On the mechanical behavior of granite: Constitutive modeling and application to percussive drilling

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PhD is tough, as though as Rock!

Mahdi
Abstract
The mechanical behavior and fragmentation response of rock materials is investigated in this work. In particular, Bohus granite is selected with application to percussive drilling. It is well known that rock behaves totally different in compression and tension and dynamic loading conditions and high strain rates under the percussive drilling process makes the material behavior even more complicated. The KST-DFH material model is shown in this work to be appropriate in order to constitutively describe granite at dynamic fragmentation. It consists of a plasticity model in compression and a damage model in tension. The yield surface locus is a quadratic function of the mean pressure in the principal stress space and the damage model is anisotropic.

Several experiments are performed in order to define the mechanical behavior and dynamic response of granite and calibrate the KST-DFH model parameters for this material. The material model is implemented as in a commercial finite element program and validated based on dynamic tests such as Edge-on Impact (EOI) and spalling test using Hopkinson bar. The numerical tool is then used to model the rock response during the percussive drilling process. In doing so, only one spherical tool button and just the first impact are considered for simplicity. The anticipated fracture mechanism in percussive drilling is captured and the penetration stiffness obtained is in agreement with practical drilling experiments.

In paper A, the experimental work is described and the granite mechanical response is explained. In particular, the influence from pre-existing cracks and defects is examined in great detail. In paper B, the experimental results are used to calibrate the material model parameters. The numerical tool discussed earlier is employed to investigate the rock fracture mechanisms at percussive drilling. In paper C, the effect of pre-existing, or structural, cracks on dynamic fragmentation of granite is investigated in detail. These cracks may be the result from former impact of the drill bit, or by means of other unconventional methods such as microwave and laser that are used to increase the effectiveness of the percussive drilling process. In paper D, the dynamic tensile behavior of granite samples is investigated. Spalling tests using a Hopkinson bar are performed and a strain rate of order $10^2$ 1/s is obtained. This experimental technique involves the same order of strain rate as present in rock materials during percussive drilling. A dynamic tensile strength of 18.9 MPa is obtained at a strain rate of 70 1/s. This is more than twice the tensile strength of the specimen (with the same size) at quasi-static conditions, which is 8 MPa.
Sammanfattning


Ett antal olika experiment har genomförts för att kunna förstå det mekaniska beteendet hos granit och dessutom för att bestämma parametrarna i KST-DFH-modellen. Materialmodellen har implementerats i ett kommersiellt FEM-program och de framtagna numeriska resultaten har jämförts med motsvarande experimentella resultat från det så kallade EOI-testet (EOI-testet är ett dynamiskt experiment där en aluminiumprojektil skjuts mot kanten av en granitplatta). Denna jämförelse visade på en acceptabel överensstämmelse mellan experiment och simulerings, och det framtagna numeriska verktyget användes sedan för att bland annat analysera sprickinitiering och spricktillväxt under det första inledande skedet av borprocessen.

I rapport A beskrivs huvudparten av det experimentella arbetet (förutom EOI-experimenten) och det mekaniska beteendet hos granit diskuteras i detalj. I rapport B används det ovan diskuterade numeriska verktyget för att analysera EOI-testet och bergborning. I rapport C undersöks i detalj effekten av redan existerande eller strukturella sprickor, sprickor som finns i materialet före belastning, på den dynamiska fragmenteringsprocessen. Dessa sprickor kan vara ett resultat av tidigare påverkan från borning eller också medvetet införda, för att underlätta borningen, med hjälp av metoder som mikrovågor och laser. I rapport D undersökes granits dynamiska draghållfasthet. Splittringstester (Hopkinson) utfördes och töjningshastigheter av storleksordningen $10^{2}$ 1/s uppnåddes. Denna experimentella teknik användes eftersom den ger ungefär samma töjningshastigheter som vid borning. En dynamisk draghållfasthet på 18.9 MPa erhölls vid en töjningshastighet på 70 1/s. Detta värde är mer än dubbelt så stort som motsvarande kvasi-statiska värde (8 MPa).
Preface

The work presented in this doctoral thesis was carried out at the Department of Solid Mechanics, KTH Royal Institute of Technology, Stockholm between November 2010 and March 2015. The work is fully funded by Atlas Copco which is gratefully acknowledged.

I would like to express my sincere gratitude to my supervisor Prof. Per-Lennart Larsson for an excellent supervision, guidance and encouragement. I would also like to thank my supervisor at Atlas Copco Dr. Kenneth Weddfelt. We have had many fruitful discussions and I have learned a lot from you.

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Last but definitely not least, I would like to thank my wife Maryam for her understanding and love during the past years. Her support and encouragement was in the end what made this work possible. My parents receive my deepest gratitude and love for their dedication and support in my life. Also my friends for always being there for me. With your help and support, a lot of things became possible.

Stockholm, Jan 2015

Mahdi Saadati
List of appended papers

**Paper A:** On the mechanical behavior of granite material with particular emphasis on the influence from pre-existing cracks and defects

**Paper B:** Granite rock fragmentation at percussive drilling - experimental and numerical investigation

**Paper C:** A numerical study of the influence from pre-existing cracks on granite rock fragmentation at percussive drilling

**Paper D:** On the tensile strength of granite at high strain-rates considering the influence from pre-existing cracks
In addition to the appended paper, the work has resulted in the following publications and presentations:\(^1\):

**Granite rock fragmentation at percussive drilling**

**Granite rock fragmentation at percussive drilling**

**Granite rock fragmentation at percussive drilling**

**Effect of pre-existing cracks on the fracture pattern of granite**

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\(^1\)A = Abstract, Ea = Extended abstract, Op = Oral Presentation, Pp = Proceeding paper
Contribution to the papers

The author’s contributions to the appended papers are as follows:

**Paper A**: Principal author. Experiments are performed together with P. Forquin. Contributed to the theoretical analysis. Wrote the paper together with P.L. Larsson.

**Paper B**: Principal author. Experiments are performed together with P. Forquin. Contributed to the theoretical analysis. Wrote the paper together with P.L. Larsson.

**Paper C**: Principal author. Experiments are performed together with P. Forquin. Contributed to the theoretical analysis. Wrote the paper together with P.L. Larsson.

**Paper D**: Principal author. Experiments are performed together with P. Forquin. Contributed to the theoretical analysis. Wrote the paper together with P.L. Larsson.
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Introduction

The work in this thesis concerns the constitutive modeling of rock fracture due to dynamic loading with particular emphasis to percussive drilling and granite material. Both experimental and theoretical investigations are involved in this work. A brief review of different drilling methods is presented. In this introduction, first a summary of the constitutive model selected for the rock fragmentation at percussive drilling is presented. Then the experimental work to validate and calibrate the model for granite is followed. Special attention is given to the effect from pre-existing structural cracks on the dynamic response of the material. Consequently some additional results from a practical drilling experiment are compared with the numerical ones.

Background

The blocks in Egyptian pyramids were obtained by using hammers and wedges to extract the rock in precise shape and size. From the time of the Roman Empire to the Middle Ages, miners used a “fire setting” system to break rock. Rock was exposed to heat followed by sudden cooling using water. This caused the rock to crack and split along the natural seams. In the seventeenth century a drill forged of wrought iron with an insert bit of tempered steel was employed to drill rock. The charges were then placed in the hole and removed the rock more effectively than those placed on or near it. Steam driven hammers were first introduced in the nineteenth century followed by pneumatic and hydraulic drills. However, these equipments competed with breaking the rock with hand even up to the beginning of twentieth century [1]. The “Swedish method”, a one-man pneumatic rock drill, was introduced in 1940s (see Fig. 1). The combination of a strong but light drill
with a pneumatic pusher leg and tungsten carbide drill bits was an important achievement in this machine [2]. The drilling equipments have been constantly evolved to this day and the drilling efficiency has increased considerably.

![Image of drilling](image.jpg)

Fig. 1 A picture of the “Swedish method”, a one-man pneumatic rock drill [2].

Rock drilling is widely used in many industries from mining, oil and water well drilling to civil engineering, the latest covers a large variety of different applications. There is a number of rock drilling techniques suitable for different needs. The most common methods are:

- **Percussive drilling** of small to medium diameter holes using drill bits, primarily used for blasting.
- **Rotary drilling** of medium to large diameter holes using tricone bits, primarily used for blasting.
- **Rotary drilling** of small diameter holes using diamond inserts, primarily used for core samples.
- **Raise Boring Machine (RBM)** of large diameter holes using disc/bit cutters, typically used for drilling shafts for installation or ventilation.
- **Full face Tunnel Boring Machines (TBM)** using disc/bit cutters for construction of tunnels.
Fig. 2 shows a drill rig Rocket Boomer WL4C30 with a percussive drill machine on top of each boom. It is used for tunnel drifting underground. The principal of percussive drilling is that a piston hits the drill rod at a velocity of about 10 m/s. This creates a compressive stress wave with amplitude of about 200 MPa, which propagates along the drill rod. The stress wave is then transferred into the rock through the tool buttons. Each tool includes around ten button inserts made of hard metal that facilitate the indentation process. Unlike the situation at quasi-static indentation, the stress waves and rapid indentation make percussive drilling a transient dynamic problem with high local strain rates in the rock. The rock is then fragmented and removed by a flushing flow delivered to the drill bit via an axial hole through the drill rod. After each blow of the piston, the drill steel is rotated so that the inserts hit a new part of the rock next time. There are different types of percussive drilling available depending on the applications and conditions. The three most common are DTH (Down The Hole), COPROD and Top Hammer Drilling, see Fig. 3.
In order to have a good understanding of the rock-bit interaction and of the rock fracture mechanism, the rock material constitutive behavior has to be carefully investigated. This possibly leads to a clearer image of rock failure in front of the tool and more effective drilling in the future. Basic defects in rocks are voids, pores and microcracks as well as other related features [3]. Such microstructures produce heterogeneity in the strength and stiffness of the material. It is well known that rock fractures via initiation, growth and coalescence of microcracks, together with sliding between individual grains and the surfaces of the microcracks. Associated with these microscopic mechanisms, rock specimens exhibit non-linear stress-strain behavior [3], [4]. Granite, which is one of the hardest rocks to drill and also widely used as a testing material at the Atlas Copco laboratory, was particularly chosen for study in this work. It has many pre-existing cracks (e.g. [5] and [6]), but the porosity is very low (about 0.2%). Bohus granite that was selected for experimental purpose mainly contains quartz 33 %, plagioclase 33 %, Potassium feldspar 29 % and biotite 6 % (tested by SP, Swedish National Testing and Research Institute). Most rocks show a transition from brittle
to ductile behavior when the confining pressure increases. However, silicate rocks with low porosity are brittle at room temperature over the whole range of normal laboratory confining pressure up to 0.5-1.0 GPa [7]. Some researchers have reported that granite exhibits brittle fracture behavior even at confining pressures up to 3-4 GPa [8].

In addition to the pre-existing cracks that are part of the so called intact rock, there may be additional cracks called structural cracks hereafter. These cracks may result from former impact of the drill bit, or by means of other exotic methods such as microwave and laser that are used to facilitate the percussive drilling process. The influence of these structural cracks on penetration stiffness (the slope of the force-penetration curve of a drill bit) and the fracture pattern in the rock at percussive drilling is investigated in this thesis. Some of the specimens used in the experimental work were exposed to a coarser mechanical loading during the cutting process in order to introduce such structural cracks to the material. CT scan is performed on some of the specimens and a clear difference is captured between the ones with structural cracks and the intact ones. For instance, the tomography results on a specimen of size 20x20x100 mm$^3$ that includes structural cracks is shown for two cross sections in Fig. 4. The size of these cracks is comparable to the size of the specimen. It should be noticed that these cracks are mainly initiated from the surface due to the machining process.
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Constitutive specification

Many studies have been performed during the past years to numerically simulate rock drilling and the fragmentation process in brittle materials. Liu [9] developed a rock and tool interaction code (R-T^{2D}) and studied the fragmentation process in

Fig. 4 CT scan results on two cross sections of the specimen with structural cracks (marked with red arrows).
a quasi-static situation. Wang et al. [10] used an in-house numerical tool to simulate the rock fragmentation process induced by indentation. Both Liu [9] and Wang et al. [10] restrict their analyses to 2D plain strain conditions and do not account for inelastic strains. Furthermore, Saksala [11]–[13] studied the impact indentation of rocks using an isotropic damage concept for tensile loading and a viscoplasticity consistency model for compression loading. This work is performed under 2D plane strain conditions. More recently, the model was extended to deal with 3D simulations [14]. Chiang et al. [15] modeled the impact of the tool to the rock and rock fragmentation in the drilling process using a 3D FE approach. A linear Mohr envelop together with a tension cut off plane is employed as a criterion for the maximum strength of rock. The material behavior is considered linear elastic before reaching final failure. Additionally, Thuro et al. [16] used Particle Flow Code (PFC$^{2D}$) to investigate the crack pattern in drilling and its correlation with existing foliations. PFC$^{2D}$ code is based on discontinuum mechanics approach and is built for 2D simulations.

A typical fracture system in rocks during quasi-static indentation is shown in Fig. 5. Different types of cracks are visible in this picture. Also in the region ahead of the indenter, a crushed zone forms due to high compressive stresses. The way that the side cracks, which are the most preferable type of cracks for removing material, are formed during indentation has been a matter of different opinions. Most researchers believe that these cracks are mainly created during the unloading stage, see e.g. [17]–[19]. This idea is, however, disputed by others who believe that these cracks are formed already during the loading stage [9], [20].
Based on classical contact mechanics and the stress states beneath a spherical indenter, the change from radial tensile stress under purely elastic condition to circumferential tensile stress under elastic-plastic condition is the main reason for the change in the fracture system from ring crack (circular crack around the indenter) with very brittle material to radial crack in semi-brittle material [22], [23]. Porous materials behave differently and in that case crushing is the main response to indentation [24].

One can run a simple quasi static FE analysis of elastic and elastic-plastic indentation to look at the stress states during the loading-unloading stages. A rigid spherical indenter of radius 5 mm is modeled using axisymmetric boundary conditions. An elastic modulus of $E = 200$ GPa together with yield stress $\sigma_y = 600$ MPa and von Mises yield criterion is used and a simple isotropic hardening law is employed for the post yielding behavior. Fig. 6 suggest a radial tensile stress forms at pure elastic conditions leading to the ring cracks; while circumferential tensile stress, present during elastic-plastic conditions, create the radial cracks. Furthermore, the amount of axial stress, which is responsible for creation of the side cracks, becomes considerable later in the elastic-plastic condition, during the unloading stage (see Fig. 7). Although simplified and in absence of an accurate constitutive model for rock material, these results are presented here to give an idea about the indentation fracture system.

Fig. 5 Fracture system at rock indentation [21].

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Fig. 6 FE results for indentation at elastic and elastic-plastic conditions at the end of loading stage.
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Unloading

Elastic

Elastic-Plastic

Γ

σ_{radial}

σ_{circumf.}

σ_{axial}

Fig. 7 FE results for indentation at elastic and elastic-plastic conditions at the end of unloading stage.
One of the aims of this thesis is to provide a constitutive model for rock material that is also applicable at percussive drilling in a dynamic situation. It is well known that rock behaves totally different in compression and tension loading [25]. A damage mechanism with stiffness reduction due to open cracks determines the rock mechanical behavior in tension. In compression, rock has a plasticity-like behavior that depends on the level of hydrostatic pressure. The combination of these two gives a complete picture of the rock behavior when exposed to mechanical loading such as drilling. The KST-DFH model [26]–[29] is composed of a plasticity and damage description that is suitable to describe dynamic fragmentation of brittle materials including rock. It is briefly discussed in the section below.

KST model
The KST model was developed to simulate the compressive behavior of geomaterials and provides a description of both the hydrostatic and the deviatoric part of the behavior [26], [27]. In the deviatoric part, the radius of the yield surface is a quadratic function of the mean pressure in the principal stress space.

\[ \sigma_{eq} = \sqrt{a_0 + a_1 P + a_2 P^2} \]  

(1)

where \( \sigma_{eq} \) is the equivalent (von Mises) stress, \( P \) the hydrostatic stress, \( a_0, a_1 \) and \( a_2 \) are material dependent coefficients. Moreover, it includes a piece-wise linear equation of state linking the volumetric strain to the hydrostatic stress. At the first stage of the hydrostatic loading, a typical brittle material behaves elastically. By increasing the pressure, collapse of pores occurs which is modeled by an irreversible volumetric strain. During the porosity breakage, the bulk modulus decreases noticeably. When the pores are closed, the material exhibits a higher bulk modulus which corresponds to the compacted material [30]. However, the bulk modulus of granite is more or less constant in the whole hydrostatic stress range, because the amount of porosity is very low [31].
The DFH fragmentation model

**Single fragmentation**

Under low-rate loading, the fracture process is generally the consequence of initiation and growth of a single crack. When the stress increases, the weakest defect is activated first. An unstable crack is then initiated and propagates very quickly, leading to failure of the whole structure.

Defects with different sizes are randomly distributed within the material and consequently the failure stress is random. A probabilistic approach may therefore be employed to model this tensile behavior. Using a Poisson point-process framework, the weakest link theory and Weibull model, the failure probability $P_F$ is given by [32], [33]

$$P_F = 1 - \exp\left[-Z_{\text{eff}} \lambda_i(\sigma_F)\right]$$  \hspace{1cm} (2)

where $Z_{\text{eff}}$ is the effective volume [34], and $\lambda_i$ is the initiation density defined by

$$\lambda_i(\sigma_F) = \lambda_0 \left(\frac{\sigma_F}{S_0}\right)^m$$  \hspace{1cm} (3)

where $m$ is the Weibull modulus, $S_0^m / \lambda_0$ is the Weibull scale parameter, and $\sigma_F$ the maximum principal stress in the whole domain.

**Multiple fragmentation**

Under high strain-rate conditions, several cracks are initiated and propagate from the initial defects leading to multiple fragmentation. The different initial defects are assumed to be randomly distributed and activated at a random level of stress. When such a crack is initiated, it propagates at a very high velocity (a portion of the stress wave velocity) and relaxes the stresses in its vicinity. This prevents activation of new defects in an obscured zone centered on this growing crack. At the same time, the stress is increasing in the non-obscured zone and new critical defects are activated leading to new crack openings [28], [29]. Therefore, dynamic fragmentation corresponds to a competition between, on one hand, new critical defects that progressively initiate cracks due to the increase of the stress level and,
on the other hand, obscuration of zones of potential critical defects by cracks created before. The fragmentation process ends when the whole domain is obscured by the opened cracks. The interaction between cracks already created and critical defects of the material is given by the concept of probability of non-obscuration [28]. If the initiation density is a continuous function, the probability of non-obscuration of point $M$ at time $T$ in a domain $\Omega$ is described by [29]

$$P_{no}(M,T) = \exp\left(-\int \frac{\partial \lambda_s(x,t)}{\partial t} dV dt\right)$$  \hspace{1cm} (4)

where the horizon is defined by

$$\text{horizon of } (M,T) = \{x,t\} \in [Z_o(T-t) = S(kC(T-t))^n \cap \Omega]$$  \hspace{1cm} (5)

where $Z_o$ is the obscured zone, $k$ a constant parameter ( $k = 0.38$ may be assumed when the crack length becomes significantly larger than the initial size), $C$ the 1D wave speed, $T$ the current time and $t$ the crack initiation time, $S$ a shape parameter (equal to $4\pi/3$ when the obscuration volume is similar to a sphere in 3D) and $n$ the medium dimension ($n = 3$ in 3D).

The probability of obscuration $P_o = 1 - P_{no} \equiv P_F$ corresponds to the failure probability, expressed by Weibull and can be used as a damage variable in the framework of Continuum Damage Mechanics. One damage variable is defined for each principal direction.

**Experimental work**

In this thesis, experiments were performed on Bohus granite to obtain its mechanical characteristics. KST-DFH model parameters are calibrated for granite based on experiments and it is shown that this model is suitable for the granite behavior at percussive drilling. A brief summary of the work is presented here.

**Direct compression and tension test**

Direct compression and tension tests are performed on the granite material in order to investigate its mechanical properties pertinent to the DFH-KST model. In
the tensile test, the experimental device is composed of two socket joints to provide a uniform stress field while the specimen is loaded by means of two platens in the compression case. Strain gauges and LVDT sensors were used to compare the nominal and local strains.

Fig. 8 Experimental setup for direct compression and tension tests.

Quasi-oedometric compression test
During a quasi-oedometric compression test, a cylindrical specimen tightly enclosed in a confinement cell, is compressed axially. Both axial and radial stresses increase during loading as the material expands in the lateral direction. This gives an indication of the strength of the material at different levels of the hydrostatic pressure. Both the deviatoric and volumetric behavior of the material can be obtained from this test [35], [36].

Fig. 9 Experimental setup for quasi-oedometric compression test.
Flexural test
The tensile failure of brittle materials depends upon the microstructure in terms of flaw density and failure stress distribution. To evaluate the quasi-static strength of the rock and its distribution, 3PB tests are carried out and Weibull statistics and size effect [32]–[34] is used to describe the strength distribution.

![Fig. 10 Experimental setup for flexural test with digital image acquisition.](image1)

Edge-on impact test
In order to validate the numerical model and also to investigate the fracture pattern after impact, Edge-on Impact (EOI) tests [37], [38] with a special sarcophagus configuration [28] are performed. An Aluminum projectile is impacted on the rock material at high velocity. In the experimental set-up, two cylindrical steel confinements are used close to the impact point on both faces of the rock specimen. This helps to increase the level of confining pressure and accordingly the strength of the rock material in order to reduce compressive damage immediately beneath the projectile.

![Fig. 11 Experimental setup for Edge-on impact test.](image2)
Spalling test
The strain rate dependency of the mechanical response in brittle materials has been widely investigated in the literature. A considerable rate dependency is reported especially in the case of the tensile strength [39]–[43]. Spalling tests are performed to investigate the dynamic tensile behavior of Bohus granite. Spalling test with Hopkinson bar is a suitable technique to measure the tensile strength of brittle materials at strain rates between $10^1$ and $10^2$ 1/s [40], [42], [44]. The main idea in this test is that the impact of the projectile induces a compressive wave that propagates through the bar and is mainly transferred to the specimen. This wave is reflected as a tensile wave from the free surface of the specimen that leads to damage in the material. The results from this test are used to validate the DFH model output for tensile strength of the material at high loading rates [45].

Fig. 12 Experimental setup for spalling test.

Numerical modeling
The numerical simulation is carried through using the KST-DFH material model implemented as a VUMAT subroutine in Abaqus explicit as a commercial FE modeling software. This numerical tool is used for simulation of dynamic experiments on granite, such as the EOI and spalling tests that are performed in this work. Pre-existing cracks are introduced in the model by considering sets of elements with negligible tensile strength. They lead to immediate failure when loaded in tension but can still carry compressive loads as crack closure occurs due to compressive stresses. The numerical tool is also used to simulate percussive
drilling. To simplify that problem, only one hemispherical button from the bit and only the first impact is considered [45]–[47].

In an attempt to compare the numerical results to real drilling results, the results from a special drilling experiment with only one spherical button is used and the incident and reflected waves in the drill rod are measured. This experiment is performed by means of the drop hammer method and a drill string made of high strength steel of about 3.7 m in length and 23.2 mm in diameter and elastic modulus of $E = 208$ GPa is instrumented using rings of strain gauges (each ring includes 4 gauges to capture also the bending effect) at five different positions along the drill string. Two at a distance of 0.32 m and 0.35 m to the end of the drill string on the piston side, and three at 0.265 m, 0.715 m and 0.745 m from the bit-rock contact point, see Fig. 13. The piston has a length of 0.3 m and is impacted to a shank adapter of length 0.43 mm that is attached to the drill string.

![Drilling experiment setup](image)

Fig. 13 Drilling experiment setup.
The wave data from the strain gauges close to the piston is used as an input incident wave to the simulation and the data from the gauges closer to the rock, which includes an interaction of incident and reflected waves, is compared to the numerical ones. The gauges data at each ring is averaged to eliminate the bending effect. It should be mentioned that the ring 5 gauges were not used during the experiment. A quarter-symmetry 3D FE model of the drilling experiment is performed and about one million 8-node linear elements with reduced integration are used in this simulation (the mesh is shown in Fig. 14).

![FE mesh used in the simulation of percussive drilling experiment.](image)

A good agreement is found between the strain data from the gauges and the numerical results that could be seen as a validation step for the numerical modeling of percussive drilling, see Fig. 15. The fracture pattern from the simulation is shown in Fig. 16 and the crush zone and different types of cracks are visible in the numerical results. This fracture system is very similar to the quasi-static indentation results presented in Fig. 5 (see e.g. [48]). However, the impacted rock in the drilling experiment (shown in Fig. 16) should be carefully cut and investigated by means of CT scan or other methods to obtain the fracture pattern, but this was not done here. Furthermore, the force-indentation data was extracted from the simulation results, see Fig. 17.
Fig. 15 Strain gauges data and the FE simulation results at different positions on the drill string.

Fig. 16 The FE simulation result for the fracture pattern and the rock surface after the impact.
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Fig. 17 Force-penetration data obtained from the FE simulation.

Concluding remarks and suggestions for future work

In this thesis, both experimental and theoretical investigations are performed to build the knowledge about the fracture response of brittle material such as rock and concrete to dynamic loading and more specifically during the drilling process. The preliminary application of interest in this study was percussive drilling with stress waves and rapid indentation that makes the problem a transient dynamic problem. Bohus granite was chosen for experimental and modeling purposes because it was already used extensively at Atlas Copco laboratories as well as being a popular and hard material in the mining industry.

Similar to other brittle materials, granite has a different response to tensile and compressive loads, which both exist underneath the indenter during the drilling process. Therefore the constitutive model should include both parts to correctly explain the material behavior in the whole range of loading. A damage mechanism with stiffness reduction due to open cracks determines the granite rock mechanical behavior in tension. Dynamic effects with strain rate dependency play an important role in tension that has to be considered. In compression, rock has a plasticity-like behavior that depends on the level of hydrostatic pressure. The combination of these two sets of data gives a complete mechanical characterization of rocks subjected to different loading situations, including percussive drilling. The KST-DFH model combining a damage law in tension and plasticity in compression is appropriate for this purpose. It is emphasized
structural cracks have a considerable effect on the damage mechanism in a mechanical analysis related to granite, for example in a drilling situation. These cracks may be the result from former impact of the drill bit, or by means of other exotic methods such as microwave and laser heating, used to facilitate the percussive drilling process. It is shown that pre-existing cracks help the drilling process regardless of their orientation.

A set of quasi-static and dynamic experiments are performed on granite to investigate the mechanical properties and to obtain the material parameters. For instance, spalling tests are performed on granite to investigate the strain rate dependency of the tensile strength. A considerable strain rate dependency of the tensile strength is obtained at strain rates of about $10^2$ 1/s, this loading-rate being pertinent to the situation of rock materials at percussive drilling. A dynamic tensile strength of 18.9 MPa is obtained at a strain rate of 70 1/s, which is more than twice the tensile strength of the specimen (with the same size) at quasi-static conditions, 8 MPa. The KST-DFH has been able to model successfully fracture of lime-stone, high strength concrete and granite. It would be a logical extension to the present work to also investigate other types of rocks such as metamorphic gneiss, sedimentary chert and igneous basalt and gabbro. Furthermore, ores of different types that naturally are of great importance to the mining industry would be considered for further work.

The numerical simulation is carried through with the KST-DFH material model implemented as a VUMAT subroutine in the Abaqus explicit software. This numerical tool is employed to simulate the percussive drilling problem. To simplify the problem, only one hemispherical button from the bit is considered so far. Another extension of the present work would be to investigate how rock fragmentation is affected by neighboring button inserts, i.e. among others how cracks interact on a larger scale.

It is emphasized here that the material model used in this study describes rock fragmentation response to dynamic loading at high strain rates. It is a general model that can be used in different dynamic applications with high strain rates. So far, percussive drilling was mainly considered. However, it is believed that the approach taken in this study is also applicable for the case of rock mechanical
excavation using cutters as there are dynamic loading and high strain rates in the rock underneath the cutters.
Bibliography


Summary of appended papers

**Paper A:** *On the mechanical behavior of granite material with particular emphasis on the influence from pre-existing cracks and defects.*

In this paper, experiments are carried out in order to determine the mechanical properties of Bohus granite. In particular, the influence from pre-existing cracks and defects is examined in great detail. Direct tensile and compression tests are performed to evaluate stiffness and strength. Quasi-oedometric tests are carried out in order to obtain the deviatoric and volumetric behavior of the material at different levels of hydrostatic pressure. Three point bend (3PB) tests are performed to evaluate the quasi-static strength of the rock and its distribution. Weibull statistics is then employed to describe the strength distribution. The intact specimens indicate a rather low scatter in the mechanical properties such as elastic modulus and tensile strength. However, specimens with initial large defects behave differently. The failure mechanism in these specimens is not as brittle as the intact ones. The crack is opened on the tensile surface of such specimens during the 3PB test at an early stage during loading, as demonstrated by digital image correlation results.

**Paper B:** *Granite rock fragmentation at percussive drilling - experimental and numerical investigation.*

In this paper, the fracture system at percussive drilling is numerically modeled. Due to the complex behavior of rock materials, a continuum approach is employed relying upon a plasticity model with yield surface locus as a quadratic function of the mean pressure in the principal stress space coupled with an anisotropic damage model. In particular, Bohus granite rock is investigated and the material parameters are defined based on previous experiments. The equation of motion is discretized using a FE approach and the explicit time integration method is employed. EOI (Edge-On Impact) tests are performed and the results are used to validate the numerical model. The percussive drilling problem is then modeled in 3D and the bit-rock interaction is considered using contact mechanics.
**Paper C:** A numerical study of the influence from pre-existing cracks on granite rock fragmentation at percussive drilling.

In this paper, the effect of pre-existing, or structural, cracks on dynamic fragmentation of granite is investigated. These cracks may result from former impact of the drill bit, or by means of other exotic methods such as microwave and laser that are used to facilitate the percussive drilling process. The pre-existing cracks are introduced in the model by considering sets of elements with negligible tensile strength that leads to their immediate failure when loaded in tension even though they still carry compressive loads as crack closure occurs due to compressive stresses. Previously performed Edge-On Impact (EOI) tests are reconsidered here to validate the numerical model. Percussive drilling is simulated, and the influence of the presence of pre-existing cracks is studied. The results from the analysis with different crack lengths and orientations are compared in terms of penetration stiffness and fracture pattern. It is shown that pre-existing cracks in all investigated cases facilitate the drilling process.

**Paper D:** On the tensile strength of granite at high strain-rates considering the influence from pre-existing cracks.

In this paper, the dynamic tensile behavior of granite samples, in some of which pre-existing cracks are introduced artificially, is investigated. Spalling tests using a Hopkinson bar are performed and a strain rate of order $10^2$ 1/s is obtained in both sets of specimens (with and without initial cracks). This experimental technique is employed because it is the same order of strain rate present in rock materials during percussive drilling. A dynamic tensile strength of 18.9 MPa is obtained at a strain rate of 70 1/s. This is more than twice the tensile strength of the specimen at quasi-static conditions, which is 8 MPa. The results from the spalling tests are used to validate the model prediction of the dynamic tensile strength of granite and also to calibrate the cohesive model parameters. On the other hand damaged elements are numerically introduced in the finite element (FE) calculations to simulate the spalling experiments performed on pre-damaged samples. A good agreement is obtained between the experimental and numerical results showing that a two-scale approach may constitute a suitable method to simulate numerically the tensile response of pre-damaged granite.