Critical energy densities of resin systems: the key to matrix dominated composites failure

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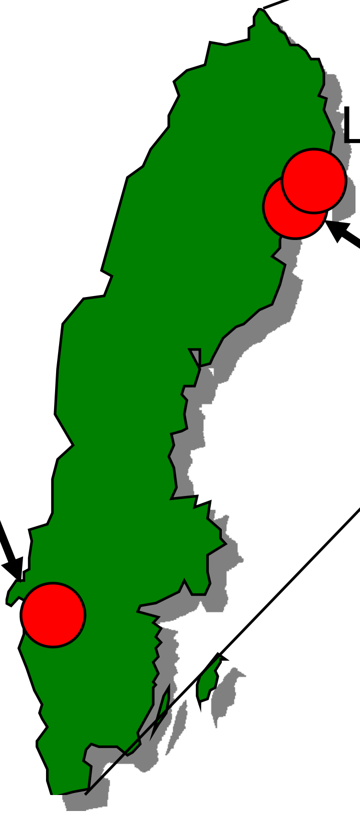
Swerea SICOMP- on the map

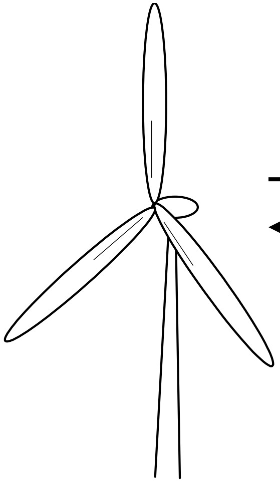
Mölndal



Luleå

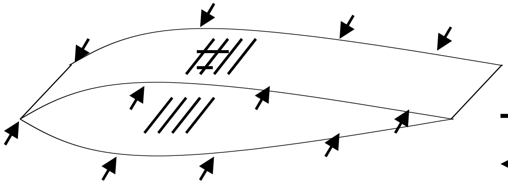
Piteå

Failure of composite structures



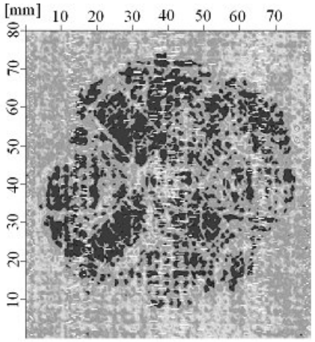
Structure

10-100 m



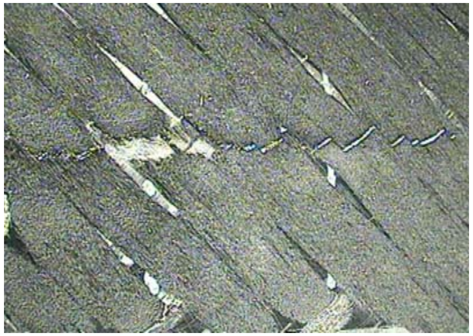
Structural element

~ 1 m



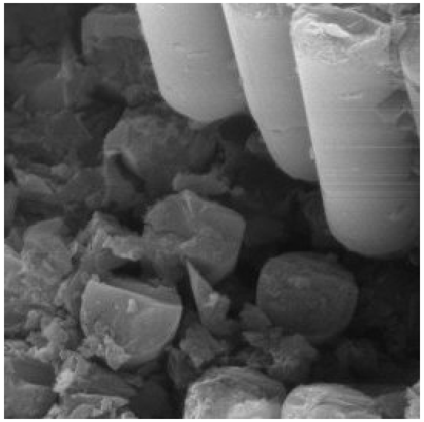
Damage zone

~ 0.1 m



Failure mechanism

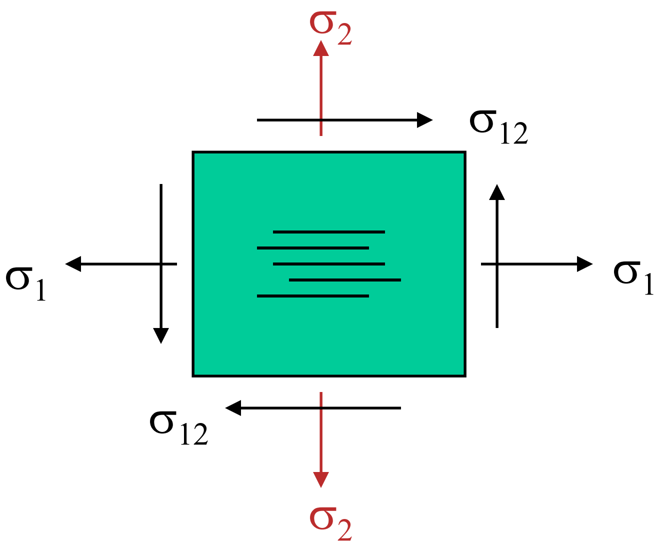
~ 1 mm

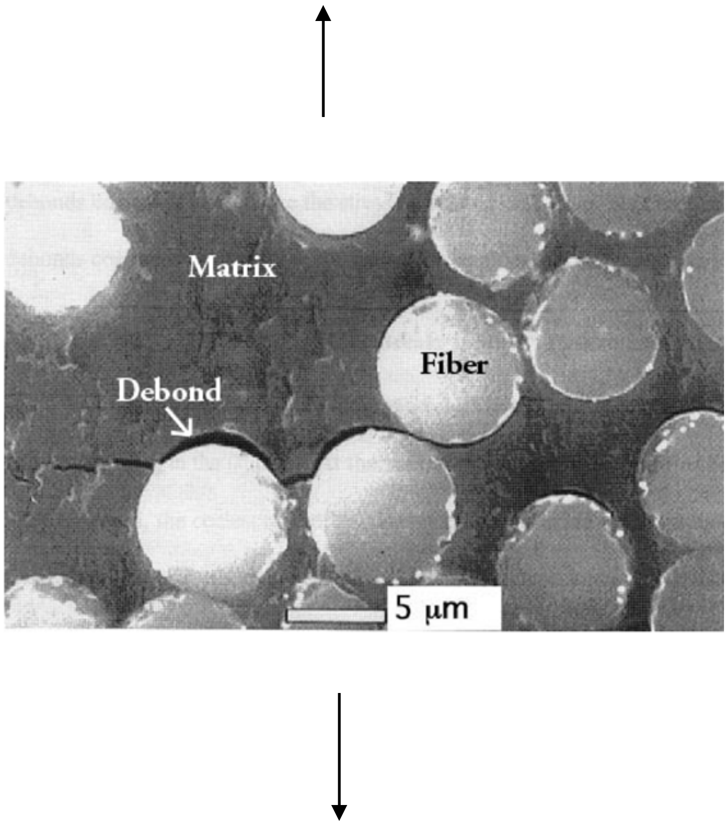


Micro mechanism

~ 1 μm

Matrix dominated failure

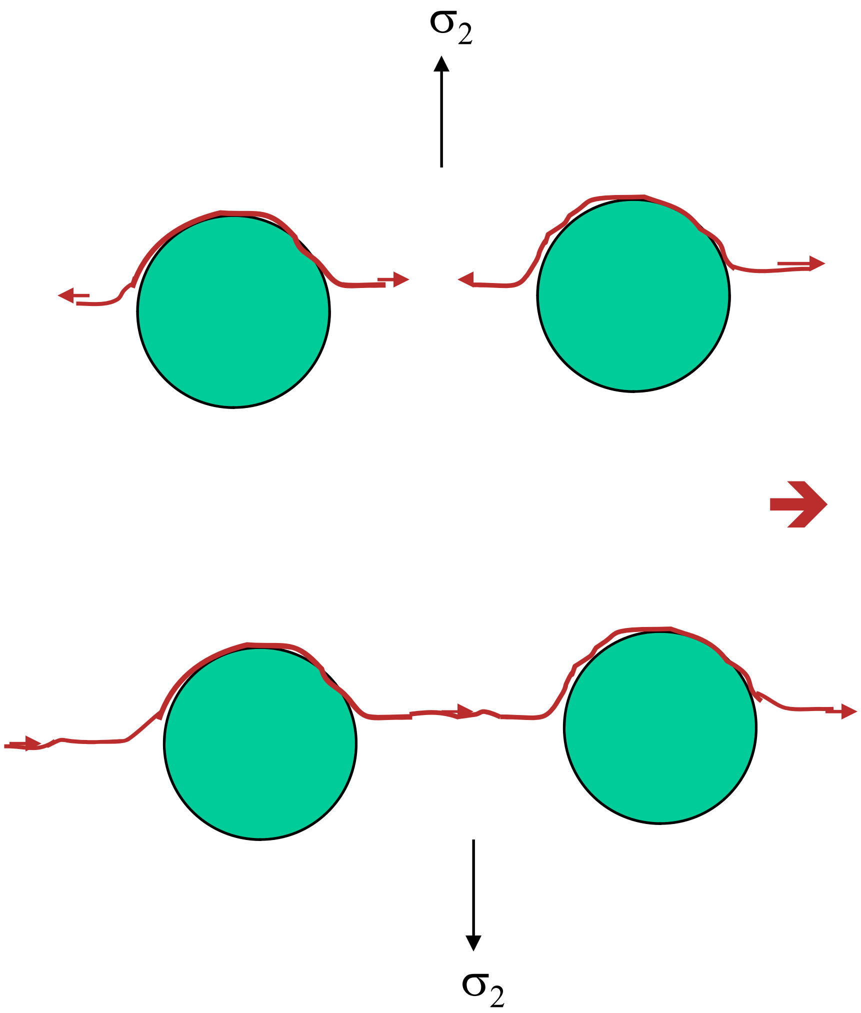




Which comes first: fibre debonding or matrix cracking?

Governing mechanisms

– fibre debonding vs. matrix cracking

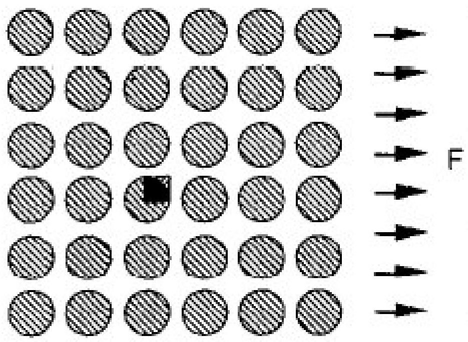


Debond cracks grow and divert into the matrix

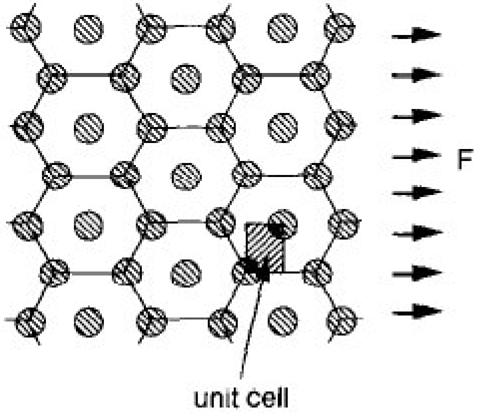
Matrix cracks grow and hit fibres, debonding them

➔ To be determined by local stress state and failure criteria!

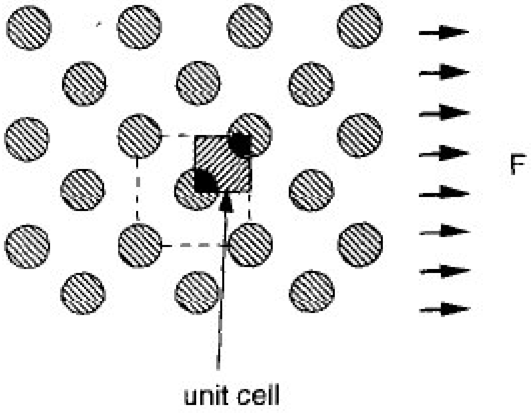
Micro structure – fibre distributions



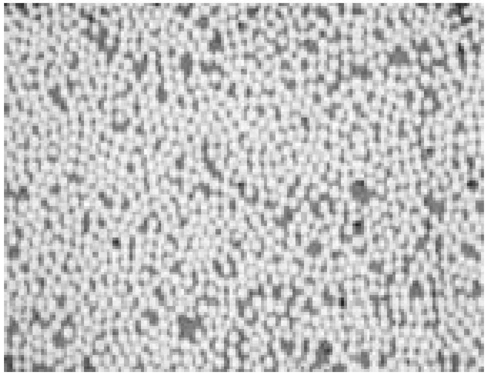
Square array



Diagonal array

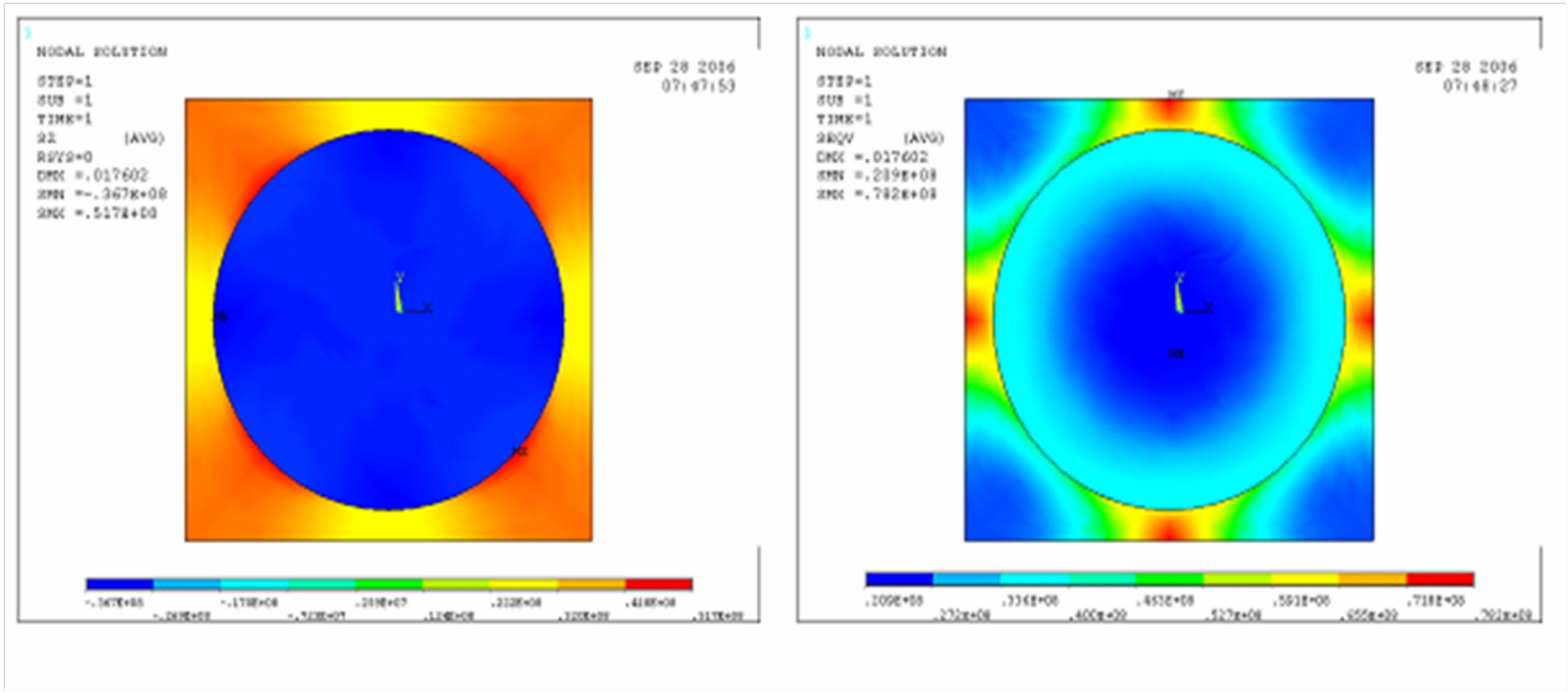


Square-diagonal array



Micro structure

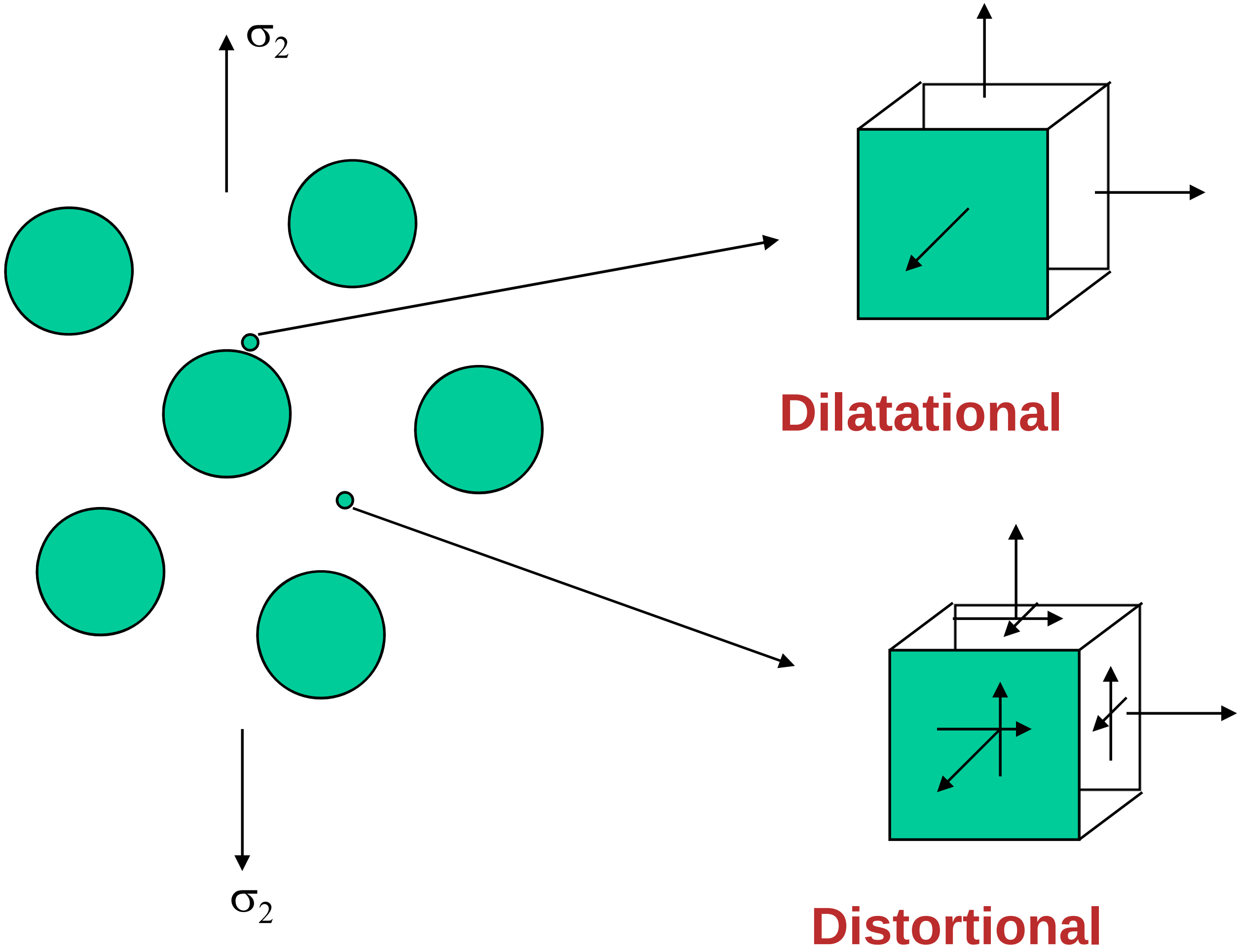
– stress distributions from thermal loading



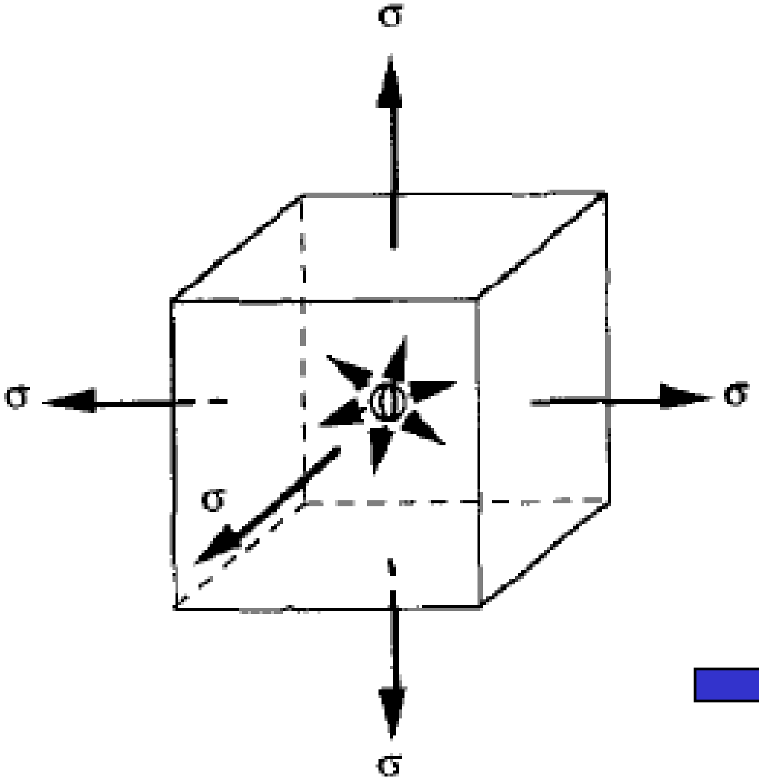
Local stress state from thermal and mechanical loads depends on:

Fibre and matrix properties; fibre distribution and V_f.

Local stress state from transverse loading (including thermal stresses)



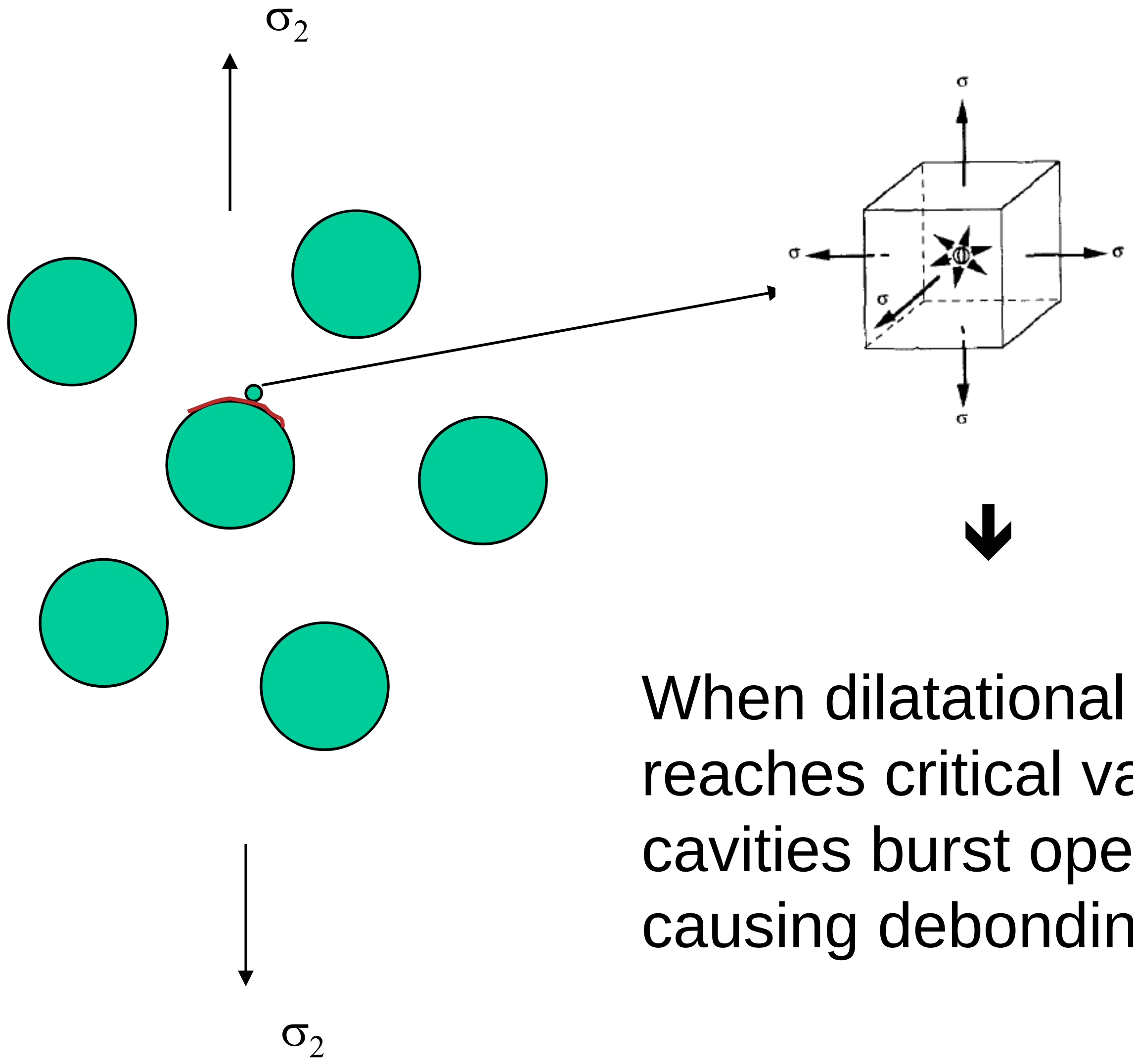
Effect of Dilatational (hydrostatic tension) stress



→ Cavitation, presumably from free volume in polymers

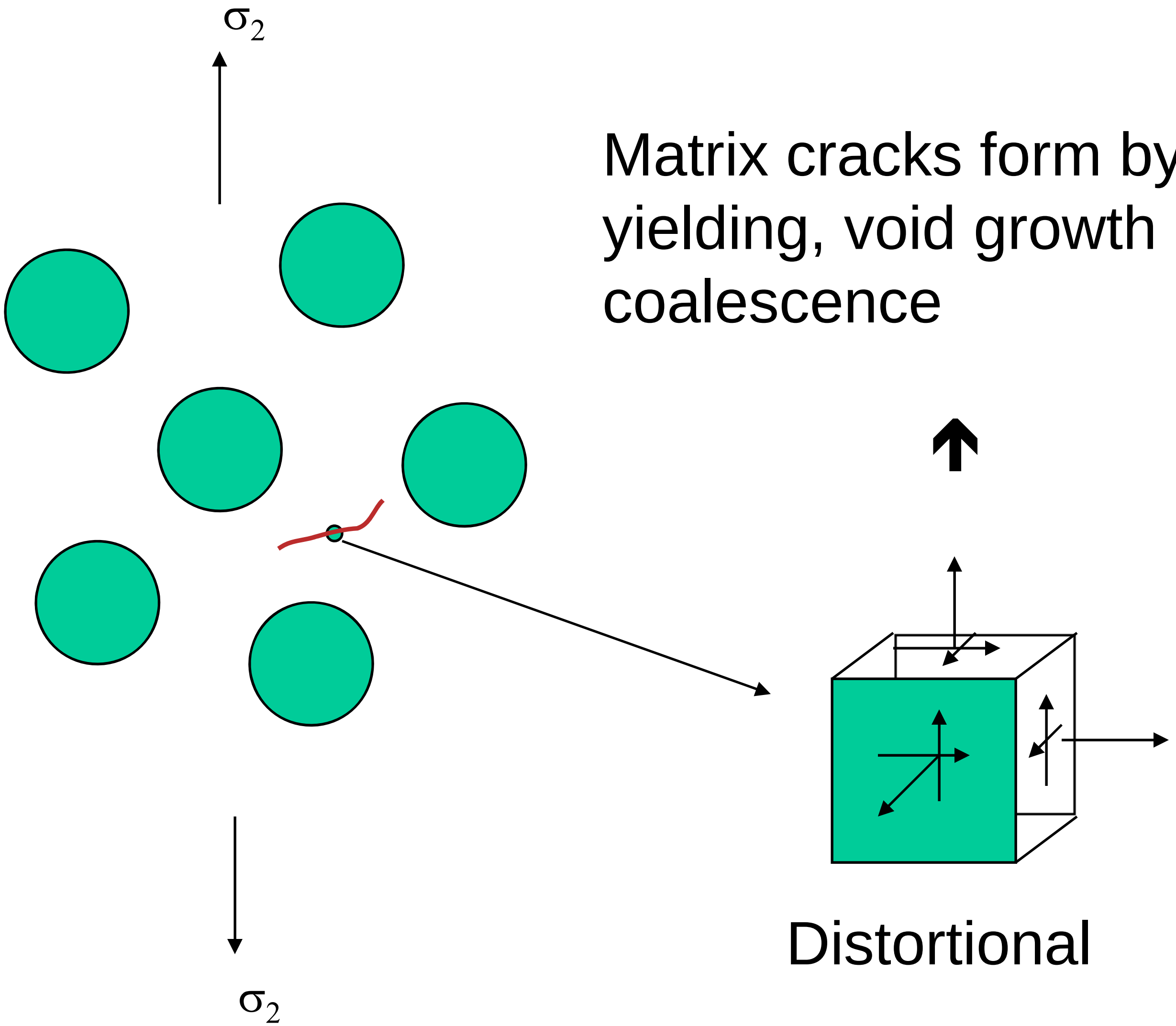
➡ Unstable growth of cavitation at critical dilatational energy

Effect of dilatational (hydrostatic tension) stress



When dilatational energy reaches critical value, cavities burst open, causing debonding

Effect of Distortional stresses



Matrix cracks form by yielding, void growth and coalescence

Debonding vs. Matrix cracking

- Depends on manufacturing induced fiber distributions and voids

Engineering Approach:

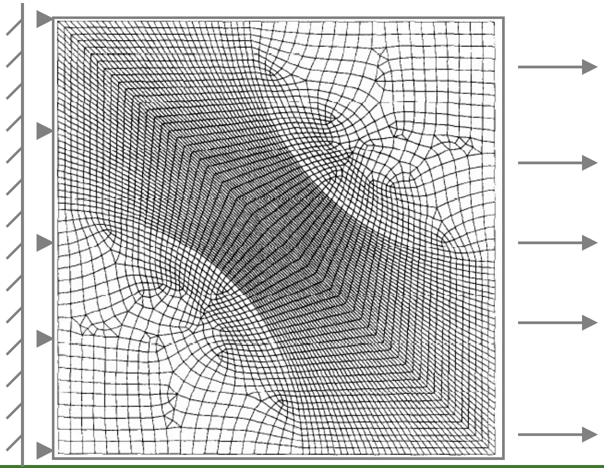
➔ Find worst-case (extreme) scenarios for design

Consider thermal loads in micro-mechanical analyses

Composite unit cell

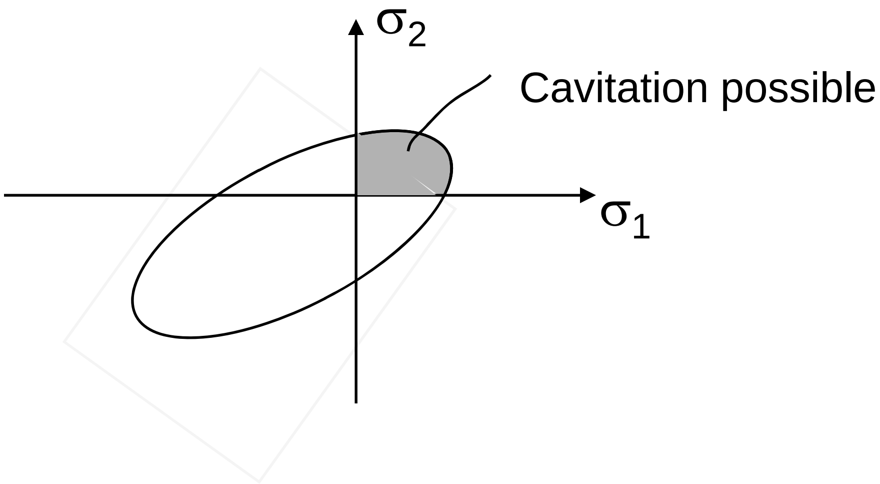
- Fibres and voids explicitly represented in the microstructure
- Material model
  - Fibre: linear elastic
  - Matrix deformation: Macromolecular model, glassy polymers
  - Matrix fracture: Yielding, e.g. New craze model (Rice-Tracy ductile fracture model)
  - Fibre-Matrix debonding: Dilatational energy density criterion

- Loading: Plane strain tension
  - Temperature
  - Strain rate



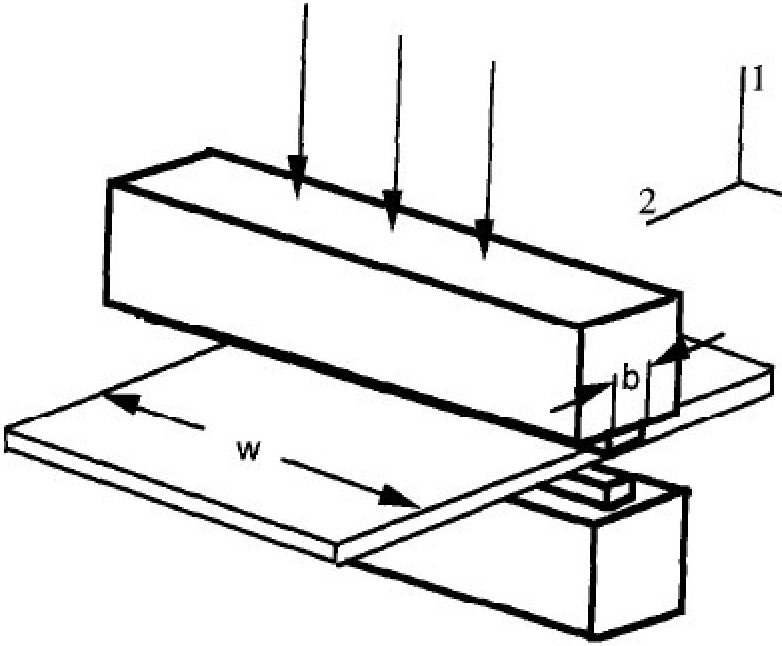
Matrix cracking: design data

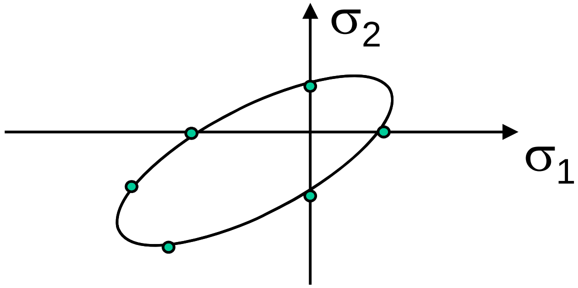
- Material data are to be measured on glassy polymers (not on composite materials!)
  - High distortional energy densities: measure yield stress
  - High dilatational energy densities: measure stress at crack initiation by micro cavitation



High distortional energy density tests – Yield stresses

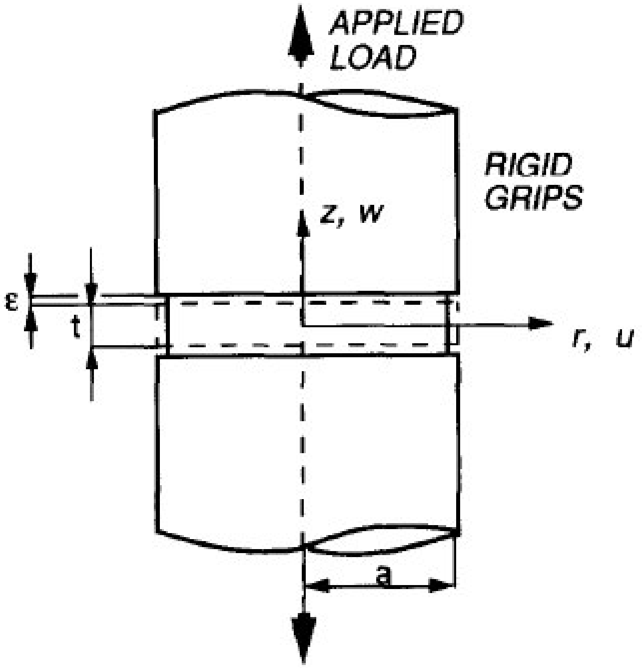
- Uniaxial tests according to ASTM D638M-81
- Plain strain compression test (friction free)

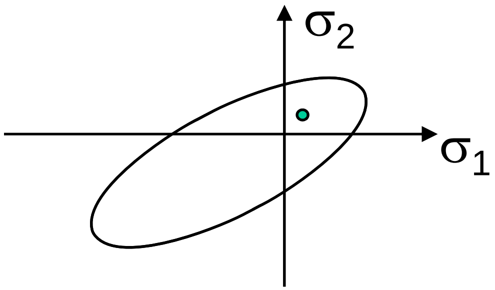




High dilatational energy density tests – Cavitation stress (3D)

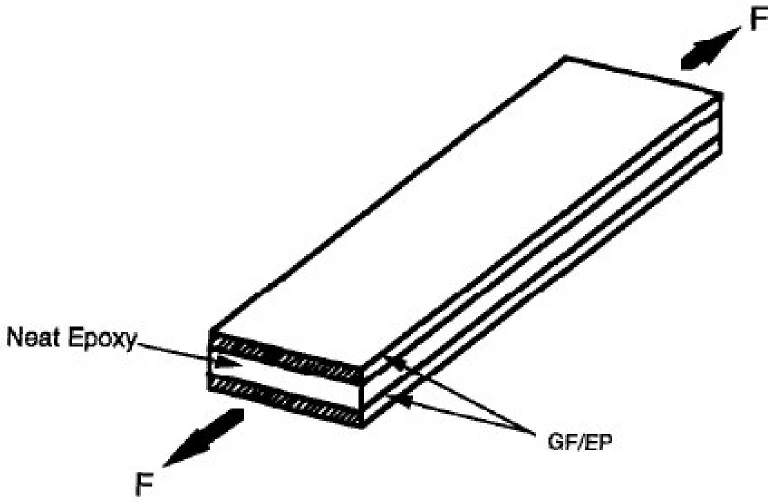
- The Poker-chip test, a 3D-tension test
  - Very difficult test to perform

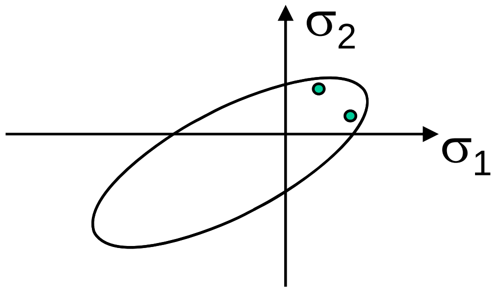




High dilatational energy density tests – Cavitation stress (plane stress)

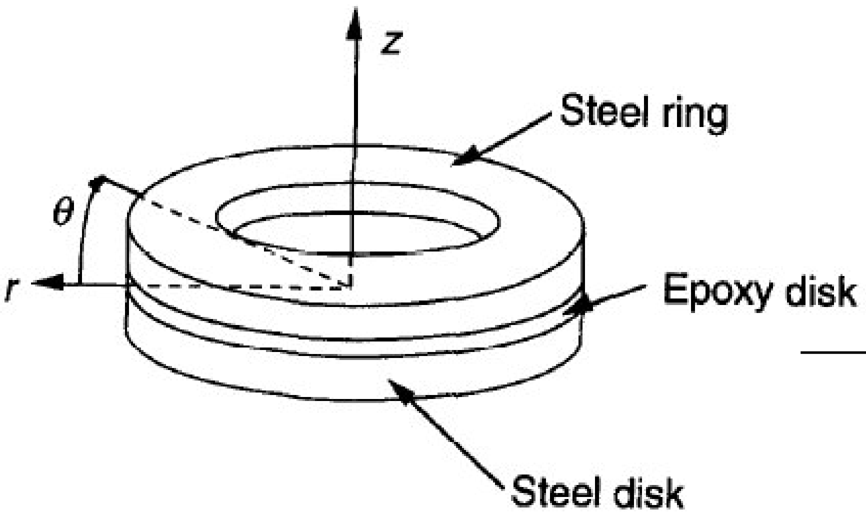
- Biaxial tension tests of hybrid composite/glassy polymer laminates (1.25mm thick polymer layer), thermal stresses considered.

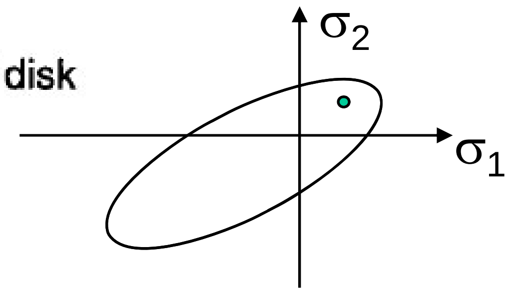




High dilatational energy density tests – Cavitation stress (equibiaxial stress)

- Thermo-mechanical disk test (loaded by cooling down to temperatures of -160ºC)
- Equibiaxial, meaning that radial and tangential stress components are equal.





Dilatational vs Distortional energy density criteria

- The dilatational energy density criteria is applicable only when the level of distortional energy density is low.
- There is a need to identify these regions in stress space where matrix failure is governed by either dilatational or distortional energies.
- These tests are to be performed on neat resins and to be used in computational analyses of composite materials and their structures.

Prediction of matrix cracking/ debonding in composite materials

- Measured dilatational and distortional energy densities are employed in micromechanical analysis of composites
  - Debonding: $U_v = \frac{1-2\nu}{6E}(\sigma_1 + \sigma_2 + \sigma_3)^2 = U_v^{crit}$
  - cracking/yielding: von Mises or modified yield criteria for polymers.

    Rice-Tracy ductile fracture model

Example: Failure initiation predictions

- Matrix cracking predicted by von Mises yield stress
- Matrix debonding/cavitation was predicted by the dilatational energy density criterion.

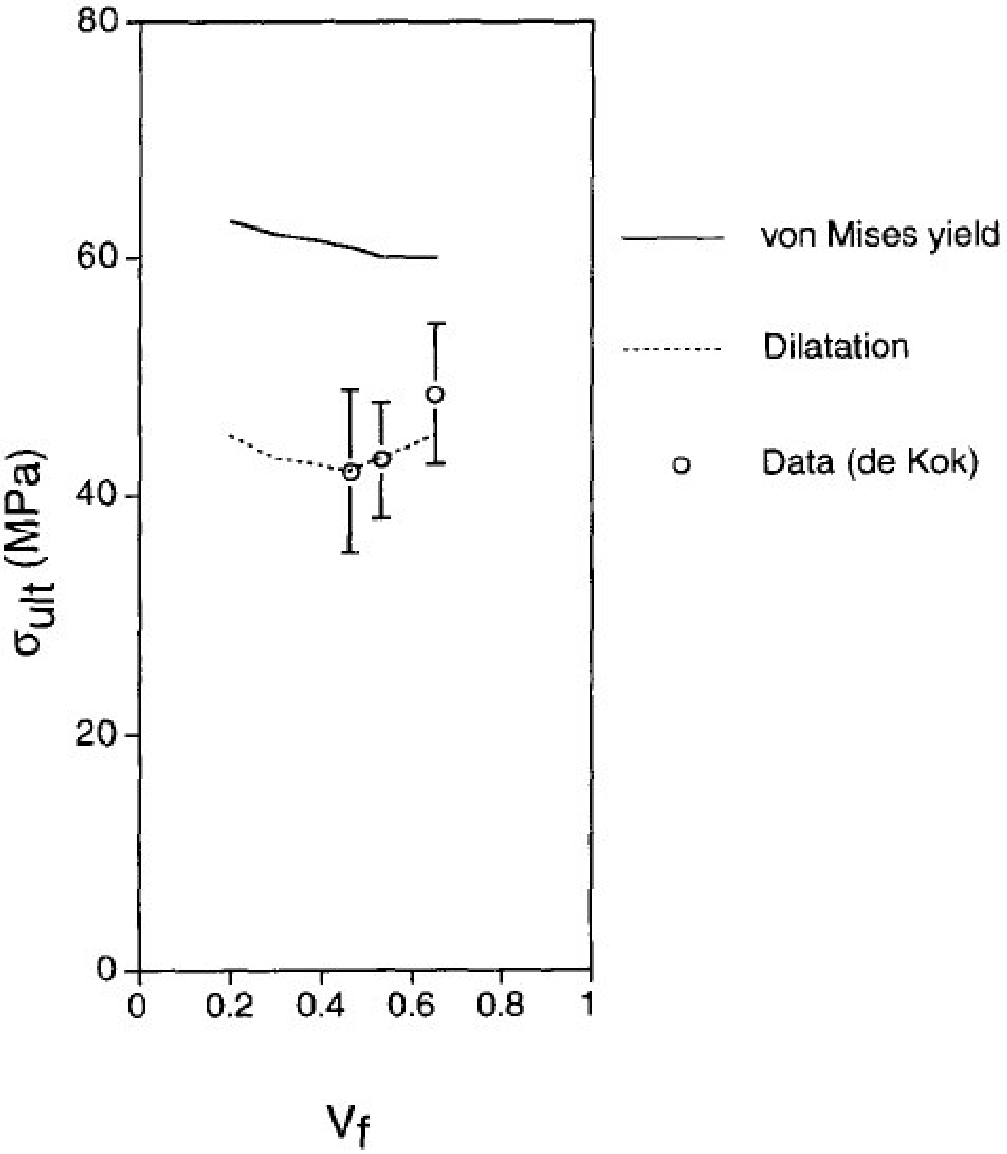
Glass/epoxy laminates

Assuming square array fibre distribution.

Material	Young's modulus (GPa)	Poisson's ratio	Thermal expansion coefficient (10^{-6}/ºC)
E-glass	70	0.22	7
Epoxy	3.2	0.37	67.5

Results

Transverse failure by debonding, i.e. cavitation, predicted for all composite laminates.



Conclusions

- Prediction of matrix dominated failure in polymer composites should rely on test data on the glassy polymer considering:
  - Matrix cracking
  - Fibre debonding/matrix cavitation
- Test methods for biaxial tensile loading with varying biaxiality ratio should be expanded
- Further studies needed:
  - composite matrix failure under more general imposed loading should be performed
  - Influence of voids, misalignments, and other defects

References

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