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Fracture asperity evolution during the transition from stick slip to stable sliding

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Keywords: Fracture asperity, stick slip, stable sliding, direct-shear experiment, acoustic emission, contact area.

Summary

Fracture asperities interlock or break during stick slip, and ride over each other during stable sliding. The evolution of fracture asperities during the transition between stick slip and stable sliding has attracted less attention, but is important to predict fracture behaviour. Here we conduct a series of direct-shear experiments on simulated fractures in homogenous polycarbonate to examine the evolution of fracture asperities in the transition stage. Our results show that the transition stage occurs between the stick slip and stable sliding stages during the progressive reduction in normal stress on the smooth and rough fractures. Both the fractures exhibit the alternative occurrence of small and large shear stress drops followed by the deterministic chaos in the transition stage. Our data indicate that the asperity radius of curvature correlates linearly with the dimensionless contact area under a given normal stress. For the rough fracture, a bifurcation of acoustic energy release appears when the dimensionless contact area decreases in the transition stage. The evolution of fracture asperities is stress-dependent and velocity-dependent.

Introduction

Fractures are ubiquitous in solid materials and induced by internal (e.g., thermal) and external (e.g., seismic) loads. After the formation of fractures, friction between opposite surfaces governs fracture behaviours, and strongly influences the mechanical behaviours of the materials. Fractures behave stick slip or stable sliding, depending on the relationship between the elastic stiffness of loading system and critical rheologic stiffness of fractures [1, 2]. Stick slip could occur under a high normal stress (or at a large shear velocity), while stable sliding may appear under a low normal stress (or at a small shear velocity). When the normal stress (or shear velocity) varies over a wide range, a transition between stable sliding and stick slip happens. Accurate prediction of the transition can avoid undesirable stick slip on material surface [3] and uncover the mechanism of earthquake recurrence [4].

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Laboratory direct-shear experiments have been used commonly to investigate the shear characteristics of pre-existing fractures [5-8]. Particularly, the transition between stable sliding and stick slip can be observed in some experiments [9-12], and is highly related to the evolution of fracture asperities [13, 14]. These asperities support external loads, and may interlock together or ride over each other to control fracture behaviour. The detachment of asperity contacts dominates the onset of fracture slip [15]. The fracture energy from asperity breakage increases with larger shear displacement [16]. The asperity degradation becomes more complex if two-order asperities (i.e., unevenness and waviness) are considered in the shear process [17]. Previous studies mainly focus on the evolution of fracture asperities in the stick slip stage but rarely look into the asperity evolution in the transition stage. The asperities may experience either catastrophic failure in the stick slip stage or minor damage in the stable sliding stage. The transition is most likely accompanied by a partial change in asperity population. Understanding the unrevealed change could provide a critical clue to predict fracture behaviour.

We perform direct-shear experiments on artificial fractures to investigate the evolution of fracture asperities during the transition from stick slip to stable sliding. We use polycarbonate as a host material to eliminate the effect of material heterogeneity on fracture behaviour, and shed light on the effect of surface heterogeneity on the behaviour using relatively smooth and rough fractures. We unload the normal stress in multiple steps to highlight the transition from stick slip to stable sliding, which has rarely been investigated but sometimes encountered from natural faults [11, 18]. In the experiments, we measure the shear stress, load point displacement and acoustic emission (AE) energy, and derive the asperity radius of curvature, dimensionless contact area and stiffness ratio to infer the evolution of fracture asperities in the transition stage. We finally discuss the influences of normal stress and load point velocity on the change in asperity radius of curvature.

Experimental methods

We performed a series of direct-shear experiments on smooth and rough fractures in Makrolon polycarbonate (Figure 1). The density, Young's modulus and Poisson's ratio of this polycarbonate are 1.2 g/cm^3 , 2.48 GPa and 0.38 , respectively. We cut the fixed and driving plates using a waterjet machine. The interface between two cut surfaces with a flatness of 0.13 mm was used to simulate a rough fracture, and a smooth fracture was formed after flattening the surfaces to 0.02 mm using a grinding machine. The root mean square (RMS) roughnesses of the smooth and rough surfaces were 0.12 and 0.28 mm , respectively, which were calculated based on the topographical contours using a structured-light 3D scanner (Figure 2). We used two load cells to measure the normal and shear loads provided by servo-controlled hydraulic rams, and installed a linear variable displacement transformer (LVDT) on the vertical hydraulic ram to measure load point displacement. A data acquisition system was employed to monitor the loads and displacement at a sampling rate of 100 kHz . An AE monitoring system was used to record AE signals at a sampling rate of 3 MHz , and four piezoelectric sensors were attached on the driving plate along the fracture. Both the pre-amplitude gain and amplitude threshold were 40 dB to compensate for ambient noise.

Figure 1 Direct-shear setup with simulated fracture formed between polycarbonate plates with a thickness of 9.3 mm.

Figure 2 Topographical contours of (a) smooth and (b) rough fractures.

The direct-shear experiments on the smooth and rough fractures were conducted at a loading point velocity of 10 $\mu\text{m/s}$. The normal stress was initially 2.5 MPa and decreased in multiple steps each with 0.2 MPa normal stress reduction and 3 mm load point displacement until the shear stress evolved nearly constant.

We also carried out stepped-velocity friction experiments to evaluate the velocity dependence of friction coefficient using the same direct-shear setup. We measured the friction coefficient when the velocity varied between V_0 and V_1 (Figure 3a) based on the rate-and-state friction constitutive law [19]. The friction rate parameter ($a-b$) can be determined as:

$$(a-b) = \frac{(\mu_1 - \mu_0)}{\ln(V_1/V_0)} \quad (1)$$

where μ_1 and μ_0 are the friction coefficients at velocities V_1 and V_0 , respectively, and a and b denote the direct and evolutionary effects of velocity change, respectively. When ($a-b$) value is negative, the fracture is velocity-weakening and has the potential for rupture nucleation, while positive ($a-b$) value indicates that the fracture is velocity-strengthening and inherently stable.

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Figure 3 Determination of friction rate parameter and critical slip distance using stepped-velocity friction experiments.

The instability of a velocity-weakening fracture occurs when the stiffness ratio (K) is less than 1 [2]. The stiffness ratio is defined as:

$$K = \frac{k}{k_c} \quad (2)$$

where k is the elastic stiffness of the test system, and k_c is the critical rheologic stiffness of the fracture and can be calculated as:

$$k_c = \frac{-\sigma_n(a-b)}{D_c} \quad (3)$$

where σ_n is the normal stress, and D_c is the critical slip distance, over which the friction coefficient evolves with the velocity change.

Experimental results

Figure 4a shows the shear behaviour of the smooth fracture when the normal stress decreases from 2.5 to 1.1 MPa in 8 steps. The fracture exhibits stick slip with similar magnitudes of shear stress drop in the first 3 steps and stable sliding with nearly zero shear stress drop at the end of the last step. In between, a transition from stick slip to stable sliding occurs, accompanied by the irregular reduction in shear stress under different normal stresses. At the beginning of the transition stage, a small shear stress drop is followed by a large shear stress drop. The number of small shear stress drop preceding a large shear stress drop then increases with lower normal stress until the shear stress drop shows an apparently random disorder, known as deterministic chaos [20], at the beginning of the last step.

(a)

(b)

Figure 4 Shear behaviours of (a) smooth and (b) rough fractures during normal stress unloading. The transition stage is highlighted in orange background.

The shear behaviour of the rough fracture is similar to that of the smooth fracture, including the stick slip, transition and stable sliding stages (Figure 4b). The slick slip stage lasts for 2 steps. Similar to the shear behaviour of the smooth fracture, the transition stage is initially dominated by the alternative occurrence of small and large shear stress drops and finally accompanied by the deterministic chaos. However, the transition stage initiates under higher normal stress, and changes to the stable sliding stage at a smaller load point displacement.

The AE energy released from the smooth fracture keeps roughly constant in the slick slip stage (Figure 5a), which agrees with the constant drop of shear stress. In the transition stage, the low and high amounts of AE energy correspond to small and large shear stress drops, respectively, indicating the occurrence of slow and fast ruptures. The AE energy progressively disappears during the development of deterministic chaos and stable sliding.

Figure 5 Evolution of shear stress and AE energy of (a) smooth and (b) rough fractures during normal stress unloading. The transition stage is highlighted in orange background.

The amount of AE energy from the rough fracture is generally smaller than that from the smooth fracture (Figure 5b), which is probably due to more AE events progressively occurring on the rough fracture. The AE energy decreases from the stick slip to transition stage, and nearly no AE energy is recorded in the stable sliding stage. In the transition stage, the amount of AE energy is not strongly correlated with shear stress drop. The random oscillation of AE energy demonstrates that the surface roughness significantly modifies the shear behaviour of the fracture. Particularly, the irregular evolution of shear stress drop is early-occurring and long-lasting in comparison to that of the smooth fracture.

A typical variation of friction coefficient with load point displacement measured from the stepped-velocity friction experiment is shown in Figure 3b. The critical slip distance and friction rate parameter as a function of load point displacement are summarized in Figure 6. The rough fracture shows larger fluctuations in critical slip distance and friction rate parameter than the smooth surface owing to higher roughness of fracture surface. The average critical slip distances of the smooth and rough fractures are 15 and 27 μm , respectively, and the average friction rate parameters are -0.039 and -0.050, respectively. The negative friction rate parameters indicate that both the fractures are velocity-weakening. The stiffness ratios of the smooth and rough fractures corresponding to each normal stress are listed in Table 1. The stiffness ratios of both the fractures increase with lower normal stress. In other words, the elastic stiffness of the test system approaches the critical rheologic stiffness of the fracture during the unloading process, resulting in the transition from stick slip to stable sliding.

Figure 6 Friction rate parameter (red) and critical slip distance (black) for smooth (square) and rough (circle) fractures as a function of load point displacement.

Table 1 Stiffness ratio of smooth and rough fractures under different normal stresses.

Normal stress (MPa)	2.5	2.3	2.1	1.9	1.7	1.5	1.3	1.1
Smooth fracture	0.41	0.44	0.48	0.53	0.6	0.68	0.78	0.92
Rough fracture	0.54	0.59	0.64	0.71	0.79	0.9	1.04	

Discussion

Our results show that the change in surface roughness strongly influences the shear behaviour of pre-existing fractures, particularly the fracture behaviour in the transition stage. The surface roughness controls contact area on the fracture, and the occurrence of shear stress drop and deterministic chaos depends highly on the evolution of contact area. The contact area (A_d) can be derived as the ratio of the peak shear load to the shear strength of the fracture. For a single, representative asperity, the radius of curvature (R) can be written as [21]:

$$R = \left(\frac{A_d E}{F_n \sqrt{\pi}} \right)^2 h \quad (3)$$

where E is the Young's modulus, F_n is the normal load, and h is the RMS roughness.

Figure 7 Asperity radii of curvature of smooth (square) and rough (circle) fractures as a function of dimensionless contact area during normal stress unloading. The solid point highlights stiffness ratio in the transition stage, and the open and half-open points denote those in the stick slip and stable sliding stages, respectively.

We use the dimensionless contact area, defined as the ratio of the derived contact area to apparent fracture area, to quantify asperity contacts on the smooth and rough fractures. As shown in Figure 7, the asperity radii of curvature of the smooth and rough fractures range 5.2-7.0 mm and 7.9-11.3 mm, respectively. When the normal stress decreases, the dimensionless

contact area reduces. Under a given normal stress, the asperity radius of curvature decreases linearly with smaller dimensionless contact area, showing that a flatter asperity corresponds to a larger derived contact area. The variation in asperity radius of curvature in the transition stage is larger than that in the stick slip stage, which may be attributed not only to asperity contact reformation but also to sheared-off particle rearrangement. In the stable sliding stage, the shear load is constant, and a single point is plotted for each fracture.

For each fracture, the AE energy decreases with smaller dimensionless contact area (Figure 8), which is similar to the change in asperity radius of curvature (Figure 7). The AE energy from the rough fracture drops faster than that from the smooth fracture, which explains the reason for the transition stage of the rough fracture appearing in an early stage (Figures 4b and 5b). The AE energy in the transition stage is lower than that in the stick slip stage, indicating that the asperity damage mainly occurs in the stick slip stage. Figure 8 also shows a more scattered AE distribution in the transition stage of the rough fracture presumably due to the breakage of asperity junctions over a wide range of derived contact area under lower normal stress. The bifurcation of AE energy while decreasing with smaller dimensionless contact area can be attributed to the non-uniform distribution of normal stress on irregular asperities [14]. A given dimensionless contact area may correspond to multiple AE energy amounts, suggesting that the asperity contact mechanisms are different even if the derived contact areas are apparently the same. The AE energy roughly correlates with shear stress drop (Figure 9), and the scattering pattern is likely dependent on surface heterogeneity. Negligible AE energy is recorded during the stable sliding stage and not shown in this figure.

Figure 8 AE energy of smooth (square) and rough (circle) fractures as a function of dimensionless contact area during normal stress unloading. The solid point denotes AE energy in the transition stage, and the open point means AE energy in the stick slip stage.

Figure 9 AE energy of smooth (square) and rough (circle) fractures as a function of shear stress drop. The solid point denotes AE energy in the transition stage, and the open point means AE energy in the stick slip stage.

The stiffness ratio is inversely proportional to the dimensionless contact area (Figure 10). When the normal stress decreases, the stiffness ratio increases, showing the transition of fracture behaviour from unstable slip to stable sliding [2]. Meanwhile, the dimensionless contact area decreases, implying the detachment of asperity contacts and the generation of sheared-off particles. In the transition stage, the variation range of dimensionless contact area becomes smaller with lower normal stress, which also reflects a minor change in surface roughness. This observation is consistent with the direct examination of asperity evolution on a granite fracture by Engelder [22], in which asperity damage and wear groove are observed in the stick slip stage, while asperity indentation and ploughing are accompanied with stable sliding.

Figure 10 Stiffness ratio of smooth (square) and rough (circle) fractures as a function of dimensionless contact area during normal stress unloading. The solid point highlights stiffness ratio in the transition stage, and the open and half-open points denote those in the stick slip and stable sliding stages, respectively.

In the transition stage, the evolution of asperity contacts can be influenced not only by normal stress but also by load point velocity (Figure 11). The asperity radius of curvature of the smooth fracture increases with higher normal stress, as the derived contact area becomes larger on a highly squeezed fracture. The increase in load point velocity induces the reduction in asperity radius of curvature, which is associated with the detachment of asperity contacts caused by shear dilation at a large load point velocity [23].

Figure 11 Asperity radius of curvature of smooth fracture as a function of normal stress at different loading point velocities in the transition stage.

This study demonstrates the transition from stick slip to stable sliding, which occurs under a narrow range of normal stress and is thus rarely captured in nature. Similar to the previous studies on the transition from stable sliding to stick slip [9, 10], the produce of the transition stage is commonly achieved based on a series of trial experiments because of our poor understanding on this transition phenomenon. The occurrence of the transition stage is dependent on surface roughness, stress condition, shear velocity, etc. The evolution of asperity contacts can reflect the joint influence of these intrinsic and extrinsic factors. Our study indicates that some asperity responses in the transition stage are different from those in the stick slip stage, such as bifurcation of AE energy, which could promote our understanding of fracture friction and our ability to predict fracture behaviour.

Conclusions

We conduct the direct-shear experiments on smooth and rough fractures to observe the evolution of asperity contacts during the transition from stick slip to stable sliding. The transition stage appears under a narrow range of normal stress, and exhibits the alternative occurrence of small and large shear stress drops, followed by the deterministic chaos. Our data demonstrate that a considerable damage of fracture asperities occurs in the cases with a great normal stress and a high

surface roughness, resulting in the early occurrence of the transition stage. The bifurcation of AE energy from the rough fracture is observed with the decrease in derived contact area. Our study indicates that the evolution of asperity contacts in the transition stage can be different from that in the stick slip stage. Understanding the difference could promote our ability to forecast fracture behaviour. For example, the prediction of fracture sliding in rock masses during underground excavation [24, 25] could be based on the transition from stick slip to stable sliding. However, the transition stage could be more complex if material heterogeneity and other environmental factors (e.g., fluid flow) are involved.

Data Accessibility

This article has no additional data.

Authors' Contributions

WW conceived the study and revised the manuscript. MC carried out the experiment, performed the data analysis, and drafted the manuscript.

Competing Interests

The authors declare that they have no competing interests.

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