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STATIC AND DYNAMIC TENDON PULL-OUT TEST RESEARCH AT THE UNIVERSITY OF WOLLONGONG

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ABSTRACT: Tendon technology is widely used for strata control in underground coal mines, in both primary and secondary support systems. The understanding of how they work is crucial to effective strata reinforcement design. Research on tendon technology is an evolving study and this paper is aiming at maintaining this evolution by continuing research on load transfer mechanisms under both static and dynamic conditions, which was reported initially by (Anzanpour, 2021) in ROC2021. This programme of study includes testing of different strength capacity cable bolts, which have been important in the stabilisation of the ground around mining excavations affected by rock bursts and ground seismicity. The aim of the study was to evaluate tendon performance in different loading environments. From a series of tests carried out in the most recent study, it was found that in pull testing, the load transfer characteristics vary with respect to the type of testing. The required dynamic energy for pulling-out a cable bolt can be between 50-80% lower than the static load, based on the cable type and its geometry (Plain or Bulbed). Debonding and pullout mechanisms regardless of loading rate, seem to be similar in both static and dynamic tests, however, plain cable bolts behave differently from bulbed cable bolts in reaction to pull-out load.

INTRODUCTION

Pull-out test research of tendons is undertaken under static conditions both in the laboratory and in the field. The laboratory pull-out tests are generally carried out using either; a simple single embedment technique (Aziz, Jalalifar and Concalves, 2006; Aziz and Webb, 2003; Benmokrane, Chennouf, and Mitri, 1995) or by double-embodiment tests (Bigby and Reynolds, 2005; Thomas, 2012).These pull-out tests are carried out on encapsulating tendon in a steel tube; in concrete or artificial rock (Ito, et al, 2001; Martin, 2012); and in situ testing (Aziz, etal,   2016; Compton and Oyler, 2005; Stillborg, 1984). For the past three decades several pull test facilities have been constructed in Australia, Canada, China, South Africa and the USA to examine load transfer capacities of tendons under dynamic conditions (Player and Cordova, 2009;. Player, et al, 2004; St-pierre, 2007; Tannant, Brummer and Yi, 1995), many are laboratory based studies, while, one rig has been reported, being used *in situ* (Hadjigeorgiou and Potvin, 2007). However, none of the developed technologies are able to undertake pull-out tests under both static and dynamic test conditions.

In the 2021 Resource Operators Conference (ROC21), two papers were presented on static and dynamic pull and shear testing of tendons aimed to better understand the tendon's behaviour under adverse ground conditions. Both approaches were considered as innovative under different test environments which aimed to evaluate tendon behaviour with respect to rock burst, gas outburst and ground seismicity. The first paper reported on dynamic shear testing of tendons by using the double shear apparatus (Khaleghparast, et al, 2020) while the second paper by (Anzanpour et al., 2021) discussed the development of the new pull testing apparatus for tendons under both static and dynamic conditions. The availability of the various types of compression testing machines to carry out static loading studies and the impact drop hammer rig in the laboratory of the faculty of Engineering and Information Sciences of the University of Wollongong provided the opportunity to carry out the static and dynamic tests in one location. In the preliminary study on pull-out testing, two plain Megabolt MW9 nine wire plain cable bolts were used, one for the static test and the other for the dynamic test. A 300 mm long section of each cable was anchored in 300 mm diameter cylindrical concrete blocks. The comparison between static and dynamic test results revealed that the dynamic pull-out force was roughly

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30% lower than that of the force spent to pull-out statically, because of the absence of time related frictional force needed to pull out the cable. Recognising the benefit and potential of the new pull out apparatus being presented, it was decided to extend this programme of research to include testing of different make tendons; accordingly, this paper is a further extension to the project which includes the testing of different cable bolts, both plain and bulbed cables, using both cementitious as well chemical resin grouts of varied strength.

TEST MECHANISM AND THEORIES:

In cable bolts, failure of the anchorage is possible due to (Figure 1):

1. Debonding of the cable end in the bore hole (Mode 1)

2. Tensile failure of the cable in the joint section (Mode 2)

3. Failure of the either cable or B&W in the outer end of the anchorage system (Mode 3).
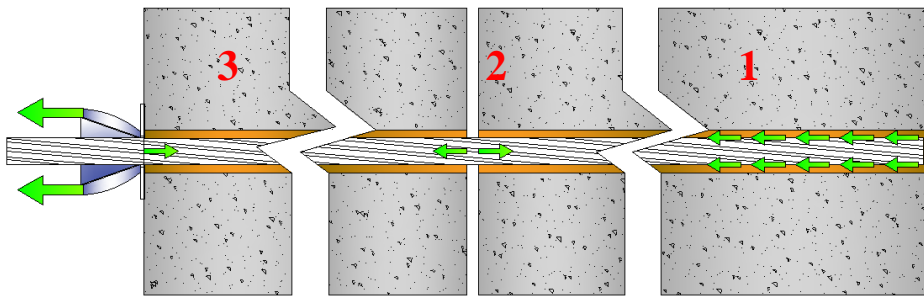

Figure 1: possible failure modes of anchorage under axial loading condition

The designed apparatus is capable of examining all three modes of failure however, in this particular paper the main purpose is to assess debonding of the cable and the encapsulation material (Mode 1) under both static and dynamic loading conditions. The design and structure of the developed rig has been previously discussed in (Anzanpour et al., 2021). **Figure 2** depicts a schematic view of the rig and loading machines, both in static and dynamic modes. Locations of the data loggers, Linear Variable Differential Transducer (LVDT) and displacement lasers are shown in the figure.

In stable ground conditions, gradual subsidence of the roof usually occurs over the life of the tunnel. In the laboratory, implementing long-term loading is not practically efficient and viable. The loading rate of the samples by hydraulic pumps can be controlled be servo-controlled systems which control the hydraulic flow rate based on either the required load or displacement. The current facility is capable of applying the displacement-controlled load at the minimum rate of 1 mm/min (10 μm/s). This rate in comparison to the static loading in a mine is much faster, however, since no kinetic load is applied to the sample during loading, it can be classified as a quasi-static loading condition. However in this study they are simply called static tests. Dynamic loading of the ground occurs as a direct result of sudden wave propagations in the ground. Waves might be produced by explosions, global ground activities (Earthquakes) or local ground activities (Mining induced earthquakes, rock bursts, coal burst, coal bump). In all the aforementioned phenomena a massive amount of energy is transferred to the surrounding medium of the tunnels and underground excavations.

The acquired data from static and dynamic tests in the laboratory are normally load changes in time or displacement (pull-lout length) in time. However, in dynamic testing, load is applied at almost 30 ms which in comparison to static testing, this time is negligible. Also, due to the impulsive nature of the load in dynamic tests, recorded load data are not easily comparable with static tests. Hence, applied load and induced displacement in both static and dynamic tests are rewritten based on work and energy laws. Then the consumed energy is divided by the length of displacement (pullout length) to produce the normalized energy per mm of the embedded cable length, expressed in Joules per millimetre (J/mm).
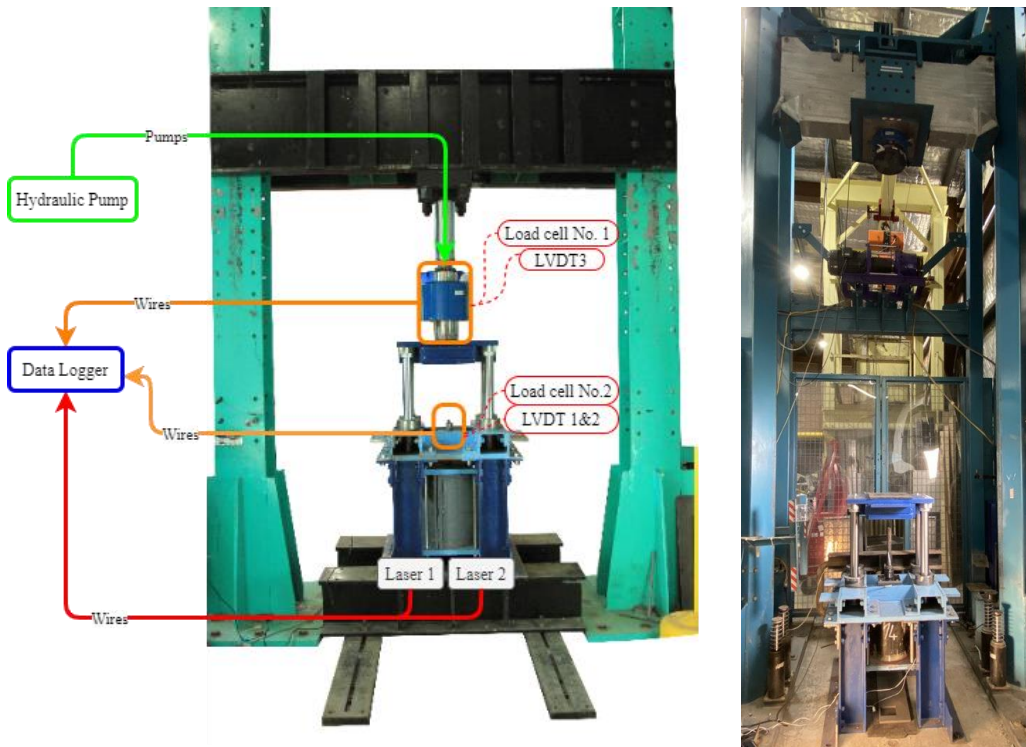
Figure 2: Diagram of static testing setup and connected data recorders and data loggers (Left), and Setup of the dynamic test by using the drop hammer (Right).

There are some physics law and assumptions that have been considered, as facts, to simplify the analysis:

- In the static analysis, according to the work and energy conservation law, the conservation of energy for the static test can be written as:

$$\int_0^l m_s g \ dl + \int_0^l f \ dl = \int_0^l f_k \ dl$$

Where m_s is the mass of the sample, f is the applied load causing the displacement of l, and $f_k \ dl$ is the cumulative energy of all resistants including energy absorbed by B&W, elastic elongation of the cable and energy spent in overcoming the pull-out force.

- In dynamic testing, the mass of the hammer (m_h) in a frictionless constrained environment, falls freely from a height of h and impacts the sample m_s in its stationary position. The velocity (v_h) of the hammer at the instant of the impact is $\sqrt{2gh}$.

- Since the applied momentum in the dynamic test causes massive deformation and destruction of the sample, the assumption of inelastic momentum can be considered. For inelastic momentum, it is assumed that the impacting hammer and the impacted sample will move together with a new velocity (v_s). Thus, the initial applied velocity on the sample (v_s) can be determined from:

$$v_s = \frac{m_h v_h}{m_h + m_s}$$

Practical developments of the testing system

While the designed system was introduced in 2021 and some trial pull-out tests were carried out and the performance was verified, there remained some minor problems, which were seen also in other similar studies. Hence, it was decided to undertake the following improvements to the testing system;

Effect of confinement: In order to prevent lateral and diameteral crack formation in the host concrete blocks during the pull-out test, concrete cylinder bocks were directly cast in 5 mm thick steel tubes. These continuous walled tubes were different from the past practices used by Hagan and Li (2017) and

Anzanpour et al., (2021).   it was thus possible to cast concrete directly inside the 300 mm diameter tubes at two different heights, 300 mm and 450 mm as shown in **Figure 3**.

Figure 3: samples cast directly in steel tubes

Double-embedment and anti-rotation: In previously developed testing technologies such as those reported by (Hagan & Li, 2017), the hollow hydraulic pump was placed between the concrete sample and the Barrel and Wedge (B&W). The uncovered length, known as the second embedment length of the cable inside the hollow pump, was separately grouted and gripped; otherwise elastic elongation, unwinding or cable failure could occur in this area. The longer the second embedment length the harder it is to prevent elastic deformation and unwinding forces. With some minor modifications to the design, the second embedment length could be reduced to 100 mm. This resulted in only 3 mm elastic elongation of the second embedment length and consequently more load being transferred to the concrete sample, which provides the chance of testing stronger and longer bonds.   Also, the anti-rotation setup may simply constrain the cable unwinding, so that an insignificant momentum is applied on the anti-rotation plates and free movements in the vertical direction can take place (**Figure 4**).

Figure 4: Shorter second embedment length and modified anti-rotation system with minimum friction

RESULTS, ANALYSIS AND DISCUSSION

Twelve different pull-out experiments were conducted using both plain and bulbed nine-wire Sumo cables in static and dynamic modes. Grout thickness, embedment length, concrete strength and curing

age were maintained constant throughout the duration of the testing programme. The loading rate for all static tests was 3 mm/min and the drop height for the dynamic test was set to 2.5 m. **Table 1** summarizes the results of pull-out tests. Normalized pull-out energy was calculated as a comparative parameter between the static and dynamic results. As stated in **Table 1**, bulbed cables are capable of absorbing up to 60% more energy and encountering less pull-out displacement under dynamic loading conditions compared with the plain cable. Higher axial load on the bulbed cable indicates that the bulb is actively working as a point anchor inside the borehole, which leads to a greater tensile load acting on the cable bolt. This is not the case with plain cables under both static and dynamic load conditions; where the tested cable debonds from grout.

Table 1: Results of static and dynamic pullout tests

Test No.	Test type	Cable Type	Pull out load	Absorbed energy*	Pullout displacement	Normalized Pullout Energy
			kN	kJ*	mm	kJ/mm
1	Static	Plain	317	14.5	68	0.21
2		Plain	353	38.5	148	0.26
3		Plain	330	28.6	114	0.25
4		Bulbed	511	15.4	55	0.25
5		Bulbed	553	14.5	54	0.28
6		Bulbed	544	50.1	120	0.42
7	Dynamic	Plain	-	8.9	69	0.13
8		Plain	-	9.6	69	0.14
9		Plain	-	7.1	56	0.13
10		Bulbed	-	9.9	48	0.21
11		Bulbed	-	9.9	47	0.21
12		Bulbed	-	10.2	47	0.22

* Absorbed energy (kJ) = $\int_0^l f \, dl$

The comparison between static and dynamic normalized energy reveasl that the required energy due to the pull-out of cables dynamically are in the range of 50-60% of the static tests for plain cable and 75-80% for the bulbed cables (**Figure 5**).
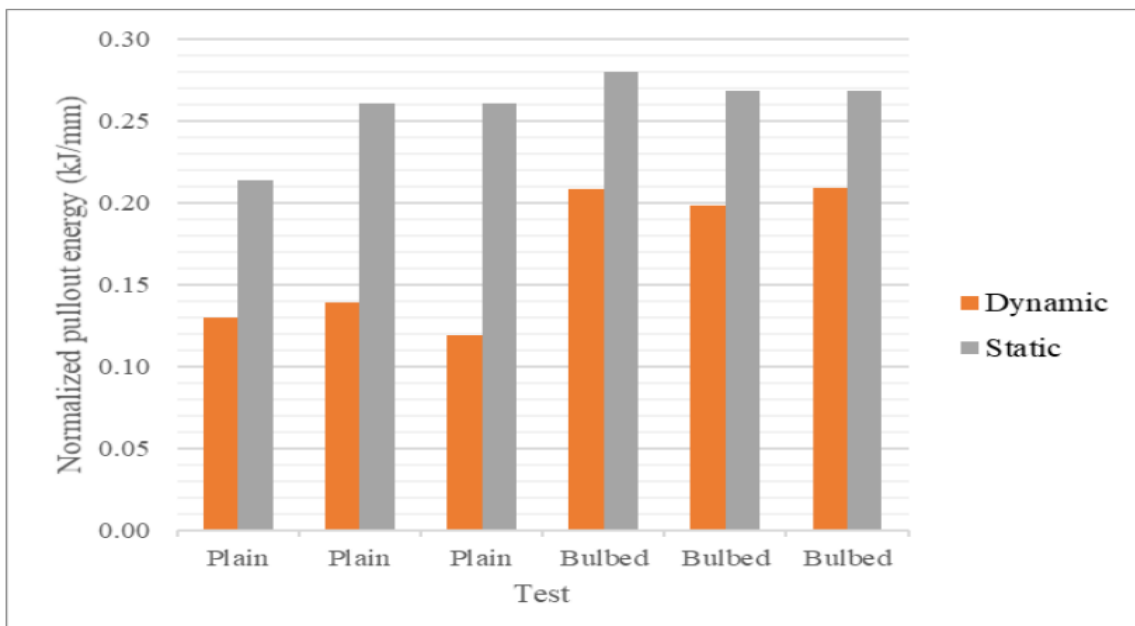

Figure 5: comparison of static and dynamic pullout tests

Test results revealed that the dynamic pull-out occurs with less required energy in comparison to static testing. This can be directly related to the effect of the friction coefficient of materials particularly under static pull conditions; further studies are needed for the better understanding of the debonding mechanism. Several high speed cameras, as well as LVDT's and displacement lasers were used for data retrieval and subsequent analysis. **(Figure 6)** shows free bottom ends of the plain cables, before the start of pull testing and after almost 30 minutes of static test. One of the wires of the cable bolt was painted white as the movement indicator. The position of the camera was placed strategically to observe

any cable movement. Observations revealed the tendency of the cable bolt to unwind at the free end in order to slide through the grooves created on the grout surface instead of breaking grout in shear. This behaviour is against what has been recorded in pull-out test rock bolts (Aziz et al., 2006).

Before starting the static test   After 30 minutes running the static test

Figure 6: 40 degree rotation in the direction of unwinding of the cable bolt during the static test

Similar unwinding behaviour can be seen in the dynamic tests, which showed that the rate of loading did not alter debonding mechanism of the plain cable bolt. Similar unwinding behaviour can be seen in the bulbed cables; however, there were some slight differences in its structure. The hollow tube of the cable bolt in the plain cable was perfectly covered by wires and welded to the wires at both ends. Hence, as the wires unwind, the hollow tube twists accordingly. In the bulbed cable, there is gap between wires and the hollow tube in the bulbed zone, which is filled by grout encapsulation material, and does not allow free twisting of the hollow tube; consequently, the middle hollow tube remains fixed to the grout, while the wires are unwound during the pullout process. Eventually, the weld between wires and tube break, and disconnected, leaving the hollow tube in place and not being pulled out with the rest of the wires (**Figure 7**). This situation could be seen in both static and dynamic tests.

Figure 7: Failure of the bulbed cable bolt in static (Left) and dynamic (Right) pull tests

In the next step, samples were cut and the debonded surface of the grout was carefully observed. The grout surface in the static test was more severely damaged especially at the top of the sample were pull-out initiates. The intensity of grout failure was decreased in the lower parts of the sample **(Figure 8).** In dynamic tests, due to the factor of time, grout was less damaged or broken, while severely burnt surfaces of the grout clearly show the high friction interaction between the cable bolt and the grout.
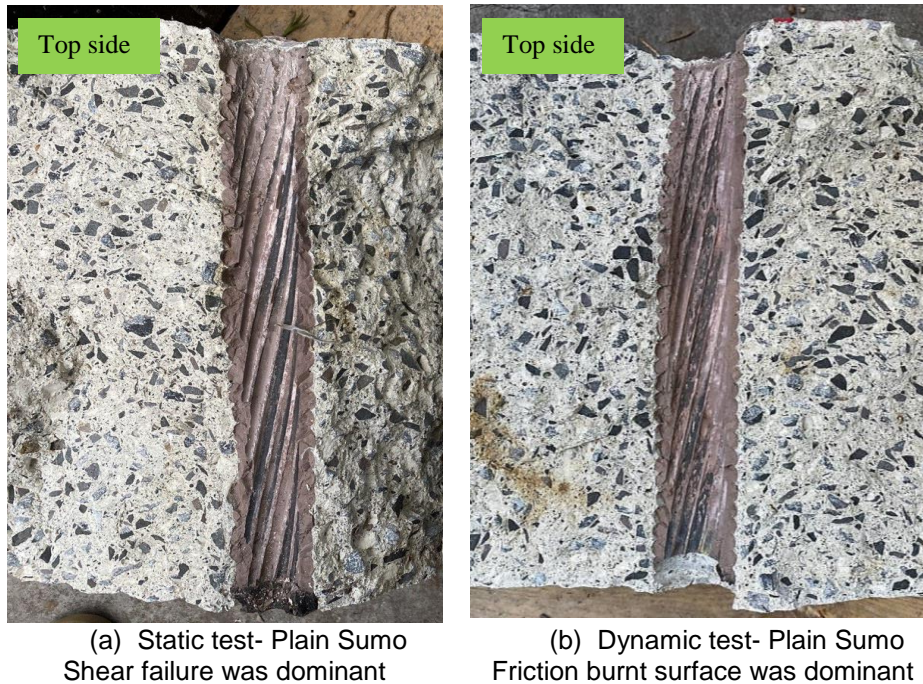

(a) Static test- Plain Sumo
Shear failure was dominant

(b) Dynamic test- Plain Sumo
Friction burnt surface was dominant

Figure 8: Grout damage intensity after static and dynamic tests with plain cable

CONCLUSIONS

This paper is following previous studies on the behaviour of tendons in tension and shear carried out at the University of Wollongong. The newly developed Pull-out test apparatus was introduced at ROC2021, and this study is a continuation of the experimental investigations around different tendons under both static and dynamic loading conditions. In two recent studies conducted on two different cables of nine-wire Sumo (Plain and Bulbed) cables, it was found that;

- the required energy for pull testing of plain cable bolts dynamically was in the range of 50 60% of the static test and 75-80% of the bulbed cable; Direct casting of concrete in solid steel tube confinement prevented radial crack formation during pull-out tests, thus enabling better evaluation of the load transfer mechanism estimation, as the presence of radial cracks results in lower values for test results.

- In general, the pull-out of cable bolts is a combination of two mechanisms; 1) Rotational movement of the cable in order to slip through the grout grooves which results in frictional force on the grout, and 2) Axial elongation and movement of the cable which results in shear failure of the grout ridges. While rotational movement of the cable was common in both static and dynamic tests, it was the dominant mechanism in dynamic tests. Unbroken grout ridges and more severe black print on the surface of the grout has aggravated the situation. But in static tests, the elastic elongation of the cable is allowed to occur, and there is greater chance of shear failure happening in the grout ridges, which necessitated more load being required for the cable to be pulled out. This statement was reinforced by physical evidences during the post-test investigations. More severe grout damage, due to shear forces, occurred in static test samples while more severe frictional prints were observed on the grout surface in dynamic tests.

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