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Thin film delamination under in-plane residual stresses

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Thin Film Cracking

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Agenda

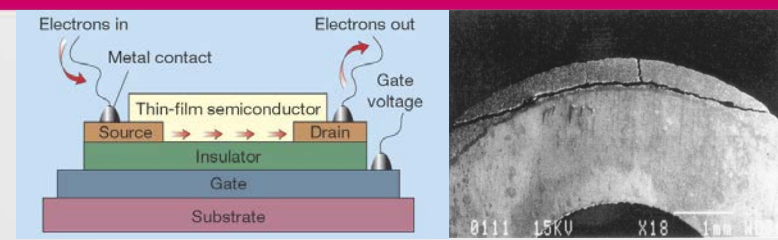
Part 1 (15 min)

1. Introduction
2. Partition of mixed-mode cracks
3. Macroscopic fracture
4. Thin film delamination

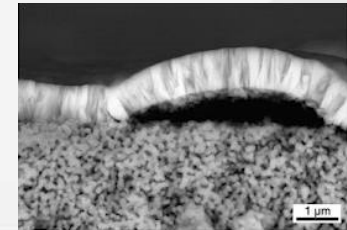
Part 2 (15 min)

5. Room temperature α -alumina spallation

Introduction



- **Thin solid films** are found in a variety of applications:
 - E.g. Electronic semiconductors; Thermal barrier coatings (TBCs); Surface protection against corrosion, friction and wear
- Not usually expected to have primary load-carrying capability
- But **residual stresses** are often present due to the fabrication process and working conditions:
 - E.g. Mismatch of thermal expansion coefficients in TBCs
- A major **cause of film cracks** and debonding
 - E.g. Buckling-driven delamination
- Fracture toughness is **mode partition-dependent**

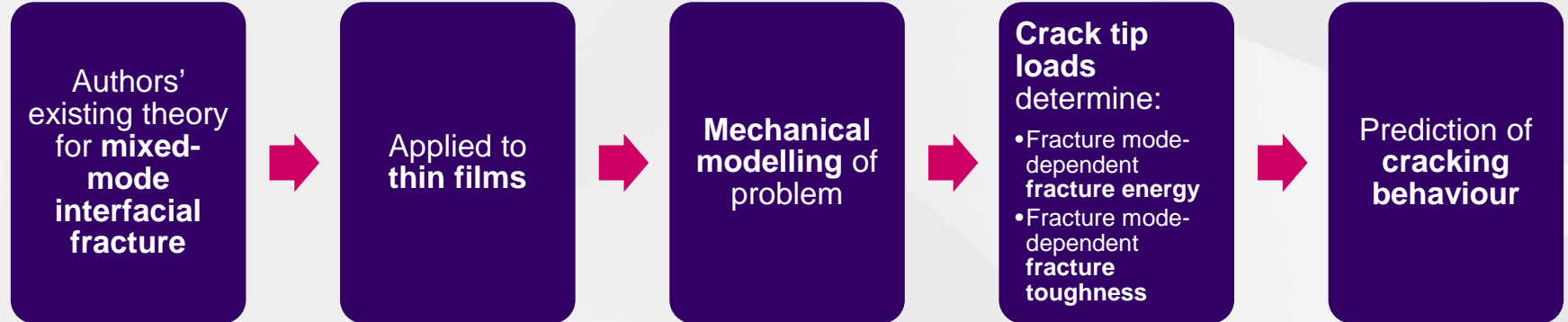




Aim

- To develop an analytical mechanical model to predict the cracking behaviour of thin films.

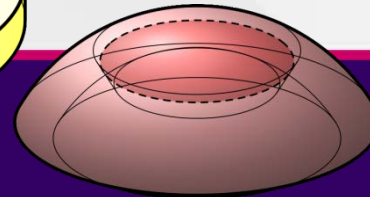
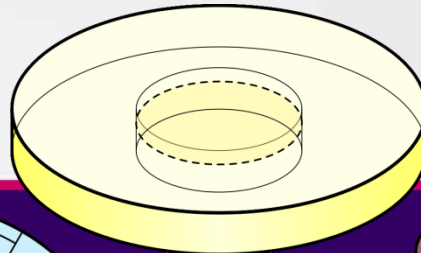
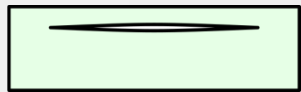
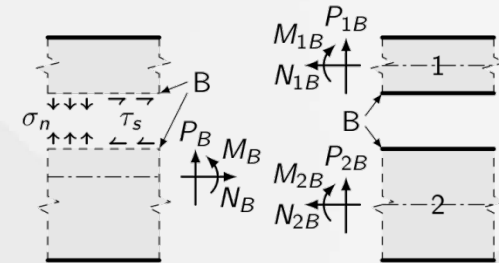
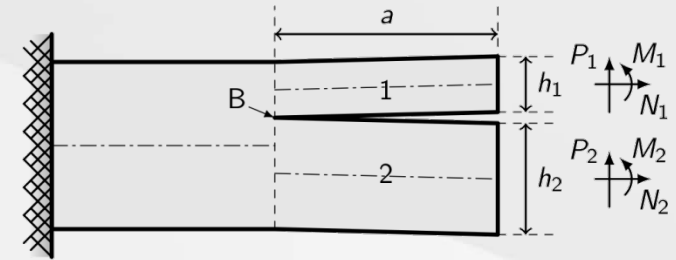
General methodology



Mixed-mode interfacial fracture

- 1D fracture of DCB is fundamental case for study
 - Bending moments M_1 and M_2
 - Axial forces N_1 and N_2
 - Shear forces P_1 and P_2
 - $\eta = E_2/E_1$, $N = \nu_2/\nu_1$, $\gamma = h_2/h_1$

Double cantilever beam (DCB)

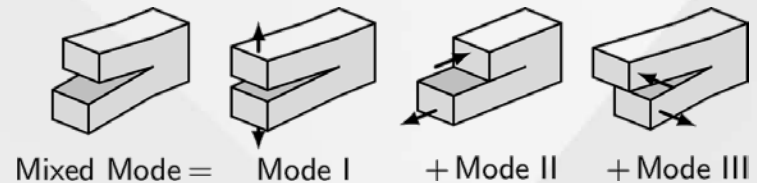


Total energy release rate

- Quadratic form and non-negative definite
- Partition total ERR G into its pure mode components, G_I and G_{II}
- Use the orthogonal pure fractures modes

$$G = \begin{Bmatrix} M_{1B} \\ M_{2B} \\ N_{1B} \\ N_{2B} \\ P_{1B} \\ P_{2B} \end{Bmatrix}^T [C] \begin{Bmatrix} M_{1B} \\ M_{2B} \\ N_{1B} \\ N_{2B} \\ P_{1B} \\ P_{2B} \end{Bmatrix}$$

$$C_{ij} = f(E_1, E_2, \nu_1, \nu_2, h_1, h_2, b)$$



Orthogonal modes

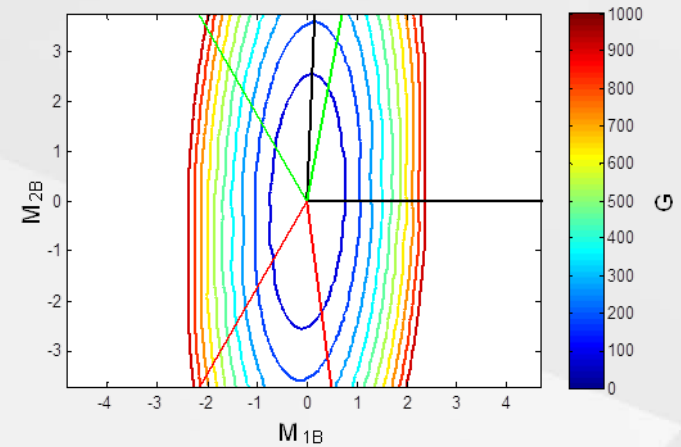
- The inner product matrix transforms the $\{M_{1B} \ M_{2B}\}$ vectors into ERR space
- In ERR space, orthogonality between two $\{M_{1B} \ M_{2B}\}$ vectors means

$$\{M_{1B} \ M_{2B}\}_1 [C] \{M_{1B} \ M_{2B}\}_2^T = 0$$

- Orthogonal pairs of $\{M_{1B} \ M_{2B}\}$ vectors exist that represent pure fracture modes
 - Denote pure mode I as $\{1 \ M_{2B}/M_{1B}\} = \{1 \ \theta_1\}$
 - Denote pure mode II as $\{1 \ M_{2B}/M_{1B}\} = \{1 \ \beta_1\}$ etc.
 - With θ_i and $\beta_i = f(E_1, E_2, \nu_1, \nu_2, h_1, h_2, b)$

$$G = \{M_{1B} \ M_{2B}\} [C] \{M_{1B} \ M_{2B}\}^T$$

Contours of ERR with $E = 1$,
 $b = 1, h = 1, \gamma = 2, \eta = 1$



ERR partitions

- Euler beam partitions:
$$G_{IE} = c_{IE} \left(M_{1B} - \frac{M_{2B}}{\beta_1} - \frac{N_{1B}}{\beta_2} - \frac{N_{2B}}{\beta_3} \right) \left(M_{1B} - \frac{M_{2B}}{\beta'_1} - \frac{N_{1B}}{\beta'_2} - \frac{N_{2B}}{\beta'_3} \right)$$

$$G_{IIE} = c_{IIE} \left(M_{1B} - \frac{M_{2B}}{\theta_1} - \frac{N_{1B}}{\theta_2} - \frac{N_{2B}}{\theta_3} \right) \left(M_{1B} - \frac{M_{2B}}{\theta'_1} - \frac{N_{1B}}{\theta'_2} - \frac{N_{2B}}{\theta'_3} \right)$$

- Timoshenko beam partitions:

$$G_{IT} = c_{IT} \left(M_{1B} - \frac{M_{2B}}{\beta_1} - \frac{N_{1B}}{\beta_2} - \frac{N_{2B}}{\beta_3} - \frac{P_{1B}}{\beta_4} - \frac{P_{2B}}{\beta_5} \right)^2$$

$$G_{IIT} = c_{IIT} \left(M_{1B} - \frac{M_{2B}}{\theta_1} - \frac{N_{1B}}{\theta_2} - \frac{N_{2B}}{\theta_3} - \frac{P_{1B}}{\theta_4} - \frac{P_{2B}}{\theta_5} \right)^2$$

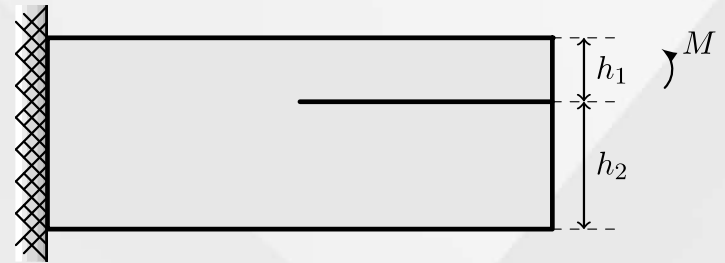
- 2D elasticity partitions:

$$G_{I-2D} = c_{I-2D} \left(M_{1B} - \frac{M_{2B}}{\beta_{1-2D}} - \frac{N_{1B}}{\beta_{2-2D}} - \frac{N_{2B}}{\beta_{3-2D}} - \frac{P_{1B}}{\beta_{4-2D}} - \frac{P_{2B}}{\beta_{5-2D}} \right)^2$$

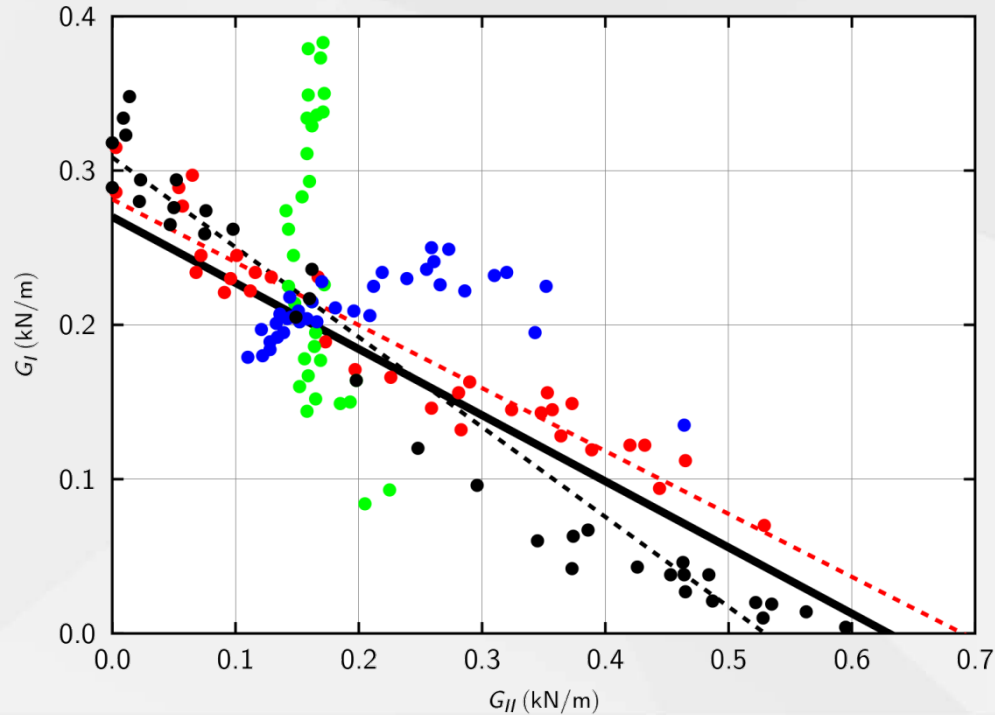
$$G_{II-2D} = c_{II-2D} \left(M_{1B} - \frac{M_{2B}}{\theta_{1-2D}} - \frac{N_{1B}}{\theta_{2-2D}} - \frac{N_{2B}}{\theta_{3-2D}} - \frac{P_{1B}}{\theta_{4-2D}} - \frac{P_{2B}}{\theta_{5-2D}} \right)^2$$

Experimental Assessment (Macro.)

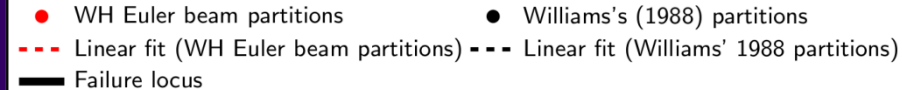
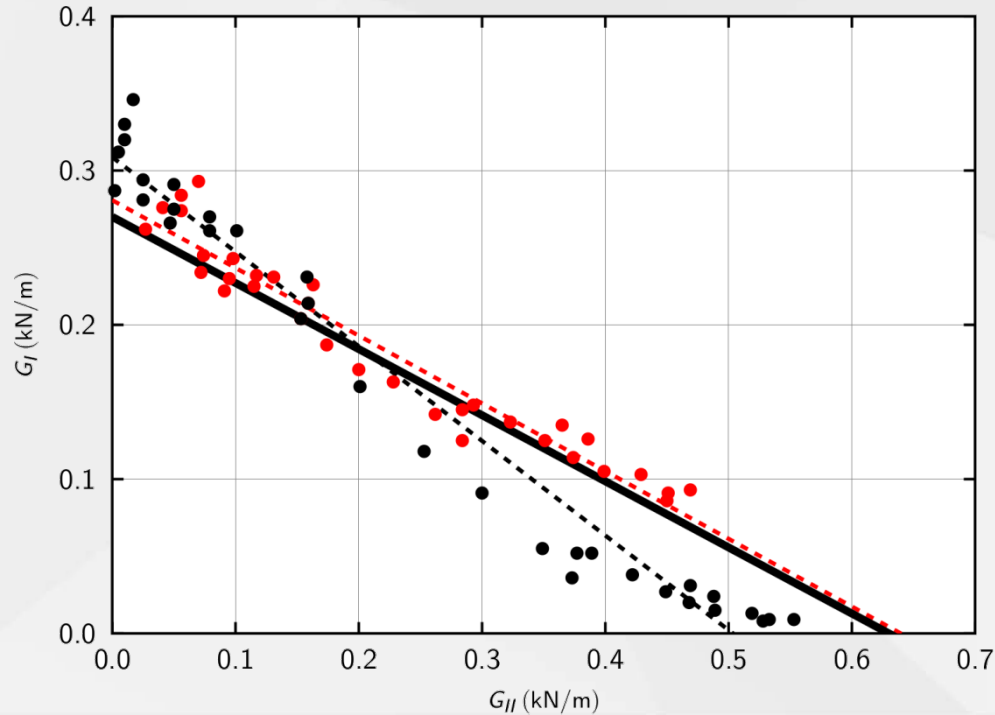
- Epoxy-matrix/carbon-fibre specimens with various values of h_1 and h_2
- Fracture toughness G_C test data from Imperial College:
 1. Charalambides, Kinloch, Wang and Williams (1992)
 2. Hashemi, Kinloch and Williams (1991)
- Partition G_C into G_I and G_{II} using different partition theories
- Obtain failure locus...
 - from specimens with $h_2/h_1 = 1$
 - from specimens with $h_2/h_1 \neq 1$
 - The same?



Data set 1



Data set 2



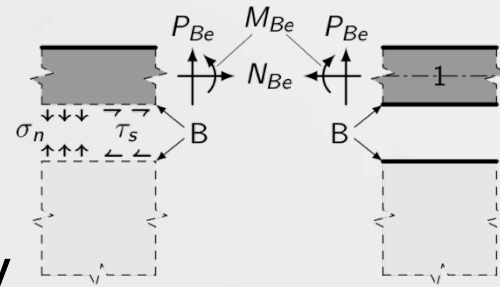
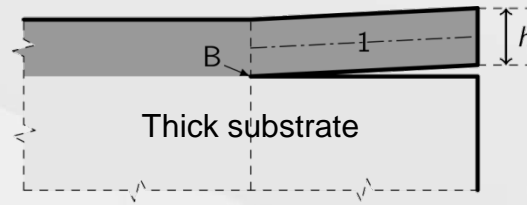
Observations from ‘macro.’ tests

- Only two partition theories are close to failure locus:
 - WH Euler beam theory
 - Williams’ (1988) theory
- 2D elasticity-based partitions are far from failure locus
- WH Timoshenko partitions are very far from failure locus
- WH Euler beam partitions are closest to the failure locus

Conclusions from 'macro.' tests

- WH Euler beam partition theory governs propagation of brittle interface fracture
- Seems in contradiction to 'common sense'
- An infinitesimal crack growth is assumed in the theories
- But crack extension develops over a finite-size distance
- WH Euler beam partition theory is insensitive to the growth size
 - It captures 'finite small growth' physics very well
 - Is also called the 'global partition theory'
- 2D elasticity-based partitions approach WH Euler beam partitions when growth size is increased

Thin films



- Reduce 2D elasticity-based partition theory
 - Thin layer of thickness h
 - and effective Young's modulus \bar{E} (neglect material mismatch)
- Mode I and II ERRs take the following form:

$$G_{I-2D} = 0.6227 \times \frac{6}{\bar{E}h^3} \left(M_{Be} - \frac{N_{Be}h}{4.450} - \frac{P_{Be}}{\beta_{4-2D}} \right)^2 \quad G_{II-2D} = 0.3773 \times \frac{6}{\bar{E}h^3} \left(M_{Be} + \frac{N_{Be}h}{2.697} - \frac{P_{Be}}{\theta_{4-2D}} \right)^2$$

- M_{Be} , N_{Be} and P_{Be} are the effective crack tip bending moment, in-plane force and shear force in the film.