SIMULATION OF BRITTLE FAILURE IN CRYSTALLINE ROCKS

by

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submitted

in fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

to the

INDIAN INSTIUTUE OF TECHNOLOGY DELHI

HAUZ KHAS, NEW DELHI-110016

March 2007

Dedicated

to

Geoscientists

CERTIFICATE

This is to certify that the thesis entitled, **"Simulation of Brittle Failure in Crystalline Rocks"** being submitted by **Mr. Hossein Noferesti** to the Indian Institute of Technology Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the bonafide research work carried out by him. Mr. Noferesti has worked under my supervision for the submission of this thesis, which to my knowledge has reached the requisite standard.

The thesis or any part thereof has not been presented or submitted to any other University or Institute for any degree or diploma.

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ACKNOWLEDGEMENTS

Praise belongs to the God, the Great, and the Unique who made this work possible from the beginning to the end. However, there is a notable saying that *whoever does not thank the people does not thank the God.* Herewith, I express my sincere gratitude and indebtedness towards my supervisor, Prof. K. Seshagiri Rao, for his inspiring guidance, continuous support, exciting discussions and constant encouragement throughout the research programme. It is because of his great care and exceptional interest that this thesis could be brought about in this form and within expected time.

I am highly indebted to the Government of Islamic Republic of Iran for sponsoring me to pursue my PhD programme at IIT Delhi. I am also grateful to the authorities of Iran Embassy and particularly present and previous secretaries of Science and Education Section, Dr. Ahmad Momeni, Dr. Mohammad Kafi and Dr. Ibrahim Hajizadeh for their constant support and encouragements during this work.

Thanks are due to Dr. G. Benipal for his valuable technical suggestions during the analytical part of the study. Thanks are also due to Dr. A.K. Dawan, Director of Central Soil and Material Research Station (CSMRS), Ministry of Water Resources, Government of India and Mr. M. Gupta and Mrs. R. Chitra, Senior Research Officers at CSMRS for providing UDEC software and necessary help during numerical modelling part of this research work.

The assistance rendered by Mr. D. S. Gusain, Mr. Kailash Kumar, Mr. D. Biswas and other supporting staff members of Rock Mechanics, Soil Mechanics, Engineering Geology, XRD and SEM Laboratories is appreciated. Thanks are also due to the staff of Civil Engineering workshop and I.D.D. Centre, IIT Delhi for their cooperation in fabrication of special split moulds.

I would like to express my gratitude towards my fellow research scholars particularly, Mr. Mahmoud Reza Mollaie Nia, R.P Tiwari, Neelima Satyam, Ganesh W. Rathod for their encouragements and sharing the treasured moments of discussion.

At last, I am forever indebted to all members of my family for the pains and suffering they have undergone during this research work. Without their kind-hearted cooperation and help this work could not come to the completion.

Date: 12.03.2007

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(2003CEZ0016)

ABSTRACT

Brittle failure is the primary type of failure occurring in rocks involving Civil and Mining Engineering works. In spite of significant developments in rock mechanics in the recent past, sufficient insight into the real mechanism of brittle failure has not been achieved.

Crystalline rocks are a major group of rocks, including most igneous and metamorphic rocks, whose structure is made of mineral crystals interlocked together. Microscopic observations have proved that no chemical bond exists between crystals and that the overall strength of these rocks is owing to their very intricate and three-dimensional interlocking only. Considering the fact that most of the crystalline rocks are igneous, they are studied further in detail in this work.

In almost all igneous rocks, five major minerals i.e. *quartz, feldspar, mica, pyroxene and olivine* are present; the percentage of other minerals is negligible. Attempts are made in the present study to simulate these minerals through suitable model materials. The ratios between uniaxial compressive strength, σ_c and elastic modulus, E of minerals are considered as the simulation parameters. Having Poisson's ratio (ν) from Belikov (1967) and static bulk modulus (k) of minerals from Knittle (1995), the E values are estimated using the following relation.

$$E = 3k(1-2\nu) \tag{3.1}$$

To calculate σ_c values the indirect method suggested by Dorner and Stöckhert (2004) is adopted. Having hardness numbers of minerals, H, through Bruland (1998), σ_c values for five major minerals are calculated using the following formulae:

$$H_v = \frac{2}{3}\left\{2 + \ln\left[\frac{E\tan\beta_v}{6\sigma_c(1-\nu)} + \frac{2(1-2\nu)}{3(1-\nu)}\right]\right\}\sigma_c \tag{3.2}$$

where, β_v is the angle between the sample surface and the indenter facet.

To find out a suitable set of compositions capable of simulating the same ratios of strength and modulus as exist in five major minerals of igneous rocks, a variety of materials are considered. After a wide-ranging review and testing of natural and industrial materials, four varieties of dental plaster are selected as model materials. Subsequent to final selection of four types of model material, a detailed characterisation program is conducted to find out their exact physical and mechanical properties for future use in the main experimental program and analysis thereupon. Specific gravity, SG, dry density, γ_d, and porosity, n, as physical properties and uniaxial compressive strength, σ_c, Brazilian strength, σ_t, elastic modulus, E, Poisson's ratio, v, cohesion, c, and internal friction angle, φ^o, as mechanical properties are determined for all model materials with respect to the procedures suggested by ISRM.

To understand the failure mechanism in a heterogeneous medium a careful testing program is conducted. In total 66 specimens were tested in biaxial loading condition and in each test recognizable incidents during loading process are recorded. To perform biaxial testing on specimens, the 1000 kN True Triaxial System (TTS) developed in IIT Delhi by Rao and Tiwari (2003) was used, but in the biaxial frame of that one pair of hydraulic jacks were removed to get sufficient space for online photography during loading process.

Intricate interlocking patterns of crystalline rocks at micro-level are partly simulated into four different simple systematic patterns at macro-level i.e. pattern-A, B, C and D. In all patterns the overall size of specimen is 180 mm × 180 mm × 76 mm. It is made of two layers, each having 38 mm thickness. Each layer is made of dissimilar element sizes interlocked together. The building elements for specimens are prepared by mixing of dental plaster with different distilled water ratios and then pouring the paste into split moulds.

After preparing of each large specimen, the specimen was carefully put in the loading pedestal of the biaxial testing machine. To ensure a friction free loading, 0.5mm tick pairs of Teflon sheets were put on four faces of the specimens. After applying certain amount of lateral load, the axial load was gradually increased up to failure and a little further to ensure that specimen has failed.

Very low strain rate was selected to provide sufficient time to observe and record cracking processes in the sample faces and to make photographic recording. Each test took around 30-45 minutes to complete. Specimens are tested at four lateral pressures i.e. 0.08, 0.15, 0.88, 3.1 MPa, four interlocking patterns and in each pattern with different configuration of element types. In order to assess the effect of elemental size, a separate study is conducted on pattern D specimens at 0.15 and 0.88 MPa. After completion of each test, specimen was carefully removed from the testing pedestal for detailed observation. Induced cracks on all six faces of specimens are mapped on printed sheets.

Results show the pronounced role of tensile microcracks in brittle failure. However, the study emphasises on the critical role of shear movements and cracks as well. A key incident exists that connect the stable phenomenon of tensile cracking to unstable phenomenon of shear cracking and subsequent macroscopic failure. This incident which is buckling of slender columns of material left in between of closely located tensile cracks was observed in this study and a failure criterion is proposed considering the geometry of the problem, and using classical beam and buckling theories:

$$\sigma_c = \frac{10K\sigma_{tm} + 9E_m}{\left(2493.3 + \frac{345.9}{K}\left(\frac{E_m}{\sigma_{tm}}\right)^{1.696}\right)^{0.381} + 10.7} - 142.5\frac{\sigma_{tm}}{E_m} \tag{7.24}$$

where, σ_c is the compressive strength of rock, σ_{tm} is the tensile strength of crystals/ grains, E_m is the elastic modulus of crystals, and K is a factor referring to the interlocking of crystals.

The Eqn. (7.24) is the short form of the originally proposed criterion (Chapter 7) with the following conditions:

$1\ GPa < E_{mi} < 200\ GPa$

$10\ MPa < \sigma_{tmi} < 500\ MPa$

$0.0001 < K < 5$

In order to further study the controlling parameters in the brittle failure, a numerical study is performed based on the Distinct Element Method and using the *UDEC* program by ITASCA Consulting Group, Inc.

Size of elements is one of the factors affecting overall strength of an interlocked system. Model results in this regard closely follow the well-known Hall-Petch Law in the following form:

$$\sigma_c = \sigma_0 + \frac{k_y}{\sqrt{D}} \tag{5.6}$$

where, $\sigma_0 = 9.0\ MPa$, $k_y = 49.7$, and D is the size of elements.

Effect of size heterogeneity that is the difference between two different sizes (ΔD_{av}) present in an interlocked system is studied by *UDEC*. Model results suggest that as size heterogeneity increases, the overall strength of the system decreases but the overall elastic modulus and modulus ratio enhance.

In addition to the size and size heterogeneity factors, role of length ratio *viz.* the ratio of the longest to the shortest dimensions of the elements, L_{max} / L_{min}, is studied using the developed numerical model. Generally, the strength enhances with length ratio following a logarithmic formula as shown below:

$$\sigma_1 = -5.34 \ln (L_{max} / L_{min}) + 23.70 \tag{6.6}$$

Contrary to the strength effect, modulus and modulus ratio of an interlocked system enhance with the length ratio.

To summarise the present study, a biaxial testing program is performed on interlocked heterogeneous specimens of dental plaster as the model material. Failure mechanism is carefully monitored and effects of different geometrical and mechanical parameters are investigated. Afterwards, a numerical modelling study is carried out to further investigate the role of heterogeneity on macroscopic behaviour of brittle materials. Based on the original observations of the failure mechanism a new analytical solution is proposed for the brittle failure of rocks. This new failure criterion is compared with the existing failure criteria and its better capability in prediction of the behaviour of crystalline rocks is established.

CONTENTS

CHAPTER 3 SELECTION AND CHARACTERISATION OF MODEL MATERIAL

CHAPTER 4 EXPERIMENTAL SET-UP