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# Transient behavior and stability analyses of a constitutive law accounting for brittle-ductile transition

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Formulating the fault constitutive law under brittle-ductile transition (BDT) which describes not only the steady state flow stress but also the transient behaviors is of great importance in understanding the deep extent of the seismogenic active faults. In this work, we extended an empirical constitutive law suggested by Shimamoto [2004, JPGU] and Shimamoto and Noda [2010, AGU fall meeting] for the steady state flow stress to the transient behavior, and conducted linear and non-linear stability analyses of a spring-slider system with one degree of freedom, similarly to Gu et al., [1984]. Most of physical parameters appearing in the constitutive law and the spring constant are estimated from the laboratory experiments by Kawamto and Shimamoto [1997] and Noda and Shimamoto [2010] for NaCl shear zone except ones related to the transient behavior in the brittle regime. Note that NaCl is so unstable that it is difficult to conduct stable friction experiments without stick-slips in its brittle regime.

In BDT, the steady state flow stress smoothly changes from a ductile flow law to a brittle friction law, and is always smaller than the predictions from both of the laws [Shimamoto, 1986]. For the empirical fitting, Shimamoto [2004, JPGU] suggested a connection:

$t = t_{dss} \tanh(t_{bss}/t_{dss})$

where t is the flow stress, $t_{bss}$ and $t_{dss}$ are ductile and brittle steady state flow stress, respectively. We extended it to:

$t = t_d \tanh(t_b/t_d)$

where $t_b$ and $t_d$ are flow stress formulated in a rate- and state-dependent framework [Ruina, 1983 for brittle friction law, Noda and Shimamoto, 2010 for ductile flow law].

The transient behavior on an abrupt change in the load point velocity is characterized by a peak-decay behavior in the brittle regime and a monotonic decay in the ductile regime. In BDT, a peak-decay is followed by another decay in an opposite direction, often observed in laboratory experiments [Reinen et al., 1994 for chrysotile, Blanpied et al., 1998 for granite, Noda and Shimamoto, 2010 for NaCl]. Such a behavior could be explained by Dieterich-Ruina law with 2 state variables with positive and negative b-values.

Stability of the steady state solution depends on the slip rate, temperature, and the normal stress if the constitutive parameters are fixed; at low slip rate, high temperature, and high normal stress, $t_d$ increases and $t_b$ decreases and thus the ductile flow law becomes dominant which shows rate-strengthening behavior. By comparing the computed stability/instability boundary and experimental data by Kawamoto and Shimamoto [1997], we can estimate the state evolution distance for the brittle constitutive law as 5 microns, based on a reasonable assumption for the a-value.

Noda and Shimamoto [2010] observed permanently sustained oscillation at multiple slip rates with fixed temperature and normal stress near BDT. The finite parameter regime for the sustained oscillation has been understood as a supercritical Hopf bifurcation and generation of a stable limit cycle around a destabilized equilibrium point [Gu et al., 1984]. We have conducted a fully nonlinear analyses using MATCONT [Govaerts et al., 2006], which is a free package for MATLAB. Unfortunately, we found that the system undergoes a subcritical Hopf bifurcation; an unstable limit cycle is absorbed at the Hopf bifurcation. Further study is needed to resolve this problem. The continuation between the brittle and ductile regime is not unique so that there may be a more plausible function following the same empirical approach. The brittle friction law may have 2 or more state variables which probably make the Hopf bifurcation super critical. Also, constructing the model of the physical processes operating in BDT and formulating a physics-based constitutive law deserves future study.

Keywords: fault constitutive law, brittle-ductile transition