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Imperfection and burial-depth sensitivity of the initiation and development of kink folds in laminated rocks

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The first objective is to study the influence of the burial depth and of an imperfection, in the form of a tilt in the inclination of the otherwise straight, laminated beam, on the conditions for the initiation and the development of kink folds. The beam, typical of sedimentary rocks, is layered with weak interfaces between the competent beds, promoting the onset of kinking by their slip. The results are analytical and based on the upper bound approach of the classical limit analysis, referred to as the maximum strength theorem in the absence of any discussion of plasticity. The weak interface strength is described by the Coulomb criterion, whereas the bulk material is also cohesive and frictional but with an additional closure in the compressive stress domain to depict the action of compacting deformation mechanisms. The new twist to the methodology is to extend its application to the development of the failure mode beyond the onset, assuming that the structure finite response is well described by the least upper bound solution. The second objective is to compare in terms of upper bounds three different failure mechanisms which are the compaction band, the reverse fault and the kink fold. Their respective domain of dominance is constructed in failure-mechanism maps in the space spanned by the imperfection angle and the burial depth.

Compaction bands are predicted at the deepest end of the beam and the reverse fault and the kink fold at the shallower end. These depth differences are resulting from the geometrical imperfection. It is found that the kink-band mode at its onset, with compaction band dominant conditions, resembles to a slip-enhanced compaction band due to the weak interface activation and the compaction along the two parallel hinges. This hybrid mode migrates suddenly through the competent beam from the deepest towards the shallowest region and develops as a kink fold, after a negligible amount of shortening. The kink fold development, beyond the onset, occurs in two phases, the first corresponding to the rotation of the kink band and the second, to its widening. The associated least upper bound is first decreasing during the development and then increasing, the minimum being controlled more by the increase in the potential energy of the system than by the most favorable orientation of the frictional weak interfaces. It is finally found that the continuous activation of slip over the weak interfaces and the widening of the kink band prevent the rotation of the kink towards the large angles which are necessary to induce its locking. It is proposed that the introduction of damage along the hinges could palliate these two effects and prompt the locking observed experimentally and in the field.

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1. Introduction

The long-term objective of this research is to develop simplified methods to predict folding and thrusting in layered sedimentary rocks typical of fold-and-thrust belts. This contribution builds on the first attempt by Maillot and Leroy (2006), referred to in what follows as paper no 1, to construct a kink fold with the help of the maximum strength theorem. The new aspects considered here are the introduction of the burial depth and of the mis-orientation of the layers with respect to the compressive force, considered as the geometrical imperfection. These two ingredients are sufficient to define the conditions for the kink fold to dominate at the onset over the compaction band (CB) and the reverse fault (RF), the two other potential modes of failure.

The modeling of folding within sedimentary layers is possible from two approaches which are extreme in terms of complexity and efficiency. The first approach, most common in the mechanics literature, is certainly the most complex and computer intensive: a constitutive model is proposed for each lithology and the finite-element method is applied, starting with some initial geometry. The predicted strain localization should reveal the position of the ramps which accommodate subsequently the large displacement jumps, fundamental to thrusting. This approach is of course sensitive to the details of the constitutive relations (Rudnicki and Rice, 1975) and the numerical schemes for strain localization are still debated and require complex bench-marking (Buiter et al., 2006). Efficiency to construct forward models for repeated calculations necessary for statistical analysis are thus not yet possible. The other opposite, extreme approach ignores such complexity and proposes to construct folds from simple geometrical rules such as length and volume conservation (Suppe, 1983). The application of this simple approach to oil-industry exploration questions, completed with a temperature evolution scheme, has had a definite success to explain potential prospects (Zoetemeijer and Sassi, 1992; Sciamanna et al., 2004). Simplicity and efficiency are thus possible but the difficulty remains that this simple geometrical approach to folding is guided only by the experience of the structural geologist. It is impossible to favor one construction from others with quantitative criteria such as mechanical equilibrium and material strength.

A first attempt to bridge the gap between these two extreme approaches was proposed by Maillot and Leroy (2003). They constructed a geometrically simple fault-bend-fold and, instead of postulating the orientation of the back thrust, they found it by the application of the principle of minimum dissipation. A more systematic construction is proposed in paper no 1 where the external approach of limit analysis, as presented by Salençon (1974, 2002), is applied to the formation of kink folds. The kink band orientation (dip) as well as the dip of its two bounding, parallel hinges is selected by optimization of the upper bound in force due to internal dissipation and work against gravity. The difference between classical applications of limit analysis in civil engineering and in the field of structural geology is that the first failure mode is not sufficient. Its evolution in time defines the fold geometry. It is thus necessary to adapt the geometrical constructions of Suppe (1983) for the fold development proposing that certain degrees of freedom are not postulated but found by optimization of the upper bound in the tectonic force. These degrees of freedom in the present contribution and in paper no 1 include the two dips of the hinges and of the kink band. This yet simple but optimized construction method has been applied to predict the onset and the arrest in the development of every thrust of a normal sequence at the toe of an accretionary prism (Cubas et al., 2008). This kinematics approach does not provide any statically admissible stress field which is at the core of the internal approach of limit analysis. The systematic application of the internal approach via the equilibrium element method, at any step of the thrust development, does provide the optimum stress field as well as an estimate of the lower bound to the applied tectonic force, useful in estimating the error on the tectonic force (Souloumiac et al., 2008). Note that in the application of these two bounding techniques, no reference is made to any plasticity theory, and in particular to flow potentials and dilatancy. This interpretation (Salençon, 2002) of the classical limit analysis explains the reference to the external approach as the maximum strength theorem in paper no 1 and here.

The present contribution concentrates on kink folds with the intention to compare the conditions of dominance at the onset of three failure modes, the kink fold, the reverse fault and the compaction band. These various modes of failure under compression are defined and illustrated in Fig. 1. The prototype is composed of three regions, the top and bottom occupied by inviscid fluids. The central region is layered with planar weak interfaces between the various beds, tilted with respect to the compressive forces. The reverse fault is possible because of the frictional properties of the competent layers. The compaction band is also a potential mode of failure since the Coulomb criterion of the bulk material is closed in the compressive stress directions. This cap-type strength criterion was found necessary in paper no 1 to initiate kinking with each layer failing partly in compression and partly in extension. The competition between the three modes of failure is controlled by the burial depth (thickness of the top region) and the geometrical imperfection. The larger depths are promoting compaction bands over the reverse faults. The imperfection, which is defined by the layers mis-orientation favors the slip along the weak interfaces and is responsible for the kink development. The comparison of the different upper bounds in tectonic forces provides systematic, quantitative conditions for the dominance of each mode of failure.

The proposed approach to the onset and the development of kinks is rather different from the methods proposed in the engineering and Earth sciences literature and a comparison is now in order. Kinks will be predicted here without recourse to the introduction of elastic or elasto-plastic buckling. Such instability analyzes were essential for fiber composites, started with the early work of Rosen (1965) and reviewed by Budiansky and Fleck (1994), as well as for the multi-layered structures considered by Biot (1965a, b). The kink band is then seen as a new solution which develops during the