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Effect of off-axis ply orientation on UD fibre microbuckling

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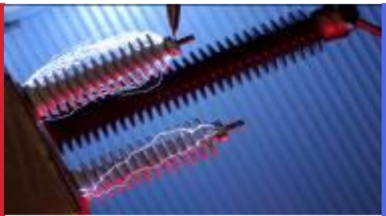
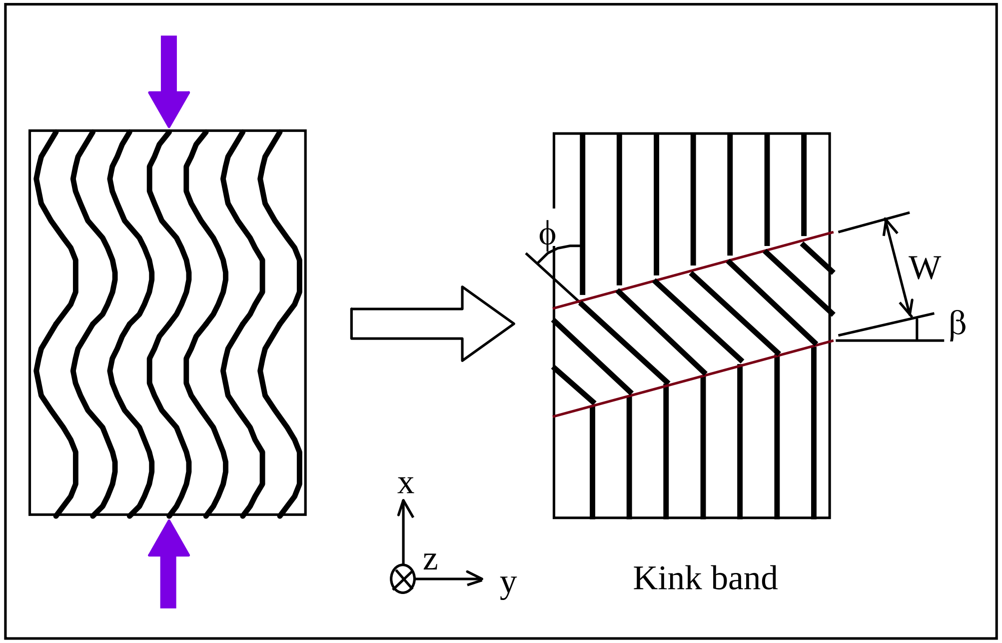
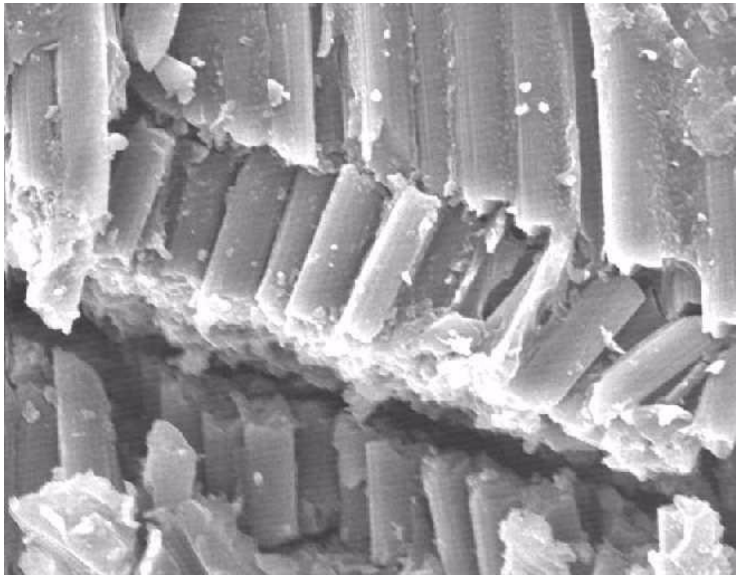


Damage Mechanisms under Compression: Fibre microbuckling

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

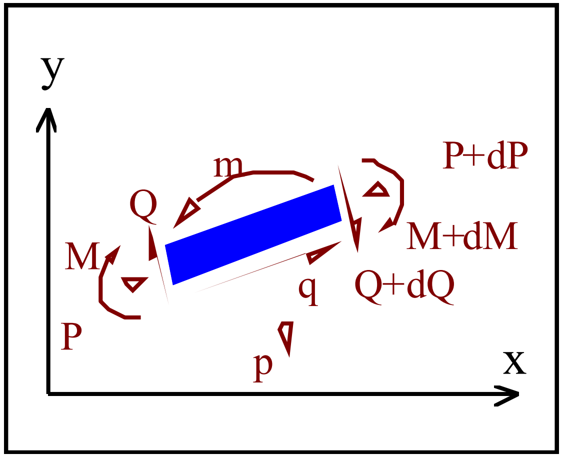


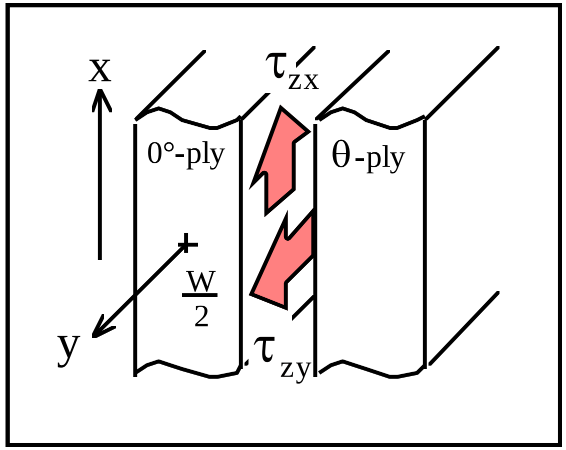


Kink band in multidirectional T800/924C laminate

0º fibre microbuckling initiation model

Berbinau, Soutis (1999)





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

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

Equilibrium equation (fibre is modelled as a beam on a non-linear foundation)

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

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

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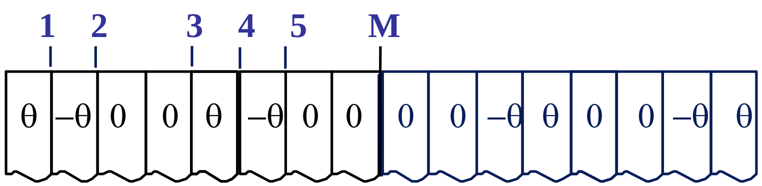
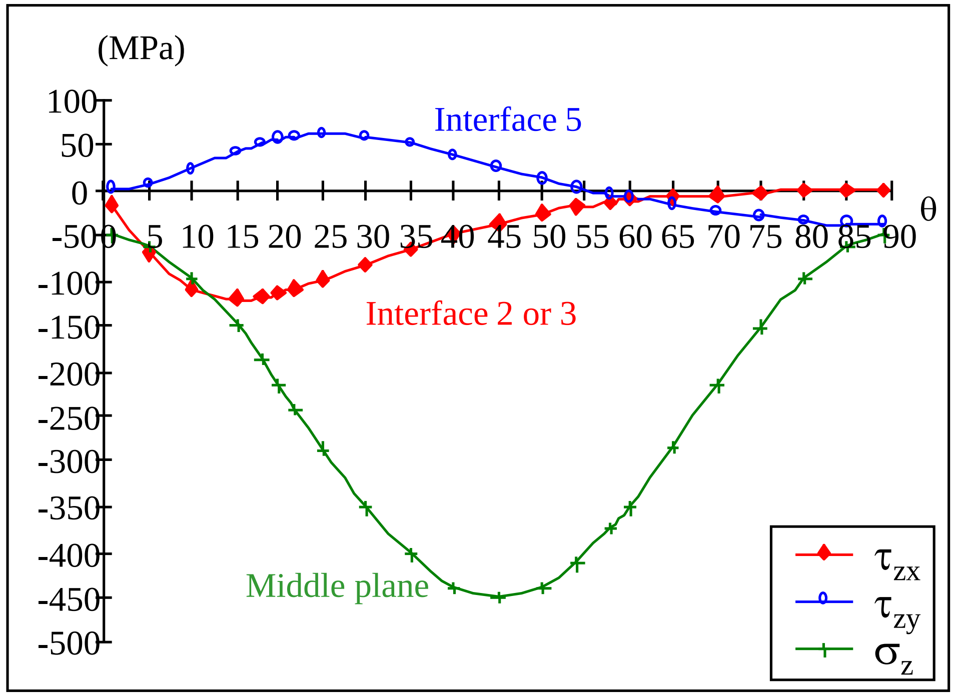
Free edge effect on fibre microbuckling

Berbinau, Soutis (1999)

- The microbuckling model of Berbinau, Soutis accounts for fibre properties, initial fibre waviness, ply interactions (interlaminar stresses), matrix non-linearity.



- Shear stress components are almost zero around 60°
- Normal component σz is compressive



Maximum interlaminar edge stresses in a $[(\theta /- \theta /0_2)_2]_s$ laminate *(strain =1%)*

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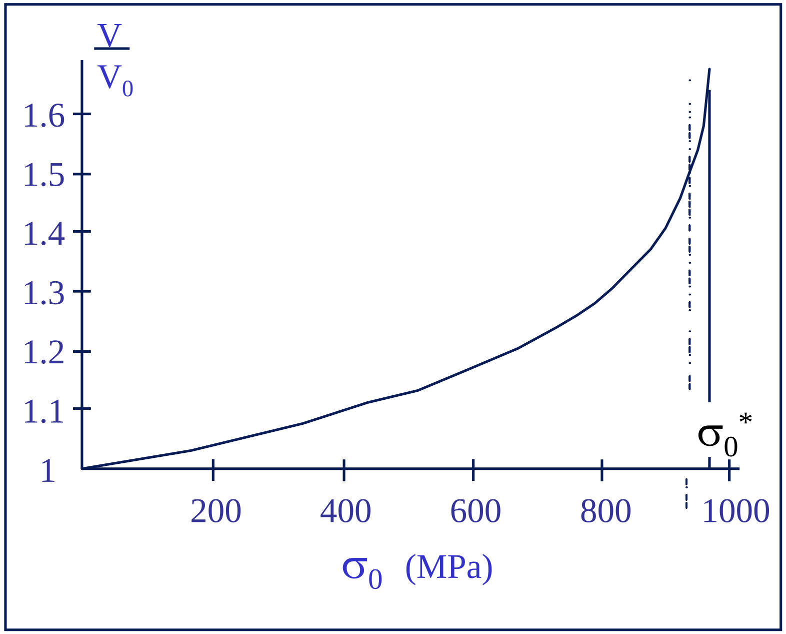
Fibre wavelength effect on fibre microbuckling triggering

Microbuckling amplitude: $\frac{V}{V_0} = f(\sigma_0)$



Microbuckling amplitude V vs. stress on a 0° -ply σ_0 for $[(30/-30/0_2)_2]_s$

Off-axis ply orientation θ°	σ_0^* Fibre half-wavelength $\lambda=10\cdot d_{fibre}$	$\lambda=15\cdot d_{fibre}$	$\lambda=20\cdot d_{fibre}$
0	968	743	657
30	961	737	637
45	961	723	635
60	975	745	673
75	977	751	680
90	979	753	683

for $[(\theta/-\theta/0_2)_2]_s$ σ_0^* depends mostly on:

- ❑ fibre wavelength
- ❑ matrix non-linearity
- ❑ less on interlaminar shear stresses but may not be the case under fatigue load

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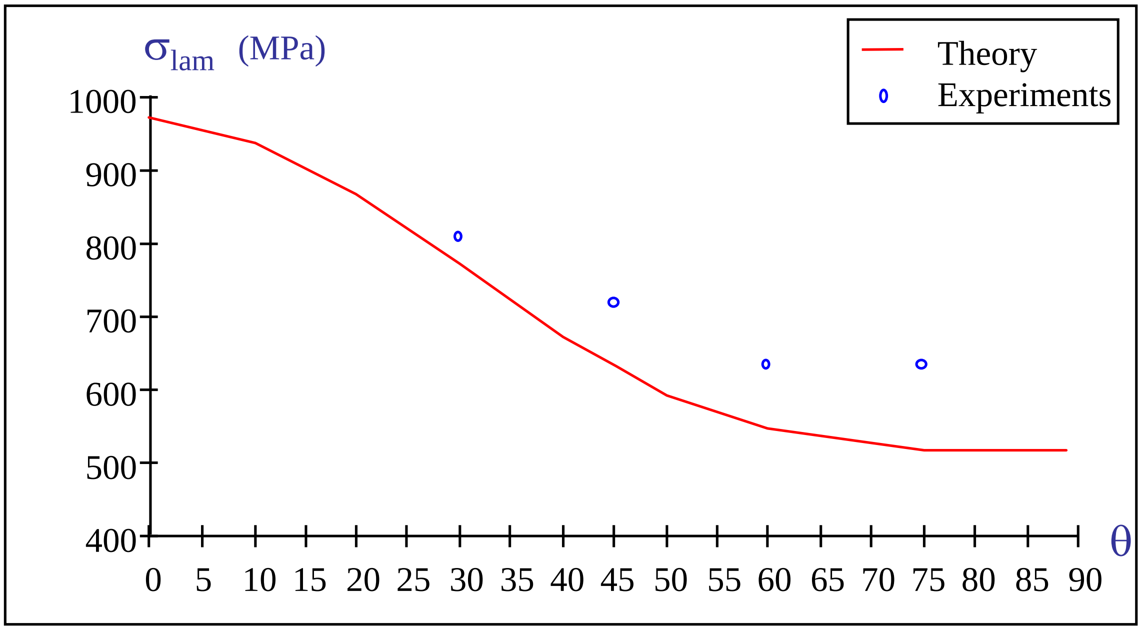
Compressive strength of a multidirectional laminate

Stiffness Ratio Method :

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

σ_0^* critical stress for microbuckling initiation in the 0° ply



Theoretical predictions are conservative

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

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Concluding remarks

The static compressive failure of UD and MD unnotched T800/924C carbon-fibre– epoxy laminates is controlled by fibre microbuckling.

Microbuckling initiates by the elastic bending of the 0°fibres, loaded by resin material in shear.

Its initiation depends on material imperfections, such as resin rich regions, voids and fibre misalignment (waviness).

Model shows the interlaminar shear stress has a small influence on the 0° fibre microbuckling initiation, while the fibre wavelength and matrix non-linearity have a more significant effect.

Average measured failure strains ε_{fav} for each of the four angles θ (30°,45°,60°,75°) examined are scattered between -0.88 and -1%.

Specimens with ±45° surface plies appear to provide the most resistance to fibre microbuckling with $\varepsilon_{fav} = -0.95\%$.

The 0°-ply stress in a such laminate is ~1300 MPa compared to 1430 MPa measured for the 100% 0° laminate.

The 10% strength reduction could be due to edge effects and fabrication defects in the form of resin-rich regions and voids introduced at the interface of the axial and off-axis plies.