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Small scale laboratory monotonic and cyclic pull out testing on grout and resin encapsulated cable bolts

Ashkan Rastegarmanesh [a,*], Ali Mirzaghorbanali [b], Kevin McDougall [b], Naj Aziz [c], Sina Anzanpour [c], Hadi Nourizadeh [a], Mahdi Moosavi [d]

[a] Centre for Future Materials, University of Southern Queensland, Toowoomba, Australia
[b] School of Civil Engineering and Surveying, University of Southern Queensland, Toowoomba, Australia
[c] School of Civil, Mining & Environmental Engineering, University of Wollongong, Wollongong, Australia
[d] School of Mining Engineering, University of Tehran, Tehran, Iran

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A B S T R A C T

Axial studies on cable bolts can be conducted using various scale testing apparatuses. Large scale testing, while providing a powerful platform for testing, is expensive and time consuming. This study presents details of a small scale pull out testing campaign on cable bolts and investigates the results achieved. Six popular types of cable bolts were studied using an anti rotation apparatus while encapsulated in cementitious grout and resin. The resin samples were tested under both monotonic and cyclic loading patterns. The results showed that grouted bulbed cables require higher displacement to reach their maximum load capacity which is lost at failure, while plain cables tend to hold lower loads for a longer time. Resin samples provided strain softening behaviour with low capacities, particularly in absence of cable indentation or bulbs. Cyclic loading tended to adversely affect the post peak behaviour of the resin samples, especially in the bulbed cables. Failed samples inspected after the testing suggested a non-uniform damage profile along the cable with extensive damage at the exit point transitioning into almost no damage at the entry point.

1. Introduction

Studying the performance of cable bolts has always been a challenging topic to approach due to the complexity and nuances that accompany cable bolts. Various laboratory tests have been proposed over the last half a century to study the axial behaviour of cable bolts. While some of these experiments[1–5] are large scale and make for a more comprehensive testing approach, small scale tests have always been preferred due to their relative simplicity and ease of use.

Small scale pull out tests can be regarded as tests in which the grout or resin acts as both the bonding agent and the confining medium. On the other hand, in a large scale test, the bonding agent is usually encapsulated within rocks or concrete. This extra confining medium typically fails in the form of radial cracking during the pull out process as the radial dilation grows. Consequently, maintaining the radial stiffness in large scale tests is almost impossible. While the same happens during a small scale (sleeve) pull out test, the extent and severity of this phenomenon is considerably less. Needless to say in both tests, the samples are encapsulated inside metal outer containment to provide stiffness and maintain integrity during the testing.

The simplest pull out testing method of cable bolts is the Single Embedment Pull Test (SEPT) or the "gun barrel" test where a cable, encapsulated into a metal pipe in one end and capped with a barrel and wedge at the other end, is pulled out.[6] This simple design has been used to study the shear load distribution along the cable while bolts were encapsulated into metal pipes.[7] One of the first systematic laboratory studies on cable bolts using the Spline-Pipe Pull Test (SPPT) consisted of two grouted pipes in which a single high tensile steel tendon was encapsulated using a cement-based grout,[8] followed by more SPPT tests from other researchers.[9]

The idea of a Double Embedment Pull Test (DEPT) for a quick and easy laboratory technique for pull out comprised two pipes of similar length tubes anchored with a bonding agent to the cable with a small gap in the middle.[10] When pulled, failure could happen at either part of the gap. Similar setups were for the United States Bureau of Mines (USBM) testing method.[11–13] A modified version of SPPT setup was developed to address the stress concentration at the threaded pulling head by resting the support test section on a platform.[8,14] The edge at the pulling head

* Corresponding author.
E-mail address: Rastegarmanesh@gamil.com (A. Rastegarmanesh).

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was small enough to cover both the confinement pipe and a portion of the grout column.

A constant radial pressure test setup by a Modified Hoek Cell (MHC)[15] enabled a constant load on the sample during the pull out test. The MHC was later bolted to the pulling head of the universal testing machine with the remainder of the naked cable in between the pulling head and the bottom grip of the machine encapsulated inside a pipe to avoid any rotation.[16]

Laboratory Double Embedment Tensile Test (DETT) was adopted for tendons in British Standard 7864–1 and 2.[17,18] This setup which had similarities to DEPT, consisted of two anchored 125 mm sections with no gap in between.[10] The tubes were internally rifled (threaded) to induce failure at the cable/grout interface. The setup could fit inside a tensile testing machine which provided high accuracy and control. The original design later inspired the Minova Pull Test apparatus.[19] Later, in BS7861-2, British Standard was modified to use the original setup based on DEPT[10] for nutcage cables in which real rock samples were confined by a biaxial cell.[10,15] For cable bolts, encapsulation lengths of 450 and 325 mm were utilised for resin and cementitious grouts, respectively. For rockbolts, an embedment length of 160 mm was deemed adequate.

Plain and indented Superstrand cables were studied using Minova Axially Split Embedment Apparatus (MASEA), which is a miniature DEPT (or split pipe) setup that can quickly and easily provide axial data on cable bolts.[19] The setup consists of two internally threaded embedment sections, one longer than the other, to impose failure on the shorter section (230–170 mm). This setup was later fitted with a thrust bearing to facilitate rotation if needed.[20]

This research covers small scale sleeve pull out tests on cable bolts. The aim of this research is to evaluate the performance of the small scale tests. Large scale laboratory testing on grout[5,21] and resin[22] are generally more expensive and time consuming which makes them impractical and undesirable in many situations. Small scale sleeve pull outs have much smaller diameter, the bonding agent is usually stronger (higher strength grouts or resin as opposed to conventional concrete in the large scale) and the entry and exit point movements (vertical and rotational) can easily be monitored.

2. Experimental plan

A total of 24 tests were designed for six cable types, two bonding agent types (cementitious grout and resin), and two loading types (monotonic and cyclic). Ten tests were conducted on the grouted cables and 14 tests were conducted on the resin samples. The resin tests included one or two monotonic tests on each cable type and one cyclic test. The following sections will cover various aspects of the experimental plan such as the testing apparatus, cable selection, bonding agents, and the final test assembly.

2.1. Testing apparatus

The main goal was to propose a simple pull out testing setup for cable bolts. The setup consists of an anchor tube bonded to a cable using grout or resin. The cable is pulled through an anchor tube using a Universal Testing Machine (UTM) or a Tensile Testing Machine (TTM) with a feed through hole at the cross heads. Fig. 1 shows a schematic of the testing method.

In this setup, the cable (dark green) is anchored inside the anchor tube (dark blue). The anchor tube is inserted into an anti rotation plate (red) so that the anchor tube reacts against the ledge of the anti-rotation plate. The void underneath the grout/resin column is important to prevent failed material compaction during the tests. During the test, the anchor tube remained fixed in the space, enabling cable movement. The anti-rotation plate is rotationally constrained, using a pin, (small red circle) to the machine's cross head. The cable is fed through the cross head hole to the machine's upper beam and the hydraulic grip (light grey) is then clamped to the cable. During the test, the upward movement of the machine pulls the cable from the anchor tube.

2.2. Cables

The cable bolts include two *Superstrand* cables with and without **surface** modification (indentation), three cables with **structural** modifications (bulb), and one high capacity unbulbed smooth cable called *Goliath*. The term *smooth* is used as opposed to *indented* and the term *bulbed* is the antonym of *plain* (unbulbed) in this paper. For instance, the ID Superstrand is an *indented plain* cable. Furthermore, a *cable* consists of multiple *strands* wound together. Fig. 2 showcases the cable cross sections where the hollow central grout tubes for bulbed cables are visible and the bulb placement for the bulbed cables. Table 1 covers the cable properties and the coding convention for addressing each cable throughout.

Prior to the test, the central tube of the bulbed cables was filled with high strength grout. The cables bolts were shortened to fit inside the testing machine. Before cutting the cables, the strands were welded together to avoid cable disintegration (i.e., unwinding or rosing). The total final length of the anchor tube is 150 mm, with the centre of the

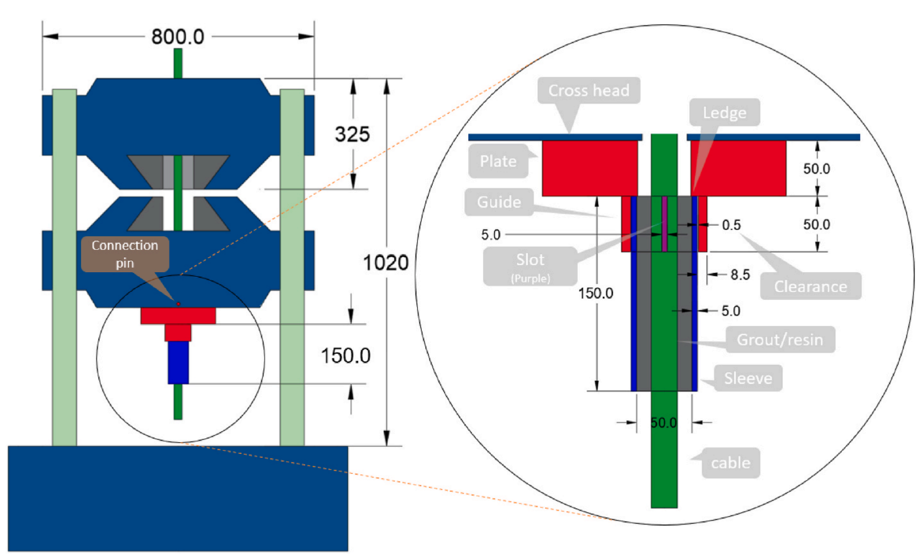

Fig. 1. Sleeve pull out schematic (dimensions in millimetres).

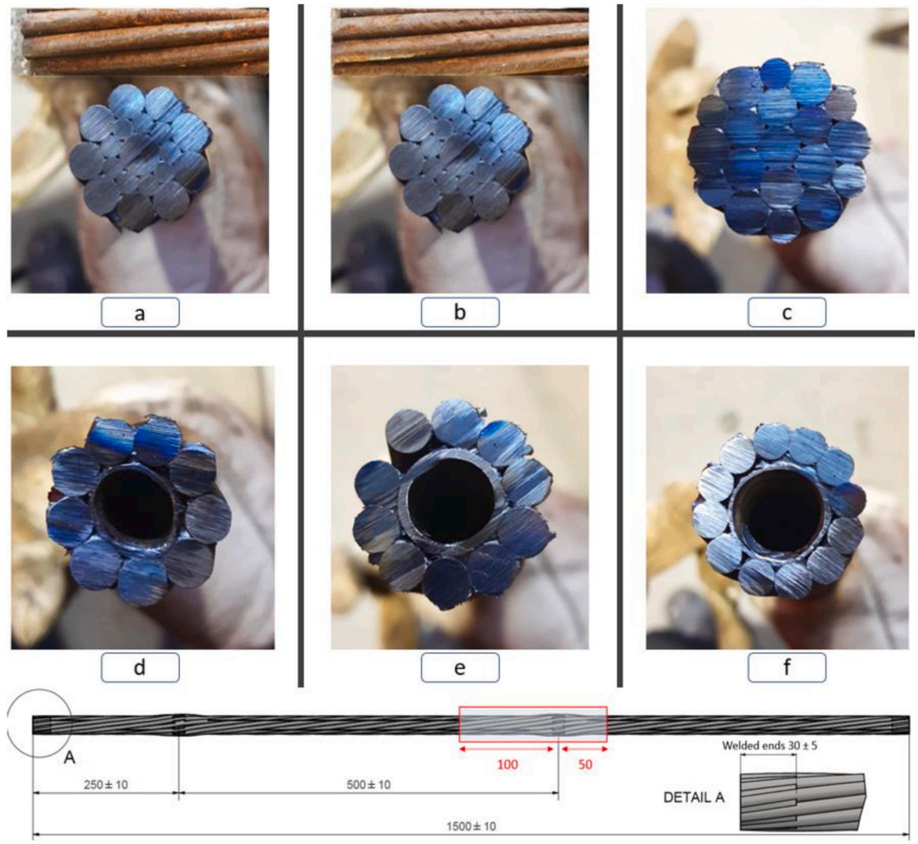

Fig. 2. Top: Cable cross sections – a) Superstrand, b) Indented Superstrand, c) Goliath, d) 9 strand SUMO, e) 10 strand SUMO, and f) 12 strand SUMO – Bottom: Schematic of the cables and the relative position of the sleeve – left is bottom, and right is top side of the cable in the experiments.[23]

Table 1
Cable specification.[23]

Cable Type	Code	Strand Diameter (mm)	Breaking Point @Strands (KN)	Breaking Point @B&W (KN)	Steel Area (mm^2)	Elongation at Failure (%)	Bulb Diameter (mm)
Goliath	Gol	28.6	970	>800	532	5–7	–
12 strand	12S	31	705	640	–	5–7	36
10 strand	10S	31	705	640	–	5–7	36
9 strand	9S	28	635	540	–	5–7	35
Superstrand	SS	21.8	590	520	313	6–7	–
Indented Superstrand	IDS	21.8	570	450	313	6–7	–

bulb 50 mm from one end and 100 mm from the other end (Fig. 2). The bulb itself is usually 100–150 mm long.

The sleeves also have internal rifling which impeded failure at the bonding agent/sleeve interface and promoted failure at cable/bonding agent interface. As a result, the smaller Superstrand and indented Superstrand cables had a thicker annulus. Table 2 describes the geometry and properties of the sleeves. A long metal ridge is welded to the side of the sleeves to lock into the anti-rotation plate (Fig. 4). Nevertheless, In the small scale tests, the longer exposed section of the cables outside the anchor tubes enables greater untwisting potential.

Table 2
Anchor tube properties - UTS average values according to ASTM A53.

Outside Diameter (mm)	*60.3*
Inside Diameter (mm)	*51.3*
Thickness (mm)	*4.5*
Length (mm)	*Original = 300, modified = 150*
Rifling Pitch (mm)	*10*
Rifling Depth (mm)	*1.5*
Ridge Length (mm)	*75*
Ridge Height (mm)	*3*
Alloy	*C250L0*
Tensile Strength (MPa)	*515*
Yield Strengths (MPa)	*410*
Elongation at Failure – 50 mm (%)	*36*

2.3. Bonding agents

Sleeves with the grout product were encapsulated using 30 % W:G ratio Stratabinder grout from Minova, a common grout in the mining industry. The 72 h UCS result on the 50 mm cubic sample were 60 MPa at 0.15 % strain. The resin choice was GeoFlex from Minova. GeoFlex is a urea silicate resin that mixes in a 1:1 ratio. The curing process is exothermic, and the maximum curing happens in less than 4 min. The resin is malleable in the first 120 s (Table 3). The GeoFlex for this research was custom-made in smaller cartridges for small scale castings in the lab.

The anchor tubes were then placed around the cable bolts. Closed cell temperature resistance foams were wrapped around the cable to

Table 3
Typical Properties of GeoFlex resin at 25 °C based on the manufacturer.[24]

Mixing Ratio	*1:1 (p.b.v)*
Foam Factor	*1*
Consumption	1310 kg/m^3
Temperature of Reaction	*~80–90°C*
Density	
Part A	*1480* ± 30 kg/m^3
Part B	*1480* ± 30 kg/m^3
Colour	
Part A	*Colourless*
Part B	*Brown*
Viscosity	
Part A	*260* ± 40 mPas
Part B	*150* ± 30 mPas
Grade Properties	*Standard*
Flow Time	*90" – 150″*
Setting Time	*190" – 260″*
Adhesive Strength (3 mm crack) N/mm2	
15 min	*4.3*
1 day	*3.7*
7 days	*4.5*
28 days	*4.7*
Modules of elasticity (7 days)	*250*

stop seepage from the bottom and ensure central position of the cables. Before casting, the cartridges were brought up to an optimal temperature for maximum flowability. Multiple 50 mm cubic and 120:60 mm cylindrical samples were prepared for the resin UCS test. The displacement and strain map were recorded through a digital image correlation (DIC) camera.

As seen in Fig. 3, GeoFlex has a strain hardening behaviour with barrel shaped failure. Even in the case of cylindrical samples, the ultimate load was achieved at 25 % strain. At such a displacement, the initial geometry of the sample would completely change, rendering the values invalid. For the sake of completion, a 2 % offset rule was used on all resin samples for extraction of the mechanical properties.

2.4. Assembly

Before the test, the modified anti-rotation plate was fixed into the machine cross head using a pin. Next, the cross head was raised to the highest position to create a large enough opening for the 1200 mm cable to be inserted into the anti-rotation plate. The other end of the cable (originally the bottom side) coming out of the cross head was gripped using the top beam of the machine with the appropriate jaw grip size. The system was then initialized by taking the slack between all elements (Fig. 4).

The load and displacement of the 1000 kN UTM machine was recorded by a 10 Hz data logger. The speed of the test for both the monotonic and cyclic test was maintained at 5 mm per minute except for the unloading section of the cyclic test where the load was released immediately. The tests were continued until at least 100 mm vertical displacement. The movement of the entry point of the cable (on the bottom side) was recorded using a camera to analyse the feed in behaviour. After each test, the samples were first investigated for

Fig. 4. Assembled test and various components - during the test the top base rose and lifted the top beam while the cross beam was spatially fixed causing cable pull.

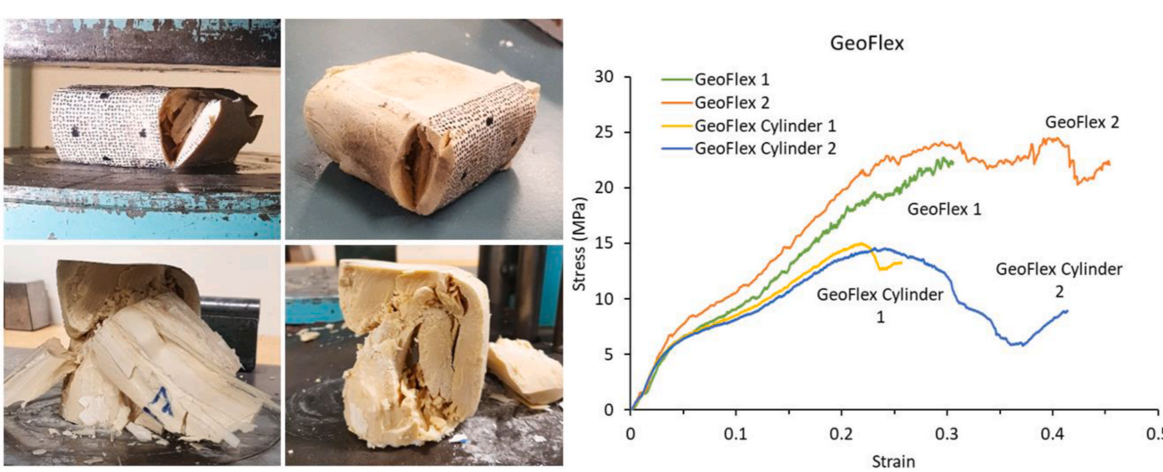

Fig. 3. Left: GeoFlex 50 mm cube UCS samples after test - Cubic (top) and cylindrical (bottom) - DIC dots for strain reading- Right: UCS test result.

superficial failure, and then cut open for further investigation.

3. Results and discussion

Various observations from the tests are presented in the following sections and, comparisons are made between the two monotonic and cyclic experiments. In the following graphs, the prefix of *M* and *C* refer to monotonic or cyclic tests (respectively), and *G* and *R* refer to either grout or resin (respectively). The suffixes *1* and *2* refer to the number of the test. Throughout this section, the term *sleeve* test is used interchangeably with *small scale* test.

3.1. Monotonic sleeve pull out test results in grout

Fig. 5 illustrates the full load–displacement curves for the monotonic testing. The overall behaviour of each type of cable is similar, however there are relatively large disparities present in the tests (repeatability). For instance, the Superstrand cable failed at around 4.5 kN and 7 kN which suggests an approximately 50 % difference. This 50 % difference is also visible for the Goliath cable, while the indented Superstrand cable had around a 30 % difference in load. This shows that, even in the small scale tests on cable bolts, achieving consistency and repeatability between experiments can be challenging due to various issues in sample preparation and the testing procedures.

The behaviour illustrated in Fig. 5 for the indented Superstrand cable shows a high initial peak load followed by attenuation into a constant residual load. This can be explained by the surface indentations of the cable which scrape grout off the brittle grout column. This is quite different from the behaviour observed for the smooth cables (Superstrand and Goliath). In the smooth cables, a strain hardening behaviour is seen, albeit with a small load drop at the initial peak. It is evident that in these cables, there is no mechanism (e.g., indentation) to damage the interfacial surface between the cable and the grout column, so the post peak load tended to stay higher. Surface indention can dramatically increase the initial load, however, the load drops rapidly to a lower constant residual value.

For the smooth cables, the initial load is smaller but, in the post peak section of the curve, the load keeps increasing or remains at a higher threshold. There seems to be a trade-off between the higher initial load and higher residual load. In other words, indentation can lead to a stiffer design where high loads are tolerated before the occurrence of debonding, however the system loses a significant portion of the load carrying capacity post peak. Conversely, the smooth cables provide a consistent increase or sustaining of load capacity with an increase in displacement. This can be translated into a more flexible (less stiff) support design choice.

Fig. 5 further presents results for the 9, 10 and 12 strand bulbed cables in the small scale tests. The 12 strand cable results show an approximately 25 % difference between each test. While not as large as the plain cables, the same repeatability complexity of small scales testing. The 9 and 10 strand cables results, nonetheless, are similar with the larger 10 strand cable having a slightly higher peak load. The small increase in the post peak section of the 9 strand cable could be associated with grout compaction between the anti-rotation plate and the sleeve.

In all the cables (excluding 10 strand), the same post peak oscillations observed in large scale studies were clearly evident. In the large scale tests, the oscillations are typically not damaging in nature and keep bouncing between a high and low value.[21] Here, however, oscillations tended to decrease as displacement increased. This attenuation could be associated with the shorter length of the small scale pull outs (150 mm) compared to the large scale tests (300 mm). The mobilised bulb can damage the shorter and stiffer sleeves significantly, which drastically reduces the load carrying capacity. The bulb can push broken and damaged grout out of the sleeve which shortens the encapsulation length.

Compared to the plain cables in Fig. 5, the loads are all higher which once again supports the use of the modified structures such as bulbs. Ignoring differences between the strain hardening behaviour of Superstrand and Goliath cables and the strain softening behaviour of bulbed cables, the bulbed cables all reached their maximum load at much higher displacements compared to the unbulbed cables. However, they failed to provide long term resistance as the debonding continued. This likely happened due to the short encapsulation length.

Fig. 6 shows the Goliath cable after the test. The opened samples clearly show more damage towards the exit point of the cable compared to the entry point. A transition along the encapsulation length between these two points can be seen by the change in the grout colour. The entry point has no significant damage, whereas a crater has clearly formed at the exit point. As seen later, these phenomena (non-uniform damage and exit point craters) were present in all the samples. However, the extent and severity were a function of the cable type and, consequently, the ultimate load. Fig. 6 also illustrates the effect of the indentation on the inside of the grout annulus and the extent of the damage. It is evident that the grout surface is damaged (scraped) considerably by the cable indentation.

Figs. 7 and 8 show 9 and 10 strand cables after the test. It is clear that the encapsulation length is not long enough to fully enclose the large 9 strand bulb, whereas the smaller 10 strand bulb seems reasonable. This is difficult to achieve as the bulb lengths between cable bolts are typically not identical even in similar cables due to manufacturing processes. A bulb defect can also be seen inside the sample in Fig. 7 in the form of non-uniform spacing between strands. If the encapsulation quality is not maintained, these cavities can remain partially grouted which can affect cable performance.

Nevertheless, the nature of the observations for both cables is similar to the unbulbed cables, apart from the greater severity of damage. At the exit point, a large, damaged zone was formed which is largely associated with the untwisting phenomenon. In the case of the 12 strand cable, this zone is completely chipped off, however the coned damaged zones are still visible. In both cases, although the entry point was damaged, the

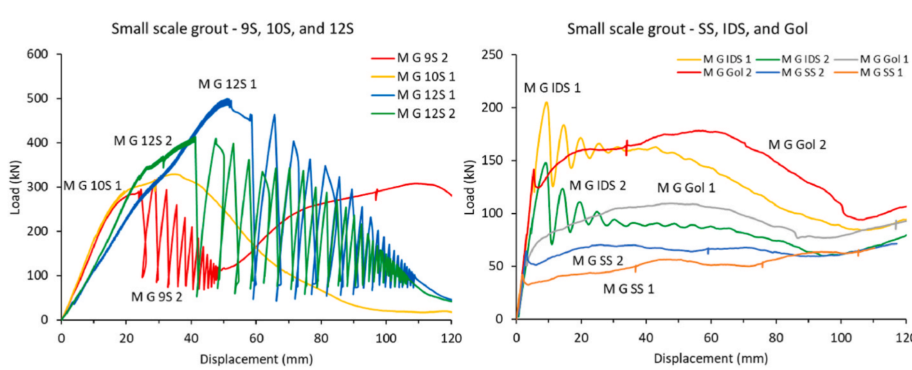

Fig. 5. Small scale pull out in grout for SS, IDS, Gol, 9S, 10S, and 12S cables.

Fig. 6. Top: Goliath cable after the test in grout – before and after cutting – Bottom: Indented Superstrand cable after the test.

Fig. 7. Open 9 and 12 strand cables after the test.

extent of damage was clearly less and the grout ridges were more intact and sharper to touch toward the entry point. Another small detail observed in these figures is a slight bulge in the sleeve near the bulb. This suggests that the 4.5 mm thick tubes were not adequate as an external confinement. However, from a practical point of view, even with this setup, almost all bulbed cables reached more than their 80 % of their allowable tensile capacity at the barrel and wedge. Therefore, increasing the thickness of the pipe should be undertaken with care.

Finally, Fig. 8 shows the 10 strand samples after the tests. Once again, the progressive damage profile of the grout interface from one end to the other is evident. The sharpness of the grout ridges toward the entry point (below the bulb) is similar to the previous small scale tests.

Fig. 8. 10 strand cable after the test – mismatched cable pattern in entry point and scraped exit point.

The exit point damage is well defined in the shape of a large crater around the cable. However, the entry point condition is so intact that the exterior pattern of cable strands on grout annulus can be seen even after 120 mm of pull out and circa 300 kN load. This provides further evidence of entry point rotational movement tendency (as opposed to a rigid direct vertical movement as seen in rockbolts). Later in the resin test, this phenomenon can be seen to be even more pronounced.

3.2. Monotonic sleeve pull out test results in resin

Fig. 9 shows the results for the monotonic pull out tests on the GeoFlex resin samples. Looking at the figure, it is clear that the performance of the cables can be divided into two main categories. The unbulbed cables (indented Superstrand and Goliath) have a strain hardening behaviour with much lower loads, whereas the bulbed cables (9, 10, and 12 strand) have a strain softening behaviour with much

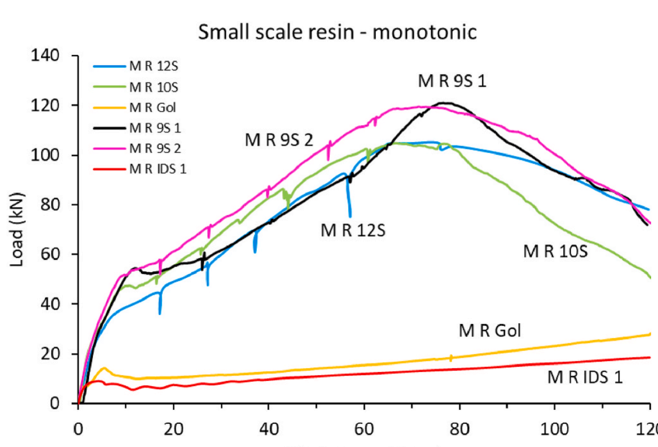

Fig. 9. Monotonic small scale pull out results for GeoFlex resin.

higher loads. It should be noted that some of the tests had high post peak oscillations. Thus, the resin results were smoothed by an exponential moving average with a coefficient of 0.99.

Comparison between the indented Superstrand and Goliath cables indicates that, although Goliath is a smooth cable, because of a higher diameter, it reached around 60 % higher load. This is opposite to the performance of these two cables in the grout tests. Regardless, the load values for both cables are extremely low, which may suggest that the resin is not a good choice for unbulbed cables.

In contrast, the bulb cables all illustrated almost similar values. The two tests on the 9 strand cables have high repeatability while the 10 and 12 strand results are very similar, but lower than the 9 strand ultimate load. This could be due to the bigger bulb to cable size ratio of the 9 strand cable (28 mm–35 mm) compared to the 10 and 12 strand cables (31 mm–36 mm). The bulbed cables have deflections in the load–displacement curve at around 5–10 mm, with the final ultimate load at approximately 70–80 mm displacement. The load then starts to deteriorate which indicates damage to the annulus as the bulb gets closer to the exit point. No significant exit point compaction was observed during the resin experiments as resin does not chip or scrape like grout.

Fig. 10 shows the indented Superstrand cable after the test. While the cable indentation imprints on the resin surface are visible, the damage to the surface is less than the corresponding grout cable tests. This is likely due to the fact that GeoFlex is a much more flexible material than Stratabinder. The condition of the entry and exit points are also visible in the figures. No crater was observed in either case, which again is a result of the GeoFlex failure type. However, the non-uniformity of the damage along the pull out length can clearly be seen in Fig. 10. The extent of the damage reduces further away from the exit point. Sharp ridges toward the entry point are also evident.

In the case of the Goliath cable, Fig. 10 shows relatively similar behaviour to the indented Superstrand cable. No significant damage is observed at either end of the sleeve, however the entry point at the far left of the sample showed greater damage. All along the sample, resin

Fig. 10. Top: Indented Superstrand sample in resin – Bottom: Goliath cable in resin after the test.

ridges were relatively sharp and undamaged with more damage evident at the exit point. It can be inferred that the lack of modification (surface or structure) in the smooth plain Goliath cable resulted in a debonding process that minimized the damage on the cable/resin interface.

In all the bulbed cables, a series of similar observations are made. According to Fig. 11, the bulbed cables all create significantly more damage to the resin. The damage is less towards the entry point with more undamaged ridges. The other unique phenomenon seen in all the bulbed cables was oiling of the resin, especially at the exit points (Fig. 12). This was also seen in the UCS testing of the GeoFlex samples where under high load, an oily substance oozed out of the samples. Here, in the pull out test, the oil was also evident, indicating high radial stresses on the resin.

As seen Fig. 12, the condition of the entry point for all the cables are quite similar with the patterns of the cable strands imprinted on the resin distinctly. However, it seems that the pull out process has **displaced** the cables such as the strands' imprints on the resin are out of alignment. This is not seen in the Goliath or indented Superstrand cables. In those cables, video footage of the entry point clearly shows a steady rotation rate during pull out, and when the load was released, the whole sleeve and the anti rotation plate rotated in one sudden motion (i.e., stored energy). The fact that the cable and the sleeve end up out of alignment at the end of the tests in bulbed cables indicates that there have been relative rotation between the two during the test.

Also, for cables with a large cable to bulb ratio, such as 9 strand, clearly a significant cavity is formed at the entry points after the test with the bulb visible from the cavity. This can happen because the bulb is an unwieldy object which has difficulty rotating as it is pulled out of the sample. Consequently, the rotation rate at the entry point cannot remain steady with respect to the pull out rate which results in a mismatching of the cable strands and ridges on the annulus on the sleeve (Fig. 12). This phenomenon is less visible in the grout samples because cementitious grouts are brittle in nature and, as the strands pass over the grout ridges, they are either broken or sheared off, leading to a damaged zone or even craters at higher loads.

3.3. Cyclic small scale pull out test results in resin

Using the ultimate load from the monotonic test of the resin samples, five equally spaced load thresholds were defined. In each stage, the load was increased monotonically with a 5 mm per minute displacement rate to a designated value, then in the unloading stage, the load was removed immediately. In the next step, the load was increased to the second threshold followed by another unloading. This was repeated until the final step. The test was continued until 120 mm displacement was reached. Not all tests were able to complete the full five steps before the 120 mm of displacement.

Fig. 13 exhibits in the case of the Goliath cable, there seems little difference between monotonic and cyclic tests, at least for the first three load cycles. For the 9 strand cable, however, the performance of the cyclic tests is around 40 % lower than the monotonic tests and the initial stiffness is lower. This suggests that the existence of a bulb can significantly reduce the performance of the cable in GeoFlex under repeated cyclic loading. The load pick up after each unloading step is almost instantaneous in both cables.

Fig. 13 also illustrates 10 and 12 strand cables in cyclic and monotonic tests. In both cases, the cyclic loading pattern shows reduced performance of the cables compared to the monotonic loading. While the initial stiffness in all the graphs is quite similar, the 10 strand cable is approximately 40 % of the ultimate load of the monotonic sample. The 12 strand cable shows a reduction of 25 % of the maximum load capacity of the monotonic sample. As can be seen, the 10 strand cable was only able to complete two loading cycles.

In both cases, the load pick-up occurred with very little displacement. By including the results of the 9 strand cable from Fig. 13, it seems that the existence of bulbs in the cyclic tests lowers the load more when compared to cyclic testing on plain cables (Goliath). The 9, 10 and 12 strand cables in cyclic tests show a reduction of 25–50 % of their ultimate load in monotonic testing, while Goliath has an almost identical performance in cyclic and monotonic testing. This suggests that GeoFlex may not be a suitable choice for the long-term use of bulbed cables in the field.

3.4. Comparison of monotonic small scale pull out in grout and resin

As seen in Fig. 14, the load in the resin samples is much lower than in the grout samples. In the case of the Goliath cables, regardless of disparities between two tests, the resin samples achieved approximately only 20–40 % of the grout samples' peak load.

In the case of the 9 strand cables, the resin sample only reaches 30 % of the grout's ultimate load, while in both cases it is evident that the initial stiffness is much higher in the grout samples. Moreover, the behaviour of grout samples is strain softening or perfectly plastic, as opposed to the resin samples with strain hardening or perfectly plastic behaviour.

Fig. 14 also illustrates the comparison between the 10 and 12 strand cables in the monotonic small scale tests. In both cases, the resin samples perform at only 20–30 % of the load of the grout samples. The difference is greater for the 12 strand cables compared to the 10 strand cables. The similarities in the monotonic and cyclic performance of the 9, 10, 12 strand cables in resin compared to the Goliath cable suggest that the mere presence of the bulb in resin is enough to dictate similar behaviour.

Lastly, Fig. 15 shows the comparison between the two types of Superstrand cables. The indented Superstrand cables in resin show

Fig. 11. Top: The entry and exit point conditions after the 9S cable test in resin sleeve pull out – Bottom: The bulb location after the 10S and 12S cables in resin sleeve pull out.

significantly less load capacity than the grout tests, with less than 10 % of the load, performing even worse than the smooth Superstrand cables in grout. However, only one resin test was conducted on the Superstrand cables so the results cannot be conclusive.

4. Conclusions

Small scale pull lout tests in grout showed that achieving high repeatability was a difficult task. Moreover, comparison between the smooth cables and indented cables suggest that smooth cables tended to have a strain hardening behaviour as indicated by holding a higher level of load for a longer displacement. Indented cables, while reaching much higher loads, lost a large portion of the load after the first failure and then the load was attenuated over displacement at a fixed level. This level was still higher than the smooth cables.

The grout tests were prone to material compaction in between the anti-rotation plate and anchor tube. This was not present in the resin samples as resin failure type was considerably different when compared to the brittle grout failure. Contrary to the large scale tests where post peak oscillations often consist of constant bouncing between a low and high values, post peak oscillations in small scale tests were attenuative (decaying). This was associated with the shorter encapsulation length, and higher sensitivity to the movement of the bulb during the tests.

Bulbed cables in grout tests reached their maximum load at much higher displacement compared to the plain cables, suggesting less stiffer behaviour for the bulb cables. This meant, bulbed cables reached higher loads but at the cost of displacement whereas plain cables were at much lower load range, but achieved it sooner and maintained longer. As for the failure, all grout samples had a crater at the exit point and the damage profile was non-uniform, increasing from entry to exit point. This is closely associated with the *Zipper* effect known in the design of anchors in civil applications, or bolted connections in mechanical applications.

Cut samples revealed that small scale tests were sensitive to the bulbs. Bulbs usually tend to vary between 100 and 200 mm in length depending on the design and manufacturing precision, thus a 150 mm long encapsulation length could make it difficult to fully encapsulate the bulb (considering a 100 mm displacement). This was one of the reasons why getting higher repeatability in small scale tests for bulbed cables was difficult. This said, diligence is advised in increasing the thickness or length of the pipes, as it might increase the pull out load higher than the cable tensile capacity at the barrel and wedge.

The pull out tests in GeoFlex resin suggested that cable diameter was more influential than the surface indentation, as the Goliath cable resulted in slightly better performance than the indented Superstrand. In fact, both cables exhibited strain hardening behaviour while bulbed cables acted in a strain softening fashion. Bulbed cables all performed almost similarly in the resin, regardless of their size. This suggests that resin had less sensitivity toward indentations and bulbs compared to grout. Furthermore, cut resin samples illustrated a similar damage distribution along the sleeve to the grout samples, with more damage at the crater than at the exit point. As for the resin cyclic tests in GeoFlex, results illustrated that the bulbed cables suffered up to a 40 % reduction in the peak load in the cyclic test. However, cyclic loading did not seem

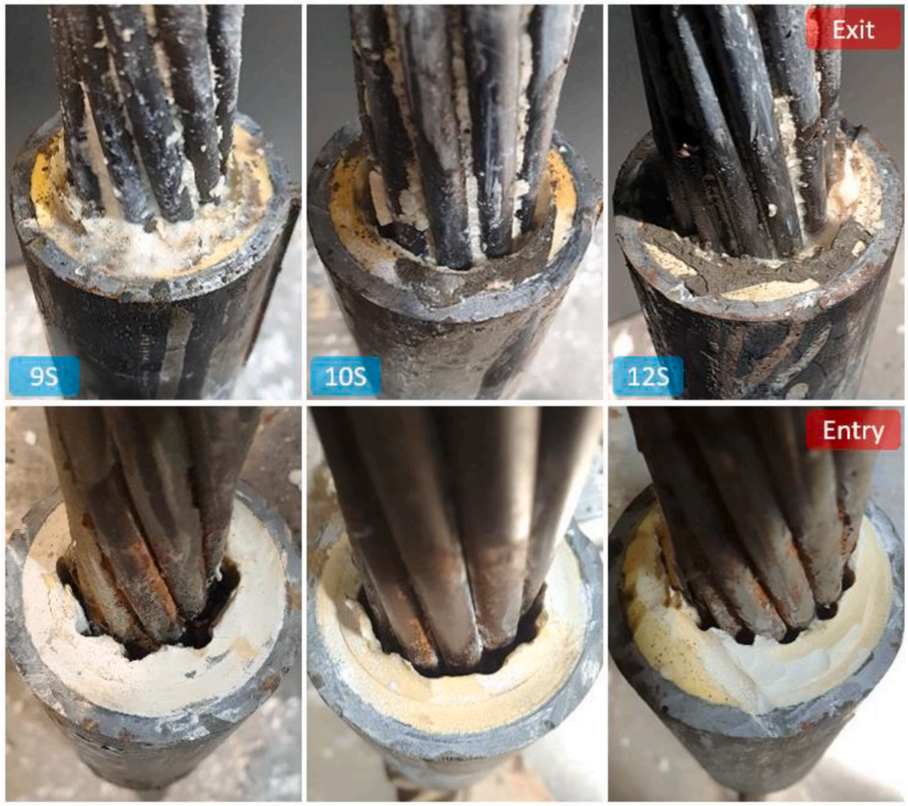

Fig. 12. Comparison of the entry and exit points of the bulbed cables in small scale pull out – Shiny sections at exit points are oil – Gape (cavity) at entry point for the 9 and 10 strand cables.

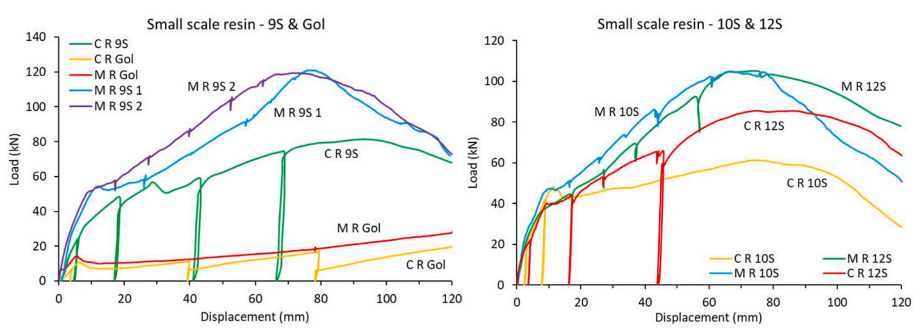

Fig. 13. Comparison between cyclic and monotonic sleeve pull out for 9S, 10S, 12S, and Goliath cables.

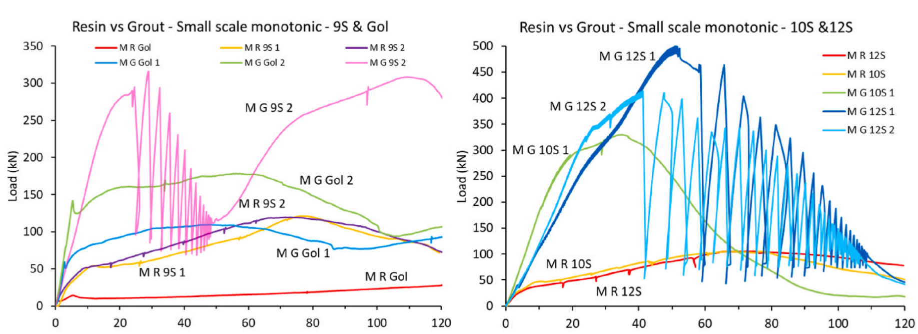

Fig. 14. Resin vs grout for 9S, 10S, 12S, and Goliath cables in monotonic small scale pull out.

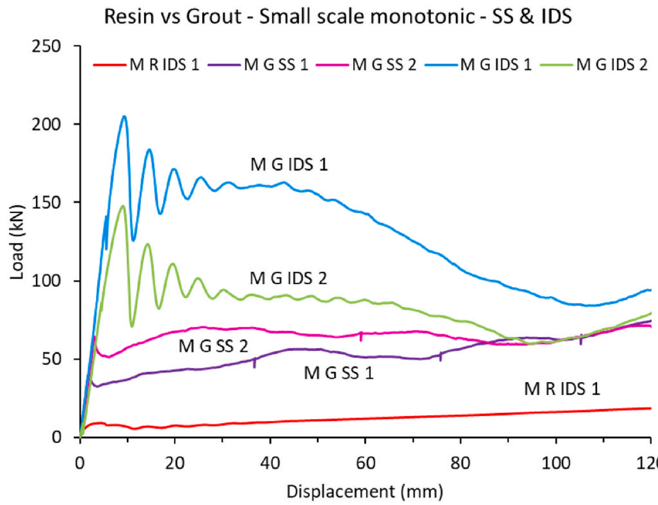

Fig. 15. Resin vs grout for Superstrand and indented Superstrand cables in monotonic small scale pull out.

to affect the smooth cable such as Goliath.

While utmost care was given in organizing and conducting this body of research, some limitations hold. The thickness of the sleeves could have been increased in order to provide a higher resistance to the radial dilation during failure. Moreover, the works could have benefited from having a higher iteration of each test as well as experimental sensitivity analysis on some of the design choices such as the embedment length, diameter, and relative location of the bulb to investigate repeatability. Lastly, since GeoFlex is a rather "soft" resin, utilizing a "stiff" resin (similar to rock bolting) could be insightful. It is recommended to have minimum naked cable length during the test to avoid unwanted untwisting movement of the cable. Moreover, small scale testing can easily enable the observation of the entry point of the cable, studying rotational movement is highly recommended. Finally, small scale tests can be a suitable substitute for the large scale test by saving time and resources more tests are recommended to fully correlate the results of the small scale tests to the large scale, and eventually to the field pull out tests.

CRediT authorship contribution statement

Ashkan Rastegarmanesh: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ali Mirzaghorbanali:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Kevin McDougall:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Naj Aziz:** Supervision, Resources, Funding acquisition. **Sina Anzanpour:** Methodology, Conceptualization. **Hadi Nourizadeh:** Methodology, Data curation, Conceptualization. **Mahdi Moosavi:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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