IDENTIFICATION OF MESO SCALE DAMAGE PARAMETERS OF CARBON-EPOXY COMPOSITE

Dmitry S. Ivanov, Stepan V. Lomov, Ignaas Verpoest

Katholieke Universiteit Leuven

Material Research Centre

Contents

- **Tests on carbon-epoxy composites**
  - **Tensile diagrams, crack initiation, failure mode**
  - **Non-linearity induced by damage**

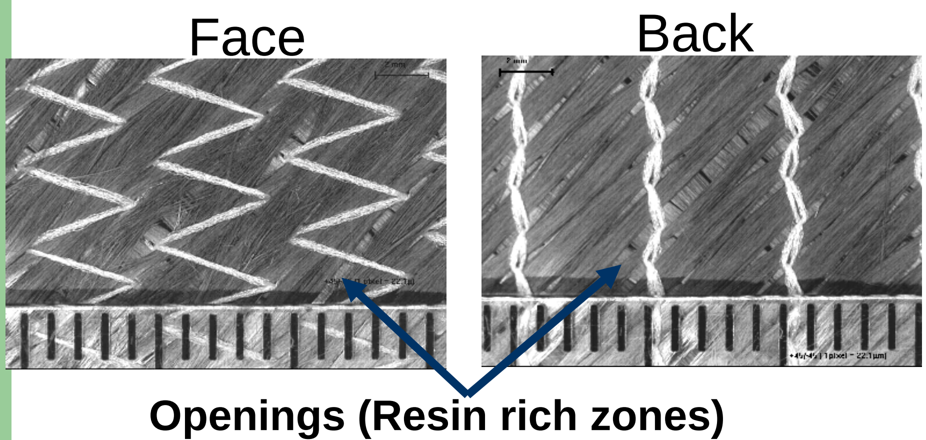
- Meso FE modelling:
  - FE model of NCF
  - Limitations due to the periodicity
  - Degradation scheme
  - The damage evolution law
  - Inverse FE procedure: damage evolution law vs. Vf

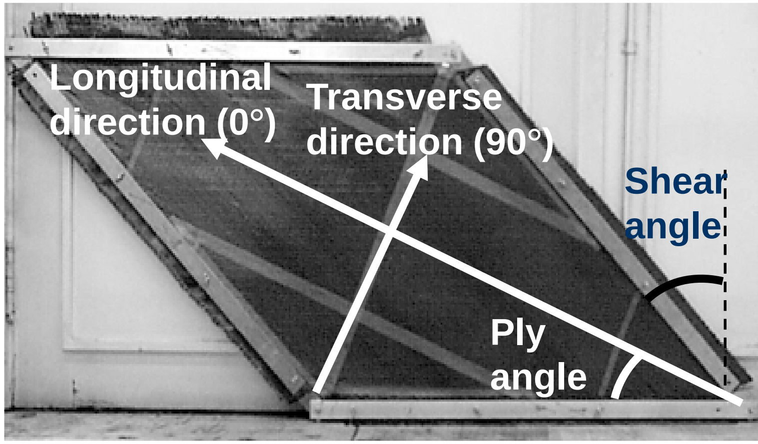
- Implementation of the damage model:
  - Analysis of damage initiation
  - NCF and 3-axial-braided

- Conclusion / discussion

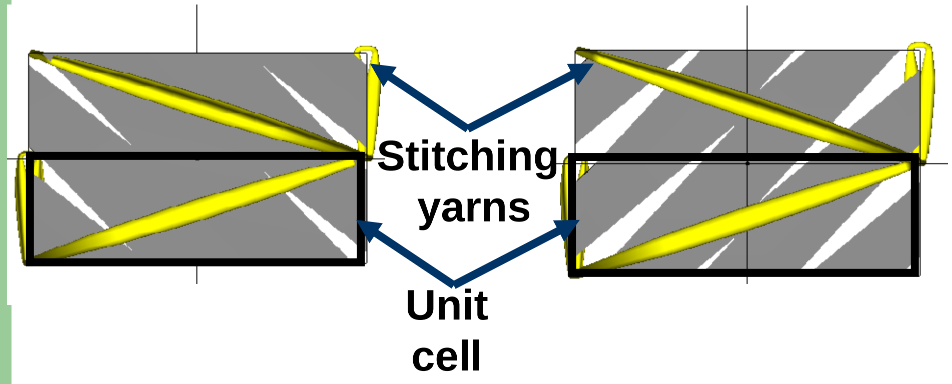
NCF geometry: sheared and non-sheared

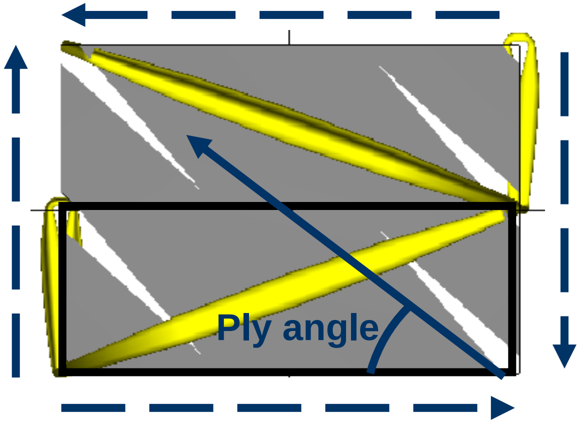
±45° NCF



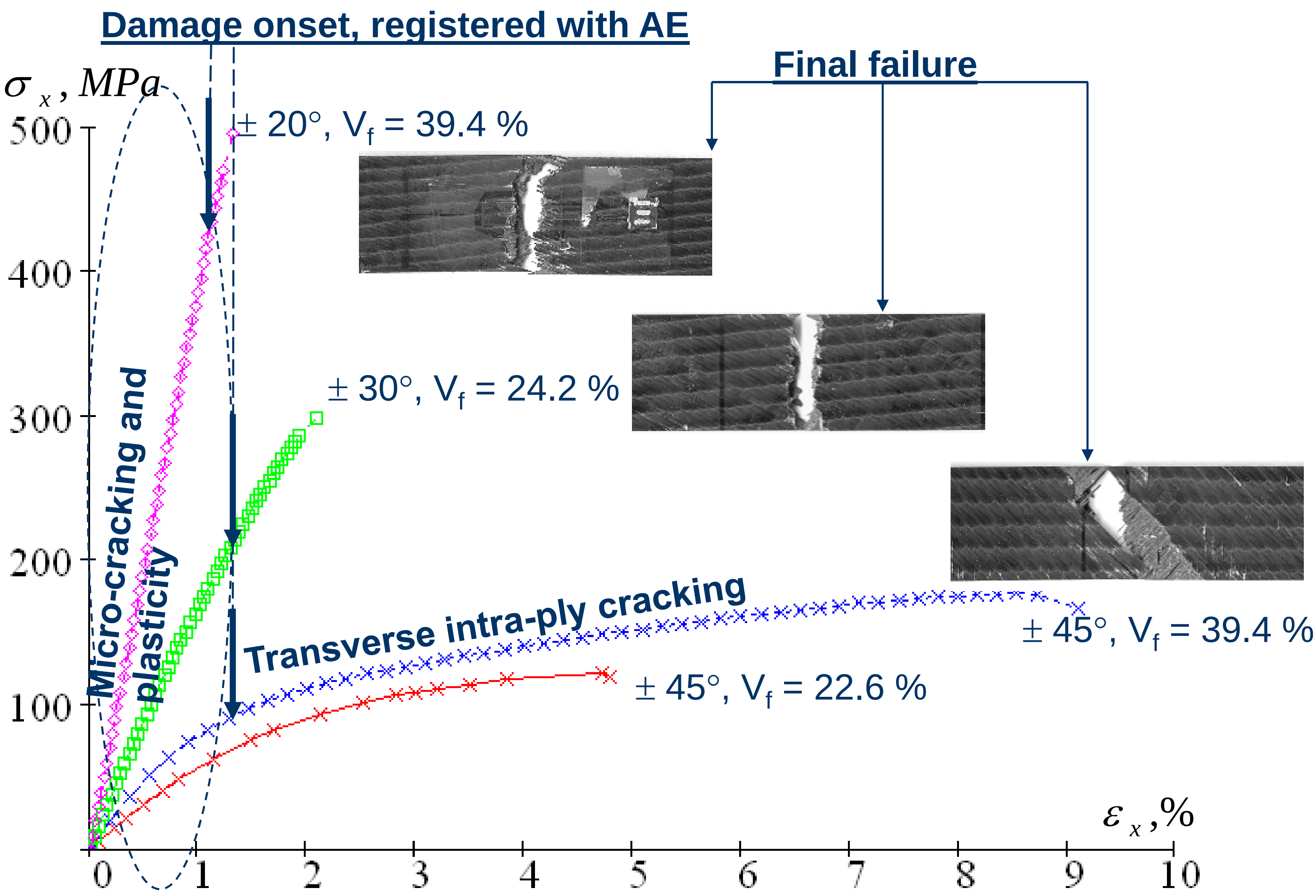


WiseTex models

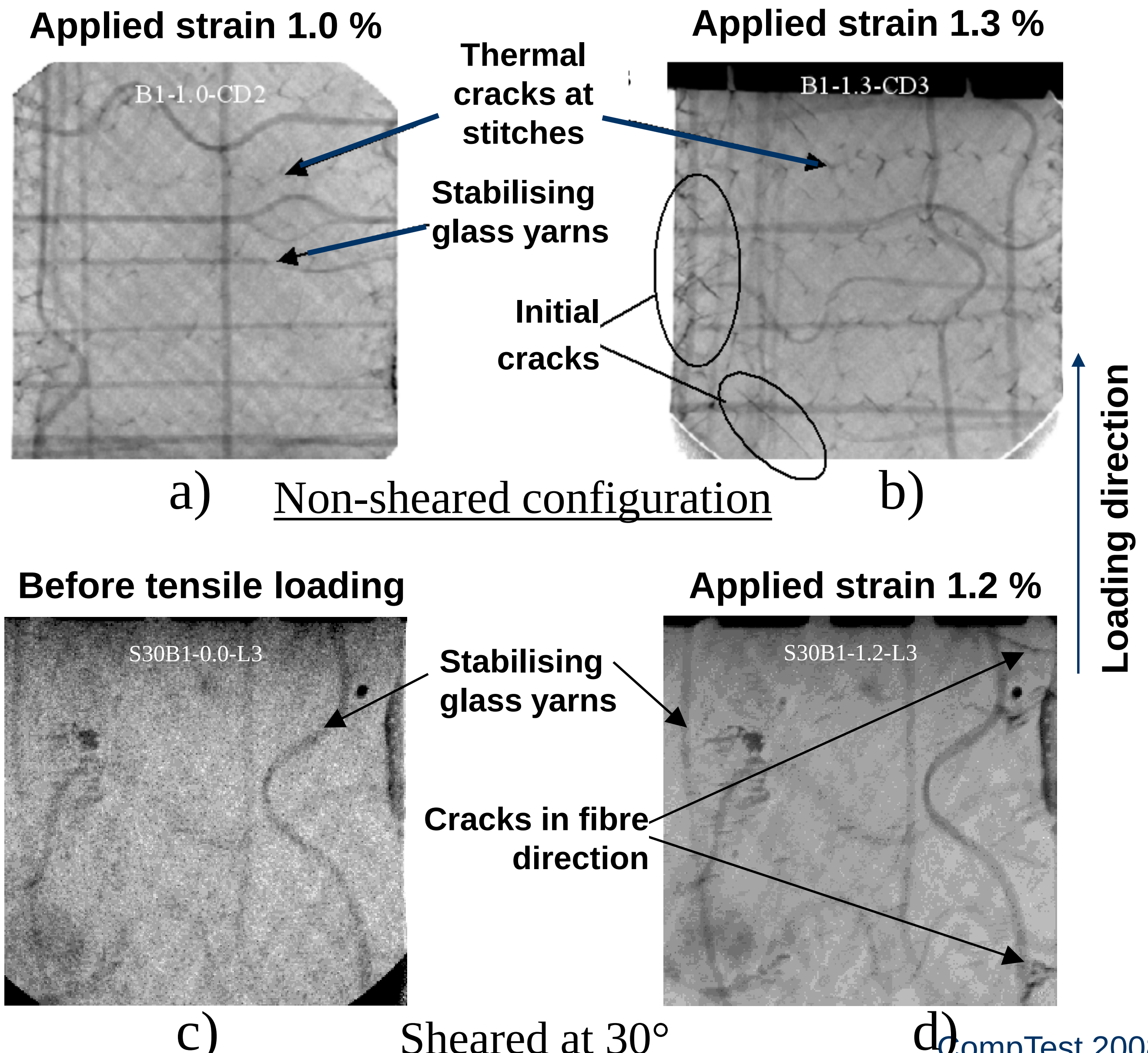




NCF: tensile test



NCF: cracking



Contents

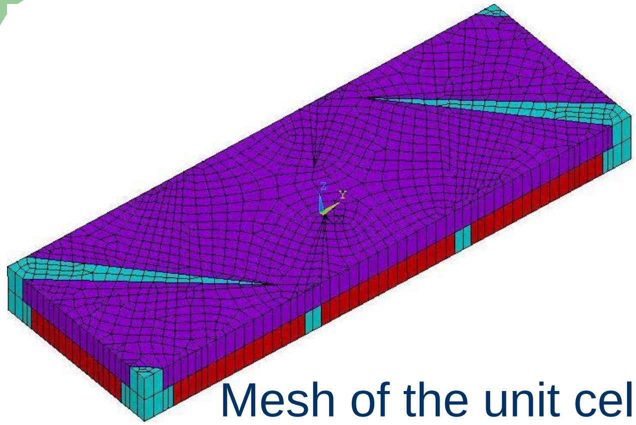
- Tests on carbon-epoxy composites
  - Tensile diagrams, crack initiation, failure mode
  - Non-linearity induced by damage

- **Meso FE modelling:**
  - **FE model of NCF**
  - **Limitations due to the periodicity**
  - **Degradation scheme**
  - **The damage evolution law**
  - **Inverse FE procedure: damage evolution law vs. Vf**

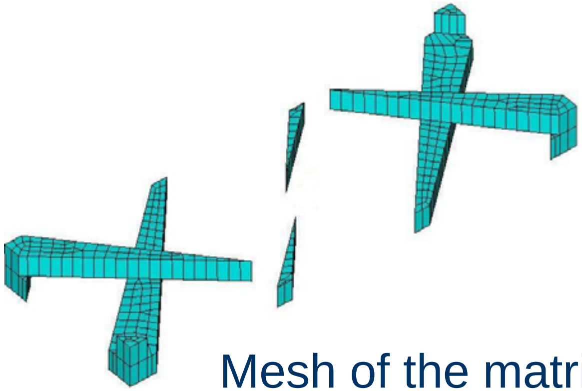
- Implementation of the damage model:
  - Analysis of damage initiation
  - NCF and 3-axial-braided

- Conclusion / discussion

FE model: geometry



Mesh of the unit cell



Mesh of the matrix

Accounted for:

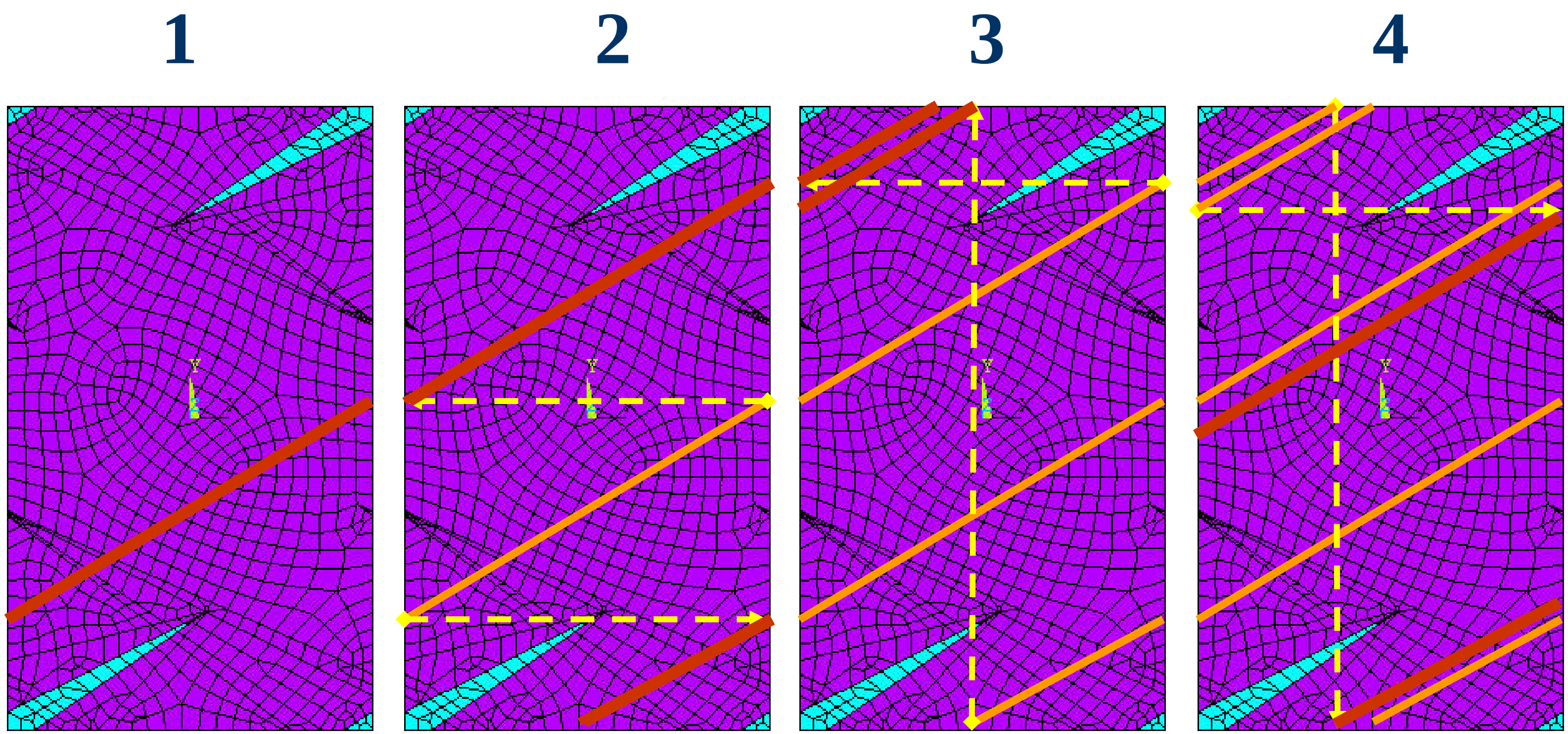
a) Geometry of the resin channels;
b) Different fibre volume fraction in the upper and bottom plies;
c) Deviation of the carbon fibre orientation cause by the stitching;

Neglected:

a) Stitching polyester yarns;
b) Ply waviness;
c) Stabilising glass yarns;

Periodicity and damage - 1

Cracks break periodicity in NCF



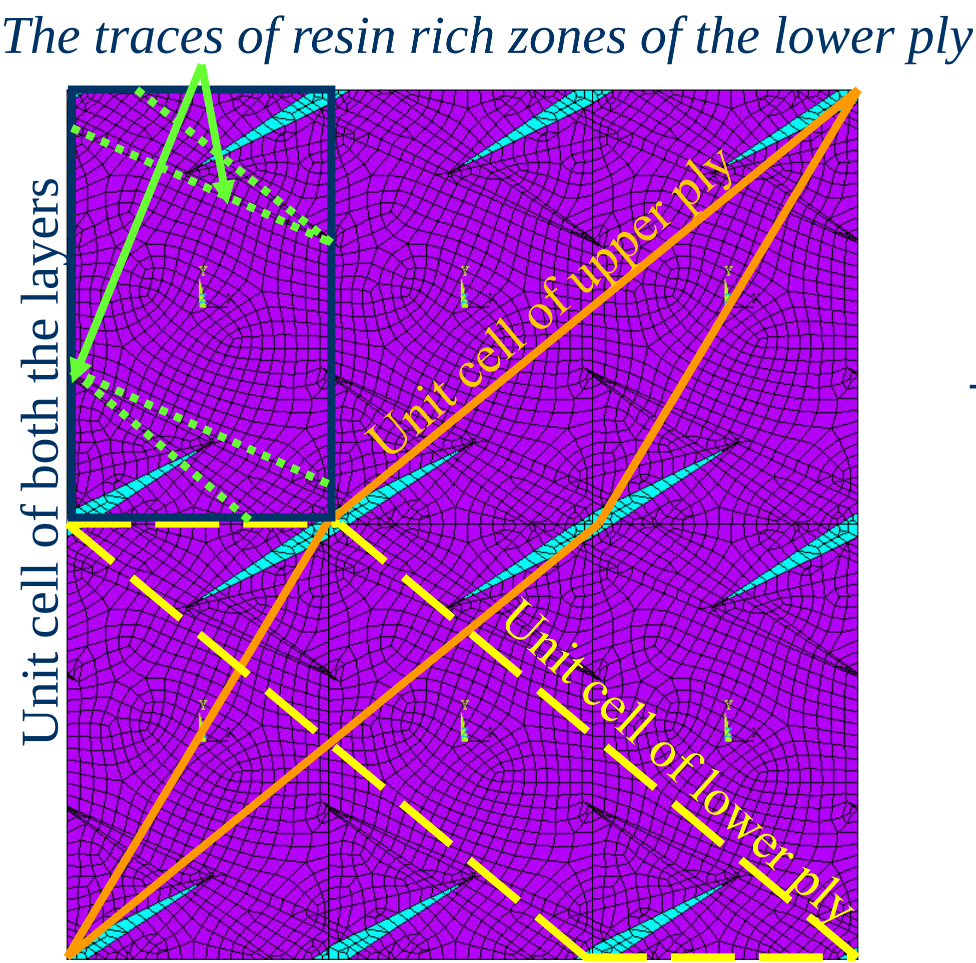
Periodical continuation of the crack

New crack in the unit

Previous crack

Periodicity and damage - 2

Crack breaks periodicity



Hence: Continuous damage mechanics

↓

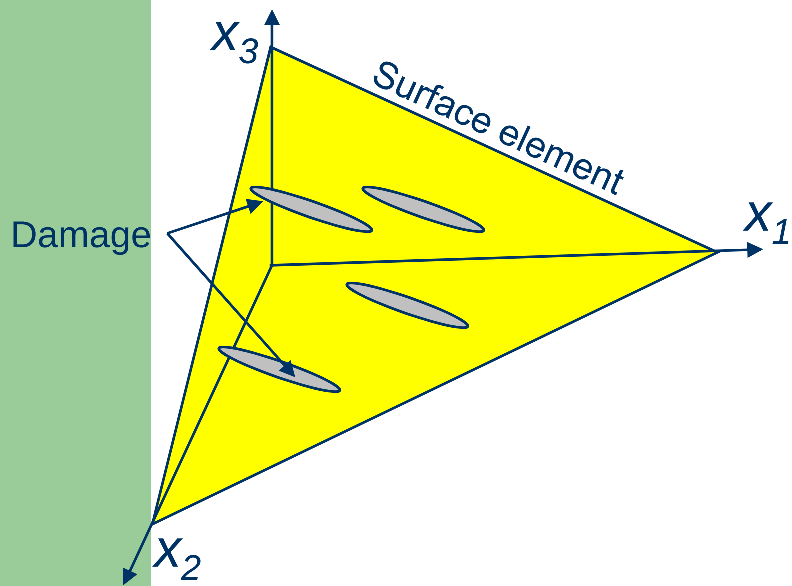
The degradation of the entire ply according to the average stress in it

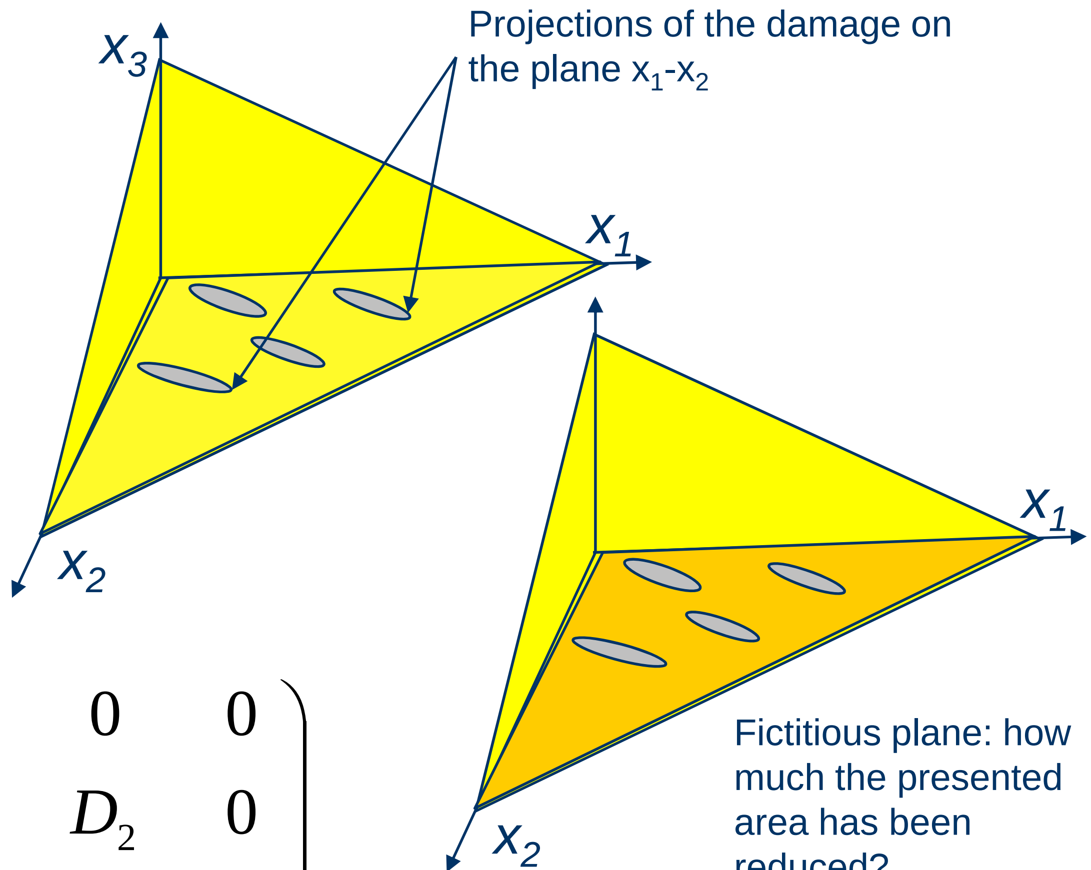
↓

+ Avoiding issues on the statistical nature of crack accumulation

Anisotropic continuum damage mechanics

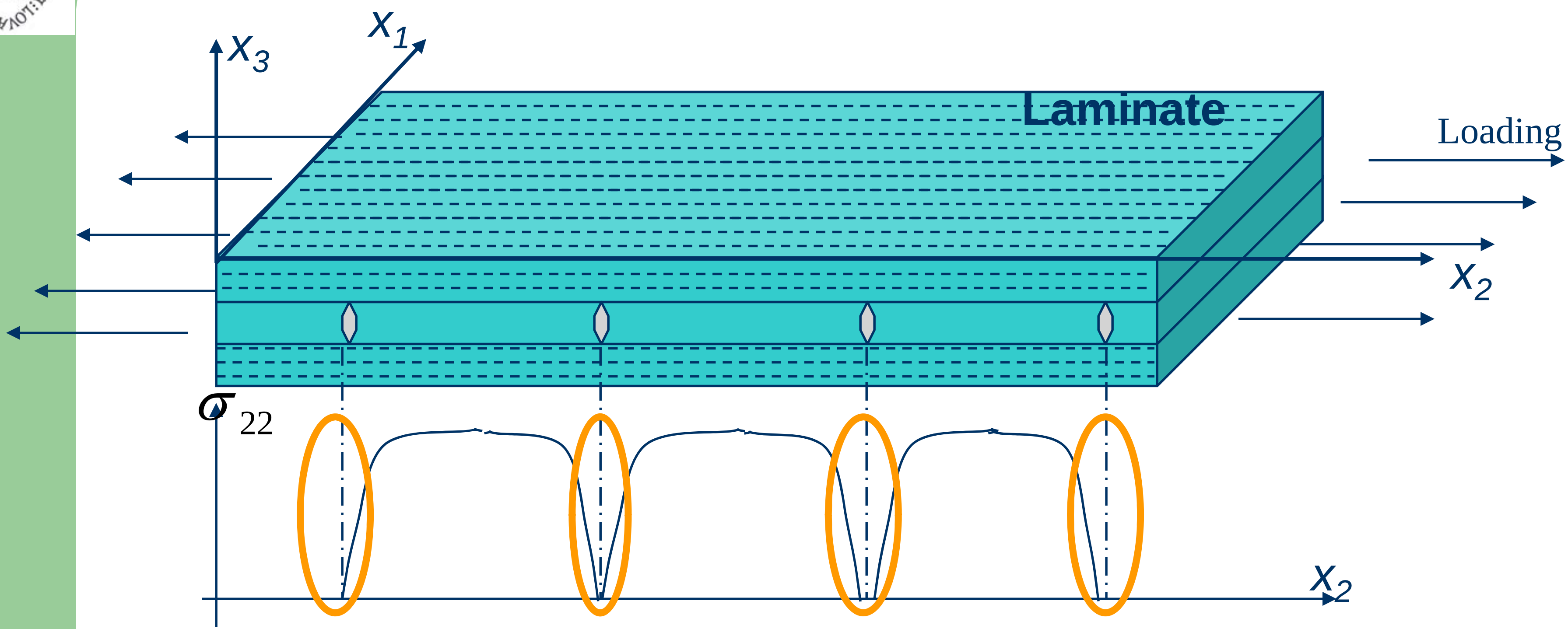
Murakami (1988):





$$D = \sum_{i=1}^{3} D_i n_i \otimes n_i = \begin{pmatrix} D_1 & 0 & 0 \\ & D_2 & 0 \\ sym. & & D_3 \end{pmatrix}$$

Anisotropic continuum damage mechanics



Effective stress (d_2=1, d_1=d_3=0):

$$\sigma^* = \begin{pmatrix} \sigma_{11} & \dfrac{\sigma_{12}}{(1-d_2)} & \sigma_{13} \\ & \dfrac{\sigma_{22}}{(1-d_2)^2} & \dfrac{\sigma_{23}}{(1-d_2)} \\ sym & & \sigma_{33} \end{pmatrix}$$

Degradation scheme

Degradation scheme (Murakami-Ohno)

$$C^d = \begin{pmatrix} C_{11}^0 & C_{12}^0(1-d_2) & C_{13}^0 & 0 & 0 & 0 \\ & C_{22}^0(1-d_2)^2 & C_{23}^0 & 0 & 0 & 0 \\ & & C_{33}^0 & 0 & 0 & 0 \\ & & & G_{23}^0\left(\frac{2(1-d_2)}{2-d_2}\right)^2 & 0 & 0 \\ & sym. & & & G_{13}^0 & 0 \\ & & & & & G_{12}^0\left(\frac{2(1-d_{12})}{2-d_{12}}\right)^2 \end{pmatrix}$$

1 damage parameter, explicit geometrical meaning: represents a degradation at a certain crack density

Relation between d_2 and d_{12}: modified

$$d_2 = \begin{cases} 0 & if \quad d_{12} < d_{12}^X \\ \dfrac{2(1-\sqrt{1-(d_{12}-d_{12}^X)})}{(2-\sqrt{1-(d_{12}-d_{12}^X)})} & if \quad d_{12} \geq d_{12}^X \end{cases}$$

d_{12}^X: the load level when the transverse cracking occurs.

(correspondent to the onset of AE events)

Assumption: Micro-cracking results in d_{12}, but not in d_2

Thermodynamic material law

$$\Psi = \frac{1}{2}\left[\begin{array}{l} \frac{{\sigma_{11}}^2}{E_1^0} + \frac{{\sigma_{22}}^2}{E_2^0(1-d_2)^2} + \frac{{\sigma_{33}}^2}{E_3^0} - \\ -\frac{2\nu_{21}^0\sigma_{11}\sigma_{22}}{E_2^0(1-d_2)} - \frac{2\nu_{23}^0\sigma_{33}\sigma_{22}}{E_2^0(1-d_2)} - \frac{2\nu_{13}^0\sigma_{11}\sigma_{33}}{E_1^0} + \\ + \frac{{\sigma_{12}}^2}{G_{12}^0(1-d_{12})} + \frac{{\sigma_{23}}^2}{G_{23}^0(1-d_{12})} + \frac{{\sigma_{13}}^2}{G_{13}^0} \end{array}\right]$$

Elastic work of the damaged UD composite:

In agreement with the Murakami degradation scheme

Energy released by damage occurrence:

$$Z_{12} = \sqrt{\underset{\tau \le t}{Sup}\left(\frac{\partial}{\partial d_{12}}\Psi\right)}$$

$$d_2 = d_2(d_{12})$$

$$Z_{12} = \sqrt{\frac{\partial d_2}{\partial d_{12}}(1-d_2)\varepsilon_{22}\left(\varepsilon_{22}C_{22}^0(1-d_2) + \varepsilon_{11}C_{12}^0 + \varepsilon_{33}C_{13}^0\right) + \frac{1}{2}\left(G_{12}^0\gamma_{12}^2 + G_{23}^0\gamma_{23}^2\right)}$$

Material law: $d_{12}^{cr} = d_{12}^{cr}(Z_{12})$ …To be extracted!..

analogical crack growth resistance curve in classical fracture mechanics

Inverse procedure

Assumption:

Degradation of the shear modulus is the main source of the non-linearity in test of NCF ±45° composite

Step-wise procedure

Apply average macro strain via periodic BC's

Find ratio of the experimental stress and average stress in FE model $R = \frac{\sigma_x^{Exp}}{\sigma_x^{FE}}$

Scale down shear moduli of the plies with factor R

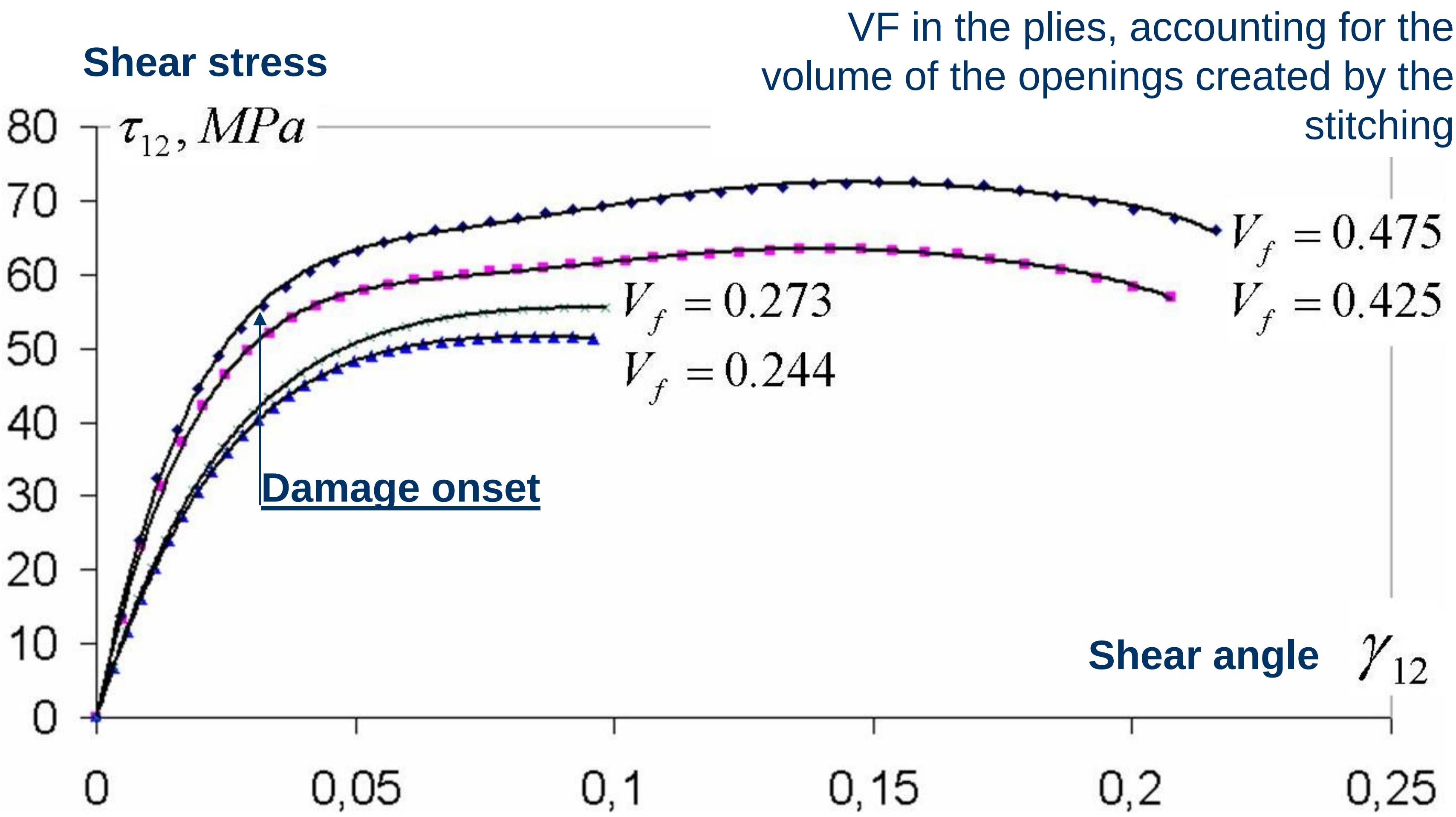
Check criterion of the damage initiation and assign transverse degradation: Murakami

Scale down stiffness constants C_{22}, C_{12}, C_{13}

Reconsider average fibre orientation in the fibre bundle: $\varphi^i = \varphi^{i-1} - \Delta\gamma^i / 2$

Calculate the parameters of the damage accumulation model

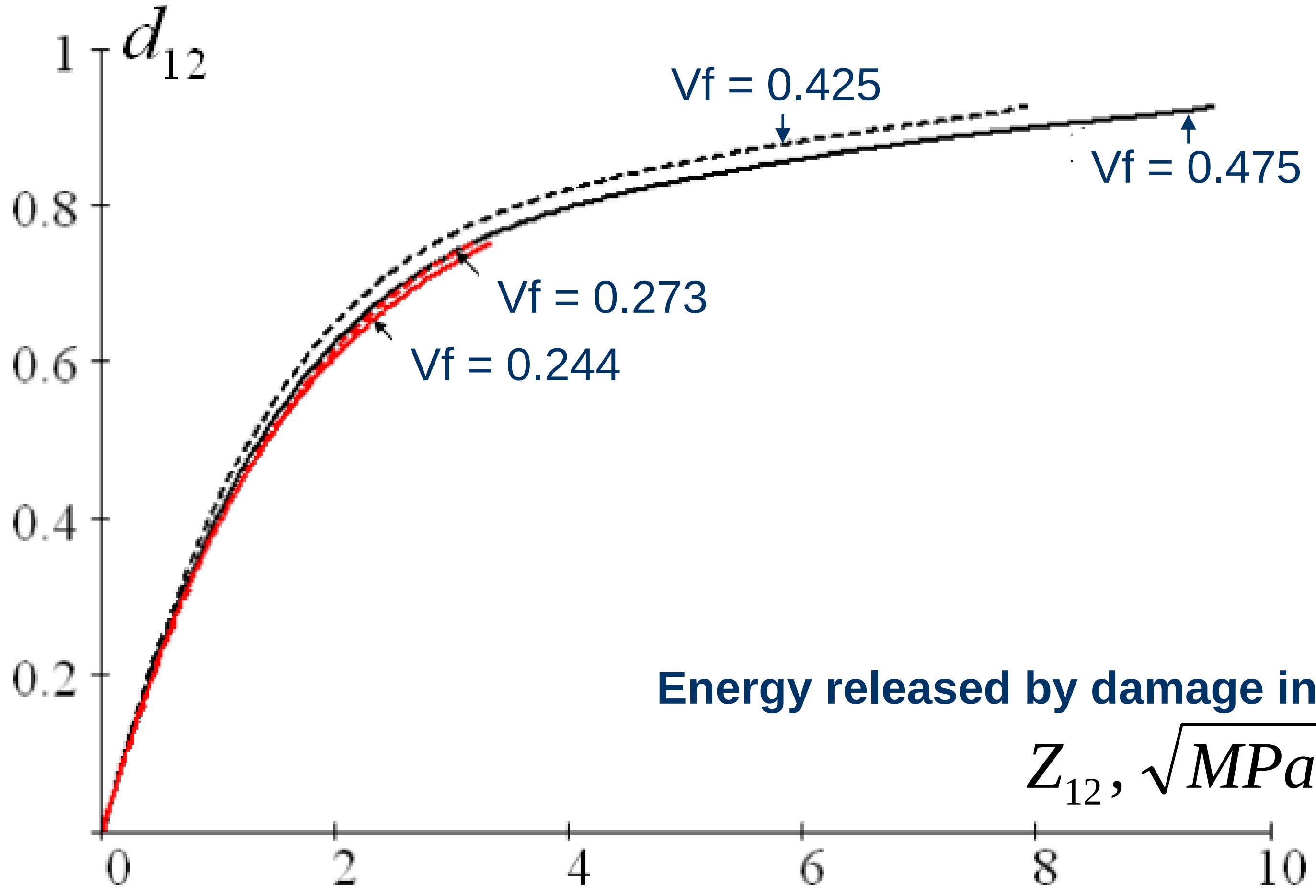
Extracted shear diagram



Confirms the common assumption about the post-critical "plateau" on the shear diagram

Extracted damage evolution law

Degradation of shear modulus



Almost does not depend on the fibre volume fraction! ⇒ convenient to use

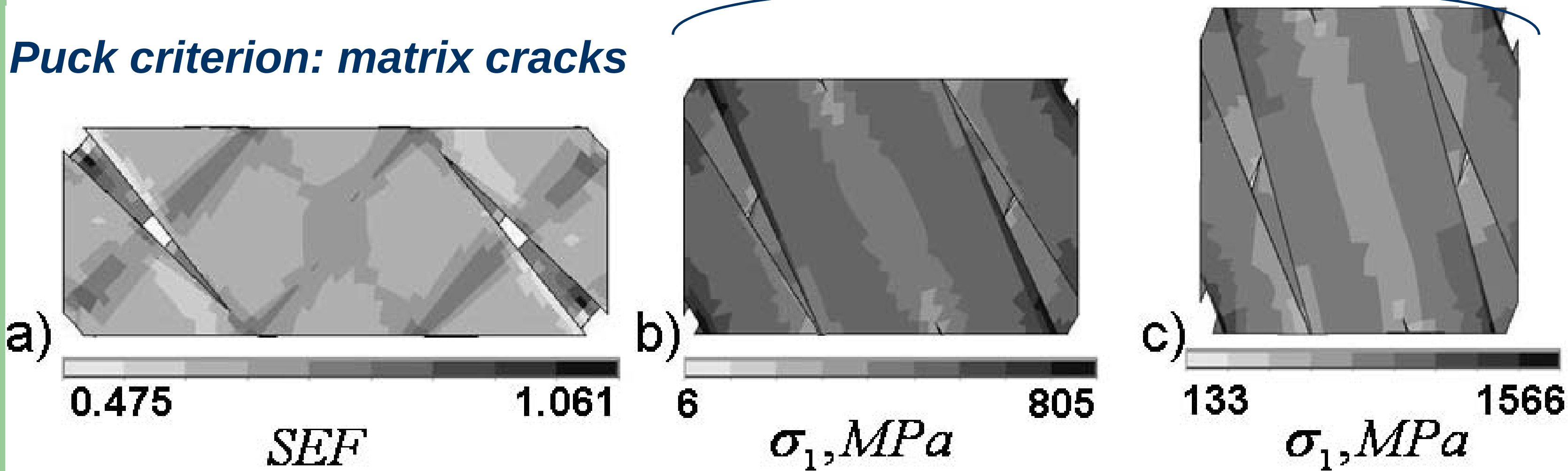
Contents

- Tests on carbon-epoxy composites
  - Tensile diagrams, crack initiation, failure mode
  - Non-linearity induced by damage
- Meso FE modelling:
  - FE model of NCF
  - Limitations due to the periodicity
  - Degradation scheme
  - The damage evolution law
  - Inverse FE procedure: damage evolution law vs. Vf
- **Implementation of the damage model:**
  - **Analysis of damage initiation**
  - **NCF and 3-axial-braided**
- Conclusion / discussion

Damage initiation and failure modes

Fiber failure maximum stress index:

Puck criterion: matrix cracks



(a) Stress exposure factor (SEF) for ± 45° composite at applied deformation 2,1 %
(b) Longitudinal (fibre) stress for ± 30° at 2,1 %,
(c) Longitudinal stress for 50 at 1.3 %.

Stiffness and failure predictions

Stiffness and damage features of the biaxial composites: Experiment / ***FEA***

Shear angle (Ply angle),°	Fibre volume fraction (%)	Young modulus, GPa	Poisson's ratio	Strain at matrix crack onset , %	Strain at failure, (%)	Stress at failure, MPa
0 (±45)	22.6	9.9±0.4 / ***9.85***	0.83±0.04 / ***0.83***	1.30 / ***1.23***	4.5±0.5 n/a	121.7±5.1 n/a
0 (±45)	39.4	6.6±0.3 / ***6.27***	0.69±0.02 / ***0.80***	n/a ***2.89***	8.7±0.3 n/a	177.4±3.9 n/a
30 (±30)	24.2	18±1.6 / ***21.1***	1.21±0.08 / ***1.46***	1.30 ***2.67***	2.1±0.2 / ***2.02***	298.7±20.9 / ***329.3***
50 (±20)	39.4	44.4±4.8 / ***52.44***	1.18±0.11 / ***1.44***	1.0 ***1.72***	1.3±0.2 ***1.0***	495.6±37.4 ***399.54***

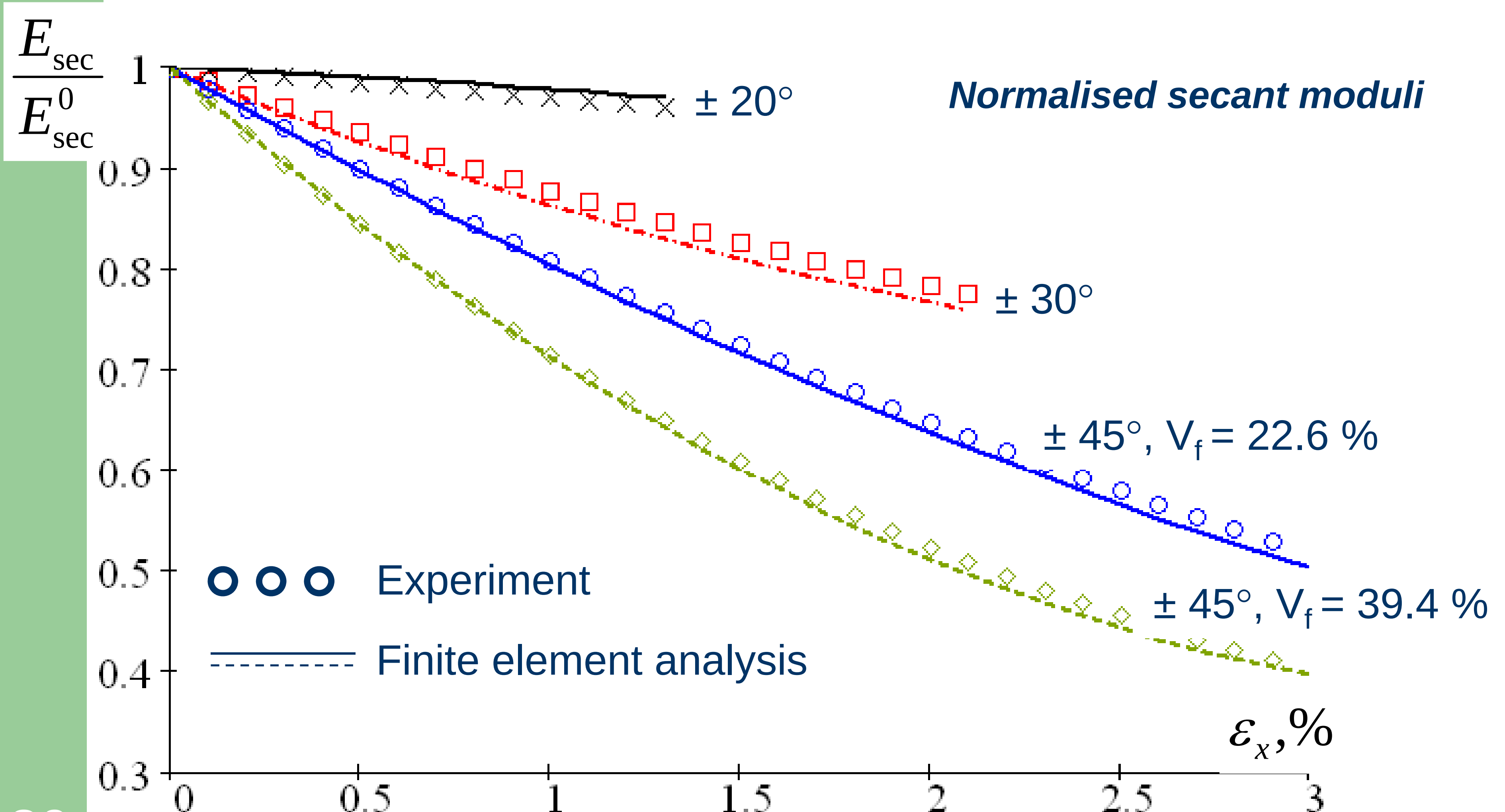
Cracks everywhere

Cracks at the edges

Hence , damage initiation and failure mode are predicted correctly

Degradation: FEA/experiments

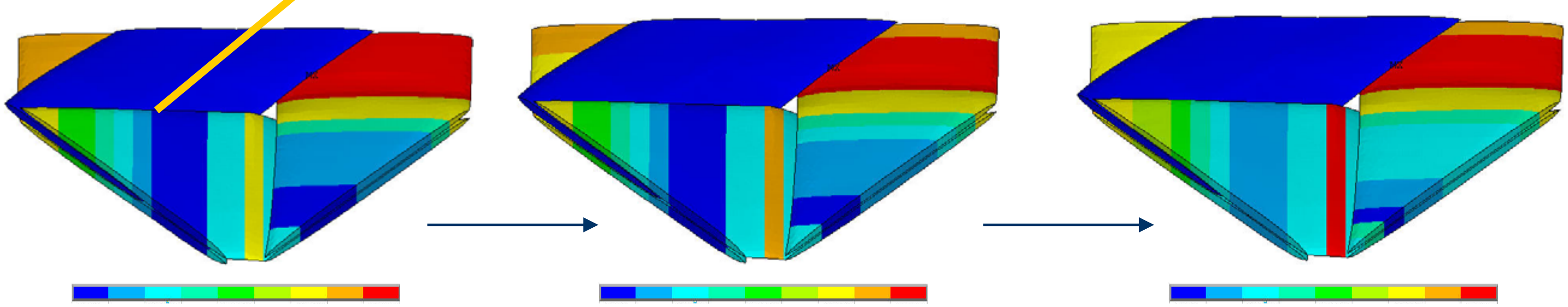
Sheared NCF composite of different ply angles:



Implementation for textile composite

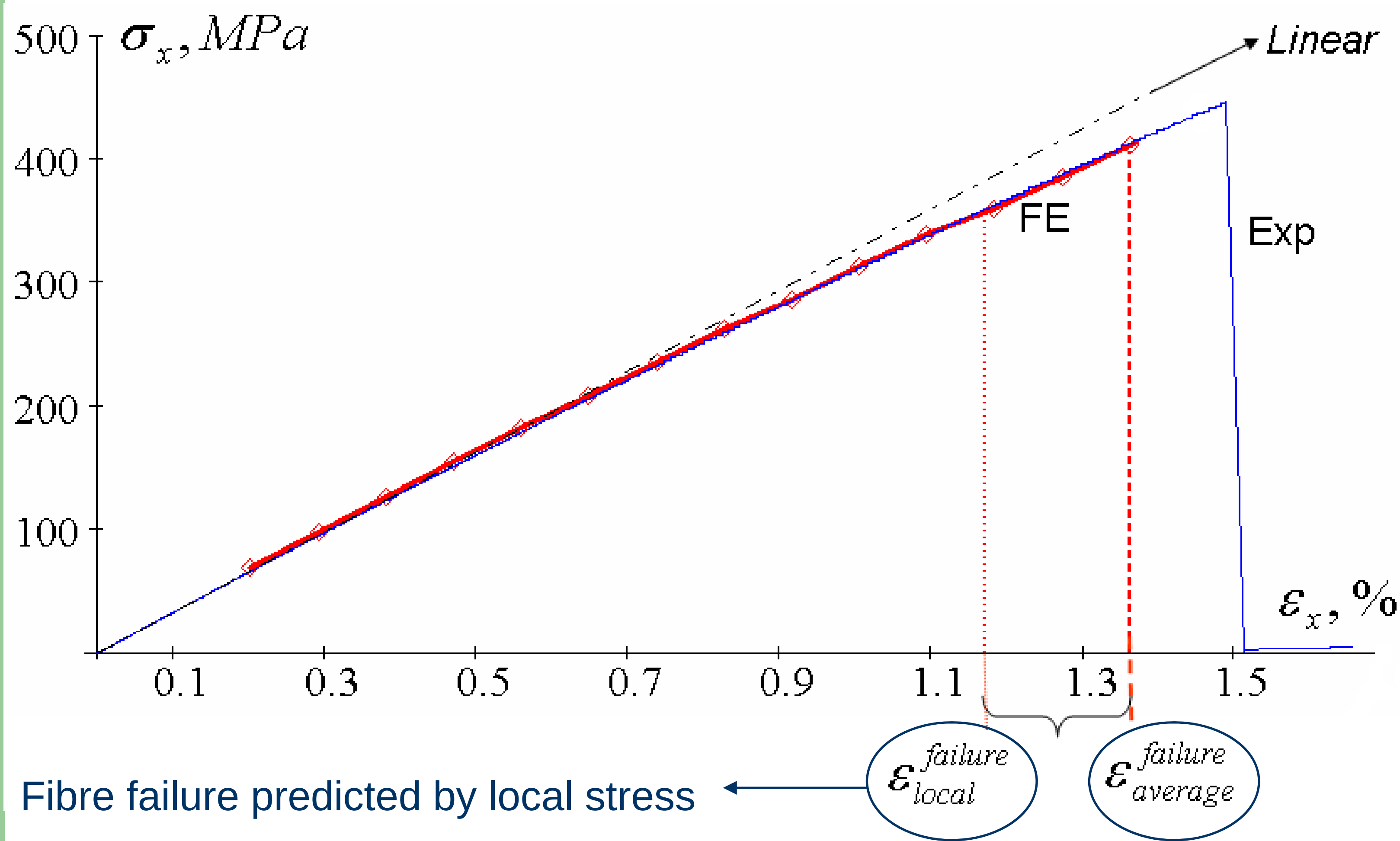
1. Minimum degrading volume is segment with a straight orientation of fibres
2. The average stress over the volume is considered
3. Degradation is assigned to the entire segment
4. Rule of degradation: thermodynamic damage evolution law based on Murakami degradation scheme

Loading direction: tensile test: 3-axial braided



d_{12}	0.07 ÷0.19	0.15÷0.40	0.23÷0.56
$\langle \varepsilon_x \rangle$, %	0.289	0.557	1.004

Prediction for carbon-epoxy braided composite



Fibre failure predicted by local stress

by stress averaged over a segment

Conclusions

1. Local stress distribution due to the resin rich zones is significant
2. Meso-stress = prediction of local damage initiation = reasonable
3. Damage evolution law based on degradation scheme of Murakami
4. Average stress concept can be used: geometrically not less meaningful than the local damage mechanics.
5. Post-critical behaviour of the UD plies – The simple reverse procedure corresponds to the known mechanical assumption
6. A reasonable correspondence with experiment is found for sheared biaxial NCF and braided composite
7. A need to use more architecture and load cases. E.g. where the degradation due to local transverse loading is a dominated mode