Interpreting variability of uniaxial compressive strength with insights from vein microstructures

Émélie Gagnon
Department of Geological Sciences and Geological Engineering - Queen's University, Kingston, Canada

Jennifer J. Day
Department of Geological Sciences and Geological Engineering - Queen's University, Kingston, Canada

ABSTRACT: The uniaxial compressive strength (UCS) test is regularly used to derive rockmass strength and stiffness properties for geomechanics numerical modelling. While the test is straightforward, selecting representative material properties from a testing suite constrained by economics relies on the practitioner's experience. This is challenging in veined rocks that exhibit significant variability in the results. To reduce this uncertainty, this study investigates the influence of intravein grain-scale geometric heterogeneity and orientation on the emergent veined specimen strength. Veins exhibit a spectrum of microstructures depending on the geological boundary conditions during their formation. Here, this is captured in a suite of 2D finite-element grain-based UCS experiments on specimens containing a single calcite vein. Results indicate that intravein grain orientation in veins with anisotropic grain arrangements is as influential on strength as the overall orientation of the vein (15-85% strength reduction) while isotropic crystal-bridged veins are less sensitive to orientation (20-45% strength reduction).

Keywords: Geomechanical laboratory testing, uniaxial compressive strength (UCS), hydrothermal veins, grain-based modelling (GBM), vein microstructures.

1 INTRODUCTION

The application of uniaxial compressive strength (UCS) laboratory test results into representative rockmass strength and elastic properties relies heavily on practitioner competence. While recommended methods exist based on voluntary consensus, these do not provide guidance on uncertainty management during specimen selection and result interpretation (ISRM 1999 and ASTM 2014). The criticality of these decisions, though, cannot be overstated; early-stage rock engineering design is often reliant on geomechanics numerical models with input material properties solely informed by laboratory testing results and rockmass classifications (Carter & Marinos 2020). Consequently, UCS testing programs require considerable planning, which become even more complex in hydrothermal environments where rocks often contain convoluted alteration and veining patterns (Clark & Day 2021). This work explores geological variability at the vein scale and the effects it has on the emergent strength of veined UCS rock specimens through illustrative 2D finite-element method (FEM) simulations of UCS tests with explicit microstructure.

1.1 Laboratory testing of veined rockmasses

The rock engineering standard-of-practice in massive, veined rock environments, is to consider veins indirectly in a representative continuum material model with other discontinuities such as joints represented discretely. Advanced numerical codes combined with extensive site-specific calibration can allow for the preparation of state-of-the-art models with discrete representation of veins. Irrespective of the selected design framework, a laboratory program with veined specimens is required to derive analogous continuum material properties or specific frictional and cohesive characteristics of individual veins. UCS testing is central to such investigations and while the ISRM (1999) and ATSM (2014) standards equip the practitioner with guidelines about hardware and specimen parameters to obtain the complete stress-strain curve of a specimen, they only advise "laboratory values for intact specimens must be employed with proper judgment in engineering applications". This is a complex undertaking for practitioners working with limited resources typical of early-stage projects in hydrothermally altered geological environments. Experiments on veined intact rock have shown that variability in the results is a consequence of the complex interaction of a multitude of geological and geometric factors that cannot be sorted in a simple manner, complicating the extraction of bulk material properties with confidence (Turichshev & Hadjigeorgiou 2017 and Clark & Day 2021).

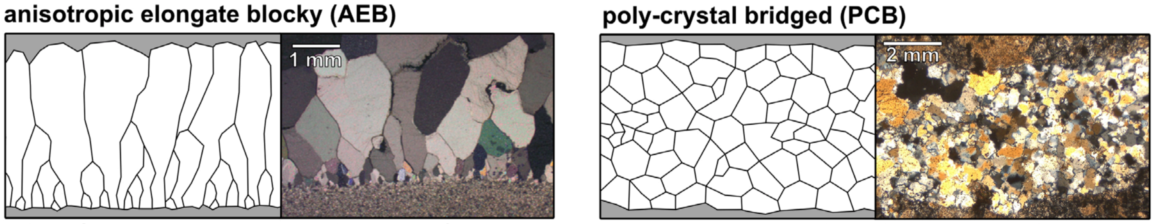
1.2 Vein microstructure

Veins have long been a focus of research in structural and exploration geology; they can be used as vectors to delineate ore deposits and help interpret the geological history of an area. Some work aims to understand their presence systematically and concentrates on their distribution in networks (André-Mayer & Sausse 2007). At a smaller scale, vein microstructure studies can provide information about environmental conditions during vein formation (Bons et al. 2012). Overall, the resulting geological knowledge base is vast and our work aims to translate this into practical knowledge for rock engineers, help organize data collection and rockmass characterization efforts, and facilitate the preparation of numerical models with improved representation of in situ conditions. As a first step, this study explores the influence of grain-scale geometric heterogeneity on the emergent strength of veined UCS specimens. The resulting microstructure varies depending on geological boundary conditions (BCs), including: (i) the relative time of crystal growth with respect to fracture opening, (ii) fluid properties (saturation, pressure, and temperature), and (iii) transport mechanisms (advection or diffusion) (Hilgers & Urai 2002 and Nollet et al. 2005).

In previous work by the authors, nine vein archetypes were identified to constrain the final microstructures observed in veins based on the BCs listed above (Gagnon & Day 2022). UCS tests on specimens with a single vein oriented at 45° to the core axis were simulated in 2D FEM models, with results showing that veins are strongest when equigranular and weaken with increasing intravein anisotropy. This study further examines the implications of vein microstructure for four archetypes through the added consideration of variability in vein orientation. The four vein types of focus in this paper are presented in Figure 1. The reader is referred to Gagnon & Day (2022), Bons et al. (2012), and references therein for details on vein genesis and microstructures.

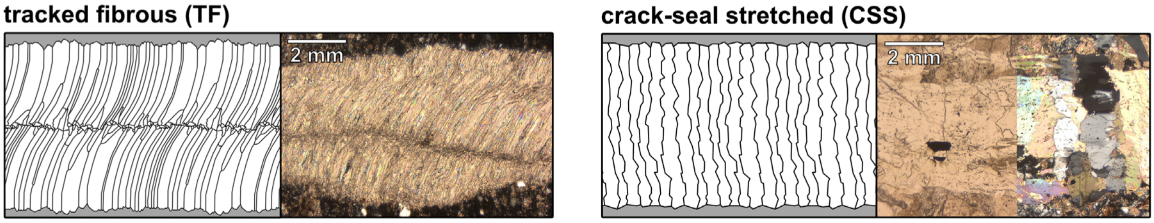
1.3 The exploration of veined rock mechanics using numerical modelling

The factors that contribute to heterogeneity in veined rockmasses are numerous: at both scales of individual veins (thickness, orientation, composition (vein and wallrock), alteration selvages, grain arrangements), and within a vein network (discontinuity spacing, length, generations of different veins) (Turichshev & Hadjigeorgiou 2015). In general, at the grain-scale, geometric, elastic, and contact heterogeneity between grains plays a key role on fracture mechanics (Diederichs 2003 and Lan et al. 2010). This complexity limits the conclusions that can be reached from physical testing and empiricism, hence numerical models become advantageous as they permit the systematic isolation and study of individual factors.



Right: Syntaxial calcite vein in limestone from Biure, Spain, exhibiting growth competition in the upwards growth direction (modified from Bons et al. 2012).

Right: Quartz vein with an isotropic "blocky" texture forming stockwork in garnet-pyroxene skarn from the Legacy deposit in New Brunswick, Canada.



Right: Antitaxial vein with a distinct center line and fibrous calcite grains in foliated grey-black argillite from the Nigadoo 7 area in New Brunswick, Canada.

Right: Syntaxial crack-seal stretched quartz-carbonate vein in sandstone with visible inclusion bands and grain boundary radiator structure.

Figure 1. The four vein archetypes simulated in this study with example cross-polarized thin sections.

In this work, 2D finite-element method (FEM) grain-based numerical modelling is used to explore fracture development within veins with varying grain fabrics. While GBMs are usually prepared using discrete or finite-discrete element method numerical codes (DEM or FDEM), the computational efficiency of FEM accelerates the calibration process while still capturing the important characteristics of brittle rock failure (Li & Bahrani 2021).

2 MODEL SET-UP

Grain-based simulations of UCS tests on veined rock specimens were prepared in 2D plane-strain conditions using the FEM in RS2 by Rocscience (V11.017; 2022). The UCS specimens were modelled as NQ diamond drill core with an aspect ratio of 1:2.25 and containing a 1-cm thick vein. Quasi-static uniaxial loading was simulated by applying equal and opposing incremental displacements of 3 μm at the top and bottom of the specimen at each model stage for 100 stages.

A Voronoi joint element network was used to simulate grains in the wallrock, while geometries of explicit boundaries for each vein archetype were imported into the models. The orientation of the vein (α) was varied relative to the upwards direction of the core axis (situated at 12 o'clock) from 0° to 180° by 15° increments. One specimen was also prepared with the vein oriented at 270° for a total of 14 specimens per vein archetype (56 total – 4 archetypes), or two specimens for each orientation. Because the veins have internal anisotropy, orientation effects must be investigated from 0° to 359° instead of a 90° quadrant with results simply reflected into the other three angular quadrants.

The material properties of the grains and grain boundaries were calibrated to granodiorite from the Legacy Skarn Deposit, representative of the common case of a calcite vein being present in a stronger igneous rock (Clark & Day 2021). Constitutive relationships in GBMs are an underdetermined system, hence the selected material properties (Table 1) are a non-unique solution which effects the macroscopic behavior. As the purpose of this work was to study the influence of grain-scale geometric heterogeneity on the emergent strength of veins, material properties that induced a realistic scenario (vein : wallrock strength ratio < 1) were sufficient. The reader is referred to Gagnon & Day (2022) for further description of the model preparation and calibration process.

Table 1. Grain and grain boundary properties used in the 2D FEM models of veined UCS tests.

Grain Properties	ρ (g/cm^3)	E (GPa)	ν	σ_t (MPa)	c (MPa)	Φ (°)	Grain Boundary Properties	K_n (GPa/m)	K_s (GPa/m)	σ_t (MPa)	c (MPa)	Φ (°)
Vein: Calcite	2.71	63	0.24	13	60	45	Platen-Specimen	20000	2000	0	0	30
Wallrock: Granodiorite	2.64	65	0.15	17	80	55	Granodiorite & VW	65000	43333	15 (0)	60 (3)	20 (65)
Platens: Steel	7.85	200	0.3	500	10.5	35	Calcite-Calcite	55000	36666	12 (0)	50 (2)	20 (45)

Note: ρ = density, σ_t = tensile strength, c = cohesion, Φ = friction angle, K_n = normal stiffness, K_s = shear stiffness; bracketed values are residual properties.

3 RESULTS AND DISCUSSION

FEM simulations of UCS tests on veined specimens with explicit microstructure were analyzed in terms of peak compressive strength and failure type. The peak strength of each simulation was measured on the axial stress-strain curve extracted at the center of specimen platens; the failure mode and mechanism of each model was interpreted by observation of the yielded joint and material elements, and maximum shear plastic strain and total displacement fields. The peak strength of each specimen is presented relative to vein orientation in Figure 2a; summary statistics are also presented by vein archetype in Figure 2b. It can be observed that by simply changing the intravein fabric, otherwise identical specimens exhibit significantly different sensitivity to changes in orientation.

Veins consisting of grains with high-aspect ratios and anisotropic arrangements such as AEB, TF, and CSS reduced specimen strength, relative to a homogeneous wallrock specimen, by ~15% to ~70%. Meanwhile, specimens containing isotropic poly-crystal bridged (PCB) veins exhibited strength reductions between ~20% to ~45%. It is interesting to note that while the range of variability in emergent strength is reduced for isotropic PCB veins, it is specimens containing veins with anisotropic fabrics that produced the highest strength in the testing program, contradictory to previous findings by the authors (Gagnon & Day 2021).

The types of failure observed in each specimen were classified by mode and mechanism as represented by icons in Figures 2b (Bewick 2021 and Clark & Day 2021). As expected, fracturing ubiquitously initiated within the weaker calcite vein, with specimens failing exclusively within the vein at low vein inclination relative to the core axis (α = 0-30° and 150-180°) and in combination through the vein and wallrock at high inclination (α = 75-105° and 270°).

Some specimens with identical vein microstructure and inclination to the core axis, but different absolute orientation to the upward axis exhibited very different peak strengths. An example of this is presented in Figure 2c, which shows two specimens with a tracked fibrous vein oriented at 75° to the core axis. The vein in specimen B was rotated 30° CW relative to the vein in specimen A. Upon simulation, both specimens failed through spalling but at differing strengths of 169 MPa and 120 MPa. This 35% discrepancy can only be the result of variability in the orientation of individual grain boundaries or geometric changes that resulted from geometry clean-up during model preparation, where vertices closer than a specified threshold are merged. Since identical procedures were followed to prepare all models, the influence of the latter is deemed negligible.

To further explore the hypothesis of intravein grain boundaries having a significant influence on emergent strength, the vein fabric directionality was quantified using a Fourier spectrum analysis in the software package Fiji/Image J (Schindelin et al. 2012). It is widely accepted that shear strength along a plane of weakness varies with orientation and is lowest at an angle of approximately 30° to the applied stress (Jaeger 1960). The results show that most of the intravein grain boundaries were oriented between α = 0-15° and 25-45° in specimens A and B, respectively (Figure 2d). Modelled grain boundaries were assigned lower strength properties than the grain material, hence a higher density of favorably oriented contacts promotes crack initiation and propagation effecting weaker emergent strengths. This provides a sound explanation for the variation in strength between the two specimens. Thus, for veins with orderly arranged high aspect-ratio grains, such as antitaxial or fibrous veins, both the angle of the vein relative to the core axis, as well as the predominant angle made between the grain boundaries and the core axis control the emergent specimen peak strength.

The conclusions derived from this work are restricted to weakening veins under UCS conditions. Limitations include the simplification to plane strain conditions and the homogeneous nature of the grains themselves. Crystallography effectively controls vein microstructure by playing a major role on crystal growth, and resulting intragrain anisotropy in elastic properties and strength, such as cleavage, could contribute to increased intragranular cracking and different fracture patterns within the veins with anisotropic fabrics.

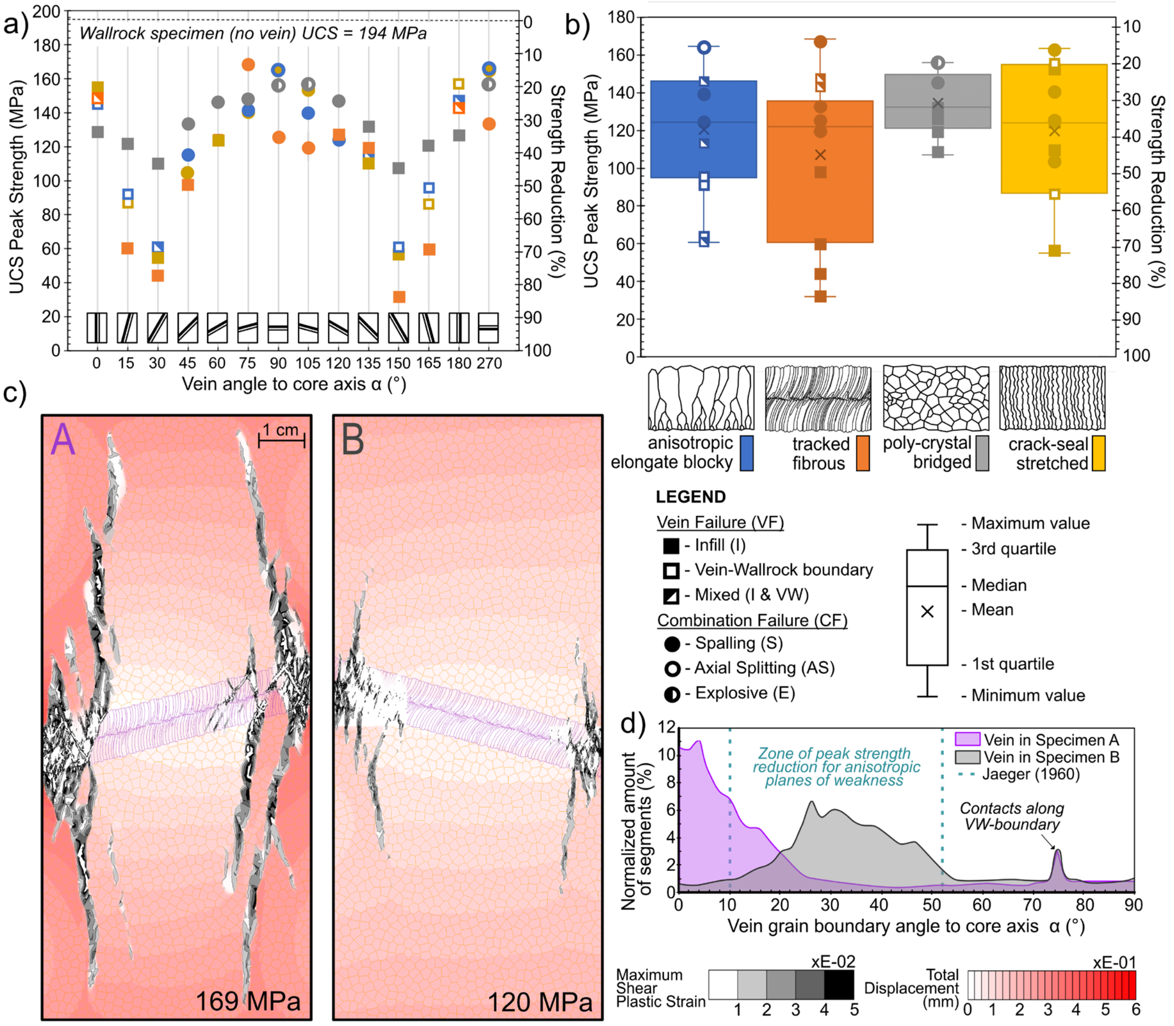


Figure 2. a) emergent peak strength results based on vein orientation, b) summarized statistics by vein archetype, c) results for two UCS specimens with tracked fibrous veins oriented at 75° and 105° to core axis, d) cumulative orientation histogram of the intravein grain boundaries in specimens A and B in c).

4 CONCLUSIONS

The derivation of material properties through a UCS testing program is a critical step in rock engineering design. In this study, 2D FEM grain-based models of UCS tests on intact rock specimens with a calcite vein were used to investigate the influence of intravein microgeometric heterogeneity on fracture development and emergent peak strengths. We conclude the influence of vein orientation on the emergent veined specimen strength varies depending on the degree of geometric anisotropy at the grain-scale. Weakening veins with anisotropic grain arrangements result in greater variations in peak strength relative to vein orientation than weakening veins with isotropic grain arrangements, and can be both stronger and weaker than isotropic veins depending on the orientation of the preferred grain alignment relative to the applied stress. A descriptor of vein fabric/type, along with infill mineralogy, thickness, and orientation should be recorded during geotechnical core logging for projects where veins are expected to influence rockmass stability. Vein microstructure is of interest since it significantly influences the overall behavior of a healed discontinuity and can provide crucial information on vein genesis. This can inform the characterization of site-specific vein sets or families based on geological history, leading to more accurate selection of strength and stiffness properties and capture of potential failure modes in numerical models.

ACKNOWLEDGEMENTS

This research was funded by the Nuclear Waste Management Organization of Canada (NWMO) and the Natural Sciences and Engineering Research Council of Canada (Canadian Graduate Scholarship – Master's, É. Gagnon; Discovery Grant, PI: J.J. Day).

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