THE NEW APPROCH DETERMINIG THE LOAD TRANSFER MECHANISM IN FULLY GRAOUTED BOLTS

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IN THE NAME OF GOD

THE MOST GRACIOUS, THE MOST MERCIFUL

This thesis is dedicated to my To my wife, ***Zahra Jamali,*** for her support, understanding and sacrifice over theses 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.

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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

The following publications are the result of this thesis project:

1- **Jalalifar.H**, Naj.A, Hadi. M. (2004). Modelling of sheared behaviour bolts across joints. *Proceedings of 5th Underground Coal Operators, Conference,* convened by the Illawarra Branch of the Australian Institute of Mining and Metallurgy, Univ. of Wollongong. Wollongong, Australia. Pp. 225-232.

2- **Jalalifar,H**. Naj. A, Hadi. M. (2004). Shear behaviour of bolts in joints with increased confining pressure conditions. *Proceedings of the International Mining Symposium*, 2-3 June, Aacken, Germany. Pp. 211-226.

3- Naj, A. **Jalalifar. H**, Hadi. M. (2004). The effect of rock strength on shear behaviour of fully grouted bolts. *Proceedings of the Fifth International Symposium on ground support in Mining and Underground Construction*. 28-30 September, Perth Australia,. pp. 243-251.

4- **Jalalifar, H**. N Aziz, M.N.S.Hadi, (2004). Non-linear analysis of bolt-grout-concrete interaction in reinforced shear joint. *International Journal of Mines, Metals &Fuels*. Vol 52- No 9&10- pp.208-216.

5- **Jalalifar. H**, Naj. A, Hadi, M. (2004). Effective factors on reinforced shear joints. *Proceedings of the 2nd Iranian rock mechanics conference*. Tarbiat Moddarres University. Tehran, Iran. pp. 475-485.(Farsi).

6- **Jalalifar. H**, Naj. A. (2005). Load transfer in bolt bending. *Proceedings of the 1st* Iranian mining conference. Tarbiat Moddarres University. Tehran, Iran 1765-1775.

7- Jalalifar. H, Naj. A, Hadi.M, (2005). Modelling of Shearing Characteristics of reinforced concrete. *Int. Symp of Global Construction: Ultimate Concrete Opportunities*. UK. 543-556.

8- Naj. A, **Jalalifar.H**, Hadi.M, (2005). The effect of resin thickness on bolt-grout-concrete interaction in shear. Proceeding of the *6th Underground coal operators' conference*. Pp. 3-10.

9- Seedaman.R, **Jalalifar.H**, Naj.A.(2005). Chain pillar design, can we? *Proceedings of the* 6th *Underground coal operators' conference*. Brisbane, Queensland University. Australia. Pp. 59-62.

10- Naj.A, **Jalalifar.H**, Hadi.M. (2005). Resin thickness effect on load transfer. *Proceedings of the 19th International mining Congress and fair of Turkey*. Pp. 65-72.

11- **Jalalifar.H**, Naj.A, Hadi.M. (2005). 3D behaviour of reinforced rock joints. *Proceedings of the 20th World Mining Congress and Expo*. Tehran. Iran. Pp. 629-639.

12- Naj.A, **Jalalifar.H**. (2005). Rock bolt Load transfer capacity Assessment methodology. *24th Int. Symposium on ground control in mining*. West Virginia, Morgantown. Pp. 285-293.

13- **Jalalifar.H**, Naj. A, Hadi.M. (2005). The effect of bolt profile, rock strength and pretension load on bending behavior of fully grouted bolts. *International Journal of Geotechnical and geological engineering*.

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ABSTRACT

Rock bolts are used both as temporary and permeant support systems in tunnelling and mining operations. In surface mining they are used for slope stability operations and in underground working in a variety of purposes, such as roadway development, shaft sinking and stoping operations. Rock bolting technology has rapidly advanced and developed during the past three decades due to better understanding of load transfer mechanisms and advances made in the bolt system technology. In discontinuous rocks, rock bolts are basically installed to prevent the movement of discontinuity planes, depending upon the direction of installation and the nature of discontinuity surface. Rock bolting can strengthen the tension and shear properties of the rock mass.

Nowadays, the application of rock bolts for ground reinforcement and stabilisation is of worldwide scale. The effectiveness of bolt / rock influenced by the rock type, strata lithology and encapsulation characteristics. Thus, the bolt / rock interaction, particularly in the vicinity of the shear joints, and the mechanism of the bolt behaviour in different surrounding conditions require a continuum evaluation and research. Work provides an in - depth study of the bolt / grout / concrete interaction during the axial and lateral loading conditions.

The programme of research undertaken is in three parts in order to achieve the objectives of better understanding of load transfer characterisation, and bolt shearing

across joint and planes. Accordingly, series of experimental study and field work were undertaken. A numerical technique was developed to obtain the stress, strain developed along the bolt and surrounding materials in both the axial and lateral loading conditions. Finally, a field investigation program was undertaken to obtain the load developed along different bolt profiles, which was another objective of this thesis. The influence of bolt profile study was also investigated by laboratory studies.

Double shearing system (DSS) was used to examine the shearing of bolts. Testing was undertaken in different concrete strength, 20, 40 and 100 MPa to simulate different rock strengths. Only three bolt types were used of axial loading tests. In both axial and lateral loading conditions, different resin thickness was evaluated. Tests subjected to lateral loading were undertaken in different pretension loads, 0, 5, 10, 20, 50 and 80 kN. From the tests results it was found that the concrete strength significantly affects the bolt joint contribution. Also shear displacement was found dramatically reduce with the increase in the concrete strength. Pretensioning enhances the system shear resistance. Bolt profile plays great role on the bolt shear performance and load transfer mechanism in both axial and lateral loading conditions.

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

The laboratory study on the shear behaviour of the bolt/resin interface of the fully grouted bolts was extended to the field studies in two local coal mines, of Appin and Metropolitan Collieries in the Southern Colfield of Sydney Basin, NSW, Australia. A total of 18 instrumented bolts were installed at both mines. Both installation sites were in the heading of a retreating longwall mines. The field investigation in both mines revealed that, the load transfer on the bolt is affected by the horizontal in situ stresses and bolt profile surface. It showed that bolt surface with higher ribs and wider spacing configurations offered greater shear resistance at the bolt/resin interface, and this was in agreement with the laboratory results.

TABLE OF CONTENTS

TITLE

CHAPTERS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

σ_p	Horizontal stress;
β □	Angle between the normal to the fracture plane and the horizontal plane
φ	Friction angle of the fracture
τ_x	Shear stress in resin annulus
ξ_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
Gg	Shear modulus of grout
k_l	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
σ_b	Applied stress
σ	Stress in the bolt at a distance y_d
σ_0	Stress at the point of applied force
α	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
Δl	The deflection at the head of the bolt

i	Apparent dilation angle
β_0	Reduction coefficient of dilation angle
$\sigma_{\lim}$	Limiting stress
φ_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
σ_c	Uniaxial compressive strength of rock
T_{re}	The reinforcement effect in shear resistance due to bolting
A_j	Joint area
σ_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
θ	The angle between the normal vector to the joint and the bolt,
φ_b	The basic joint friction angle
t_r	Load induced in the bolt
Q	Force due to dowel effect
α_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
σ_{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
σ_{ec}	Failure stress of the bolt
l_e	Hinge length

E_c	Concrete Modulus of elasticity
ρ	Concrete density
f_{cm}	Mean value of the concrete compressive strength at the relevant age
τ_p	Peak shear stress,
$T_{\max}$	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
σ_{aij}	Change in axial stress between two adjacent gauges
ε_{ai}	Axial strain at gauge 1
ε_{aj}	Axial strain at gauge 2
τ_y	Grout shear strength
τ_{res}	Residual bond strength
μ	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_t	Joint contribution
$F_{\max}$	Maximum tensile strength of the bolt
$f(u)$	Dimensionless factor in terms of shear displacement,
u_b	Shear displacement
T_b	Yield point at shear load- displacement curve (bolt contribution)
f_{ty}	Pretension load
u_y	Joint movement, which is usually twice bolt deflection
D_h	Hole diameter
Pr	Pretension load

E_g	Modulus of elasticity of the grout
I	Bolt moment of inertia
K_s	Bolt stiffness
t_a	Resin thickness
σ_t	Tensile stress in bolt
γ	Shear strain at any point in the interface
γ_r	Shear strain at residual shear strength
$\gamma_{\max}$	Shear strain at peak shear strength
τ_r	Residual shear strength of the interface
$\tau_{\max}$	Peak shear strength of interface
T_{ab}	Actual bond stress in the grout
T_y	Yield stress of the grout in shear
f	Axial force in the bolt
A	Contact interface area
y	Deflection of the bolt
K_m	Stiffness of subgrade reaction
E_m	Modulus of subgrade
N_{cf}	Normal force at yield limit
N_p	Normal force at failure
Q_p	Shear force at failure
M_D	Bending moment at yield limit
M_p	Bending moment at plastic limit
N_D	Axial force in hinge point
σ_f	Failure stress at bolt material
Q_e	Shear force acting at point C in elastic limit
β_j	Joint slope
p_r	Pretensioning
K_i	Interface load transfer factor
p_u	Support reaction

K_m	Lateral stiffness,
u_y	Lateral deformation
S	Section modulus.
$\sigma_{\max}$	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
ν	Poison ration of rock mass
Po	In situ stress
r_e	The boundary between the zone of plastic and elastic
E_{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