Stiffness Controls on the Stability of Frictional Systems

J.R. Leeman, M.M. Scuderi, C. Marone, D. Saffer
The Pennsylvania State University - Rock and Sediment Mechanics Laboratory
@geo_leeman
www.johnrleeman.com
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Introduction

It has become evident in the last decade that fault failure is not simply bimodal stable sliding or stick-slip, but occurs on a spectrum encompassing complex failure modes such as slow-slip and low frequency earthquakes. Here we address the role of controls on failure mode and analyze the role of stiffness in failure mode determination by targeting two fundamental questions:

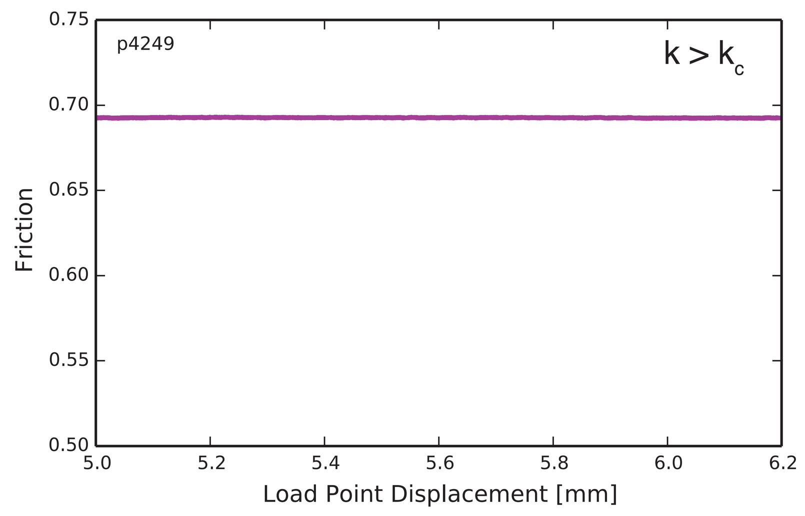
1. Does critical stiffness fully describe the frictional failure mode of a material? If not, what other factors control the failure mode?

2. How does fault zone stiffness and behavior evolve with time and accumulated slip?

Critical Stiffness Hopf Bifurcation Point

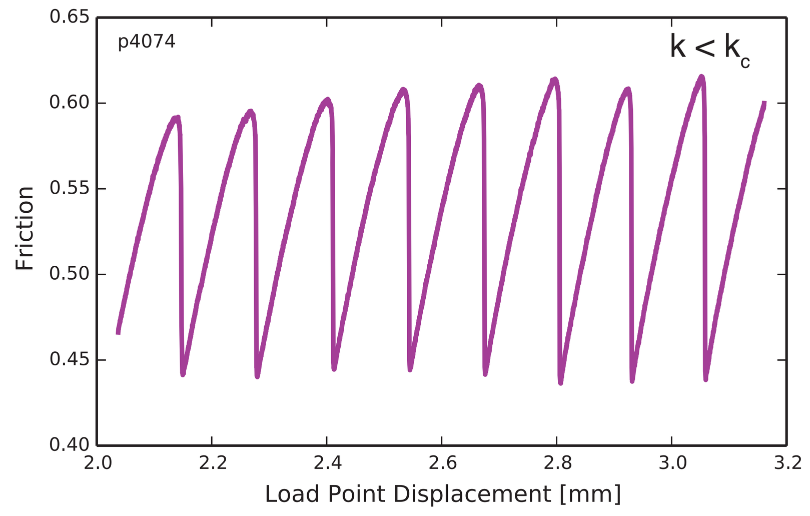
Stable Sliding (Creep)

Stable sliding, or creep, occurs in stiff systems and is analogous to a fault that does not host major earthquakes. In these systems we can measure the velocity response of friction and the time dependent healing behavior.



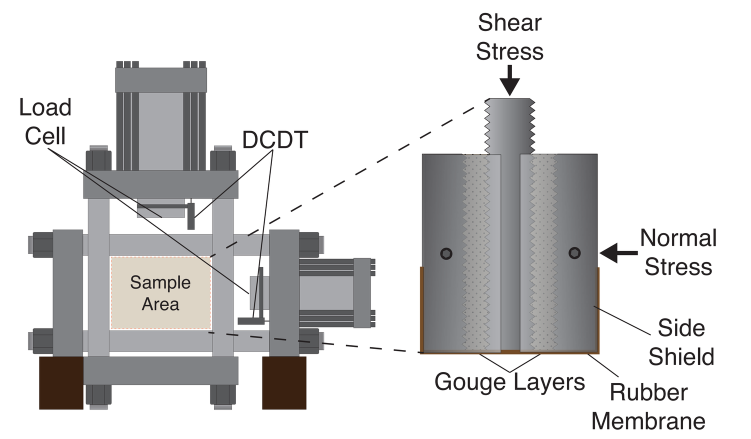
Stick-Slip (Earthquakes)

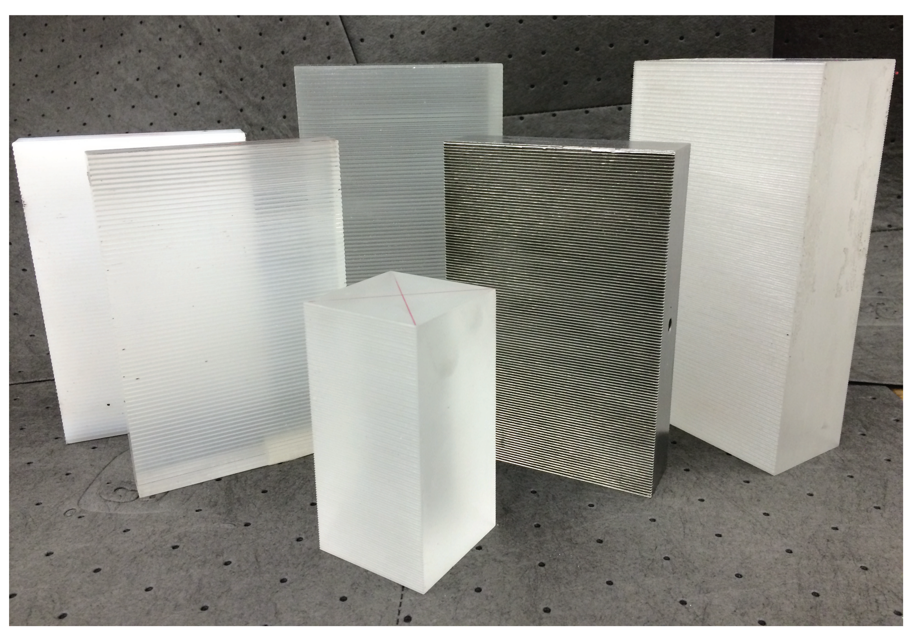
In compliant systems, elastic energy is stored and released in a way that may radiate seismic energy. This behavior depends on the frictional healing properties of the material, the velocity dependence of friction, and the stiffness.



Experimental Methods

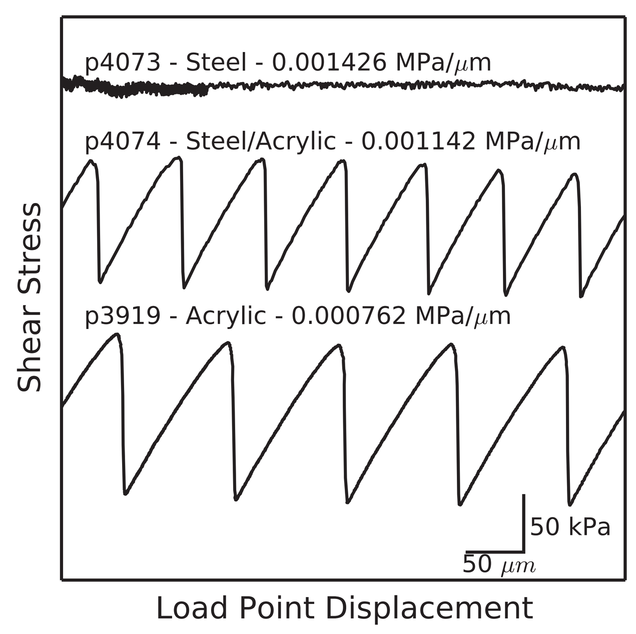
We shear layers of quartz powder (Min-U-Sil) with a bi-axial apparatus in the double-direct-shear geometry. All experiments were conducted in a 100% relative humidity environment as this has been shown to alter the behavior of materials by modifying healing times.



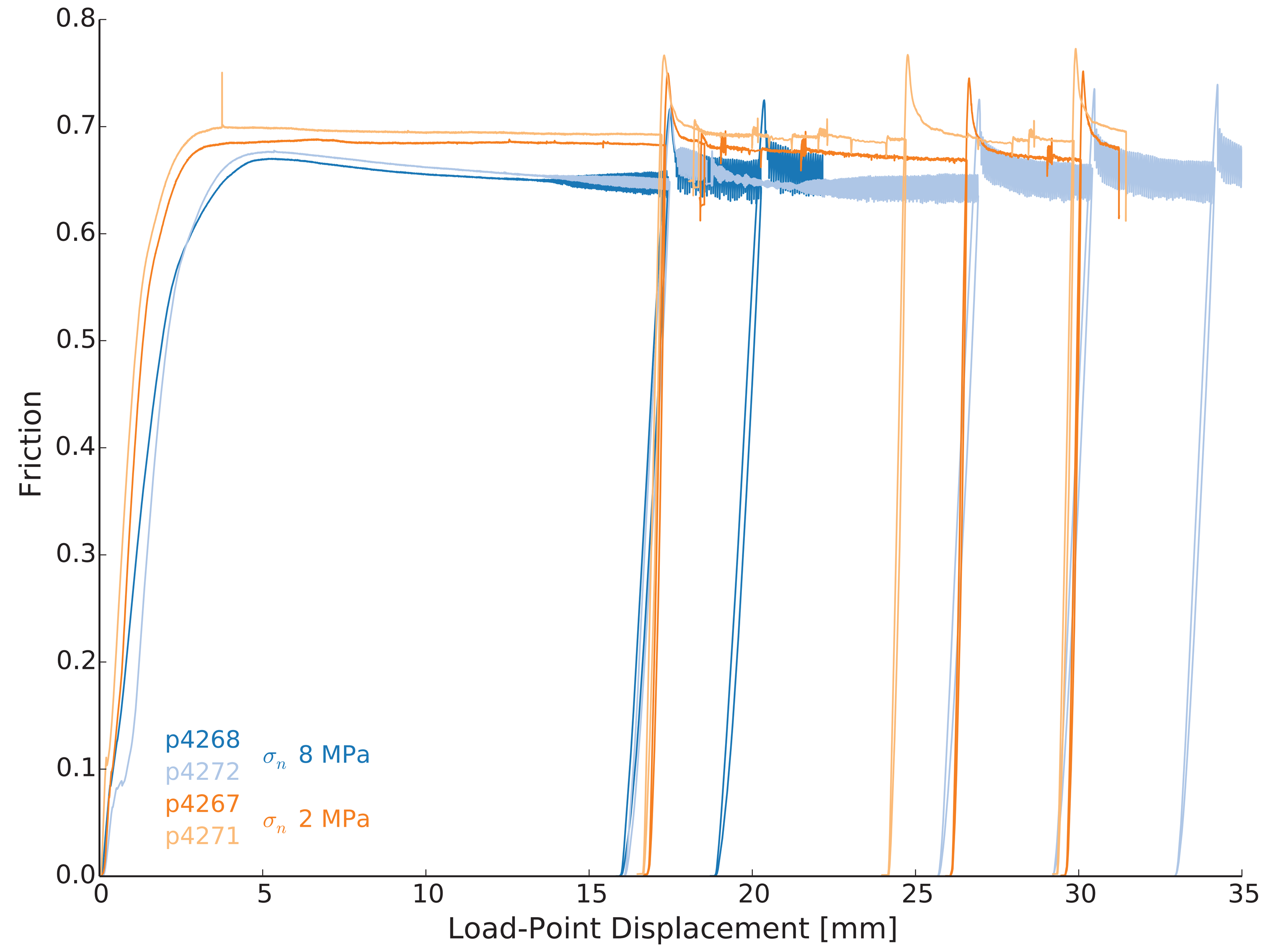


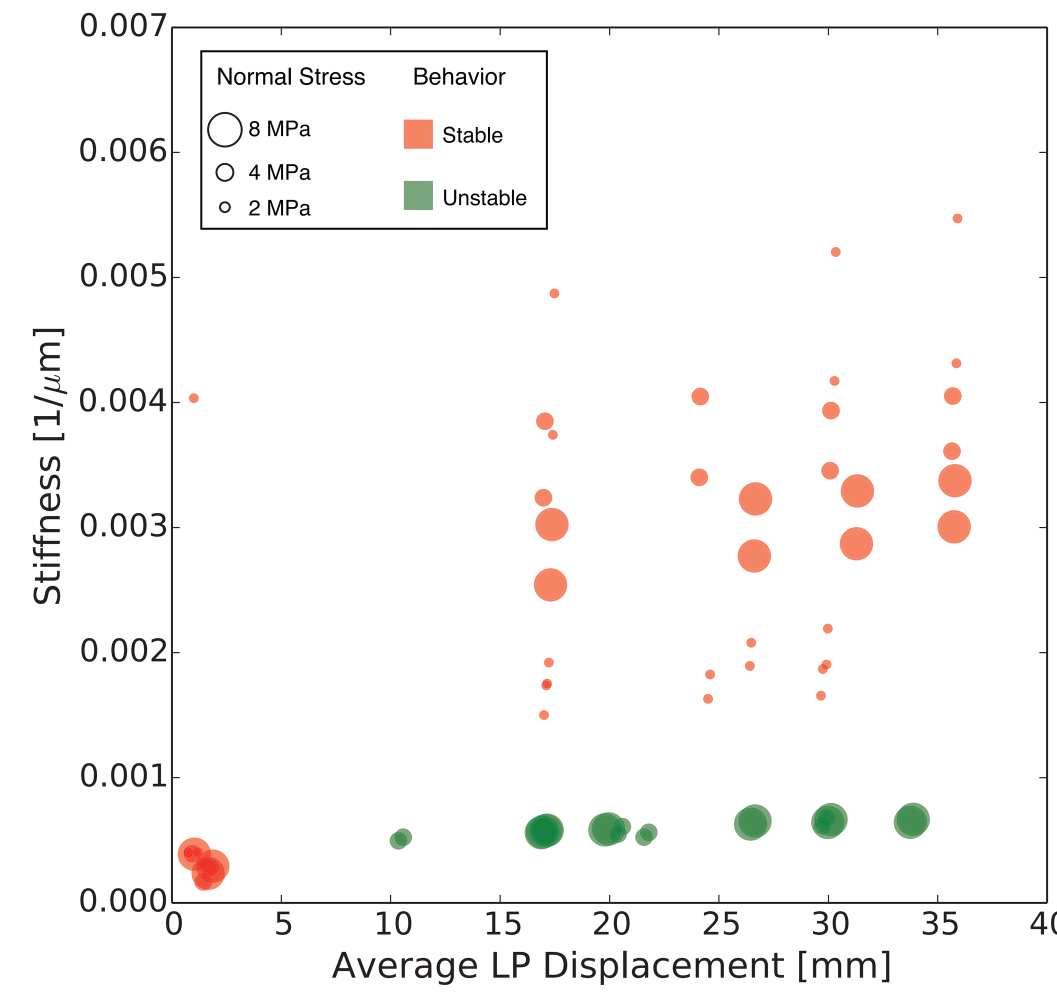
System stiffness is modified by using central forcing blocks made out of different materials. Traditional steel forcing blocks are the most rigid, but cast acrylic and ultra-high molecular weight plastic are used to reduce the aggregate stiffness of the system. Thickness, roughness, and normal stress can be altered as well.

Experiments with another material (traditional baking flour) show that altering the forcing blocks is enough to push the system across the critical stiffness boundary. All steel blocks exhibit linearly stable behavior, a combination of steel and acrylic blocks produce stick slip, while all acrylic blocks produce larger stick slips with longer recurrence times. This is exactly what the rate-and-state friction model would predict. All experiments shown are conducted at 1 MPa normal stress. Data shown are all at identical load-point displacements.



Results

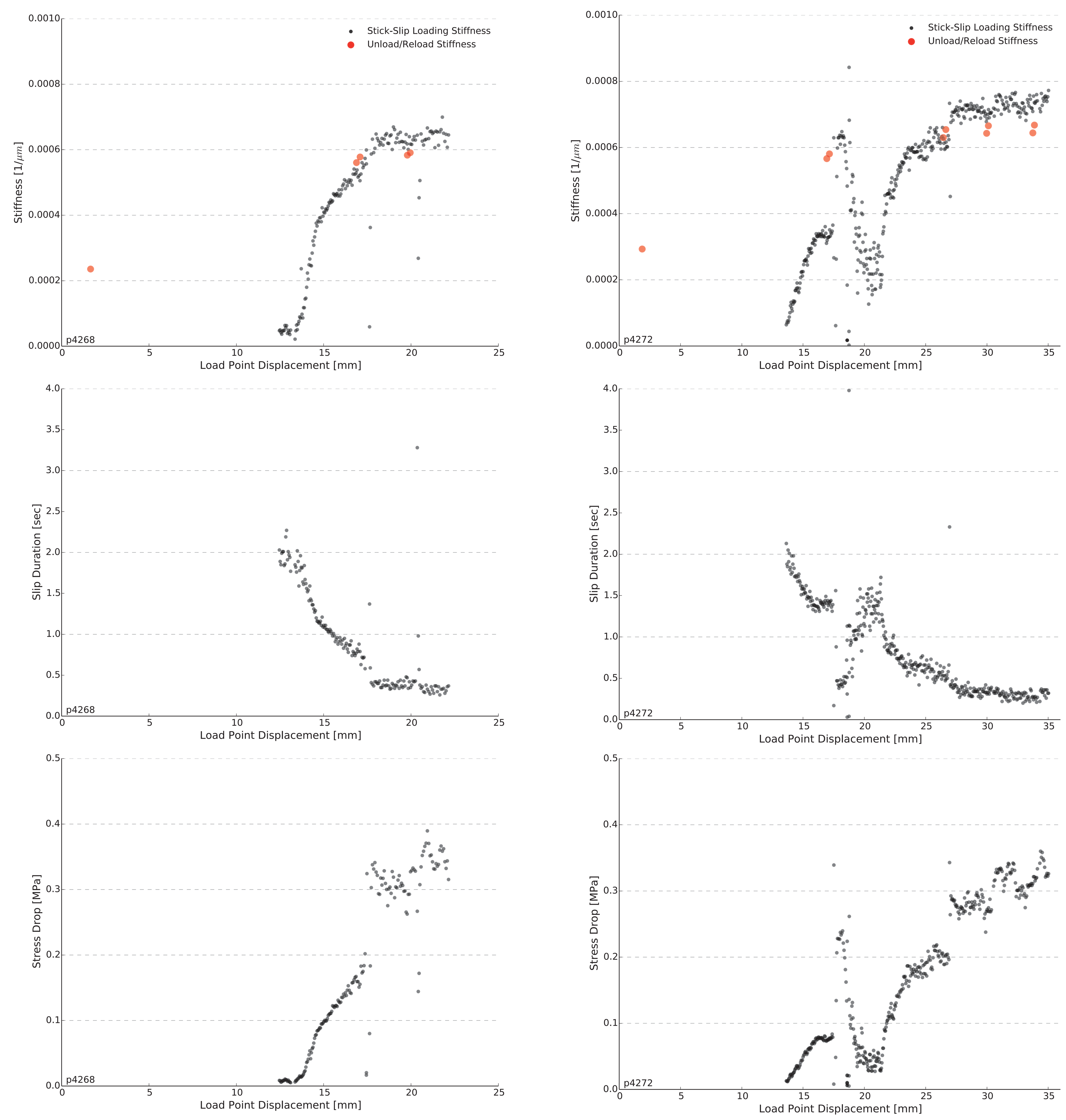




Experiments conducted with an acrylic center block (top left) at different normal stresses show different loading stiffnesses. The stiffer system exhibits a linearly stable response to velocity steps, but the more compliant system spontaneously becomes unstable at a displacement of approximately 12 mm. Periodic unload/reload cycles are performed to monitor the aggregate shear-stiffness as the layer evolves.

Stiffness can also be obtained by fitting the linear-elastic portion of each stick-slip loading curve. Stick-slip events are located by a derivative based algorithm and the peak and trough shear-stress times recorded. From this, stick-slip parameters such as slip duration and stress drop are calculated. The stiffness is determined by fitting different window lengths of data with a line using a least-squares fit. The fit with the highest correlation is chosen and its slope recorded as the stiffness. This technique provides values compatible with unload/reload stiffnesses (right) and provides better time resolution to monitor stiffness evolution. Two experiments shown at right were conducted under identical conditions and show stiffness, duration, and stress drop all evolving with shear strain on the layer.

Results from experiments with both steel and acrylic forcing blocks (top right) at different normal stresses show a clear transition between stable and unstable behavior. Notice that all experiments begin stable, then transition with displacement. All unstable experiments were conducted with a cast acrylic center block. The current best estimate for the critical stiffness is at the lower bound of the unstable experiment stiffnesses, suggesting that we are in a transitional behavior.



Conclusions/Future Work

From the data already collected we can say that the critical stiffness bifurcation agrees, to first order, with the switch in failure mode from stable to unstable. Estimates of shear stiffness using two different methods provide comparable estimates and show a stiffness evolution with strain suggesting that fabric development influences the stiffness and therefore system behavior. Further data collection and modeling of velocity steps is required to better characterize the critical stiffness.

We plan to conduct a suite of bi-axial tests to further characterize behavior across the critical stiffness boundary. New techniques employing on-board slider displacement measurements will be used to produce phase plane plots for further analysis and comparison to models. These analyses will allow us to assess to what degree stiffness is the controlling factor, as other factors such as fabric are obvious contributors to mode determination as well.

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