Composite Materials 261 and 262

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11. LS-DYNA Forum 2012, 9. - 10. Oktober 2012, Ulm

Outline

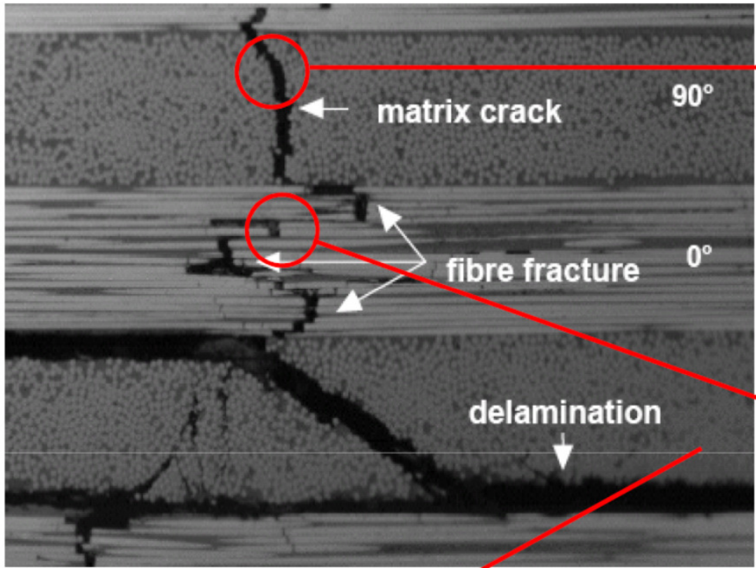
- Introduction
  - failure mechanisms / modeling possibilities

- Material models 261 and 262 for intralaminar failure
  - *MAT_LAMINATED_FRACTURE_DAIMLER_PINHO
  - *MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO
  - summary and comparison

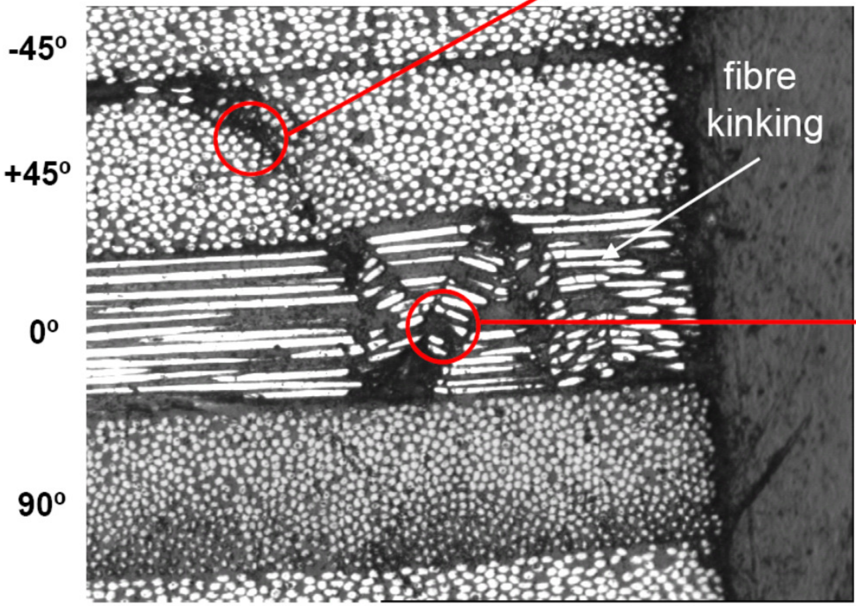
- Preliminary results
  - three point bending of flat specimen / three point bending of a hat profile / shear specimen / drop tower test

- Summary and Outlook

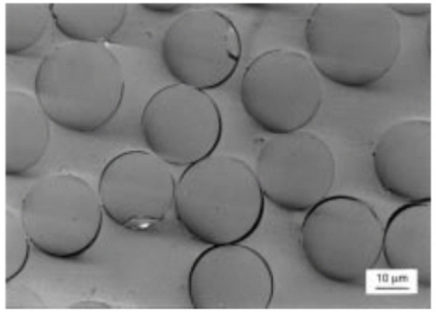
Introduction – failure mechanisms in fiber reinforced composites

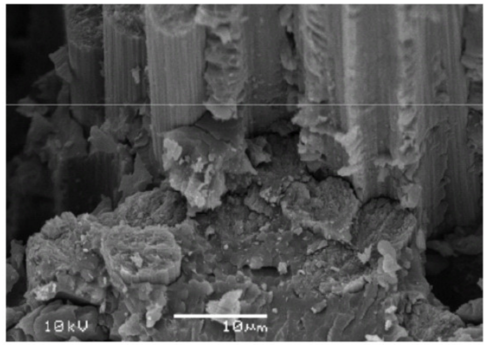


R Olson, Imperial College London

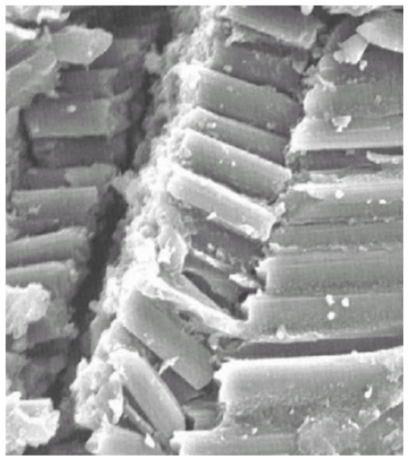


PP Camanho, PhD thesis, Imperial College London





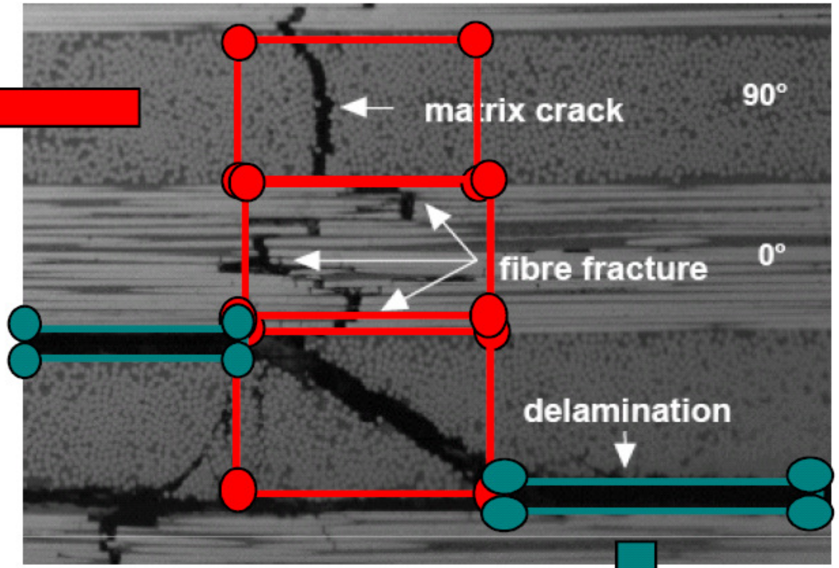
ST Pinho, PhD thesis, Imperial College London

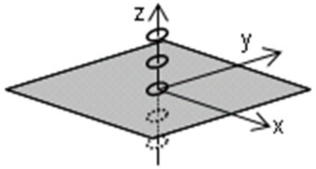


C Soutis, University of Sheffield

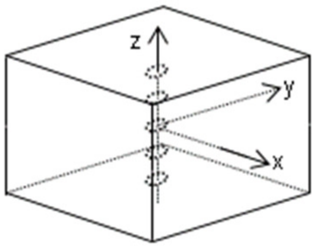
Introduction – modeling possibilities

- **intralaminar**
  - element: layered (thin/thick) shells
    one solid element per ply
  - material: plasticity / damage models

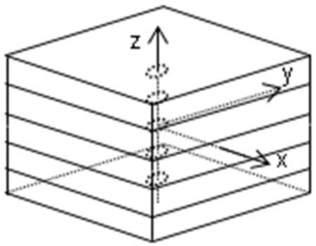




layered thin shell elements
+ numerical „cheap“ (thickness does not influence the critical time step size)
+ combination of single layers to sub-laminates
- no stresses in thickness dir. (no delamination)



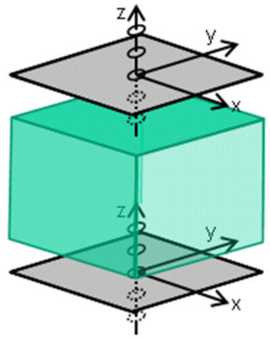
layered thick shell elements
+ 3D stress state
+ combination of single layers to sub-laminates
- thickness influences the critical time step size



solid elements
+ 3D stress state
- one element for every single layer (no layering)
  → numerical „expensive“

- **interlaminar** (delamination)
  - cohesive elements
  - tiebreak contacts

stacked shells

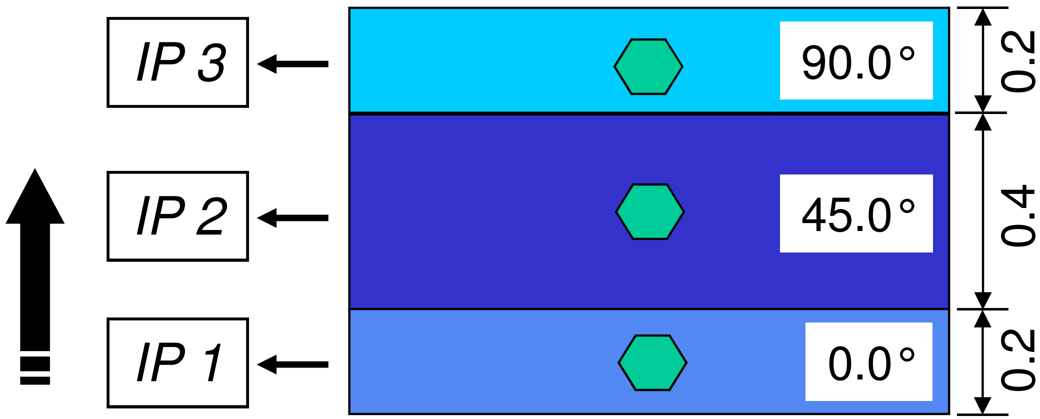


Introduction – layered thin shell definition with *PART_COMPOSITE

- no *SECTION_SHELL-keyword card needed
- different material models allowed

```
*PART_COMPOSITE
Composite Lay up (Version 971)
$--------1---------2---------3---------4---------5---------6---------7---------8
$      PID|   ELFORM|      SHRF|      NLOC|     MAREA|      HGID|     ADOPT|
        28         2        0.0        0.0        0.0          0          0
$     MID1|   THICK1|      BETA|                 MID2|    THICK2|     BETA2|
         1       0.2        0.0                     2        0.4       45.0
$     MID3|   THICK3|      BETA|                 MID4|    THICK4|     BETA4|
         3       0.2       90.0
```

Listing of integration points begins from the bottom

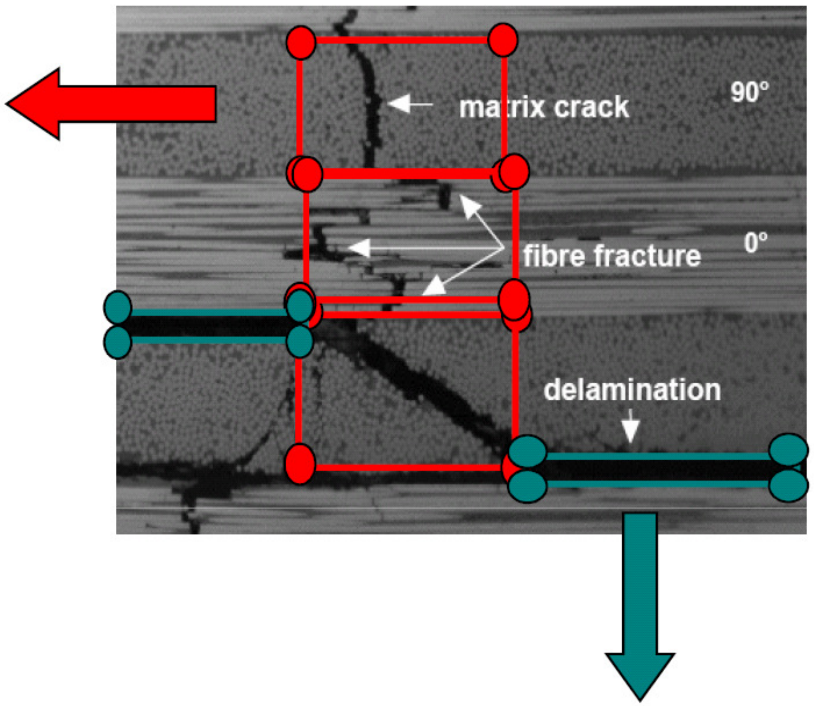


Material models for intralaminar failure

***MAT_261:** [1]
***MAT_LAMINATED_FRACTURE_DAIMLER_PINHO**

***MAT_262:** [2]
***MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO**

(Development together with Daimler AG)



[1] Pinho, S.T., Iannucci, L.; Robinson, P.: “Physically-based failure models and criteria for laminated fiber-reinforced composites with emphasis on fiber kinking: Part I – Development & Part II – FE implementation”, Composites: Part A 37, 2006

[2] Maimí, P., Camanho, P.P., Mayugo, J.A., Dávila, D.G.: “A continuum damage model for composite laminates: Part I – Constitutive model & Part II – Computational implementation and validation”, Mechanics of Materials 39, 2007

***MAT_261** (*MAT_LAMINATED_FRACTURE_DAIMLER_PINHO):

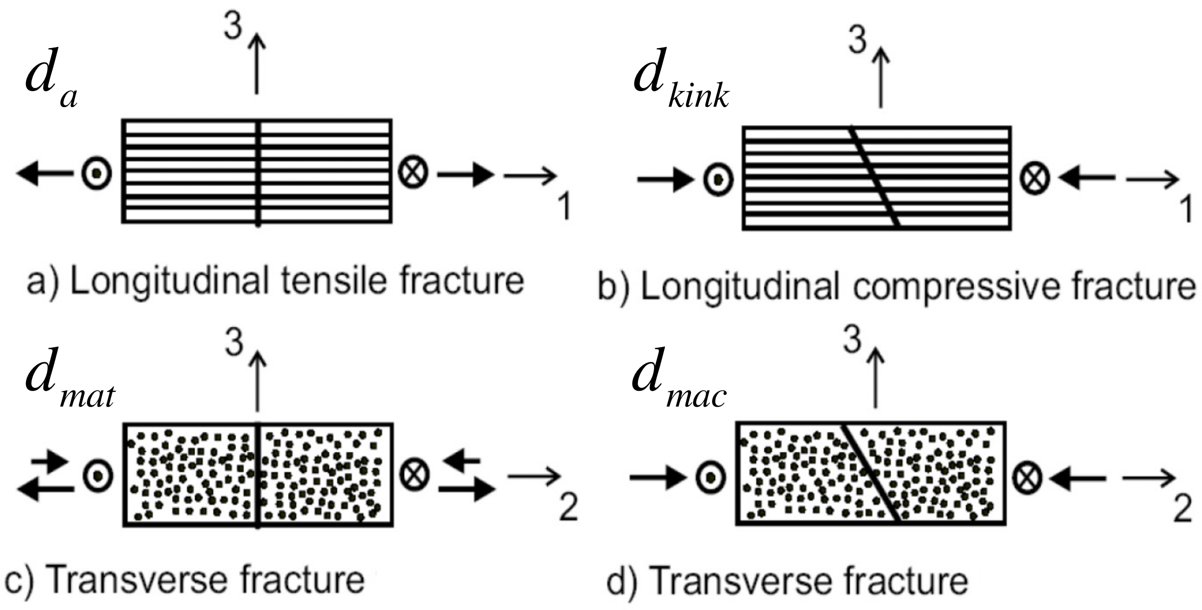
- constitutive law

$$\hat{\sigma} = (1 - d)\tilde{\sigma}$$

4 damage parameter

$$d_{mat};\ d_{mac};\ d_{kink};\ d_{a}$$

- 4 failure criteria



a) Longitudinal tensile fracture

b) Longitudinal compressive fracture

c) Transverse fracture

d) Transverse fracture

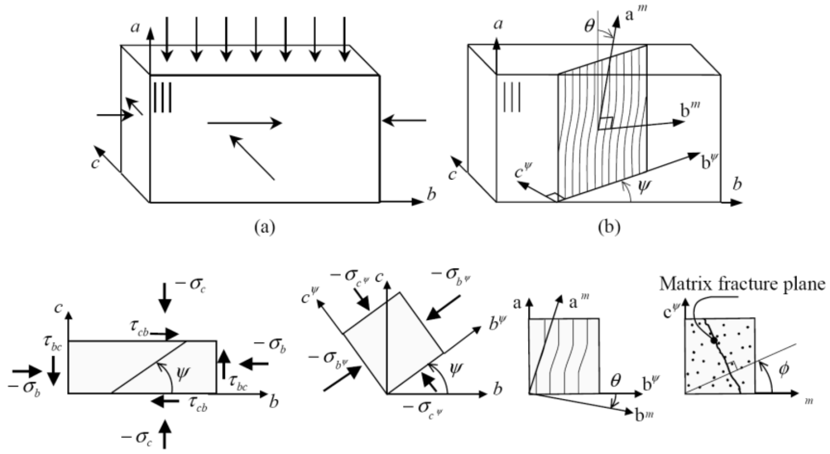
*MAT_261 (*MAT_..._PINHO):

fiber tension (maximum stress)

$$f_a = \frac{\sigma_a}{X_t} = 1$$

fiber compression (3D-kinking model)
(interaction, transformation to fracture plane - 3D)

$$f_{kink} = \begin{cases} \left(\frac{\tau_T}{S_T - \mu_T \sigma_n}\right)^2 + \left(\frac{\tau_L}{S_L - \mu_L \sigma_n}\right)^2 = 1 & if \quad \sigma_{b^m} \le 0 \\ \left(\frac{\sigma_n}{Y_T}\right)^2 + \left(\frac{\tau_T}{S_T}\right)^2 + \left(\frac{\tau_L}{S_L}\right)^2 = 1 & if \quad \sigma_{b^m} > 0 \end{cases}$$



$$\sigma_n = \frac{\tilde{\sigma}_{b^m} + \tilde{\sigma}_{c^\psi}}{2} + \frac{\tilde{\sigma}_{b^m} - \tilde{\sigma}_{c^\psi}}{2}\cos(2\phi) + \tilde{\sigma}_{b^m c^\psi}\sin(2\phi)$$

$$\tau_T = -\frac{\tilde{\sigma}_{b^m} - \tilde{\sigma}_{c^\psi}}{2}\sin(2\phi) + \tilde{\sigma}_{b^m c^\psi}\cos(2\phi)$$

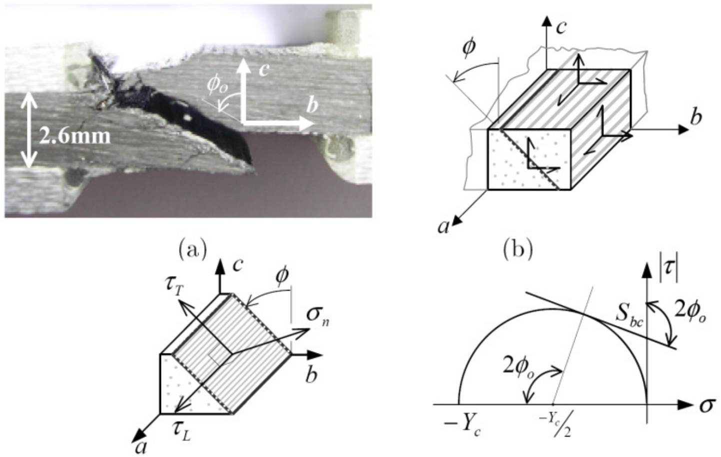
$$\tau_L = \tilde{\sigma}_{a^m b^m}\cos(\phi) + \tilde{\sigma}_{c^\psi a^m}\sin(\phi)$$

matrix failure: transverse tension
(transformation to fracture plane)

$$f_{mat} = \left(\frac{\sigma_n}{Y_t}\right)^2 + \left(\frac{\tau_T}{S_T}\right)^2 + \left(\frac{\tau_L}{S_L}\right)^2 = 1$$

matrix failure: transverse compression/shear
(Mohr-Coulomb: Puck/Schürmann)

$$f_{mac} = \left(\frac{\tau_T}{S_T - \mu_T \sigma_n}\right)^2 + \left(\frac{\tau_L}{S_L - \mu_L \sigma_n}\right)^2 = 1$$



ϕ_0 : *fracture plane for pure compression*

ϕ : *fracture plane under general loading*

*MAT_261 (*MAT_LAMINATED_FRACTURE_DAIMLER_PINHO):

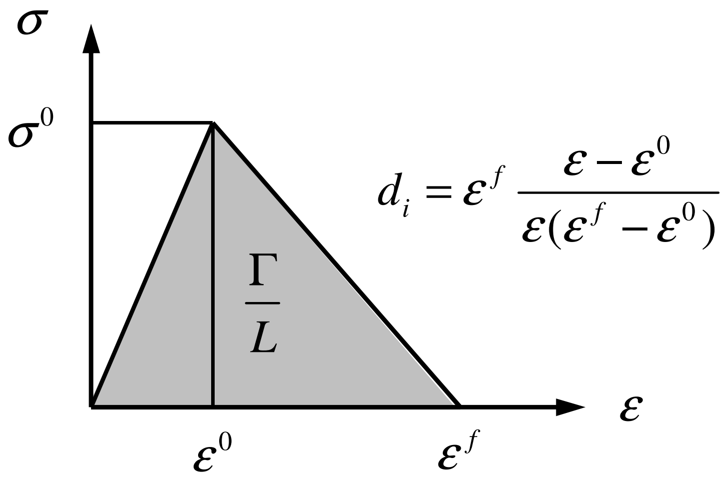
- linear damage laws

$$\hat{\sigma} = (1-d_a)[\tilde{\sigma}_{11}, \tilde{\sigma}_{22}, \tilde{\sigma}_{12}, \tilde{\sigma}_{23}, \tilde{\sigma}_{31}]$$

$$\hat{\sigma} = (1-d_{kink})[\tilde{\sigma}_{11}, \tilde{\sigma}_{22}, \tilde{\sigma}_{12}, \tilde{\sigma}_{23}, \tilde{\sigma}_{31}]$$

$$\hat{\sigma} = (1-d_{mat})[\tilde{\sigma}_{22}, \tilde{\sigma}_{12}, \tilde{\sigma}_{23}, \tilde{\sigma}_{31}]$$

$$\hat{\sigma} = (1-d_{mac})[\tilde{\sigma}_{22}, \tilde{\sigma}_{12}, \tilde{\sigma}_{23}, \tilde{\sigma}_{31}]$$



$\Gamma_a, \Gamma_{kink}, \Gamma_b, \Gamma_T, \Gamma_L$:

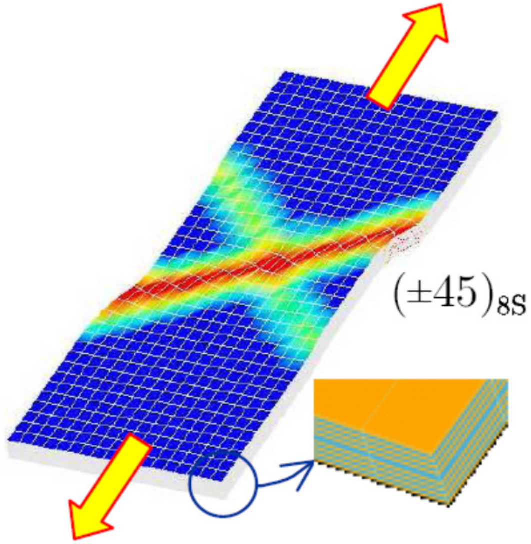
fracture toughness from: CT, CC, 4-point bending, mode II interlaminar fracture (T,L)

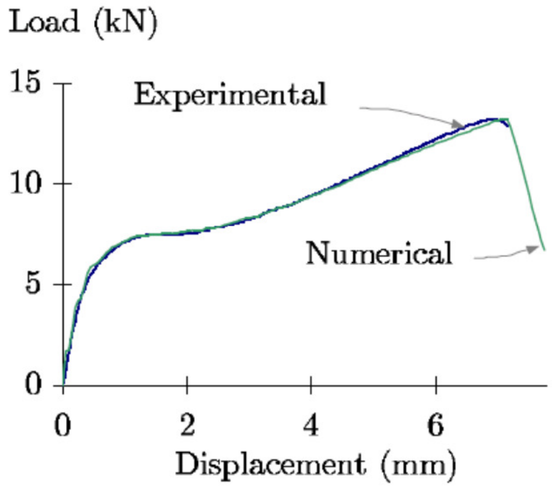
L:

internal (characteristic) length for objectivity (localization!)

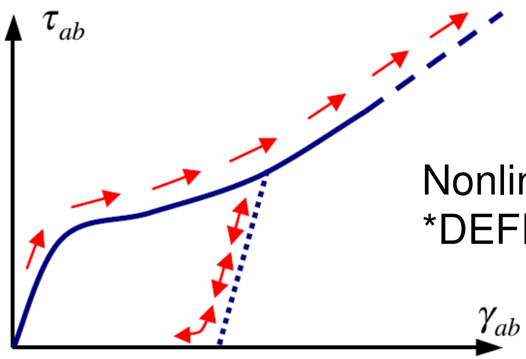
*MAT_261 (*MAT_LAMINATED_FRACTURE_DAIMLER_PINHO):

- in-plane shear behavior

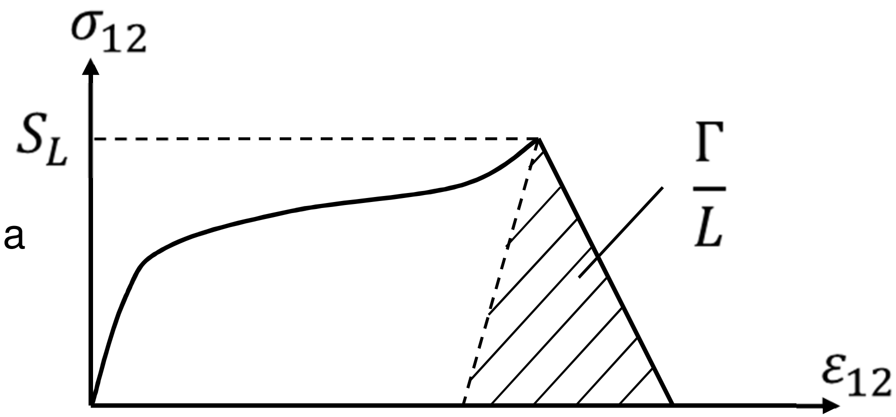




1D plasticity formulation with combined isotropic/kinematic hardening – coupled with linear damage model



Nonlinearity defined via *DEFINE_CURVE



*MAT_262 (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):

- constitutive relation

$$\boldsymbol{\varepsilon} = \boldsymbol{H} : \boldsymbol{\sigma} \quad \rightarrow \quad \boldsymbol{\sigma} = \boldsymbol{H}^{-1} : \boldsymbol{\varepsilon}$$

$$H = \begin{bmatrix} \frac{1}{(1-d_1)E_1} & -\frac{\nu_{21}}{E_2} & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{(1-d_2)E_2} & 0 \\ 0 & 0 & \frac{1}{(1-d_6)G_{12}} \end{bmatrix}$$

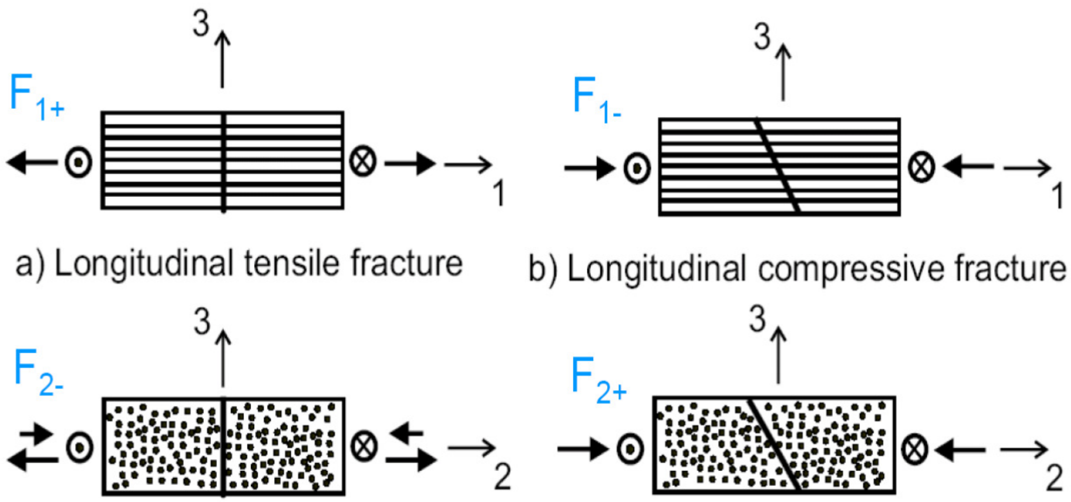
5 damage variables

$$d_{1-}(r_{1-}, r_{1+});\ d_{1+}(r_{1+});\ d_{2-}(r_{2-});\ d_{2+}(r_{2+});\ d_6(r_{2+})$$

$$d_1 = d_{1+}\frac{\langle \sigma_{11} \rangle}{|\sigma_{11}|} + d_{1-}\frac{\langle -\sigma_{11} \rangle}{|\sigma_{11}|}$$

$$d_2 = d_{2+}\frac{\langle \sigma_{22} \rangle}{|\sigma_{22}|} + d_{2-}\frac{\langle -\sigma_{22} \rangle}{|\sigma_{22}|}$$

- 4 failure criteria (LaRC03/04)



a) Longitudinal tensile fracture b) Longitudinal compressive fracture

c) Transverse fracture with α=0° d) Transverse fracture with α=53°

damage activation functions

$$F_{1-} = \phi_{1-} - r_{1-} \leq 0$$

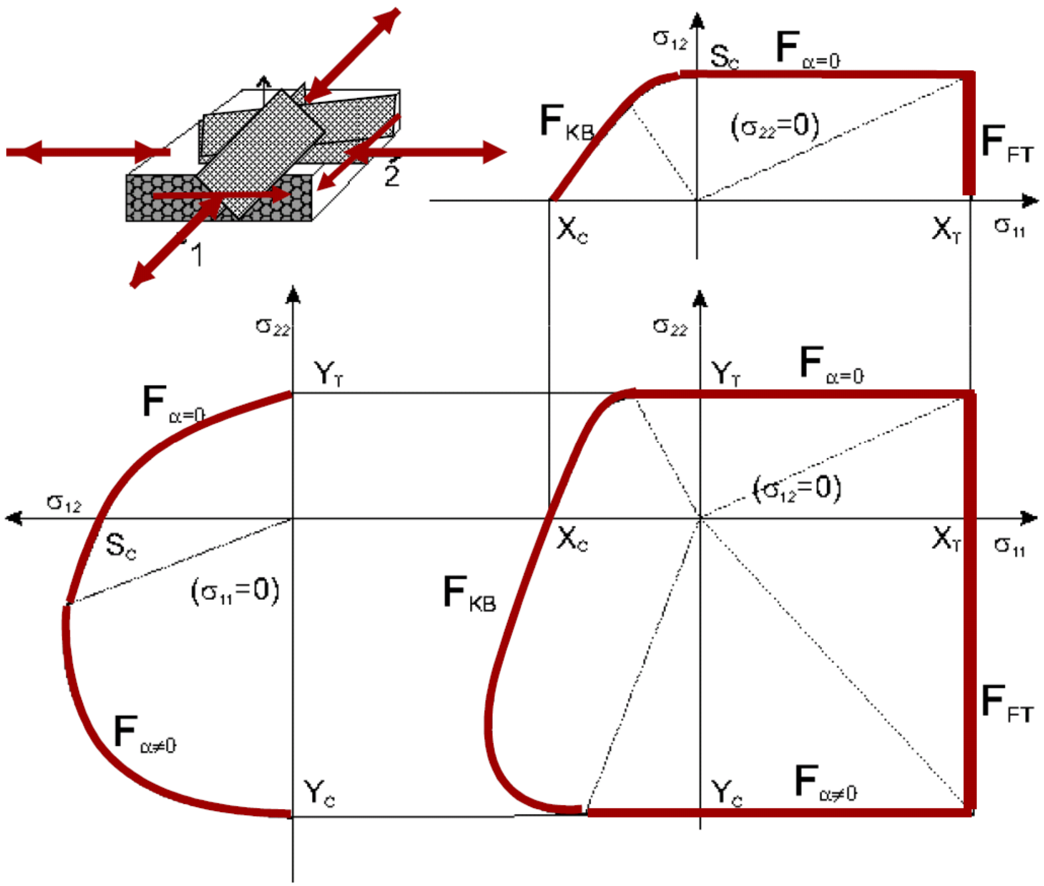
$$F_{2-} = \phi_{2-} - r_{2-} \leq 0$$

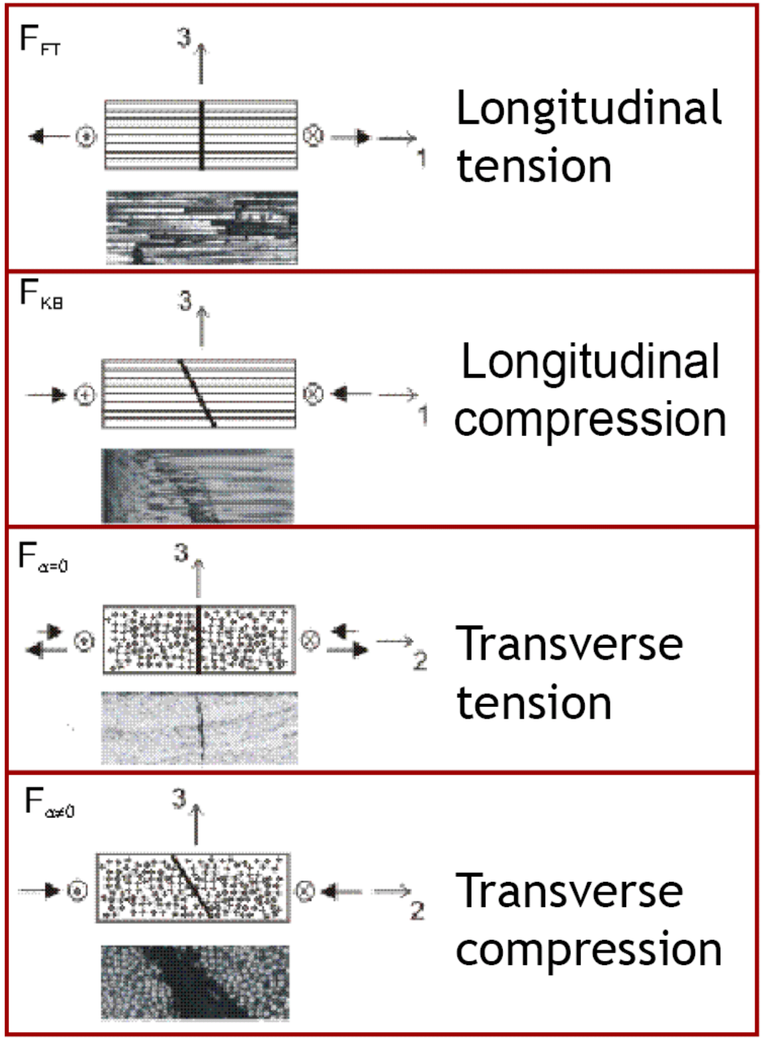
$$F_{1+} = \phi_{1+} - r_{1+} \leq 0$$

$$F_{2+} = \phi_{2+} - r_{2+} \leq 0$$

*MAT_262 (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):

- failure surface (assembly of 4 sub-surfaces)





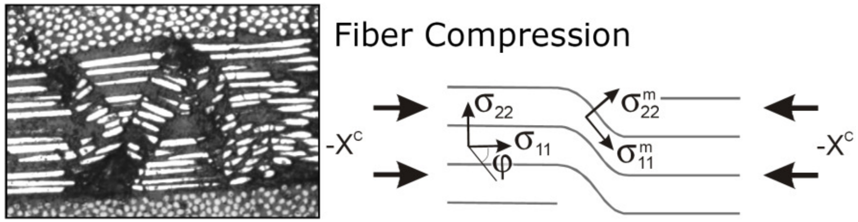
*MAT_262 (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):

fiber tension (maximum strain – LaRC04)

$$\phi_{1+} = \left(\frac{\tilde{\sigma}_{11} - \nu_{12}\tilde{\sigma}_{12}}{X_T}\right)^2$$

fiber compression (LaRC03)
(transformation to fracture plane - 2D)

$$\phi_{1-} = \left(\frac{\left\langle \left|\tilde{\sigma}_{12}^{m}\right| + \mu_L \tilde{\sigma}_{22}^{m} \right\rangle}{S_L}\right)^2$$



$$\tilde{\sigma}_{12}^{m} = -\frac{\tilde{\sigma}_{11} - \tilde{\sigma}_{22}}{2}\sin(2\varphi^C) + \left|\tilde{\sigma}_{12}\right|\cos(2\varphi^C)$$

$$\tilde{\sigma}_{22}^{m} = \frac{\tilde{\sigma}_{11} + \tilde{\sigma}_{22}}{2} - \frac{\tilde{\sigma}_{11} - \tilde{\sigma}_{22}}{2}\cos(2\varphi^C) - \left|\tilde{\sigma}_{12}\right|\sin(2\varphi^C)$$

matrix failure: transverse tension (LaRC04)
(assumption: crack perpendicular to mid-surface)

$$\phi_{2+} = (1-g)\frac{\tilde{\sigma}_{22}}{Y_T} + \left(\frac{\tilde{\sigma}_{22}}{Y_T}\right)^2 + \left(\frac{\tilde{\sigma}_{12}}{S_L}\right)^2 \qquad (\tilde{\sigma}_{22} \geq 0)$$

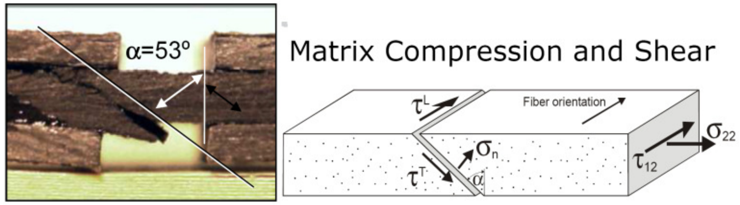
(in-plane shear & transverse tension)

$$\phi_{2+} = \left(\frac{\left\langle \left|\tilde{\sigma}_{12}\right| + \mu_L \tilde{\sigma}_{22} \right\rangle}{S_L}\right)^2 \qquad (\tilde{\sigma}_{22} < 0)$$

(in-plane shear & small transverse compression)

matrix failure: transverse compression/shear (LaRC04)
(transformation to fracture plane)

$$\phi_{2-} = \left(\frac{\tau_T^{eff}}{S_T}\right)^2 + \left(\frac{\tau_L^{eff}}{S_L}\right)^2$$



$$\tau_T^{eff} = \left\langle -\tilde{\sigma}_{22}\cos(\alpha_0)\left[\sin(\alpha_0) - \mu_T\cos(\alpha_0)\cos(\theta)\right]\right\rangle$$

$$\tau_L^{eff} = \left\langle \cos(\alpha_0)\left[\left|\tilde{\sigma}_{12}\right| + \mu_L\tilde{\sigma}_{22}\cos(\alpha_0)\sin(\theta)\right]\right\rangle$$

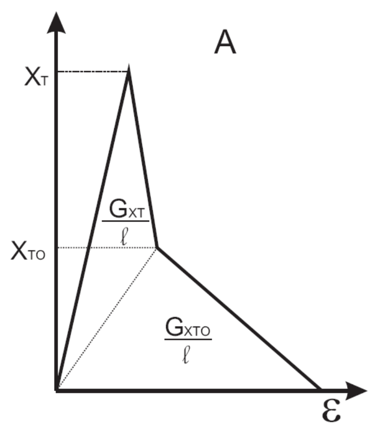
***MAT_262** (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):

- evolution of threshold (internal) variables $\left(r \in [1 \rightarrow \infty]\right)$

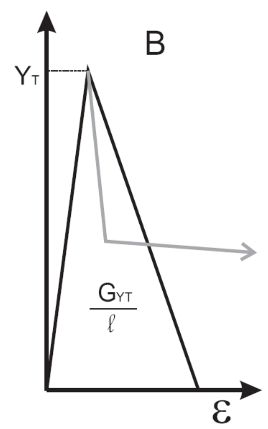
compression:	$r_{1-/2-}^{n+1} = \max\left\{1, r_{1-/2-}^{n}, \phi_{1-/2-}^{n+1}\right\}$
tension:	$r_{1+/2+}^{n+1} = \max\left\{1, r_{1+/2+}^{n}, r_{1-/2-}^{n+1}, \phi_{1+/2+}^{n+1}\right\}$

no damage due to crack (tension); crack closure

- evolution of damage variables $\left(d \in [0 \rightarrow 1]\right)$

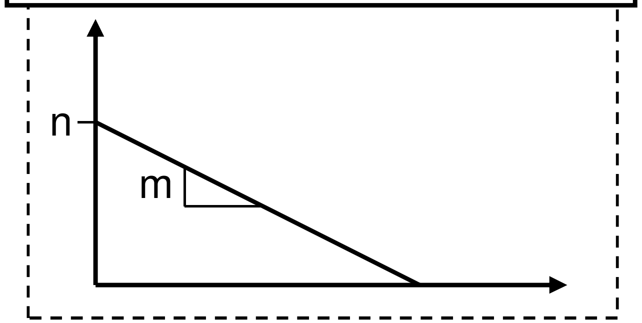


bi-linear in fiber direction



linear in transverse direction

$$d(r) = 1 - \frac{m(X,G)}{E} - \frac{n(X,m)}{E\varepsilon(r)}$$

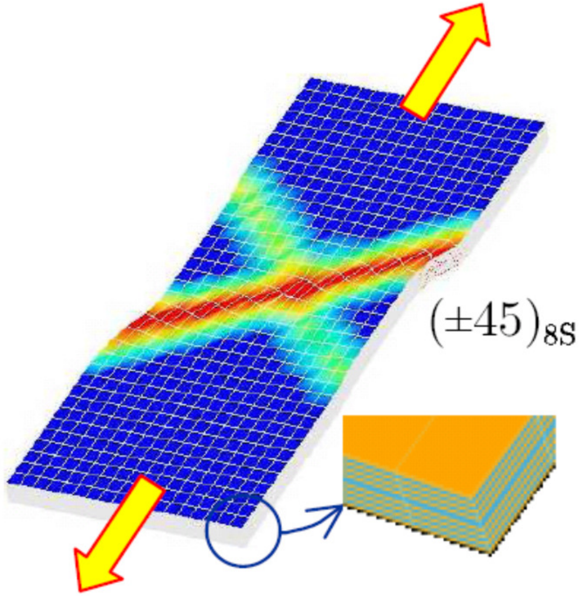


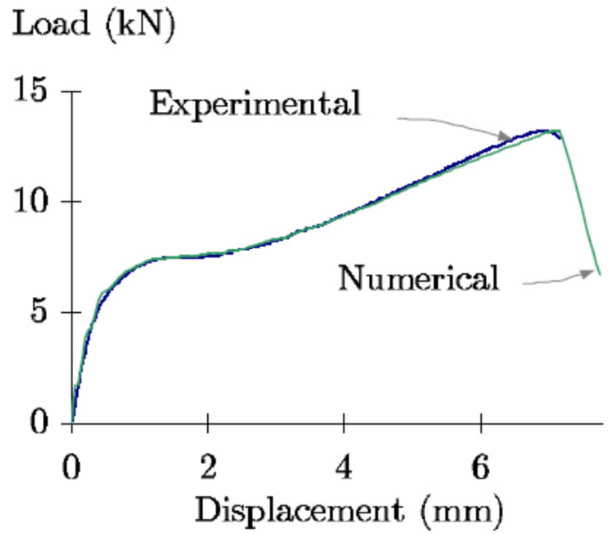
$G_{XT}, G_{XC}, G_{YT}, G_{YC}, G_{SL}$

fracture toughness from: CT, CC, DCB, - , 4-ENF

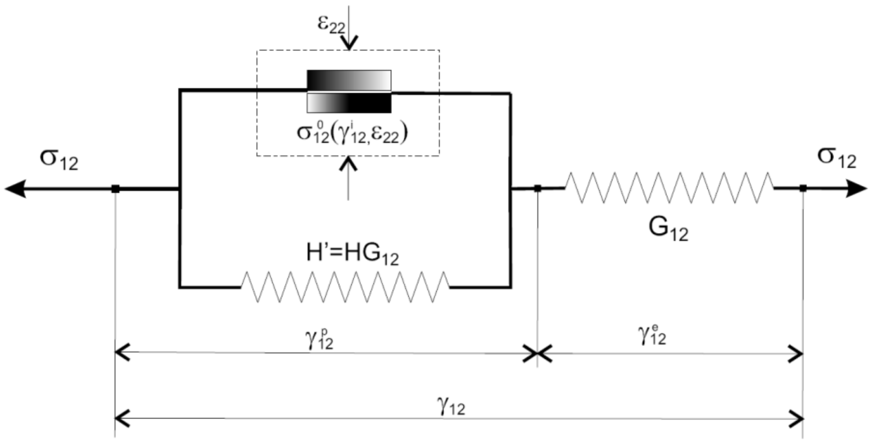
ℓ : internal (characteristic) length for objectivity (lokalization!)

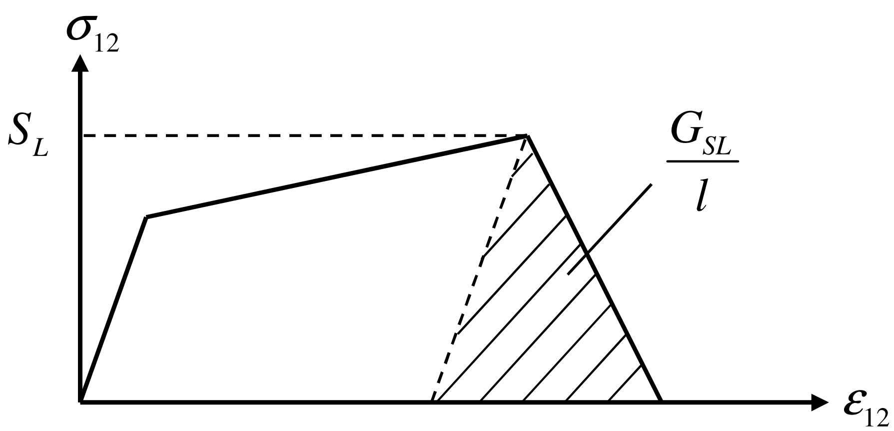
*MAT_262 (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):





1D elasto-plastic formulation with combined iso/kin hardening – coupled to a linear damage evolution law





***MAT_261** (Pinho)	***MAT_262** (Camanho)
failure criterion may use 3D-stress state	failure criterion based on plane stress assumption
fiber tension	
maximum stress criterion	maximum strain criterion
fiber compression	
complex 3D-fiber kinking model, expensive search for controlling fracture plane	use constant fiber misalignment angle based on shear and longitudinal compressive strength
matrix failure: transverse tension	
search for controlling fracture plane	assume perpendicular fracture plane
matrix failure: transverse compression/shear	
search for controlling fracture plane	assume constant fracture plane angle (i.e. 53)
in-plane shear treatment	
1D-plasticity model with combined (iso/kin) hardening based on *DEFINE_CURVE	1D-plasticity model with combined (iso/kin) linear hardening
damage evolution	
linear damage based on fracture toughness	bi-/linear damage based on fracture toughness

Material Models in LS-DYNA (Intralaminar)

***MAT_261: (*MAT_LAMINATED_FRACTURE_DAIMLER_PINHO)** (together with Daimler AG)

- ✓ solid, shell, tshell (3,5)
- ✓ linear elastic orthotropic
- ✓ coupled failure criteria (plane stress) – fracture plane: fiber tens./compr., matrix tens./compr.
- ✓ complex 3D fiber kinking model
- ✓ 1D plasticity formulation for in-plane shear
- ✓ linear damage evolution based on fracture toughness

Not yet available!
(validation)

S.T. Pinho, L. Iannucci, P.Robinson:
Physically-based failure models and criteria for laminated fibre-reinforced composites with emphasis on fibre kinking:
Part I: Development & Part II: FE implementation, Composites: Part A 37 (2006) 63-73 & 766-777

***MAT_262: (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO)** (together with Daimler AG)

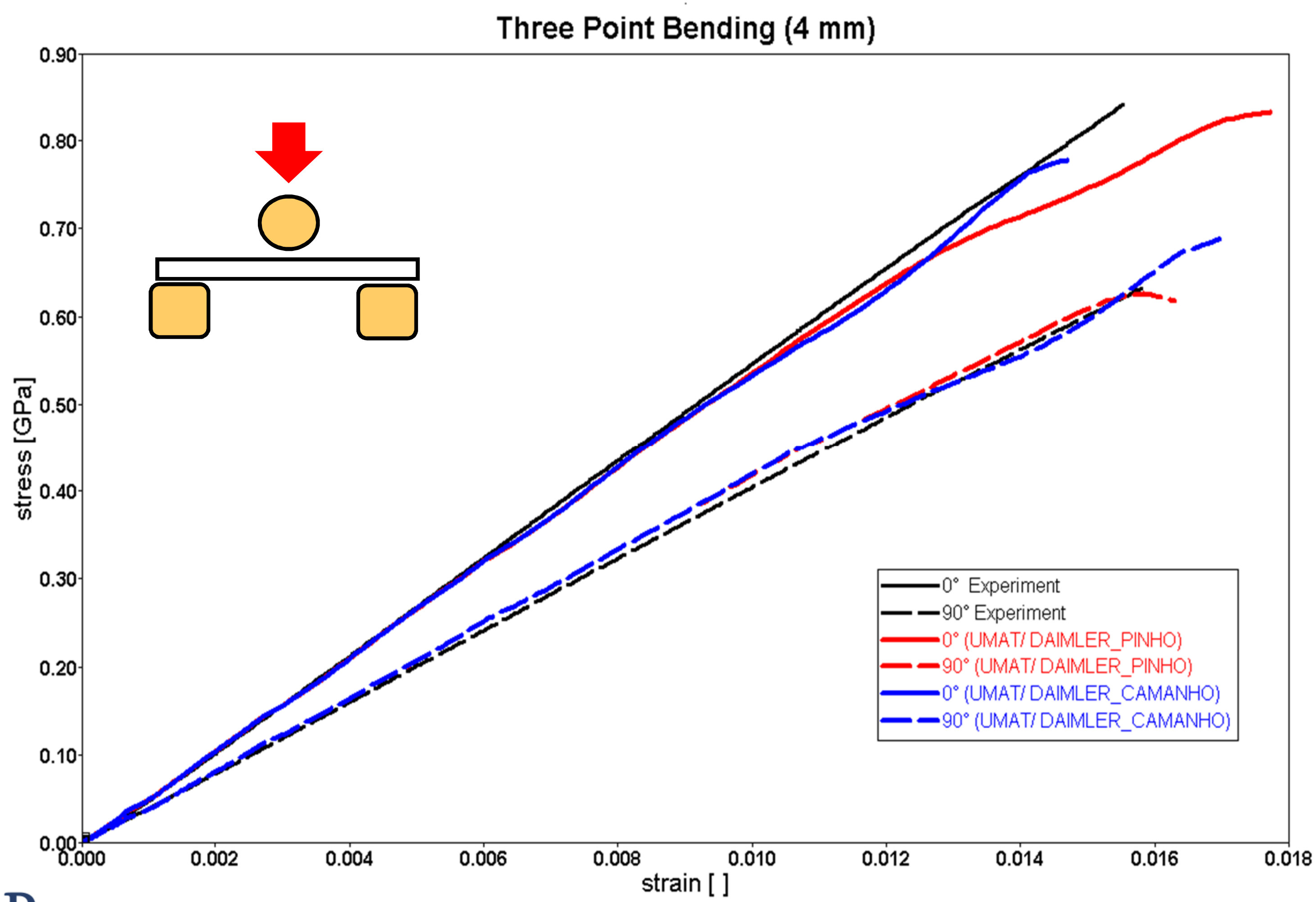
- ✓ solid, shell, tshell (3,5)
- ✓ linear elastic orthotropic
- ✓ coupled failure criteria (plane stress) – fracture plane
- ✓ 1D plasticity formulation for in-plane shear
- ✓ bi-linear damage evolution based on fracture toughness

Not yet available!
(validation)

P. MaimÍ, P.P. Camanho, J.A. Mayugo, C.G. Dávila:
A continuum damage model for composite laminates:
Part I: Constitutive model & Part II: Computational implementation and validation, Mechanics of materials 39 (2007) 897-908 & 909-919

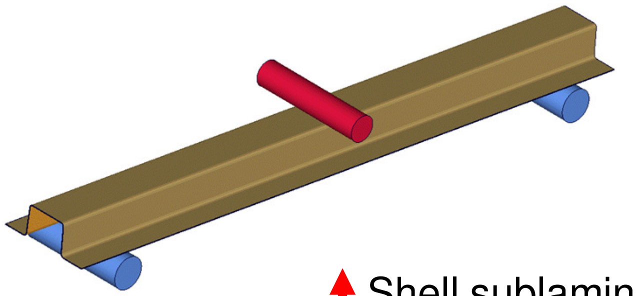
Preliminary results – three point bending of flat specimen

- single shell with a thickness of 4mm / carbon fibers in epoxy resin
  - [0]$_{5s}$ (fibers in longitudinal direction of the plate)
  - [90]$_{5s}$ (fibers in transverse direction of the plate)

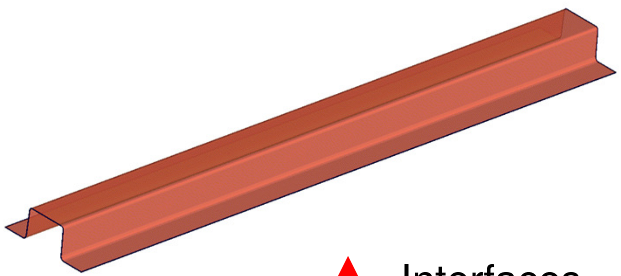


Preliminary results – three point bending of a hat profile

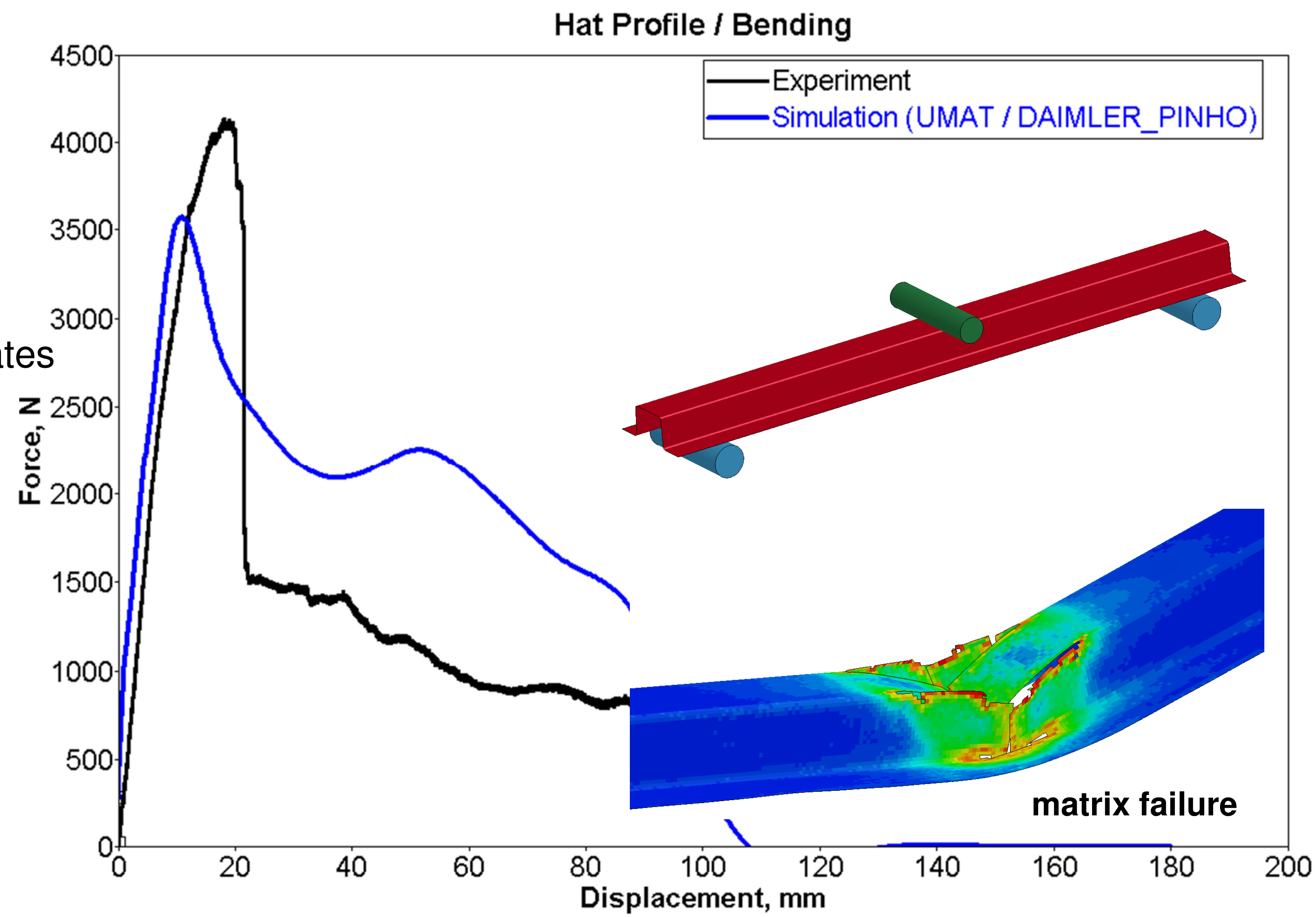
- single shell with a thickness of 2mm / carbon fibers in epoxy resin
  - [90 /0 /45 /-45 /0 /90 /-45 /45 /0 /90]



Shell sublaminates
Local failure



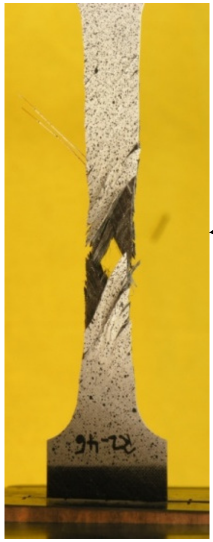
Interfaces
Local failure

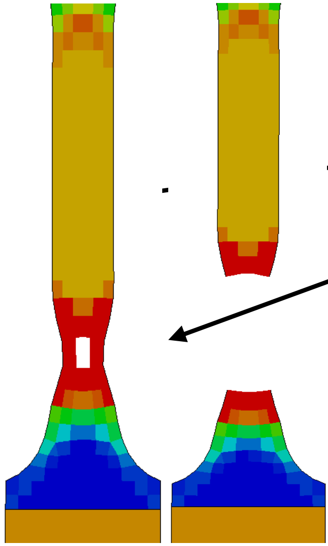


DAIMLER
Universidade do Porto FEUP Faculdade de Engenharia

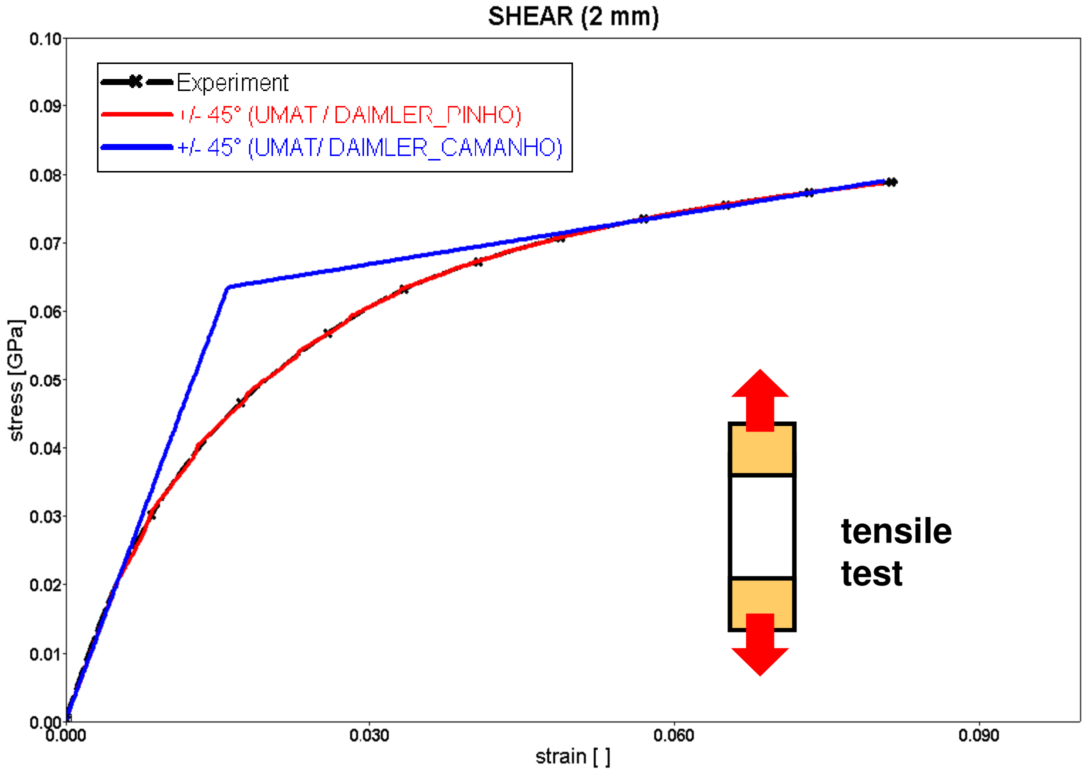
Preliminary results – shear specimen

- single shell with a thickness of 2mm / carbon fibers in epoxy resin
  - [45 /-45]$_{3S}$


Experiment


Simulation

Shear plasticity



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Summary

- two continuum damage models implemented into LS-DYNA
  - advanced, coupled failure surfaces (transformation to fracture plane)
  - bi-linear/linear damage evolution laws (based on fracture toughness)
  - 1D elasto-plastic formulation for in-plane shear non-linearity

- preliminary results
  - material models able to represent general behavior, especially non-linearity in shear

Outlook

- many detailed numerical studies necessary for further improvements
  - comparison and parameter studies with experiments
  - different element formulations and modeling techniques (stacked shells)

Acknowledgement

- Thank for technical support to:
  Prof. Pedro Camanho, Dr. Pere Maimí & Dr. Silvestre Pinho

Thank you!