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Spacing of bending-induced fractures at saturation: Numerical models and approximate analytical solution

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John G. Ramsay's sketch of structures developed in a layer progressively folded and deformed by tangential longitudinal strain (Figure 7-65 in Folding and Fracturing of Rocks) and the associated strain pattern analysis have been reproduced in many monographs on Structural Geology and are referred to in numerous publications. Although the origin of outer-arc extension fractures is well-understood and documented in many natural examples, geomechanical factors controlling their (finite or saturation) spacing are hitherto unexplored. This study investigates the formation of bending-induced fractures during constant-curvature forced folding using Distinct Element Method (DEM) numerical modelling. The DEM model comprises a central brittle layer embedded within weaker (low modulus) elastic layers; the layer interfaces are frictionless (free slip). Folding of this three-layer system is enforced by a velocity boundary condition at the model base, while a constant overburden pressure is maintained at the model top.

The models illustrate several key stages of fracture array development: (i) Prior to the onset of fracture, the neutral surface is located midway between the layer boundaries; (ii) A first set of regularly spaced fractures develops once the tensile stress in the outer-arc equals the tensile strength of the layer. Since the layer boundaries are frictionless, these bending-induced fractures propagate through the entire layer; (iii) After the appearance of the first fracture set, the rate of fracture formation decreases rapidly and so-called infill fractures develop approximately midway between two existing fractures (sequential infilling); (iv) Eventually no new fractures form, irrespective of any further increase in fold curvature (fracture saturation).

Analysis of the interfacial normal stress distributions suggests that at saturation the fracture-bound blocks are subjected to a loading condition similar to three-point bending. Using classical beam theory an analytical solution is derived for the critical fracture spacing, i.e. the spacing below which the maximum tensile stress cannot reach the layer strength. The model results are consistent with an approximate analytical solution, and illustrate that the spacing of bending-induced fractures is proportional to layer thickness and a square root function of the ratio of layer tensile strength to confining pressure. Although highly idealised, models and analysis presented in this study offer an explanation for fracture saturation during folding and point towards certain key factors that may control fracture spacing in natural systems.