Modelling of high-strain zones produced by folding in plastically deforming rocks

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Abstract

Buckle folding in layered rocks shows strain localizations in the embedding medium as well as within the layers undergoing folding. Using analogue and numerical model experiments we investigated such fold-induced strain localization in plastically deforming media. We performed experiments on analogue models prepared with PMMA (Misra and Mandal, 2009), a type of polymer with a typical elastic-plastic behaviour at room temperature conditions (30ºC). It yielded at an axial stress of 120 MPa following an elastic strain of 6 - 7 %, and underwent plastic creep with a slight strain hardening property (Fig. 1). The PMMA used in our experiments is optically isotropic, but becomes anisotropic as it starts to creep plastically. The optical birefringence was utilized to map plastic (high-strain) zones in the deformed models. In this study we investigated the patterns of high-strain zones for sinuous buckle folds in single layers, and kink folds in closely spaced multilayers. Single-layer buckle folds were developed on 2 mm thick, stiff steel layers embedded in the PMMA matrix. In these experiments the matrix yielded preferentially at the intrados of sinuous folds, forming elongate high strain zones perpendicular to the bulk shortening (Fig. 2). With increasing tightness of the folds the high-strain zones propagated along their

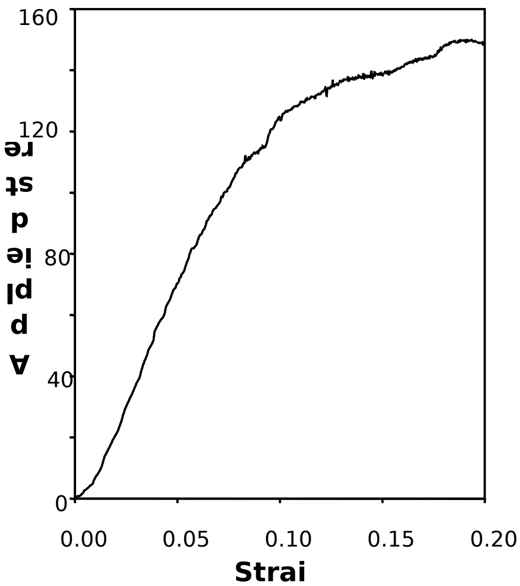

Fig. 1. Stress versus strain relation for a homogeneous PMMA model

axial planes (Ramsay and Lisle, 2000). We analyzed the fold-induced strain localization employing finite element models. The FE models were developed, considering a stiff visco-elastic (Maxwell) layers hosted in another visco-elastic medium with viscosity contrast of 10, keeping the relaxation time (10^{13}S) constant across the layering. We induced in the stiff layers a fold wave with the wavelength as estimated analytically from the theory of buckling instability for visco-elastic layers (Biot, 1967). FE experiments also show localization of maximum von-Mises stresses at the fold intradoses, delineating potential plastic zones, as observed in analogue models (Fig. 3a). Mapping of finite shear strain reveals a pair of parallel bands with opposite senses of shear at the fold limbs (Fig. 3b), which resemble F-bands described by Ramsay and Lisle (2000). In case of multilayers, the shear bands coalesce with one another, and form a typical F-band like structure when the viscosity ratio between high- and low-viscosity layers ≥ 10. Both analogue and numerical experiments indicate that plastic strain localization in the embedding medium can be an important mechanism for the growth of band structures in layered rocks subjected to layer-parallel shortening.

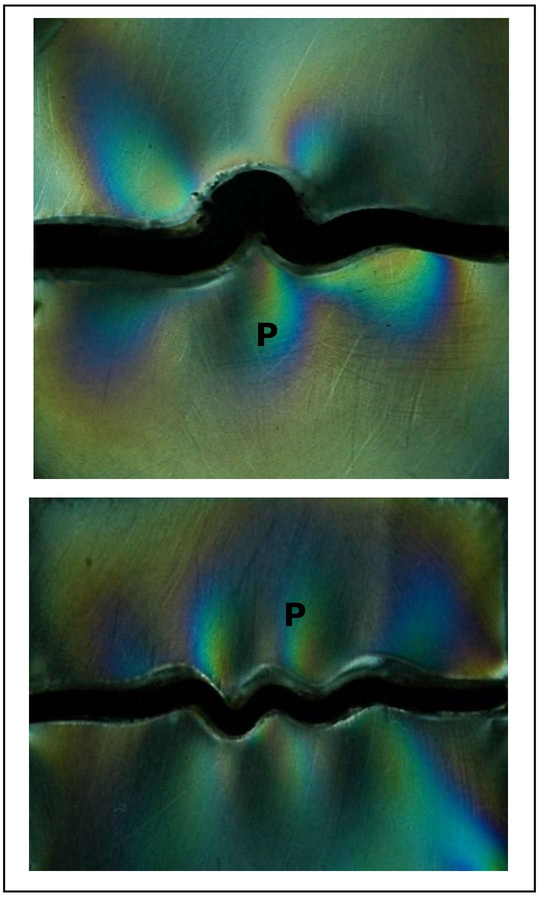

Fig. 2. Formation of fold-induced plastic zones (P) (strongly birefringence) in the PMMA matrix. Layer thickness of stiff unit (dark): 2 mm

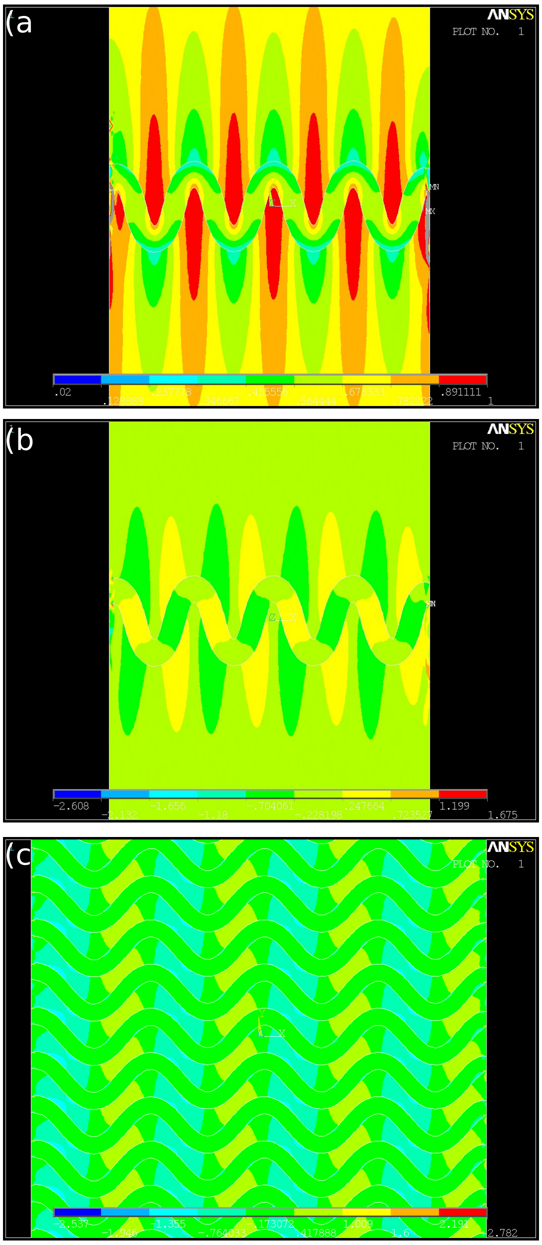

Fig.3. FE simulations of stresses and strains developed by folding in single- and multi-layer models. (a) von-Mises stress map, (b) Finite shear strain map, and (c) Band like shear localization

Closely spaced multilayered PMMA models produced conjugate kinks at an angle of 60º to the bulk compression direction. The kinks showed higher orders of birefringence, indicating plastic strain localization. The two adjoining kinks of opposite shear senses were spaced, and had similarity with F bands. However, they differed from typical F bands perpendicular to the principal shortening direction. Large plastic strain localized along the lines of kinking, and produced subsidiary high-strain bands within the kinks (Fig. 4a). Multilayers consequently gave rise to composite structures of high-strain bands. Model deformation by layer-oblique shortening formed a pair of kink bands with the same inclination (~70º) to the principal shortening direction (Fig. 4b). The bands coalesced with another, forming a chevron type of fold.

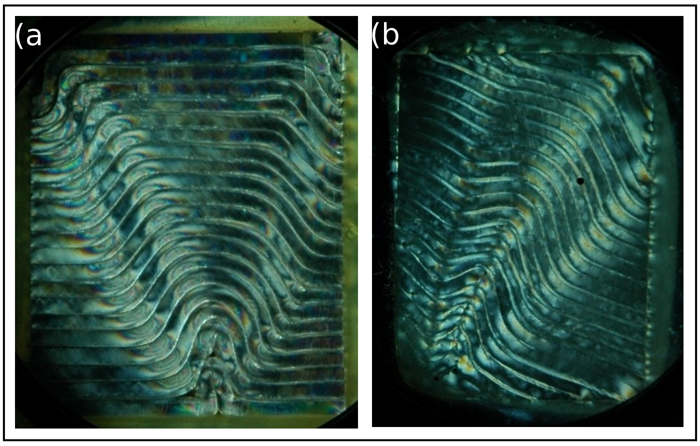

Fig. 4. Buckling in PMMA multilayers under (a) layer parallel and (b) layer oblique horizontal compression

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