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WHY THE PEAK SHEAR LOAD OF INDENTED CABLES INCREASES WITH INCREASED WIRE FAILURES?

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ABSTRACT: In shear testing of indented cables it has been found that indented cables peak share load failures behave contrary to the normal failure behaviour. The gradual strength loss with each individual wire failure in an indented cable strand may not lead to subsequent peak shear failure of the remaining strands in decline. This failure behaviour is characteristic of indented cables and occurs irrespective of the test method used (single shear or double shear test). Accordingly in this study all wires in a tested cable strand were instrumented with strain gauges. Each instrumented wire was individually colour coded to assist in determining the location of the wires in the strand circumference with respect to the direction of shear. The location of wires in the perimeter was identified at the sheared joint surface areas. During testing of the cable using a circular MKIV double shear apparatus (Naj Aziz DS Box) the initialisation of wire failure was identified by the strain gauge readings. This data found that the wires failing early were located on the upper segment of the bent strand during shearing process, indicating that the indentations introduced stress concentration spots on the wire, causing the strand wires to fail prematurely with less tolerance to bending than smooth wired cable.

INTRODUCTION

The use of long tendon ground support elements (cable bolts) is now common practice in modern underground coal mines, hard rock mines, tunnels and other underground structures. Due to their material properties cable bolts contribute significantly to the overall ground reinforcement provided by a support system. Cable properties in tension and shear are in many cases vital to maintaining a safe and productive underground environment. Accordingly, tension and shear properties must be assessed accurately using both valid and reliable methods.

Testing of tendons for tension is a common method of evaluating the load transfer properties of tendons and also for strength. This is reported by various researchers and can be undertaken both in the field and in the laboratory (Stillburg, 1984, Fuller 1983, Windsor (1992) Hagan and Chen, 2015, Hyett*, et al.,* 1992., *Aziz, et al.,* 2014, Tadolini, *et al*., 2012, Thomas, 2012). Tendon shear testing methods can differ with varied purpose and outcome. Until recently cable strength and load transfer capacity of cables were examined using a guillotine type single shear testing apparatus, which is, based on the British Standard (BS7861- Part 2, 2009). Recently there has been the increasing interest on shear testing of cables with the focus being directed to cable or tendon load transfer capacity as well as cable de bonding, this emphasis has led to the development of more credible methods and currently the testing of tendons is more closely simulated to ground conditions in which cable shear testing is carried out in concrete of varied strength and using double shear methods as reported by Aziz *et al.,* 2010, 2014, 2015, and 2016, and single shear method by McKenzie and King (2015) and Aziz, *et al*, (2017, 2018) and Yang, *et al.,* (2018). The later tests with simulated conditions demonstrated that the profile and surface conditions of the strand wires affect their load transfer characteristics. Some cable

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wires' failure during testing, particularly by shear testing, show that some strand wires fail less than the final peak shear load. In particular the indented cables appear to contribute to such unusual wires failure behaviour. Clearly, there is a need to shed light on this failure phenomenon and determine what contributes to some wires' premature failure. This is the subject of study in this paper.

SINGLE AND DOUBLE SHEAR APPARATUS

Shear testing of tendon rock bolts and cable bolts can be carried out using either the single shear or double shear testing apparatus.

Single shear apparatus

The conventional guillotine type apparatus based on British Stand BS 8761-part 2 (2009) and Megabolt single shear apparatus are methods for shear testing of tendons. The Megabolt single shear apparatus (McKenzie and King, 2015) is an integrated system that incorporated 120 t compression testing machine to the system and is also capable of evaluating bonding and debonding characteristics of tendon with respect to surface roughness. The performance of both types of rigs for testing cable bolts, as shown in Figure 1, are also reported by Aziz*, et al* in (2015 and 2018 a, b) and Mirzaghorbanali, *et al.,* 2017 respectively.

Figure 1: Single shear apparatus; (a) British standard based single shear and (b) Megabolt single shear apparatus

Double Shear (DS) apparatus

Four types of double shear apparatus have been developed over the years by researchers at the University of Wollongong. Three types are rectangular box types and the fourth circular shaped. The four are listed as:

- MKI- 150 mm x 150 mm x 300mm.rectangular box
- MKII - 300 mm x 450 mm x 300 mm rectangular box. A larger box, double the size of MKI box
- MKIII - 300 mm x 450 mm x 300 mm rectangular box. This is the same MKII rig but fitted with lateral truss system to eliminate friction between the joint faces. In this situation the applied shearing force will be totally spent of shearing the cable.
- MKIV – 300 mm x 450 mm x 300 mm circular shaped box, which is also as known as Naj Aziz DS Box.
- The above mentioned double shear box types, with and without lateral truss system are reported by Aziz*, et al.,* (2019)

Cable strand wires performance in shear

Several cables tested in shear using various types of the UOW double shear boxes have resulted in different failure behaviours of strand wires. The variance in failure pattern is related to the surface condition of smooth or indented wires as shown in load – displacement in Figure 2. The peak failure load of a cable bolt would normally be the maximum load and occur as the first wire failed with each subsequent wire failure continuing to shed load. Some indented wires appear to fail in an abnormal fashion, particularly when compared with smooth wire type, in which its peak failure load is lower than the smooth wired cables and may not be reached when the first wire fails. The subsequent wire failures may lead to increased peak shear load with the failure of indented wires. No abnormal failures were found in plain/ smooth wire cables with the first wire failure always being the peak load. Abnormal load failures in indented wire cables may also lead lower ultimate peak load failures.

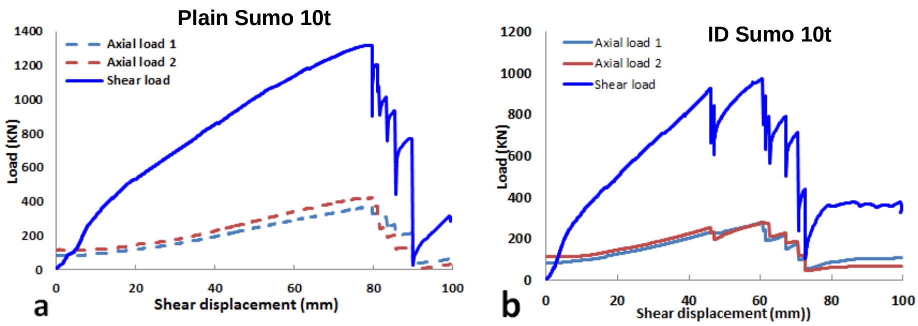


Figure 2: Shear testing of (a) plain and (b) indented cable bolts in 40 MPa concrete subjected to 10 t pretension load

WHY ABNORMAL FAILURES:

Based on several shear tests, it was observed that, due to the location of different wires along the perimeter of the cable with respect to the direction of shearing force, some indented wires were subjected to extra bending and early snapping in comparison with others in the cable periphery. The wires in question are those located on the top half of the cable perimeter with respect to the direction of shearing. Three possible factors may contribute to the abnormal failure of indented wires in the cable strand; (a) excessive bending of wires residing on the top part of the cable strand with respect to the wire location on the perimeter and shear direction and (b) wire weight loss due to indentation. This loss may cause up to 10% decrease in peak load depending on tested cable tyre as reported by Aziz, *et al.,* (2015), and (c) development of localised stresses due to the indentation process of the wires.

TEST PROCEDURES

Pull testing of wires under varying stress conditions

To demonstrate the strength performance behaviour under different test environments, three 400 mm long sections of the same cable bolt wire were cut and subjected to various forms of stress environments, as described above. Figure 3a shows three wires with one wire subjected to impact punch, the second was spot welded and the third one was intact. All three wires were then pull tested to failure using 50 t capacity Instron universal testing machine. The tested wires are shown in Figure 3b. The peak failure load of the intact wire was 69 kN, the failure load of punched wire was 67 kN and spot welded wire was 51 kN. All tested wires were from Sumo cable strand. This finding demonstrated clearly that failure of wires varies with respect to test wire conditions and that excessively stressed wire fails prematurely.

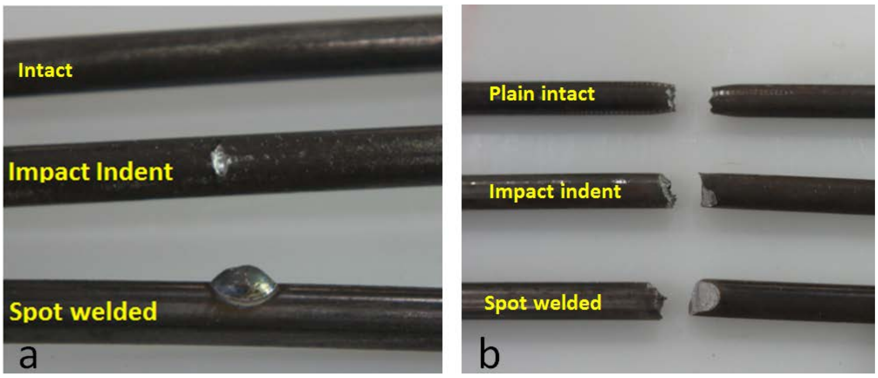
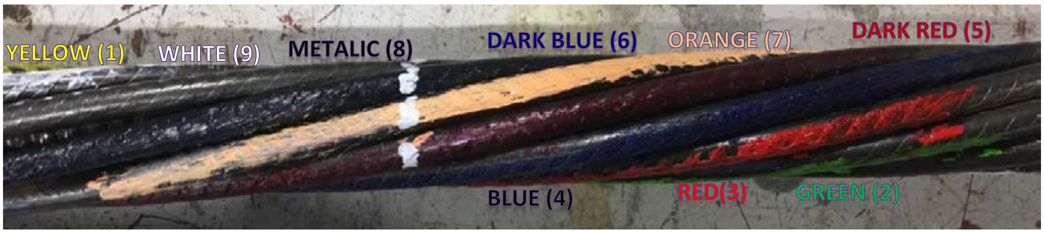


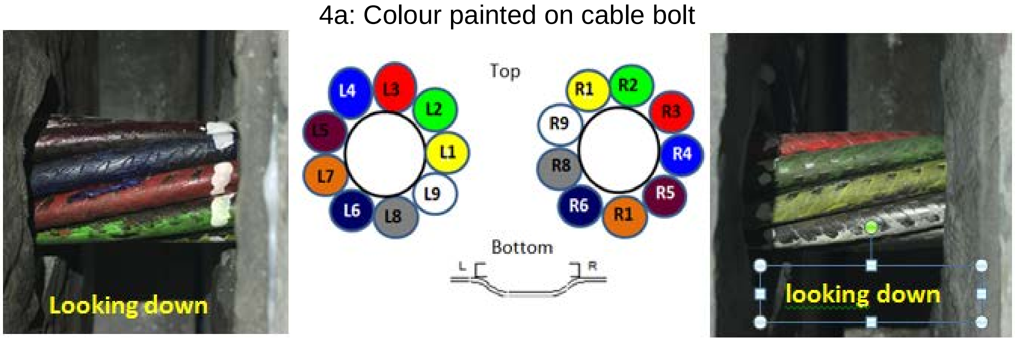
Figure 3: Impact free and stressed wires

Monitoring wire strength by instrumentation shearing of the cable bolt

To obtain reliable results on the location of the early wire failure and their identification, all wires of the cable strand periphery were painted with different colours, using oil-based paints as shown in Figure 4a. The orientation of each wire in the sheared joint areas was clearly marked. Then one strain gauge was installed on each strand wire and the wires were numbered and marked for identification in relation to wire location in the perimeter of the strand and the shear force direction. The application of the strain gauges required a clean and flat surface on each wire, which was achieved by sanding a small area of the wire surface, located some distance away from the sheared section so that the glued strain gauge will not be affected by changes in the wire cross section area. The area was polished and wiped clean with an alcohol based cleaner to ensure any impurities on the wire surface were removed. All strain gauges were subsequently checked for functioning and line continuity prior to start of shear loading. The profile of the cable wires, location at both sheared joint faces were identified and drawn as shown in Figure 4b. The strain gauge wires were carefully coursed out of the circular MKIV double shear box in such a way that all wires were not damaged during assembling and subsequent shearing. Figure 5 shows the assembled and instrumented Naj Aziz double shear box mounted on a 500 t compression testing machine.



4a: Colour painted on cable bolt



4b: wires orientation at both Lift and right joint planes zones

Figure 4 location of strand wires at the shearing zones across joint planes

Figure 5: test sample installation and strain gauges connecting monitor channels

RESULTS AND DISCUSSIONS

Figure 6 shows the load-displacement graph of the instrumented cable under shear and Figure 7 shows the individual strain gauge readings from different wires. The first wire (R9) in the strand snapped at 25.6 mm of displacement, at shear load of 338.4 kN and occurred on the right side (R side) of the double shear testing joint face area. This was followed by the failure of the second wire (R8) at 27 mm displacement. However, the maximum shear load of 443.1 kN of R7 was reached before failure of R7 wire occurred at 38.2 mm displacement. This is followed by erratic loads failures, occurring in indented wire strand and is contrary to the past test results from plain cables as reported by Aziz, *et al*., (2015, 2016, and 2017). In plain wire strand the peak load decreases gradually with each subsequent wire failure, as shown in Figure 2a.

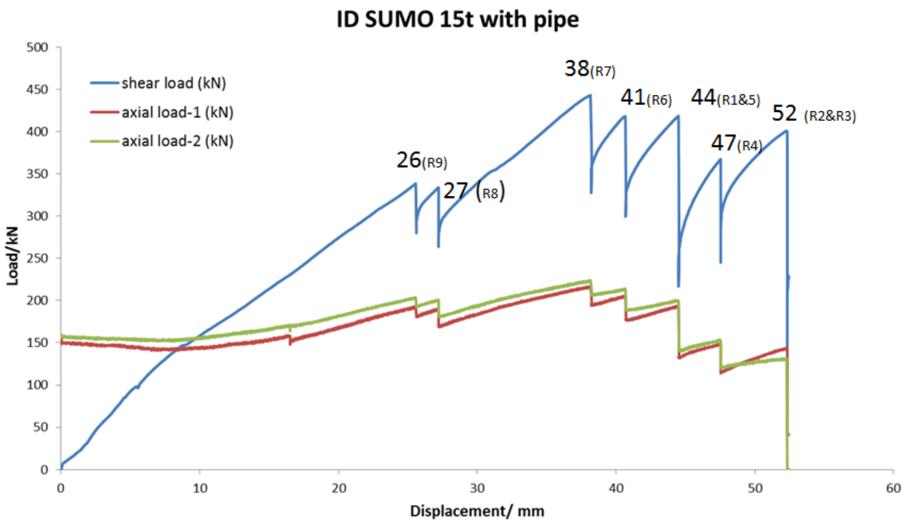


Figure 6: shear/ axial load vs displacement

During the early stage of shearing process some cable strand wires, namely Green (R2), Red (R3), Blue (R4), Black (R5), orange (R7), were subjected to early negative strain of shear loaddisplacements as shown in Figure 7, while others Yellow (R1), Dark Blue (R6), Metallic (R8) and White (R9) recorded positive strains right from the start of shearing, This suggests that those wires with positive strain were subjected to tensile and shear failure and they were mostly located on the top side (upper side)of the strand with respect to the vertical shear direction. The failed wires are characteristically either in tensile shear or in tension with cone and cup as shown in Figure 8. These failure patterns are documented in Table 1.

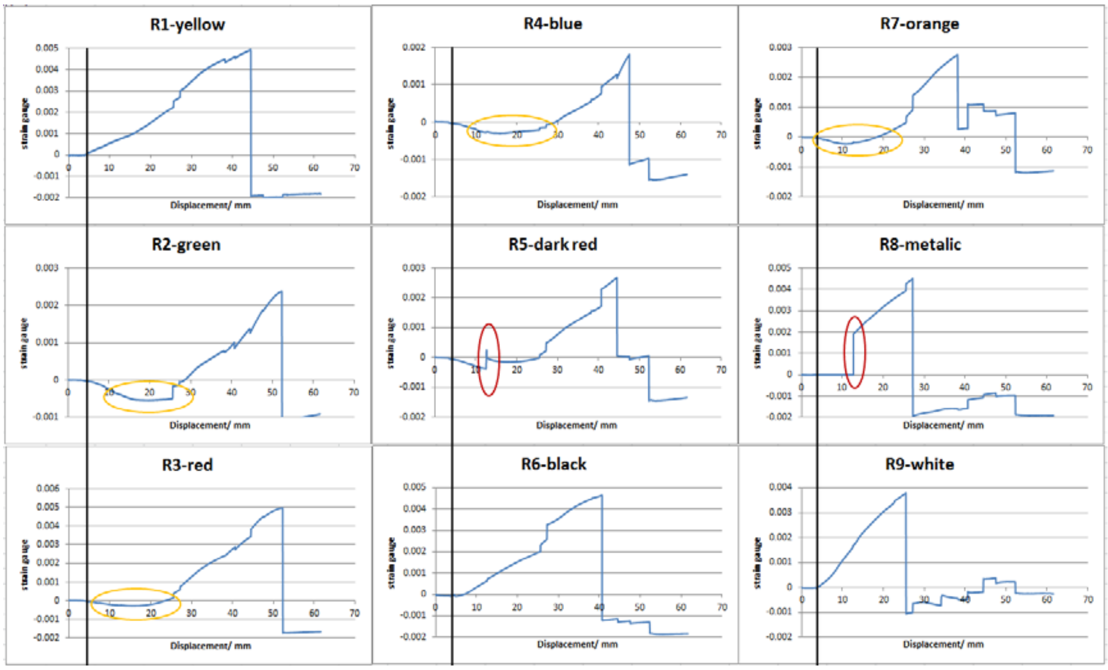
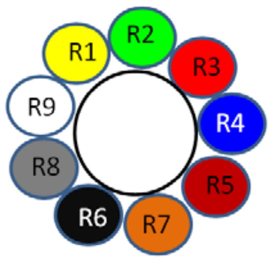


Figure 7: Strain vs displacement of instrumented wires during shearing

Table 1: pattern of wires failure on the RHS Joint shear side

Wire	Colour as seen on the RHS joint face	Location	Observed Failure pattern
R1	Yellow	Topside	Tension
R2	Green	Topside	Tension
R3	Red	Topside	Tension
R4	Blue	Topside	Shear
R5	Dark red (Maroon)	Bottom	Tensile/shear
R6	Dark Blue (Navy)	Bottom	Tensile/shear
R7	Orange	Bottom	Tension
R8	Metallic	Bottom	Tensile /shear
R9	White	Bottom	Tensile /shear



RHS- Sheared Cross section

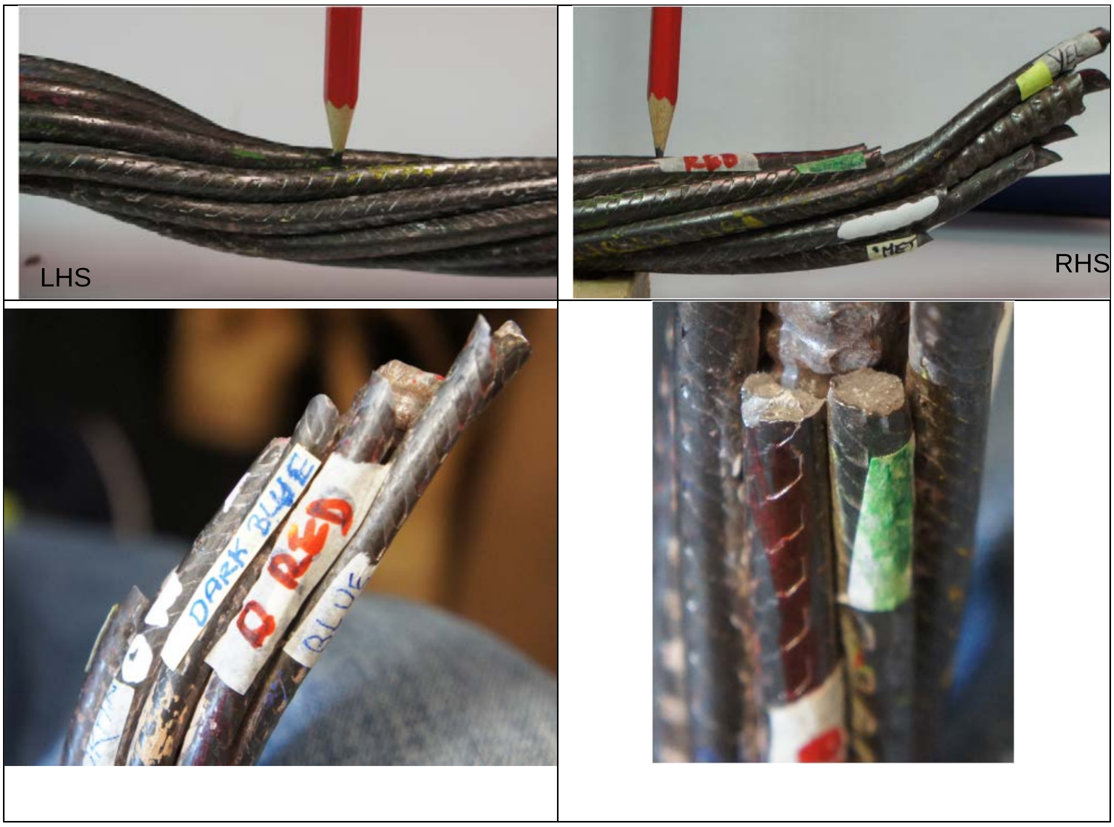


Figure 8: failure pattern of wires during shearing (right side of sheared cable in double shear test)

CONCLUSIONS

- Cable wire failure under shear across the joint plain all occur as wires undergo excessive bending and stretching as expected. Wires located on the topside of the cable would fail in and combination of pure tension and tensile shear, while wire on the opposite side exhibit only tensile shear failure. The early wire failures appear to occur on wires that are closest to the direction of the applied shear load.
- Cable strand wire Indentation may not be an advantage to cable strength and shear performance. Indentation process introduces stress zones, which when loaded in the double shear apparatus lead to earlier wire failure (lower load and lower displacement compared with smooth wire), with failure initiation at the indentation. This appears to be due to that area being subjected to a local stress.
- Wire weight loss due to indentation process, may contribute to early load failures, but it is not deemed a significant factor. Depending of the type of indentation made on the wire, the strength loss of the indented wire typically varies between 2 -10 %.
- There were irregularities in the order of peak shear load failures. Contrary to general belief that each wire snapping would lead to a subsequent reduction in peak load of the strand. No such case was found when tested in shear. Further tests are required as it is important to validate the true performance of strand wire indentation for effective application in varied strata formations and with reference to the benefits of cable debonding.

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