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Flexural-slip during visco-elastic buckle folding

Davi R. Damasceno, Andreas Eckert*, Xiaolong Liu

Department of Geosciences and Geological and Petroleum Engineering, Missouri University of Science and Technology, Rolla, MO, USA

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A B S T R A C T

Flexural-slip is considered as an important mechanism during folding and a general conceptual and qualitative understanding has been provided by various field studies. However, quantitative evidence of the importance of the flexural-slip mechanism during fold evolution is sparse due to the lack of suitable strain markers. In this study, 2D finite element analysis is used to overcome these disadvantages and to simulate flexural-slip during visco-elastic buckle folding. Variations of single and multilayer layer fold configurations are investigated, showing that flexural-slip is most likely to occur in effective single layer buckle folds, where slip occurs between contacts of competent layers. Based on effective single layer buckle folds, the influence of the number of slip surfaces, the degree of mechanical coupling (based on the friction coefficient), and layer thickness, on the resulting slip distribution are investigated. The results are in agreement with the conceptual flexural-slip model and show that slip is initiated sequentially during the deformation history and is maximum along the central slip surface of the fold limb. The cumulative amount of slip increases as the number of slip surfaces is increased. For a lower degree of mechanical coupling increased slip results in different fold shapes, such as box folds, during buckling. In comparison with laboratory experiments, geometrical relationships and field observations, the numerical modeling results show similar slip magnitudes. It is concluded that flexural-slip should represent a significant contribution during buckle folding, affecting the resulting fold shape for increased amounts of slip.

1. Introduction

Flexural-slip during fold evolution is an important mechanism that contributes significantly in the development of chevron and kink-band folds (de Sitter, 1958; Ramsay, 1974; Dubey and Cobbold, 1977; Hudleston et al., 1996). The Zagros Mountains in Iran are a well-studied example of large-scale parallel fold formation by buckling of a competent group together with the flexural-slip mechanism (e.g. Colman-Sadd, 1978). The flexural-slip mechanism during fold evolution involves the initiation of slip on surfaces of discontinuity (e.g. pre-existing bedding planes) between individual layers as the upper layer slides towards the fold hinge (e.g. Ramsay, 1974; Tanner, 1989 and references therein; Price and Cosgrove, 1990). The flexural-slip model presented by Ramsay (1974) and also by Tanner (1989) describes slip values as increasing towards the inflexion points in the limbs and decreasing to zero at the fold hinge and then appearing in opposite sense in the opposing limb at the same stratigraphic level (Tanner, 1989). As the limbs of flexural-slip folds rotate, bedding parallel shear is relieved by an increasing number of movement horizons, while layers between movement horizons are also deformed internally by simple shear (Tanner, 1989). The slip vector on the bedding parallel slip surfaces, based on slickenfibre patterns, is at right angles to the fold axis (Nieuwenkamp, 1928; Tanner, 1989). Field, experimental and theoretical studies on flexural-slip folds (Behzadi and Dubey, 1980; Williams, 1980; Ramsay and Huber, 1987) have assumed that slip takes place between each competent-competent or competent-incompetent layer. However, Sanz et al. (2008), using elasto-plastic numerical models to simulate the Sheep Mountain Anticline (Wyoming) as a forced fold, show that the flexural-slip mechanism develops between pre-existing layers with similar stiffness. Wherever a significant stiffness difference between layers is present, the frictional strength of the bedding surface is not exceeded, as the incompetent layer preferentially deforms internally by simple shear (Sanz et al., 2008). This is in agreement with observations for multilayered folds in the Zagros Mountains (Iran), which show less influence of the flexural-slip mechanism where

* Corresponding author. Department of Geosciences and Geological and Petroleum Engineering, Missouri University of Science and Technology, 129 McNutt Hall, 1400 N. Bishop Av, Rolla, MO, 65409-0410, USA.
E-mail address: eckertan@mst.edu (A. Eckert).

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incompetent layers deform (i.e. shear penetratively) rather than slip (Casciello et al., 2009).

Couples et al. (1998) observed the role of bedding-plane slip on strain partitioning and superposition during bending. As an individual layer deforms, superimposed strains result in contradictory senses of strain as new slip surfaces develop and activate, and create independent deforming layers in the limbs of the competent layer. In addition, Couples et al. (1998) state that hierarchical initiation of slip surfaces during folding of a multilayered sequence of rocks occurs, assuming that activation of sliding surfaces takes place at different times. This is in agreement with the studies conducted by Tanner (1989) in South Georgia (South Atlantic), North Devon (England) and Cardigan Bay (Wales), and by Horne and Culshaw (2001) in Nova Scotia, Canada, which show that only some bedding planes initiate local slip during folding, while other beds remain welded. Based on numerical models of an extensional fault-tip monocline, Smart et al. (2009) show that for models where inter-bedding slip is permitted, strain localization occurs in individual layers bounded by the slip surfaces. For models where slip is prevented, strains are more homogeneously distributed across layer boundaries.

While the observations of flexural-slip folding from field outcrops provide significant qualitative evidence of the importance of the flexural-slip mechanism during fold evolution, a lack of planar strain markers across natural folds makes a comprehensive quantitative analysis of identifying the amount and timing of flexural-slip a difficult task (Tanner, 1989). This limitation can be overcome by the use of numerical models, and the studies of Couples et al. (1998), Sanz et al. (2008) and Smart et al. (2009) provide additional insights into the flexural-slip mechanism. However, from these studies it is clear that the development of flexural-slip and the conditions for its initiation within fold structures depend upon different, specific folding mechanisms (such as forced folding and buckle folding). Due to the large variety of structures resulting from forced folding, a generalized quantitative flexural-slip model does not exist and the slip pattern strongly depends on the specific structural geometry (Perritt and Roberts, 2007; Sanz et al., 2008; Smart et al., 2009).

The main objective of this study is to numerically simulate flexural-slip during visco-elastic, buckle folding (using 2D finite element analysis) in order to provide a better and more quantitative understanding of the flexural-slip mechanism. Buckle folds are chosen here, since they can be successfully simulated under *in situ* stress conditions (e.g. Eckert et al., 2014, 2016; von Tscharner and Schmalholz, 2015; Liu et al., 2016). Moreover, the initiation, amplification and strain history of buckle folds is well understood, thus enabling the study of the influence of scale-independent parameters on the spatial and temporal evolution of flexural-slip during buckle folding.

The occurrence of flexural-slip is investigated for single-layer and multilayer models. Of particular interest is how the number and distribution of slip surfaces evolve during buckling. Moreover, the sensitivity of the flexural-slip mechanism to such parameters as rheology, overburden load and frictional resistance is discussed. The conditions for which flexural-slip takes place are identified and a conceptual model of how the initiation of flexural-slip results in buckles with different shapes during buckling is presented.

2. Methodology

2.1. Governing equations

Following the studies of Mancktelow (1999), Zhang et al. (2000), Schmalholz et al. (2001) and Eckert et al. (2014, 2016), the numerical models are based on a linear Maxwell model to simulate the development of single layer and multilayer visco-elastic buckle folds. Effective stress analysis is introduced by utilizing pore pressure assuming an incompressible fluid and rock grains (i.e. Biot coefficient $\alpha = 1$; Biot and Willis, 1957; Nur and Byerlee, 1971). 2D plane strain finite element analysis (via the commercial software package ABAQUS™) is employed to solve the equations of equilibrium, conservation of mass, constitutive equations, and the equations for pore fluid flow. The unknowns of the problem comprise the stress tensor components σ_{xx}, σ_{zz} and σ_{xz}, the pore pressure P_p, the material velocities in x and z directions v_x, and v_z, and the material density ρ_m. Since the system of governing equations and its derivation is identical to Eckert et al. (2014), it is not repeated here.

2.2. Dominant wavelength

In order to select the appropriate dominant wavelength for the visco-elastic buckle folds the parameter R (after Schmalholz and Podladchikov, 1999; Schmalholz et al., 2001) is used to determine if the competent layer is folded viscously ($R < 1$) or elastically ($R > 1$). R is defined as the ratio between the viscous dominant wavelength, λ_{dv}, and the elastic dominant wavelength, λ_{de}. For the effective single layer mode:

$$R = \frac{\lambda_{dv}}{\lambda_{de}} = \sqrt[3]{\frac{\eta_l}{6\eta_m}}\sqrt{\frac{P_o}{G}} \quad (1)$$

For the multi-layer mode:

$$R = \frac{\lambda_{dv}}{\lambda_{de}} = \sqrt[3]{\frac{N\eta_l}{6\eta_m}}\sqrt{\frac{P_o}{G}} \quad (2)$$

where N is the number of competent layers, η_l is the viscosity of the competent layer/s, η_m is the viscosity of the matrix, G is the shear modulus and P_0 is the initial layer parallel stress. With a constant viscosity ratio of 100 between the folding layer and the surrounding matrix, the value of R from equations (1) and (2) mainly depends on the applied viscosity and strain rate, since the initial layer parallel stress is given by $P_o = 4\eta_l\dot{\varepsilon}$ (Schmalholz and Podladchikov, 1999). Using a constant geologic strain rate of 10^{-14} s^{-1} (Twiss and Moores, 2007), the values of viscosity and the Young's modulus chosen determine the values of R as shown in Table 1.

For low competent layer viscosities ($\eta_l < 10^{21}$ Pa s), the resulting deformation in the models is close to purely viscous (R ranges between 0.07 and 0.18; Table 1) and flexural-slip is not initiated (see Appendix A1). For large viscosities ($\eta_l > 10^{22}$ Pa s), R becomes larger than 1 (Table 1), indicating more elastic deformation resulting in a rapid increase in the resulting stress magnitudes and subsequent bulk failure initiation and evolution would need to be addressed. This is considered beyond the scope of this contribution and is best addressed with an alternative modeling approach such as the

Table 1
Parameter R (after Schmalholz and Podladchikov, 1999) in order to determine whether the competent layer is folded viscously ($R < 1$) or elastically ($R > 1$). A value of $5*10^{21}$ Pa s is chosen for the viscosity of the reference model, as this represents a case of mainly viscous deformation for which all surfaces initiate slip, and for which the resulting stress magnitudes are below failure conditions.

R		η_l		
		$5*10^{20}$ Pa s	$5*10^{21}$ Pa s	$5*10^{22}$ Pa s
E_l	$1*10^{10}$ Pa	0.18	0.57	1.81
	$3*10^{10}$ Pa	0.10	0.33	1.04
	$6*10^{10}$ Pa	0.07	0.23	0.74