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Comparison of the shear test results of a cable bolt on three laboratory test apparatuses

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A B S T R A C T

The shear performance of cable bolt is important in assessing its load transfer capacity for effective rock strata reinforcement, which has not yet been thoroughly investigated and understood. Tests carried out in laboratory to study the cable shear performance can be simply classified into two types, the Single Shear Test (SST) and the Double Shear Test (DST). A variety of single and double shear test apparatuses developed in the past were reviewed and the main controlling factors when designing a new shear test apparatus were concluded based on the existing shear test apparatuses and their application. Four cable bolts were tested in laboratory conditions using the DST apparatus developed in the University of Wollongong, the British Standard Single Shear Test apparatus (BSST) and the Megabolt Single Shear Test apparatus (MSST) to compare and assess these different shear test apparatuses. Test results showed that the MSST results were completely different from the BSST results but similar to the DST results. Cable bolts tested in BSST tended to fail at small shear force and shear displacement in the form of inclined shear failure surfaces, whilst cable bolts installed in MSST and DST both tended to fail at greater shear force and shear displacement in the form of tensile cone and cup with bending deformation. It is concluded that both single and double shear test methods can effectively assess cable bolt shear performance as long as suitable apparatus dimensions and boundary conditions are used.

1. Introduction

Bolting is currently a commonly accepted method of reinforcing underground excavations and open pit slopes to maintain stability and control their deformation. The estimated annual consumption of bolts in mining and civil engineering projects is in excess of 7 million in Australia and 500 million worldwide (Hillyer, 2012).

Knowledge achieved from field application, laboratory tests and theoretical analysis has provided good guidance to coal mine operators in solving specific daily reinforcement problems. A variety of classical reinforcing theories were put forward and established, including suspension theory, composite beam theory, composite arch theory, maximum horizontal stress theory, surrounding rock strength reinforcement theory (Qian and Shi, 2003). All these theories are mainly based on the load transfer mechanism along the bolt axis between bolts and surrounding rock masses, normally named bond-slip relationship. Yet, coal mine operators, manufactures and researchers have been progressively recognising that the performance of bolts under combined tension and shear loading conditions is important in understanding the real behaviour of bolts in the field but has been insufficiently investigated. In field conditions, especially areas of high horizontal stress and or geological structures, shear loading plays a very significant role in bolt performance. Bolts anchored through shear joints provide resistance to shear movement of adjacent rock masses (Mahony et al., 2005). When adjacent rock masses slide relative to each other, the bending moment and axial force are mobilised in bolt. Thus, bolts will bend, crushing rock masses to adapt to the rock mass shear movement. When bolts eventually fail, the shear resistance offered are far greater than simply the shear strength of the bolt material (Aziz et al., 2015a, 2015b; Li et al., 2015), which is normally more than the half of its tensile strength for steel bolts. The bolt shear resistance is dependent on a variety of factors related to bolt, grout and rock masses, including rock strength, rock deformability, joint surface roughness, bolt size, bolt strength, bolt deformability, hole size, bolt installation angle, bolt pretension and grout properties. These influencing factors were grouped by Hartman and Hebblewhite (2003) into three categories, rock mass, the reinforcement element system and the loading conditions. Among these factors, the bolt installation angle is practically difficult to realize in the laboratory, thus only a few tests were carried out on it (Azuar, 1977; Bjurstrom, 1974; Egger and Fernandes,

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1983; Ge and Liu, 1988; Grasselli, 2005; Haas, 1981; Hibino and Motojima, 1981; Spang and Egger, 1990). For other influencing factors, most of existing shear test apparatuses are capable of investigating them. Generally these apparatuses can be classified into two types, the single shear ones in which there is only one shearing plane for a bolt, and the double shear ones in which a bolt will be sheared at two separate shearing planes. Compared to single shear apparatus, the double shear one has simple structure and can be easily manufactured (Aziz et al., 2003; Li et al., 2014). In contrast, most single shear apparatuses require special design to maintain their stability during the shearing process. Normally, the single shear apparatus is much more complex than the double shear counterpart. Since the double shear apparatus is generally developed with symmetric designation, theoretically, a bolt is loaded symmetrically in the double shear test apparatus during the shearing process. Therefore the half of recorded loads can represent the bolt shear strength. In practice, however, the whole double shear system and the loading condition cannot be perfectly symmetrical, thus bolt failure will not occur simultaneously at both joints (Haile et al., 1995; Hartman and Hebblewhite, 2003). This means the recorded peak shear load is less than two times the possibly potential single joint shear load. How much the difference is and whether the double shear test result can represent the bolt shear strength has not been investigated quantitatively in detail. In addition, even among different single shear apparatuses, test results could be quite different due to their structural difference and different loading conditions.

This paper reviews the development of shear test apparatuses and analyses their strength and shortcomings comparatively. Accordingly, principles of designing shear test apparatuses are summarized based on the past apparatuses. One type of double shear tests and two types of single shear tests on cable bolts were carried out and the results were analysed and compared.

2. Existing laboratory test methods

The earliest traceable investigation of bolt shear performance was conducted by Dulacka in 1972. The test rig used by Dulacka was a single shear test apparatus in which the bolt installation angle was adjustable, and thus allowed the investigation of varied bolt installation angles (Dulacka, 1972). Then in 1974, Bjurstrom used another single shear test rig, in which, aside from the abilities of Dulacka's design, normal stresses were applied and precisely controlled during the shearing process (Bjurstrom, 1974). From then on, similar single shear test designs were developed during the 80s and 90s and into the 21st century and some typical ones are given in Table 1. Double shear test apparatuses are also included in Table 1. The earliest reported double shear tests were performed by Haile et al. (1995), followed by Aziz et al. (2003), then Li et al. (2014). The advantages and disadvantages of these shear test apparatuses are analysed and listed in Table 1 as well.

From the analysis in Table 1, it is concluded that these shear test apparatuses mainly differ in the following aspects:

- The consideration of joint friction or not
- The size of rock or concrete samples
- The constraint condition of rock or concrete samples
- The availability of different installation angles of bolts
- The availability of applying pretension load to bolts
- The constraint condition of bolt ends

By analysing and comparing these shear test apparatuses, it is known that when developing a new laboratory shear test rig attention needs to be placed on the following factors:

Table 1
Summary of shear test apparatus.

Method	Advantages	Disadvantages
Single shear (Dulacka, 1972)	Different installation angles	Only thin bolts can be tested due to small allowable shear displacement
Single shear (Bjurstrom, 1974; Dight, 1983; Ge and Liu, 1988)	Normal stress can be smoothly adjusted; Different installation angles	Specially designed complex apparatus is required
Single shear (Goris et al., 1996; Spang and Egger, 1990)	Normal force is possible	No bolt pretension; Specially designed apparatus is required
Single shear (Bawden et al., 1994; Hutchinson and Diederichs, 1996)	Different bolt installation angles	The apparatus does not produce the maximum capacity of standard cable bolts in most cases
Symmetric single shear (Grasselli, 2005)	Different bolt installation angles. Symmetric setup intrinsically avoids instability	Only thin bolts can be loaded to failure due to the collapse of concretes; Big Samples
Single shear (British Standard Institution, 2009)	The setup is simple and can be loaded in general compression machines	Small shear force; Steel tube-bolt contact; No bolt pretension; Constant bolt installation angle
Single shear (McKenzie and King, 2015)	No steel tube-bolt contact; No full debonding; Integrated testing system	Big samples; Constant bolt installation angle
Single shear (Srivastava and Singh, 2015)	Adjustable normal force; Large shear box allows a set of blocks assembled together to study a complex situation	No bolt pretension; Specially designed complex apparatus is required
Double shear (Haile et al., 1995; Li et al., 2014)	Bolt pretension can be studied; Tested in a general compression machine	Thick bolts cannot be loaded to failure due to the collapse of concrete. Bolt may not fail at both joints simultaneously
Double shear (Aziz et al., 2003, 2014)	Bolt pretension can be studied; Steel frame avoids the concrete collapse; Tested in general compression machines	Bolt may not fail at both joints simultaneously

1. *The joint friction:* The joint friction is one of the main sources of shear resistance of bolted rock masses. During the shearing process, the bent bolt interacts with rock masses and thus changes the normal force on the shear joint. Besides, the joint friction coefficient varies during the shearing process due to the damage to joint plane asperities and the crush of rock masses around bolts. The difficulty in measuring and recording the variance of joint friction coefficient and normal force on joints makes it practically impossible to accurately investigate the joint friction effect in shear test.
2. *The bolt debonding:* When shear-loaded, the bolt bends and axial force is generated and propagates along the bolt axis to its end. Thus, with the increase of bolt axial force, bolt debonding might occur and develop along the bolt axis as well. The extent of bolt debonding will affect the shear stiffness and shear strength of the entire shear system, thereby influencing the overall performance of a bolt in reinforcing jointed rock masses. Factors controlling bolt debonding need to be considered when developing a new design. These factors primarily include the cross section area of rock samples (diameter for circular samples) (Hagan et al., 2015), the bolt encapsulation length, the external confining stress of rock samples, the bolt end constraint condition.