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Experimental and numerical study on the compressive failure of multidirectional laminates made of Carbon Fibre Reinforced Polymers

F. Laurin, C. Fougerouse, A. Mavel

Modelling of longitudinal compression failure of UD ply

Physical mechanisms ?

Fibre kinking

Experimental evidences

Instability of carbon fibres in polymer matrix observed at microscopic scale (*structural effect*)

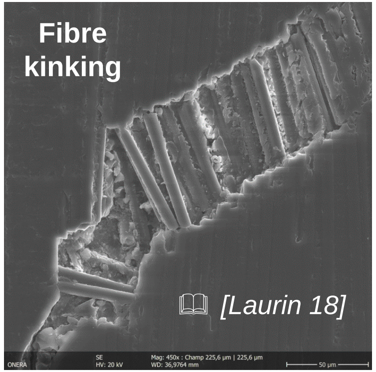
📖 *[Argon 72]*
📖 *[Vogler 01]*
📖 *[Gutkin 10] …*

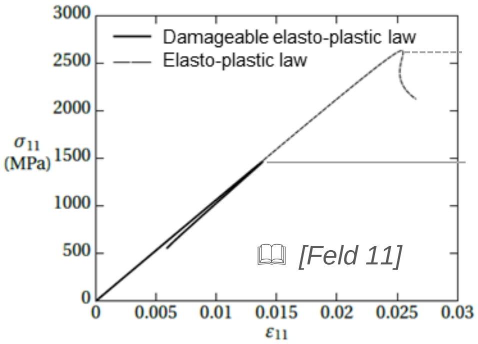
Micromechanical modelling

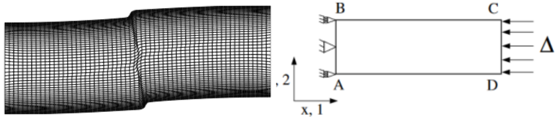
Models at microscale depend on:

- Mechanical properties of fibres **and** matrix (*and behaviour*)
- Applied loadings (*compression, bending …*)
- Boundary conditions (*inner or outer plies*)

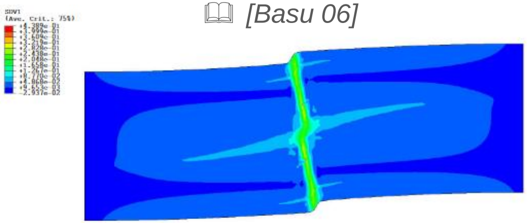
📖 *[Lee 99]*
📖 *[Drapier 99]*
📖 *[Pimenta 09]*
📖 *[Feld 11]…*





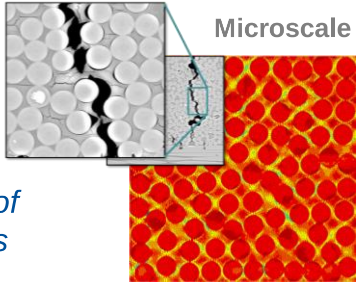


📖 *[Basu 06]*



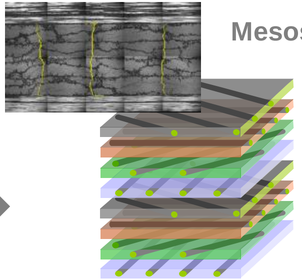
Modelling of longitudinal compression failure of UD ply

What is the relevant modelling scale?

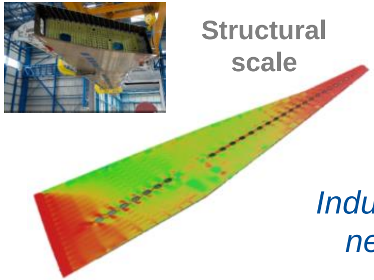


Microscale

Scale of events



Mesoscale



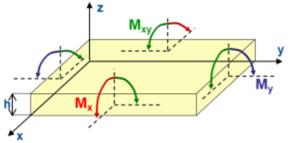
Structural scale

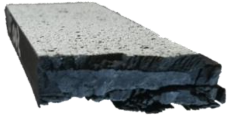
Industrial need

Proposed strategy at mesoscale

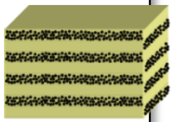
Laminate

Applied loading





Final failure

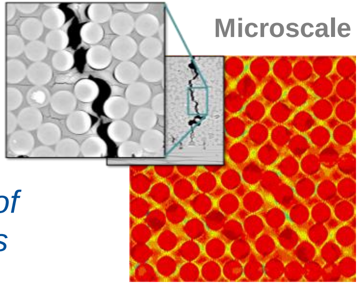


UD ply

Estimation of $\sigma/\ \varepsilon$ in plies → Failure of UD ply → Degradation of failed ply

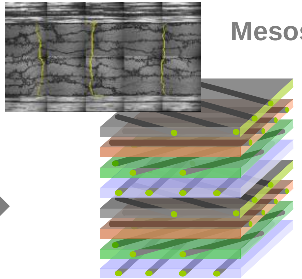
Modelling of longitudinal compression failure of UD ply

What is the relevant modelling scale?

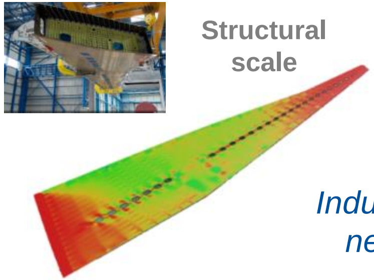


Microscale

Scale of events



Mesoscale



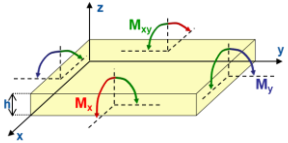
Structural scale

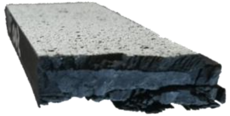
Industrial need

Proposed strategy at mesoscale

Laminate

Applied loading



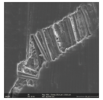


Final failure

UD ply

Estimation of σ/ ε in plies → Failure of UD ply → Degradation of failed ply

Microscale



X_c **longitudinal compressive strength** from a micromechanical approach

Mesoscale failure approach

Estimation of macroscopic failure

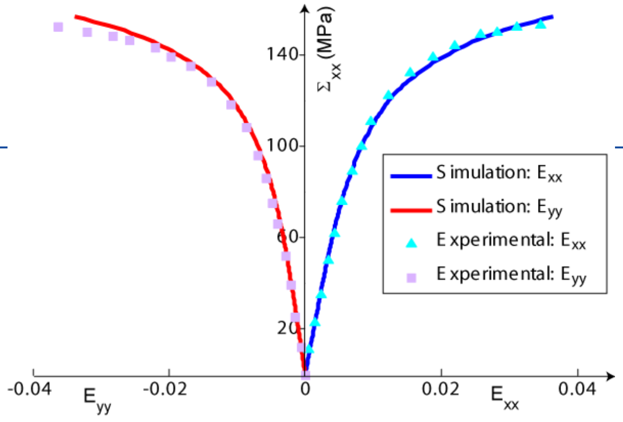
Onera Failure Model

Key points

- Thermal residual stresses 🕮 *[Huchette 05]*
- **Non-linear longitudinal elastic behaviour**
  🕮 *[Laurin 07]*
- **Viscoelastic behaviour**
  🕮 *[Schieffer 03, Laurin 05]*
- Influence of ply thickness on IFF strengths
  🕮 *[Parvizi 78, Chang 87]*
- Advanced failure criteria
  🕮 *[Puck 02, Laurin 07, Pinho 13, Carrere 13]*

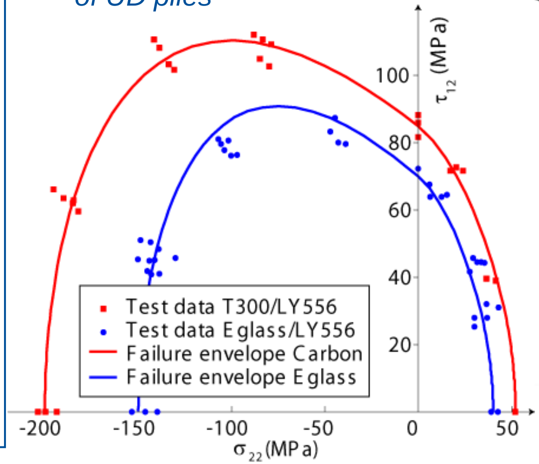
Identification and validation

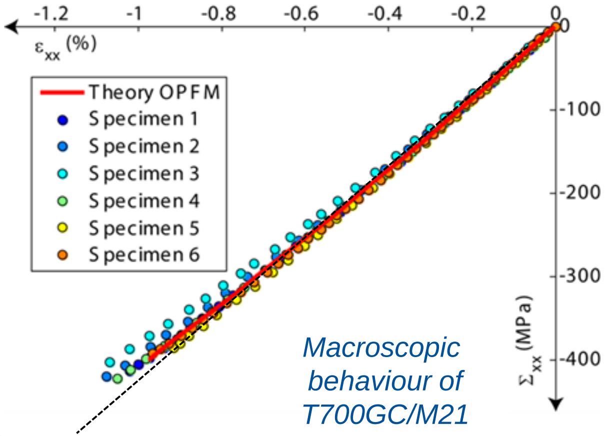
- Already identified and validated on
  a Carbon/Epoxy **T700GC/M21**
  🕮 *[Huchette 05, Laurin 07]*



Macroscopic behaviour of T700GC/M21 [±45°]$_{2s}$

Failure envelopes of UD plies





Macroscopic behaviour of T700GC/M21 [45/90/-45/0]$_s$

Mesoscale failure approach

Estimation of macroscopic failure

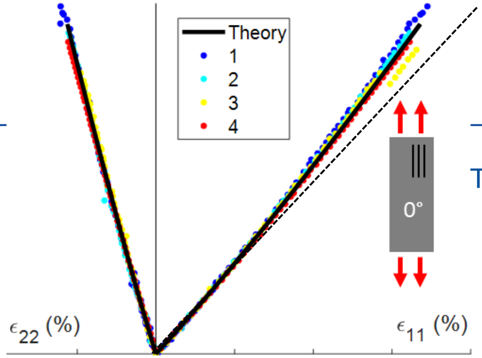
Onera Failure Model

Key points

- Thermal residual stresses *[Huchette 05]*
- **Non-linear longitudinal elastic behaviour**
  [Laurin 07]
- **Viscoelastic behaviour**
  [Schieffer 03, Laurin 05]
- Influence of ply thickness on IFF strengths
  [Parvizi 78, Chang 87]
- Advanced failure criteria
  [Puck 02, Laurin 07, Pinho 13, Carrere 13]

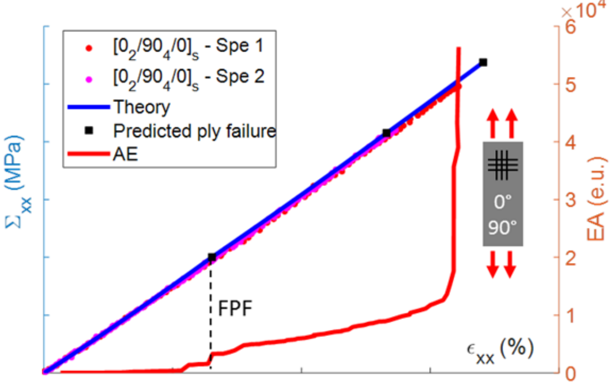
Identification and validation

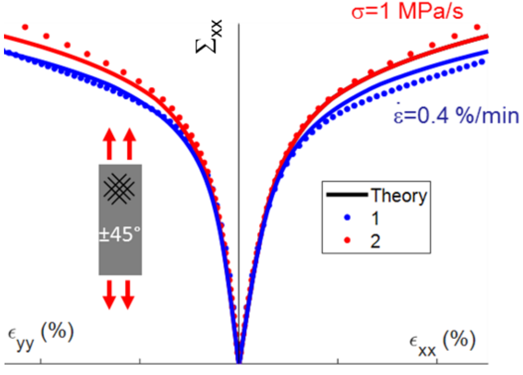
- Already identified and validated on
  a Carbon/Thermoplastic **TC1225**
  [Laurin 21]



Tensile test on TC1225 $[0]_{8s}$

Macroscopic behaviour of TC1225 cross-ply laminates





Macroscopic behaviour of TC1225 $[\pm 45]_{2s}$

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How the fibre-dominated strength of a multidirectional laminate relates to the strength of a UD composite?

Micromechanical approach

Estimation of longitudinal compressive strength of UD ply

Microscale modelling

Analytical formula

Based on FE simulations at microscale

📖 *[Drapier 99], [Gardin 02], [Grandidier 12], [Mechin 18]*

- Two main aspects are considered in the proposed model

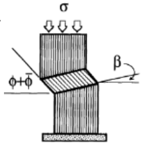
$$\sigma_{UD}^{crit} = \frac{1}{1 + n_{UD}\left(\frac{3}{7}\right)^{\frac{1}{n_{UD}}}\left(\frac{\phi_0/\gamma_{UD}^{y}}{n_{UD}-1}\right)^{\frac{n_{UD}-1}{n_{UD}}}} + 2r_{gf}\frac{\pi}{e_b}\sqrt{\frac{E_m E_f}{1-\nu_m^2}V_f(1-V_f)}$$

Micro-buckling mechanism

- Fibre buckling 📖 *[Budiansky 93]*
- Plasticity of matrix

Ramberg Osgood behaviour

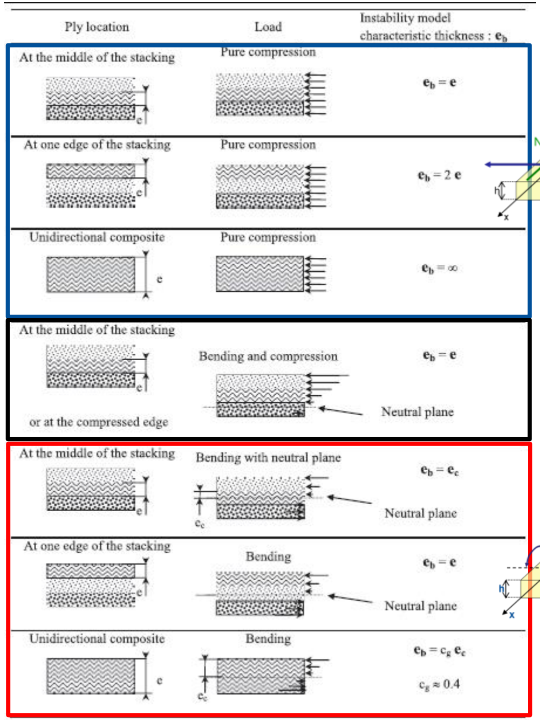
$$\frac{\gamma}{\gamma_{UD}^{y}} = \frac{\tau}{\tau_{UD}^{y}} + \frac{3}{7}\left(\frac{\tau}{\tau_{UD}^{y}}\right)^{n_{UD}}$$



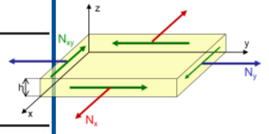
Structural effect

- Ply thickness
- Inner & outer plies
- Different loadings

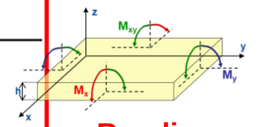
Compression & Bending



Compression



Compression + Bending



Bending

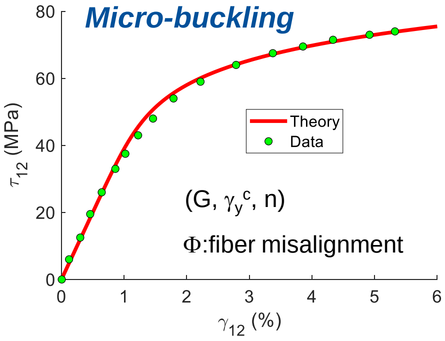
📖 *[Grandidier 12]*

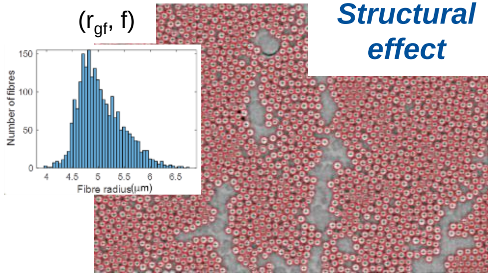
Analysis of available tests on T700GC/M21

Compression vs. Bending loading

Comparison with experimental data

- **Identification of micromodel on a Carbon/Epoxy**

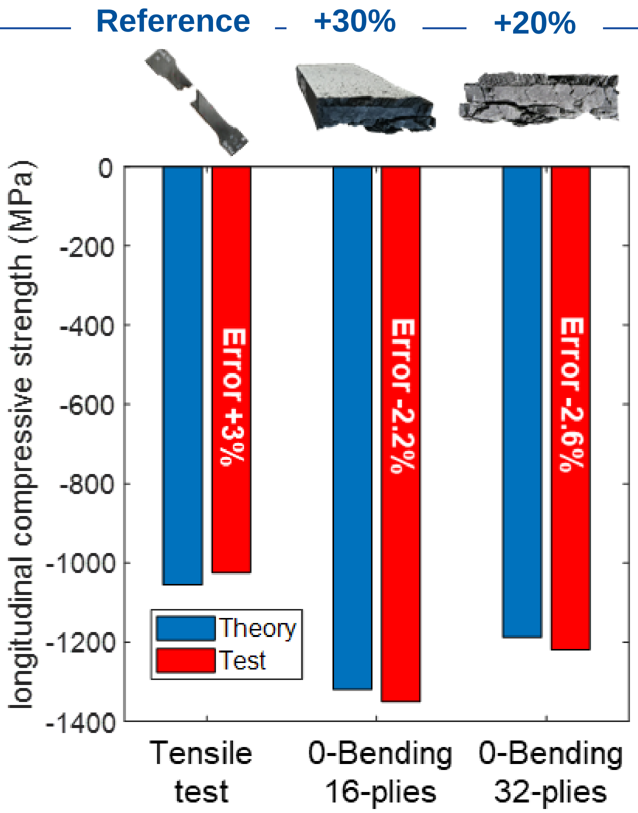




(E_f, E_m, ν_m) from literature

- **Validation on bending and compression tests**
  - Tensile tests on laminate which failed in compression (*reference*)
  - Bending loadings applied on UD plies 📖 *[Laurin 16, Laurin 18]*

- **Micromodel analysis agrees with test data**

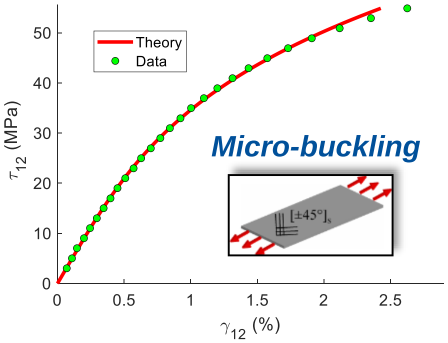


Analysis of available tests on TC1225

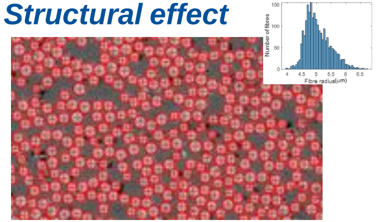
Influence of 0-plies position through the thickness

Comparison with experimental data

Identification on Carbon/Thermoplastic



Structural effect

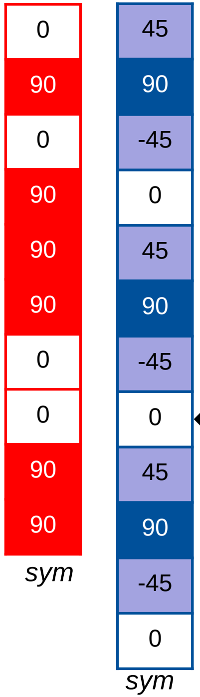


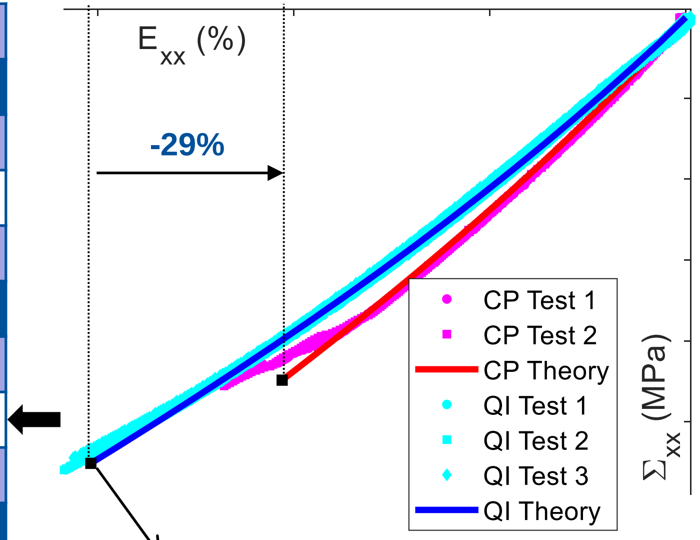
(E_f, E_m, ν_m) from inverse identification

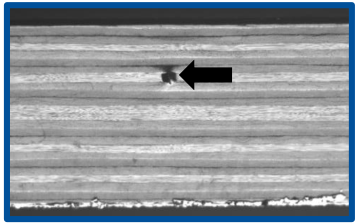
Validation different compression tests

- Cross-Ply and **Quasi-Isotropic** laminates 📖 *[Fougerouse 23]*
- Different strains at failure for inner and outer 0-plies

Micromodel analysis agrees with test data







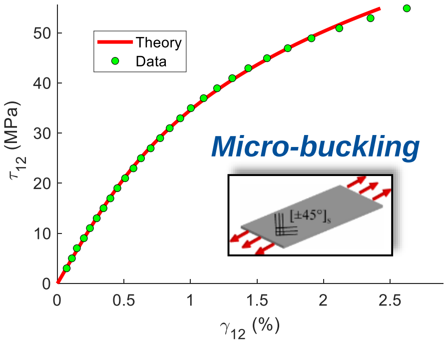
Fibre kinking
in inner 0-plies
In QI laminate

Analysis of available tests on TC1225

Influence of 0-plies position through the thickness

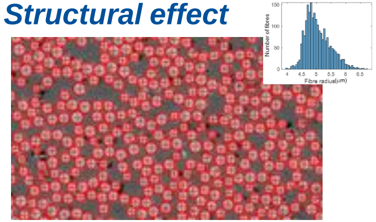
Comparison with experimental data

Identification on Carbon/Thermoplastic



Micro-buckling

Structural effect



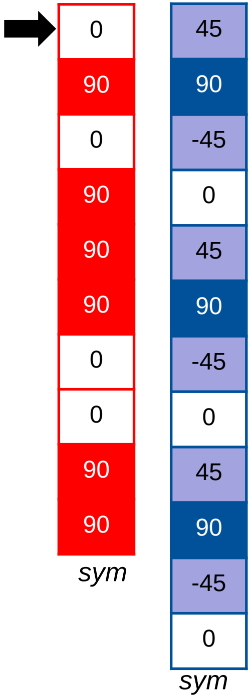
(E_f, E_m, ν_m) from inverse identification

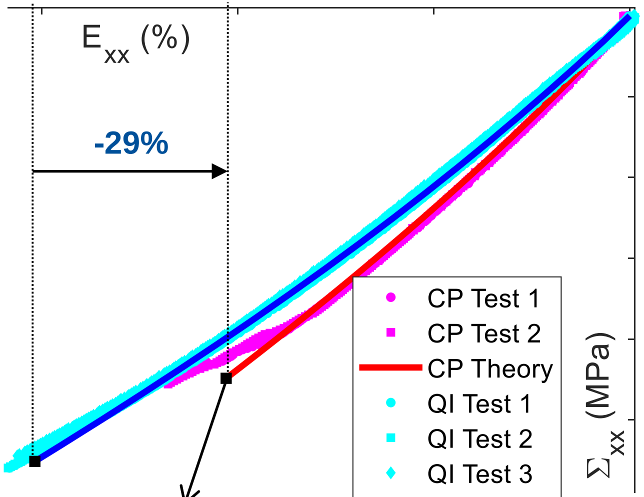
Validation different compression tests

- **Cross-Ply** and Quasi-Isotropic laminates 📖 *[Fougerouse 23]*
- Different strains at failure for inner and outer 0-plies

→ Perspectives: 📖 *[Laurin 18], [Wu 23]*

- To consider different bending loadings on TC1225





Fibre kinking in outer 0-ply in CP laminate

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