Damage modelling of woven composites at micro and meso scales

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1. **Introduction**

2. Homogenization procedure

3. 3D numerical model construction

4. Microcracking analysis and numerical results

5. Conclusions and perspectives
Motivations

Woven composites scale problem

Macro

Meso

Micro
Motivations

Woven composites scale problem

Micro-meso bridge

Objectives

Improving the existing models* in order to take into account of the damage mechanisms at their scales

*Hochard 2010

Using homogenization techniques to create a bridge to pass from the micro-scale to the meso-scale, which is suitable for structural analysis

Modeling the micro damage phenomena with the construction of a proper numerical micro model
Scientific context and objectives

Unidirectional composites

\[ d = f(\rho) \]

\[ E_{Dmicro} = E_{Dmeso} \]

\[ d = f(\rho) \]

Micro

Transverse crack density variable

[Bridge]

Meso

Diffuse damage variable


[Ladevèze 1986, 1992]

[Lubineau and Ladevèze 2008]

Thermodinamic force

Diffuse damage variable evolution law

\[ Y = \langle\langle \frac{\sigma_{12}^2}{2G_{12}(1 - d)^2} \rangle\rangle \]

\[ d = \sup_{t \leq \tau} \left( \frac{< \sqrt{Y} - \sqrt{Y_0}> +}{\sqrt{Y_c} - \sqrt{Y_0}} \right) \]

Damage evolution model introduced for UD composites can be used also to describe woven behavior.
Damage mechanisms in woven composites

On the meso scale the laminate is formed by a series of plies and interfaces.

Ply problem

Interface problem

On the micro scale different damage mechanisms act at the ply or interface level.
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Woven ply homogenization procedure

Micro solution

\[ u = \bar{u} + \tilde{u} \]

\[ \sigma = K \varepsilon (\bar{u} + \tilde{u}) \]

Hypothesis: the problem will be studied locally in the elastic domain

Ply problem: the problem is written in the form of a residual problem which allows us to demonstrate an important property to link the two scales

Find \( \tilde{u} \in U_p \)

\[ \int_{\omega} Tr \left[ K \varepsilon (\bar{u}) \varepsilon (u^*) \right] d\omega + \int_{\omega_E} Tr \left[ (K - \bar{K}) \bar{\varepsilon} \varepsilon (u^*) \right] d\omega = 0 \quad \forall u^* \in U_p \]

Residual stress \( R = (K - \bar{K}) \bar{\varepsilon} \)

The residual problem is auto equilibrated and its impact is local
Woven ply homogenization procedure

Property:
\[
\frac{1}{S} \int_S \Pi \varepsilon \Pi dS = \bar{\varepsilon} \quad \text{over} \quad \omega_E \\
= 0 \quad \text{elsewhere}
\]

The average plane part of micro strain is equal to the meso strain over the woven ply and 0 elsewhere

\[
\int_{\omega} Tr [K \varepsilon^* (\bar{\varepsilon} + \bar{\varepsilon})] d\omega - \int_{\omega_E} Tr [\bar{K} \bar{\varepsilon} \varepsilon^*] d\omega = 0 \quad \forall \bar{u}^* \in U_p
\]

The link between the micro and meso scales is assured by the equivalence between the micro and meso strain energies

\[
E = \int_{\omega} Tr [K (\bar{\varepsilon} + \bar{\varepsilon}) (\bar{\varepsilon} + \bar{\varepsilon})] d\omega = \int_{\omega_E} Tr [[\bar{\sigma}] \bar{\varepsilon}] d\omega_E = \int_{\omega_E} Tr [[\bar{K}] \bar{\varepsilon} \bar{\varepsilon}] d\omega_E
\]

The micro strain energy of the whole cell is equal to the homogenized strain energy of the woven ply

\[
[\bar{\sigma}] = [\bar{K}] \bar{\varepsilon}
\]
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5-harness satin FE model

Optical micrography observations
5H Satin Carbon fibre/Epoxy matrix

GeoTis tool
[Hivet, Boisse 2005]

Satin 3D Geometry

Periodic boundary conditions

Hexaedral compatible meshing
- The yarns are divided in subcells in order to control the number of elements
- A Python script enables us to project the nodes of a yarn in the same position of the corresponding nodes of the yarn in contact

Yarns material modeling
- The yarns are modeled as homogeneous orthotropic elastic solids

[Tagiano, Baranger 2012]
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4. **Microcracking analysis and numerical results**
5. Conclusions and perspectives
Intra-yarn microcracking analysis

Research of high strain energy density zones in transverse yarns: 0/90° loading

\[ e = \frac{1}{2V} \int_V \frac{\sigma_{ij}^2}{E_i} dV \]

\[ \bar{\epsilon}_x = 0.01 \]

The strain energy due to crack opening stress is constant over the transverse yarns.
Intra-yarn microcracking analysis

Introduction of cracks at different locations

The higher the strain energy release rate is, the earlier the crack will appear

The slight difference between cases 1 and 2 leads to the conclusion that cracks in transverse yarns will appear stochastically in the central part of the yarn

Woven composites transverse microcracking behavior is the same as UD composites

Calculation of the strain energy release rate of the whole cell

\[ G = \frac{\Delta E}{A} \]
Intra-yarn microcracking analysis

Calculation of strain energy release rates for new crack formation

Crack appearing in another yarn \( G = 115 \text{ J/m}^2 \)

Crack appearing in the same yarn \( G = 102 \text{ J/m}^2 \)

The area around the existent crack is unloaded and is excluded from the creation of new possible cracks
Intra-yarn microcracking analysis

Microcracking rate \[ \rho = \frac{H}{D} \]
Intra-yarn microcracking analysis

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Microcracking rate \[ \rho = \frac{H}{D} \]

As long as cracks are distant each other the strain energy release rate is constant, when they start interacting, \( G \) starts decreasing.
Intra-yarn microcracking analysis

Strain energy release rate evolution is a function of microcracking rate and strain

\[ G = G(\rho, \varepsilon) \]
\[ G \propto \varepsilon^2 \]

The evolution of the microcracking rate with respect to the imposed strain can be extrapolated from the contour plot of \( G \). The curve is an iso-\( G \) line where

\[ G = G_{\text{crit}} \]

The critical strain energy release rate has to be identified experimentally.
Critical strain energy release rate calculation

Calculation taking into account thermal residual stresses

\( \varepsilon_f \approx 0.006 \)

[Gao, 1999]

\( G_C = 150 \text{J/m}^2 \)

\( \Delta T = -160^\circ C \)

\( \bar{\varepsilon}_x = 0.006 \)
Healthy ply homogenization

\[ \bar{\varepsilon}_{11}, \bar{\varepsilon}_{22} \]

\[ \bar{\varepsilon}_{12} \]

Strain energy density [Nmm]

<table>
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<th>FEM</th>
<th>Experimental</th>
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<td>( E_{xx} = E_{yy} )</td>
<td>59.31</td>
<td>61±1</td>
<td>GPa</td>
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<td>-</td>
<td>-</td>
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<td>( G_{xy} )</td>
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<td>4</td>
<td>GPa</td>
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<tr>
<td>( v_{xy} )</td>
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<td>0.06</td>
<td>-</td>
</tr>
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</table>
Cracked ply homogenization

0/90° loading

Meso damage parameter

\[ d = 1 - \frac{E_{1h}}{E_1} \]

The transverse microcracking phenomenon for 0/90° loading represents a hidden damage that can trigger delamination processes.
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Conclusions

✶ A proper 3D numerical model for a woven microstructure has been built basing on a real material geometry

✶ An homogenization procedure for healthy and cracked woven plies has been set up to link the micro and meso scales

✶ The intra-yarn microcracking scenario has been introduced and it shows the same behavior as UD composites

Perspectives

✶ The damage evolution for +-45° load case will be studied, a local intra-yarn fiber-matrix debonding model will be introduced in the yarns to simulate diffuse damage scenario

✶ The interface problem will be introduced in order to complete the micro-meso bridge model and to study delamination
  - Firstly micro delaminations will be introduced inside the ply problem at yarn interfaces
  - Inter ply delamination will be studied analysing the behavior of cohesive interface between two cracked plies
Thank you for your attention