear load and displacement compared with mechanical direct shear.

Figure 2: Cone and cup tensile failure of wires (left), and grout de-bonding and concrete block deformation during a double shear test (middle from Aziz *et al*, 2014), and bending and tensile failure during Megabolt Shear Testing (right from Megabolt, 2015)

The angle and direction of shearing has been found to influence the performance of the cable. Hutchinson and Diederichs 1996 (Figure 3) reported the stiffest response was found by a combination of shear and tension (135°), then direct shear (90°). The least stiff response was shear and compression (45°).
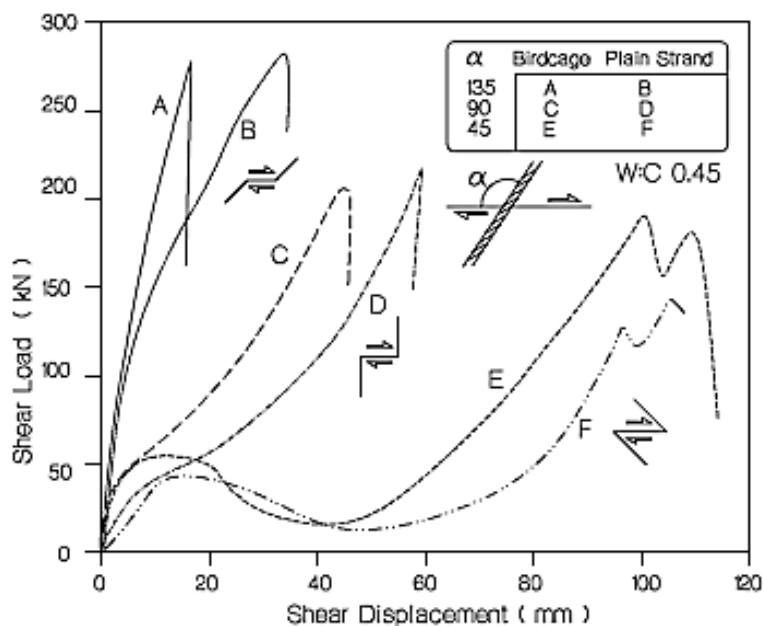

Figure 3: Typical results from direct shear tests of cablebolts (after Windsor and Thompson 1993, Windson 1992 and Windsor *et al* 1988) from Hutchinson and Diederichs 1996

The embedded material properties influence the shear load. Similar 21.8 mm diameter cables were embedded in resin and grout and double-shear tested at the UOW (Aziz *et al* 2014 and 2015). The variation in shear load may be explained by the difference in embedment materials.

The length of resin embedment affects the performance of the cable in shear. RMT 2006 found that the greater the length of embedment, the lower the shear load achieved prior to failure (Table 1). Longer embedment lengths resulted in a reduction in variation of measured shear load (RMT 2006). Megabolt 2015 found an embedment length of 1800 mm was required to stop cable de-bonding of non-bulbed cables from causing high levels of shear displacement.

Table 1: Test variables and results of embedded shear tests on 21.8 to 24 mm diameter plain cables.

Test	Cable Description	Wire Type	Cable Diameter (mm)	Cable Pretension (kN)	Resin or Grout	Embedment Length (mm)	Hole Diameter (mm)	Confining Material	Single Shear	
									Maximum Shear Force (kN)	Average Shear Force (kN)
Fuller and O'Grady 1994	Flexibolt 21 wire	Plain	23	0	Resin (Chemfix SCP4)	350	27	Steel pipe	410, 470	440
RMT 2006	Reflex 7 wire	Indented	23	0	Resin (AT)	250	27	Steel pipe	410, 441, 393	414.6
						500			382, 389, 373	381.3
						900			358, 361, 367	362.2
RMT 2006	Megastrand 8 wire	indented	24	0	Resin (AT)	250	27	Steel pipe	384, 414, 424	407.3
						900			350, 314, 341	335.1
Aziz *et al* 2014	Hilti 19 wire	Indented	21.8	50	Grout (FB400)	300	28	Concrete (40 MPa)	316.4*	Na
		Plain							358.4*	
Aziz *et al* 2015	JSS 19 wire	Indented	21.8	250	Resin ("oil-based")	300	28	Concrete (40 MPa)	391*	Na
		Plain							441*	

*double shear tests: calculated maximum single shear value equals half maximum x 0.3 (Aziz, 2016)

Pre-tension levels affect the stiffness of the cable in shear. Megabolt (2015) found that increasing levels of pretension reduced both the shear load and shear displacement. However, double shear testing by Aziz *et al,* (2015) returned contradictory results for the relationship between pretension and shear load. This contradiction is arguably due to the Megabolt test method being more effective in reducing friction across the shear face than the method used in the UOW tests.

It is accepted that annulus has been shown to influence the load transfer properties of bolts and cables. Hence annulus size must be considered when testing embedded cables in shear, because it affects the inherent tensile loads that are produced during testing. It also has an influence on de-bonding.

Double shear tests are typically performed using three solid blocks, typically concrete or sandstone. The strength of the block material has an influence on the development of bending and tensile loads, and these variables then influence the shear load. Hagan and Mahony (2006) found maximum shear load resistance decreased with rock-mass strength.

The magnitude of confinement of the embedment material (the test blocks) influences the measured load in pull testing (Hyett *et al*, 1992, Thomas, 2012). Due to the tensile loading present in shear tests, the influence of confinement was factored into recent shear test methods (Megabolt, 2015).

Friction across the shear plane increases the shear load in single and double shear tests. The test rig must be suitably designed (such as the Megabolt single shear test method) to reduce friction both during the shearing process and due to pre-tension.
Finally, a host of factors vary across cable products, including steel grade, geometry, wire treatment (indented vs plain), whether it is bulbed or non-bulbed, the number of wires, and the cable lay. Each of these factors will influence cable shear properties.

To summarise, a large number of variables affect the results of embedded cable shear tests. Noting that while the differences between different cables should be the focus of shear property assessments, it is actually often lost in the mix of other test variables. Therefore, it is argued that a standardised test method is critical. However, the problem of test validity first needs to be solved.

CURRENT CABLE SHEAR TEST RESULTS

Published shear test results for plain strand (non-bulbed) 21.8 to 24 mm cable are limited (Table 1). The results consist of:

- A single shear test by Fuller and O'Grady 1994 on the 21 wire flexibolt;
- BS 7861-2 standard single shear tests by RMT 2006 on 7 wire Osborne Reflex cables and 8 wire Megabolt Megastrand cables;
- University of Wollongong double shear tests of 19 wire Jennmar Superstrand cables (Aziz *et al* 2015) and 19 wire Hilti cables (Aziz *et al* 2014).

Even within the limited testing available, a host of factors significantly influence the results. These include: plain vs indented wire, cable diameter, resin or grout type, embedment length, hole diameter and confining medium. Table 1 indicates:

i. Indented wire cables returned lower shear load than plain wire cables. This is thought to be due to the reduced cross-sectional area of indented strand cables, but may also be due to higher bond strength of embedded indented strands reducing bending and tensile load development.

ii. The shorter embedment lengths (250 to 350 mm) returned higher shear load than longer embedment lengths. However, 900 mm embedment tests returned the least variance. This may be due to longer embedment reducing pull-through, bending and tensile load development.

iii. The tests using grout embedment returned lower shear load than those using resin. Resin in this case may provide less stiffness and hence reduced potential for a direct shear.

iv. Shear load ranged from 314 to 470 kN, with an average of 385 kN from a total of 21 tests.

Table 1 shows significant variation in the test results. This is not surprising given the differences in test machinery and test parameters. Further, interpretation of these test method variables is made difficult because of the lack of understanding of the mechanical properties of the cables in shear.

MECHANICAL DIRECT SHEAR TEST METHOD

The aim is to provide the mechanical direct shear properties of the cable. However, the aim is not to provide an approximation of in-situ cable performance. The reasons for this are:

i. In-situ performance of cables is a function of a vast number of parameters that are often unique to each mine site. Hence, any laboratory-based testing designed to approximate in-situ conditions is highly specific to a small selection of mine sites or conditions.

ii. While installation parameters will change from site to site, the cable itself will have identical mechanical properties. So while the specification or performance of grout, resin or rock type may change and influence the *in situ* shear performance, the cable itself will behave according to the same inherent mechanical properties.

iii. Mechanical direct shear is the worst-case shear property of the cable, just as mechanical tensile tests are the worst-case tensile measure. Previous laboratory testing and field experience indicates the cable failure mode will be a combination of bending and tension. Therefore, in practice the cable failure loads will typically be between the mechanically-derived shear failure load and the mechanically derived UTS.

In general, the mechanical shear test method needs to have the following features:

- Accurate, replicable and valid direct shear test methodology that produces results with minimal variation.
- Shears the cable at 90° without introducing bending or tensile forces.
- Measures the shear load of the cable without (or minimising) shear plane friction.
- Eliminates the influence of resin or grout embedment on shear load results.
- Can evaluate the influence of various magnitudes of pre-tension (axial tensile load) on the cable peak shear load.
- Is cost effective and can be easily conducted providing increased availability of test data.

The test procedure involves:

- Passing a 21.8 mm 19 wire cable (Hi-Ten) through the 22 mm diameter holes drilled in two hardened 4140-grade steel cylindrical jigs (Figure 4). Two methods were used, single shear plane and two (double) shear plane for comparative purposes.
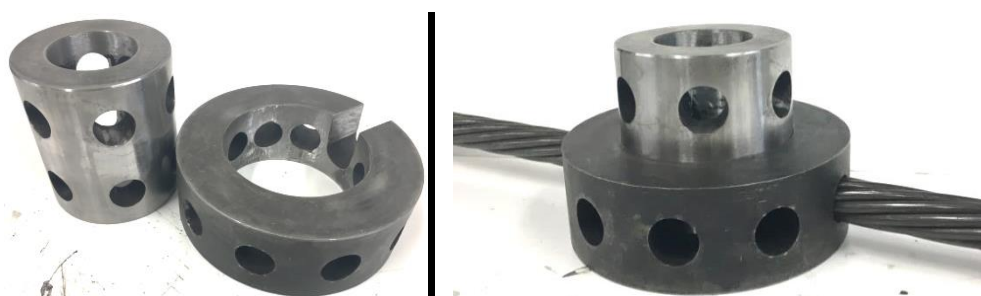

Figure 4: Test cylinders showing slotted sections used for single shear tests (left) and arranged with cable prior to testing (right)

- The cable is free to move through the cylindrical test jigs when tensioned as the jigs are not connected to the frame used to pre-tension the cable (Figure 5).
- The cable is tested without pre-tension (Figure 4 – right) and with pre-tension of 10 tonne and 20 tonne (Figure 5). Pre-tension is applied using commonly available barrel and wedges and hydraulic tensioning device.

Figure 5: Cable pre tensioning frame – note the axially loaded cable does not increase loading on the shear plane surface

- The inner cylindrical jig is displaced downwards by the Universal Test Machine (UTM) at a constant rate. To minimise sliding friction, both the inner and outer cylindrical jigs have very tight tolerances, and oil is used to provide fluid pressure and lubrication. The cylindrical shape ensures the inner jig is unable to rotate or tilt. These measures reduce the sliding friction and bending moments inherent to embedded shear test methods.

- The displacement of the inner jig causes the cable to shear at 90°. The tests are continued until either 23 mm displacement is achieved or complete loss of load is recorded. Data collected is load versus displacement, and photographs of the test samples.

MECHANICAL DIRECT SHEAR TEST RESULTS

The results of shear testing are in two forms: visual observations and quantitative data from the UTM.

Observations of shearing

Photographs were taken of the cables after shearing. The photographs indicate that the cables were sheared at 90 degrees in direct shear (guillotine effect). Typical tensile failure indicators -such as necking or cone and cup features - were not observed. Cables that sheared without pre-tension had both a distinctive flat shear face and a high angle (80-90°) shear for individual wires. Five wires on each side of the shear plane had evidence of compression before shear failure (causing wire flattening). However, the wires on the other side of the shear plane retained their round profile (Figure 6).

Figure 6: Typical high angle direct shear of 21.8 mm cable without pre-tension (left) and with 20 tonne pre-tension (right)

Pre-tensioned cables typically had mid to high angle shear faces (60-90°). Compression of outer wires was observed, as was the rounded profile of the wire on the other side of the shear plane. The outer wires were seen to retract away from the shear face after wire failure; logically caused by relief of axial tension. Loss of the outer wire confinement was believed to have caused the inner wire bending. Observed failure mode was essentially the same for single and double shear tests.

Shear load and pre-tension data

The peak shear results for the single and double shear tests at 0, 10 and 20 tonnes pre-tension from the UTM are shown in Table 2. The variation in the results can be due to measurement error in the test method, or individual differences in the product. Resolving the source of the variance will benefit suppliers and end users, because it will either lead to improvement in the testing method or help distinguish between products based on the quality control (variations or lack of) in the measured properties of those products.

Table 2: Mechanical single and double direct shear load for 0, 10 and 20 tonne pre-tension

Test Type	Pre-Tension (tonnes)	Individual Test Peak Shear Load (kN)	Average Peak Shear Load (kN)	Standard Deviation
Single Shear	0	321.05	326	4.7
		330.41		
	10	306.86	307	0.2
		306.48		
	20	233.13	241	8.3
		249.71		
Double Shear	0	298.42	304	5.7
		309.84		
	10	244.90	250	5.3
		255.45		
	20	206.32	213	6.2

The shear load in Table 2 and Figure 7 was recorded during single shear tests. From Table 2 and Figure 7 the following comments are made:

- Shear stiffness of the cables in all tests prior to yield was essentially the same at 75 kN/mm.
- Peak shear load was highest for the non-tensioned cables with an average of 326 kN, followed by the cables pre-tensioned to 10 tonnes with 307 kN, and then cables pre-tensioned to 20 tonnes with an average of 241 kN.
- The variance in results was greatest for the highest pre-tension value of 20 tonnes, and lowest for the cables with 10 tonnes pre-tension.
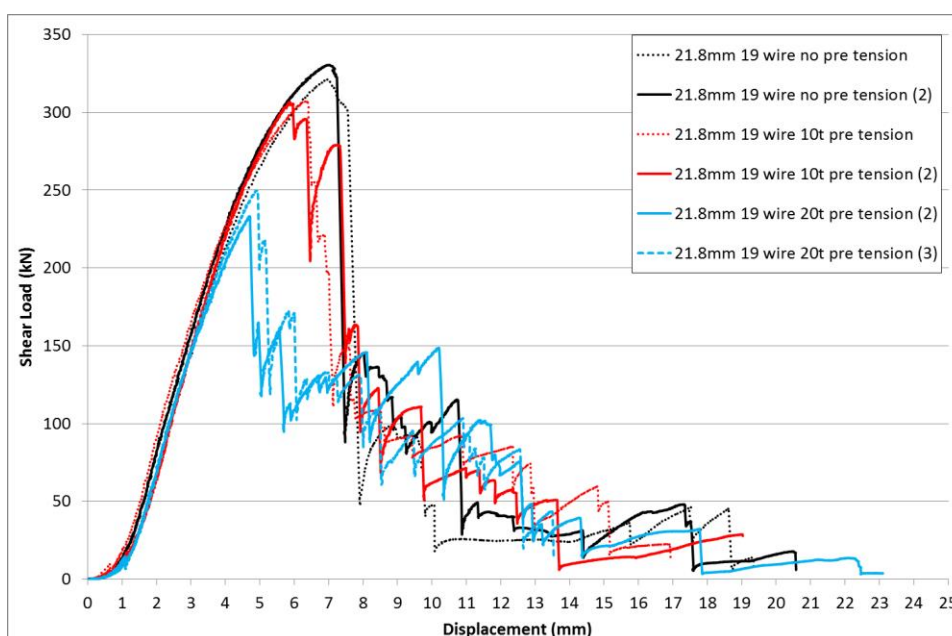
Figure 7: Shear load and displacement plot of single shear 21.8 mm diameter cables

The shear load in Table 2 and Figure 8 was determined by halving the double shear test load. This was done to account for the higher load caused by two shear planes. From Table 2 and Figure 8 the following comments are made:

- Shear stiffness of the cables in all tests prior to yield was essentially the same at 67 kN/mm.

- Peak shear load was highest for the non-tensioned cables with an average of 304 kN, followed by the cables pre-tensioned to 10 tonnes with an average of 253 kN, and then cables pre-tensioned to 20 tonnes with an average of 213 kN.
- The variance in results was greatest for the highest pre-tension value of 20 tonnes, and lowest for the cables with 10 tonnes pre-tension. Compared with the single shear tests the variance was more consistent across the different levels of pre-tension.
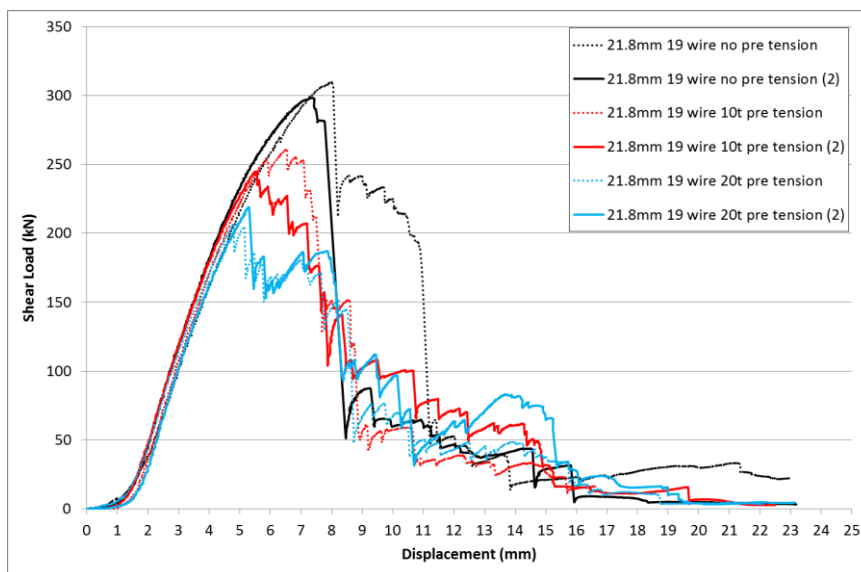

Figure 8: Shear load and displacement plot of double shear 21.8 mm diameter cables

Figure 9 shows the relationship between average peak shear load and pre-tension for the single and double shear tests. From Figure 9 the following comments are made:

- The single shear tests had a higher peak shear load by approximately 30 kN for the given levels of axial load.
- The single and double shear tests displayed essentially the same linear relationship of decreasing peak shear load for increasing pre-tension. The results indicate a 43 to 47 kN reduction in shear load for every 100 kN of pre-tension applied.
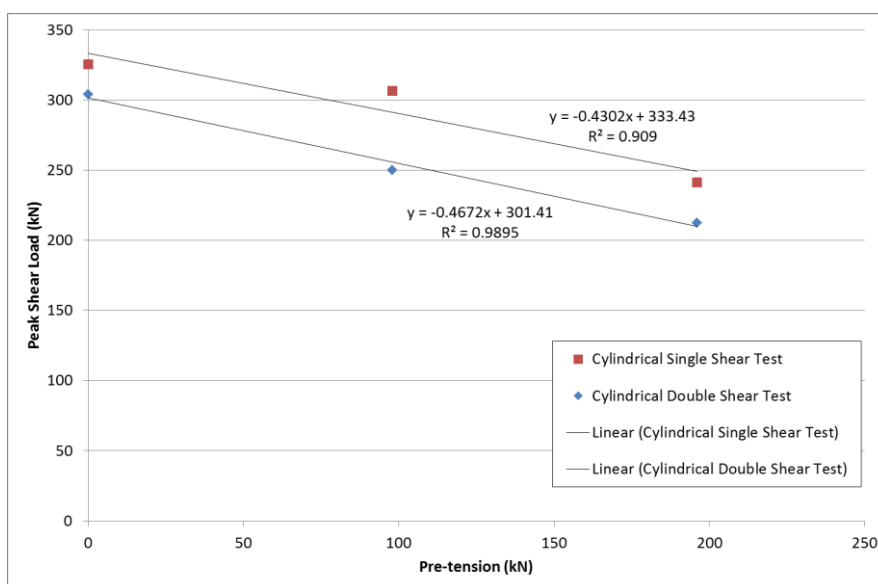

Figure 9: Average peak shear load and pre-tension plot of single and double shear tests

DISCUSSION

Shear stiffness

Shear stiffness was 10% greater for the single shear tests than the double shear tests (75 kN/mm vs 67 kN/mm). It is suggested that the higher stiffness was caused by additional friction between the two test cylinders due to rotation (or tilt) of the inner cylinder. There was no visible evidence of friction between the cylinders after double shear testing. However, some evidence of friction on the inner cylinder was observed after single shear testing.

Stiffness was the same for cables that have no pre-tension and for those with 10 and 20 tonne pre-tension. This confirms that shear stiffness is not affected by cable tension. The non-embedded stiffness results are not directly comparable with previous single and double shear embedded results because those methods contained bending and tensile loading of the cable and shear plane friction.

Shear load and tensile load

The results showed that peak shear load was highest for cables that had no pre-tension applied. Load then decreased with increasing levels of pre-tension. This is thought to be due to a combination of:

- The axial load contributing to the early failure of individual wires due to a combination of shear and tension, and
- Peak shear failure occurring when a smaller number of wires failed when the cable was in tension, but a larger number of wires failing simultaneously when the cable was not tensioned. This may be caused by differential compaction effects in the cable void space. Evidence of this can be seen in the post-peak failure differences shown in Figures 7 and 8.

Past research has shown that peak shear load during embedded shear testing averaged 385 kN for a range of pre-tension loads (Table 1). In comparison, the non-embedded direct shear tests returned an average peak shear load of 315 kN (combining all single and double shear results) when no pre-tension was applied. The lower shear load and displacement of the non-embedded direct shear tests is thought to be due to the lack of bending and tensile loading of the cable. Therefore, the non-embedded direct shear load results are considered the worst-case shear failure mode for cables and thus return the lowest shear load.

The 30 kN difference in peak shear load is relatively constant for the mechanical single and double shear plane test methods (Figure 9). This could be due to:

- Higher friction during the single shear tests caused by tilting of the inner cylinder, and/or
- High localised cable stresses caused by closely spaced shear planes in the double shear test.

Further work is being undertaken to understand the difference in peak shear load.

CONCLUSION

The mechanical direct shear test method is not designed to replace existing embedded single and double shear test methods. These methods remain valid because they offer a simulation of cable shear performance in mines or tunnels. Rather, the direct shear test method adds to embedded test methods in the following ways:

- It is simple and rapid, and repeatable and cost effective.
- By using two tight-fitting cylinders, the amount of friction generated on the shear plane is minimal and a 90° direct shear is achieved.

- Isolating the cable tensioning frame from the shear jig results in no additional friction being placed on the shear surfaces. This provides a clear relationship between different magnitudes of tensile load and shear load.
- It provides the mechanical properties of cables in shear isolated from other test variables.

The shear test method presented in this paper provides the worst-case performance of cables when subject to 90° direct shear in a non-embedded state. The test produces consistent minimum shear values that can be evaluated in the same light as the mechanical tensile tests. With this information end users can:

- Undertake robust comparative assessment of different cable types,
- Undertake embedded shear testing with a greater understanding of the mechanical shear properties of the cable, and
- Use the minimum shear properties either when designing ground support requirements for future underground excavations, or during back-analysis of ground support performance.

Finally, it is noted that this test method is considered a work in progress. Development of the method is required to further understand test variability, maximise its applicability to a range of cable products, and to develop a mechanical direct shear test method that can be used to standardise the reporting of cable shear properties by suppliers.

ACKNOWLEDGEMENTS

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