A structural enigma: Towards a unified understanding of kink-band formation across the scales through modelling with the combined finite-discrete element method

Principle Supervisor: John-Paul Latham (Earth Science and Engineering, Imperial College London)
2nd supervisor: Ahmer Wadee (Civil and Environmental Engineering, Imperial College London)
3rd supervisor: Jiansheng Xiang (Earth Science and Engineering, Imperial College London)
Collaborators: Professor Giles Hunt (School of Mechanical Engineering, University of Bath)
Professor John Cosgrove (Earth Science and Engineering, Imperial College London)

Abstract

Kink band and box fold geometries in geological structures are widely observed in multilayered rock systems across the scales of crustal deformation and the kink-band’s tabular angular localised rotated geometry is immediately recognisable from mm to km scales. Physical analogue experiments, deformation of engineered and natural composites such as wood and the many postulated kink-band theories suggest possible mechanisms of formation include a complex mix of phenomena and material behaviours. Layer-bending and straightening, localised hinge yield, hinge migration, de-lamination, interlayer slip, anisotropy-enhanced rotational instability have been suggested by eminent structural geologists, composite materials specialists and buckling instability experts.

Until recently, computer simulation tools have been inadequate to represent all the key discontinuous, large strain, elastic-inelastic, dynamic-quasi-static component processes that we suspect are important in kink-band development. As kink-bands initiate and evolve, discretely layered components exploit lower shear resistance and localised yielding occurs within highly stressed bent layers – it’s a lot to ask from one computational tool. The power of AMCG’s in-house FEMDEM Solidity software is that it combines the finite element method, FEM (for the internal deformation with potentially fracturing or plastically yielding layers) with the discrete element method, DEM (for the discrete interactions between sliding layers).


What is the multi-scale nature of the project?

Kink-bands express a mode of deformation widely seen in anisotropic materials whether rapidly evolving in engineered fibre and laminate composites, or slowly in laminated geological systems on all scales. These include fine mm bilaminate layering in quartz-mica schist or phyllitic rocks, alternating 100-500mm sandstone-shale beds sharply rotated into kink-chevron shape structures, and 10-100m thick competent layer reflector horizons within sedimentary basins which exhibit kink-like box folds in kilometre-long seismic sections. Theory suggests anisotropic continua/discontinua with bending resistance and non-linear yielding play a role. Published progressive deformation experiments together with proposed FEMDEM modelling studies can address this problem and scale dependence.
How do the expertises of the supervisors complement each other?
Dr Latham, Reader in Geomechanics, (PhD: The influence of anisotropy on the formation of geological structures, supervisor Professor John Cosgrove) heads up the in-house development of the FEMDEM code Solidity (formerly VGeST) amongst ESE colleagues in AMCG. Cosgrove co-wrote the pioneering paper ‘Development of internal structures in deformed anisotropic rocks’ (1971, 240 citations), drawing on Maurice Biot’s theory which Latham (1985) explored further for kink-bands. In 2010, MSci student Adrian Shelley, (mark >80%) addressed layer-parallel multilayer compression through FEMDEM modelling. Back then, the code was less versatile, and CPU-hungry. Shelley was able to initiate beautiful rounded folds which unfortunately recovered stored energy unrealistically. Kink-like features were later modelled with FEMDEM’s fracture models. With 3D plasticity and fracture implemented, we now have high confidence in a successful PhD project outcome. Prof Giles Hunt (ex-IC Civil Engineering), and Prof Ahmer Wadee have a long-standing collaboration with Cosgrove to examine mathematical and geological rather than computation simulation approaches to multilayer buckling instability to explain the formation of kink-bands. Ahmer Wadee’s expertise on rapid kink phenomena, of direct industrial application, complements Latham’s. Dr Xiang is lead developer of the Solidity FEMDEM platform, a vital third supervisor. Professors Cosgrove and Hunt will provide invaluable inputs.

Literature Review
How do kink-bands form and propagate in time and space? – a review of mechanisms suggested by experiment and theory.


MSc Project
The main thrust of the MSc project is to perform new FEMDEM simulations of multilayer compression in 2D, following up on a previous MSci project (Shelley 2010). The student will aim to reproduce the mechanism of kink-band formation seen in the card deck experiments of Wadee et al. and if successful, progress to examine bilaminates to discover the role of property and thickness contrasts. The student will:
1. Train in the use of the FEMDEM simulator: pre-processing by setting up the loading frame and multilayer domain geometry and physical properties, mesh, boundary conditions,
problem type and parameter settings, eg time step, penalty function, run duration; executing runs on HPC CX1 cluster, extracting deformation results through post-processor *Paraview*.

2. Learn methods for rapidly changing fundamental geometry/properties of layer stacks of ~100+ layers.

3. Review limitations imposed by computational practicalities of simulation time needed to achieve interesting amounts of bulk finite strain.

4. Generate internal sinusoidal buckling with no interlayer slip.

5. Introduce interface sliding and in-elastic yielding properties designed to reproduce kink-band experiments on paper/card decks, consulting Wadee’s experiments archive.

6. Pay special consideration to mesh size effects, scale effects, e.g. geometric boundary or internal perturbations and discuss results w.r.t theory.