The role of constituents on the compressive strength of composites

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# Introduction

## Goals
- Enabling material development
- Increase accuracy of models
- Identify gaps in characterisation

## Outline
- Properties of the matrix
  - Shear non-linearity
  - Plasticity parameters
- Properties of the fibres
  - Shear (and transverse) modulus
- Properties of interface
  - Matrix- vs. interface-dominated failure
  - Interfacial shear strength
- Conclusions

## Longitudinal compressive failure

### Kink-band formation:
- Fibre misalignments
- Matrix shear response

[Image of longitudinal compressive failure]
FE models for compressive failure

Fibre/matrix **unit cell** with periodic BCs

- **T300 carbon fibres**
  - Non-linear elastic longitudinal response
  - Transversely isotropic

- **Epoxy matrix (Epon 862)**
  - Non-linear shear response
  - Drucker-Prager plasticity

**L** = 900 μm

misalignment geometry: *Paluch* (1996)

*Ueda & Akiyama* (2018)

*Sorini et al.* (2021)
**Sequence of events (baseline constitutive law, $\theta_0 = 1^\circ$)**

**Global stress-strain curve**

- Longitudinal compressive stress (MPa)

![Graph showing stress-strain curve with key points labeled](image)

- Onset of matrix plasticity
- Peak stress
- Matrix failure

**Matrix evolution at max. misalign.**

- Matrix equivalent shear stress (MPa)

![Graph showing matrix evolution](image)

- Matrix equivalent shear strain (%)

**Longitudinal fibre compression fields**

![Field showing compression fields](image)
Matrix non-linearity ($\theta_0 = 1^\circ$)

Matrix shear constitutive law

Matrix shear stress (MPa)

- Linear-Elastic / Perfectly-Plastic
- Trilinear

nominal (Sorini et al., 2021)

Composite compressive strength

Composite strength (MPa)

\[ \nabla: \text{Instability model (Wisnom, 1990)} \]

\[ X^{\text{FRP}} = \max \left[ \frac{\tau_m}{\sin(\gamma^{\text{FRP}} + \theta_0)} \right] \]

- $\tau_m$ / sin($\gamma^{\text{FRP}} + \theta_0$)

FE

17%

18%

Matrix shear strain (%)

0 10 20 30 40

0 10 20 30 40

Composite non-linearity in shear

FE

FE

FE

trilinear

nominal

LE-PP
Matrix plasticity: material parameters

**Friction angle**
- Controls **tension/compression/shear asymmetry**

- Matrix under complex 3D stress state

- \( \beta^m = 9.1^\circ \)

**Dilation angle**
- Controls volumetric strains ("dilation") during plastic deformation

- Fibres constrain matrix dilation during plasticity
Matrix plasticity: friction angle, $\beta^m$ ($\theta_0 = 2^\circ$)

### Effect on composite strength

Composite strength (MPa)

- $\beta^m = 9.14^\circ$ (Sorini et al., 2021)
- $\beta^m = 39^\circ$ (Sun et al., 2017)

### Apparent constitutive law

Matrix von Mises stress (MPa)

- $\beta^m = 0^\circ$ (input: pure shear)
- $\beta^m = 39^\circ$

36% increase in composite strength
Matrix plasticity: dilation angle, $\varphi^m$ ($\dot{\theta}_0 = 2^\circ$)

Effect on composite strength

Composite strength (MPa)

Hydrostatic pressure at peak

Matrix hydrostatic pressure (MPa)

$\varphi^m = 0^\circ$
(von Mises, plenty!)

$\varphi^m = 28^\circ$
(Dean & Crocker (2001) + plenty!)

$\varphi^m = 39^\circ$
(Sun et al., 2017)

Increase dilation angle

- Increase hydrostatic compression
- Increase apparent shear strength ($\beta^m > 0$)
Fibre elastic response (T300 carbon fibres)

Non-linear longitudinal response

Compressive stress (GPa)

Baseline elastic constants:

$E_{11}^f = 226.5$ GPa (Mesquita et al., 2021)

Transversely isotropic (linear)

Baseline elastic constants:

Csanádi et al. (2017)

$E_{22}^f = E_{33}^f = 27.6$ GPa

$G_{12}^f = G_{13}^f = 10.9$ GPa

$\nu_f^f = 0.3$

Effect on composite’s shear modulus

Composite shear modulus (GPa)

$E_{22}^f = 7.79$ GPa, $E_{22}^f = 7.79$ GPa, (Naito et al. (2017))

$E_{22}^f = 10.9$ GPa, $E_{22}^f = 27.6$ GPa, (Csanádi et al., 2017)

$G_{12}^f = 75$ GPa (Sun et al., 2017)

Chamis model
Fibre shear and transverse moduli \( (\theta_0 = 1^\circ) \)

### Effect on composite strength

- **Composite strength (MPa)**
  - Graph showing the effect of fibre shear and transverse moduli on composite strength.
  - Key points:
    - \( E_{22}^f = 7.79 \text{ GPa}, \) \( E_{22}^f = 27.6 \text{ GPa}, \) \( G_{12}^f = 10.9 \text{ GPa}, \)
    - \( G_{12}^f = 75 \text{ GPa}, \) \( G_{12}^f = 75 \text{ GPa}, \) \( G_{12}^f = 10.9 \text{ GPa}, \)

### Hydrostatic pressure at peak

- **Matrix hydrostatic pressure (MPa)**
  - Graph showing the relationship between fibre shear modulus and matrix hydrostatic pressure.
  - Key points:
    - \( \frac{E_{22}^f}{E_{22}^{f,\text{nom}}} = \frac{G_{12}^f}{G_{12}^{f,\text{nom}}} \)
    - \( \frac{E_{22}^f}{E_{22}^{f,\text{nom}}} = 1 \)
Cohesive element modelling

Cohesive properties

- **Same shear modulus & strength as matrix**
- Fracture toughness: 2-10 J/m² (no influence), Zhou et al. (2018)
- Failure initiation & propagation: quadratic interaction

Interfacial shear strength

- Experimental data for same composite

Huge experimental uncertainty!

Pitkethly et al. (1993)
Interface: effect on compressive response

**With vs. without interface**

Longitudinal compressive stress (MPa)

- **1.** Onset of matrix plasticity
- **2.** Interfacial failure
- **3.** Peak stress
- **4.** Interfacial failure

**Effect on composite strength**

Composite strength (vs. model without interface)

- With interface: 6% weaker
- 25% higher IFFS needed for same composite strength
Interface: preventing plasticity on matrix

Fractography

Does interfacial failure really prevent plasticity in the matrix?

"Band of out-of-place microbuckling"  
(Greenhalgh, 2009)

Equivalent plastic strains in matrix

Without interface, peak stress (3)

With interface, interfacial failure (4)
Conclusions

Matrix:
- Plasticity
  - Materials: confinement & strengthening
  - Characterisation: friction & dilation angles

- Shear non-linearity
  - Characterisation: include strain @ peak
  - Models: beware of LE-PP assumption & strain localisation

Fibres:
- Materials: increase shear stiffness
- Models: account for finite shear stiffness
- Characterisation: shear modulus

Interfaces:
- Characterisation: IFSS (consistency) & complex 3D loading
- Models: are CZM adequate?

"Pure shear and compression-shear characterisation of polymer matrix..."
Bohao Zhang
Wednesday 2nd, 3.20 pm

"Experimental characterisation of the dilation angle of polymers"
Gustavo Quino Quispe
Thursday 3rd, 10.00 am
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