A new approach in determining the load transfer mechanism in fully grouted bolts

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A NEW APPROACH IN DETERMINING THE LOAD TRANSFER MECHANISM IN FULLY GROUTED BOLTS

A thesis submitted in fulfillment of the requirements for the award of the degree

DOCTOR OF PHILOSOPHY

from

UNIVERSITY OF WOLLONGONG

By

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B.Sc, M.Sc. Rock Mechanics

School of Civil, Mining and Environmental Engineering

2006
This thesis is especially dedicated to my family. To my mother, for her unfailing support and long patience, I am extremely grateful of her. To my wife, Zahra Jamali, for her support, understanding and sacrifice over these years and also to my little beautiful daughter, Fatemeh Jalalifar, who was eagerly waiting for me every night to come back home, although I could not spend as much time as I wished with her, I am truly grateful.

My brother, Mohammad, who lost his children in Bam’s Quack

And other relatives who suffered intensively from the Bam’s Quack

For their love, encouragement, support and patience
AFFIRMATION

I, Hossein Jalalifar, declare that this thesis, submitted in fulfillment of the requirements for the award of Doctor of Philosophy, in the School of Civil, Mining and Environmental Engineering, Faculty of Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The thesis was completed under the supervision of A/Prof. N.I.Aziz and A/Prof. M.S.N. Hadi and has not been submitted for qualification at any other academic institution.

Hossein Jalalifar

2006
The following publications are the result of this thesis project:


ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to my thesis supervisor A/Prof. Naj.I. Aziz, faculty of engineering University of Wollongong, for his supervision, generous support, encouragement, and guidance provided during the research and also providing the necessary facilities to conduct my research work during three years. I would also like to express my sincere thanks to A/Prof. Muhammad Hadi my thesis co-supervisor for his helpful advice in this thesis particularly in numerical simulations.

I also wish to express my sincere thanks for helpful contributions and comments made by Dr Seedsman and also Dr Alex for helpful assistance in Numerical modelling.

I also would like to thank the technical staff in the School of Civil, Mining and Environmental Engineering, especially Bob Rowlan, Alan Grant, for laboratory assistance and also Ian Bridge and Ian laird.

I greatly appreciate the contributions made by Mr Des Jemison, Mrs.Leonie McIntyre and Mr Peter Turner of the ITS staff. The assistance provided by the Faculty of Engineering, University of Wollongong, in particular Mrs Lorelle Pollard is also appreciated.

I would like to acknowledge with sincere appreciation, the financial support of the Ministry of Science, Research and Technology of the Islamic Republic of Iran and the Kerman University for awarding me a research scholarship through which the complete financial support for this research was provided.

I also would like to thank Bill Huuskes manager of the Metropolitan Colliery and Rod Doyl geotechnical engineer of Appin Colliery for their great assistance in field work.

Most importantly, I would also like to express my great thanks to my wife and little daughter for their patients here and mother and brothers in Iran who have provided continued support throughout this study.

I would also like to thank all my fellow Iranian at Wollongong University in particular Mr Saeid Hesami, Mr Mohammad Hosseini and Mr Mahdi Emamjomeh for their support and encouragement.
ABSTRACT

Rock bolts are used as temporary and permanent support systems in tunnelling and mining operations. In surface mining they are used for slope stability operations and in underground workings to develop roadway, sink shafts, and stoping operations. Rock bolting technology has developed rapidly over the past three decades due to a better understanding of load transfer mechanisms and advances made in the bolt system technology. Bolts are placed into discontinuous rock to prevent movement between the discontinuity planes, depending on the direction of installation and nature of the discontinuity surfaces. Rock bolting can increase the tension and shear properties of the rock mass.

Nowadays, the application of rock bolts for ground reinforcement and stabilisation is worldwide, but its effectiveness depends on rock type, strata lithology, and encapsulation characteristics. Thus the bolt, rock interaction, particularly near the shear joints, and how a bolt reacts to surrounding conditions require continuous evaluation and research. Work provides an in depth study of the bolt, grout, concrete interaction during under axial and lateral loading.

To better understand load transfer characterisation bolt shearing across joint and planes, this research programme consists of three parts. Accordingly, a series of experimental studies and field work was undertaken. A numerical technique was developed to obtain the stress and strain developed along the bolt and surrounding materials under axial and lateral loading. Finally, a field investigation programme was undertaken to obtain the load developed along different bolt profiles (another objective of this thesis). Bolt profiles were also investigated by laboratory studies.
A double shearing system (DSS) was used to examine bolts shearing. Testing was undertaken in 20, 40, and 100 MPa strength concrete to simulate different rock strengths. Only three bolt types were used in axial loading tests and different thicknesses of resin were evaluated under axial and lateral loading. Tests subjected to lateral loading were undertaken in 0, 5, 10, 20, 50 and 80 kN pre-tension loads, which revealed that the strength of the concrete significantly affects the bolt - joint contribution. Also shear displacement was dramatically reduced when the strength of the concrete was increased. Pre-tension increases the shear resistance of the system. The profile of a rock bolt affects the shear performance and load transfer under axial and lateral loads.

The 3-D FE code, ANSYS V. 9.1 was used. To investigate the load transfer and interaction between bolt, grout, and concrete under non-linear conditions, special element types for the materials and contact interfaces were introduced. The stress and strain built up along the materials under axial and lateral loads was examined.

A laboratory study on shearing at the bolt, resin interface of fully grouted bolts was extended to field studies in Appin and Metropolitan Collieries in the Southern Coalfields of the Sydney Basin, NSW, Australia. Twelve instrumented bolts were installed at both mines. Both installation sites were in the heading of a retreating long wall mine. The field investigation revealed that the load transfer on a bolt is affected by horizontal in-situ stresses and profile of the bolt surface. It showed that bolt with higher ribs and wider spacing offered greater shear resistance at the bolt - resin interface, which agreed with the laboratory results.
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LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

\( \sigma_p \) Horizontal stress;
\( \sigma_b \) Bolt axial stress
\( \beta \) Angle between the normal to the fracture plane and the horizontal plane
\( \varphi \) Friction angle of the fracture
\( \tau_s \) Shear stress in resin annulus
\( \varepsilon_x \) Extension in the bolt
\( a \) Radius of bolt
\( x \) Distance along the length of bolt starting at free end of grout
\( R \) Radius of the borehole
\( G_g \) Shear modulus of grout
\( k_i \) Long term shear deformation modulus of rock
\( w(x) \) Expression for bolt displacement
\( u(x) \) Bolt displacement due to strain
\( u \) Neutral point displacement
\( P \) Radial distance to the neutral point
\( r_o \) Tunnel radius
\( A_b \) Bolt cross-section area
\( D_b \) Bolt diameter
\( \sigma_b \) Applied stress
\( \sigma \) Stress in the bolt at a distance \( y_d \)
\( \sigma_0 \) Stress at the point of applied force
\( \alpha \) Decay coefficient 1/in which depends on the stiffness of the system
\( y_d \) Distance along the bolt from the applied load
\( p_a \) Load applied at the bolthead
\( E_b \) Modulus of the bolt
\( \Delta l \) The deflection at the head of the bolt
i  Apparent dilation angle
\( \rho_i \)  Reduction coefficient of dilation angle
\( \sigma_{\text{lim}} \)  Limiting stress
\( \varphi_0 \)  Friction angle between the bolt and grout
\( P_p \)  Ultimate pull out load
\( l_a \)  Anchorage length
\( s \)  Slip between anchorage and grout
\( k, t \)  Coefficients which depend on the type of anchor, grout and stages of shear.
\( T \)  Shear force carried by bolt
\( \sigma_c \)  Uniaxial compressive strength of rock
\( T_{re} \)  The reinforcement effect in shear resistance due to bolting
\( A_j \)  Joint area
\( \sigma_n \)  Normal stress on joint
\( p_u \)  The bearing capacity of the grout or rock
\( t \)  Axial bolt load in the position of the plastic moment,
\( t_y \)  Axial load corresponding to the yield strength
\( \theta \)  The angle between the normal vector to the joint and the bolt,
\( \varphi_b \)  The basic joint friction angle
\( t_r \)  Load induced in the bolt
\( Q \)  Force due to dowel effect
\( \alpha_j \)  Angle between the joint and the dowel axis
\( F \)  Global reinforced joint resistance
\( Q_{oe} \)  Shear force acting at point O at the yield stress of the bolt
\( N_{oe} \)  Axial force acting at shear plane at the yield stress of the bolt
\( \sigma_{el} \)  Yield stress of the bolt
\( Q_{of} \)  Shear force acting at shear plane at failure of the bolt
\( N_{of} \)  Axial force acting at shear plane at failure of the bolt
\( \sigma_{ec} \)  Axial failure stress of the bolt
\( l_r \)  Hinge length
$E_c$ Concrete Modulus of elasticity

$\rho$ Concrete density

$f_{cm}$ Mean value of the concrete compressive strength at the relevant age

$\tau_p$ Peak shear stress,

$T_{\text{max}}$ The peak shear load at bolt-grout interface

$a_r$ Height of rib

$D_s$ Rib spacing

$U$ The shear displacement at each step of loading

$\sigma_{aij}$ Change in axial stress between two adjacent gauges

$\varepsilon_{ai}$ Axial strain at gauge 1

$\varepsilon_{aj}$ Axial strain at gauge 2

$\tau_y$ Grout shear strength

$\tau_{\text{res}}$ Residual bond strength

$\mu$ Friction coefficient between bolt-grout interface

$N_c$ Confining load

$c$ Cohesion between block joints

$n$ Normal force

$f(t)$ Bolt contribution

$T_v$ Shear load

$T_i$ Joint contribution

$F_{\text{max}}$ Maximum tensile strength of the bolt

$f(u)$ Dimensionless factor in terms of shear displacement,

$u_b$ Shear displacement

$T_h$ Yield point at shear load-displacement curve (bolt contribution)

$f_{\text{ry}}$ Pretension load

$u_y$ Joint movement, which is usually twice bolt deflection

$D_h$ Hole diameter

$Pr$ Pretension load
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$E_g$</td>
<td>Modulus of elasticity of the grout</td>
</tr>
<tr>
<td>$I$</td>
<td>Bolt moment of inertia</td>
</tr>
<tr>
<td>$K_s$</td>
<td>Bolt stiffness</td>
</tr>
<tr>
<td>$t_s$</td>
<td>Resin thickness</td>
</tr>
<tr>
<td>$\sigma_t$</td>
<td>Tensile stress in bolt</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Shear strain at any point in the interface</td>
</tr>
<tr>
<td>$\gamma_r$</td>
<td>Shear strain at residual shear strength</td>
</tr>
<tr>
<td>$\gamma_{\text{max}}$</td>
<td>Shear strain at peak shear strength</td>
</tr>
<tr>
<td>$\tau_r$</td>
<td>Residual shear strength of the interface</td>
</tr>
<tr>
<td>$\tau_{\text{max}}$</td>
<td>Peak shear strength of interface</td>
</tr>
<tr>
<td>$T_{ub}$</td>
<td>Actual bond stress in the grout</td>
</tr>
<tr>
<td>$T_y$</td>
<td>Yield stress of the grout in shear</td>
</tr>
<tr>
<td>$f$</td>
<td>Axial force in the bolt</td>
</tr>
<tr>
<td>$A$</td>
<td>Contact interface area</td>
</tr>
<tr>
<td>$y$</td>
<td>Deflection of the bolt</td>
</tr>
<tr>
<td>$K_m$</td>
<td>Stiffness of subgrade reaction</td>
</tr>
<tr>
<td>$E_m$</td>
<td>Modulus of subgrade</td>
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<tr>
<td>$N_{cf}$</td>
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<tr>
<td>$N_p$</td>
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<td>$Q_p$</td>
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<tr>
<td>$p_u$</td>
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</tr>
</tbody>
</table>
\( K_m \)  
Lateral stiffness,

\( u_y \)  
Lateral deformation

\( S \)  
Section modulus.

\( \sigma_{\text{max}} \)  
Normal stress acting on the bolt

\( E_i \)  
Modulus of elasticity of intact subgrade

\( Q_{cf} \)  
Shear force

\( L_{cp} \)  
Reaction length

\( F_x \)  
Shear load due to bond per unit length in elastic behaviour

\( K \)  
Shear stiffness of interfaces (N/mm^2)

\( u_r \)  
Rock displacement along the bolt

\( u_{ro} \)  
Total deformation of the excavation wall

\( \nu \)  
Poison ration of rock mass

\( Po \)  
In situ stress

\( r_e \)  
The boundary between the zone of plastic and elastic

\( E_{\text{as}} \)  
The mean actual strain measured by an active gauge,

\( V_d \)  
The change in SBM reading, and

\( G \)  
The gauge factor of the strain gauge

\( \Delta \tau \)  
Average shear stress at the bolt-resin interface,

\( F_1 \)  
Axial force acting in the bolt at strain gauge position 1

\( F_2 \)  
Axial force acting in the bolt at strain gauge position 2

\( l \)  
Distance between strain gauge position 1 and strain gauge position 2.

ABREVIATIONS

\( JRC \)  
Joint roughness coefficient

\( JCS \)  
Joint compressive strength