Study on Mechanical Mechanism of Kink bands via BEM

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Kink band

Definition:
1. A tabular zone, normally mesoseopic, along which foliation is deflected. (Tectonic Dictionary)
2. An asymmetric, linear zone of deformation characterized by short fold limbs and very small hinge zones. Kink bands commonly occur as conjugate sets (see CONJUGATE FOLD). (Dictionary of Earth Science)

History and usage:
• Several early authors (e.g., Clough, in Gunn et al., 1897; Dale, 1899; Read, 1934) recognized these structures and described them.
• Analogous structures were observed in single crystals by Orowan (1942), who named them "kink-bands."
• Voll (1960, p. 548) adopts this term for the corresponding structures in foliated rocks, and this usage continues (e.g., T. Anderson, 1964).

Size scale (in the past): millimeter ~ decameter

(From Ramsay & Huber, 1987)

(From Ashwin, 1957)

(Fossen, 2010)
Some previous studies (Orowan, 1942, Nature)

Kink in originally cylindrical cadmium (鎘) single-crystal wires

Structure of the kink in Fig. 1 a.

Legend

--- glide planes

--- Planes of kinking

--- Boundaries of wedge-shaped regions of flexural glide

(Adapted from Orowan, 1942, Nature)
Mechanism of Kinking

Kink bands

Fig. 3.
MECHANISM OF KINKING.

Fig. 5.
EXTENSION AND COMPRESSION OF A CRYSTAL PRODUCED BY KINK BANDS.
Thin parallel lines, glide planes.
Foliated rock: Phyllite

(Paterson and Weiss, 1962, Nature; 1966, GSAB)
Densely layered with restricted ease of sliding

Coarsely layered with restricted ease of sliding

Embedded with Great ease of sliding

Great ease of sliding
Fig. 1. Apparatus used to deform experimental multilayers.
$N$: power law stress exponent
Seismic reflection (張波等人, 2010, 地質探勘)

High-angle faults replaced by kink bands

Size scale: up to a few kilometer
Motivation (Shaw et al., 1999, Nature; 2002, BSSA)

Earthquakes vs. Faulting  ? Earthquakes vs. Kinking
Our BEM model

Layers are assumed to slip according to a Coulomb friction law,

\[ |\sigma_s| \leq C + \mu \sigma_n \]

\( \sigma \): traction  
\( C \): cohesion 
\( \mu \): coefficient of friction

Similar to the experiments (Ghosh, 1968, Tectonophysics)
Validation

Illustration of a multilayer

Graph showing the relationship between $q_1$, amplification factor, and $L/h$, the ratio of wavelength to thickness of a single layer. The graph includes data points for $N=2$, $N=4$, and $N=10$, with lines indicating Boundary Element Theory and Folding Theory. The graph also shows $N$, the number of identical layers, with $N=6$ indicated in the illustration.
Research questions

◆ Are the conditions enumerated below sufficient for the formation of symmetric conjugate kink bands according to our theoretical analysis?

1. a multilayered material (bedded stiff layers or interbedded stiff and soft layers),
2. a nonlinear relation, such as cohesive or frictional strength, between shear stress and flexural slip at contacts of layers or within interbeds,
3. maximum principal compression inclined parallel to the layering in the outer limbs, Horizntal shortening: 35.9% (this study)
4. and an initial perturbation of layer orientation. sinusoidal wave (this study)

◆ If the answer is yes, then, given certain theoretical properties, can you quantify the states of stress that will produce conjugate kink bands in a multilayer material?
Effect of frictional strength

Friction angle, $\phi$

cohesionless ($C = 0$) for the interfaces without remote vertical stress, i.e. $\sigma_{yy} = 0$

(a). $\phi = 0^\circ$
(b). $\phi = 10^\circ$
(c). $\phi = 20^\circ$
(d). $\phi = 30^\circ$

$L_o$: initial wavelength
Effect of frictional strength under remote vertical stresses

Friction angle, $\varphi$, of 10°

(a). $\infty \sigma_R = 0$

(b). $\infty \sigma_R = 0.25$

(c). $\infty \sigma_R = 0.5$

(d). $\infty \sigma_R = 1$

$L_0$: initial wavelength

$(*L_0)$

$(*L_\varphi)$
Effect of cohesive strength

$C_0$ : cohesion normalized by Young’s modulus

frictionless

(a). $C_0=0$

(b). $C_0=0.001$

(c). $C_0=0.01$

(d). $C_0=0.1$
Accumulative slip pattern

Frictionless and cohesiveless

Frictional without remote vertical stress

Frictional with remote vertical stress

\( \phi = 0, C_0 = 0, \sigma_R = 0 \)

\( \phi = 30^\circ, C_0 = 0, \sigma_R = 0 \)

\( \phi = 30^\circ, C_0 = 0, \sigma_R = 1 \)
Accumulative slip pattern

frictionless and cohesiveless

(a) $\varphi = 0, C_0 = 0, \sigma_R = 0$

(cohesive but frictionless)

(b) $\varphi = 0, C_0 = 0.01, \sigma_R = 0$
Result for effect of frictional strength under varying initial vertical stress
Result for combined effect of frictional vs. cohesive strength

without remote vertical stress, $\sigma^\infty_R = 0$
Result for combined effect of frictional vs. cohesive strength

With varying remote vertical stress
Discussion

Our BEM elastic model

\[
\text{Fold form } = f(A_0, L_0, h, N, C_0, \psi, \infty \sigma^i, \infty \varepsilon^L_{xx}, \infty \varepsilon^L_{xy})
\]

Fixed values

\[
\text{Conjugate fold } = f(A_0, L_0, h, N, C_0, \psi, \infty \sigma^i, \infty \varepsilon^L_{xx}, \infty \varepsilon^L_{xy})
\]

\(A_0\): initial amplitude

Illustration of a multilayer of 6 layers

Growth of fold amplitude, \(A\), vs. number of interfaces, \(N\),

![Graph showing growth of fold amplitude vs. number of interfaces](image-url)
Conclusions

◆ Are the conditions enumerated below sufficient for the formation of symmetric conjugate kink bands according to our theoretical analysis?

1. a multilayered material (bedded stiff layers or interbedded stiff and soft layers),
2. a nonlinear relation, such as cohesive or frictional strength, between shear stress and flexural slip at contacts of layers or within interbeds,
3. maximum principal compression inclined parallel to the layering in the outer limbs,
4. and an initial perturbation of layer orientation.

**Ans: Yes.**

◆ If the answer is yes, then, given certain theoretical properties, can you quantify the states of stress that will produce conjugate kink bands in a multilayer material?

**Ans: Yes.**

- We find a multilayer with certain cohesive strength stand-alone on its interfaces can produce conjugate folds under compression parallel to the interface but with frictional strength alone only cannot.
- We find that the lower bound of stand-alone cohesion divided by Young’s modulus ranges from $10^{-3}$ to $10^{-2}$ and friction cannot produce conjugate folds if the ratio of the vertical initial remote stress to horizontal initial remote stress is small than 0.2 under the shortening of 36% with an incremental far-field strain of 0.02 for multilayer models of 16 interfaces.
Future work

◆ Given certain theoretical properties, can you quantify the states of stress that will produce these three kinds of kink folds in a multilayer material?
Thank you for your attention!
Monocline kink fold
Monocline kink fold

initial remote stress ratio, $\sigma_R$

friction angle, $\varphi$

- Sine-like folds
- Transition
- Kink bands
- Complex folds