Principal Investigator: Germanovich, Leonid N.
Organization: GA Tech Res Corp - GIT
Title: Three-Dimensional Crack Initiation and Propagation in Transparent Rock-Like Material Subject to Compression

Project Participants

Senior Personnel

Name: Germanovich, Leonid
Worked for more than 160 Hours: Yes
Contribution to Project: Post-doc

Graduate Student

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Cornell University - Endowed
Grant 9625406 was given to Cornell University (PI - Prof. A. Ingraffea) for collaborative research with the PI of this project.

Other Collaborators or Contacts

Activities and Findings

Research and Education Activities:

RESEARCH ACTIVITIES:

The objective of this research was to understand the various mechanisms and phenomena underlying rock fracture in compression through experiments, analytical study, and numerical simulation.

Both uniaxial and biaxial experiments - compression of specimens made of transparent polyester resin and containing single and multiple pre-existing penny-shaped 3-D cracks - were performed. Laser technique was used to prepare cubic specimens with 1, 10, 100, and 1000 laser-induced internal cracks. The objective of this experiment was to determine how different densities of laser-induced cracks affect the resulting fracture patterns and to better understand the effect of mode II and mode III stress intensity factors on crack evolution. Additional experiments have been conducted on Mode III crack segmentation. Mode III causes the crack front to break into segments as it tilts. It is not possible for the entire crack front to tilt, so it breaks into smaller segments, seen as 'petal cracks' or 'factory roof cracks'.

In biaxial compression, single 3-D cracks grew extensively parallel to the load directions and caused splitting. This is very different from what was observed in uniaxial compression where the crack growth was limited and did not cause failure. The presence of the intermediate principal
compressive stress radically changes the mechanism of crack growth in these specimens.

The 3D fracture analysis codes, FRANC3D and BES, developed at Cornell University by the collaborators (Prof. A. Ingraffea and Dr. B. Carter) have been modified during the course of this project. FRANC3D was used to model crack intersections and crack branching associated with mode III segmentation. If during the mixed mode crack growth the Mode III stress intensity factor is significant, the crack front breakup is possible.

Using FRANC2D, we have performed 2D simulations of crack growth under compression. The simulations included a Fairhust-Cook type crack and an inclined sliding crack. Comparing to experimental results, we concluded that 2D simulations are inadequate to capture the real 3D crack growth behavior however.

We have simulated 3D crack growth of a single inclined crack under compression. We have examined the stress field around the single inclined crack as well as the stress field between adjacent inclined cracks. We have varied the spacing between the neighboring inclined cracks to determine how they interact in terms of their stress fields.

We have performed both analytical and numerical studies to determine suitable criteria for growing 3D cracks under compressive stress fields. The Mode III stress intensity factor plays a very important role in mixed mode fracture and this has not been studied in detail in the past. Mixed Mode I and Mode II stress intensity factors cause the crack tips to kink or curve. This is quite easily simulated in FRANC2D. In 3D, the crack front must kink. The crack path in 3D is highly dependent upon the initial crack shape and the mode mixity. In general, a 3D crack front subjected to mixed Mode I and Mode II will also have Mode III stress intensity factors. The Mode III stress intensity factors increase as the crack twists if we do not allow the crack front to breakup at the same time. We have been performing a number of simulations to try to determine the effects of the 3D crack geometry and the effects of the mixed mode stress intensity factors.

We are simulating Mode 3 crack growth numerically using a single 'petal' crack extending from a single part through crack. We are using this configuration to evaluate the stress fields near the splitting crack front. This will allow us to extend our analytical models for the case of several 'petal' cracks on an extending 3D crack front in mixed-mode. We have performed additional 3D simulations looking at the effects of 3D crack geometry and mixed mode loading on crack paths.

Conference and Meeting Presentations


International Conference on Structural Integrity and Fracture, Perth, Australia, September 2002 (Keynote lecture).

International Workshop on Bifurcations and Instabilities in Geomechanics, Collegeville, Minnesota, June 2 - 5, 2002.


The 9th Annual David S. Stipes/Clemson Hydrogeology Symposium, Clemson University, South Carolina, April 12-13, 2001.


Thermo-Hydro-Mechanical Coupling in Fractured Rock, 3rd Euroconference on Rock Physics and Rock Mechanics, Bad Homburg (Bonn), Germany, November 14-18, 2000.


Latest Advances in Hydraulic Fracturing, Workshop in Memory of Jacob Schlyapobersky, Vail, Colorado, June 3-4, 1999.


EDUCATIONAL ACTIVITIES:

This grant supported graduate students and undergraduate students. Two Ph.D. dissertations have been completed with the support of this grant (see the publication section). The results of this research are incorporated into both undergraduate and graduate level courses taught at Georgia Tech. In particular, courses CEE 6751 Physical Properties and Rheology of Rocks, CEE 6451 Rock Mechanics, and CEE 6482 Applied Fracture Mechanics benefited from this research.

Findings:

The experiments indicate that crack growth in brittle materials under compressive loading cannot be accurately modeled in 2D. We used three dimensional crack growth experiments and numerical simulations to identify the stable processes of fracture up to the point of failure. In 2-D, a single flaw can cause failure of the sample, whereas, in 3-D it is usually many flaws that cause failure. New experiments using a brittle transparent material were employed to illustrate the evolution of three dimensional crack growth. Different arrangements of flaws of various sizes produce either an explosion-like or a splitting-fracture type of failure. Two dimensional modeling of crack growth from a single inclined flaw closely matches experimental results, but cannot capture the true nature of three dimensional cracking. Most initial cracks in the material are not aligned with the stress field and are therefore subject to all three modes of stress intensity factors. Mode I causes opening of the crack, mode II cause twisting, and mode III causes tilting of the crack. Mode III cannot be captured in 2D models, but it is an important component of the crack evolution behavior. Mode III produces a tilting of the crack front which leads to the crack front breaking into pieces. The breakup of the crack front is dependent upon the material, loading and geometry. Simulation of the growth of a crack is very complex if we try to model all the details. The interaction of multiple growing cracks is much more complex. Crack-surface interaction further complicates the fracture mechanisms. To make the problem tractable we thoroughly studied elements of this complicated process.

A simple model of 3-D wing crack growing in compression from a disk-like initial crack has been developed. At the initial stage of growth the wings are modeled in vertical cross sections as 2-D cracks wedged at one end by the displacement produced by the contact area (former initial crack). This displacement is evaluated by replacing the contact area with a Mode III crack of the length equal to the wing width. It is shown that the contribution of the contact area into the crack-generated stress field is at least comparable with that of the wings. To analyze the possibility of extensive growth, the crack is modeled by a vertical disk-like crack where the opening (wedging) action of the sliding contact area is
simulated by the uniform pressure distributed over a central circular area of the same radius as the initial crack. It is shown that the continuation of the wing crack growth in such a mode would require a considerable increase in the load, which probably explains why extensive (few times the initial flaw size) growth of a single 3-D crack has never been observed in experiments. The mechanism of producing really large tensile fractures by pairs of 3-D wing cracks has also been investigated. On the basis of the dipole (far field) asymptotics, it has been shown that it is the total tensile stresses induced by the wing cracks in the direction perpendicular to the compression direction that could be responsible for the appearance of the tensile fractures. The magnitude of these stresses is affected by the crack locations and spacings.

We employed the beam and dipole asymptotic techniques for modeling interaction of a crack with parallel free boundaries. Two configurations are considered: (1) a crack in a half-plane and (2) a crack in the centre of an infinite strip. Both, the stress intensity factors and the areas of the crack opening are calculated. For the crack situated close to the boundary, the part of the material between the crack and the boundary is represented by a beam (plate in plane-strain). This allows calculating the area of the crack opening. The stress intensity factors are calculated by matching the beam approximation with Zlatin and Kharchukov's (1986) solution for a semi-infinite crack parallel to the boundary of a half-plane or with Salganik and Birtov's (1965) solution for a central semi-infinite crack in a strip. It has been shown that this asymptotic method allows obtaining two leading terms for the SIFs and the crack opening area. When the distance between the crack and the free surface is large, the problem is treated in the far field approximation. This, dipole asymptotic method allows finding the loading asymptotic terms responsible for the crack-boundary interaction. For intermediate distances between the crack and the boundary, simple interpolating formulas are derived. Particular examples of cracks loaded by pair of concentrated forces and for uniform loading are considered. The obtained results are compared with available numerical solutions.

We used the above findings to model fracture processes around underground excavations. When drilling circular openings (e.g., tunnels or boreholes) in brittle rock, the in-situ stress conditions are often such that failure is initiated at or near the wall of the opening. We considered a mechanism of open hole instability based on growth of pre-existing micro-fractures in the direction of greatest compression. The major factor enabling the pre-existing 3-D cracks to propagate extensively is the presence of the intermediate principal compression near the opening wall (in the direction of the opening axis). The unstable growth of wing cracks leads to separating thin rock plates from the bulk of the rock mass followed by their buckling, separation, and exposure of the fresh surface. Then this process of rock surface spalling repeats itself eventually changing the shape of the hole. As the opening develops, its shape becomes elongated which, in turn, can affect this mechanism primarily through continuous changes in the stress concentrations around the opening. The role cause of the unstable phase of crack propagation is the crack-boundary interaction. The breakouts develop if the unstable crack growth proceeds at least up to the buckling size. Otherwise, the opening shape gets stabilized. This approach also allows for determining the final stable cross-section as well as its relationship to the applied boundary stresses. The extent of failure is primarily determined by the initial parameters of crack distribution.

Another application of obtained results is rock fracture caused by concentrated energy fluxes. We developed a micro-mechanical model of massive thermal spalling which results from the localized heating of the surface of a brittle, low porous material (such as many types of ceramic, concrete, glass, and rock). While macroscopically the spalling amounts to an advance of the free surface into the material, microscopically thermal spalling can be attributed to successive growth of inherent cracks in the surface layer subjected to high thermoelastic compression. An inclined sub-surface initial flaw ejects branches (wings) which continue to open and propagate as tensile fractures parallel to the direction of compression, that is, parallel to the surface. If the crack is small and suitably far from the boundaries, it grows stably; when the crack size becomes comparable to the distance between the crack and the free surface, the crack-surface interaction takes over leading to unstable crack propagation. The separated layer eventually buckles resulting in the separation of the spall.

Finally, we used the obtained results to analyze the engineering concept of strength criteria from fracture mechanics point of view. Based on the catastrophe (singularity) theory, it has been shown that the same combination of the principal stresses can either result, or not, in material failure, depending upon the loading history. This implies that the classical concept may not be adequate and has to be replaced. Accordingly, two strength criteria characterizing the possibility and probability of a failure have been suggested.

Training and Development:
The graduate students, Dmitriy Astakhov and Rajesh Champura, graduated with Ph.D. degrees with the support from this project. In addition, they both served as Graduate Research Assistants for course CEE 6451 Rock Mechanics. This course incorporated results from their research.

Outreach Activities:

**Journal Publications**


Germanovich, L. N., and Astakhov, D. K., "Stress dependent permeability and fluid flow through parallel joints", *Journal of Geophysical*


Books or Other One-time Publications


Editors): Cherepanov, G. P.
Collection: Fracture: A topical Encyclopedia of Current Knowledge Dedicated to Alan Arnold Griffith

Bibliography: Georgia Tech, Atlanta, Ph.D. Dissertation

Bibliography: Georgia Tech, Atlanta, Ph.D. Dissertation

Web/Internet Site

URL(s):
http://www.ce.gatech.edu/~geosys/geomat/
Description:

Other Specific Products

Contributions
Contributions within Discipline:
This project has led to the development of sophisticated fracture analysis simulation software for modeling 3D crack growth in brittle materials under compressive loading. This software was developed by our collaborators at Cornell University. The experiments performed at Georgia Tech have helped us formulate ideas on how arbitrary 3D cracks evolve and interact under compressive loading. This has guided the development of the software which otherwise would not be possible. This is important for many applications, including hydraulic fracturing, core disking, borehole and tunnel stability, and rock cutting for example.

Contributions to Other Disciplines:
The developed understanding of fracture growth in compression as part of this project can be and is used to study fracture evolution in a wide variety of materials and structures. The experimental and analytical studies performed at Georgia Tech in combination with numerical experiments conducted at Cornell will help us to formulate theories to guide the simulation of mixed mode crack growth, specifically to study in greater detail the effect of Mode III on crack path and stability. This is a critical issue for such disciplines as mechanical and aerospace engineering, petroleum engineering, geology and geophysics.

Contributions to Human Resource Development:

Contributions to Resources for Research and Education:
We are providing our results on our web site for other researchers to use at: http://www.ce.gatech.edu/~geosys/geomat/

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:
Activities and Findings; Any Outreach Activities
Any Product
Contributions: To Any Human Resource Development
Contributions: To Any Beyond Science and Engineering