Department of Mechanical Engineering

The University of Sheffield

Stress analysis versus modes of fracture in composites

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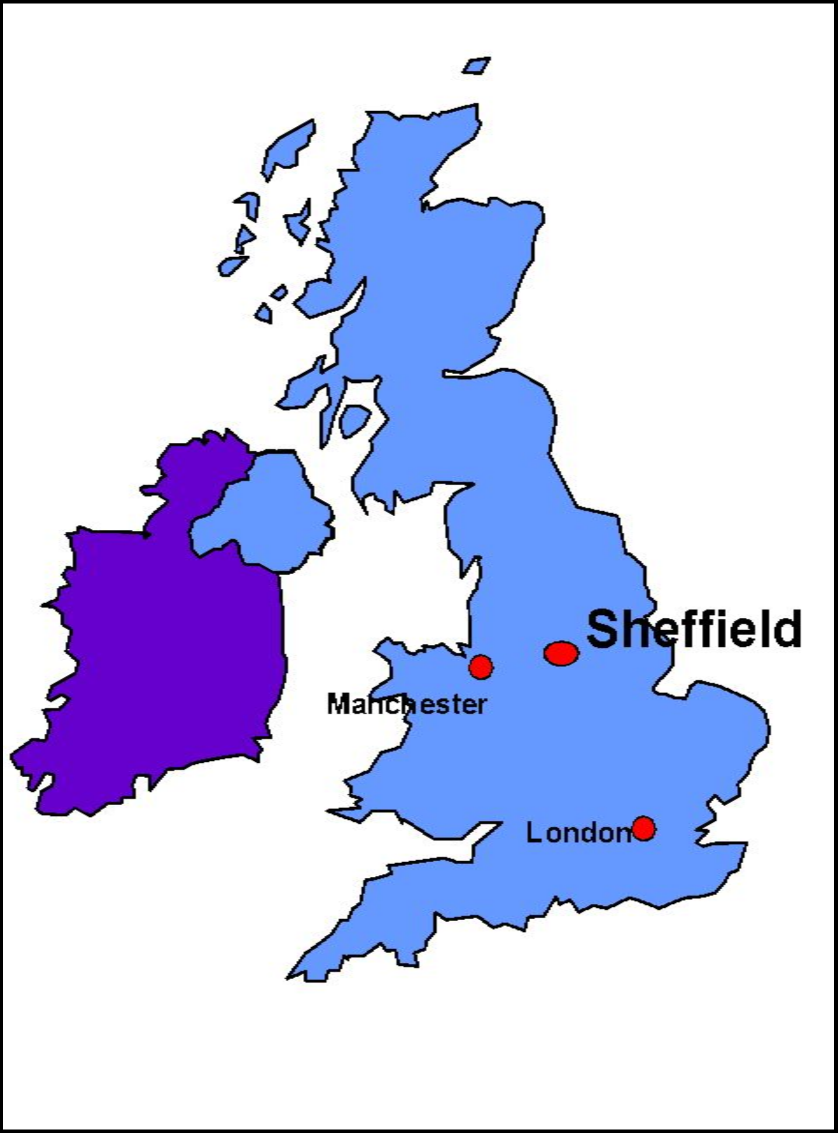
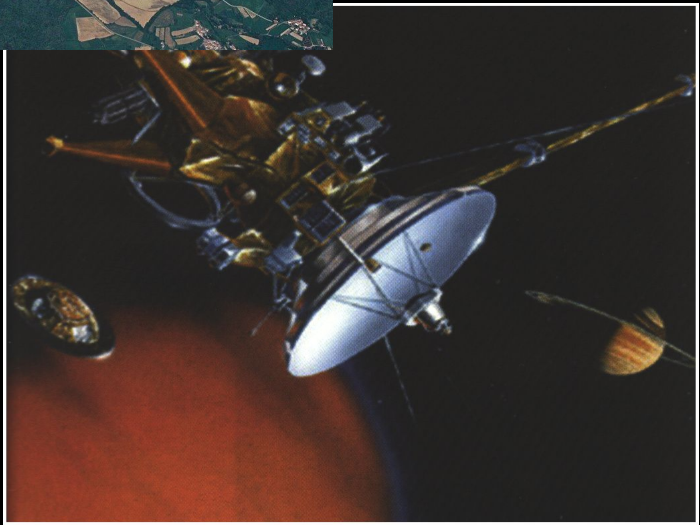
Location



- Major long-term Industrial partnerships with:

Rolls-Royce
Airbus
Boeing
BAe Systems
DSTL
European Space Agency
EADS
Smiths Industries
GlaxoSmithKline
ICI, Unilever
AstraZeneca, Novartis,
QinetiQ, IBM….
Cytec Engineered Materials



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Faculty of Engineering

- Automatic Control & Systems Engineering (5*A)
- Electronic and Electrical Engineering (5*A)
- Engineering Materials (5*A)
- Mechanical Engineering (5A)
  - Aerospace Engineering
- Computer Science (5B)
- Civil and Structural Engineering (5B)
- Chemical and Process Engineering (4B)

- **The total research income > £40 mil pa**

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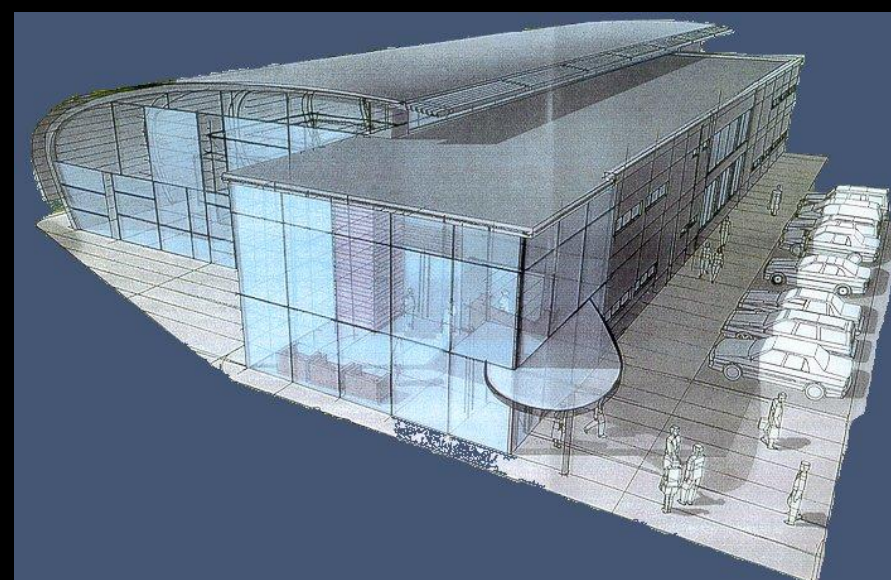
RR UTCs, AMRC and CamTec

- Four R-R UTCs are located at UoS



- Advanced Manufacturing Centre with Boeing
- CAMTeC with Boeing

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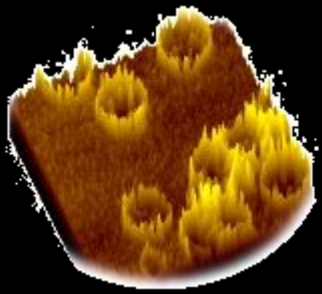
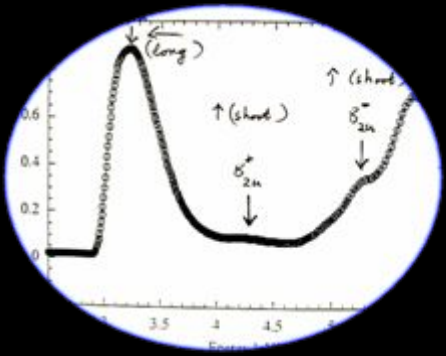
The Polymer Centre

- Established in June 2001
- 41 Academic staff, >140 Researchers
- More than £12M funding

Focus on Speciality Polymers

- ❑Synthesis
- ❑Structure
- ❑Properties
- ❑Processing
- ❑Characterisation
- ❑Applications





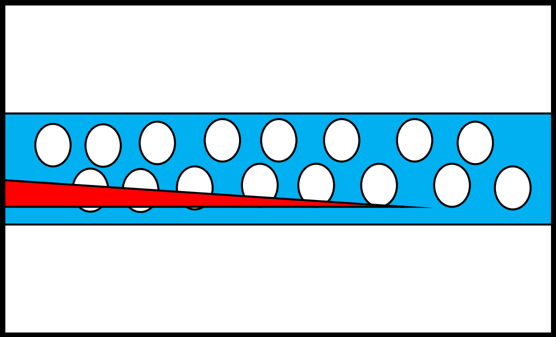
Home of the Composites Group

The Kroto Research Institute:

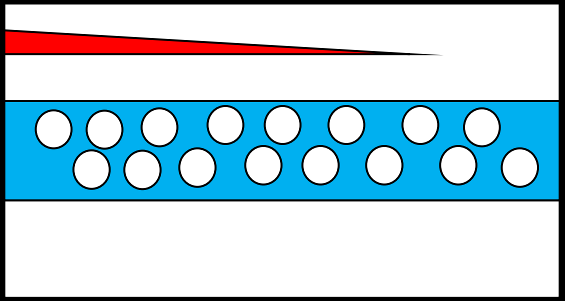
A £20M multidisciplinary investment

The Kroto Research Institute

Giic Summit Problem Statement



Crack running in the INTERLAMINAR region [Desired]



Crack running in the INTRALAMINAR region [Undesired]

- *We have found out that some particles are able to deliver excellent toughening as constantly demonstrated by the superior CAI and low damage area that can be achieved using this technology, if compared with standard commercial interlaminar particles.*
- *However, despite the good CAI, Giic performance could not be improved consistently.*
- *What can we do to keep the crack in the interlaminar region?*

Key Questions

1. Why is the crack slipping from the interlaminar region to the intralaminar region? What is the main cause for this to happen?
   1. Is our interlaminar region “too tough”?
   2. Is the modulus of our particles too high or inadequate?
   3. Can the fibre matrix interface strength be playing a role?
   4. Is it related to test? (We are using the ENF method, to evaluate Giic – we know that propagation is not stable). If the test is important why do some materials work better than others?
2. What happens in real life?
   1. How does the Giic test method (ENF) compare with real life structure problems (i.e. cobonded structures/ structures having radii…etc.)?
   2. How does Giic correlate to other properties? Literature provides correlations to CAI (that in our case does not seem to apply). What about Gic, ILS, CILS?
3. How should our particles and resin be designed to maximise Giic while keeping the balance of the other properties?

Question

- How is the laminate stress related to fracture toughness?

Strains and Curvatures

- Inserting plate deformation equations into the strain-displacement relations and simplifying yields:
- <u>Strains in terms of midplane strains and curvatures</u>

Stress Resultants for a ply/laminate

Plate Stiffness and Compliance

- stress strain relationships for a single ply

Laminate Stiffness and Compliance

- Inserting plate stiffness relationships into laminate stress and moment resultant equations in terms of strains and curvatures

ABD Matrices

- Coefficients A_{ij}, B_{ij}, D_{ij} are functions of thickness, orientation, stacking sequence and material properties of each layer
- [A] =in-plane stiffness matrix
- [D] = bending stiffness matrix
- [B] =bending-extension coupling matrix
  - B=0 if laminate is symmetric around mid-plane

- where i,j =1,2,6
- z_k is the coordinate of the top and bottom of ply surface
- 18 Constants

The extent of Laminate Theory in design against delamination

1. Elastic constants are used to calculate Q matrices for each ply
2. Q matrices are used to calculate A, B and D matrices
3. Coefficients from A & D matrices are used to calculate the effective stiffness of the beam's cross-section
4. Loads and dimensions are used to calculate moment resultant, and deflection
5. Curvature is calculated and strains are calculated for each ply (all values are very close and can be approximated into a single strain value)
6. Stresses are calculated from strains and Q matrices
7. Max stresses identified
8. Failure criterion applied to selected (or all) plies
9. Onset of delamination predicted, mode unknown
10. Position of the ply-to-fail unknown

Question

- What is a crack, what are the parameters of crack propagation?

Background theory

- In infinite plates with a crack opening defined with a and b:

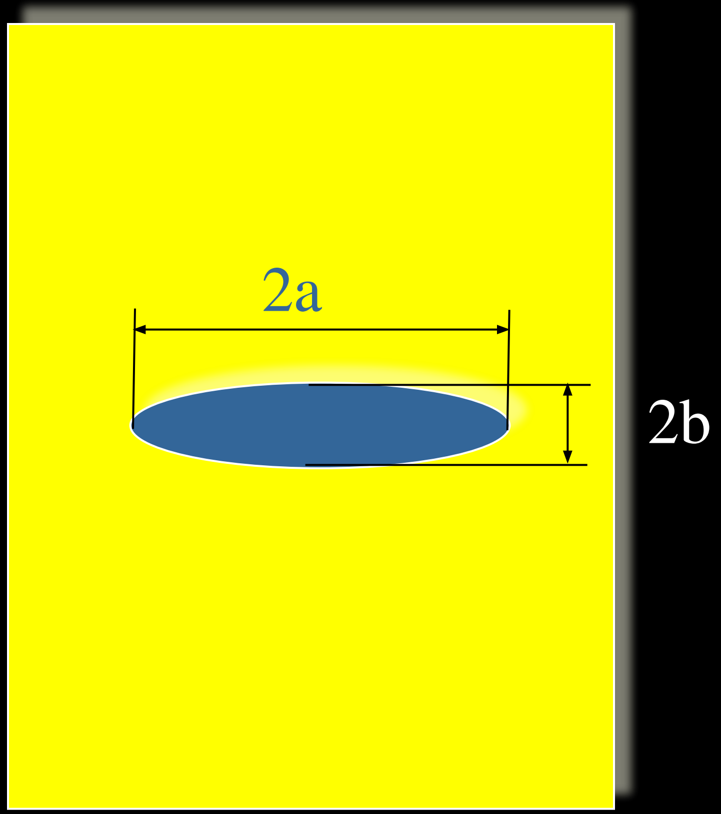
$\sigma_{max} / \sigma_a = 1 + (2a/b)$

Or

$\sigma_{max} = 2\sigma_a (a/\rho)^{1/2}$

Where stress concentration factor:

$K_T = 2(a/\rho)^{1/2}$



For the fixed size *a*, any change in size of thickness of a crack (*b*) will directly influence the stress at the crack tip and the outcomes of the subsequent failure prediction.

Failure in composites

- Under crack propagation, there can be two types of failure in composite materials:
  - Cohesive, crack propagation through matrix phase without interfacing with fibres
  - Adhesive, without matrix residue on the fibre: this failure mode is the basis for all assumptions in fracture mechanics
- Adhesive crack propagation assumes very sharp crack tip in order to avoid cohesive failure
- Thickness of the crack must be in the order of one ply (laminae)
- K_T must be high
- After deriving stress through Griffith criterion, stress intensity factor is defined as:

$$K = K_c = \sigma (\pi a)^{1/2}$$

Allowable flaw size

Design stress

Critical stress intensity factor
Material selection

Based on the assumption that the crack tip is sharp

Introducing crack in composites

- 3 Principal failure modes, retarded by design, regardless of the type of applied load:
  - Intraply cracking
  - Interlaminar delamination
  - Fibre breakage
- Other failure modes:
  - Debonding
  - Voids, wrinkles inclusions
  - Fibre misalignment

Strength prediction? K_c and G_c

Even if the layer orientation remains the same, different stacking sequence will produce a different effect and a different failure mode (under any applied load, with or without blast).

Delamination

- Major life-limiting failure process in composite laminate
- Produced by:
  - Out-of-plane loading
  - Eccentricities in load paths
  - Discontinuities in the structure
- Consequences:
  - Stiffness loss
  - Local stress concentration
  - Local instability

    Buckling failure under compression

Methods

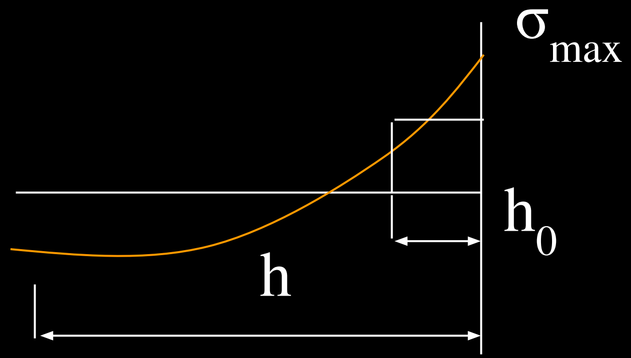
- Crossman: the onset of free-edge delamination:
  - $a^* = E^0 G_c / \pi \sigma_c^2$

  Effective modulus   Critical stress

  a* is usually one ply thickness for carbon/epoxy
- The strain energy release rate
  - Laminate plate theory is used to analyse the onset of delamination
  - Delamination induced stiffness reduction is proportional with strain energy release rate
  - Crack is initiated when strain reaches critical value ε_c
  - $\varepsilon_c = [2G_c/t(E_1 - E^*)]^{1/2}$ where $E^* = \Sigma \varepsilon_i t_i / t$ stiffness of delaminated laminate

Methods continued

- Stress approach: detailed analysis near the free edge and use of failure criterion
  - In angle-ply laminates, all max stresses are localised around the free edge region
  - Crack tip induces additional stress concentration
  - The average value of each stress component is the effective stress level that dictates the failure at the free edge
  - Values of max stresses are averaged along the length of one ply thickness from the free edge



Stress criterion for the onset of delamination

$$\bar{\sigma}_i(z) = 1/h_0 \int \sigma_i(y,z)\,dy$$

Sum of individual stresses over a fixed distance h_0 from the free edge

Methods continued

- Tsai-Wu quadratic failure criterion
  - Introducing $R = \sigma_{ult}/\sigma_{app}$
  - When R=1, failure occurs
  - $(F_{zz}\sigma_{zz}^{2} + F_{tt}\sigma_{xz}^{2} + F_{uu}\sigma_{yz}^{2})R + (F_{z}\sigma_{z})R - 1 = 0$

    Where $F_{zz} = 1/zz'$, $F_{tt} = 1/S_tS_t'$, $F_{uu} = 1/S_uS_u'$, $F_z = 1/z - 1/z'$

    Z,z' - interlaminar tensile and compressive strength

    $S_{t,}$ S_t' – the positive and negative shear strength in x and z

    S_u S_u'- - … in y and z
- In angle ply laminates for Θ= 15° dominant failure is by mixed shear (xz and yz),and by increasing angle, normal stress in z becomes significant
- If greater than 37.5° ,transverse tension
- If greater than 45°, initial failure moves to midplane

Fracture propagation

- Governed by one or two dominant intensity factors or critical strain energy release rates
- Several criteria using mode I and II
- Input: G_{Ic} and G_{IIc}
- Input: static strength data
- Required: experimental values
- (mode I – DCB and mode II – ENF test)
- Sharp cracks only

$$(G_I/G_{Ic})^m + (G_{II}/G_{IIc})^n = 1$$

Delamination growth occurs when the total strain energy release rate reaches a critical value:

$G_T = G_I + G_{II} \rightarrow G_c$ if $G_I = G_{II}$ then it is mixed mode

Effect of delamination

- Stiffness loss of a partially delaminated laminate:
- $E = (E^* - E_1)A/A^* + E_1$
- E^*: stiffness of completely delaminated laminate, E_1 : extensional stiffness, A^*: total interfacial area, A: delaminated area
- Loss in modulus leads to iterative and complex failure mechanism under dynamic load - prediction complexity requires stable and accurate parameters to be determined before blast effect can be analysed

Question

- Giic: is it related to the interface?

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G_{iic}: crack propagation notes

- Crack does not ‘know’ that it is running in a composite material – it recognises its local zone only
- Three phases: matrix, particles & interface
- Stress distribution in a composite is different for each ply (ply orientation)
- Stress distribution changes as the crack propagates and it is not continuous
- Modulus and stiffness of the plate change as the crack propagates
- In statically indeterminate systems, the stronger member (or phase) carries more stress
- In a changing modulus environment, the stress values will also change

G_{iic}: ENF

- 3ENF has been used to measure Giic however high instability is reported, and the difficulty in following the crack path (tip)
- 4ENF has been assessed as a more stable method, however difficulties with friction and the crack observation continue
- $G_{iic} = 9P_c^2a^2C/2W(2C^3 + 3a^3)$
- $C = (2L^3 + 3a^3)/(8EhW)$
- Pc: critical load of delamination
- E: flexural modulus
- The method currently limited to 0° ply laminates

G_{iic}: fibre matrix debonding

- The fibre and the matrix deform differentially causing local Poisson contraction
- Large local stresses are built up in the fibre at the same time
- The level of shear force at the interface exceeds the apparent interfacial shear bond strength and causes debonding (max shear strength criterion)
- Debonding toughness is evaluated by the total elastic strain energy stored in the fibre over the debond length, and fracture toughness as the work of debonding over the cylindrical debond area:

- $R_d = V_f (\sigma_f^*)^2 l_d/2E_f$

- $G_{ic} = \sigma_d^2 d/8E_f$

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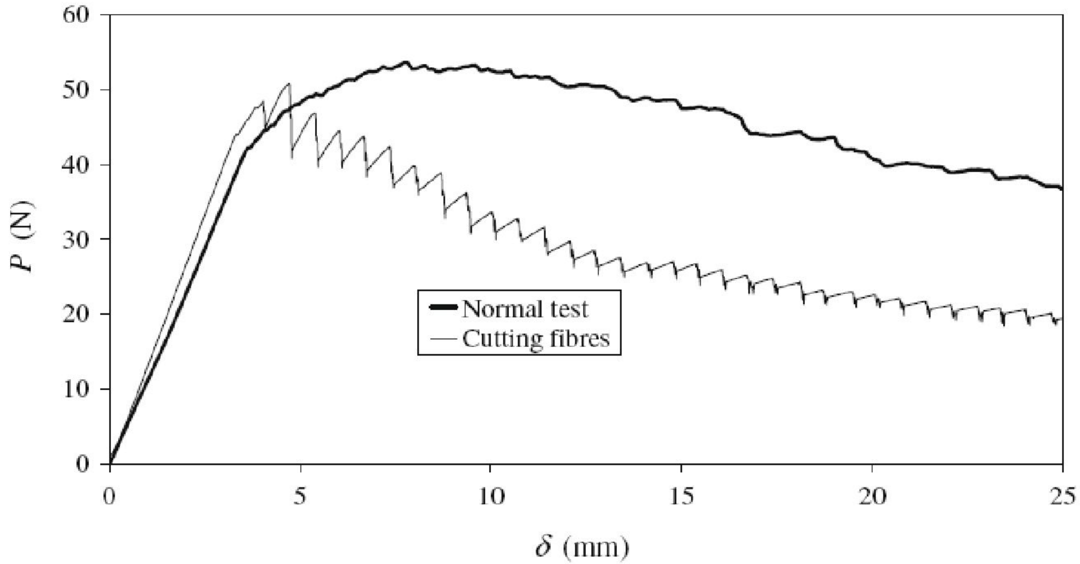
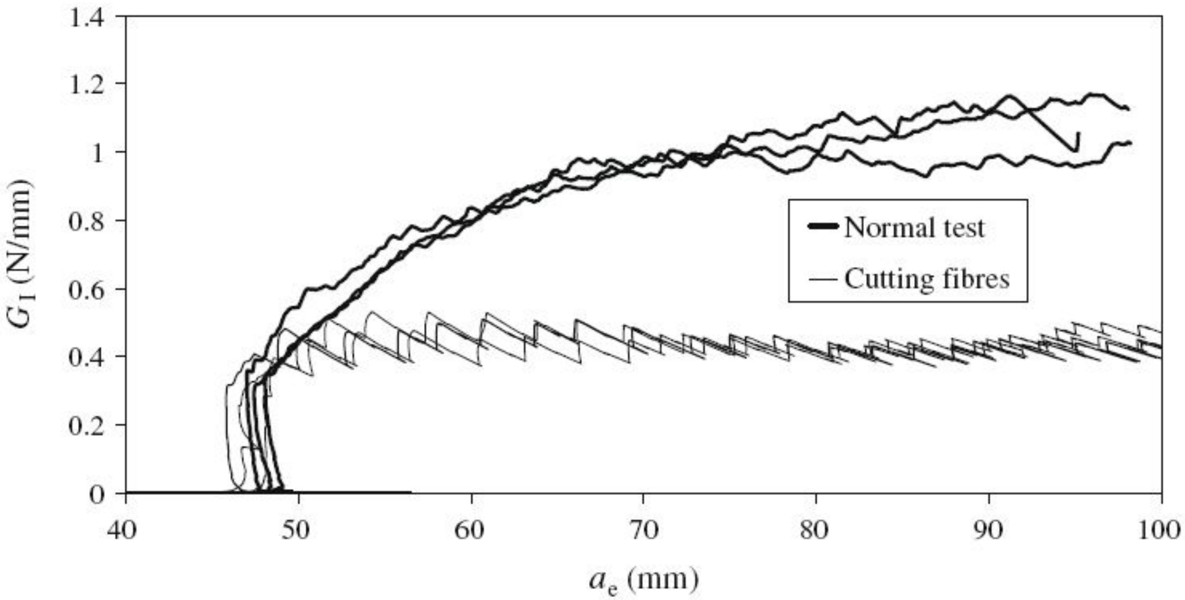
G_{iic} : G_{ic}

- The principle in the opening mode I is similar as the beam theory is used again:
- $G_{ic} = P_c^2 a^2/WEI = 3P_c^2 C/2Wa$
- Both G_{ic} and G_{iic} are correlated to the elastic laminate properties in bending
- P_c is expected to be different for mode I and mode II
- Crack propagation is measured – thus the causes leading to the crack initiation and propagation are not determined by these tests

De Moura: crack bridging & G_{ic}





G_{iic}: ENF vs. multidirectional plies

- Multidirectional lay-ups: crack branching and deviations from central plane observed
- No dependence on the delaminating interface
- Recent round-robin test report on 0/90 and angle ply laminates identified 50% invalid tests in the report due to:

Deviation from the mid-plane

Delamination oscillation between adjacent 0 plies

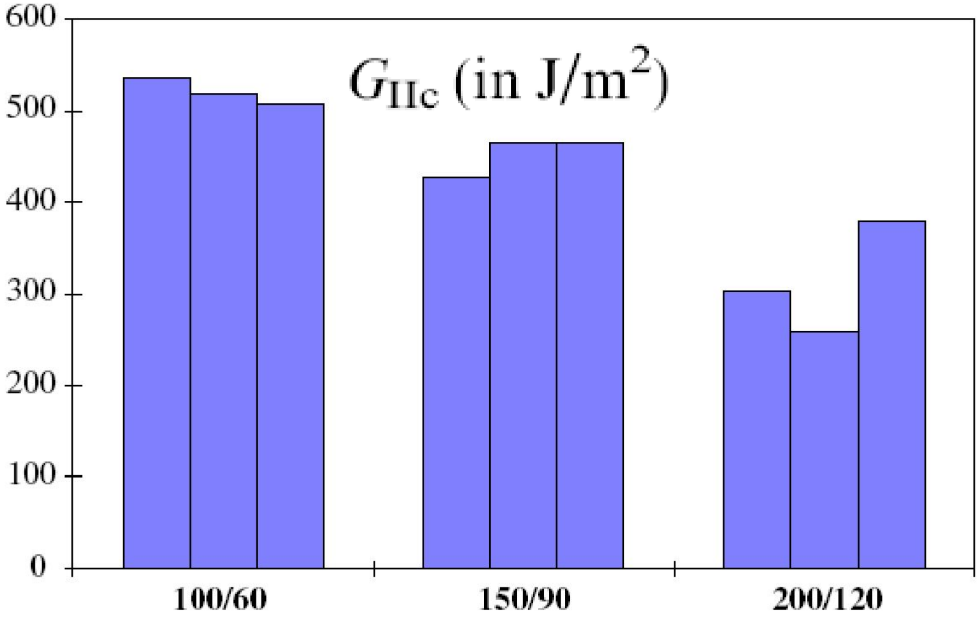
Friction contribution which may vary between 2-20% as reported in various studies

Matrix cracking in angle-ply laminates introduces coupling between extension and shear

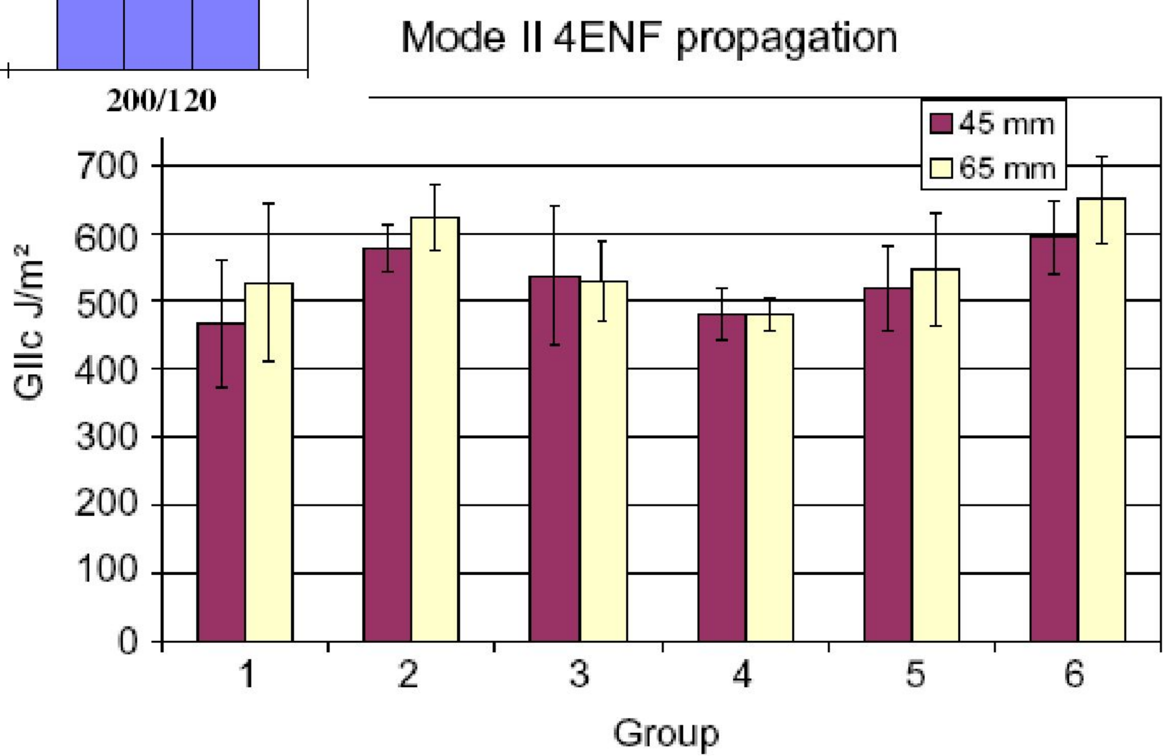
G_{iic}: ENF vs. Real life structures

- G_{iic} reported higher for multidirectional composites, with the same initiation value
- Premature yielding and intraply failure
- Locally mode I dominated with 45 degree microcracks growth from the thickness direction
- Contradictory data reports for angle ply laminates
- In a study by Tao & Sun, delamination always ‘jumped’ to 0°/Θ interface in ENF

G_{iic}: round robin (Tanaka, 2nd VAMAS)



Influence of span on Giic



4ENF: influence of crack size

G_{iic}: Inter-intra jumping

- Two adjacent lamina with two different fibre angles induce extensional and bending stiffness mismatch
- In combination with the matrix, this region becomes sensitive to delamination at interfaces
- Crack front propagation does not correlate to failure criteria which are ply-stress determined
- Crack front is ‘attracted’ to the highest stress value in the vicinity of the crack
- The zone of influence: ply thickness

Question

- Why is Giic sometimes correlated with CIA?

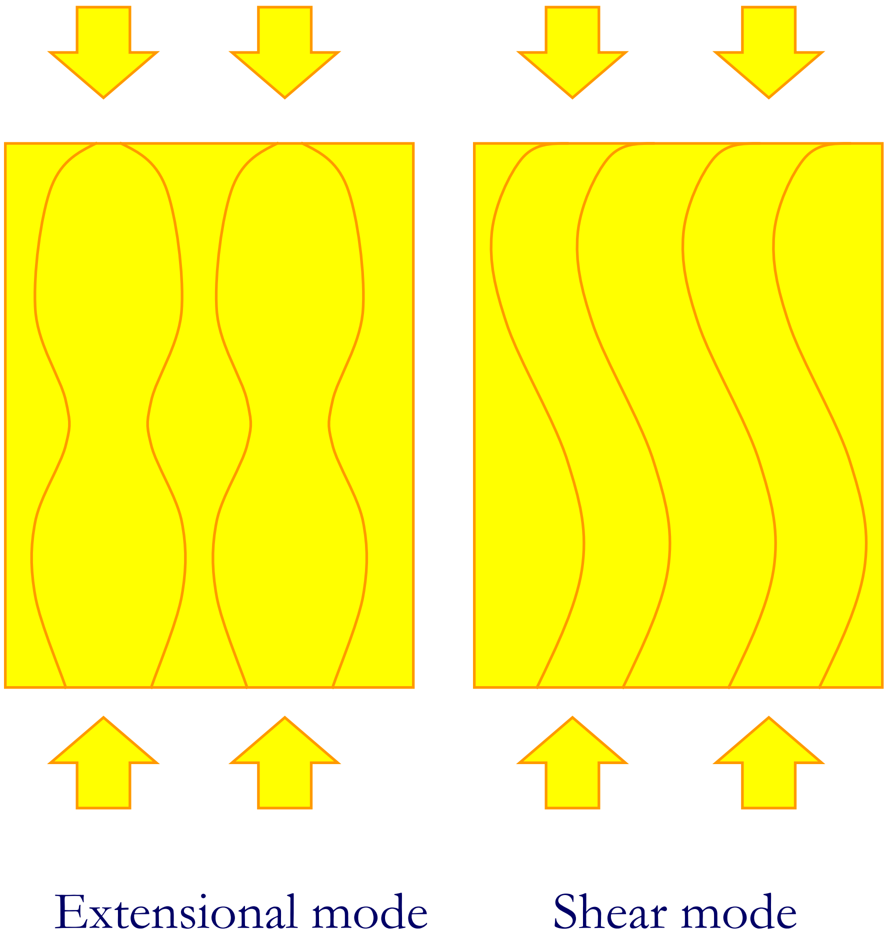
Compressive strength prediction

- Fibres under compression fail by local buckling
- Two possible modes: extensional and shear
- Extensional: stretch and compression of the matrix in an out-of-phase manner.

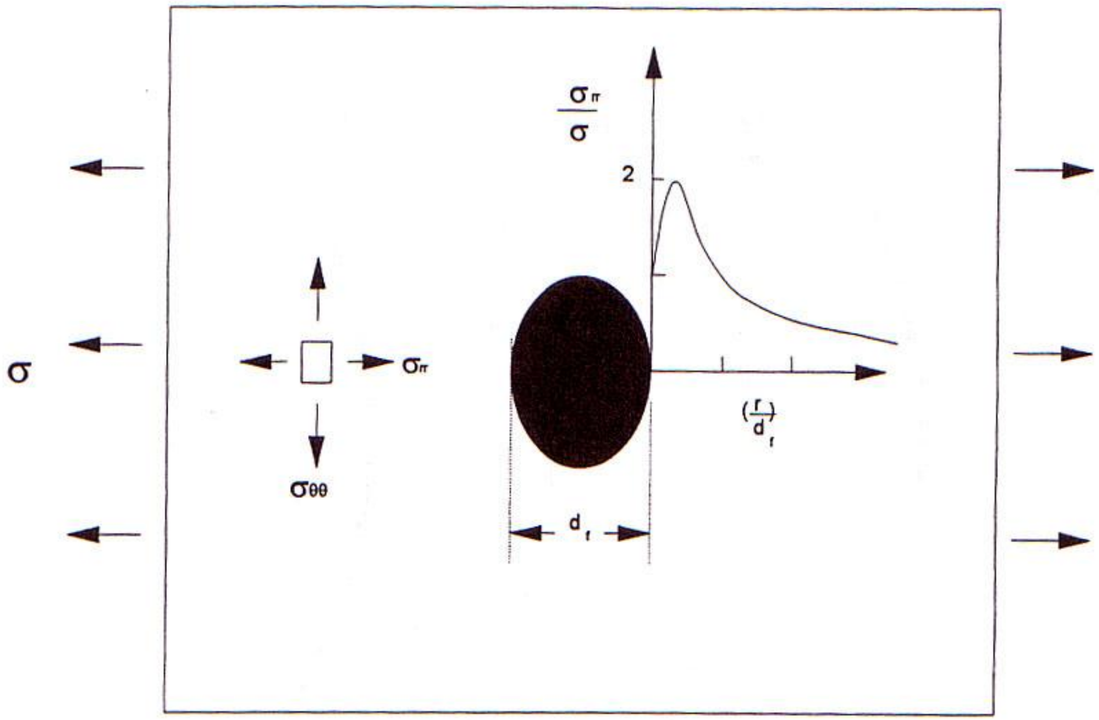
$$\sigma_{cu} \sim 2V_f\,[(V_f E_m E_f)/(3(1-V_f))]^{0.5}$$

- Shear mode: the fibres buckle in phase and the matrix is sheared. Buckling stress:

$$\sigma_{cu} \sim G_m/(1-V_f)$$



Transverse Strength and Failure Modes



Schematic of the radial stress at and near the fiber-matrix interface in a composite under transverse loading

MAXIMUM STRESS CRITERION

- When a load is applied to the lamina at an angle of 90° with respect to fibres, fibres act as hard inclusions and the stress near the interface is 50% higher than the applied stress
- With higher V_f, better stress distribution is achieved
- The local stress increases with higher Ef/Em ratio, but the strength may be reduced
- Greszczuk prediction:

$$\sigma_{2u} \sim \sigma_{mu}/K$$

Where the transverse strength depends on the ultimate tensile strength of the matrix.

K represents the maximum stress concentration in the matrix

Points for further discussion

- Can we assume the elastic properties mismatch a genuine composite phenomenon, ignore causes for intraply failure and focus on prevention by design?
- Can Cytec provide any experimental data for discussion and analysis?
- To prevent a complete modulus loss in a cracked lamina, should self-healing methodologies be considered?