A fault constitutive law in a brittle-plastic transitional regime accounting for geometry of deformation in a shear zone

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A fault constitutive law in a brittle-plastic transitional regime is of great importance in considering generation processes of large earthquakes that are nucleated around the deeper limit of a seismogenic layer [Sibson, 1982]. There are several published models such as a two-mechanisms model [Reinen et al., 1992], a phenomenological connection between brittle (frictional) and plastic (flow) laws [e.g., Shimamoto and Noda, 2014], and microphysics-based homogenized granular models [e.g., CNS model by Chen and Spiers. 2016].

CNS model is one of the most involved one among them, and can explain many characteristics in the fault property such as switching between rate-strengthening and rate-weakening at the onset of dilatant deformation and dependency of so-called a-, b-, and d_c-values on slip rate [e.g., Chen et al., 2017]. However, the assumed granular structure of the shear zone may not be a good approximation to ductile shear zones, and it is difficult to interpret typically observed composite surface structures as model parameters. In addition, existence of fault-parallel normal stress is ignored in this model. In the present study, the two-mechanisms model is extended to tensorial deformation expression and demonstrate the smooth connection between the frictional and flow laws in the transitional regime.

In the two-mechanism model, two deformation mechanisms share the stress and contribute to the net deformation. The previous model by Reinen et al. [1992] treats the deformation as a vector (relative motion across the fault), and results in a discontinuous transition between rate-strengthening and rate-weakening behavior with a metastable stronger steady-state strength than frictional resistance. In experiments, the transition is usually accompanied by smaller shear strength than both frictional and flow resistances, and thus the model by Reinen et al. [1992] is not realistic as pointed out by Shimamoto and Noda [2014].

Internal deformation of the shear zone has four displacement gradient components and three strain components (e.g., fault-normal extension, fault parallel extension, and simple-shear strain) if the problem is idealized as a 2-D in-plane problem. In the present model, frictional and flow deformation mechanisms share a stress tensor and contribute to the net deformation in the tensorial form. A rate- and state-dependent logarithmic law is assumed the brittle deformation with a slip plane which maximizes the shear traction per the normal compressional traction on it. A power-law is assumed for the flow law in which the flow strain rate is parallel to the deviatoric stress tensor. In addition, a geometrical constraint is given by the condition that the length and thickness of the shear zone does not evolve at a steady state. These set of equations can be solved numerically to obtain, for example, shear traction and fault-parallel normal traction on the fault as a function of applied fault-normal traction, slip rate, and temperature.

The present model yields a continuous transition consistently with experimental data and the empirical connection by Shimamoto and Noda [2014]. Localized shear planes of brittle deformation are expected to develop in a shallow angle from the shear zone. The angle is about zero (Y-plane) for almost purely frictional case and increase towards the transition up to about 15°. This range is consistent with previously reported internal structure of experimental shear zones [Hiraga and Shimamoto, 1987],

although rotation of those planes is not considered in the present model.

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