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Rock and bolt properties and load transfer mechanism in ground reinforcement

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ABSTRACT

Load transfer capacity and failure mechanism of a fully grouted bolt installed across joints in shear is evaluated in both experimental and numerical approaches in 5 types of bolts. The strength of the concrete, bolt profile configuration and bolt pretension load plays significant influence on the shear resistance, shear displacement and failure mechanism of the reinforced medium. Bolt yields at low level of loading at hinge points. Failure location moves towards the bolt joint intersection due to the increasing shear load, shear displacement and bolt pretension load. Finally bolt failure occurs as a result of the induced axial and shear stresses acting between hinge point distances at the vicinity of shear joint plane.

Key words: bolt failure, load transfer, bolt bending, grouted bolt, numerical modelling.

INTRODUCTION

Fully grouted rock bolts are used for ground reinforcement as both temporary and permanent systems to support the efficiency of reinforcement system. This depends on the load transfer mechanism and the shear stress sustained at the joint interface. Factors influencing the shear resistance are; bolt diameter, hole diameter, steel quality, bolt extension, confining pressure, strength of the rock and the strength of the grout. Significant progress has been made in both the numerical and laboratory research to study the mechanical behaviour of bolted rock joints, and much of the theoretical studies were undertaken include the finite element and finite difference methods.

The first systematic research on fully grouted rock bolts was conducted on bolts embedded in blocks of granite [5]. Failure mode, strength and deformation stiffness of the sheared bolted joints were found to be dependent on the bolt angle of installation across the joint. Dight (1982) carried out a series of laboratory tests, to evaluate the shear resistance of bolted joints using various materials and found the failure of the bolt was caused by the combination of axial and shear forces, the normal stress acting on the joint surface had no influence on the shear resistance and joints with inclined bolts were stiffer than the perpendicular ones.

Joint surface friction, bolt inclination and the degree of rock and grout deformability are the major influencing parameters on joint shear strength and bolt contribution [6]. Ferrero [7] found that the overall strength of the reinforced joint was considered to be the combination of both the dowel effect and the incremental axial force increase due to bolt deformation. A shear strength model for reinforced rock joints was proposed, based on the numerical modelling and laboratory tests and suggested a modified analytical model for bolts installed perpendicular to the joint plane in stratified bedding plane.

During the shearing process, the bolt is deformed with joint displacement. The longitudinal axis of the sheared bolt is deformed into a curve producing a lateral shear load, an axial load, and two critical points: one in bolt-joint intersection and the other at the hinge point. These loads produce stress resultants in the form of bending moment, shear and axial forces throughout the beam at joint-bolt intersection or at the hinge point.

EXPERIMENTAL STUDY

Laboratory tests were carried out in five types of bolt. These were bolt Types T1, T2, T3 (high strength steel) and Bolt Types T4 and T5 (low strength steel). The tests were carried out in three piece pre-cast concrete blocks, of strengths 20, 40, and 100 MPa respectively. Concrete was used to simulate different rocks, as it was easier to prepare and to simulate different strengths. 12 and 22 mm diameter bolts were installed in 18 and 27mm diameter holes in appropriate strength concrete blocks using Minova PB1 Mix and Pour resin grout.

Figure 1 shows the general set-up of the assembled double shear box in a 500 ton capacity compression testing machine and the photographs of different deformed bolts. Tests were made with and without pretension loads of 20, 50 and 80 KN. Figure 2 shows the profiles of various bolts used in the study. To achieve a meaningful result, the shearing tests were carried out under the following conditions:

- Tests were carried out in high capacity compression machine (5000 kN), thus allowing the bolts to snap at the sheared joint plane.
- Carry out the shearing tests in much greater concrete strengths
- Carry out the tests using lower concrete strengths
Laser
displacement
test
Figure 1: (a) General set-up of the assembled double shear box in a high capacity testing machine (1500kN) (b) Post test deformed bolts and resin encapsulation

Figure 2: Bolts profile configuration

Figure 3 shows typical shear load versus shear displacement in both 20 and 40 MPa concrete and at various pretension loads. Both concrete strengths and bolt pretensioning loads played a significant and favourable role in shear resistance level. Figures 4, 5 and 6 show the failure locations in bolts Types T4, T5 and T1 respectively. In all three cases the failure occurred along the bolt section, in between the hinge points at the vicinity of shear joint.

**SHEAR LOAD BUILT UP**

During the shearing process the shear displacement is increased, lateral and axial loads are developed along the bolt and surrounding reinforcement. The factor of shear resistance may be the resultant of both lateral and axial loads due to the bolt deflection. As can be seen in Figure 3, three distinct stages of bolt deformation take place and are as follows:

- **Elastic stage**: This part of the test associates to the elastic behaviour of the bolt, and occurs at the early stages of the central concrete block shearing. The steel bolt elastic behaviour depends on the young’s Module and also the level of applied pretensioning. Though relatively in small deformation, bolt, grout and the concrete will be in elastic conditions. Concrete and grout fracturing occurs at this stage.

- **Non-linear stage**: This stage corresponds to elasto-plastic stage of bolt shearing which, in this situation, is known as non-linear stage. This stage is characterized with bolt yielding, grout detachment from the bolt as well as from the concrete. This is because of low bonding characteristics at bolt/grout and concrete interfaces. Further widening of the fractures in the grout and concrete will take place as the load and displacement increases. This stage can be observed usually between 3 and 6 mm deflection depends upon the strength of materials, bolt profile type and pretensioning level.

- **Plastic stage**: In this stage all the materials involved are in plastic stage. The plastic limit of the bolt is characterized by low rate of loading at increased vertical displacement. Hinge points are created in the bolt at both sides of the shear joint plane, with the gap being increased between bolt-grout and grout-concrete. Grout is completely damaged at compression zones and concrete is fractured along the bolt axis in all three blocks, as shown in Figure 9. The failure process of the system is dependent upon the strength of the concrete. Bolt failure in strong concrete occurs in shear at the shear joint plane or under the axial stresses between hinge points. In weak concrete, no bolt failure takes place as the bolt cuts through the concrete.

**BOLT-JOINT CONTRIBUTION**

Bolt contribution to the shear strength of the reinforced shear joint plane depends upon the rock/concrete strength, grout strength, bond strength between the interfaces, mechanical and physical properties of the steel bolt, joint specification and bolt pretension loads. Each of these parameters plays significant role in affecting the shear resistance and failure mechanism. The bolts joint contribution versus shear displacement in bolt types T4, T5 and T1 are shown in Figures 7 and 8 respectively, which was calculated from the following

\[ T_r = \frac{T_v - 2N\tan\phi}{2F_{\text{max}}} \]

Where, \( T_r \), \( T_v \), \( N \), \( \phi \), \( F_{\text{max}} \) are bolt contribution, shear load, confining load, joint friction angle and maximum tensile strength of the bolt respectively.
Figure 3: (a-f). Shear load versus shear displacement of bolts in 20 and 40 MPa concrete under different tensile strengths.

- a) bolt Type T1 in 20 MPa concrete
- b) bolt Type T1 in 40 MPa concrete
- c) bolt Type T2 in 20 MPa concrete
- d) bolt Type T2 in 40 MPa concrete
- e) bolt Type T3 in 20 MPa concrete
- f) bolt Type T3 in 40 MPa concrete

Figure 4: Failure of Bolt Type T4 in 18 mm diameter hole in 40 MPa concrete.

Figure 5: Failure location in Bolt Type T5 surrounded in concrete 40 MPa and 18 mm hole diameter.
The shear load at the bolt yield point was found to increase with increasing bolt pretension. This behaviour was evident with low height and widely spaced profiled bolts.

The strength of the medium has influenced the shear load level but not the trend. Shear load values for all the bolts were generally less in 20 MPa concrete medium in comparison to the shear load values of bolts tested in 40 MPa concrete.

Pretensioning of the bolts will increase the normal stress on the joint surface, and hence the shear resistance of the joint.

The displacement rate at post peak yield point was relatively higher than the yield zone. This is attributed to the combination of the reduced bolt bending force as well as the reduction of the contact area of the joint surfaces shearing progression. Obviously, there were some variations to the rate for different bolt types due to varying bolt surface profile configurations, with other parameters being equal.

Deflected bolt sections experienced regions of tension and compression. Resin columns remained adhered to the sides of the bolt region that experienced compression, but had broken off the sides that were in tension.

The yield limit at the hinge points occurred at about 0.32P and 0.45P (P is the yield strength of the bolt) in concrete strengths of 20 and 40 MPa respectively.

With increasing shear load and bolt deformation, failure position moves towards the bolt joint intersection and finally bolt will fail between hinge point locations.

Bolt joint contribution in low and high strength steel is around 80-90% and 55% respectively.

The bolt failure mechanism is due to the combination of axial and shear stresses, which are located along stiff region, between hinge points, at vicinity of shear joint.

**3D FEM**

3D simulation of the bolt shearing process was carried out to examine the behaviour of bolted rock joints in relation with the experimental results. The model bolt core diameter \( D_b \) of 21.7 mm and the grouted cylinder \( D_h \) of 27 mm had the same dimensions as those used in the laboratory test. Figure 10 shows finite element model of bolted joint with initial loads and other specifications, which is simulated by numerical modeling of the same as in laboratory test.

The stress-strain relationship of steel was assumed as bilinear kinematics hardening model and the modulus of elasticity of strain hardening was accounted as one hundredth of the original value. The 3D solid elements (Solid 65 and Solid 95) that have 8 nodes and 20 nodes were used for concrete, grout and steel respectively, with each node having three translation degrees of freedom, which tolerated irregular shapes without significant loss in accuracy.

The numerical modeling was carried out at several sub steps and the middle block of the model was gradually loaded in the direction of shear. Simulation of several models in varying conditions (a range of bolt tensile load and concrete strength) was carried out under a progressive vertical load and results were analyzed for both linear and nonlinear regions of the load - deflection behaviour.
Confining effect on joint surface

Created gap between bolt-grout interface

Overwhelmed grout under high pressure

High reaction zones in concrete

Grout and concrete

Figure 9: Failure location in Bolt Type T1 surrounded in concrete 100 MPa and 27 mm hole diameter in full details of failure process

NUMERICAL RESULTS

BOLT BEHAVIOUR

The steel bolt encapsulated with near 3 mm thick resin in each of 20 and 40 MPa concrete blocks were simulated with respect to the changes in stresses and strains along the bolt. As Figure 11 shows, the stresses in the upper convex section of the bolt are in tension, while the lower opposite side is in compression. This situation will occur in reverse on the concave section of the bolt in the other side of the shear joint plane. In addition, the numerical simulation showed that the tensile stress in the bolt was increased and expanded towards the shear joint with increasing the pretension load and bolt deformation. Figure 12 depicts the rate of distribution of axial stress changes along the bolt.

The distribution of shear stress along the bolt in the vicinity of the sheared joint is drawn in Figure 13. The maximum shear stress is concentrated at the bolt joint intersection. Pretension caused a reduction in bolt shear stress. With increasing shear load and bolt deflection axial stresses are expanded and moved towards the shear joint location. Thus, from the combination of shear stress and axial stress bolt will fail in that area, as it was discussed in experimental section. At the post-elastic yield point the shear stress was almost constant and unaffected by the increase in both the shear and pretension loads. This behaviour occurred approximately 4 mm of bolt deflection in concrete 20 MPa. The shear stress diagram in all concrete strength, had the same trend, but the value of shear stress was found to decrease with increasing the pretension load.

Figure 10: FE model and Initial state of bolted joint, one fourth of the model: C, T = compression, and tension area respectively

Softer concrete has experienced higher strain along the bolt and the value of induced tensile strain is higher than the compressive strain. Induced strain is increased with increasing
the shear load. With increasing pretension load in post failure behaviour there is no significant changes in strains along the bolt. However, the area of tensile strain has expanded and compression strain reduced.

From the comparison of the plastic strain in concrete 20 and 40 MPa it is recognized that the strains in weaker media are higher than in harder media. In addition, there are two hinge points around the shear plane, and the distance of each hinge point from shear plane is approximately equivalent to 2.3 \( D_b \), (\( D_b \) is the bolt diameter). This distance is simulated in a 20 MPa concrete and with bolt pretension load of 20 kN. However, the laboratory test showed that the hinge points distances was around 44 mm (2 \( D_b \)). The hinge point distance decreases with increasing shear displacement.

**BEHAVIOUR OF SURROUNDING MATERIALS**

The behaviour of concrete under shear load was analyzed and the rate of stress changes in concrete along the bolt length is shown in Figure 14. The high level of stress produced in the concrete caused fractures and failures in the vicinity of shear joint region. The zone of high stress concentration in weaker concrete is significantly broader, at 90 mm from the shear joint plane, in comparison to 60 mm length, obtained for 40 MPa concrete. It should be noted that in failure region, which needs higher level of shear load, this reaction zone and overwhelmed length is definitely high. When shear load increases, grout will break at tensile zone and overwhelmed at compression zones. This situation usually will start at bolt elastic behaviour region and progresses beyond the yield point. Then grout will separate from the bolt at tension zone at the vicinity of the shear joint. Due to the axial bolt load, yield in the grout can be determined when the actual bond stress, between bolt and grout is equal to the grout yield strength. The plastic strain is generated along the grout layer, in particular between hinge points, when the induced stresses are exceeds the grout strength. Figure 15 shows the contours of induced strain along the grout layer in an installation consisting of 21.7 mm bolt core diameter and 27 mm hole diameter. The value of strain in the grout layer in plastic state is 10 times greater than at the linear region, particularly at the critical zones in the vicinity of shear joint. Obviously the grout under such severe condition will be fragmented as shown in Figures 1. When the shear stresses on the bolt/grout interface reach critically high values, the process of slippage between bolt and grout will begin.

![Figure 11: The location of critical stresses and failure zone](image1)

![Figure 12: The rate of stress changes along the bolt in 20 MPa concrete with 20 kN initial tensile load](image2)

![Figure 13: Shear stress contours in vicinity of shear plane in 20 MPa concrete and 20 kN pretension bolt load](image3)

![Figure 14: Yield stress and deflection curve in 20 MPa concrete in 80 kN bolt pretension load](image4)

**CONCLUSIONS**

The double shear testing represents a useful method of assessing the bolt behaviour in stratified reinforcement. The evaluation of the shear strength of rock joints reinforced with fully grouted bolt was analysed both experimentally and numerically. The main conclusions drawn from both the experimental analyses and numerical design are as follows.

1) The composite bolt/concrete deflection at a given vertical
load was higher in weaker medium.

2) Tensile and compressive stress zones along the bolt are located on each side of the shear plane. The nature of stress concentration is dependent upon the deflection direction of the sliding blocks relative to each other.

3) Higher value of shear stress contours occurs along the shear plane.

4) For small-applied loads (before yield point), pretensioned, does not influence much on the magnitude of the shear displacement and resistance of the system. That is evident for both the experimental and FE results.

5) In all type of bolts tested experimentally, the shear load of the bolt, in general, increased with increasing bolt tension.

6) Due to combination of shear load and axial load along the bolt, and movement of failure position towards the bolt joint intersection bolt will fail at vicinity of shear joint between hinge point distances.

7) The distance between hinge points is reduced with increasing the strength of material. However, there are no significant changes in hinge point distance with increasing pretension effect.

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