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Measurement of granite shear fracture toughness from Grimsel and Bedretto underground laboratories

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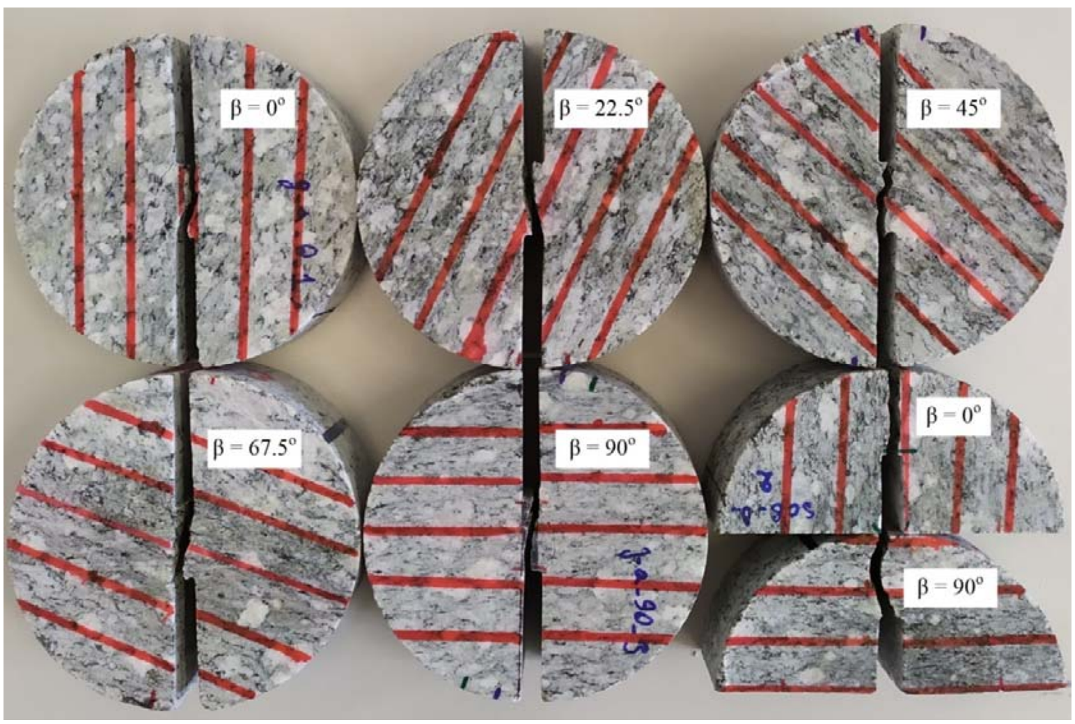

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Zusammenfassung

Der Bruchwiderstand ist eine wichtig Kenngrösse für die quantitative Modellierung der Prozesse, die während hydraulischer Stimulationsexperimente ablaufen. Dies gilt gerade auch in Hinblick auf das langfristige Ziel, effiziente geothermische Wärmetauscher im Rahmen sogenannter "enhanced geothermal systems (EGS)" routinemässig anzulegen. Insbesondere für den Scherbruchwiderstand (auch "Mode II" Bruchwiderstand genannt) sind die bisherigen Messmethoden jedoch entweder sehr ungenau (da sie durch eine erhebliche Komponente and Zug-/Extensionsbruchfestigkeit verfälscht werden) oder erfordern spezialisierte und aufwändige Installationen, die wenig verbreitet sind und zudem nicht auf Bohrkernproben angewendet werden können. Um verlässliche Daten für die Modellierung und Auswertung von hydraulische Stimulationsexperimenten in den Grimsel- und Bedretto-Untertagelaboratorien zu messen, wurde im Rahmen dieses Projekts eine neue Messanordnung mit entsprechenden Verfahrensregeln entwickelt (double-edge notch Brazilian disk (DNBD)), mit der der wahre Scherbruchwiderstand zuverlässig bestimmt werden kann. Die Vorteile des Verfahrens werden aufgezeigt und diskutiert. Mit dem neuen Verfahren wurde dann der Scherbruchwiderstand (K_{IIc}) für Proben von Bedrettogranit in unterschiedlicher Grösse und für den anisotropen Grimselgranit in verschiedener Orientierung bestimmt. Es stellte sich heraus, dass sowohl die Probengrösse beim Bedrettogranit als auch die Belastungsrichtung beim anisotropen Grimselgranit den Wert des Scherbruchwiderstands beeinflussen. So ist z.B. der K_{IIc}-Wert des Bedrettogranits für eine Probe mit 101 mm Durchmesser ca. 60% grösser als für eine mir 27 mm Durchmesser. Für den Grimselgranit ist der Scherbruchwiderstant senkrecht zur Foliation ca. 50% grösser and entlang der Folitation. Diese Resultate des projekts liefern Schlüsselwerte für ein besseres und schlussendlich quantitatives Verständnis der Scherbruchausbreitung während hydraulischer Experimente in den Grimsel- und Bedretto-Untertagelaboratorien sowie eine neue Messmethode, um zuverlässige Werte auch in anderen Projekten zu generieren.

Résumé

La ténacité à la rupture est un paramètre clé pour la modélisation quantitative des processus de stimulation hydraulique, notamment pour l'objectif à long terme de l'ingénierie de routine des échangeurs de chaleur souterrains dans les systèmes géothermiques stimulés (SGS). Cependant, les essais existants pour mesurer la ténacité à la rupture par cisaillement (également appelée «en mode II»), K_{IIc}, se sont révélés soit très imprécis (car ils mesurent principalement la composante de traction plutôt que la vraie composante de cisaillement) ou - s'ils sont plus précis - nécessitent des installations expérimentales spéciales qui ne sont pas facilement disponibles et ne peuvent pas être utilisées sur des échantillons de carottes de forage. Afin de pouvoir fournir des données fiables pour la modélisation et l'interprétation des expériences de stimulation hydraulique dans les laboratoires souterrains de Grimsel et Bedretto, nous avons développé une nouvelle méthode expérimentale, appelée disque brésilien à double entaille (DBDE), pour mesurer la vraie résistance à la rupture en mode II des roches. La supériorité de ce test par rapport aux approches existantes est démontrée et discutée. En utilisant le test DBDE, les valeurs de ténacité à la rupture (K_{IIc}) en mode II pour différentes tailles d'échantillons de granite de Bedretto et différentes directions du granite anisotrope de Grimsel ont été mesurées. Il est démontré que la taille de l'échantillon pour le granite de Bedretto et, en outre, la direction de chargement pour le granite Grimsel sont des paramètres importants qui affectent la valeur mesurée de la ténacité à la rupture en mode II. Par exemple, le K_{IIc} mesuré pour le granite de Bedretto à partir d'un échantillon de rayon 101 mm est presque 60% plus élevé que celui de l'échantillon de rayon 27 mm. De plus, pour le granite de Grimsel, le K_{IIc} dans la direction perpendiculaire à la foliation était environ 50% supérieur à celui mesuré dans la direction parallèle. Ces résultats sont cruciaux pour une meilleure compréhension et a terme une compréhension quantitative des processus de croissance des fractures en cisaillement lors des expériences de

stimulation hydraulique dans les laboratoires souterrains de Bedretto et Grimsel et la nouvelle méthode de mesure peut fournir des valeurs fiables dans d'autres projets futurs.

Summary

Fracture toughness is a key parameter for quantitative modelling of hydraulic stimulation processes, namely for the long-term goal of routine engineering of subsurface heat exchangers in enhanced geothermal systems (EGS). However, existing tests to measure shear fracture (also called "mode II") toughness, K_{IIc}, were shown to be either very inaccurate (because they measure a dominantly tensile component rather than true shear toughness) it or - if more accurate - require specialized experimental setups that are not readily available and cannot be operated on drillcore samples. In order to be able to provide reliable data for modelling and interpreting hydraulic stimulation experiments in the Grimsel and Bedretto Underground Laboratories, we developed a new test setup and protocol, called double-edge notch Brazilian disk (DNBD), to measure the true mode II fracture toughness of rocks. The superiority of this test with respect to the existing approaches is demonstrated and discussed. Using the DNBD test, the true mode II fracture toughness (K_{IIc}) values for different sample sizes of Bedretto Granite and different directions of the anisotropic Grimsel Granite were measured. It is shown that both the specimen size for Bedretto Granite and, additionally, the loading direction for Grimsel Granite are important parameters which affect the measured value of the true mode II fracture toughness. For instance, the measured K_{IIc} for Bedretto Granite from a sample of radius 101 mm is almost 60% higher than that for the sample of 27 mm radius. Additionally, for Grimsel Granite, K_{IIc} in the direction perpendicular to the foliation is about 50% higher than parallel to the foliation. These findings are crucial for a better and ultimately quantitative understanding of the shear-based fracture growth processes during hydraulic stimulation experiments in Bedretto and Grimsel underground laboratories and the new measurement approach can deliver reliable values in other, future projects.

Main findings

- A new and experimentally simple test (referred to as DNBD test) is developed for accurate, true mode II fracture toughness, K_{IIc}, measurements as input to modelling and interpreting hydraulic stimulation experiments
- Using the new test, we measured K_{IIc} for Grimsel and Bedretto Granite
- We find a significant effect of the specimen size on the measured value of K_{IIc} for Bedretto Granite
- The influence of material anisotropy on the K_{IIc} of the Grimsel Granite is also evaluated

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Nomenclature

a	Notch length
R	Radius of the DNBD specimen
F	Applied load on the DNBD specimen
t	Thickness of the DNBD specimen
α	Loading angle in the DNBD specimen
2l	Ligament size in the DNBD specimen
K_I, K_{II}	Modes I and II stress intensity factors
K_I^*, K_{II}^*	Normalized Modes I and II stress intensity factors
T, T^*	T-stress and its normalized form
Abbreviations	
DNBD	Double-edge notched Brazilian disk
ISRM	International society for rock mechanics
SCB	Semi-circular bend
PTS	Punch through shear

1 Introduction

1.1 Background information and current situation

Hydraulic stimulation is commonly employed to increase permeability in enhanced geothermal systems [1,2]. Based on this approach, fluid injection allows shear displacement along existing fractures or faults, thus creating dilational jogs as pathways for increased fluid flow within the fractures. Recent experiments in the Grimsel Underground Laboratory [3–5] showed that hydraulic stimulation can also enhance permeability in ductile and ductile-brittle shear zones that do not match the classical picture of shear displacement of an open fracture with rough fracture surfaces. Rather, complex, interplaying mechanisms of transient and partially irreversible opening of weak structures plus potential propagation of existing fractures may explain observed patterns of fluid pressure propagation and seismicity [6–8]. Also, during hydraulic stimulation, new fracture growth may be induced, ranging from dominantly tensile (mode I) to dominantly shear (mode II).

In the context of enhanced geothermal systems (EGS), this multitude of scenarios and possible mechanisms acting on often complex geometrical arrangements of rock types and structures such as fractures, faults, and shear zones challenges the long-term goal of being able to routinely engineer efficient heat exchangers. A quantitative assessment by means of numerical simulation of how different hydraulic stimulation protocols may result in different permeability distributions is therefore seen as a possible pathway to improve our understanding by utilizing it as a "virtual testbed" for developing and optimizing stimulation strategies.

Accurate predictions of these processes, however, rely on accurate values of the relevant material parameters. While classical rock mechanical parameters such as the various elastic moduli can routinely be determined with sufficient accuracy, the accurate determination of the fracture resistance of rocks against shear rupture has remained a major challenge. In an accompanying publication (Appendix 1), we demonstrate that existing experimental approaches either measure highly inaccurate values (as they measure a dominantly tensile component rather than the actual shear-related value), or cannot readily be applied on samples taken from drillcore, or require specialized setups that are restricted to very few laboratories.

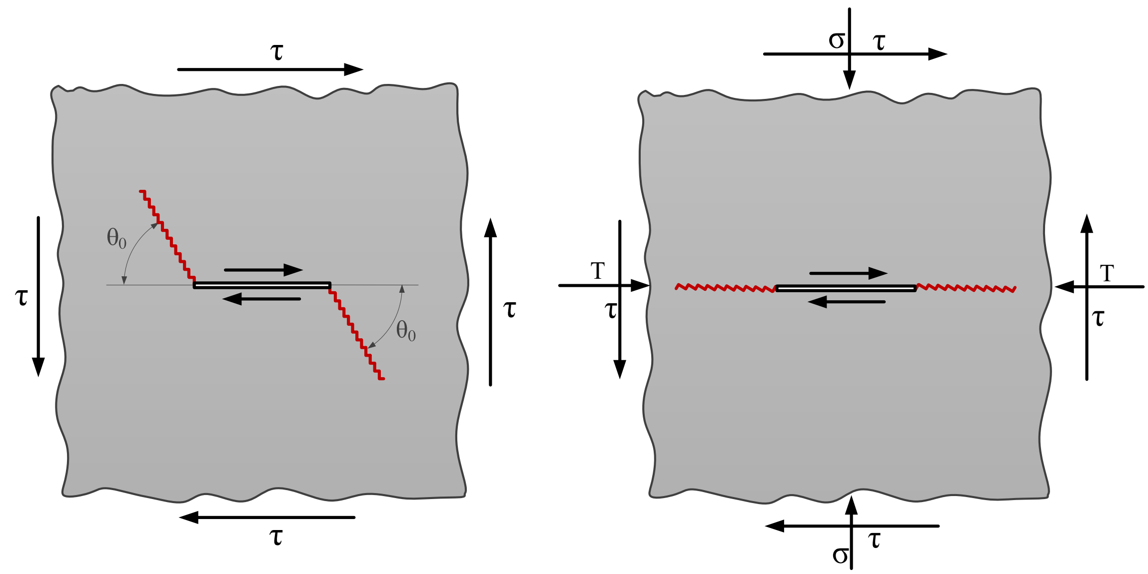
More specifically, shear or mode II loading of fractures is referred to a type of loading in which fracture surfaces solely slide against each other. For classical test geometries, however, such a loading condition rather causes a tensile type of failure than a shear-based rupture. The tensile-based failure is directly related to the mode I fracture toughness (K_{Ic}), and is well predicted by the tensile-based fracture criteria such as the maximum tangential stress that suggests a mode II crack kinks at an angle around $\theta_0 = 70^o$ as schematically illustrated in Fig. 1a. However, a shear-based fracture occurs in a situation where there is a high level of confinement that suppresses the generation of tensile-based fracture growth. In this case, a self-planar growth happens in response to the compressive stresses normal (σ) or parallel (T) to the crack plane, which counteract kink formation driven by the tensile stress (see Fig. 1b). In such condition, the mode II stress intensity factor (K_{II}) reaches its critical value, K_{IIc}, at a critical load, for which K_{IIc} can be interpreted as an independent material property. In order to distinguish the tensile- and shear-based fracture types from each other, we refer to the former as the mode II fracturing process and the latter as the *true mode II fracturing* mechanism. In fact, a true mode II fracture not only is under dominant shear stress, but also propagates mainly due to the shear stresses. The measurement of K_{IIc} is currently a challenging task, and the limited number of tests proposed for such measurement have several severe drawbacks.

Due to the difficulties of conducting a true mode II fracturing test, only two tests have been mainly employed for K_{IIc} measurement. These tests include (i) the punch through shear (PTS) test proposed by Backers et al. [9], and (ii) the shear box test suggested by Rao et al. [10]. The PTS is the most common test for true mode II fracturing, and several research studies have investigated the effects of different parameters such as confining pressure, sample size, loading rate, etc. on the measured values of fracture toughness [11–13]. After the suggestion of PTS by International society for rock mechanics (ISRM) as the approved test for determining the true mode II fracture toughness [14], this test has been used in several articles to measure K_{IIc} under static [15,16] and dynamic [17,18] loading conditions. Despite the widespread use of the PTS test, it has several important limitations:

- For anisotropic rocks, due to the variations of the angle between the anisotropy orientation and notch surface, K_{IIc} cannot be measured along a specific orientation with respect to the rock anisotropy.
- Since the specimen is positioned inside a pressure cell, and due to the cylindrical geometry of the crack, the vicinity of the notch tip is not accessible visually, rendering techniques such as digital image correlation inapplicable for fracture study.
- The suggested 15 mm ligament between the two notch tips is rather small, which may cause the underestimation of KIIc for rocks with large fracture process zones. Digital image correlation measurements showed that the mode I fracture process zone of Grimsel Granite is as large as 10mm [19].
- This test requires a pressure cell, which is not necessarily available in standard rock mechanics laboratories. More fundamentally, the PTS test cannot measure K_{IIc} under low-confinement values, due to the generation of wing cracks (kinking).

The shear-box test uses cubic samples with single or double external notches in a shear-box fixture to measure K_{IIc}. Rao et al. [10] investigated the influence of the size and the thickness of the specimen as well as the inclination angle of the notch on K_{IIc}. Despite being a successful test, the special test configuration imposes the following additional requirements beyond standard testing approaches:

- The specimen is cubic and not core-based, making the sample preparation time-consuming.
- This test ideally requires a shear-box with a customised size for every sample size.
- The alignment precision of the fixtures on the sample surfaces determines how stresses are distributed. In case of poor alignment, stress may be transferred to the specimen locally, causing an error in the fracture toughness determination.
- To avoid crack kinking, the setup requires a certain minimum compressive stress normal to the notch plane. This compressive stress, regarded as a sort of confinement, can impact the measured value of the fracture toughness since fracture toughness is generally dependent on the confinement.



(a) (b)

Fig. 1. Mode II (a) versus true mode II (b) fracturing.

1.2 Purpose of the project

In order to support modelling and interpretation of recent experiments at the Grimsel test Site [3–5] and of upcoming experiments at the Bedretto underground Laboratory, the prime goal of this project was to deliver accurate values for the fracture shear toughness for the Grimsel and Bedretto Granites. Due to the special requirements and/or limitation of the PTS and shear-box tests described above, only limited and often questionable data are available for K_{IIc} of rocks despite its importance in fracture growth analyses and the respective equipment is not available in Switzerland.

This project therefore aimed at (1) developing a new, better, and simpler experimental measurement configuration for more convenient, faster, and reliable measurement of K_{IIc} and, (2) using the new test scheme to measure the shear fracture toughness of the Grimsel and Bedretto Granites.

Representative test samples of Grimsel and Bedretto Granite were taken from the rock volumes in which the in-situ hydraulic stimulation experiments have been or will be carried out. Such measurements will help to develop better numerical models that can distinguish tensile- and shear-based fracturing in stimulation projects. It should be noted that although the samples are representative for the main rock masses in the laboratories, deviations from the measured values can be expected if stimulation targets specific variants of the rock. For example, while Bedretto Granite appears largely homogeneous and nearly isotropic over large volumes and in the samples measured here, it displays significant variations in the lower half of most boreholes drilled into the to-be-stimulated volume so far. The variations are due to numerous shear zones of greatly varying width and intensity, locally intense hydrothermal overprint (including the creation of voids of at least up to 15 cm length and 2-3 cm width) and combinations thereof. Covering the full parameter space created by these variations was beyond the scope of this study and new measurements are recommended once the exact stimulation targets have been identified and agreed upon.

1.3 Objectives

In this project, we design a new testing scheme named double-edge notched Brazilian disk (DNBD) test to determine the fracture toughness of rocks in shearing mode. Numerical simulations of the DNBD test were performed to ensure that fracture propagation occurs under (nearly) pure shear in a self-planar manner. Once the sample configuration and the loading scheme were fully characterised, DNBD tests were conducted in different angles with respect to the foliation direction for the Grimsel Granite, in order to study the effects of anisotropy on the true mode II fracture toughness. Additionally, for the Bedretto Granite, the tests were performed on different sizes of the DNBD specimen, in order to study the effects of specimen size on K_{IIc}. To summarize, the objectives of the project are as follows:

1. Developing the DNBD test and investigating its suitability for K_{IIc} measurement.
2. Measuring K_{IIc} in Grimsel Granite and evaluating how the anisotropy orientation influences it.
3. Measuring K_{IIc} in Bedretto Granite and assessing potential sample size influences.

2 DNBD test

The DNBD test is based on the diametrical compression of a double-edge notched Brazilian disk specimen, schematically shown in Figure 2a. The preparation of the DNBD specimen is simple and straightforward, i.e. by cutting two diametrical external notches of length a each, in a Brazilian disk of radius R. The size of the ligament between the two notch tips is therefore $2\mathrm{l} = 2\mathrm{R} - 2\mathrm{a}$. This specimen is loaded diametrically at an angle α with respect to the notch plane. As α increases, the magnitude of mode I stress intensity factor (K_I) increases, while the magnitude of the mode II stress intensity factor (K_{II}) decreases. In order to apply the diametrical load, we suggest employing small jaws of flexible materials (with low stiffness) such as polymethyl-methacrylate (PMMA), wood, etc. Such flexible materials deform in a larger extent compared to the rock material, whereby the load is well distributed along the thickness and over a small arc of the disk circumference. Such distribution of the load prevents the local concentration of stress at the loading points which can potentially yield fracturing there. Generally, using a material that has a Young's modulus of about one-fifth to one-tenth of the tested rock would give a satisfactory outcome. Based on our experience, small wood sheets perform better than PMMA sheets in terms of the load distribution and the prevention of failure initiation at the loading points.

The true mode II fracture toughness is defined as the critical mode II stress intensity factor (K_{II}) occurring at the failure load. The accurate computation of the stress intensity factors of the DNBD specimen is therefore essential for fracture toughness determination. We performed finite element analyses to determine the mode I and II stress intensity factors as well as the T-stress for the DNBD specimen with various crack lengths and loading angles. A two-dimensional DNBD specimen of $R = 50$ mm radius was modelled and subjected to the load of $F/t = 1\ kN/mm$ where t is the thickness of the specimen. We considered a wide range of notch lengths from $a/R = 0.55$ to $a/R = 0.9$ in intervals of 0.05, yielding ligament sizes between $l/R = 0.1$ and $l/R = 0.45$. The load angle α was also increased from 0° to 45° in 5° increments. Fig. 3 presents the variations of the three normalized parameters of K_{II}^*, $K_{\mathrm{I}}^*/K_{\mathrm{II}}^*$ and T/K_{II}^* against l/R, for different values of α. The following relations were used to normalize the values of K_I, K_{II} and T:

$$K_I^* = K_I \frac{\pi R t}{F\sqrt{\pi a}}, \qquad K_{II}^* = K_{II} \frac{\pi R t}{F\sqrt{\pi a}}, \qquad T^* = T\frac{\pi R t}{F} \tag{1}$$

The gray-shaded regions in the plots of Fig. 3 illustrate the zones where the DNBD test can be conducted optimally. The reasoning is as follows.

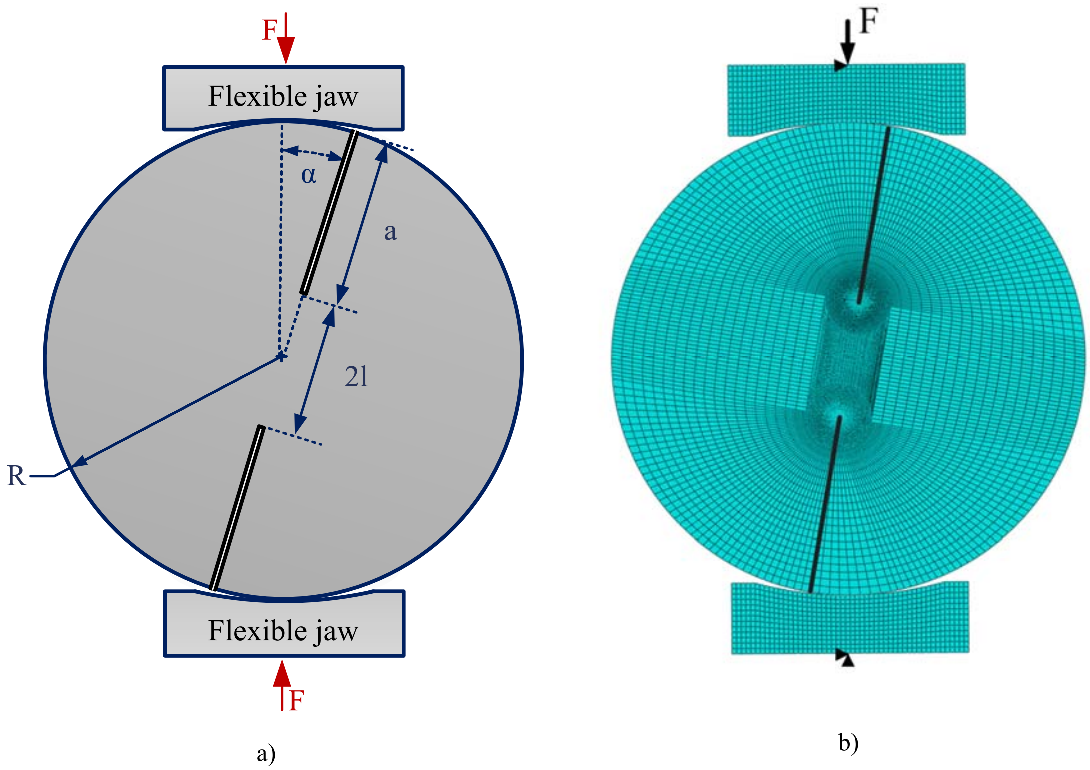


Fig. 2. a) A schematic view of the DNBD test configuration. b) A sample mesh pattern used for the finite element modelling of the DNBD test.

Ligament size: The ratio l/R should not be too small to allow the crack tip FPZs to overlap. Such overlap may lead to fracture toughness underestimation. On the other hand, the ratio l/R should not be too large to allow potential failure at the loading points. A large l/R is associated with a small notch length, which results in a higher fracture load. Based on these considerations, we suggest the optimal range of $0.2 < l/R < 0.35$. Note that K_{II}^* does not significantly vary with l/R in this optimal range (small gradients in Fig. 3a). Therefore, a potential small error in l/R measurement in a tested specimen does not propagate to a large error in fracture toughness determination.

Load angle: A very small load angle α may cause failure at the loading point due to its proximity to the notch flank. On the other hand, a large load angle causes a high compressive K_I, that may influence the values of the fracture toughness. Moreover, a large α is associated with a high failure load due to the smaller values of K_{II}^*. This can potentially allow failure at the loading points. We therefore, consider the range $10° < \alpha < 20°$ as the optimal range for the loading angle. According to Fig. 3b, $K_{\text{I}}^*/K_{\text{II}}^* <$ 0.5 in such a range of α.

Finally, the optimal configuration should not allow crack kinking. As discussed previously, large values of compressive T-stress prevent crack kinking. Generally, the higher the value of $/K_{\text{II}}^*$, the less the preference of crack to kink. Fig. 3c shows that T/K_{II}^* holds considerable values in the entire proposed range. Therefore, we expect that kinking does not occur when a configuration in the suggested range is chosen for the test. To sum up, the ranges of $0.2 < l/R < 0.35$ and $10° < \alpha < 20°$ are proposed for the optimal performance of the DNBD test.

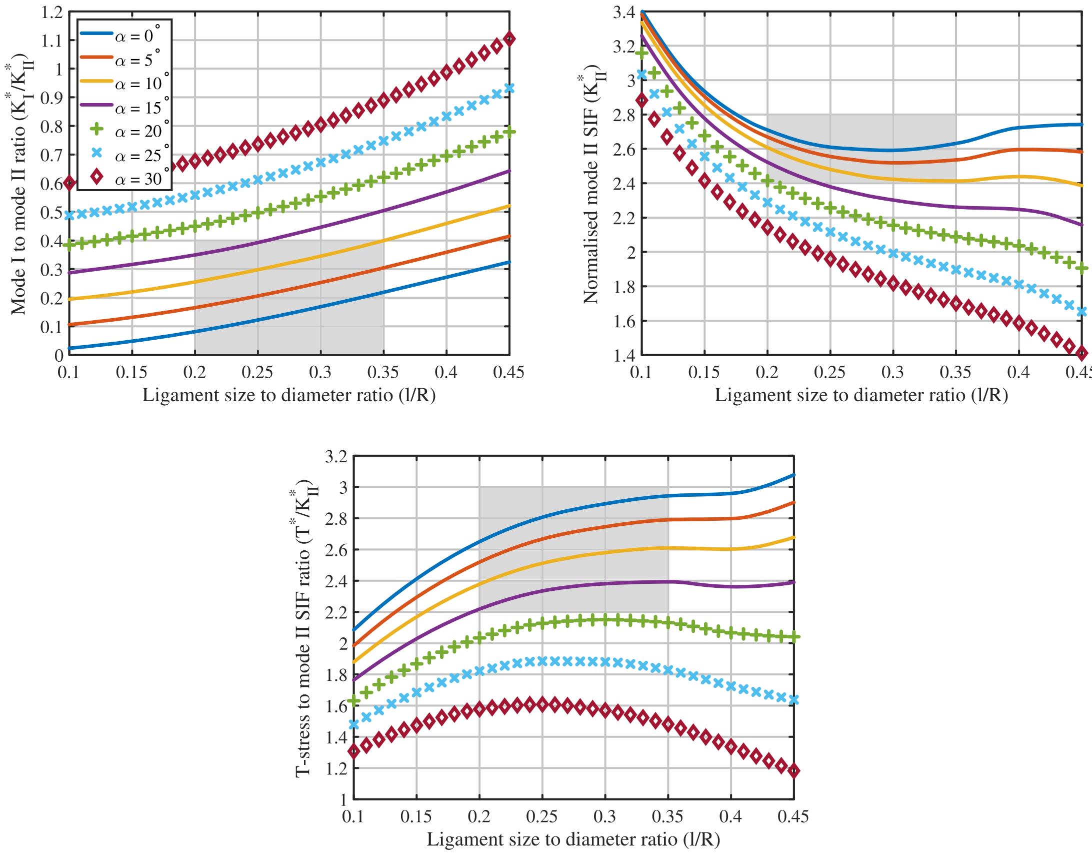


Fig. 3. Variation of normalized crack tip parameters for different values of loading angle versus the ligament between two notch tips.

3 Experiments

3.1. Bedretto rock samples

To prepare samples, rock cores were taken from the Bedretto Underground Laboratory for Geoenergies (BULG) of ETH Zurich, situated in the Bedretto tunnel, a 5.2 km long access gallery to the Furka railway tunnel in southern Switzerland. The ETH research facility is located in a 100 m long cavern below an overburden of about 1000-1200 m, and is hosted in part of a granitic intrusion called the Rotondo Granite, that was emplaced into pre-alpine crystalline basement rock around 300 Mio years ago and is now part of the tectonic unit called the Gotthard Massive. The Bedretto (Rotondo) Granite is a largely homogeneous granitic rock with small to medium grain size. The petrophysical and geomechanical properties of this rock type is given in [20]. Cores with the original radius of 101 mm from the CB borehole were first cut in small lengths of about 30 cm, and then sub-cored into four additional radii of 27, 34.5, 47 and 72 mm, whereby providing Brazilian disk samples of five different sizes. These include Brazilan disks of radii 27, 34.5 and 47 mm with the thickness of about 30 mm and the ones of radii 72 mm and 101 mm with the thickness of about 40 mm.

To prepare the double edge notch Brazilian disk (DNBD) specimens (shown in Fig. 2), the edge cracks for all of the specimens were introduced using a rotating sawing machine. Table 1 reports the geometrical dimensions and the number of specimens for each size of the DNBD tests. Similar to the process used for preparing the DNBD tests, semi-circular bending (SCB) specimens were also prepared to analyze the scale effect on the mode I fracture toughness. The details of the SCB test is given in [21]. Table 1 gives the geometrical details and the number of repetitions for the produced SCB samples. In this table, *a* is the crack length, *S* is the half of support span and *R* is the radius of the specimen.

Table 1. Geometrical details of the test samples for the DNBD and SCB tests on Bedretto Granite.

Experiment set	Radius (*mm*)	Number of repetitions	a/R	α(°)	S/R	Thickness (*mm*)
DNBD	27	8	0.71-0.79	10		29-34
	34.5	9				
	47	10				
	72	9				38-42
	101	6				
SCB	27	8	0.48-0.52		0.6	30-33
	34.5	6				
	47	8				
	72	7				40-42
	101	8				

3.2. Grimsel rock samples

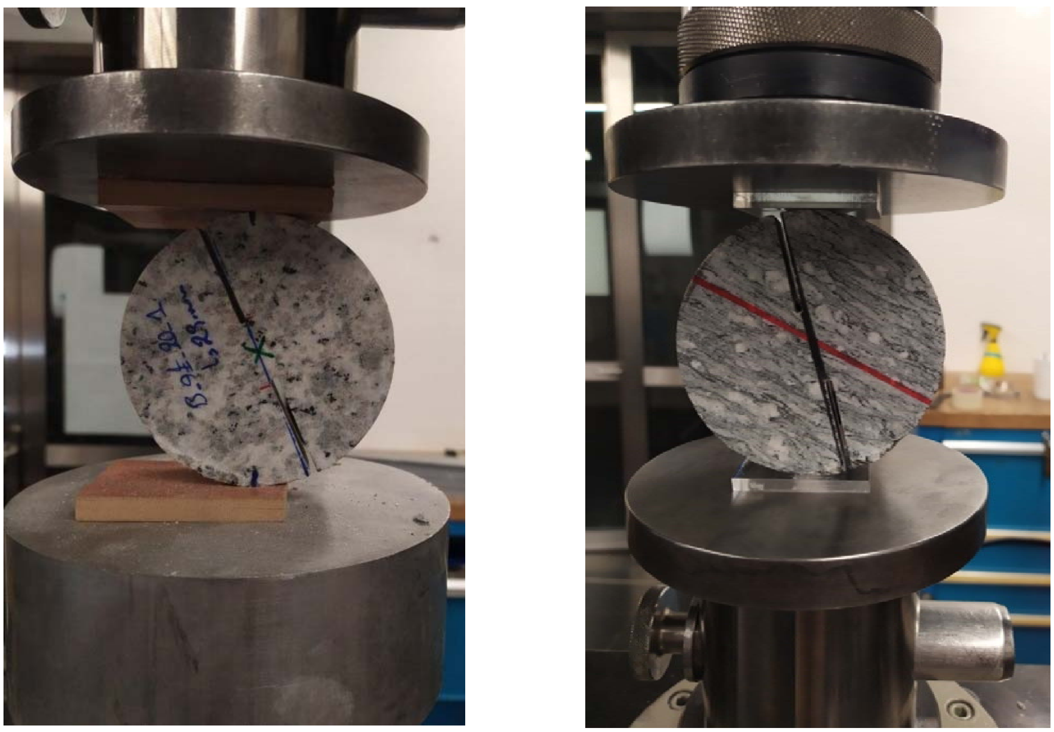
The DNBD specimens of Grimsel Granite were obtained from the cores extracted from the Grimsel Test Site (GTS) in the central Swiss Alps, Switzerland, which is part of the Aare massif. The rocks found in the rock laboratory consists of granitic to granodioritic composition. The rock cores were extracted from the injection borehole, and then sub-cored to make cores of 47mm radius parallel to the foliation, followed by a cutting process to make Brazilian disks with the thickness of around 30mm. To compare the results of K_{IIc} with K_{Ic}, we also prepared SCB specimens with β = 0° and 90°, where β is the angle between the crack and foliation direction. Table 2 summarizes the dimensions and loading configurations of the DNBD and SCB Grimsel samples.

Table 2. Geometrical details of the test samples for the DNBD and SCB tests on Grimsel Granite.

Experiment set	Radius (*mm*)	Number of repetitions	a/R	α(°)	β(°)	S/R	Thickness (*mm*)
DNBD	47	5	0.79-0.8	10	0		26.5-38
		5			22.5		
		5			45		
		4			67.5		
		5			90		
SCB	47	4	23.5		0	0.6	30-32
		2			90		

3.3. Test setup

All the DNBD and SCB tests for Bedretto and Grimsel were conducted using the Zwick/Roell 1474 RetroLine universal testing machine with a load capacity of 100 kN. The displacement rate of 0.5 mm/min was used for the tests while for the DNBD test, two wooden or PMMA sheets were used as flexible jaws (see Fig. 1) to properly distribute the applied load and prevent any possible fracture from the specimen border. Fig. 4 shows the setup used for applying the load to the DNBD Bedretto and Grimsel specimens. Also, For the SCB tests, two roller supports were used to reduce the effect of friction between supports and specimen. The results obtained from the tests are presented in the results and discussion section of the report.



(a) (b)

Fig. 4. DNBD test configuration for (a) Bedretto and (b) Grimsel specimens.

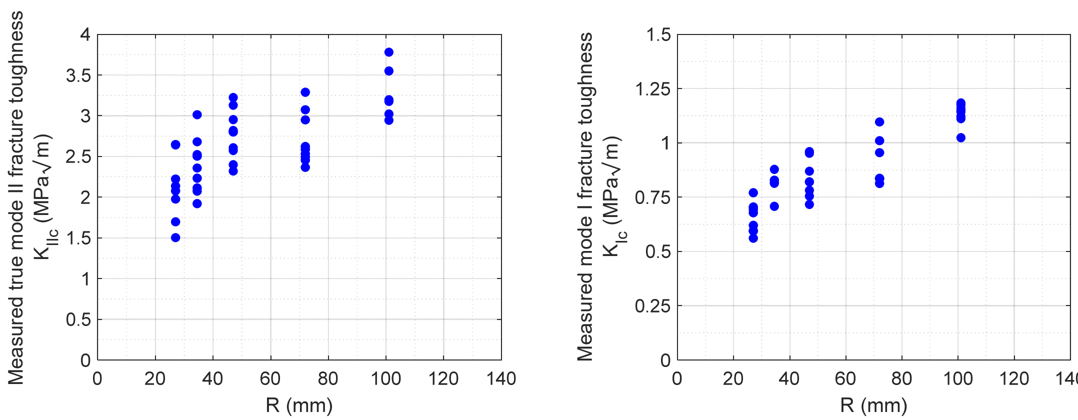
4 Results and discussion

4.1. Bedretto

The fractured DNBD and SCB Bedretto Granite are shown in Fig. 5 in different sizes. As is seen, for all sizes of the DNBD specimens, the fracture has propagated along the initial crack demonstrating the successfulness of the DNBD test in providing true mode II fracture condition.

Fig. 5. Fractured DNBD and SCB Bedretto specimens in different sizes.

After measuring the experimental fracture loads of the DNBD specimens, K_{IIc} values were calculated based on the normalized stress intensity factors presented in Fig 3a. Fig. 6a shows the variations of the true mode II fracture toughness versus the radius of the DNBD specimens. According to Fig. 6, the average of the measured K_{IIc} for the DNBD specimens with the radius of 101 mm is about 60% more than that of with the radius of 27 mm demonstrating the high impact of specimen size on the measured fracture toughness. Noteworthy to mention that the relatively high scatter in the results of each configuration might be due to the mild anisotropic behaviour of the Bedretto Granite.



(a) (b)

Fig. 6. Variation of (a) K_{IIc} and (b) K_{Ic} against the size of the DNBD specimen for Bedretto Granite.

Fig. 6b depicts the scale effect on the measured values of K_{Ic} showing the high dependency of the measured values on the specimen size. For calculating the K_{Ic} values, the procedure detailed in [22] was used. Similar to K_{IIc}, the average of the measured K_{Ic} for the biggest specimen is about 60% higher than the smallest specimen. This shows the significant influence of size on the fracture toughness measured using laboratory sized samples. The results indicate that the fracture toughness values from small size specimens must be corrected before using in the prediction of fracture growth in large-scale experiments such as the ones in in-situ stimulation experiments.

4.2. Grimsel

Fig. 8 demonstrates sample fractured DNBD specimens for five different configurations of β = 0°, 22.5°, 45°, 67.5° and 90°. The anisotropy of the Grimsel Granite has been well characterized in recent years [23–26]. The pictures indicate the self-planar fracture growth in all of the samples demonstrating the shear-based fracture and the applicability of DNBD specimen for anisotropic rocks. As previously mentioned in the introduction section of this report, the PTS test cannot measure K_{IIc} in anisotropic rocks as it is not possible to control the angle between the notch plane and anisotropy orientation. However, it is seen that thanks to the simple loading configuration of DNBD specimen, the variation of K_{IIc} in respect to the angle between the anisotropy orientation and notch surface can be easily measured. Fig. 8 also shows two SCB samples of $\beta = 0° \; and \; 90°$. The variation of K_{Ic} with direction in Grimsel Granite is investigated in details in [27,28].

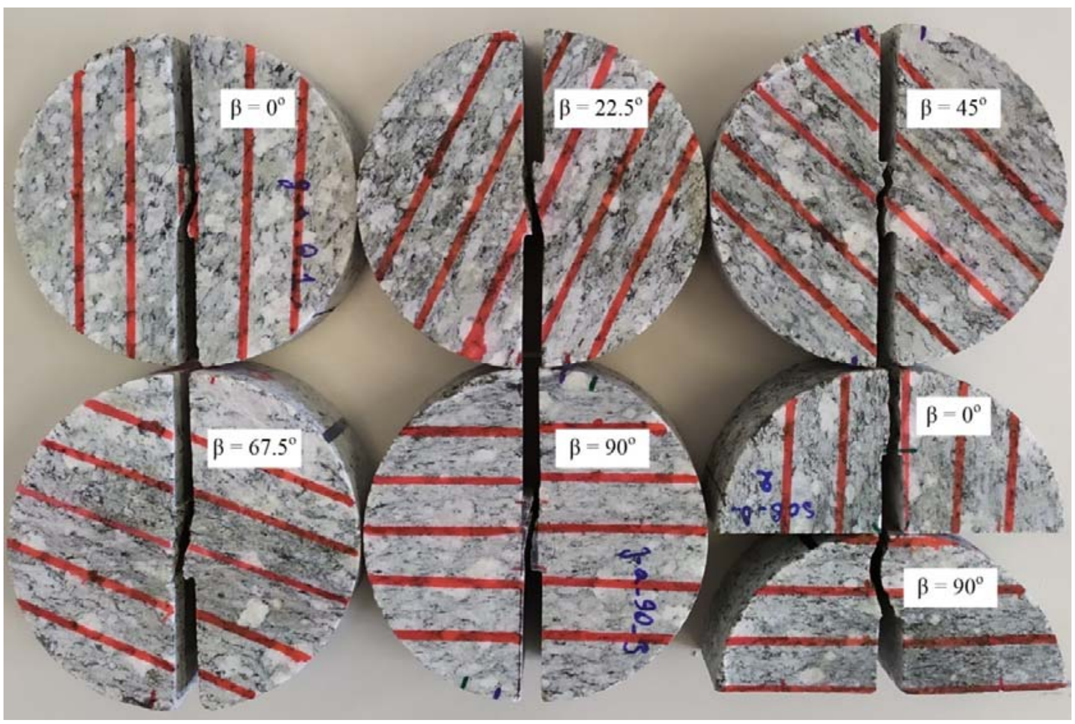


Fig. 8. Fractured DNBD and SCB Grimsel specimens in different directions.

Fig. 9 shows the variations of K_{IIc} against β for Grimsel Granite. As seen, when the notch plane is perpendicular to the foliation direction (β = 90°) the measured KIIc is almost 50% higher than the condition in which the foliation direction is along the notch plane (β = 0°). Additionally, it is seen that by increasing the values of β the scatter between the measured values of K_{IIc} increases. This observation has also been reported for mode I fracture toughness of rocks where the scatter for β = 90° is much higher than β = 0° [19]. Comparing K_{IIc} and K_{Ic} in Fig. 9 reveals that for β = 0°, K_{IIc} is about 2.5 times higher than K_{Ic} while for β = 90°, this ratio is around 2.

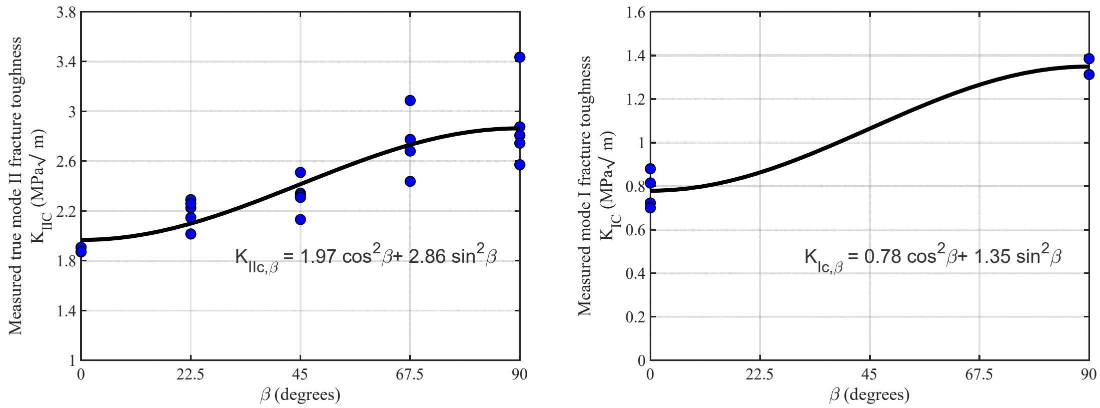


Fig. 9. Variations of the K_{IIc} and K_{Ic} against β for the DNBD specimens made of Grimsel granite.

4.3. Fracture toughness data

Table 3 summarizes the measured values for mode I and true mode II fracture toughness values of Bedretto and Grimsel Granite. Comparing the reported results for K_{Ic} and K_{IIc} demonstrates that K_{IIc} is almost 3 and 2.2 times greater than K_{Ic} for Bedretto and Grimsel Granite, respectively. Similar results have also been reported by researchers using PTS specimen where they showed that K_{IIc} is about 2-4 times greater than K_{Ic} in different types of rocks [14]. We again note that these values of fracture toughness must be corrected for the size effect before using to predict fracture growth in large-scale experiments. An ongoing effort is undertaken by the authors to develop theories to introduce scale-dependent correction factors.

Table 3. Measured K_{IIc} and K_{Ic} values for Bedretto and Grimsel Granite.

Rock type	Specimen	Radius (*mm*)	β(°)	K_{Ic} (*MPa m*$^{0.5}$)	K_{IIc} (*MPa m*$^{0.5}$)
Bedretto	DNBD	27			2.11 ± 0.4
		34.5			2.38 ± 0.34
		47			2.76 ± 0.29
		72			2.71 ± 0.32
		101			3.28 ± 0.32
	SCB	27		0.65 ± 0.07	
		34.5		0.81 ± 0.06	
		47		0.83 ± 0.09	
		72		0.91 ± 0.11	
		101		1.13 ± 0.05	
Grimsel	DNBD	47	0		1.90 ± 0.04
			22.5		2.19 ± 0.11
			45		2.32 ± 0.13
			67.5		2.75 ± 0.27
			90		2.89 ± 0.33
	SCB	47	0	0.78 ± 0.08	
			90	1.35 ± 0.05	

5 Conclusions

To measure the true mode II fracture toughness of rocks, a new specimen and test geometry called double-edge notch Brazilian disk (DNBD) was developed. It was found that this specimen has important advantages comparing to the previously proposed tests, including the applicability of DNBD to anisotropic rocks. Using the finite element simulations, the optimal loading configurations for DNBD test were defined.

Using the new approach, different sizes of the DNBD specimen ranging from 27mm to 101mm were prepared and tested to study the effect of specimen size on the true mode II fracture toughness of Bedretto Granite. Additionally, several DNBD specimens were prepared from Grimsel Granite to investigate the influence of foliation angle on K_{IIc}. Fracture patterns in all the DNBD tests were self-planar, demonstrating a true mode II fracturing in the specimens. It was demonstrated that the measured K_{Ic} and K_{IIc} of Bedretto Granite from the biggest sizes of DNBD and SCB test are 60% higher than that of the smallest ones which shows the significance of the size effect on the measured values of K_{Ic} and K_{IIc}. Also, for the Grimsel Granite, the average value of measured K_{IIc} for $\beta = 90°$ was about 55% higher than K_{IIc} of $\beta = 0°$.

6 Outlook and next steps

The experimental results obtained in this research will be used to derive significantly improved formulations for fracture propagation in anisotropic rocks that can directly be integrated into numerical simulation codes. Predictive simulation is a key step towards future routine engineering of fracture networks by hydraulic stimulation and we will transfer it to large laboratory-scale pilot & demonstration in the Bedretto underground laboratory experiments. By including both tensile-based and shear-based values of fracture toughness we will be able to give more accurate estimations of the fracture growth. Before application in Bedretto, we will validate the simulations at the example of fracture growth near the boreholes from the Grimsel stimulation project. Methods and results will be made available for knowledge transfer through the diverse channels established for the Bedretto initiative.

7 National and international cooperation

This project was conducted via establishing a collaboration between the department of Earth Sciences of ETH Zurich, Switzerland, and the Fatigue and Fracture Research Laboratory of Iran University of Science and Technology, Iran.

8 Publications

1- Bahador Bahrami, Morteza Nejati, Majid Reza Ayatollahi, Thomas Driesner, Theory and experiment on true mode II fracturing of rocks, Engineering fracture mechanics, In press (manuscript attached as Appendix 1).

2- Bahador Bahrami, Morteza Nejati, Majid Reza Ayatollahi, Thomas Driesner, True mode II fracturing of rocks: A size-effect study, In preparation.

3- Bahador Bahrami, Morteza Nejati, Majid Reza Ayatollahi, Thomas Driesner, On the competition of tensile failure and shear rupture at the crack tip, In preparation.

4- Morteza Nejati, Bahador Bahrami, Majid Reza Ayatollahi, Thomas Driesner, True mode II fracture toughness in anisotropic rocks, In preparation.

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10 Appendix I. Preprint of Bahrami et al. (2020)