Characterisation of Rough Fractures in Crystalline Rocks

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Abstract The full characterization of the rough surfaces of fractures and their resulting apertures is an important step in the drive towards an improved understanding of the factors, which control fluid flow through rocks. This is crucial in igneous and metamorphic rocks since fractures in these rocks may form the only significant pathways for fluid migration. Here we describe a three-prong approach for the full characterization of rough fracture surfaces in a selection of crystalline rocks using a suite of in-house developed software. Firstly, profiling is carried out using an optical method, which converts images of epoxy fracture surfaces covered with dyed water into topographies using the Lambert-Beer Law. Many hardware and software (OptiProf) developments give this method the upper hand over previous attempts at spectrophotometric analysis. It is not possible to profile every fracture surface therefore numerical modelling of fluid flow must be carried out using synthetic fractures with rough fracture surfaces that are representative of the natural rock fractures. ParaFrac software allows the analysis and parameterisation of fracture surfaces and apertures. SynFrac software enables the numerical synthesis of fracture surfaces and apertures with prescribed basic parameters. Both procedures take full account of the complex matching properties of the fracture surfaces as a function of wavelength, as well as anisotropy within the properties defining the fracture surfaces and their resulting aperture. They have been rigorously tested on a large suite of synthetic fractures as well as real rock fractures. These tests have allowed relationships between the standard deviation of surface asperity heights, the fractal dimension and the matching parameters to be related to the resulting aperture of the fractures.

Keywords: Rough Fractures, Optical Profiling, Apertures, Synthetic Fractures

Understanding the influence of rock fractures upon fluid flow has much practical benefit in the petroleum (Jones *et al.*, 1998), water (Gudmundson, 2000), geothermal, (Barton, 1998) and nuclear industries (Moreno *et al*., 1985). This is of particular importance in tight and crystalline reservoirs as flow occurs mainly in fractures (Abelin *et al*., 1994; Sahimi, 1993; Hakami & Larsson, 1996) and also due to current trends of depletion of hydrocarbon reserves in clastic reservoirs.

Recently, quantification of fracture surface roughness upon fluid flow has received much attention (Brown, 1987; Iwano & Einstein, 1995; Glover *et al*., 1998a,1998b; Meheust & Schmittbuhl, 2000; Renshaw *et al.*, 2000). The scale invariance of such surfaces, important in modeling their effect upon fluid flow has been described in a variety of crystalline rocks including marble (Poon *et al*., 1992), granite (Brown, 1988), gabbro (Durham & Bonner, 1995) and basalt (Plouraboué *et al*., 2000). To incorporate realistic fracture roughnesses into models of fluid flow in rough fractures we must be able to

(i) measure the roughness of a range of fracture surfaces in nature, (ii) analyse the characteristic features of the measured surfaces, and (iii) create synthetic fractures numerically that share these characteristic features. A suite of in-house software has been developed to fulfil these aims (Fig. 1). Firstly, an optical method for the profiling of rough fracture surfaces in a variety of crystalline rocks is described using OptiProf^{TM} software. This forms the basis for the parameterisation of fracture surfaces using ParaFrac^{TM} software to provide the basic statistical parameters for the creation of synthetic models. These suites of numerical fractures are generated by a new powerful and flexible method implemented in SynFrac^{TM} software. The synthetic fractures can then be used for modelling fluid flow using the local cubic law, solution of Reynolds equation or solution of Navier Stokes equation (Brown *et al.*, 1995; Oron & Berkowitz, 1998), (Fig. 1). High-quality synthetic numerical fractures can be also used for investigations of the statistical properties of rock fractures. Particularly, the mean fracture aperture dependence on the properties of bounding surfaces can be obtained.

Fracture Surface Profiling

The majority of profiling is carried out by mechanical or optical techniques, which are comprehensively reviewed in Adler & Thovert (1999) and in Devili *et al.* (2001). Mechanical stylus profilometers, popularly used for surface characterisation of real rock fractures in the laboratory (e.g., Power *et al.* 1987; Poon *et al.* 1992; Glover *et al.* 1998b) or in the field (e.g., Power & Tullis, 1992; Schmittbuhl *et al*., 1993) work by tracking a stylus across the rough surface with surface elevations measured on a grid at various spacings. The problem is that the range of admissible vertical displacement decreases as the accuracy increases (Schmittbuhl *et al*., 1995), complete coverage of the surface is not possible at high resolution because it takes too long, and there are problems aligning accurately the multiple profiles.

Optical methods popularly involve casting of real rock fractures and the pointwise measurement of aperture using the Lambert-Beer Law (Brown *et al*., 1998; Yeo *et al*., 1998; Amundsen *et al*., 1999). This contribution describes the development of an improved optical method, which provides a fuller and more formalized framework for measuring the surfaces and apertures of fractures than these attempts. This involves (i) advances in high fidelity polymer model (HFPM) preparation, (ii) significant improvements in hardware image capture, lighting and in firmware image capture, (iii) robust methodologies for reliably calibrating the fluids used in the imaging process, and (iv) improved control over the imaging process by using OptiProf^{TM} software (Fig. 1) to correct for technical difficulties and calculate the final measured topography of the surface by calibrating the image produced to dye thickness. This is a fast and high-resolution process, allowing high resolutions (20-200 μm) to be attained in the mean plane of the fracture surface using a high-resolution digital camera.

Methods and Measurements

Sample descriptions

A suite of 3 crystalline rocks (granite, syenite and granodiorite) were trimmed to form blocks with 120×120×100 mm nominal dimensions. Two parallel grooves were created on the opposite face of each block and mode I fractures were carefully propagated from one groove to the other.

These samples were chosen as have low intact rock permeability (1.97×10^{-17} m^2 to 4.83×10^{-16} m^2) and low helium and mercury technique measured porosities, from 0.31% to 1.5%, (Table 1). Sample C (syenite) has the largest pores and best sorted pore size distribution (Fig. 2) and consists of coarse, labradorite laths, which define a parallel, anisotropic fabric. In turn it splits more easily than the others producing a smooth surface with lower fractal dimension.

HFPM preparation

Each fracture half was moulded with Silastic rubber and once set the mould was filled with *c.* 400 cm^3 of clear casting resin (Fig. 3). When fully set the casting resin was removed from the mould, trimmed to 100×100×30 cm, and polished on all surfaces except that of the rough surface. The original rock surfaces are reproduced to within 1 μm as illustrated in Fig. 4, where only a gas bubble on the SEM image of the cast of Sample B (granite) (Fig. 4b) distinguishes between it and that of the real rock surface (Fig. 4a). We therefore have the confidence to term these high fidelity polymer models (HFPMs). Polycarbonate walls were attached to the sides of each HFPM in preparation for digital optical imaging (Fig. 3b). The fracture surfaces may also be mated and inserted into a cell for future fluid flow experiments (Fig. 3c).

Digital Optical Imaging

The HFPM is placed on a light box under a digital colour camera (640×480 pixels, 8-bit grey-scale depth) and imaged, first containing distilled water, and then containing dyed water (Fig. 5). The ratio of the intensity of light for a given pixel at a given location on the fracture between the images containing dye and those containing water is related to the thickness of fluid covering the rough surface i.e., the Lambert-Beer Law, $I_x = I_o \, e^{-K\,c\,T}$, where, I_x is the intensity of the transmitted light, I_o is the intensity of the incident light, K is a material dependent property describing the efficiency with which a material adsorbs light, c is the concentration of the material, and T is the thickness of the material through which the light has passed.

Fluid Calibration

Here, more robust methodologies for calibrating the fluids used in the imaging process are described than the previous attempts (Persoff & Pruess, 1995; Renshaw *et al.*, 2000). Calibration was carried out for distilled water and dyed water (1 g/l) using a polycarbonate tile and a secondary wedge vial device (Fig. 6), providing a measurement of the light extinction properties of the dye and to calculate the fluid thickness. The topography of the fracture surface for each pixel (640×480) is then calculated from the calibrated fluid thicknesses.

Each pocket of the tile was filled with each of the fluids, and a flat transparent cover plate was placed on top to seal the fluid in place during imaging (Fig. 6a). The tile was then imaged multiple times, producing 8-bit greyscale images, intensities varying from 0 to 255 (Fig. 6b). The mean (stacked) image was calculated to remove possible dynamic fluctuations in the incident light intensity or in the sampled video stream. A clearfield equalisation was then performed i.e., subtraction of background image (without subject) from that of the subject to remove spatial variations in incident light intensity. The corrected image for the dyed water was divided pixel-by-pixel by that of the undyed water to remove the effect of the polycarbonate composing the tile and its cover plate. The resulting image represents the ratio of the intensities recorded when the calibration tile is full of dyed water and undyed water, and is dependent upon the fluid thickness if the type and concentration of the dye remains constant. This image was analysed in SigmaScan Pro 5^{TM} to obtain the intensity (0 to 255) distributions for each well (Fig. 6c). Gaussian curves were fitted to this data to obtain the mean intensity value and the standard deviation in intensity for each well. The calibration curve of intensity as a function of fluid thickness for all nine wells is shown in Fig. 6d. This curve is linear on the log-lin scales used in this diagram, thereby conforming to the Lambert-Beer Law, and we can derive a value for K_d of the dye, $K_d = 282.7 \text{m}^2/\text{kg}$. The wedge data was analysed in the same way and the scatter in the data effectively constrains the standard deviations of the tile data.

Conversion to Fracture Surface Topographies

A function fitted to the tile-derived calibration data provides us with a conversion from intensity ratio to dye thickness that allows each pixel of the fracture intensity ratio map to be converted to a thickness of dye below the fluid surface. The resulting data was transformed to provide a fully determined topography for each surface using OptiProf^{TM}, and data from each of two surfaces can be combined to provide an aperture map of the fracture for the scenario where the surfaces touch at a single point or any greater mean aperture.

Technical difficulties

There are several technical difficulties, which must be overcome in the imaging process if the fracture surface roughnesses are to be profiled accurately and the variable apertures calculated correctly. These, together with their solutions provided by software (OptiProf ^{TM}) and hardware developments are listed in Table 2; some of which are illustrated in Fig. 7.

Rough Fracture Parametrisation

We could carry out flow modelling on data from the natural fracture. However, profiling and analysing a natural fracture is expensive and time consuming, and we only have fluid modelling data from a single fracture that might not be representative of all such fractures in the rock. Synthetic fractures tuned to the properties of the rock fractures can be created with different physical properties for modelling application in differing structural situations. Flow modelling on a suite of such fractures allows the mean flow behaviour to be judged, which is representative of that type of fracture enabling us to recognise and account for particular topographic geometries, which may be unrepresentative of the suite in general. Furthermore the scatter in the flow modelling results represents the range of expected values for all fractures with the given geometrical parameters. The fracture parameters chosen to represent the complexity of fracture surfaces are listed below; some of which are defined for the first time. These are determined from profiling data and used in the creation of the synthetic fractures.

Fracture Parameters

We classify the fracture parameters into those parameters associated with individual surfaces, parameters that are only defined when using two surfaces to make a fracture, and arbitrary parameters.

Surface Parameters

1. Standard deviation σ_s (or variance σ_s^2) of asperity heights on each fracture surface. This is a measure of the roughness of the surface asperities (i.e., the difference between the peaks and troughs). It is commonly Gaussian for rock fractures (Brown, 1987; Brown, 1995; Hakimi & Larson, 1996; Meheust & Schmittbuhl, 2001).
2. The fractal dimension D_f of each fracture surface. This is a measure of the scaling behaviour of the surface, and contains information regarding the relative positions of asperities of different sizes on the surface. This parameter is calculated from the log-log slope of the power density spectrum of the surface as a function of wavelength. Durham & Bonner (1995) found this to be a

useful parameter to distinguish fracture surface roughnesses in different rock types; gabbro, D_f = 2.2, granite, D_f = 2.4.

3. The anisotropy of fractal dimension of the surface $A_{sD,}$ which allows the surface to have different fractal dimensions in different directions across the surface.
4. The resolution of the measurement in the fracture plane. This is expressed in measurement points per fracture size, and may be any value for measured fractures depending upon the measurement technique, but is a binary multiple for synthetic fractures (ranging from 256×256 pixels to 1024×1024 pixels in this paper).

Fracture Parameters

5. Once the fracture surfaces have been separated for profiling it is important to fit them back together again for numerical modelling using the correct "matching" approaches. Rough fractures are matched to some degree at long wavelength and relatively unmatched at short wavelength (i.e., the surfaces are relatively independent) (Fig. 8a). In between, the degree of matching varies, but currently it is unknown for any given rock what function describes this gradational behaviour (Fig. 8b). The Brown (1995) approach uses the Mis-match Wavelength (*ML*), and it represents the wavelength lower than which there is no correlation between two fracture surfaces, and higher than which there is complete matching (Fig. 8c). Glover *et al.*, (1998a;1998b) introduces the Maximum Matching Fraction (*MFMAX*) (Fig. 8d) to define the degree of matching reached using the fracture model used. These advances are still not flexible enough to take account of the variation in real rock fractures. To do this, we define a (i) Mis-matching wavelength (ML), (ii) the size of a transition zone centred on the mis-match wavelength (TL), (iii) a minimum matching fraction (*MFMIN*), (iv) a maximum matching fraction (*MFMAX*), and (iv) the shape of the function describing the transition (Fig. 8e).
6. Standard deviation σ_a (or variance σ_a^2) of the aperture defined by the two fracture surfaces. This parameter is a measure of the complexity of the aperture (i.e., the difference between the constrictions and wide portions of the aperture) irrespective of the position of the asperities on the surface. It is commonly non-Gaussian for rock fractures apertures (Iwano & Einstein, 1995; Hakami & Larson, 1996; Olsson & Brown, 1998). In this paper the fracture aperture distributions

are assumed to approximate to a Gaussian distribution. However, this does not lead to invalidities in the procedures described below as this parameter is used only as supporting information.

7. The fractal dimension of the aperture D_f (Cox & Wang, 1993). This parameter is a measure of the scaling behaviour of the aperture, and contains information regarding the relative positions of asperities of different sizes on the surface. This parameter can be calculated from the log-log slope of the power density spectrum of the aperture as a function of wavelength. However it is necessary to notice that the aperture distribution character is not exactly fractal, especially at the low spatial frequencies.
8. The anisotropy of fractal dimension of the surface A_{aD}. This parameter results from any anisotropy in the standard deviations of the fracture surfaces.

Arbitrary Parameters

9. The arithmetic mean height of each surface $<z_s>_a$. This occurs at the peak of the probability distribution of surface heights. This is an arbitrary parameter if a fracture surface is used singly, and only important if two surfaces are used together, as the relative arithmetic mean height of each surface will then control the resulting aperture, with the minimum difference between the arithmetic mean height of each surface being non-zero and controlled by the scenario where the surfaces just touch.
10. The mean aperture. This depends upon the mean surface heights of the two surfaces used to define the fracture aperture. The drawback with popularly used geometric mean apertures $<z_a>_g$ (Brown, 1987), and harmonic mean apertures $<z_a>_h$, (Oron & Berkowitz, 1998) as measures of hydraulic aperture of a fracture is that they collapse to zero is any touching point exists. We therefore introduce a Dual Mean approach (Isakov *et al.*, 2001); the arithmetic mean of the geometric mean apertures along all profiles in the direction of presumed fluid flow through the fracture. It has a physical basis, and is sensitive to anisotropy in the plane of the fracture; i.e., it has different values in different directions through the fracture. We use the dual mean in the two cartesian directions in the plane of the fracture x and y, and give them the symbols $<z_a>_{dx}$ and $<z_a>_{dy}$, respectively.

Fracture parameterisation

The two profiled surfaces comprising the fracture are loaded into ParaFrac software (Fig. 1), then a number of tabbed menus accesses areas for (i) the calculation of basic statistical parameters for each surface and the resulting aperture, (ii) the display and Gaussian/non-Gaussian fitting of probability distributions for surface heights and apertures, (iii) the calculation and display of power spectral density plots of the surfaces and apertures together with the calculation of their respective fractal dimensions, and (iv) the calculation and display of power spectral density ratio plots of the fracture for the derivation of matching parameters.

Basic Statistics

This section takes the individual surfaces and the resulting aperture data, and for each calculates and displays the probability density plot of surface heights and the fracture aperture, respectively. These plots can be used to judge the normality of the distribution. A range of standard distributions can be fitted to the calculated distribution, and these are also shown on the plot. The statistical data produced are summarised in the first section of Table 3.

Fourier Analysis

This section takes the individual surfaces and the resulting aperture data, and for each uses Fast Fourier Transforms (*FFTs*) to calculate and display the power spectral density (*PSD*) of the surfaces and their resulting aperture as function of wavenumber on log-log scales (where the wavenumber k, the wavelength λ and the frequency ν of the Fourier components are related by $k = 1/\lambda$ and $\nu = 2\pi/\lambda$). Linear regression to the full *PSD* for the surfaces, and to the linear high wavenumber portion of the aperture allow the fractal dimensions of the surfaces and the aperture to be calculated. Anisotropy in the fractal dimensions of surfaces and the resulting apertures are obtained by unwrapping the surface (or aperture) in the appropriate direction prior to application of the *FFT*. The *PSDs* and their fitted regressions are displayed and can be printed.

Matching Parameters

This section calculates the ratio of the *PSDs* from the aperture with the sum of the *PSDs* of the two surfaces composing the fracture and plots it as a function of wavenumber on a log-log scale. This parameter is the PSD Ratio (*PSDR*). At large wavenumbers, *k* (i.e., high frequencies and small wavelengths) the *PSDR* tends to unity if the surfaces are completely independent. If the *PSDR* is less than unity, it shows that there is some matching occurring at the highest wavenumbers available in the dataset. It can be seen, therefore that the *PSDR* at the highest wavenumber of the dataset $(PSDR)_{kmax} = (1 - MFMIN)$, and hence *MFMIN* can be obtained. As matching of the two surfaces occurs, the *PSDR* drops to values below unity, but never below zero. This is because there is increasing correlation between the two fracture surfaces that results in loss of power of the Fourier components of the aperture. Consequently, the *PSDR* at the lowest wavenumber of the dataset $(PSDR)_{kmin} = (1 - MFMAX)$, and hence *MFMAX* can be obtained. We define the mis-matching wavelength (*ML*) for the system as the wavelength λ_{ML} (represented by the wavenumber k_{ML}, where $\lambda_{ML} = 1/k_{ML}$) which lies equidistant between the wavelength at which minimum matching occurs and that at which maximum matching occurs in the dataset. The transition length (*TL*) is defined as the difference in wavelength between that at which maximum matching occurs and that at which minimum matching occurs, and corresponds to the width (expressed in wavelength) of the transition zone.

Creation of Synthetic Fractures

SynFrac software, allows the numerical synthesis of fracture surfaces and apertures with 8 prescribed basic parameters to be carried out (Fig. 1). It can provide fractures calculated using the Brown (1995) method, Glover *et al.* method (1998a;1998b), or our improved method of controlling the degree of fracture surface correlation with wavelength. Fracture surface generation is carried out using spectral synthesis (Saupe, 1988) on a grid up to 1024×1024 pixels and at any physical scale. The program implements three different types of high quality random number generation methods, allowing suites of physically distinct fractures to be created which all share the same basic parameters, allowing them to be used in statistically rigorous modelling studies.

Two random number seeds control the actual topographies of the two fracture surfaces, and therefore control the resulting aperture. Hence, we can create a suite of synthetic fractures, say 20, using 20 sets of two random numbers and one set of geometrical parameters derived from a natural fracture. The resulting 20 synthetic fractures will each share the same geometrical parameters as the original natural fracture, but they will be different physically.

Fracture Synthesis Procedure

The spectral synthesis method involves defining a symmetric matrix containing Fourier components. These Fourier components are calculated to obey the various parameters for the fracture. Each component has two parts; (i) the amplitude and (ii) the phase. The amplitude scales with a power law that contains the fractal dimension information, and any information about the relative anisotropy of surface heights. The phase part is controlled by random numbers, which depend in their turn upon the two original random number seeds and the matching parameters.

The first step is to generate two matrices where each point in each matrix corresponds to that in the final matrix of Fourier components. These two matrices contain random numbers that are partially correlated to some degree. The degree of partial correlation depends upon the matching parameters. This step is not necessary for the Brown (1995) approach, as one surface can be generated with one set of random numbers. He then generated a second fracture surface using (i) a different set of random numbers for the Fourier components corresponding to wavelengths that were less than the mis-match wavelength (i.e., where the surfaces were independent), and (ii) the same random numbers that were used to generate the first fracture for the Fourier components corresponding to wavelengths that were greater than the mis-match wavelength (i.e., where the surfaces were perfectly matched). The implementation of the Glover *et al.* (1998a;1998b) method required the use of two different sets of random numbers for the wavelengths that are less than the half the mis-match wavelength, but to generate and use partially correlated random numbers for wavelengths above this value. To do this they naïvely linearly mixed the two random number sets using a linear weighting, which varied from zero at half of the mis-match wavelength to some fraction less than unity representing the maximum matching fraction at the largest wavelength contributing to the fracture. While this procedure does produce a partially correlated set of numbers, they cannot be considered to be truly random because they lose their uniform distribution over the interval zero to unity. Hence, there is a fundamental fault in mixing random numbers this way. We have overcome this problem by implementing a position swapping algorithm that enables a given mixing of two uniformly distributed random number data sets to be attained while retaining a uniform distribution in the final mixed and partially correlated random number data set. This is an elegant solution, but one that requires significant CPU time. Consequently, we use the improved method for creating partially correlated random number data sets to both the new matching approach and our improved implementation of the Glover *et al.* (1998a;1998b) approach.

When all the Fourier components are known and arranged in a 2D complex and symmetric matrix, they are submitted to a 2D Fast Fourier Transform (FFT), the real part of which is the fracture surface with a mean value of zero. It only remains then to scale the surface to the required physical size, to scale the asperities to the size defined by the standard deviation of surface heights, and to shift the mean level of the fracture surface to whatever is required.

Results & Discussion

The optical profiles for each surface have been combined to produce the apertures and are accurate representations of the fracture surfaces (Fig. 9). There are however limitations in terms of the amount of profiles which can be produced therefore any combination of numerical fractures with the same basic geometry but with different physical topographies are generated using SynFrac^{TM} software. The fracture parameters analysed for this process from the respective fracture surfaces are listed in Table 3.

A large number of synthetic rough fractures (100×100 mm) in rocks were created (Fig. 9) as a function of fractal dimension (from 2 to 2.4), standard deviation of bounding surfaces (from 0.01 to 5 mm), mismatch length (from 1 to 50 mm), and minimum and maximum matching fractions (from 0 to 20% and from 80% to 100%, respectively). For each set of parameters a suite of 10-30 fractures was created. Each fracture was analysed to ascertain whether the resulting synthetic fractures had parameters, which matched the synthesizing parameters. In this way we verified the synthesizing algorithms and their implementation in the software.

Aperture distributions are gaussian for all 3 samples (Fig. 10). This is a common situation (e.g., Hakimi & Larson, 1996; Meheust & Schmittbuhl, 2001). The mean arithmetic apertures of the resulting fractures were obtained for each suite of fractures, and have been examined as a function of (i) surface asperity distribution (standard deviation), (ii) fractal dimension, (iii) anisotropy, and (iv) mismatch parameters (Fig 11).

Dependence of mean fracture aperture on the standard deviation of bounding surfaces is shown in Fig. 11a (isotropic fractal dimension 2.2, mismatch length $\lambda_c = 10$ mm, transition length $\tau = 20$ mm). The scattering in the mean fracture aperture increases as well as the mean fracture aperture increases, so the relative scattering values are constant.

The fracture aperture depends non-linearly upon the fractal dimension (Fig. 11b). Two data sets are presented in this figure, symbols Δ and ∇ correspond to surface standard deviations of 0.3 mm and 0.6 mm, respectively. The change of the standard deviation causes a proportional change of fracture aperture again. The fracture aperture increases with fractal dimension as the roughness of fracture surfaces increases. It was found, that isotropic fractures have the least mean aperture, if all other parameters remaining constant (Fig. 11c, fractal dimension 2.1, standard deviation 0.5 mm). The mean aperture increases as anisotropy appears.

Variation of the transition length parameter yields smooth transition between Brown (1995) and Glover *et al.* (1998a;1998b) methods. The variation of the mean fracture aperture during this transition is shown in Fig. 10d. The method of Brown gives the smallest values of fracture aperture and can underestimate it. The mean aperture of the synthetic fracture increases as the transition length increases up to 80 mm. As the transition length become comparable to the size of whole fracture (100 mm), further increasing of the transition length does not affect the fracture properties. A large transitional length causes considerable scattering of mean aperture values, because the correlation between long-wave harmonics with highest amplitude becomes random.

Power spectral densities (PSD) ratios for the 3 samples are shown in figure 12. It is clear that the Glover et al., (1998a;1998b) model and our new model more closely reflect the matching properties of real rock fractures than the Brown (1995) approach and therefore qualify as better predictors of fracture apertures in rough fractures.

Conclusions

A three-stage process for the full characterization of rough fracture surfaces aided by specially developed software has been described. The optical profiling of fracture topographies from 3 crystalline rocks is carried out by OptiProf^{TM} , the images of which are imported into ParaFrac ^{TM} and then analysed to provide the input parameters for SynFrac^{TM} to create suites of synthetic fractures tuned to the real rock fractures.

Our optical method involves new developments that make existing concepts (i.e., spectrophotometric analysis of epoxy casts) into a very robust method for determining rough fracture apertures. Firstly, advances in HFPM preparation result in fidelity of reproduction at the sub-millimetre scale (<+1 μm). There are improvements in hardware image capture from previous attempts (Persoff & Pruess, 1995; Brown *et al.*, 1998; Hakami & Larsson, 1996; Yeo *et al.*, 1998) using high quality digital cameras and video streams. This method has a high lateral resolution, which was 15 μm for our camera/imaging set-up but can be better than this if higher resolution cameras are used. It has a similar height resolution (15 μm) but could be smaller if 16-bit or 24-bit imaging hardware is used. There are also improvements in firmware image capture i.e., the capturing of images from the camera through to the final stored images. Advances in the multiple capture of images from the video stream has improved the quality of the initial images as well as making advanced image analysis options possible on the captured image data.

Robust methodologies have been developed for reliably calibrating the fluids used in the imaging process. This allows the Lambert-Beer law to be applied to the measured data to convert intensities into accurate surface heights. Although the Lambert-Beer law has been used previously, few studies report the calibration of the fluids used in the imaging process (Persoff & Pruess, 1995; Renshaw *et al.*, 2000), which resulted in only arbitrarily scaled relative surface height measurements being possible (Brown *et al*., 1998; Hakami & Larsson, 1996).

In-house developed OptiProf^{TM} software was used for the analysis of the image data to correct for and negate problems with the image capture process. Techniques that are newly implemented are (i) multiple imaging, (ii) clearfield equalisation, (iii) stacking, (iv) software keying, (v) bubble detection, (vi) static detection, (vii) individual pixel calibration, (viii) and precise filling. A full comparative analysis of the sources of error in the measurements, together with the scope for their reduction is presented. The lack of such an analysis in many of the previous papers may stem from a lack of confidence in some of the relatively primitive methods then being employed (Brown *et al*., 1998; Hakami *et al*., 1996; Yeo *et al*., 1998).

A new definition of mean aperture is used (the dual mean) which removes the difficulty of zero calculated aperture for rock apertures that touch at a single point, but is physically reasonable.

This data can be used for computational fluid flow modelling purposes. However, we describe new, more realistic and flexible approaches for the creation of synthetic fractures tuned to the properties of the real rock fractures. The Brown (1995) and Glover (1998a;1998b) models tend to underestimate fracture aperture as use restricted parameters to control the fracture aperture. In this paper we introduce four parameters to describe the matching characteristics of a fracture, which are described in the previous section. These parameters define not only the mis-match wavelength, but also a maximum matching fraction, a minimum matching fraction and a transition length to describe the length scale over which the change in matching occurs.

Relations between the fractal dimension, matching parameters and the resulting aperture was established. It was found that the resulting aperture increases linearly with the standard deviation of the fracture surfaces increase. The resulting aperture depends non-linearly on the fractal dimension and anisotropy of bounding surfaces. It was also found that the Brown model of rough fracture essentially underestimates the fracture aperture, while the Glover et al. model slightly overestimates it. The new AUPG model is most flexible and allows the range of fracture instances between the Brown and Glover et al. models in order to reflect features of natural fractures in the best way.

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Tables

Table 1. Petrophysical data for intact samples.

	Rock Type	Sample Location	Grain Size	$Hg\phi$ (%)	S_{WI} (%)	$He\phi$ (%)	K_L (mD)
A	Granodiorite	Finland	Fine	0.31	98.8	0.10	0.002
B	Granite	Sweden	Coarse	0.50	99.2	4.45	0.004
C	Syenite	S. Norway	Coarse	1.20	94.5	0.20	0.0004

Notes: $Hg\phi$ **= mercury injection porosity,** S_{WI} **= irreducible water saturation derived from mercury porosimetry,** $He\phi$ **= helium porosity,** K_L**-Klinkenberg-corrected (Hassler-sleeve) gas permeability.**

Table 2. Technical difficulties encountered during the imaging process and their solutions, which are incorporated into OptiProf^{TM} software.

Technical Difficulty	Solutions
1. Fluid Level Control: Each of the fractures must be filled with dyed and undyed water up to exactly the same arbitrary level.	A horizontal datum line is marked onto opposite walls surrounding the fracture. Lining these up and filling to this level removes the parallax errors.
2. Lateral alignment: The imaged surface must be in exactly the same *xy* position for imaging with dyed water and undyed water even though it must be moved for replacing the fluids.	Four fixed reference points within the software are set over point marks that are etched into the top of the walls surrounding the fracture These are used to realign the HFPM when removed and refilled.
3. Dynamic noise in the imaged light intensity: From the light source and video stream. Leads to variations in brightness of the imaged intensities.	Taking multiple images of the HFPM with each fluid in place, and averaging the result pixel by pixel.
4. Static noise in video signal: A stripe effect on an image of a uniform field, which varies with camera lens aperture.	The variation in the sensitivity of the CCD between each pixel on its surface was removed by calibrating each pixel of the CCD individually, for every aperture.
5. Non-uniformity of the light source.	Each of the averaged intensity images from the measurements on the undyed and dyed water were subjected to a clearfield equalization to remove variations due to changes in the incident light source.
6. Bubbles and dust in the fluids: Particles and bubbles in the fluids are mobile if the fluid is perturbed.	The software compares multiple images with bubbles and dust in different locations and recognizes characteristics, which move. These are removed from the relevant images prior to averaging.
7. Opaque particles in the HFPM: Small, uncommon and obvious in the final image as thin low intensity spikes.	Recognized and removed with the affected pixel being reduced to the weighted mean of the surrounding 8 pixels.

Table 3: Rock Fractures Tested with the New Method

Parameter	A	B	C
Surface Parameters			
Standard deviation (upper), ${}_U\sigma_s$ (mm)	2.91	1.60	1.56
Standard deviation (lower), ${}_L\sigma_s$ (mm)	2.91	1.67	1.65
Variance (upper), ${}_U\sigma_s^2$ (mm^2)	8.47	2.56	2.43
Variance (lower), ${}_L\sigma_s^2$ (mm^2)	8.47	2.79	2.72
Fractal dimension (upper), ${}_UD_f$ (-)	2.35	2.24	2.13
Fractal dimension (lower), ${}_LD_f$ (-)	2.35	2.23	2.21
Anisotropy in fractal dimension (upper), ${}_UA_{sD}$ (-)	2.06	0.87	0.96
Anisotropy in fractal dimension (lower), ${}_LA_{sD}$ (-)	1.82	0.82	1.01
Physical size, L (mm)	103	95.9	96.8
Measurement points per fracture size (-)	512	477	505
Resolution (μm)	200	200	190
Fracture Parameters			
Mis-match Wavelength (*ML*)	13	4.5	3.3
Transition Length (*TL*)	20	7.5	6.4
Maximum Matching Fraction (*MFMAX*)	0.98	0.97	0.98
Minimum Matching Fraction (*MFMIN*)[1]	-0.07	-0.02	-0.06
Standard deviation, σ_a	0.92	0.56	0.39
Fractal Dimension, D_f	2.50	2.70	2.60
Anisotropy in fractal dimension of the aperture, $A_a\sigma$	1.13	1.00	1.03
Arbitrary Parameters			
Arithmetic mean aperture $\langle z_a \rangle_a$ (mm)	2.57	1.76	1.34
Harmonic mean aperture $\langle z \rangle_h$ (mm)	0	0	0
Geometric mean aperture $\langle z \rangle_g$ (mm)	0	0	0
Dual mean of fracture aperture in x-direction (mm)	2.22	1.52	1.18
Dual mean of fracture aperture in y-direction (mm)	2.08	1.55	1.21

Notes: Harmonic and geometric means of the fracture are 0 because at least one touching point exists, where the aperture is 0. A = Granodiorite, B = Granite, C = Syenite.

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[1] The theory presumes the minimum value for the Minimum Matching Fraction (MFMIN) to be zero. Negative values were found in the process of measurements and characterization may mean the theory does not reflect fracture features perfectly. Authors have no reasonable explanations to these negative values.

Figure Captions

Fig. 1: The software framework for characterisation of rough fractures in crystalline rocks. OptiProf^{TM} provides considerable control over the imaging process and calculates the final surface topographies. This data can be input into Femlab ^{TM} physical process modelling software, however, this is more likely to be obtained from numerical models created using ParaFrac^{TM} and SynFrac^{TM} software and tuned to the profiling data.

Fig. 2: Mercury injection pressure curves for the samples used for profiling. Sample C (syenite) has the largest pores as evidenced by easier breakthrough of mercury relative to samples A and B.

Fig. 3: (a) The procedure for creating high fidelity polymer models (HFPMs). (b) HFPM with built-up sides for pointwise determination of aperture (c), 2 surfaces mated and housed in flow cell for fluid flow experiments.

Fig. 4: The quality of reproduction of the surfaces by HFPMs. (a) SEM backscattered image of the surface of the original rock showing muscovite mica growth in two directions to the right of the field of view and kaolinite to the left, and (b) the exactly corresponding area of the resulting HFPM.

Fig. 5: Digital optical imaging set-up. This set-up is arranged so that the intensity of light captured by the camera can be accurately measured. Hence, the camera was set to manual exposure control, manual light colour balance, and a high quality manual aperture and focus zoom lens was used. The whole arrangement was shielded from ambient and reflected light, using black-out curtains and a thick rubber mat that covered all parts of the light box except that directly under the subject.

Fig. 6: Fluid calibration. (a) The polycarbonate tile. (b) Image of dyed water occupying the calibration tile. (c) The number of pixels in each well as a function of the ratio of the intensity with dyed water to that with undyed water (0 to 255, 8-bit). (d) The calibration curve.

Fig. 7: An image of the HFPM during measurement by fracture surface profiler software (OptiProf^{TM}) showing the different technical difficulties encountered: (1) Usage of location marks on walls to lock HFPM in position during imaging. (2) Dynamic noise across whole image. (3) Particles in the HFPMs. (4) Static distortions giving regular structure in video signal. (5) Bubbles and dust in fluids.

Fig. 8: Approaches in the matching of fracture surfaces. (a) upper: well matched at large scale, lower: independent behaviour at small scale, (b) variation in matching behaviour between scales, (c) the classic approach used by Brown (1995), (e) the approach used by Glover *et al.* (1998a;1998b), and (f) the approach developed in this work to more accurately reflect matching behaviour in natural fractures.

Fig. 9: Profiled and numerical fracture results for Sample C (syenite), (a), rough fracture surface 1 & 2 (b), surface 1 & 2 combined to produce aperture, and (c) synthetic fracture.

Fig. 10. Basic statistics for rough fracture apertures; all apertures approximate gaussian distributions (a) granodiorite, (b) granite and (c) syenite.

Fig. 11: (c) Mean synthetic fracture aperture as a function of the anisotropy of surfaces. Fractal dimension 2.1, mismatch length 10 mm, transition length 20 mm, standard deviation of surfaces 0.5 mm. (d) Mean synthetic fracture aperture as a function of the transition length. Fractal dimension 2.2, mismatch length 10 mm, transition length 20 mm, standard deviation of surfaces 0.5 mm.

Fig. 12: Power spectral density (PSD) ratio plots for derivation of fracture parameters (a) granodiorite, (b) granite and (c) syenite. Natural fracture (—), AUPG model (**---**), Glover *et al.* model (—), Brown model (---).