Behavior of Fully Encapsulated Cable Bolt in Various Double-Shear Methods and the Sequence of Wire Failure in the Newly Developed Shear Apparatus

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Abstract. The use of long-tendon ground support elements (cable bolts) is now a common practice in modern underground coal mines, hard rock mines, tunnels, and other underground structures. The paper briefly introduces the development of test methods for rock and cable bolts, including single- and double-shear methods, in the last 30 years and focuses on the novel development of the fourth generation of cylindrically shaped shear test apparatus (MK-IV Double Shear Box) for assessing tendon performance in shear based on the experience gained from the development of previous versions of shear experiment apparatus. The results were compared with similar test findings using a rectangular-shaped double-shear apparatus with and without friction across joint faces. The sequence of wire failure was studied by using the newly developed double-shear test apparatus, and the performance of abnormal phenomena in the double-shear tests was analyzed. The sequence of wire failure can be inferred based on the positive and negative values of strain gauge readings, and the wire of cable bolt under shearing may be broken in the joint area. The failure possibly occurred from one side to the other instead of from top to bottom. The modified double-shear test apparatus with a long section of concrete cylinder was proposed to conduct further research on cable bolt debonding.

1. Introduction

The use of long-tendon ground support elements (cable bolts) is now a common practice in modern underground coal mines, hard rock mines, tunnels, and other underground structures. Given their material properties, cable bolts contribute significantly to the overall ground reinforcement provided by support systems. Cable tension and shear properties are in most cases, vital to maintaining a safe and productive underground environment [1-3] Singh et al. [4] created a scaled physical model of underground excavation and proved that both axial and shear/bending loads are subjected to the rock bolt, which determines its overall performance and failure behavior. Accordingly, tension and shear properties must be assessed accurately using valid and reliable methods.

The traditional consideration of cable bolt is to gain the tension of tendons, which is a common method for evaluating the load transfer properties and strength of tendons. Such evaluation has been reported by various researchers and can be undertaken both in the field and laboratory [5-10]. Theoretical models and mathematical algorithms of the behavior of rock/grout/cable interaction systems have been also developed by various researchers, and plentiful models have been proposed to determine the capacity of fully grouted bolts and cables based on the bond strength model [11-14].
Shear testing methods for tendons can differ with varied purposes and outcomes. 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 [15]. The later tests with simulated conditions demonstrated that the profile and surface conditions of strand wires affect their load transfer characteristics. The failure of several cable wires during testing, particularly in shear testing, shows that certain strand wires fail at less than the final peak shear load. The following single-shear apparatuses were designed to study the performance of cable bolts under the single joint face, but the validity of the results was not verified due to the unbalance reversal of encapsulated material during the tests. The Megabolt single-shear apparatus [16] is an integrated system that incorporates a 120-t compression testing machine to the system and can evaluate the bonding and debonding characteristics of tendons with regard to surface roughness; this method is considered as a better method for shear testing of tendons than conventional guillotine-type apparatuses. More credible methods that use double symmetrical structures were developed after more than 25 years of uninterrupted research on ground support technology at the University of Wollongong to overcome the unbalance reversal during the shear test of tendons. Currently, the testing of tendons is closely simulated to ground conditions, in which cable shear testing is carried out in concretes of varied strength and by using double-shear methods. Several factors, including cable-belt pretension axial load, cable wire roughness, angle of installation, grout type, loading rate, and loading time (creep effect), are important variables determining the effectiveness of ground reinforcements with cable bolts; the overall failure component of cable bolts was also proposed [17]. However, the behavior of every single wire has not been considered in the past experiments, and the principle of wire failure has not been revealed. Therefore, the chronology of double-shear testing methods was introduced in this paper, and the different behaviors of cable bolt in various test apparatuses were compared. Furthermore, the sequence of wire failure was studied by using the newly developed double-shear test apparatus, and the abnormal performance in the double-shear tests was analyzed.

2. Development of Double-Shear Methods with Behavior Comparison

The earliest reference to the use of double-shear testing rigs was a paper detailing the work carried out by the rock mechanics research group led by Aziz et al. [18]. The 600 mm-long shear box is known as MK-I Double-Shear Box (MK-I DSB). MK-I can be used for shear testing of fiberglass rods and small-diameter mild-steel rib bolts as reported by Aziz et al. [19-21]. However, this box has a relatively small dimension and is unsuitable for shear testing of large-capacity rock bolts and cable bolts in low-strength concrete. Currently, the dynamic test of steel tendon is carried out by using this mold.

Two new versions of double-shear testing rigs were subsequently developed to accommodate shear testing of large-capacity rock and cable bolts (Figure 1a). The rectangular MK-II DSB consists of two 300-mm-long outer cubic boxes and a 450-mm-long middle central cuboid box with $300 \times 300 \text{ mm}^2$ cross-sectional area. The opposing concrete joint faces with an overall length of 1050 mm are in contact with each other. Therefore, the applied shear force is spent on overcoming the combination of the shear failure load and friction force of the sheared medium joint faces. Figure 1b presents the MK-III DSB apparatus, a modified MK-II DSB, with opposing concrete joint faces that are not in contact with each other; therefore, for the second apparatus, the measured shear resistance force is spent only on shearing the cable strand wires; in other words, MK-II DSB is a frictionless shearing box. However, Li [22] reported the cracking of a rock sample during shear testing. Once the encapsulating rock is cracked, it can no longer provide the conditions conducive to shear testing. A shear failure becomes a bending failure due to the sample and grout crushing around the joint intersection with the bolt. Excessive fractures in rectangular-shaped concrete blocks contribute to the inconsistency of shear test results. Normally, rectangular blocks are difficult to confine laterally in equal directions and therefore may lead to radial cracking. Resekh offered additional information on MK-II and MK-III DSBs [17].
The newly shear apparatus was developed as the Naj Aziz DSB (NADSB) or MK-IV DSB to apply the effective confinement of concrete and prevent axial and lateral cracks on the joint face of concrete (Figure 1c) based on the experience gained from the development of previous versions of rectangular DSBs. The new NADSB is circular in shape and is fitted with a truss system, which permits friction-free shear testing of tendons across joint planes [23].

Figure 2 shows the comparison of cable bolt behaviors in the three shear test apparatuses. These curves all exhibited three phases, i.e., elastic, plastic, and breaking stages, which were separated by the evident inflection point in the graph. The shear load value in the table is the maximum load achieved during shearing in the whole testing process and not the snapping of the first wire. However, the measured shear load and shear displacement on MK-III and MK-IV DSBs were smaller than those in MK-II DSB due to the absence of friction between the two joint surfaces. The load spent in overcoming the friction forces amounted to 30% of the applied total shear load. Cable bolt breaking at short displacement in MK-II DSB was caused by the pinching or squeezing effect (guillotine effect) under higher stiffness in the axial direction without gaps. Although the curves of MK-III and MK-IV DSBs had similar behaviors in the elastic and plastic stages, the shear failure loads tested in the cylindrical MK-IV apparatus was generally lower in comparison with the test results from MK-III DSB due to the circumferential direction encapsulation in MK-IV DSB. In the breaking stage, all the curves presented a stair-down tendency due to the individual failure of wires. However, determining the sequence of wire failure without specialist devices in the tested period, which was overlooked by previous research, was difficult. Therefore, this paper proposed a tracking method to study the sequence of wire failure by using the newly developed double-shear test apparatus (MK-IV apparatus). The performance of abnormal phenomenon occurring during the test was also analyzed.
3. Sequence of Wire Failure
All wires of the cable strand periphery were painted with different colors using oil-based paints to obtain reliable results on the sequence of wire failure (Figure 3a). A SUMO cable strand with 635 kN breaking load was installed into 40 MPa concrete blocks sample; the 28 mm-diameter hollow cable bolt consisted of nine wires and three birdcage bulbs that were processed at intervals of 0.35 m. The orientation of each wire in the sheared joint areas was marked. The profile of cable wires and location on sheared joint faces were identified and drawn (Figure 3b).

![Figure 3. Location of strand wires at the shearing zones across joint planes](image)

A 2 mm-long 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. All the strain gauges were placed on the outer 50 mm of the right side of the cable bulb (Figure 4). The application of each strain gauge required a clean and flat surface, which was achieved by sanding a small area of the wire surface, located a certain distance away from the sheared section. Thus, the glued strain gauge was unaffected by the changes in the wire cross-sectional area. The area was
polished and wiped clean with an alcohol-based cleaner to ensure the removal of any impurities on the wire surface. All strain gauges were subsequently checked for functioning and line continuity prior to the start of shear loading.

The strain gauged wires were carefully coursed out of the circular MK-IV DSB in such a way that all wires were not damaged during assembling and subsequent shearing. Figure 5 shows the assembled and instrumented MK-IV DSB mounted on a 500 t compression testing machine.

Figure 6 shows the load-displacement graph of the instrumented cable bolt under shear and the individual strain gauge readings from different wires. All the cable bolt wires were broken on the right joint after opening the concrete sample, and the points where the reading of individual strain gauge dropped down were marked by dots with corresponding colors. The first wire (R9) in the strand snapped at 25.6 mm of displacement at the shear load of 338.4 kN, on the right side (right side) of the double-shear testing joint face area. This event was followed by the failure of the second wire (R8) at 27 mm displacement. However, the maximum shear load of 443.1 kN of R6 was reached before its failure at 38.2 mm displacement. This phenomenon was followed by erratic load failures, occurring in the indented wire strand and is contrary to the past test results for plain cables as shown by previous experimental results.
During the early stage of the shearing process, several cable strand wires, i.e., the green (R2), red (R3), blue (R4), black (R5), and peach (R6) ones, were subjected to the early negative strain of shear load displacements (Figure 7), whereas the others, including the yellow (R1), white (R9), black (R7) and no-color (R8) wires, recorded positive strains right from the start of shearing and were broken earlier than the other wires. The failed wires were characteristically either in tensile shear or in tension with a cone and a cup (Figure 7). Table 1 documents these failure patterns. Cable wire failure under shear across the joint plain all occurred as wires expectedly underwent excessive bending and stretching. Wires located on the top side of the cable failed in combination of pure tension and tensile shear, whereas those on the opposite side exhibited tensile shear failure only. This finding suggests that the wires with positive strain were subjected to tensile and shear failure and were mostly located on the top side (upper side) of the strand with respect to the vertical shear direction.

Figure 6. Relationship between shear load/strain and shear displacement

Figure 7. Failure image of each single wire in the tested cable bolt
### Table 1. Patterns of wire failure on the RHS joint shear side

| Wire | Color 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                            | Bottom   | Tensile/shear            |
| R6   | Black                               | Bottom   | Tensile/shear            |
| R7   | Peach                               | Bottom   | Tension                  |
| R8   | No-color                            | Bottom   | Tensile/shear            |
| R9   | White                               | Bottom   | Tensile/shear            |

### 4. Discussions

Given the individual wire of cable bolts, one-time complete failure in a static loading environment was difficult to achieve, and the wires broke separately. In general, the stress state of the wire will be reformed after one wire snaps, and stress will be transferred to the neighboring wires, which would resist more stress and be broken easily. Hence, wire failure is directional. As per general knowledge, the first failure of cable bolt occurs on the right top side of joint faces, with reference to the stress distribution of rebar bolt. However, this phenomenon started from the side of the cable bolt (white and metallic) in this test. This phenomenon did not occur occasionally, as observed in other cable bolts (Figure 8). Four wires of SUMO plain cable bolt with 2 t pretension failed in the joint face. The wire on the right side totally snapped, and the middle top wire presented necking. The failure direction was predicted to start from the right side to the top, which corresponds to the phenomenon observed in this test and opposes the common knowledge.

![Top view](image)

**Figure 8.** Failure sequence of cable bolt

However, the curve of shear load in Figure 6 presents that the shear load still increased after the first wire snapped, which only occurred in the indented wire strand and is contrary to the past test results observed in plain cables. The early wire failures occurred on wires that were closest to the direction of the applied tension load (Figure 7). The stress state of the wire in the vicinity joint face with strain gauges attachment was monitored. The wires in tension zone can resist the shearing load in the start stage and bear additional stress throughout the test period, in which they were easily broken. Cable strand wire indentation may not be an advantage to cable strength and shear performance. The indentation process introduced stress zones, and the stress concentration occurred in the indented wire, which led to early wire failure during loading in the double-shear apparatus, with failure initiation at the indentation. The maximum strength of the cable bolt has not been reached, whereas several wires
failed in the early stage due to stress concentration caused by weight loss. After the partial wire failure, the cable bolt can also resist more stress than the left wires and structure with stress failure. Meanwhile, the wrecked cable bolt lost efficacy compared with the unabridged wire.

**Figure 9.** Post-failure wires in the abnormal failure test

The influence of interlocking and friction was severest on the wires located laterally with respect to the direction of shearing. In the plain cable, the whole cable construction reached the peak limit, and the resistant load declined as wires broke one by one either in shear or tension or their combination. However, in the indented cable, once the peak value achieved the interlocking effects between wires, the shear failure transformed into tensile failure by creating localized shear forces along the length of the wires. The top wires failed on the compression side of the hinge point, whereas wires on both sides failed with the increased elongation on the tension side on the post-failure wire (Figure 9). The shape of cable wire distribution changed from circle to oval. As shown in the schematic graph, the top wires suffered more bending moment in the plastic hinge point, whereas the wires on the two sides carried more tensile strength to resist shear displacement. Therefore, the early failure of squeezed wires occurred due to stress concentration, and the side wires snapped early because of heavy squeezing on the compression hinge point, whereas the third wires underwent additional tension on the tensile hinge side of the wire with less elongation.

5. Conclusion and Recommendations
(1) Compared with single-shear test apparatus, the testing of tendons is more closely simulated to ground conditions in which cable shear testing is carried out in concretes of varied strengths and using double-shear methods. The load spent in overcoming the friction forces in MK-II DSB amounted to 30% of the applied total shear load, and the shear failure loads tested in the cylindrical MK-IV apparatus were generally lower in comparison with test results from the MK-III DSB due to the circumferential direction encapsulation caused by the steel clamp.
(2) All wires of the cable strand periphery were painted with different colors, and strain gauges were attached on each wire in the cable bolt to obtain reliable results on the sequence of wire failure. The sequence of wire failure can be inferred based on the positive and negative values of strain gauge readings, and the wires with positive strain were subjected to tensile and shear failure and were mostly located on the top side (upper side) of the strand for the vertical shear direction after opening the concrete sample. Furthermore, the wire of the cable bolt under shearing may be broken in the joint area, and the failure possibly occurred from side to side instead of from top to bottom.
(3) Abnormal failure occurred in this experiment, in which the shear load still increased after the first wire snapped. The early failure phenomenon only occurred in the indented wire strand and is contrary to the past test results observed from plain cables.
(4) For future research, the NADSB/MK-IV DSB can be modified by dispensing with one load cell and replacing it with a long section of circular steel clamp, enabling the encapsulation of long-length cable bolt for cable bolt debonding studies. The extent of axial load in the bolt during the shearing process was still monitored by the second load cell on the other side of the shear apparatus. The behavior of the cable bolt under dynamic shear load will be the next research emphasis.

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