The University of Manchester

Prof C Soutis PhD, Ceng, FRAeS, FIMechE, FIM, AFAIAA
Chair of Aerospace Engineering
Director of the Aerospace Research Institute

MANCHESTER
1824
The University of Manchester

Who are we?

“The largest single-site university in the UK, with a history dating back to 1824, in one of the most vibrant cities in the world”

Manchester

- Birthplace of the industrial revolution
- Population of Gtr Manchester: 2.5M
- Largest student population in Western Europe
- 2 hours from London by train
- International Airport

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Key Facts

- 39,000 students
    - 11,000 Postgraduate
    - 29,000 Undergraduate
    - 9,000 International students
- 9,800 staff
    - 4,300 Academic and Research
- 25 Nobel prize winners, including the Nobel prize for Physics in 2010

History and Achievements

- In 1824 Manchester pioneered courses in Mechanical Engineering
- Birth place of the Reynolds Number
- Where Rutherford split the atom
- First programmable computer was built
- 3rd largest steerable radio telescope and home to the Square Kilometre Array control centre
- Associated with 25 Nobel prize winners

Ernest Rutherford

Academic Structure

- Faculty of Engineering and Physical Sciences (EPS)
- Faculty of Medical and Human Sciences
- Faculty of Life Sciences
- Faculty of Humanities

<u>~10,000 students</u>

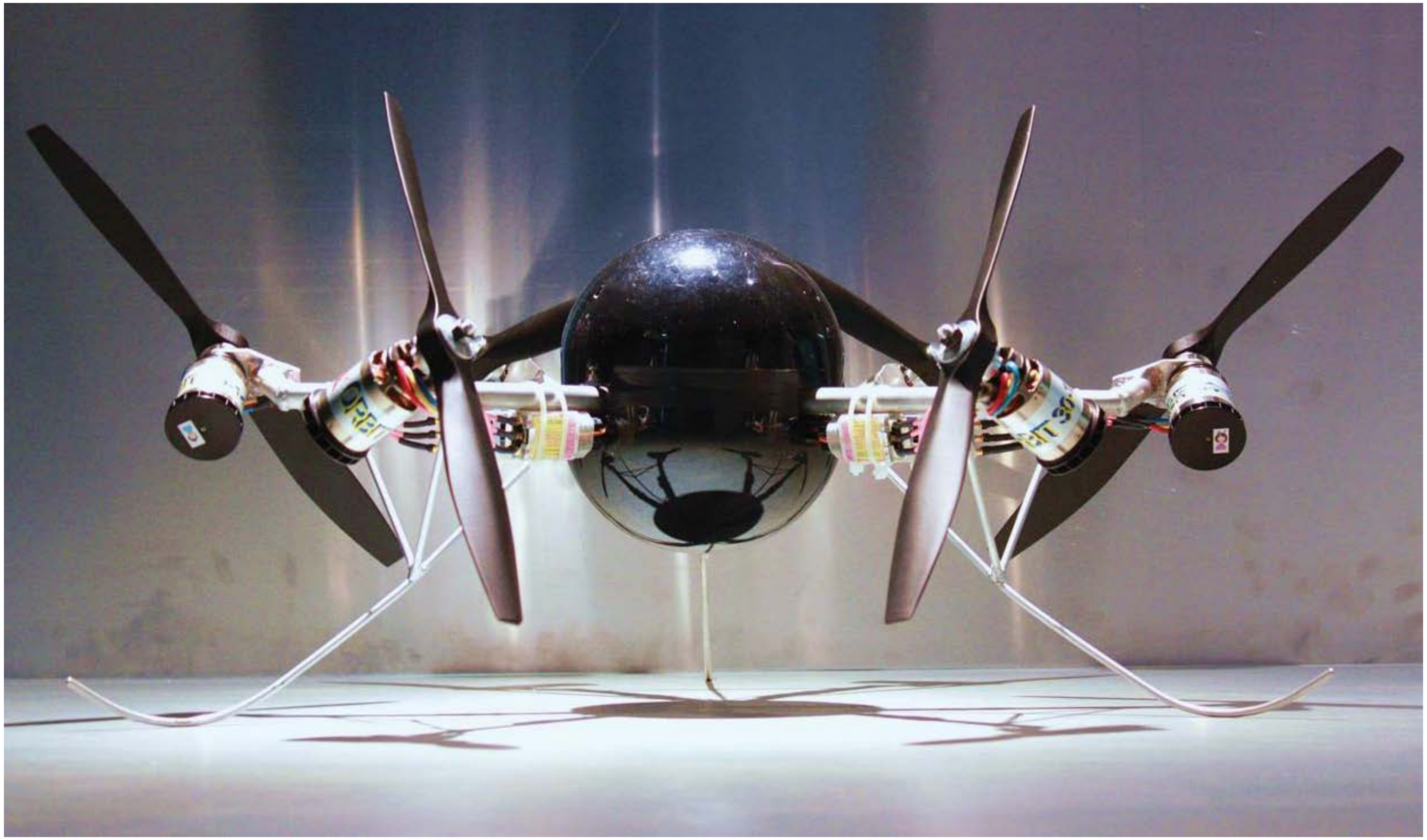
~3,500 international students

7,200 undergraduates
(24% international)

1,800 taught postgraduates
(67% international)

1,400 research postgraduates
(40% international)

Aerospace Research Institute



The University of Manchester
Aerospace
Research Institute

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northwest
composites
centre

Composites in Aerospace: A Multi-Physics Approach

Prof Costas Soutis PhD, CEng, FIMechE, FRAeS, AFAIAA

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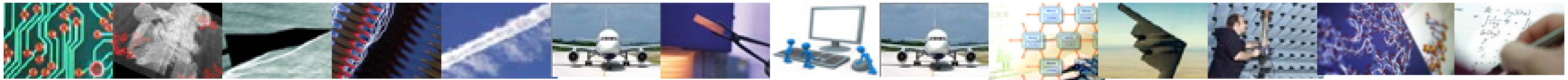
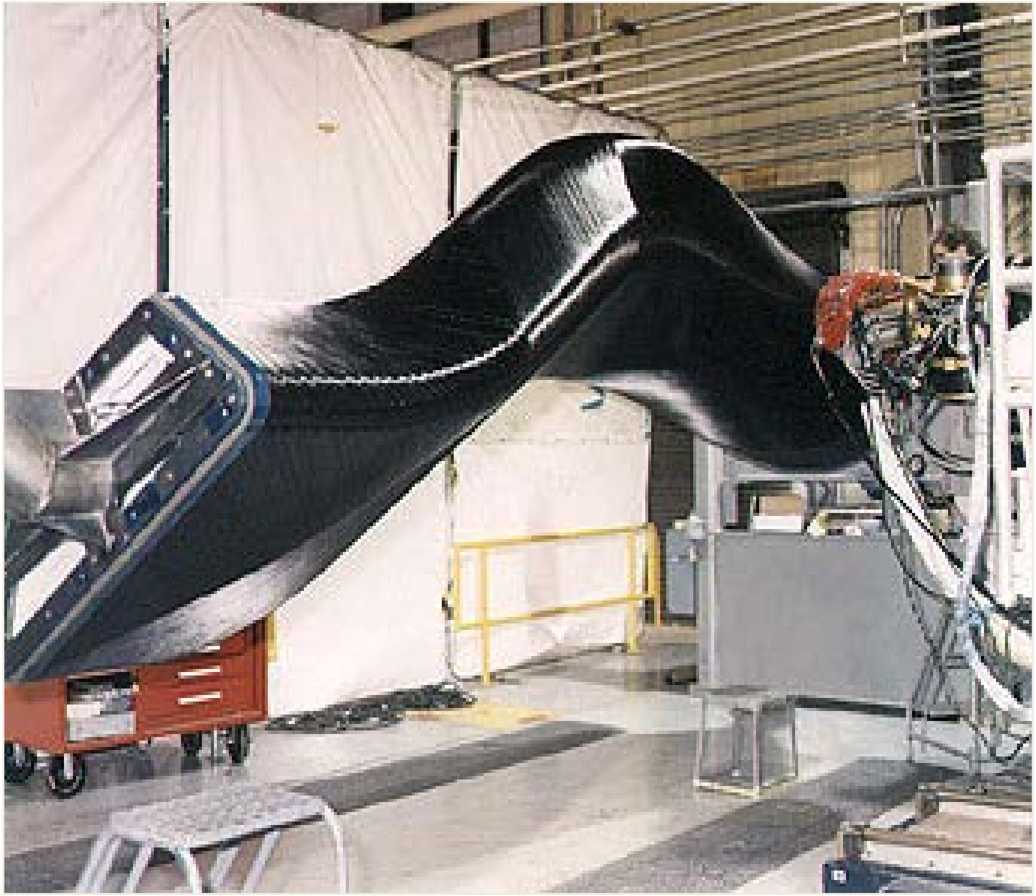


Complex inlet duct manufactured by ATP

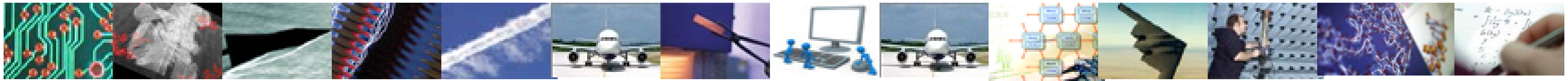
JSF/F-35



Multi-head robots are needed where combination of tape-laying and fibre placement can be performed

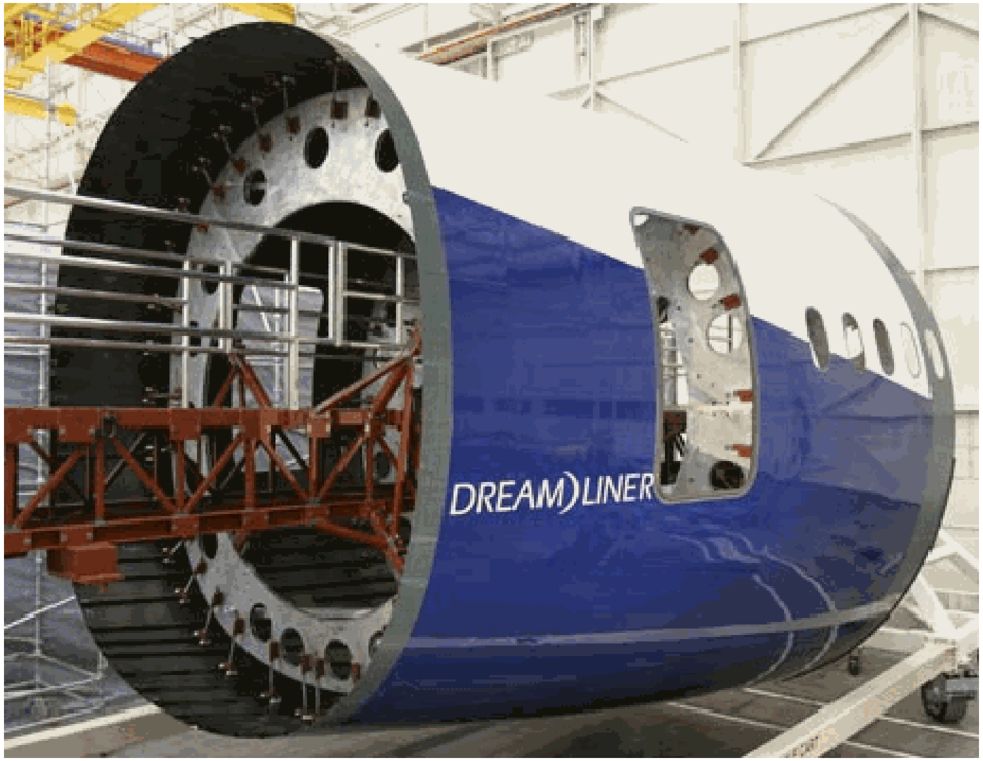
B787 Composite window

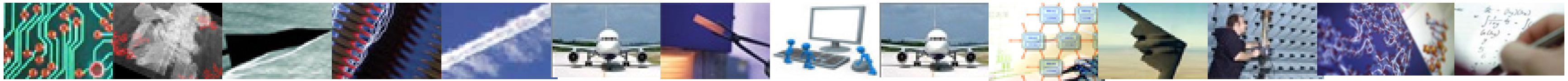
Industry’s 1st composite wide-body jet



Boeing 787

Full-scale composite one-piece fuselage section for the new Boeing 787





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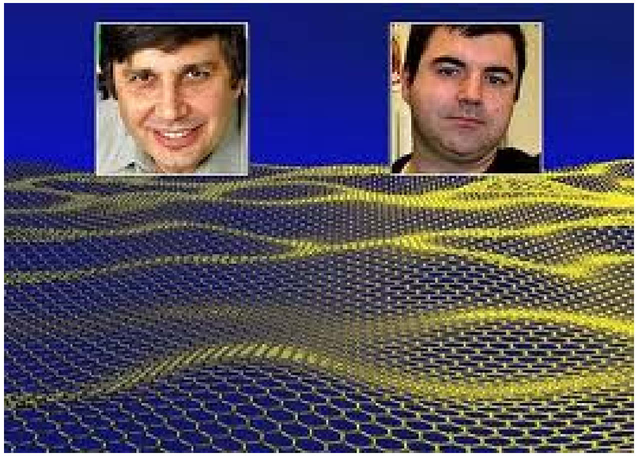
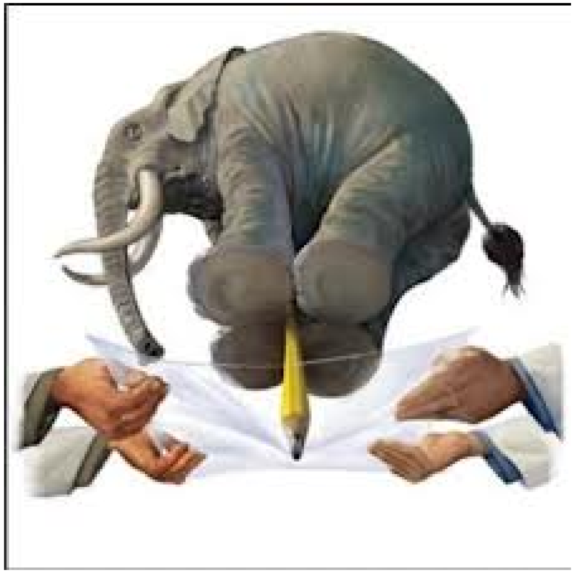
Graphene: Made in Manchester

It is a one atom thick (0.33 nm) sheet made of carbon atoms, arranged in a honeycomb (hexagonal) lattice





- ➢The University of Manchester, the Nobel prize for Physics in 2010

TODAY’S COMPOSITES CHALLENGES?

- Increase supply of raw materials
- Reduce materials costs
- Reduce finished part cost
- Reduce processing costs
  - Increase speed and volume of manufacture
  - Design to composites’ strengths – no longer treat as “Black Aluminium”
  - Machining, drilling, joining, assembly

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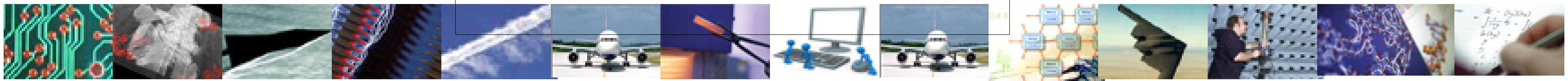
Current Typical Final Part Cost Breakdown

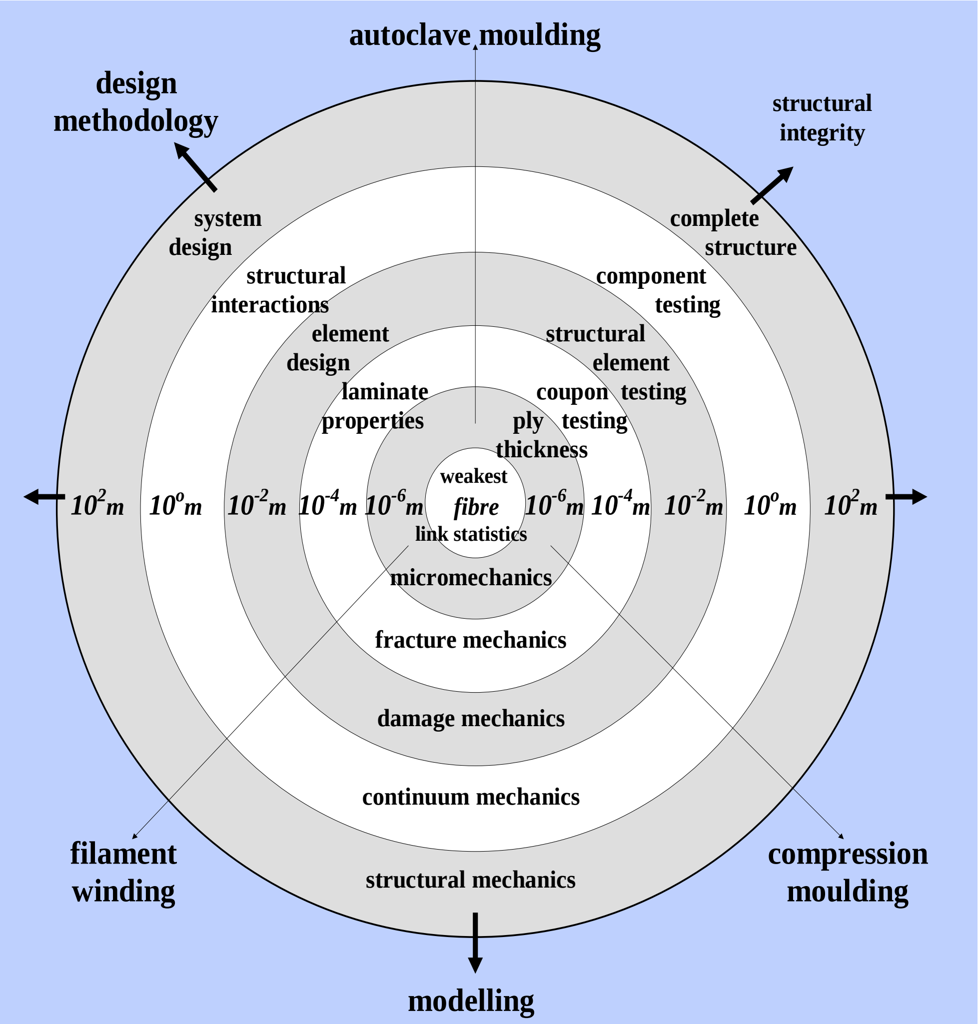
Material Cost

Customer Processing Costs

Processing 60-75% of Total Part Cost



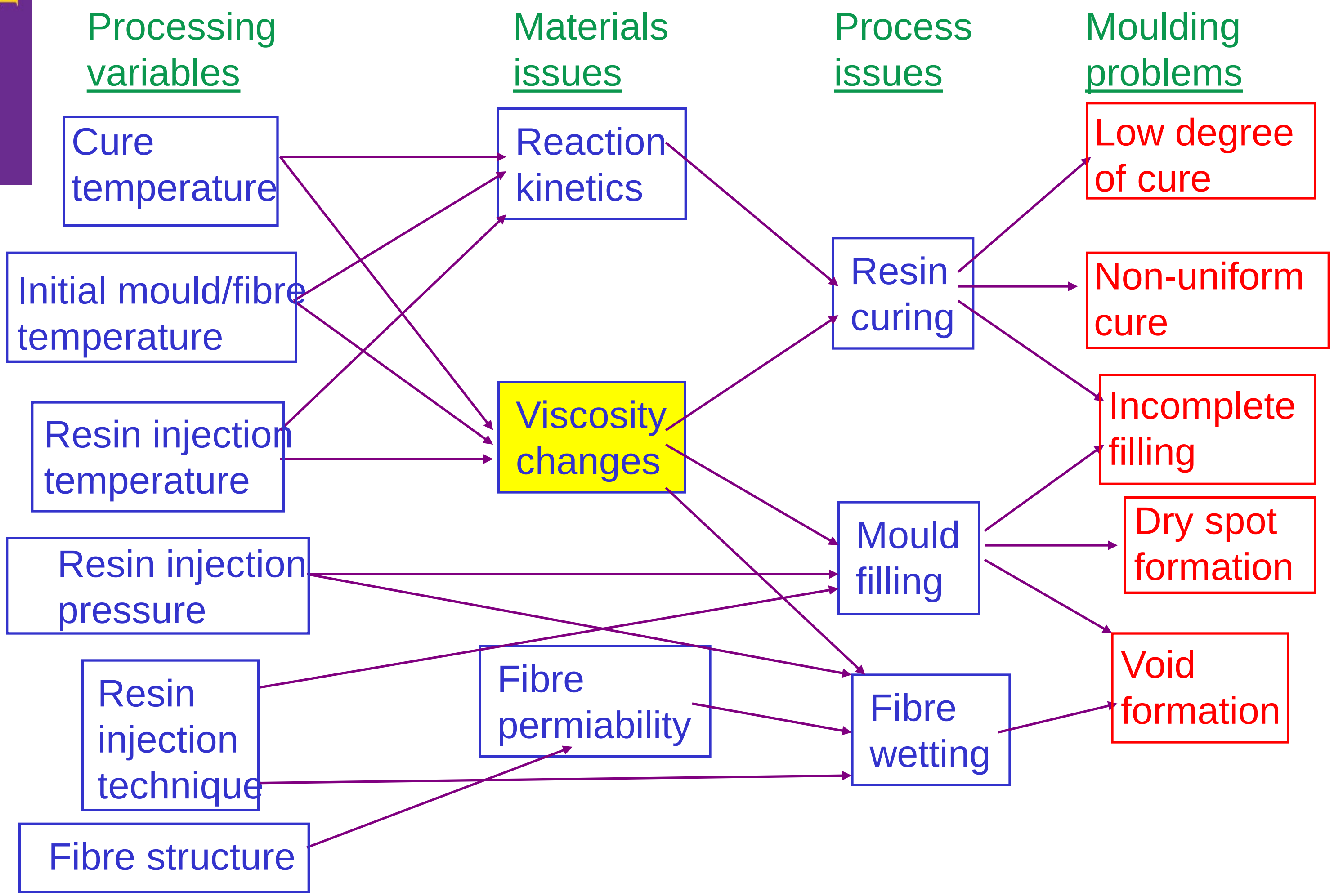
Composites Design



Soutis & PWR Beaumont
Multi-scale modelling

- ☐ Confidence in failure criteria is low, need to include manufacturing defects

Problems in liquid composite moulding

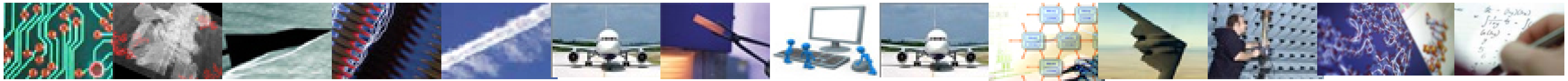


Processing variables
- Cure temperature
- Initial mould/fibre temperature
- Resin injection temperature
- Resin injection pressure
- Resin injection technique
- Fibre structure

Materials issues
- Reaction kinetics
- Viscosity changes
- Fibre permiability

Process issues
- Resin curing
- Mould filling
- Fibre wetting

Moulding problems
- Low degree of cure
- Non-uniform cure
- Incomplete filling
- Dry spot formation
- Void formation



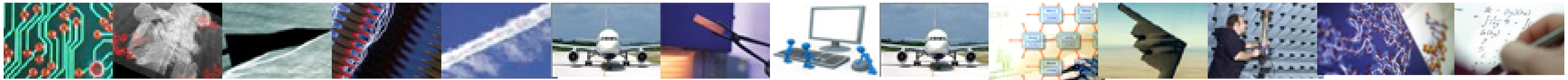
Mechanics of Composite Failure

- **The fundamental problems in composites are to determine the stresses and deformation within each layer in terms of known load resultants and the prediction of onset of failure in a layer and its progression towards final failure**

- **In regions remote from boundaries and stress raisers the analysis of stresses can be accomplished by LPT**

- **Prediction of failure is far less satisfactory especially in 3D woven composites**

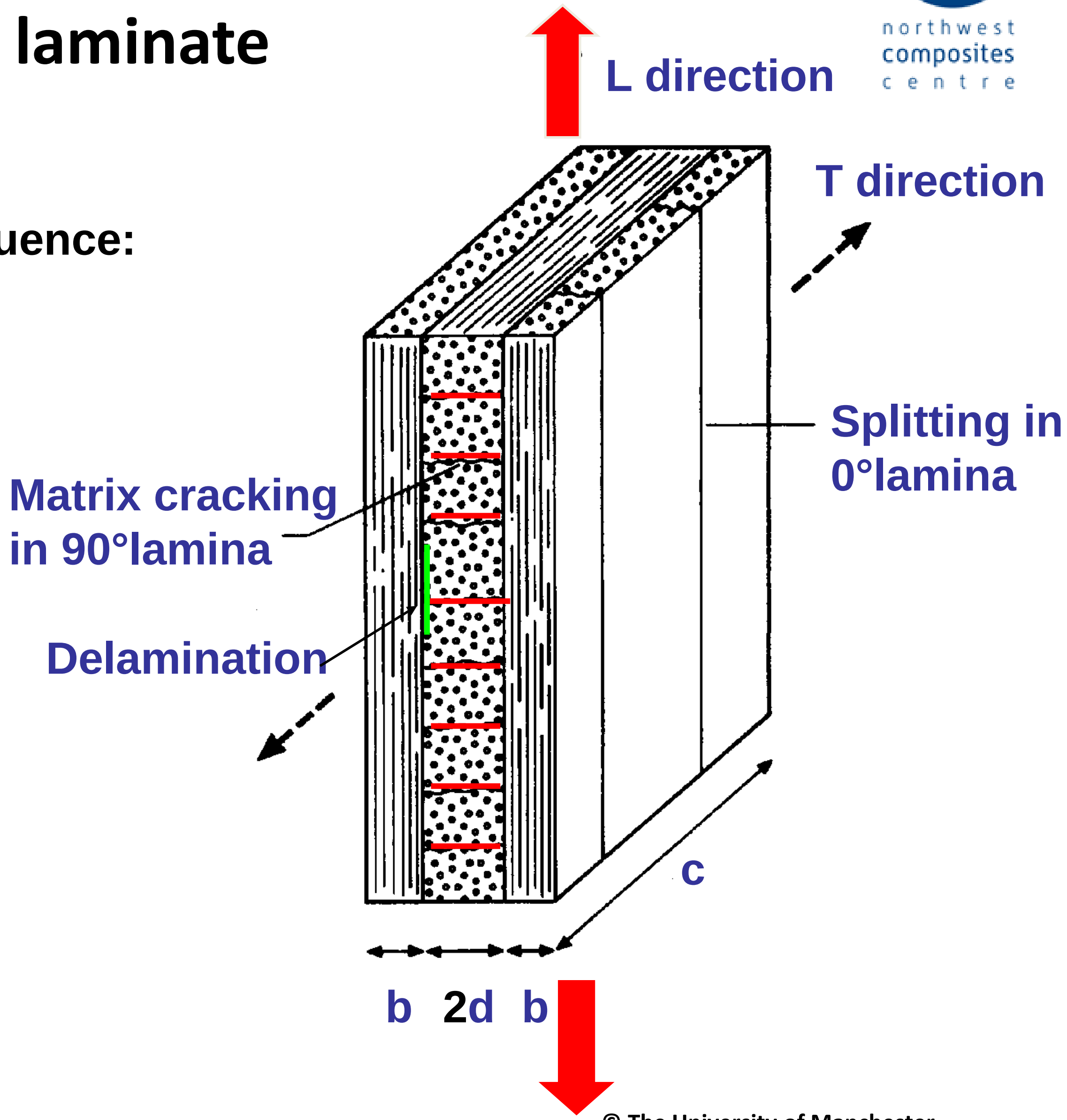
- **Need for improved design tools to optimise fibre architecture and cover local stress details** (OHC, impact, CAI) **but also life prediction and damage and damage growth**

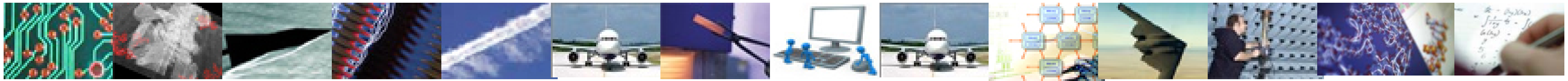


Failure of a 0/90 laminate

Damage accumulation sequence:

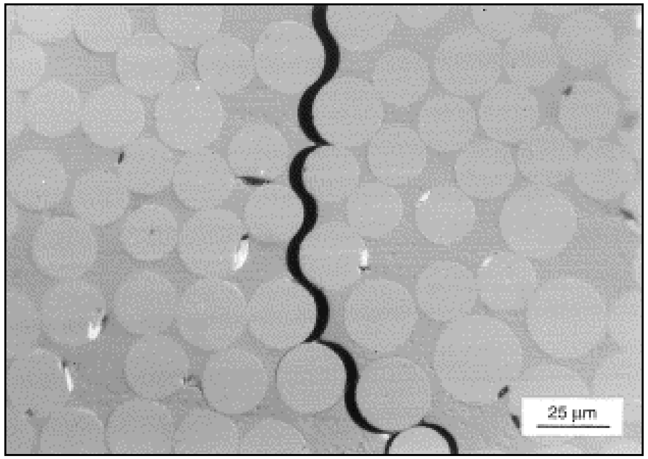
- Transverse cracking
- Longitudinal splitting
- Delamination
- Fibre fracture

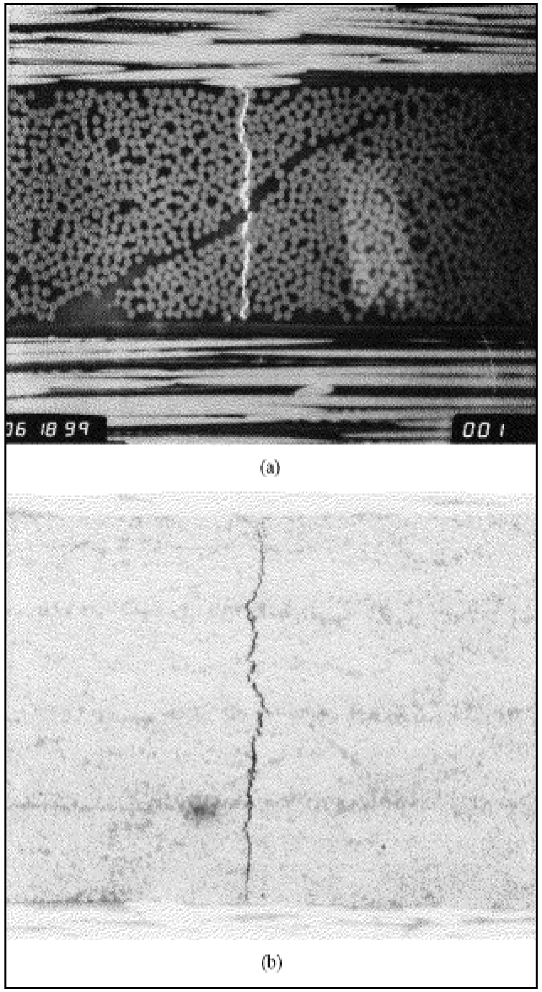




Damage Mechanisms under Tension

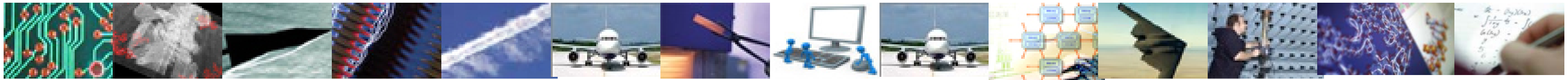
- **Matrix Cracking** causes degradation of the overall stiffness properties of the laminate
- Triggers development of other damage modes, delamination and fibre breakage



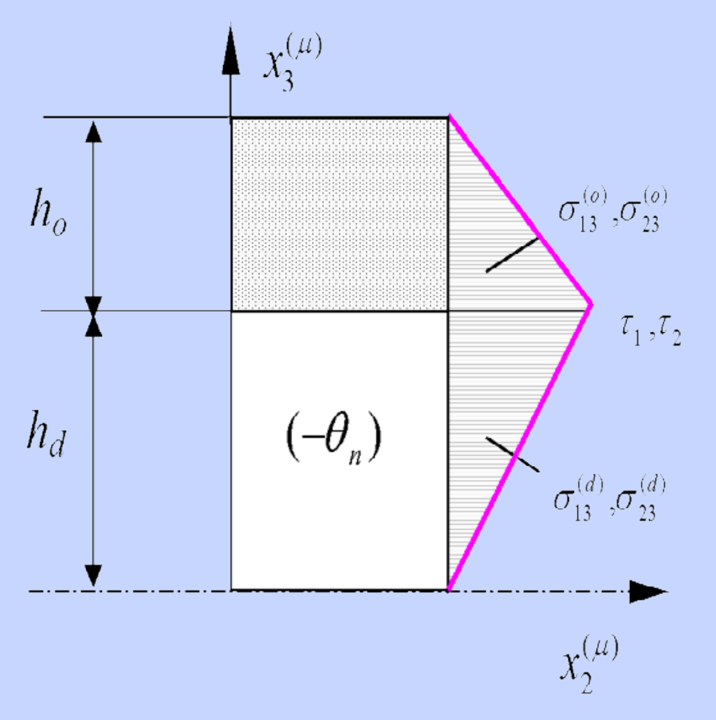


(a)

(b)



Stress Analysis of cracked laminates

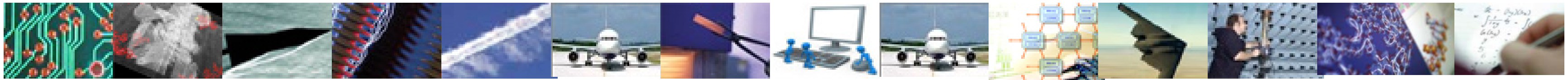


$$\frac{d\sigma_{j2}^{(d)}}{dx_2^{(\mu)}} - \frac{\tau_j}{h_d} = 0, \quad j = 1,2$$

$$\tau_j = K_{j1}(u_1^{(d)} - u_1^{(o)}) + K_{j2}(u_2^{(d)} - u_2^{(o)})$$

- constitutive equations for the damaged layer
- constitutive equations for the outer sublaminate
- equations of the global equilibrium of the laminate
- generalised plane strain condition

$$\bar{\sigma}_{j2}^{(d)} = \left(\sum_{k=1}^{2} A_{kj} \frac{D_\mu^{mc}}{\lambda_{1k} h_d} \tanh \frac{\lambda_k h_d (1 - D_\mu^{ld})}{D^{mc}} + C_j (1 - D_\mu^{ld}) \right) \bar{\sigma}_x$$

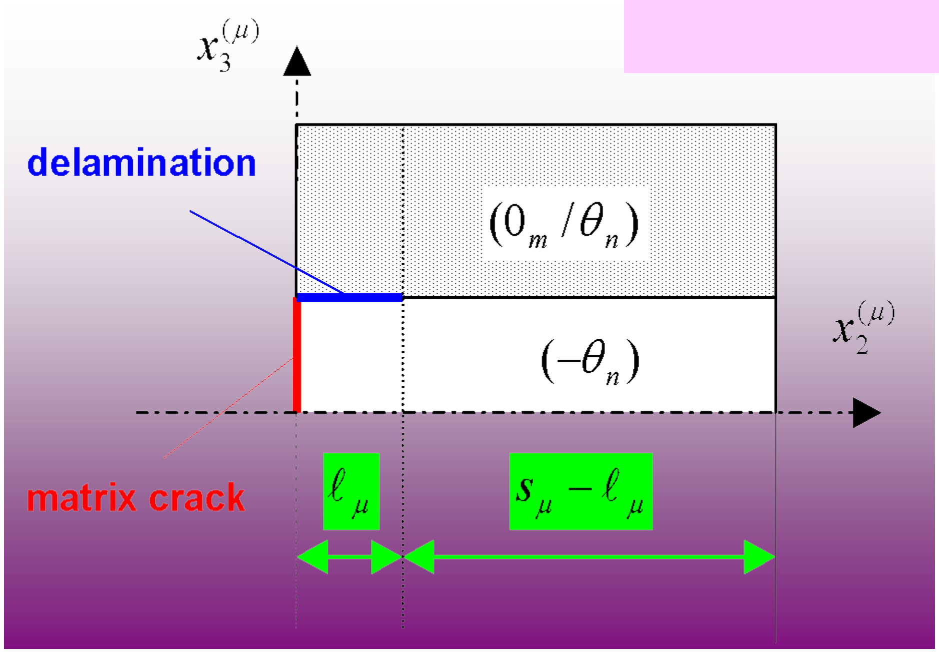


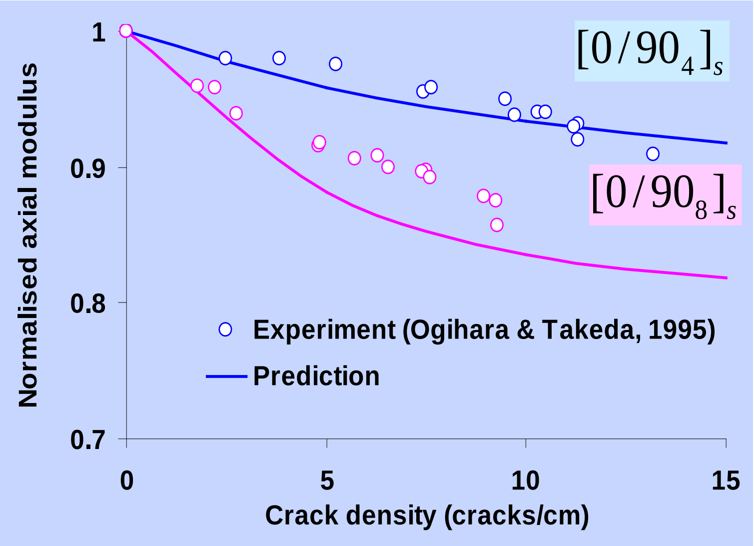
Equivalent Constraint model-Residual Stiffness

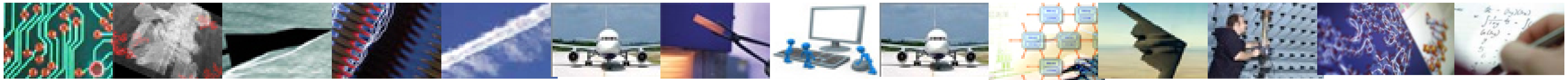
In-situ Damage Effective Functions

$$\Lambda_{22}^{(\mu)} = 1 - \frac{\overline{\sigma}_{22}^{(d)}}{\hat{Q}_{12}^{(\mu)}\overline{\varepsilon}_{11}^{(d)} + \hat{Q}_{22}^{(\mu)}\overline{\varepsilon}_{22}^{(d)}}, \qquad \Lambda_{66}^{(\mu)} = 1 - \frac{\overline{\sigma}_{12}^{(d)}}{\hat{Q}_{66}^{(\mu)}\overline{\gamma}_{12}^{(d)}}$$

$$[\overline{Q}^{(\mu)}] = [\hat{Q}^{(\mu)}] - \begin{bmatrix} (\hat{Q}_{12}^{(\mu)})^2 / \hat{Q}_{22}^{(\mu)}\Lambda_{22}^{(\mu)} & \hat{Q}_{12}^{(\mu)}\Lambda_{22}^{(\mu)} & 0 \\ \hat{Q}_{12}^{(\mu)}\Lambda_{22}^{(\mu)} & \hat{Q}_{22}^{(\mu)}\Lambda_{22}^{(\mu)} & 0 \\ 0 & 0 & \hat{Q}_{66}^{(\mu)}\Lambda_{66}^{(\mu)} \end{bmatrix}$$

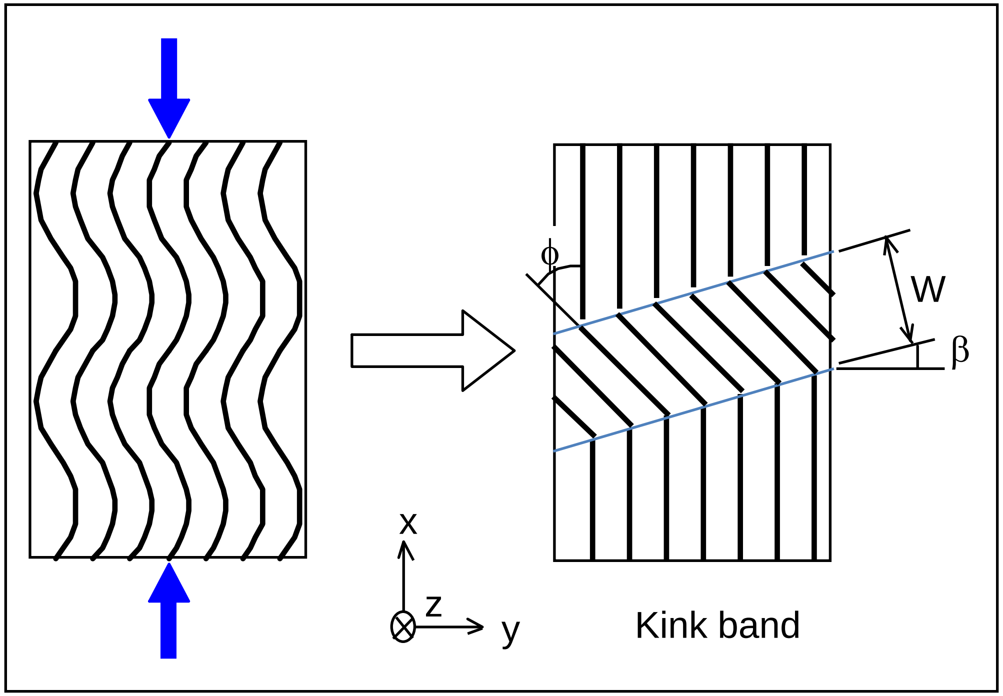


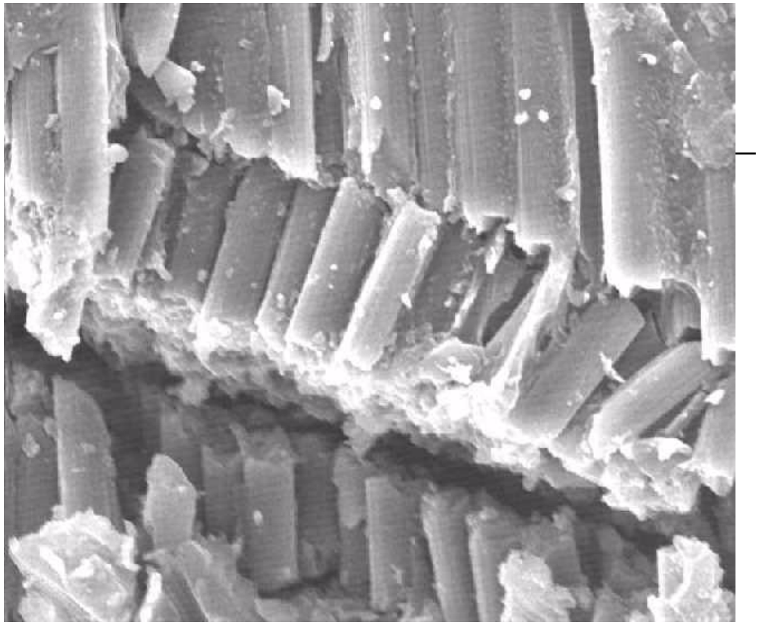




Damage Mechanisms under Compression

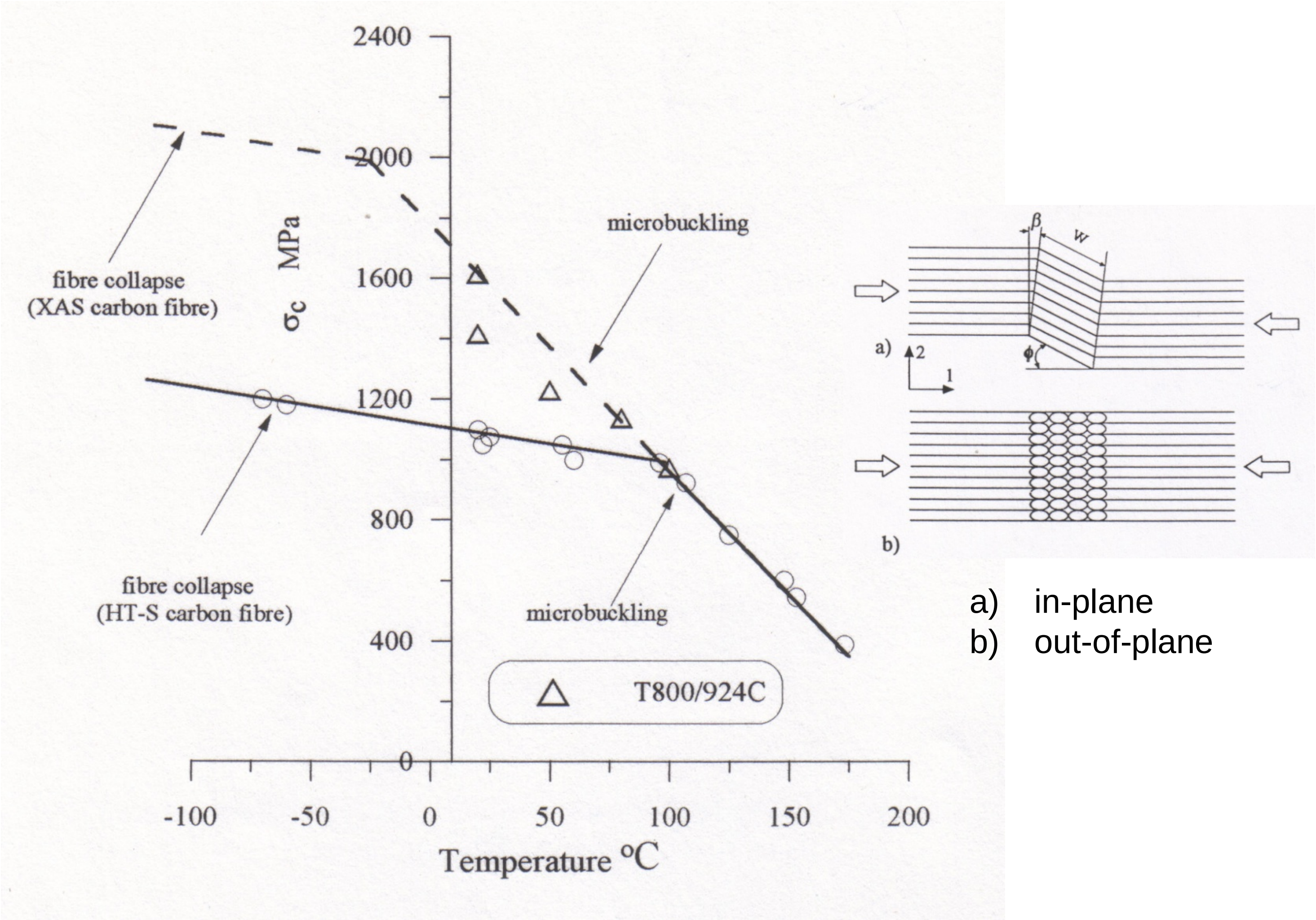
Compression failure of laminates occurs by fibre kinking of 0°-plies (microbuckling) immediately followed by delamination (catastrophic failure).



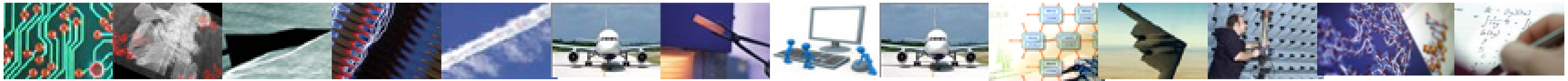


Kink band in multidirectional T800/924C laminate

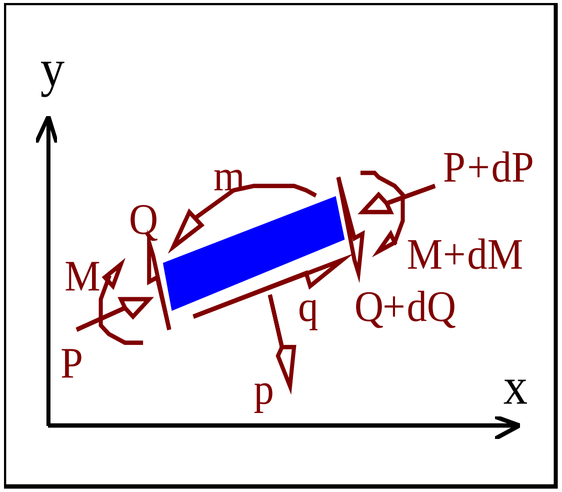
Carbon fibre failure modes

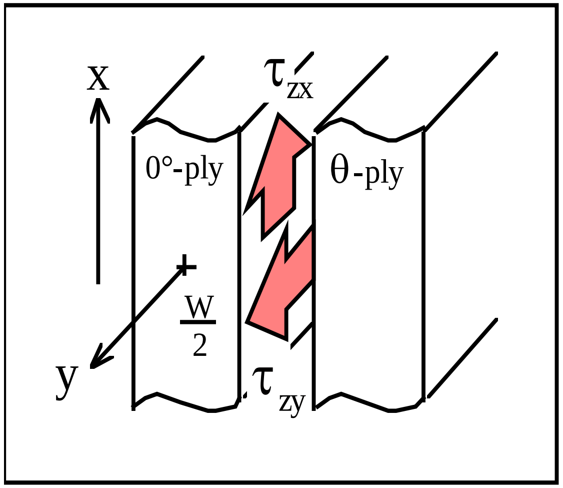


a) in-plane
b) out-of-plane



Damage Mechanisms under Compression





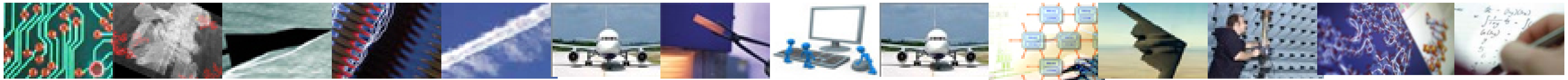
$$v_0(x) = V_0 \cdot \sin\left(\frac{\pi x}{\lambda}\right)$$

$$p(s) = d_{fibre}\left(\tau_{zx}\, n \cdot i + \tau_{zy}\, n \cdot j\right)$$

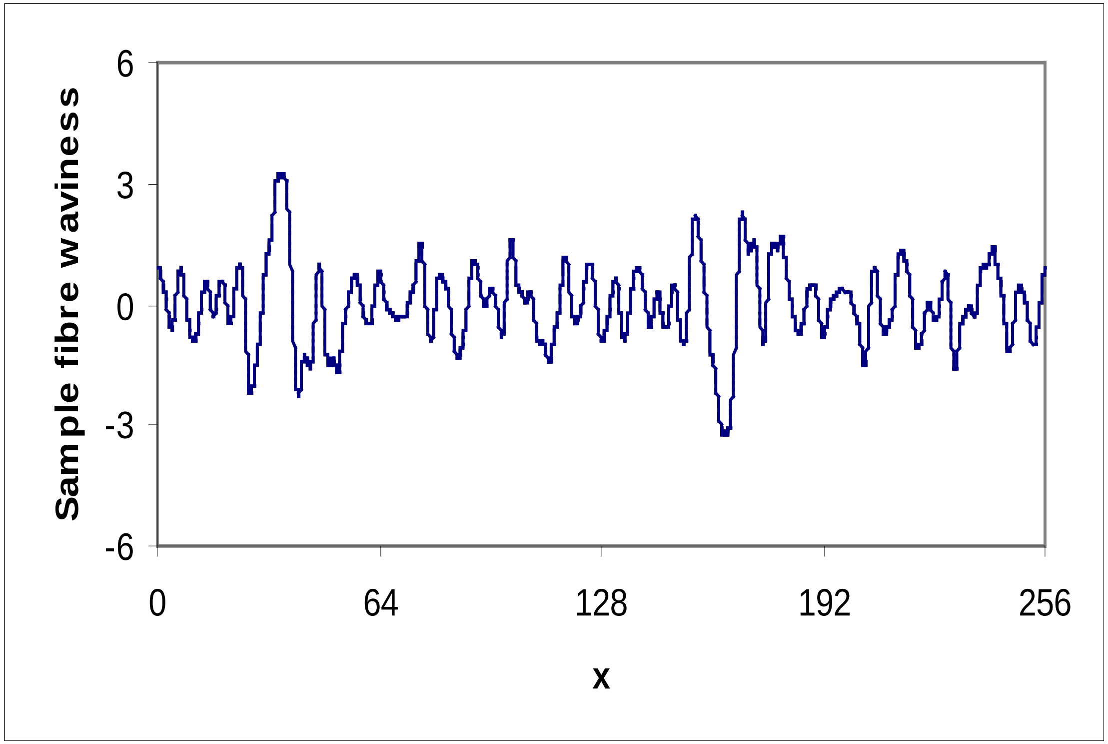
Equilibrium equation:

$$E_f I \frac{d^4(v - v_0)}{dx^4} + \frac{A_f\, \sigma_{0^o-ply}}{V_f} \cdot \frac{d^2 v}{dx^2} - 2\, d_f \left\{ \left[\frac{d\tau_{zy}}{dy} \right]_{\frac{w}{2}} \right\} \cdot v - A_f G \left(\frac{d(v - v_0)}{dx} \right) \cdot \frac{d^2(v - v_0)}{dx^2} = 0$$

Non-linear differential equation that gives the compressive stress σ_0 in the 0°-ply in terms of the fibre maximum buckling amplitude V



Random fibre waviness

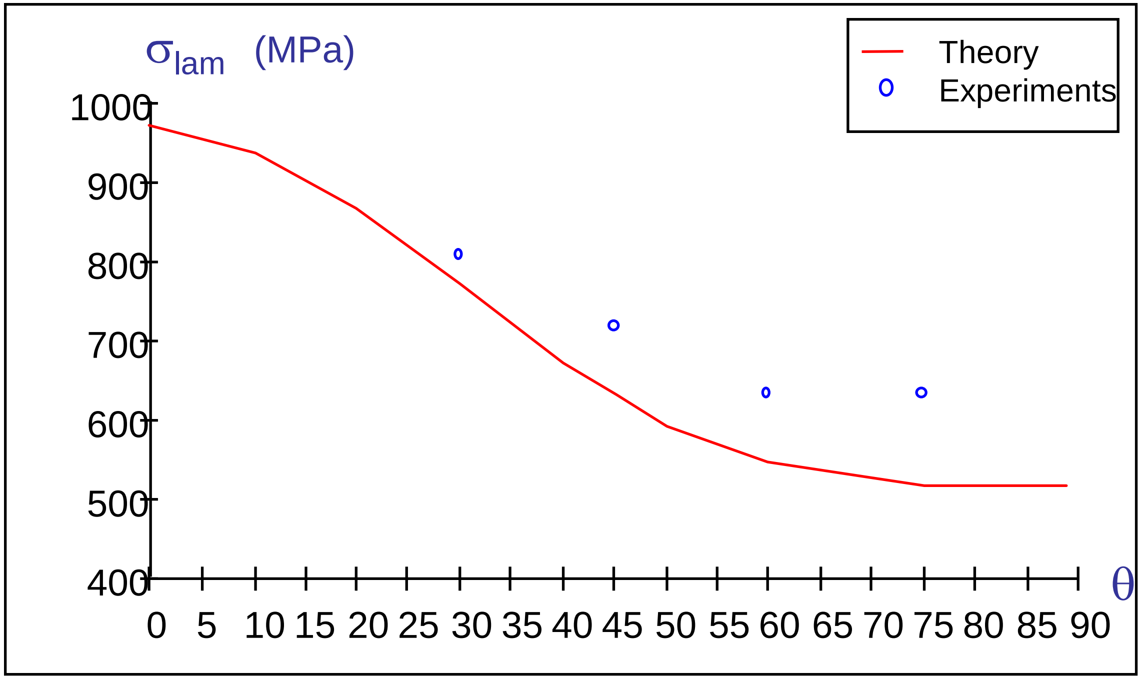


Sample function of wavy fibre

Compressive strength of a multi-ply laminate

Stiffness Ratio Method :

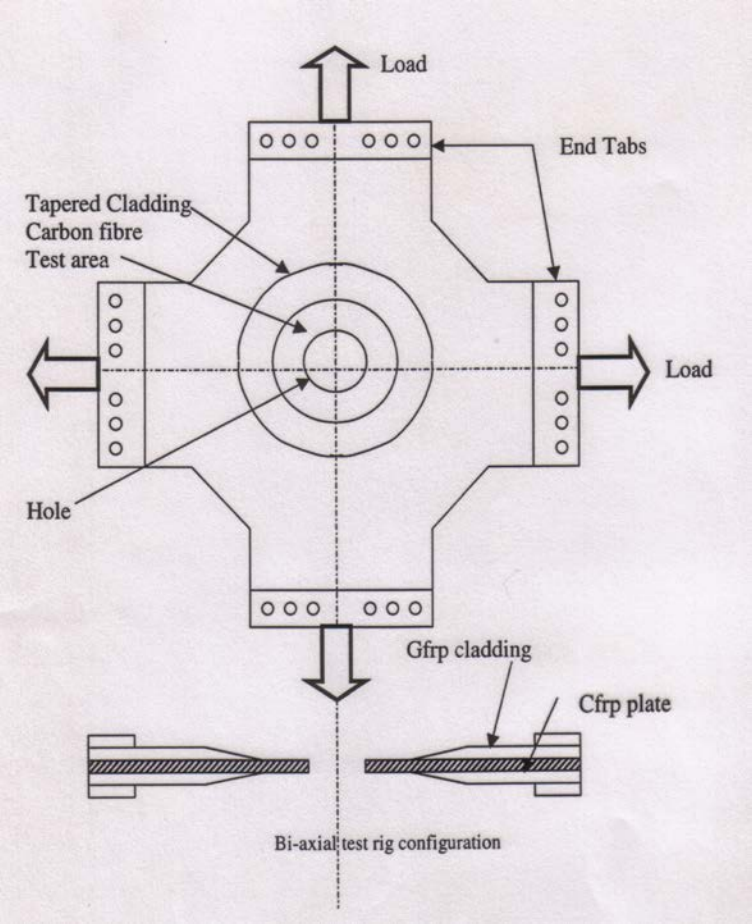
$$\sigma_{lam} = \frac{\sigma_0^*}{N E_{11}} \sum_{k=1}^{N} n^{(k)} \cdot E_{x\theta}^{(k)}$$



Theoretical predictions are conservative

Comparison of experimental and experimental compressive strengths for laminates $[(\theta/-\theta/0_2)_2]_s$

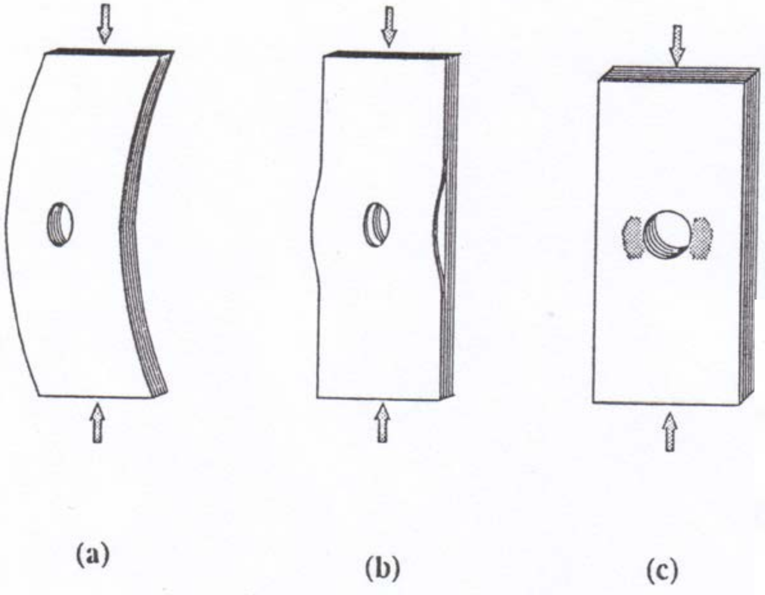
Response of a laminate with an open hole



- Composite failure is a hot topic, particularly for biaxial stress fields
- Tests on plates with holes because of weakness of CFRP to stress concentrations
- Compression is of particular interest due to fibre microbuckling

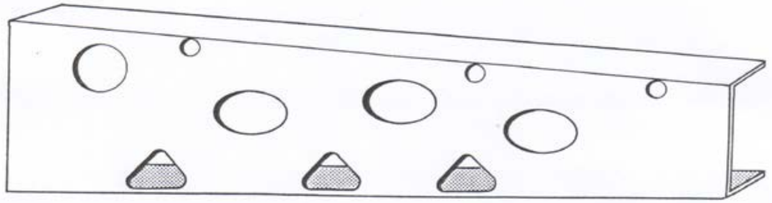
AA587, A300-600 fin

Compressive behaviour of a laminate with a hole



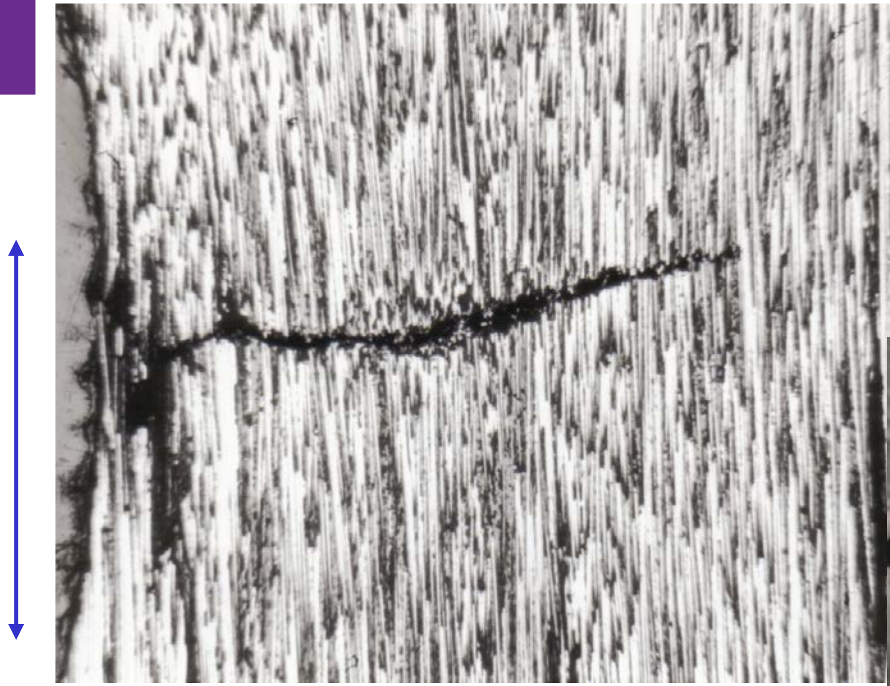
Compressive failure modes:

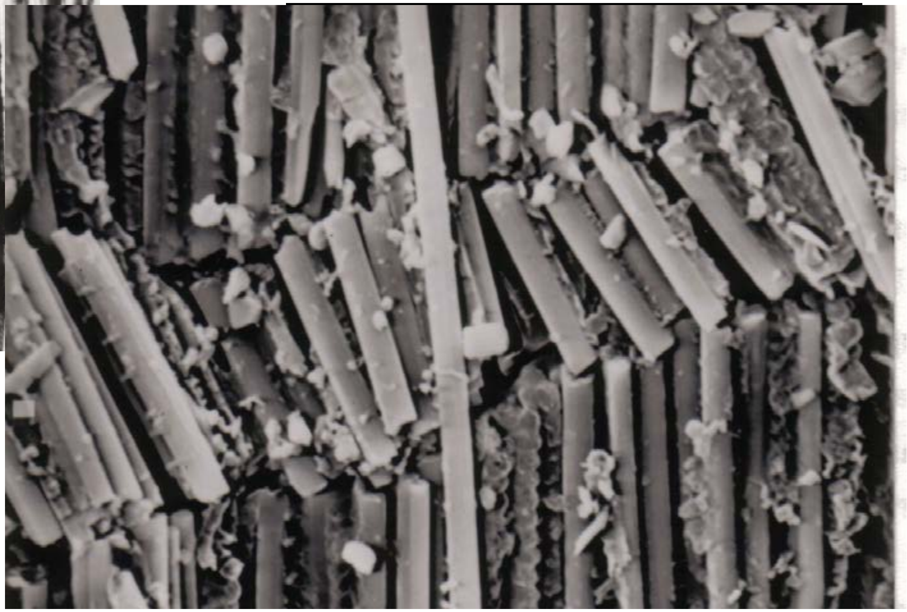
a) Euler buckling
b) Sublaminate buckling
c) Local damage due to in-plane stresses (fibre microbuckling)



A schematic of a typical CFRP beam structure in an a/c wing

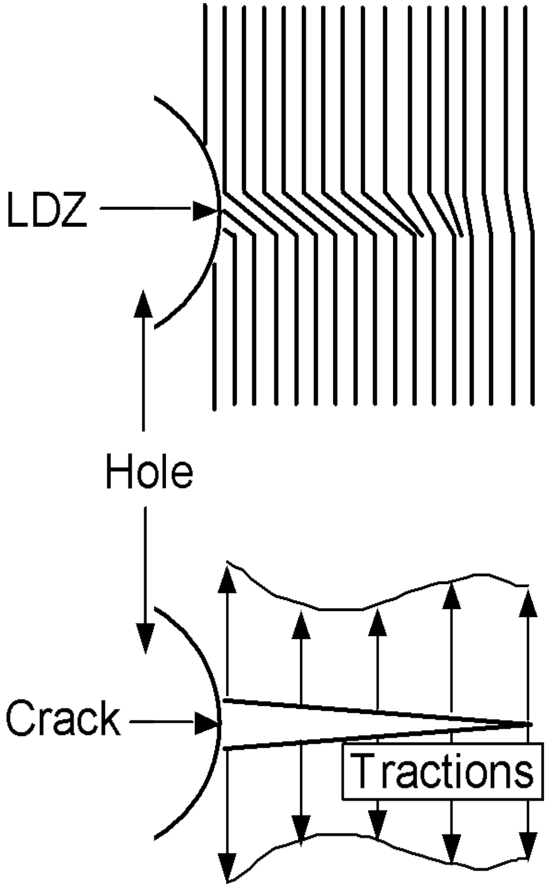
Compressive failure of a CFRP plate with a hole



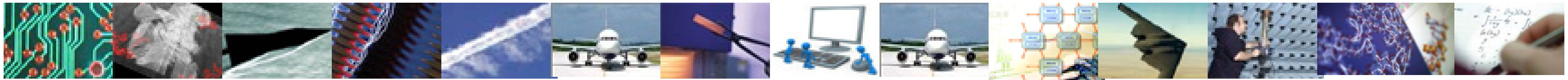


Fibre microbuckling in a T800/924C Laminate (6µm fibre diameter)

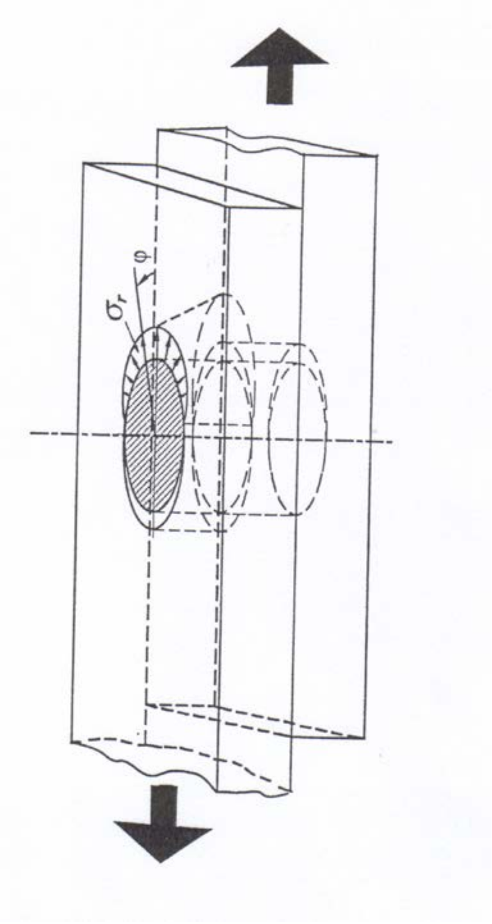
A Damage Zone Modelling

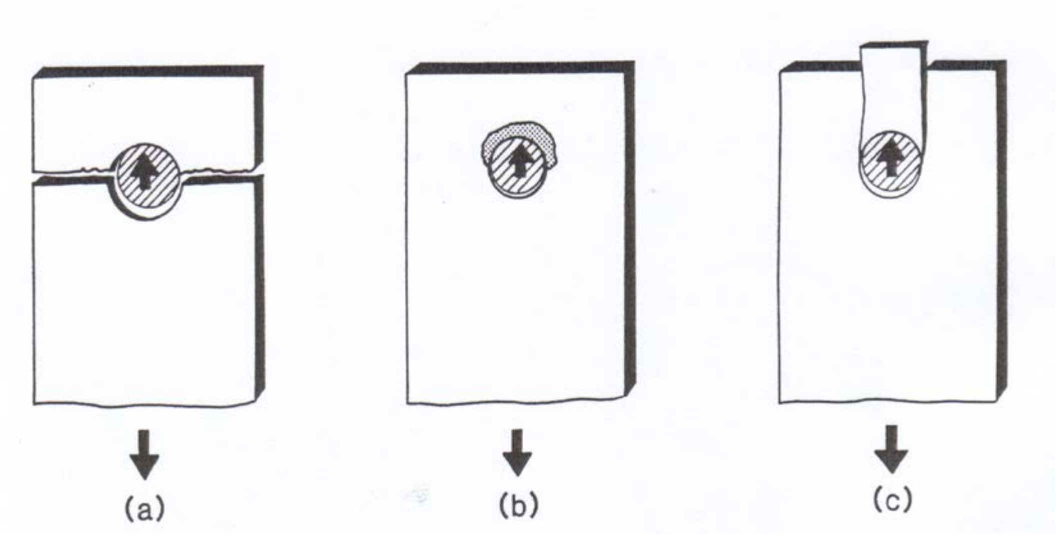


- ➢The DZ is treated as an equivalent crack
- ➢The traction distribution describes the load transfer characteristics of the damage zone
- ➢Damage propagation is controlled by *traction law* and applied loading
- ➢Three experimentally measured phenomena are predicted with a consistent physically-based model: DZ growth, critical length, ultimate failure load



Stress analysis of bolted joints

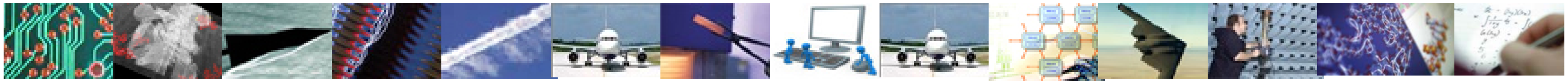




Tensile failure

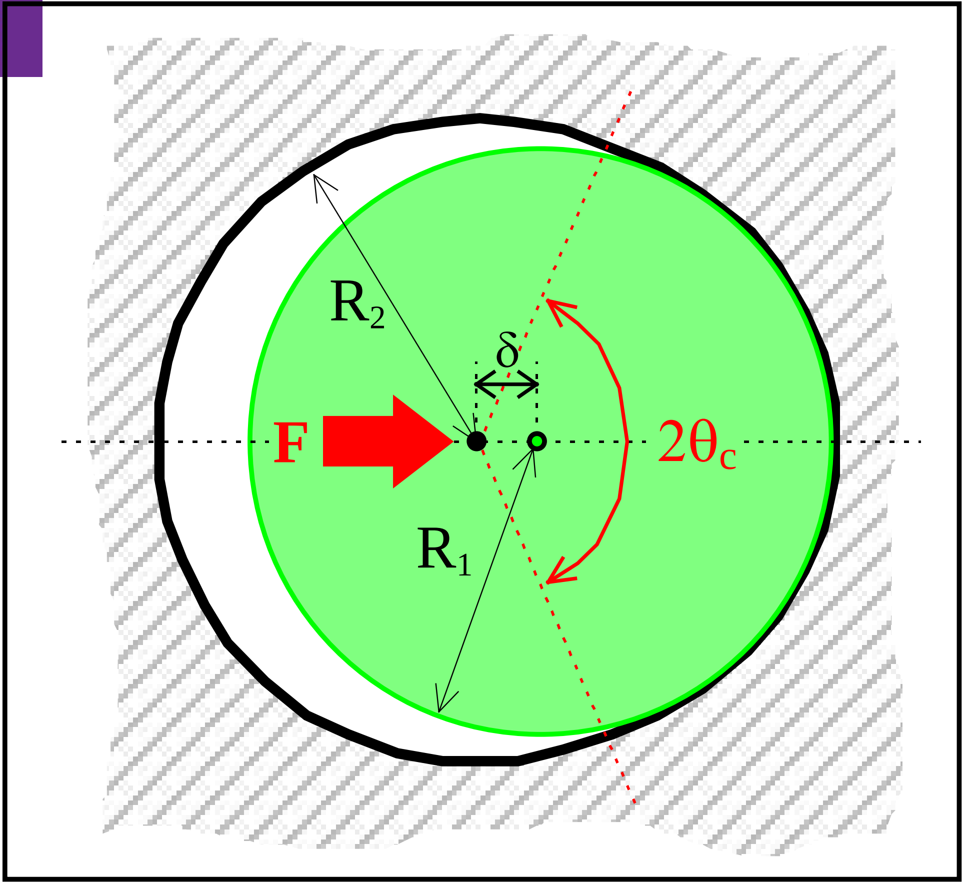
Bearing failure

Shear-out failure



Stress analysis of pin-loaded holes in orthotropic laminates

Complex Variable Theory

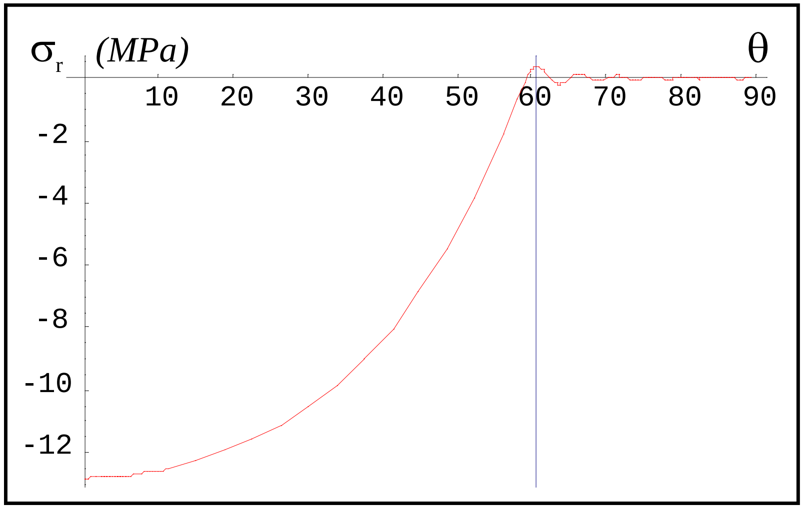


θ_c is the contact angle.

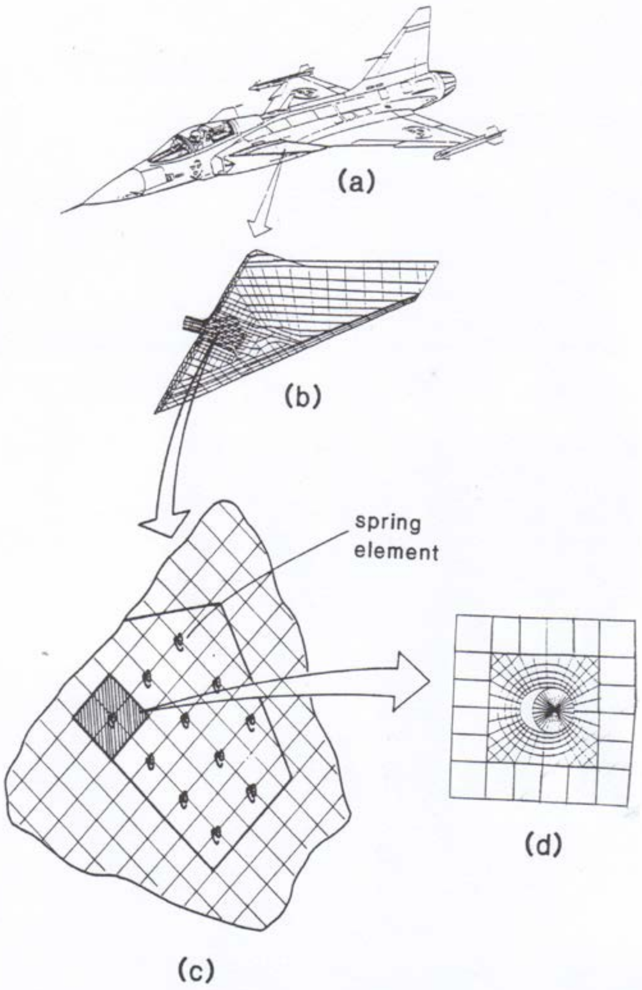
δ is the applied pin displacement.

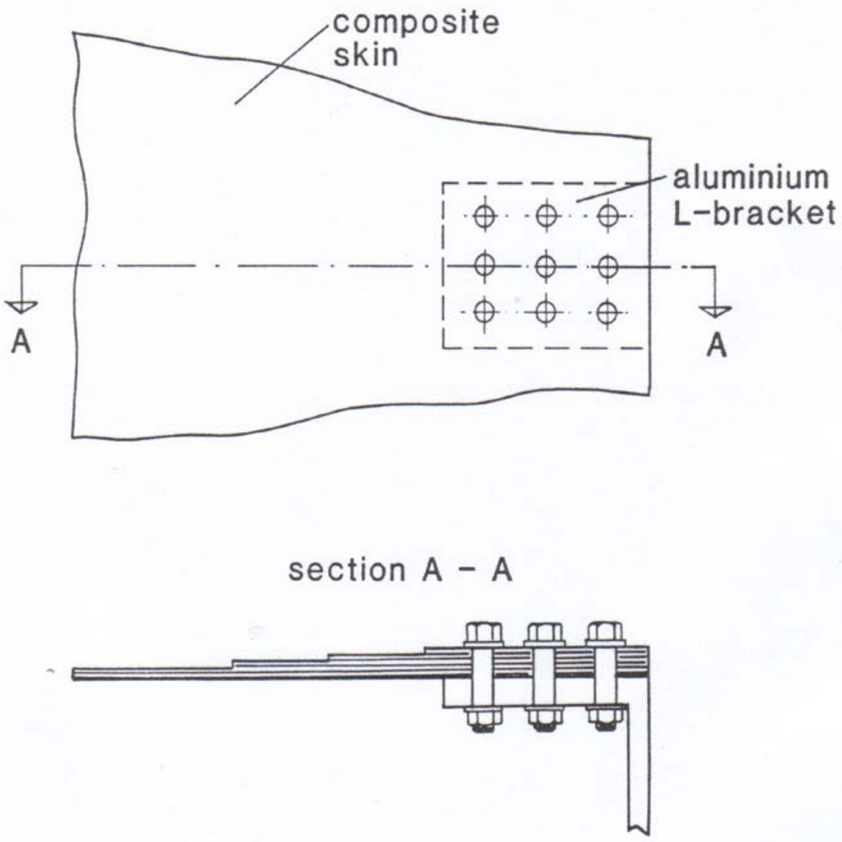
F is the (unknown) applied load corresponding to δ.

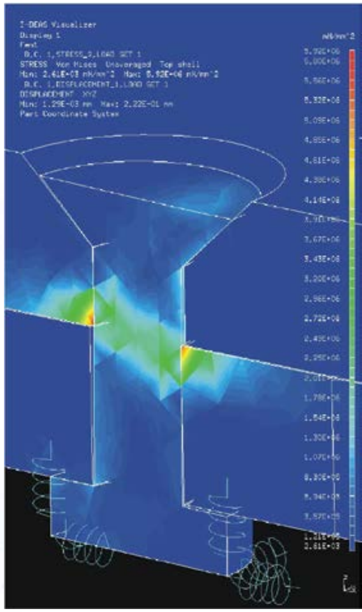
λ is the initial clearance.



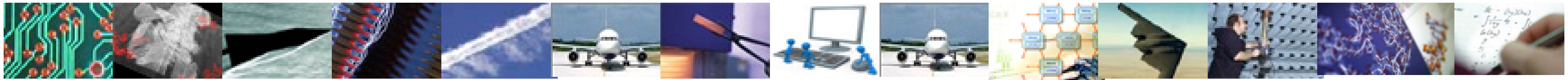
Stress analysis of bolted joints in an a/c structure



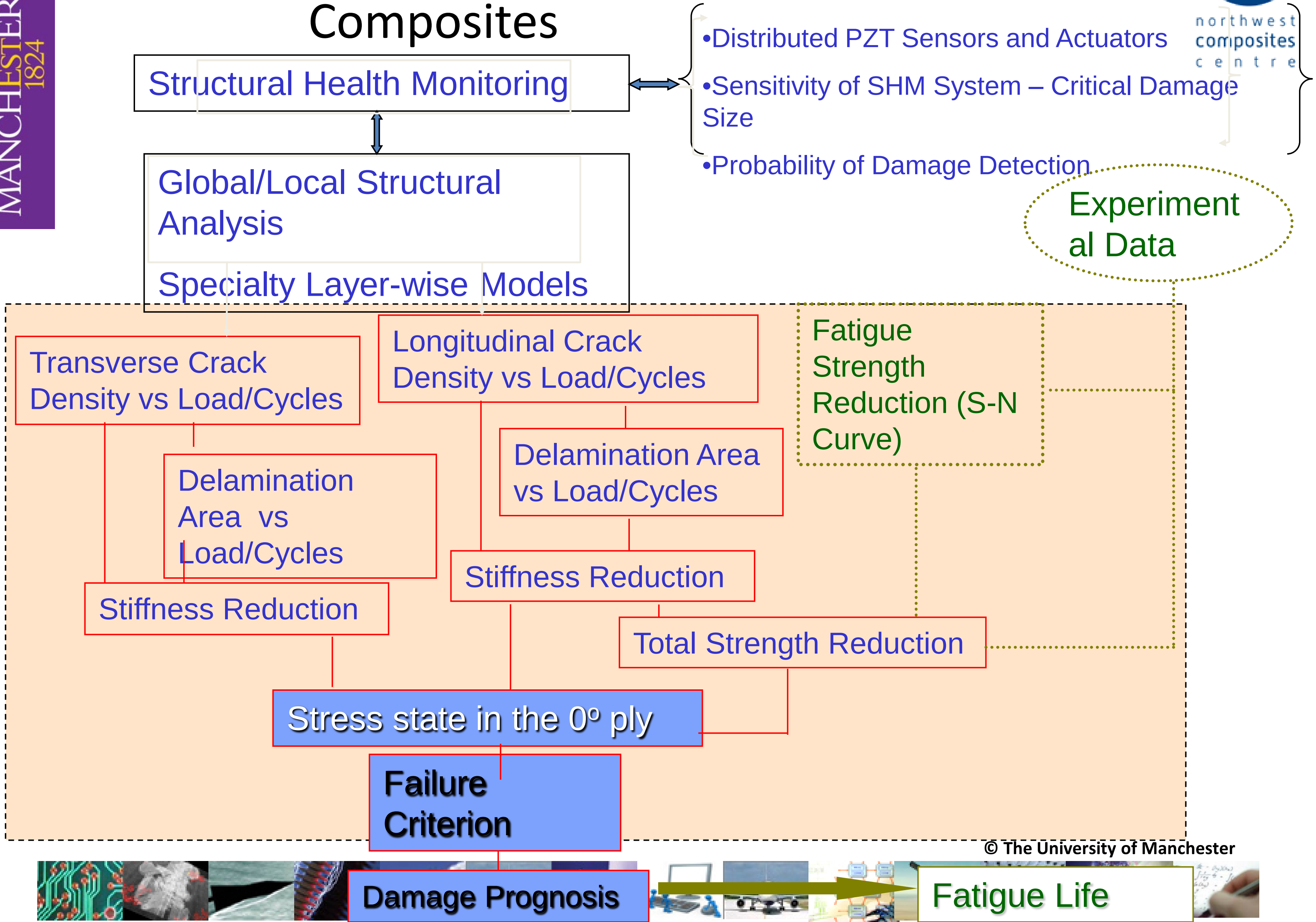




Composite wing skin bolted to a metallic L-bracket



Damage Detection and Prognosis in Composites



Structural Health Monitoring

- Distributed PZT Sensors and Actuators
- Sensitivity of SHM System – Critical Damage Size
- Probability of Damage Detection

Global/Local Structural Analysis

Specialty Layer-wise Models

Experimental Data

Transverse Crack Density vs Load/Cycles

Longitudinal Crack Density vs Load/Cycles

Fatigue Strength Reduction (S-N Curve)

Delamination Area vs Load/Cycles

Delamination Area vs Load/Cycles

Stiffness Reduction

Stiffness Reduction

Total Strength Reduction

Stress state in the 0º ply

Failure Criterion

Damage Prognosis

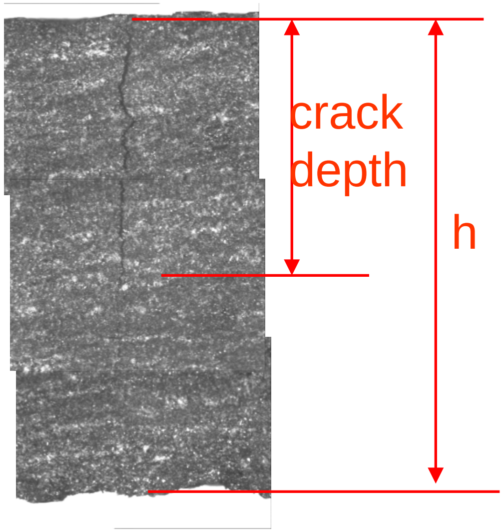
Fatigue Life

Damage Detection in a $[90^{o}]_{16}$ Beam

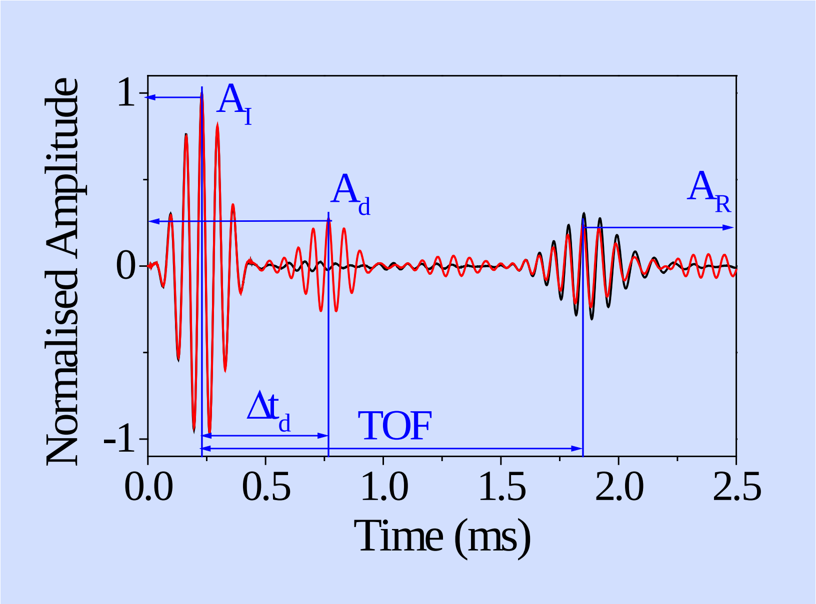
- A matrix crack across the width was generated, perpendicular to the propagation path with an impact energy of 2 J.

Location of damage:

$$\left.\begin{array}{l} TOF = C_g \times 2L \\ \Delta t_d = C_g \times 2x \end{array}\right| \Rightarrow \quad x = \Delta t_d / TOF = 196.3mm$$

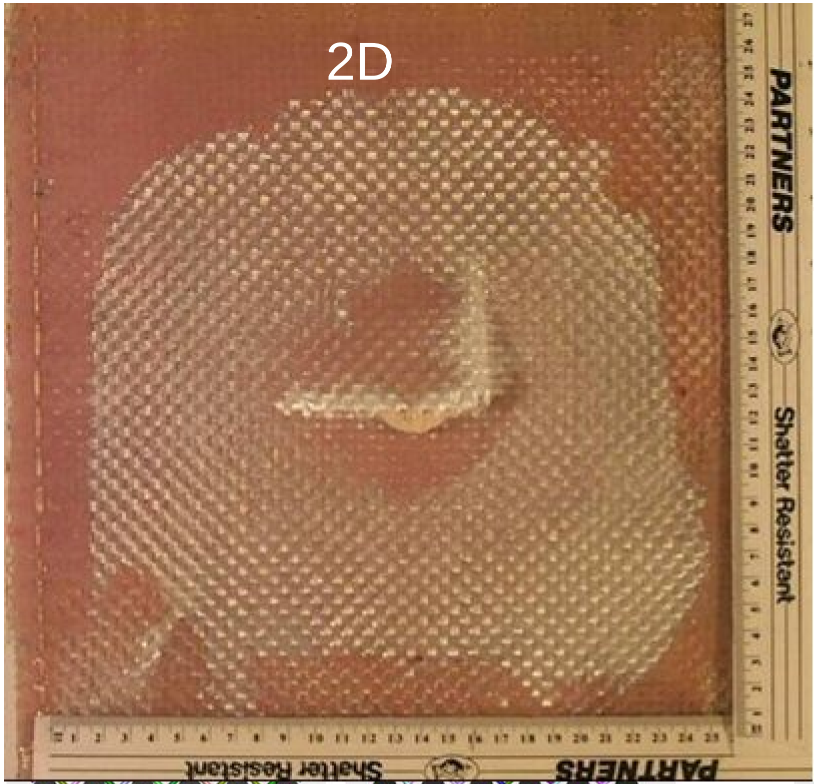


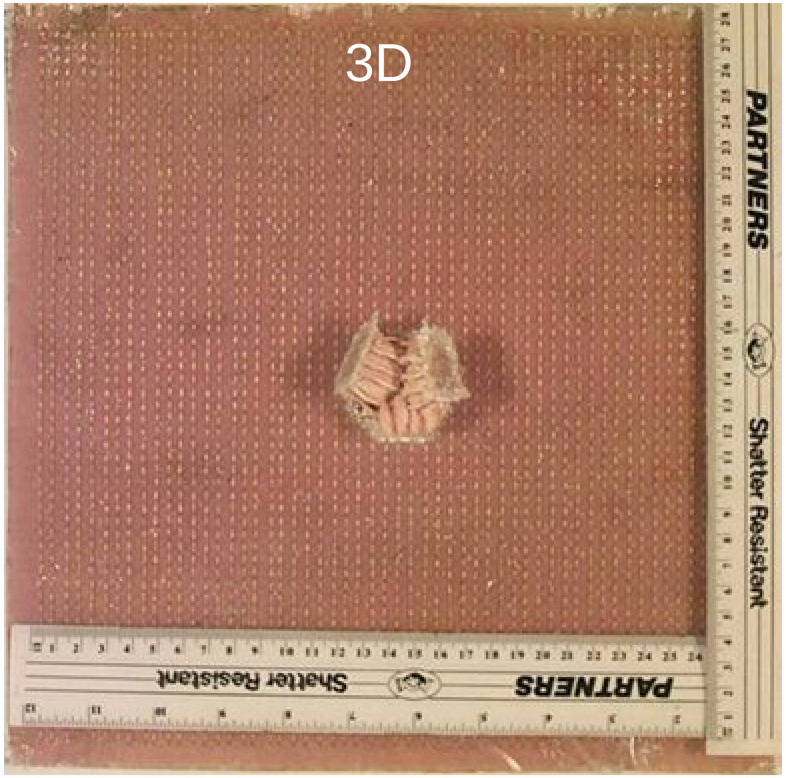
Side view of the generated crack.

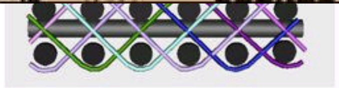


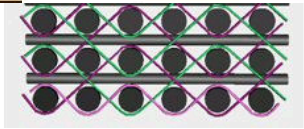
Lamb wave signal from the pristine and damaged beam.

3D weaving flat fabric

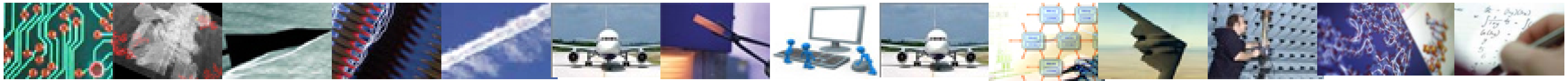






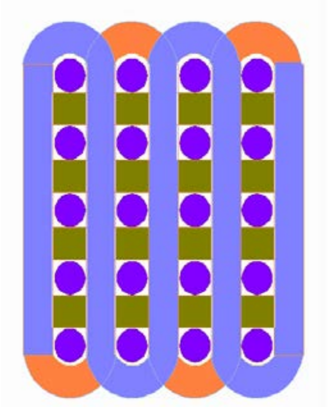


important for Fan Blades

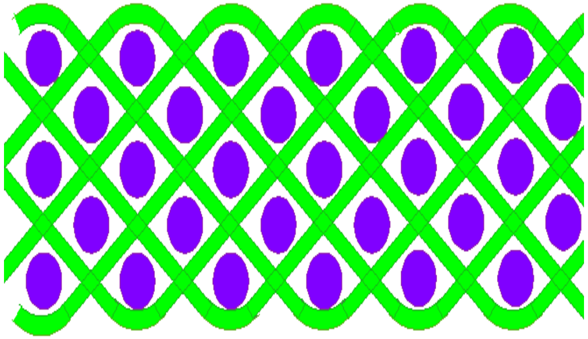


3D Weave styles used in current work

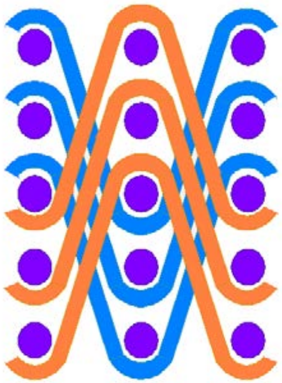
orthogonal



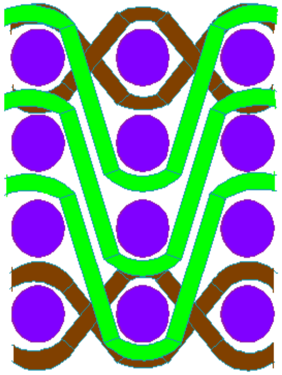
Angle interlock

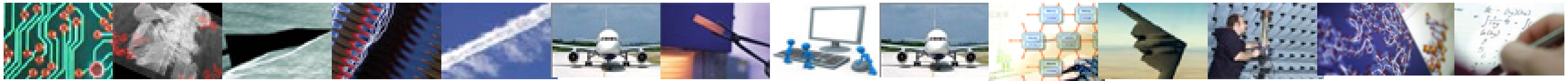


Layer-to-layer

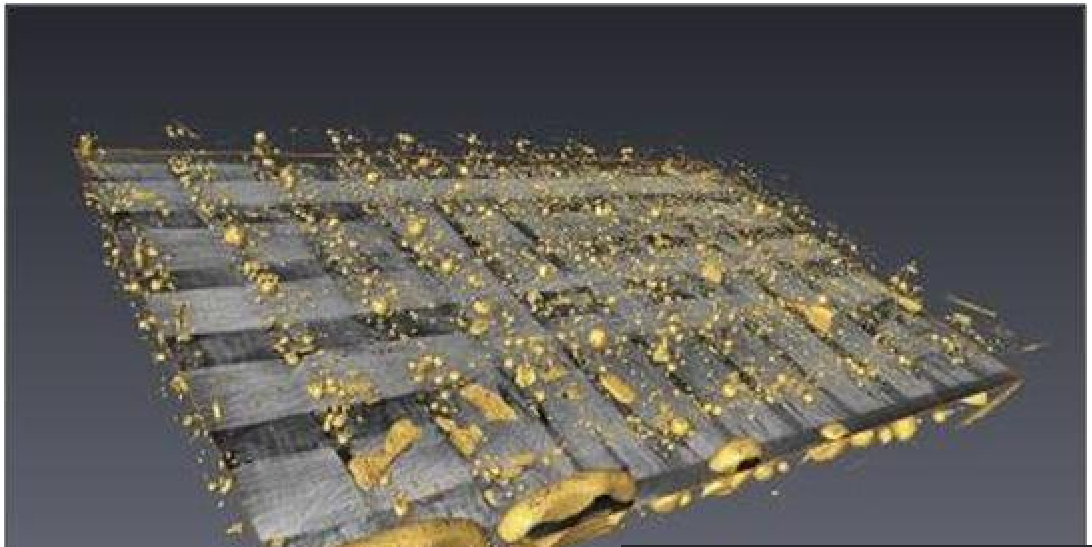


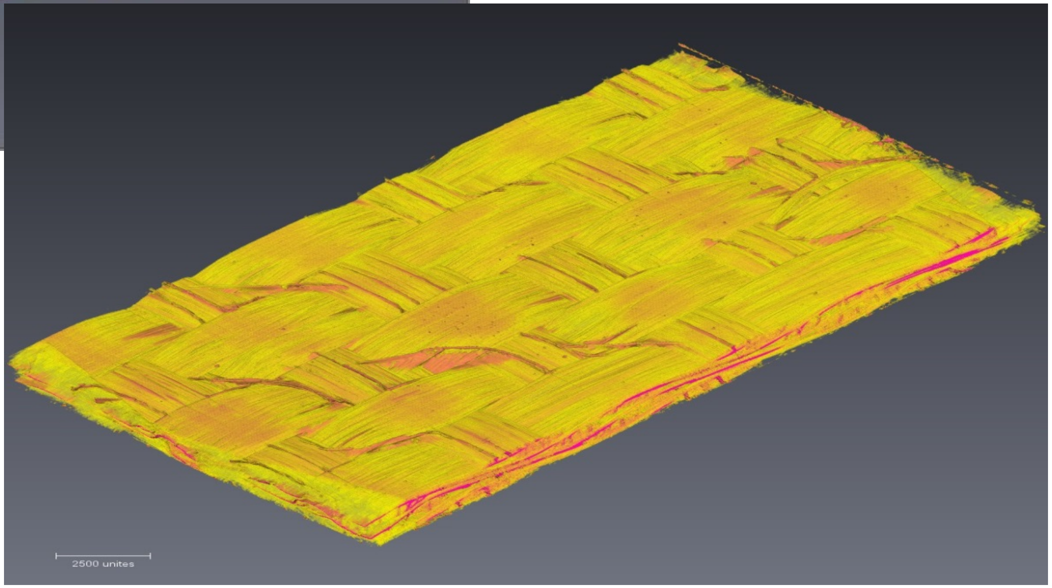
Modified layer-to-layer





Micro-CT Images of 3D Woven Textile Samples

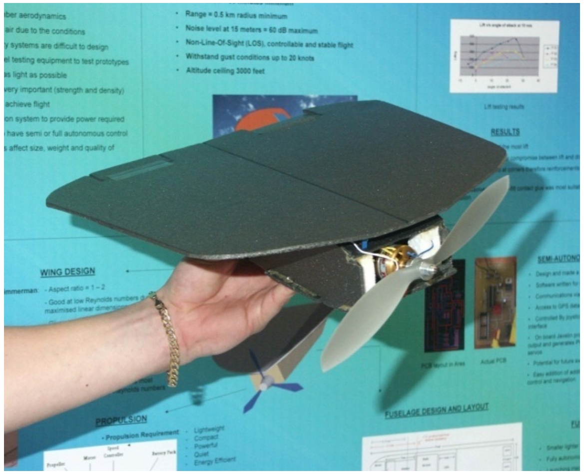




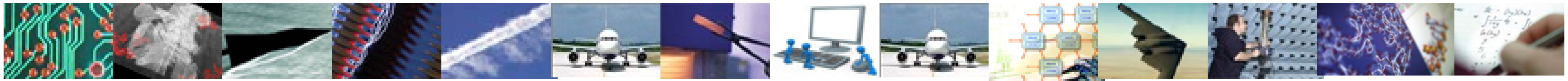
3D woven and infused carbon fibre composite sample

Concluding Remarks

- ➢**Composite Materials properties are excellent**
  - But still challenges to be met, especially in fabrication & design
- ➢**Usage of Composites is growing at an increasing rate in Civil Aerospace**
  - Airbus A380, A350 & Boeing 787 will make major use of composites
- ➢**In military systems, composites are becoming the 1st choice**
- ➢**Future military strike aircraft may be unmanned**
  - •Brings materials problems and challenges
  - •Balance performance, stealth and cost



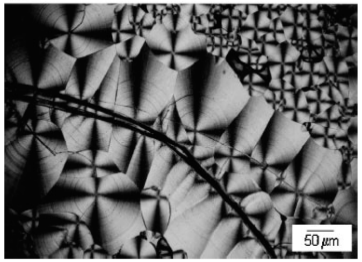
Need to better understand failure, especially of **3D fibre composites**, reduce cost of all stages through design, materials and fabrication

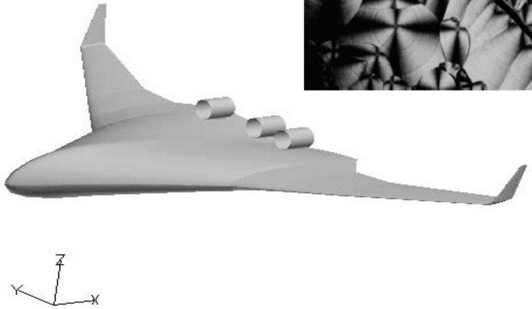


Concluding Remarks

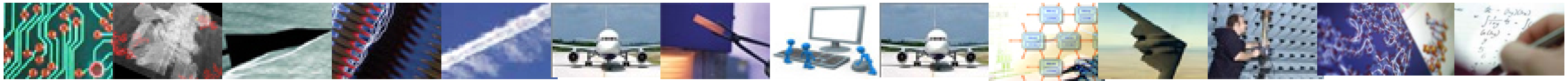
Priority Topics on composites:

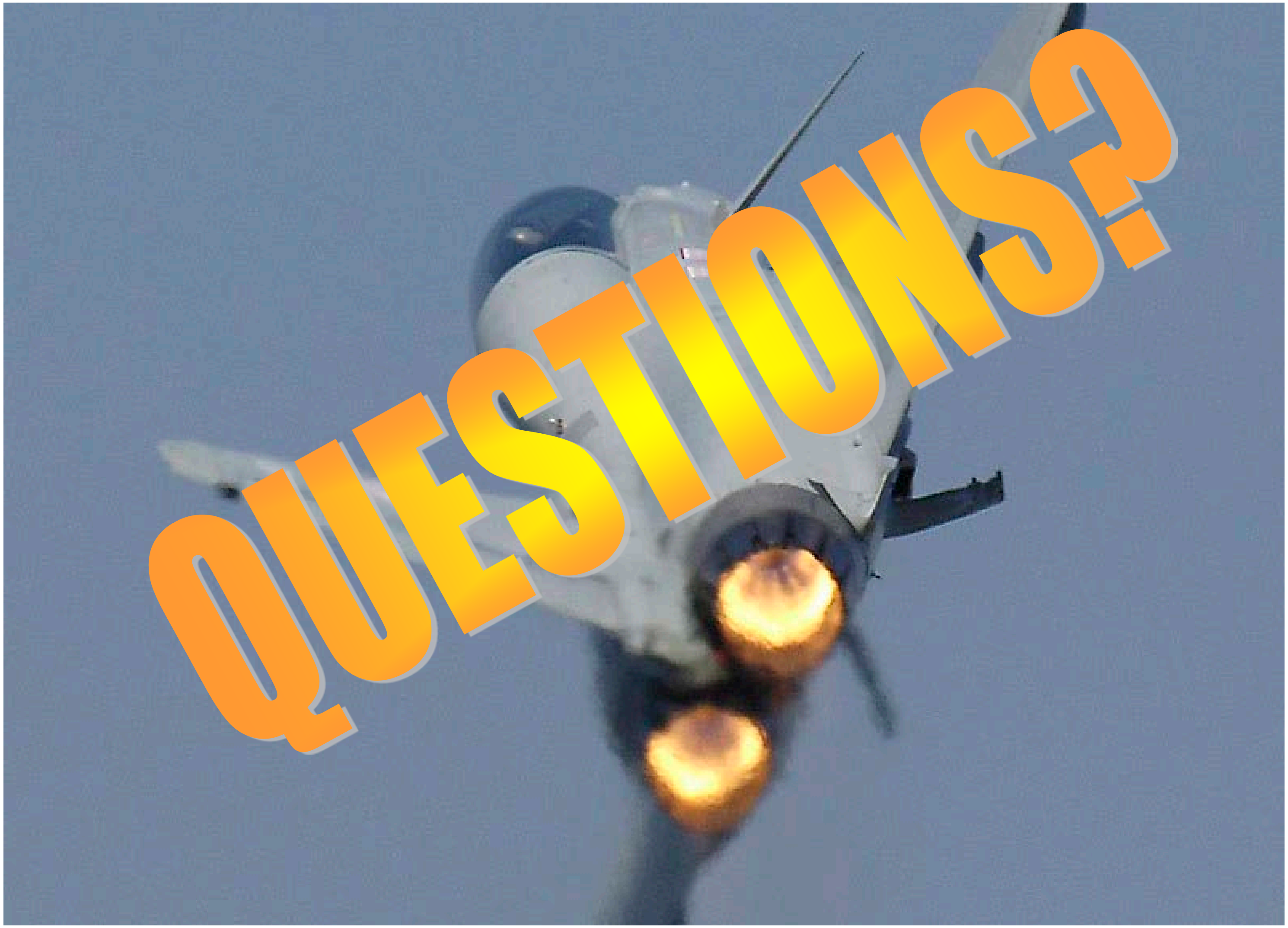
- Novel materials (hybrid composites with Al, Li, Ti; new fibres and/or resins with nanoparticles; natural fibres) and Processes, Design tools and methods
- Materials by design (from the nano to macro level)
- Large-scale structures
- Inspection and Smart Structures
- Adaptive shapes/structures (morphing aircraft)



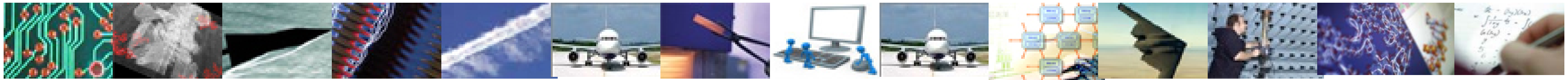


- Joining and Joints, Repair, Recycling/Disposal
- Can they be manufactured? What is the cost?
- Maintenance cost?





QUESTIONS?



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Thank you

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