International Journal of Rock Mechanics and Mining Sciences 109 (2018) 138–154

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Mechanical response of fully bonded bolts under cyclic load

Xiaowei Feng*, Nong Zhang, Sen Yang, Fengzhen He

Key Laboratory of Deep Coal Resource Mining, Ministry of Education of China, School of Mines, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China

ARTICLE INFO

Keywords:
Bolt
Cyclic load
Hysteresis loop
Creep behavior
Pullout test

ABSTRACT

The mechanical properties of a bolting system under cyclic loading were investigated experimentally by pullout tests. Bolts of different diameters were inserted into steel tubes and bonded together by resin or cement to prepare simulated bolting systems for further pullout tests. Uniaxial compression tests showed that cement has a comparatively higher stiffness and peak stress compared with resin. A monotonic pullout test was conducted to determine the safety threshold for cyclic loading and the stress distribution along the steel tube. Interesting results were observed for specimens that were tested under different cyclic loading patterns. For instance, the deformation–memory property of the bolting system under a cyclic disturbance was evaluated; the triggering mechanism of creep behavior under cyclic loading is discussed; contributing factors associated with a hysteresis loop during a cyclic process were investigated; and weakening factors, such as the amplitude, upper loading level, and lower loading level were considered. The influence of cyclic mode on the failure patterns of specimens with different bonding materials was analyzed. Dominating failure modes, such as reversed-cone shaped resin agglomeration, flake-shaped scrapping, and bolt–resin interface debonding for resin-bonded specimens were exhibited and these are discussed. An annulus-shaped bonding block, brittle collapse, and cement–tube interface debonding for cement-bonded specimens is displayed and elucidated.

1. Introduction

1.1. General research approach for rock bolts

For almost a century, human activities have influenced our planet significantly above and below ground. Many constructions have been built deep into the earth to achieve a variety of objectives. From an engineering perspective, the underground region should be in a comparatively stationary state for a certain period, depending on the different serving destinations, a required period for underground hydropower station or subway may surpass one hundred years whilst for some coal mine gateways may only has several years. To maintain stability and to restrain underground space deformations, rock bolt supporting has proven most reliable and effective, and has achieved popularity in the civil and mining areas.[1] Reinforcement provided by rock bolt is the promotion or retention of the natural self-supporting ability within the host rock mass.[2]

In recent years, mechanical mechanisms and bolt failures have been studied extensively in a variety of ways, including laboratory tests, numerical simulations, and field verification. Literature on this topic is presented below.

At the laboratory scale, the most acceptable measure is to use steel tube to simulate rock mass. To do so, a bolt is inserted in the tube, with the annulus between them being filled by bonding material, resin or cement. Achievements using this method include the validation of an analytical model of fully grouted rock bolts[3]; an assessment of bonding interface behavior of fully grouted rock bolts[4]; bond strength measurements by bolt push testing[5]; an optimization of the bolt profile, anchorage bolt performance, and installation resistance by the assembled test equipment[6]; a determination of the effect of Poisson's ratio in laboratory push-and-pull testing of resin-encapsulated bolts[7]; the determination of the dynamic performance of D-bolts by which a split steel tube was used to simulate boreholes[8]; the use of a bend and tension-loading apparatus (BaTLA) in which a hollow hydraulic cylinder was assembled to examine stress-corrosion-cracking properties of rockbolts[9]; the addition of rigid particles into the grouting material to improve the load-transfer capacity;[10,11] the conduction of full-scale static-pull tests on rock static performance at the CANMET Mining and Mineral Sciences Laboratories, Canada.[12] In general, a short-encapsulation pull test (SEPT) is accepted as the norm, because the bolt is extended and deformed similar to in-situ conditions.[13] Nonetheless, disputes may still exist, because it is not known how well a SEPT can reflect real conditions of a fully grouted resin bolt.[14]

A second option is to replace the steel tube with small-scale cement

---

* Corresponding author.
E-mail address: fxw_mining@foxmail.com (X. Feng).

https://doi.org/10.1016/j.ijrmms.2018.06.018
Received 16 September 2017; Received in revised form 15 June 2018; Accepted 25 June 2018

blocks or cement cylinders. Related research includes determining the effect of cylindrical sample diameter on fully grouted bolts,[15] comparing the shear behavior between fiberglass bolts, rock bolts, and cable bolts, where bolts were installed in small-scale concrete blocks and their final failure modes were analyzed[16]; reinforcing a number of 200-mm × 200-mm × 200-mm concrete blocks with a 30-mm-thick weak interlayer and two 85-mm-thick hard rock layers with the assistance of aluminum bar, and investigating and applying the mechanical characteristics and failure patterns to the bolt behavior[17]; and designing an improved type of laboratory short-encapsulation pullout test (LSEPT) device, in which the bolt can be inserted into cementitious material to reveal the load-transfer behavior.[18] A similar experimental device is available in literature,[19] in which the bolt–grout interface behavior is investigated.

The third approach is to use large-scale (1:1) test systems, in which a specimen close to the original dimensions is used, and the obtained results approximate engineering reality. This approach has a high requirement for testing equipment, space, and economic costs. Parallel tests tend to be prohibitive because of specimen limitations and cost. Relevant latest developments are summarized as follows. A weight-dropping test arrangement or (Split-Hopkinson Tension Bar) SHTB system was investigated, through which the dynamic response and endurance capacity of some energy-absorbing or constant-resistance bolt could be tested and confirmed[20,21]; the three-dimensional behavior of bolted rock joints and several concrete blocks were used to explore the effects of joint inclination on passive bolts[22]; the abutment pressure on the stability of bolt-reinforced roof strata was studied, in which a massive roof and a laminated roof were considered[23]; and the anchorage performance of rebar bolt and a D-bolt under pull-and-shear load was studied, during which different displacing angles, different rock materials, and different joint gaps were considered.[24]

The fourth approach is field observation. The loading conditions and failure of bolts in some high-stress rock were studied, and new supporting methodologies were proposed[25]; supporting optimization was conducted based on field investigations, numerical simulations, and field verifications[26–28]; a performance comparison between the offset head versus the standard by overcoring bolts from the engineering field, and the mixing degree of resin and gloving problems were investigated[14]; an instrumentation strategy was studied by using long base-length strain gangues to measure the stretch along the bolt and contour patterns[29]; static pull tests and dynamic drop tests were used to confirm the effectiveness of energy-absorbing bolts (D-bolts), and results were confirmed by field measurements[30]; field tests were conducted to study the stress evolution in rock bolts[31]; a series of factors that influences the quality of encapsulation in rock bolting based on short encapsulation pull tests in the field and laboratory were studied[32]; roof bolts were recovered by overcoring to investigate gloving problems of fully encapsulated roof bolts[33]; and pull tests of rock bolts and cable bolts in sandstones and shales of the Sydney region were conducted, and a series of recommendations was proposed to detect and prevent the problems encountered.[34] Numerous other examples could be discussed here.

In the selected literature above, more than one research approach has been adopted, such as a multiple research programs that comprise two or more of these approaches: numerical simulations, analytical solutions, laboratory tests, or field observations. These excellent work provides a foundation for us to understand the inner mechanism of rock bolts, and they contribute extensively to the development of underground engineering from a global perspective.

1.2. *Necessity of revealing the bolt behavior under a cyclic load*

An appropriate research approach needs to be established to understand the mechanical response of bolts under a cyclic load. Unfortunately, bolt failure under cyclic loading has not been reported extensively to date and only limited literature can be referred to.

A scientific explanation for the bolt behavior under cyclic disturbance is important to guide engineering fields. The resulting discussion on this problem is whether it is necessary to study the bolt's behavior under a cyclic load. The authors believe that an answer to this problem is imperative. Many activities can cause cyclic impacts in the engineering fields, including rock/gas bursts, mine earthquakes, tunneling advancements, and drilling and blasting, ranging from underground excavation, marine engineering, rock slopes, to mining activities.[35–37] Previous research has focused largely on the supporting target, that is, the rock mass, and many interesting results have been confirmed, including creep deformation,[38] rheological behavior,[39] hysteresis loop,[40] and deformation–memory. A hysteresis loop is observed frequently in some non-elastic rock's response to the cyclic load. The connection of upper limits in the cyclic process is almost similar to that of original monotonic curves, it appears that the test object suffers no impact from the cyclic load, and this is the deformation–memory of rock mass. In terms of creep behavior, the rock-deformation phenomenon exhibits a mitigative increase as time elapses under a certain stress level.

If we consider the general research approaches mentioned above, an appropriate measure is vital to achieve scientific results. Ideally, a field experiment is recommended because it most closely approximates actual situations, and provides authentic results; however, the application of a man-made cyclic load to a bolting system that was installed originally to support the rock mass may be dangerous, and the specimen numbers are limited. A numerical simulation offers an economical way to study the mechanism of bolts under a cyclic load, but this procedure is arduous because of the parallel variabilities in cyclic load, and the failure mode is also unobservable. Furthermore, results may not be realistic as the approach does not consider the roof-bolt-installation procedure, or the fact that resin-reinforcement relies on the friction/interlocking between the resin annulus and borehole wall.[41] Widely applied analytical approaches that are based on a finite-difference formula, convergence–confinement method, tri-linear bond–slip model, and Mohr–Coulomb criterion may experience identical shortcomings.[42–45] Therefore, laboratory experiments have been used in this study, in which parametric changes are easy and laws that are more specific can be concluded.

1.3. *Current research situation on bolt behavior under cyclic loading*

As mentioned above, bolt degradation under cyclic loading has not been reported extensively and only a limited literature exists on this topic with most neighboring information related to this topic including cyclically loaded reinforcing bars in concrete. A brief summary of relevant research is provided below.

Rehm and Eligehausen explored the bond behavior of ribbed bars under repeated loads and 308 pullout specimens were tested. By varying parameters, such as the maximum load, load amplitude, bar diameter, concrete quality, and bond length, the authors demonstrated that a repeated load had a similar influence on the slip and the bond strength of deformed bars to the deformation and failure behavior of unreinforced concrete.[46]

Ballivy et al. placed passive anchors in concrete cylinders, which were grouted in cement. The results indicated that the service life and the number of repeated loadings at failure had a close connection with the amplitude and the upper/lower levels of repeated loads.[47] These findings were confirmed based on a report issued by the American Concrete Institute,[48] and design recommendations for high- and low-cycle fatigue disturbances were addressed.

Benmokrane et al. reported that the mechanism and failure pattern of anchors that were impacted by repeated loads may differ from those impacted by static loads, and prestressed and passive anchors were chosen as research targets. The results indicated that prestressed anchors could withstand long-term load fluctuations.[49] The test setup that was used is shown in Fig. 1a. Oh and Kim proposed a realistic model on