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Characterization of tensile and shear loading on indented PC-strand cable bolts

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ABSTRACT

The tensile and shear strength of intrinsic bolting support systems has always been a major concern of designers. A comprehensive laboratory testing program was designed to evaluate the tensile and shear strength of individual wires and completely wound PC-strand cables. PC-strand cables with smooth wires and the recent anchorage enhancement innovation of indentation were evaluated and compared. The testing protocol detailed in ISO Standard 15630 utilizes a mandrel system that was investigated at 3 different diameters which alters the wire to mandrel ratio from 2:1 to 9:1. The results demonstrate that the difference between smooth and indented wires is statistically insignificant when larger diameter mandrels are used, and that indentation does not adversely affect strand properties and performance. Insight into the shearing mechanism and evaluation techniques are discussed with the introduction of triaxial loading to describe the PC-strand tensile and shearing mechanisms. Another important result indicates that the shear strength of PC-strand cable bolting systems has a greater shear strength value than traditional steel bar bolting systems.

1. Introduction

PC-strand cable bolts have proven to be a global cost effective ground control solution in metal/non-metal and coal mines. The inherent strength to weight ratio of cable supports, combined with flexibility has been used in underground entries that range from 20 to less than 1.2 m in height. In coal mining, the systems are used as primary and secondary support installed both passively or actively with installation tensions that range from 38 to over 178 kN. While cable can be specified in several diameters, the most predominant sizes in the US remain 15.2 and 18 mm. The capacity of the systems defined in the ASTM 432-13 is 90% of the minimum strand strengths of 260 and 320 kN, respectively.

Cables are not only suitable to support vertical loads, but are also often used to effectively support fractured and jointed materials and can be exposed to shear forces across the wound PC-strand structure. In fact, Goris et al. reported that cable bolts placed across jointed surfaces could more than double the shear resistance. These results were duplicated for both smooth and rough jointed surfaces [1]. An example of tensioned cable bolts used to support a fractured and sliding roof in a longwall tailgate entry is shown in Fig. 1.

Additional shearing experiments were conducted under laboratory conditions to simulate shearing failure in hollow strand cables [1]. The cables were embedded in a concrete anchorage medium and a shear box was designed to create a double shearing action perpendicular to the cable axis. The analysis of the failure mode and load capacities indicated that the cable strands bent and the concrete crushed along the shear plane; the shear loading across the concrete and grouted cable then reached the tensile strength of the steel wires [2]. Another significant observation by the authors was that the “shear” failures were a combination of bending and twisting actions as shown clearly in Fig. 2.

These laboratory studies examined the effective shear resistance of PC-strand cable supports. However, the results also included other variables that prevent the shear strength of the strand from being isolated, i.e. joint roughness, applied normal forces, concrete embedment, hollow steel grout tubes, etc.

A recent laboratory study that examined inflatable steel bolts, completed by Ayers and Gardner, concluded that a component of rotation must be considered in support design systems for wedge failures and shearing motions [3]. An illustration from that study is shown in Fig. 3, which clearly defines the transition from pure

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Fig. 1. A mine entry subjected to high horizontal stresses, supported with PC-strand cables subjected to combinations of tensile and shear loading.

Fig. 2. Strand failure due to a combination of bending and tension and not solely due to shear [2].

tension to pure shear, passing through combinations of tensile/shear components caused by lateral loading and movements.

Combinations of loading created on a vertical failure plane under the influence of gravity at various intersection angles [3].

The shear strength in normal solid bolts can be determined by submitting the material to pure shear. The relation between shear stress and shear strain can be established experimentally. Such a relationship is usually shown by a diagram in which the abscissa represents the shear strain and the ordinate represents the shear stress. The diagram, shown in Fig. 4, is similar to that of a tensile test and you can mark the proportional limit *A* and the yield point *B*.

Experiments show that for a material such as a solid steel bolt, the yield point in shear t_{YP} is only about 0.55–0.60 of the working stress, s_{yp}, t_{YP} is the yield point. Since at the yield point considerable distortion occurs without an appreciable change in stress, it is logical to take as the working stress in shear only a portion of the yield stress point, so that the working shear, $\boldsymbol{t}_W = t_{YP}/\eta$, where is the safety factor. Taking this factor of the same magnitude as in tension or compression, we obtain

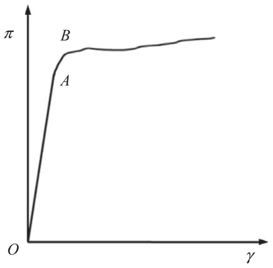

Fig. 4. Shear stress and shearing strain diagram [4].

$$\boldsymbol{t}_W = 0.55 \text{ to } 0.60 \text{ of } s_W$$

which indicates that the working stress, s_W in shear should be reduced when compared with the working stress in tension. Qualified ground control engineers always estimate that the shear strength of a solid steel bolt is about 55% to 60% of the tensile strength.

In PC-strand, the shearing forces are not as simple to test and describe, as movement and compression occurs between the individual wires which prevent a uniform distribution across the cross section, so the cable bolt undergoes not only shear but also bending under the action of the tensile forces. The result is triaxial loading conditions; effects of which are complex to isolate. In a 7X strand [1 king or center-wire surrounded by 6 outer wires], each wire is stressed in a different plane due to the specific orientation of each wire opposite to the applied forces, as illustrated in different views in Fig. 5. As shown, the "lay" of the outer wires wrapped around the king-wire creates axial loading that varies in complex angles normal to the king-wire. The "lay" length is the distance that it takes a wire to completely surround the king-wire (360°). The shorter the lay length is, the steeper the angle of the individual outside wrapped wires.

As shown in Fig. 5, it should note that the effect of lay in strand on the axis of loading in each wire.

When a shear force is applied perpendicular to the axis of the PC-strand, this will result in a combination of bending and twisting since the individual wires try to realign themselves and distribute

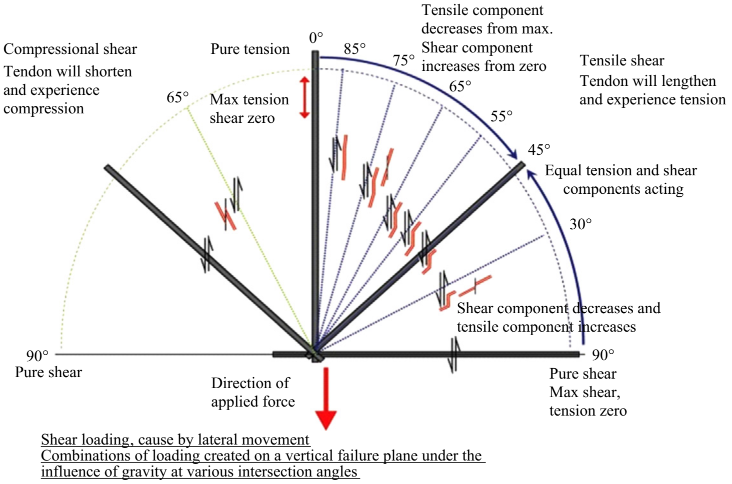

Fig. 3. Shear loading caused by lateral movement.