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The role of viscoelasticity on heterogeneous stress fields at frictional interfaces

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ABSTRACT

We investigate the evolution of heterogeneous stress states along frictional interfaces. Using finite-element simulations, we model the occurrence of precursory slip sequences on a deformable-deformable as well as a deformable–rigid interface between two solids. Every interface rupture creates a stress concentration at its arrest position and erases the stress concentrations produced by previous slip events. While the interface is sticking perfectly between two slip events, erased stress concentrations reappear and survive several cycles of ruptures. Such reestablished stress concentrations are smaller than they were before the rupture. We show that the decrease rate of these stress concentrations is exponential with respect to the number of subsequent events and that the bulk viscoelasticity is at the origin of this history effect. During a slip event, the friction tractions at the interface change almost instantaneously, which leads, between two ruptures, to a relaxation-resembling viscous effect that restores the stress concentration. We describe the decrease rate analytically and highlight that it is proportional to the ratio of the viscous over the instantaneous Young's moduli, and illustrate it by varying the material properties in our simulations.

1. Introduction

Understanding the dynamic behavior of frictional interfaces is relevant for a broad range of applications in engineering, mechanics and geophysics. Despite longstanding research on friction, its dynamics is today still not well understood. For instances, the knowledge of the macroscopic frictional strength is essential to the design of new engineering applications. Nevertheless, the transition from sticking to sliding, which is closely related to the macroscopic friction coefficient, is still an only partially known phenomenon. The classic view considers that sliding initiates when the macroscopic shear force overcomes the macroscopic friction force, which is proportional to the normal loading. This simplistic picture does not account for the complexity of local slip occurring during the initiation of sliding. The transition from sticking to sliding was shown, in experiments, to be particularly interesting when the shear load of an interface between two blocks is applied by a pusher that is located near the interface (Rubinstein et al., 2007; Maegawa et al., 2010). In these conditions, the sliding initiation is a succession of local slip episodes that propagate at macroscopic stress levels much below the friction coefficient of the system. These precursors to global sliding initiate at the trailing edge, where the pusher is applied, and propagate along the interface until they stop before the other edge. Generally, each slip event propagates further than the previous rupture, until they reach the leading edge, which is considered to be global sliding. Numerical simulations using mass-spring models (1D (Maegawa et al., 2010; Amundsen et al., 2012) and 2D (Trømborg et al., 2011)) reproduced qualitatively this behavior and show the

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importance of asymmetric shear loading for the existence of such precursory slip. Other aspects of local slip observed in experiments (Rubinstein et al., 2004; Ben-David et al., 2010), such as a large range of rupture velocities, were also successfully reproduced by numerical simulations (Bar-Sinai et al., 2013; Kammer et al., 2012; Otsuki and Matsukawa, 2013).

The global sliding initiation is complex due to the presence of precursors, but the dynamics of these local slip events is complex in itself. Every precursor modifies durably the stress state of the interface (Rubinstein et al., 2007). Recursively, this means that every precursor propagates at an interface of highly heterogeneous stresses created by the history of previous ruptures. Furthermore, inhomogeneous stress states affect the propagation velocity of local slip events (Ben-David et al., 2010; Kammer et al., 2012), which results also in modified stress states after the current rupture and hence affects the succeeding slip event as well.

In addition to local dynamics influencing the stress state of the interface, it is suspected that a bimaterial effect contributes to the complexity of the problem. Most experiments were conducted on a non-symmetric interface, with a thin slider in contact with a much thicker base block (Rubinstein et al., 2007; Ben-David et al., 2010; Maegawa et al., 2010). The difference in thickness results in different effective stiffnesses, making the interface bimaterial. Ruptures at bimaterial interfaces are known for their richness of complex mechanics (Coker et al., 2003; Lykotrafitis and Rosakis, 2006) and to date no experiments of similar material interfaces have been conducted to compare with the bimaterial system of Rubinstein et al. (2007). In all numerical studies of the transition from sticking to sliding, this bi-material effect has been approximated by a deformable-rigid interface (Maegawa et al., 2010; Amundsen et al., 2012; Trømborg et al., 2011; Kammer et al., 2012; Bar-Sinai et al., 2013; Otsuki and Matsukawa, 2013).

In recent numerical simulations, Radiguet et al. (2013) revealed that stress concentrations created by the arrest of precursory slip survive several succeeding interface ruptures. Using an analytic approach, they proposed that the viscous property of the bulk material is at the origin of this history effect. In this paper, we confirm the proposed analytic model with new numerical results by varying the material properties. Further, for the first time, we present results from simulations of precursory slip at a deformable-deformable interface, and analyze the effect of the bimaterial interface on the survival of stress concentrations.

2. Simulation setup

2.1. Loading characteristics

The simulated system (Fig. 1) consists of a two-dimensional rectangular top plate (slider), of length $L_t = 0.2$ m and height $H_t = 0.1$ m, in plane-stress approximation. The slider is in contact with a two-dimensional rectangular bottom plate (base) of dimensions $L_b = 0.4$ m and $H_b = 0.05$ m. The base, is either approximated as a rigid body, as it has been done in previous numerical studies, or as a deformable viscoelastic solid in plane-strain or plane-stress approximation. If the base is rigid, its dimensions have no influence on the system. The bottom edge of the block is fixed in the x and y direction. On the lateral sides of the base, no displacements or forces are imposed. A constant normal load F_N is applied to the top surface of the slider. The shear load is applied via a spring of stiffness K_S and a rigid pusher to the left side of the top plate. A constant loading velocity V_x is imposed and the macroscopic shear force F_S is measured at the spring of the pusher. The values given in Table 1 are equivalent to the parameters used in the simulations of Radiguet et al. (2013), corresponding to an out-of-plane thickness of 6 mm. The pusher of width w_p is located at a distance h_p from the interface, which is a lower position than was used in Radiguet et al. (2013). We use the finite-element code Akantu (2013) to simulate the continuum of the two solids. The formulation is discretized in time using an explicit Newmark-β scheme. The plates are discretized using quadrangular elements, and the element size is 1 mm, which is fine enough to ensure mesh convergence.[1]

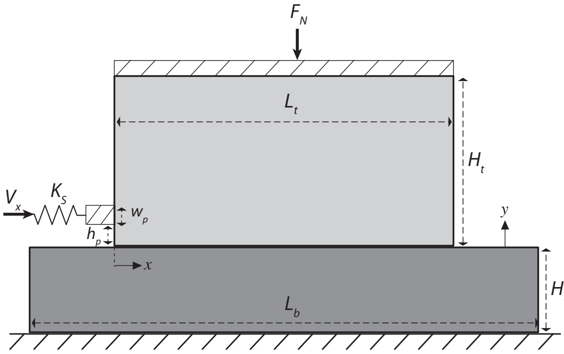

Fig. 1. Simulation setup. The upper plate (slider) of dimensions $L_t \times H_t$ is viscoelastic in plane-stress approximation. This plate is in contact with a bottom plate (base) of dimensions $L_b \times H_b$, which can be either rigid or deformable (plane-stress or plane-strain). The origin of the reference axis is the initial position of the lower left corner of the upper plate.

2.2. Friction law and interface description

Contact and friction at the interface are modeled using the traction-at-split-nodes technique (Andrews, 1999). The boundary conditions at the interface can be described by:

- For $\dot{u}_x(x, y = 0) \neq 0$ (during slip):

$$\sigma_{xy}(x, y = 0, t) = \tau^s(x, t) \quad \& \quad [|u_y(x, y = 0, t)|] \geqslant 0$$

- For $\dot{u}_x(x, y = 0) = 0$ (during stick):

$$\sigma_{xy}(x, y = 0, t) < \tau^s(x, t) \quad \& \quad [|u_y(x, y = 0, t)|] = 0$$

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[1] Simulations performed with a finer mesh (element size of 0.5 mm) show no significant differences in the global behavior, and in the evolution of the amplitude of stress concentrations compared to the mesh size used in this study.