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Using Synthetic Rock Mass and Discrete Fracture Network approaches to study rock mass strength properties

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ABSTRACT: It is widely accepted that fractures decrease the strength of rock masses in comparison to intact rock. This phenomenon is evaluated by rock mass classification systems, such as the Geological Strength Index (GSI). However, their predictive ability is limited when applied to larger scales and fracture anisotropy. In order to gain a fundamental understanding of the interplay between preexisting fractures, damage creation, and eventual failure, we model the rupture of fractured rock mass through numerical simulations. Additionally, our objective is to quantitatively assess the correlation between preexisting fracture networks and rock mass strength. To achieve this, we use the Synthetic Rock Mass (SRM) approach, which models the rock as an assembly of individual blocks embedded with in situ joint fabric using a Discrete Fracture Network (DFN) representation. Indicators are developed to quantify the induced damage in the stressed sample until failure.

1 INTRODUCTION

Assessing the strength behavior of fractured rock masses is of critical importance for industrial applications such as mining, civil engineering, or nuclear waste disposal. Fractures are natural and ubiquitous discontinuities in rocks, that reduce the strength of the rock mass. Rock Mass Classification (RMC) charts were developed for use in civil and mining engineering, mostly based on both quantitative and qualitative observations of the fracture system geometry (e.g. fracture frequency) and surface quality (e.g., roughness, quality from fresh to weathered, sealing). Although the simplicity of the approach makes it both flexible and efficient for most construction and support design, the method does not consider anisotropy and scale effects, which are known to be important and potentially critical for some applications. Numerical simulations represent a way to understand fractured rock mass mechanical failure by modelling the progressive rock damage occurring at rock bridges (i.e. the intact rock matrix between natural fractures). In the Synthetic Rock Mass (SRM) approach (Mas Ivars et al., 2011), the intact material is embedded with fractures explicitly represented as planar surfaces using a Discrete Fracture Network (DFN) approach (Selroos et al., 2022).

In this study, we perform numerical strength test on SRM samples derived from various DFN models, using the 3-D distinct element code 3DEC (Itasca Consulting Group, 2020). Stress-strain curves are systematically derived, and several indicators are introduced to measure the evolution of damage during the simulations to investigate the role of pre-existing fractures in the specimen failure, both in tensile and Unconfined Compressive Strength (UCS) conditions.

2 METHOD

We analyse mechanical properties of fractured rock by numerically modelling the fractured rock volume using the SRM approach. The intact rock is modelled using the Bonded Block Model (BBM) approach (Garza Cruz et al., 2014), where the matrix is seen as an assemblage of bonded deformable polyhedral blocks within 3DEC, delimited by subcontacts (Figure 1). Intact

subcontacts between blocks constituting the surrounding material are assigned mechanical properties that differs from subcontacts crossed by fracture planes. Rock damage is then captured by the rupture of intact subcontacts.

Numerical tests are performed on the SRM sample to study the evolution of the specimen deformation with stress increase, and local failure of individual subcontacts between blocks, until specimen scale failure occurs. The fracture network of a rock mass is explicitly represented using a DFN approach, where fractures are represented as disks according to a given fracture density scaling model. In this study, we generate DFN models with constant size and power-law fracture size distributions, for various fracture densities. Fracture density can be characterized by fracture intensity P_{32} (total fracture surface per unit volume), and percolation parameter p (total excluded volume around fractures per unit volume), which is a good proxy for DFN connectivity (Bour and Davy, 1998). Numerical mechanical tests are performed on the DFN-SRM samples to simulate the evolution of fractured rock mass deformation with stress increase. A constant vertical strain rate is applied on the top and bottom SRM faces. The stress and deformation in each direction is recorded during all the simulation. By doing so, it is possible to construct the SRM stress-strain curve $\sigma_{zz} = f(\epsilon_{zz})$ of the mechanical test. The effective Young's modulus E is computed based on the linear part of the stress-strain curve, and the effective Poisson's ratio ν is defined as the ratio between lateral and vertical strain. The peak stress σ_p and peak strain ϵ_p are defined as the maximum axial stress value and the corresponding strain. The total volumetric strain ϵ_{vol} , defined as the unit change in volume, can be recovered as $\epsilon_{vol} = \epsilon_{xx} + \epsilon_{yy} + \epsilon_{zz}$. We then define the crack volumetric strain $\epsilon_{vol,c}$ (Martin and Chandler, 1994), i.e., the inelastic portion of the total volumetric strain, by retrieving the elastic part of the total volumetric strain:

$$\epsilon_{vol,c} = \epsilon_{vol} - (\sigma_1 - \sigma_3) \frac{1-2\nu}{E} \quad (1)$$

We also keep track of the fracture density during the mechanical tests, recording at any time the P_{32} as the sum of each broken contact surface divided by the SRM volume. We also record for each fracture, the so-called ‘‘oriented percolation parameter’’ contribution $p_{\sigma,f}$ (Davy et al., 2018, Darcel et al., 2021) defined from connected broken subcontacts that belongs to a fracture, taking into account orientation components (subcontact orientation and stress loading direction).

The numerical setup (Figure 1) covers all modelling steps from DFN generation to analysis of effective mechanical properties and evolution of damage.

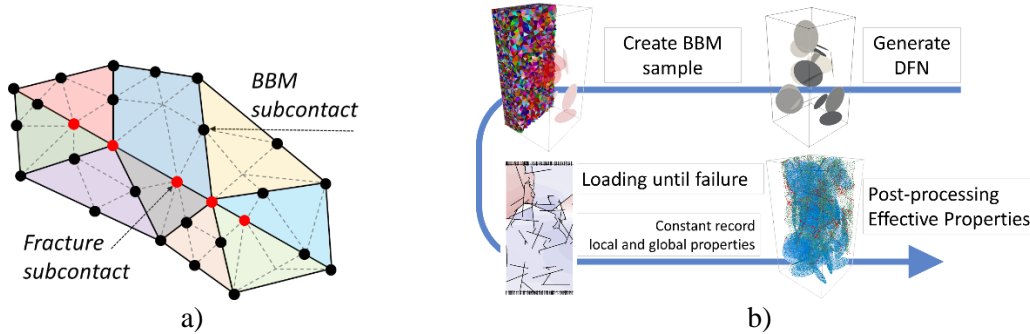


Figure 1: a) Schematic representation of the DFN-BBM approach. b) Workflow of the numerical study, from DFN generation to results analysis.

3 NUMERICAL RESULTS

3.1 Tensile conditions

Figure 2 shows the evolution of vertical stress σ_v , fracture intensity P_{32} and oriented percolation parameter $p_{\sigma,f}$ with applied vertical strain for intact SRM and SRM-DFN with constant fracture size $l = 2m$ and different percolation parameter in tensile condition. One can see from the stress strain curves that for $p < 4$, the peak strain is constant, while both effective Young's modulus and peak stress are decreasing. For $p = 4$, the peak strain is much lower. Both P_{32} and $p_{\sigma,f}$ follow a plateau for small strain (beginning of the simulation), which corresponds to the elastic part of

the stress-strain curve where no damage occurs. The value corresponding to this plateau is used to define the initial fracture intensity and initial oriented percolation parameter. Deviation from this value is interpreted as damage increase in the SRM sample. It can be noted that a small increment of P_{32} is needed to reach peak stress, while these quantities increase significantly after the stress peak. Figure 2c also shows broken subcontacts in the SRM samples at peak stress: the blue dots represent preexisting fractured subcontacts, while red dots represent newly broken subcontacts. One can see that for $p = 0.5$ and $p = 4$, damage develops around one preexisting fracture plane, referred as the “critical fracture” here. Note that for these two simulations, the critical fractures are almost horizontal, i.e., perpendicular to the tensile stress direction, which maximizes the forces applied on the fracture plane, hence the stress concentration at the fracture tips. For these two simulations, the critical fractures are different, which may be responsible for their peak strain discrepancy.

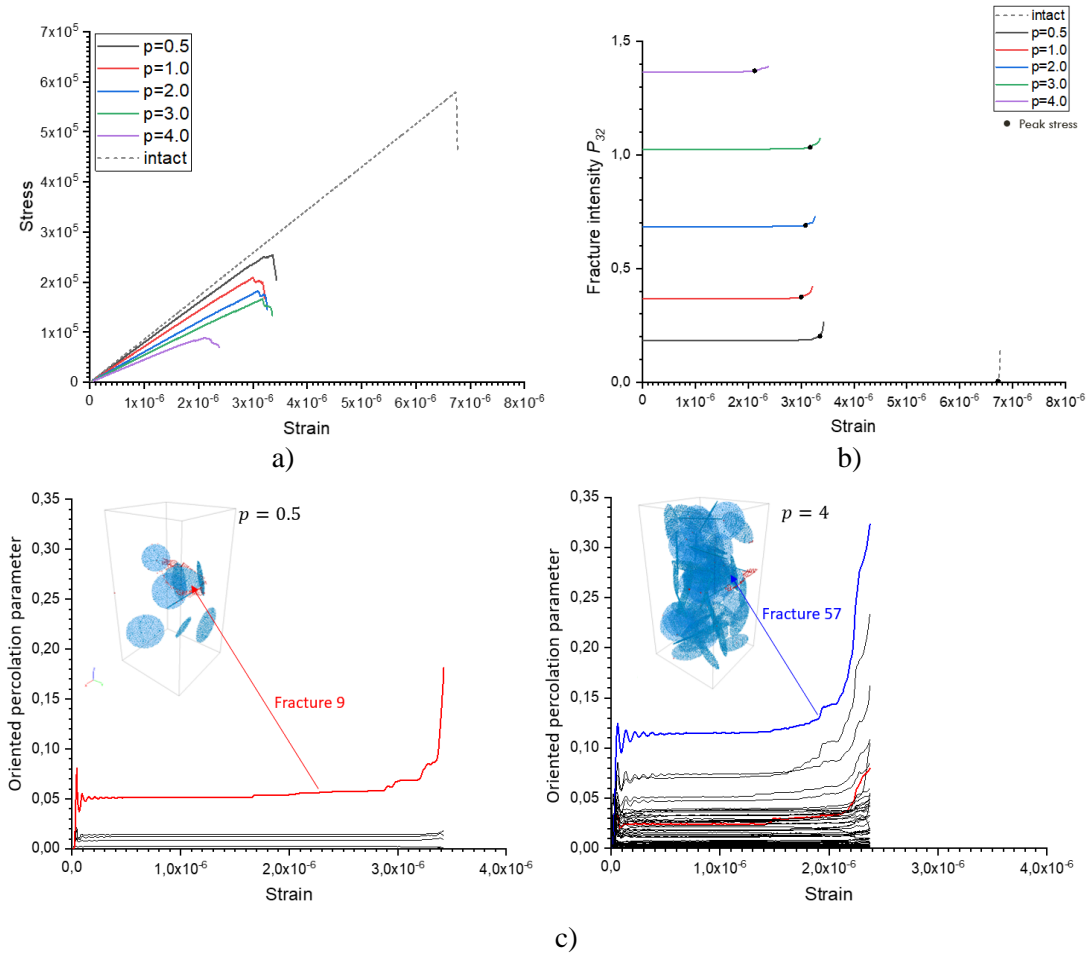


Figure 2: Simulation result for intact SRM and SRM-DFN with constant fracture size $l = 2m$ for different percolation parameters in tensile conditions. (a) Stress-strain curves, (b) Evolution of fracture intensity $P_{32}(t)$ with strain, and (c) Evolution of the “oriented percolation parameter” for each fracture of two DFN with different densities.

3.2 UCS conditions

Figure 3a shows the evolution of vertical stress σ_v and volumetric strain with applied vertical strain for intact SRM and SRM-DFN with constant fracture size $l = 2m$ and different percolation parameters in UCS condition. One can see that both peak stress and peak strain decrease when increasing the percolation parameter. As for the real rock samples, the stress-strain curves of the our SRM samples in UCS conditions can be divided into three parts using the analysis of total and crack volumetric strain (Martin and Chandler, 1994). The elastic part corresponds to the linear

part of the stress-strain curve, until crack volumetric strain starts to differ from zero, which is referred to as crack initiation stress σ_{CI} . This corresponds to the point where contacts around pre-existing fracture planes start to break. Crack damage threshold σ_{CD} is defined as the applied stress when total volumetric strain reaches a maximum, which may correspond to the point where fracture planes start to connect, speeding up damage evolution. The large strain increment needed between σ_{CI} and σ_p shows that the damage increment needed to reach macroscopic failure is much more important in UCS than in tensile conditions. This can also be noticed visually on Figure 3b, showing all the broken subcontacts at peak stress for the DFN with percolation parameter $p = 4$. One can see that damage around preexisting fractures occurs both in tensile and shear conditions (green and red dots, respectively).

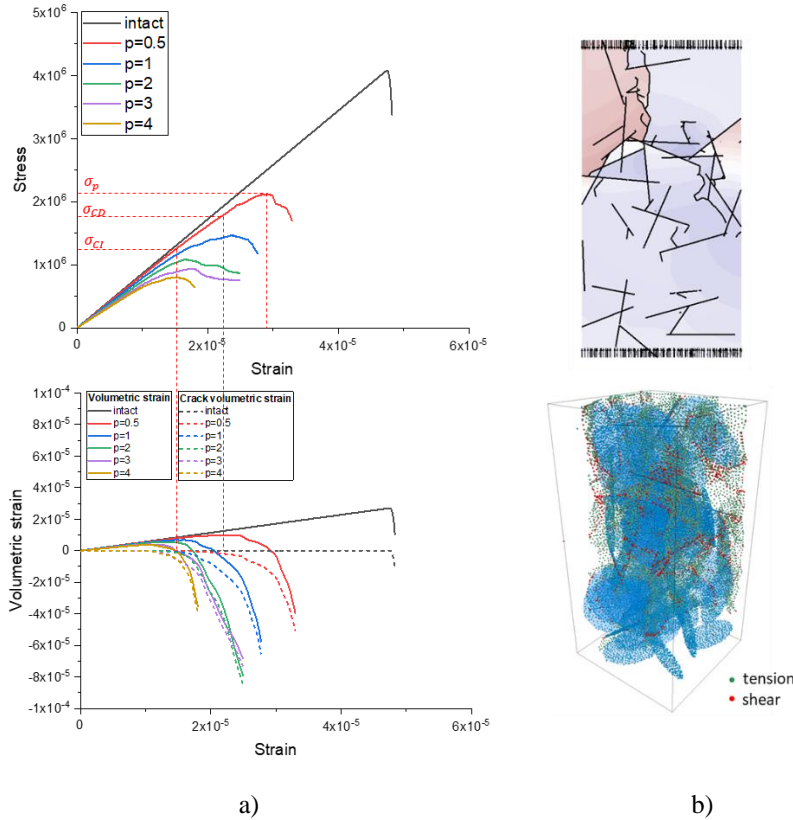


Figure 3: Simulation result for intact SRM and SRM-DFN with constant fracture size $l = 2m$ for different percolation parameters in UCS conditions. a) Stress-strain and volumetric strain curves with CI, CD, and σ_p marked for the case of $p = 0.5$. b) Example of damage (red and green dots) around preexisting DFN (blue dots), for the DFN with percolation parameter $p = 4$.

4 CONCLUSION

In this work, we performed numerical simulations of mechanical tests on Synthetic Rock Mass samples using various Discrete Fracture Network models and densities, to better understand the role of pre-existing fractures on fractured rock mass macroscopic failure.

We show that in tensile conditions, a very small increment of fracture surface is needed to reach macroscopic failure, localized around a “critical fracture”, which corresponds to the largest well-oriented fracture towards the applied remote stress field. In UCS conditions, we show that significant damage is required to reach the peak stress, while the failure is less sensitive to a single critical fracture. For real rock samples (Martin and Chandler, 1994), the stress strain curve can be divided into three parts until macroscopic failure of the SRM sample. Further work is on-going to study the impact of preexisting fracture size distribution, and to compare peak stress conditions with a GSI approach.

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