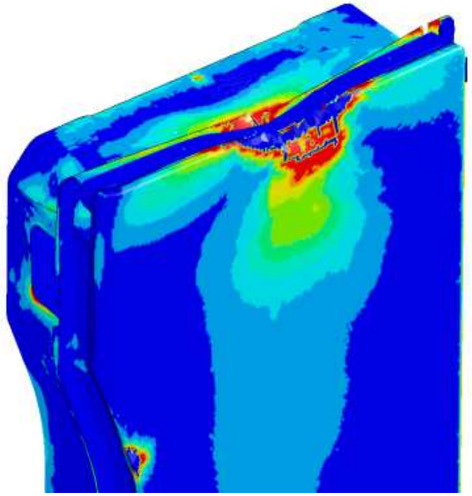
Neue Materialmodelle für Composites in LS-DYNA



Stefan Hartmann

DYNAmore GmbH, Stuttgart

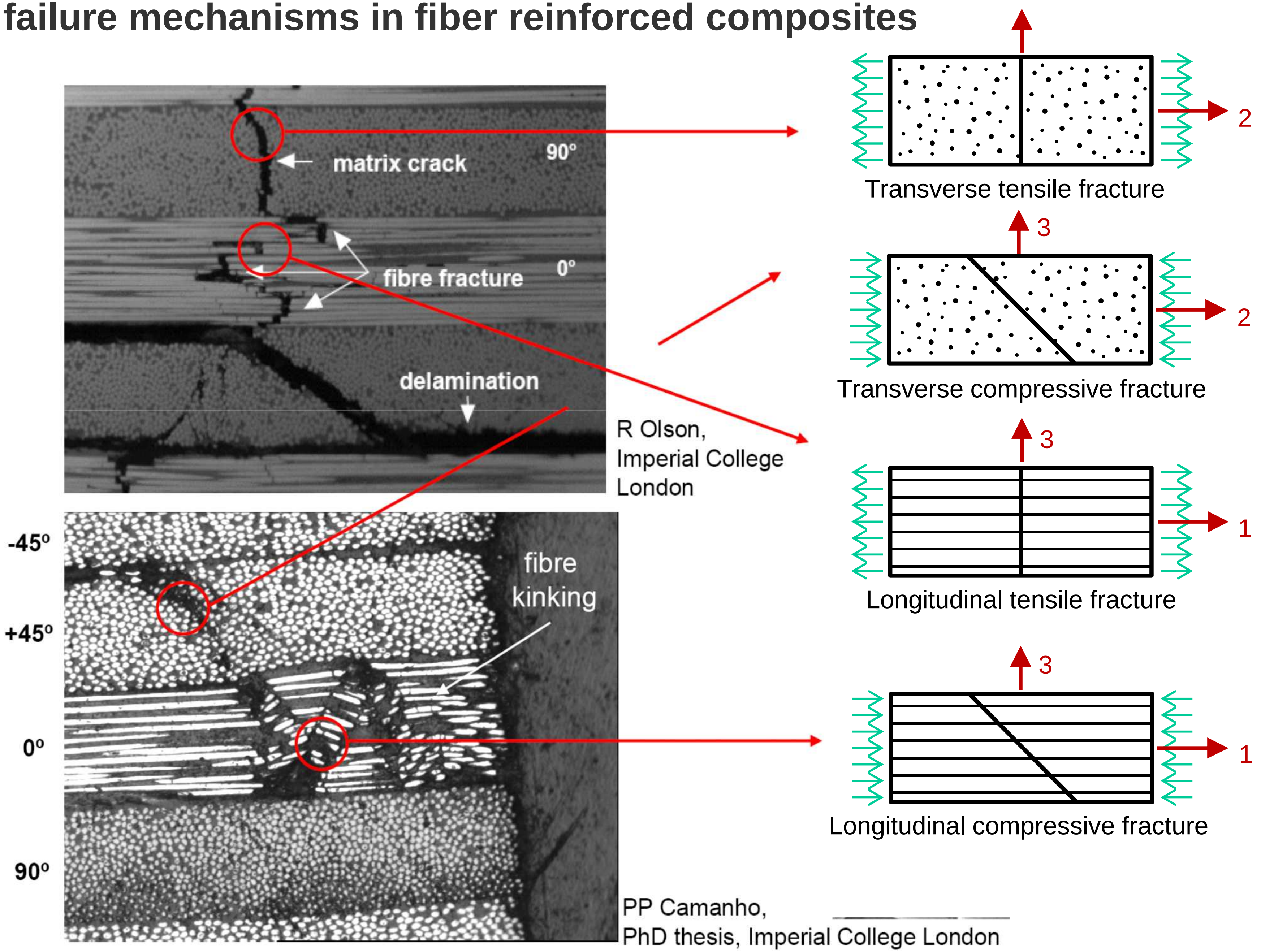
Infotag:

Composite Berechnung mit LS-DYNA, 17. April 2013, Stuttgart

Outline

- Introduction
  - failure mechanisms / modeling possibilities / layer definition / remarks
- Material models for intralaminar failure
  - *MAT_LAMINATED_FRACTURE_DAIMLER_PINHO (*MAT_261)
  - *MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO (*MAT_262)
  - 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

failure mechanisms in fiber reinforced composites

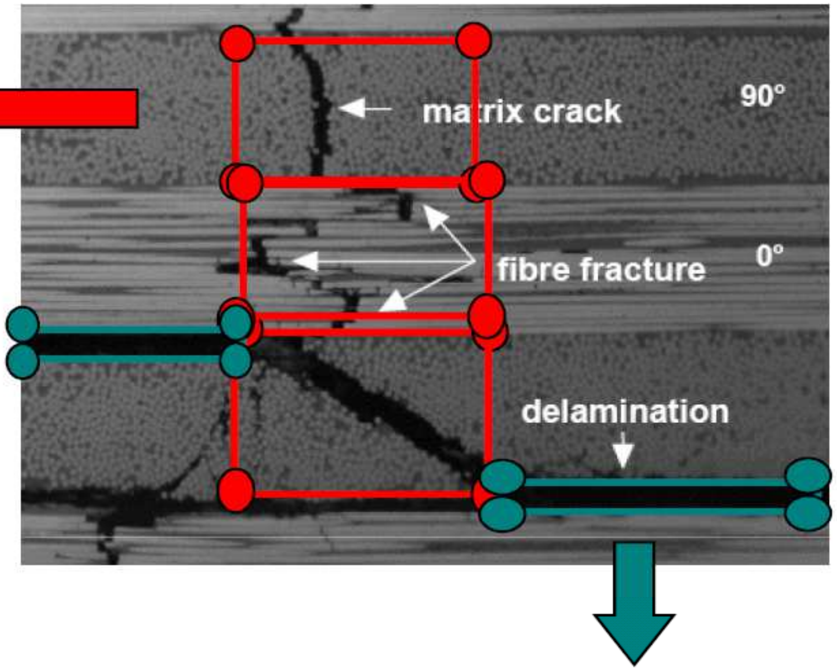


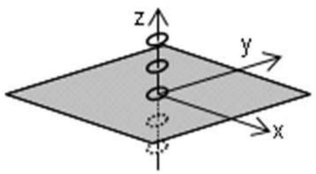
R Olson, Imperial College London

PP Camanho, PhD thesis, Imperial College London

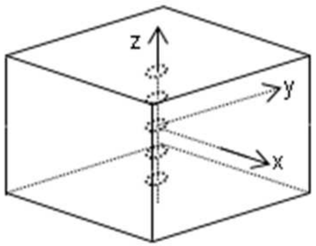
modeling possibilities

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

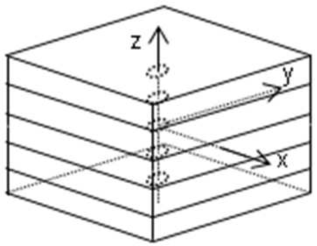




layered thin shell elements
+ numerical „cheap" (thickness does not influence the critical time step size)
+ combination of single layers to sub-laminates
- no stresses in thickness dir. (no delamination)



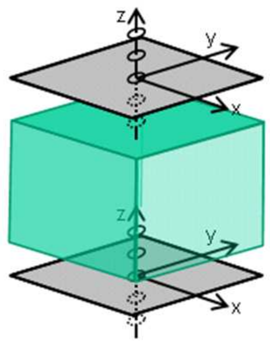
layered thick shell elements
+ 3D stress state
+ combination of single layers to sub-laminates
- thickness influences the critical time step size



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

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

stacked shells



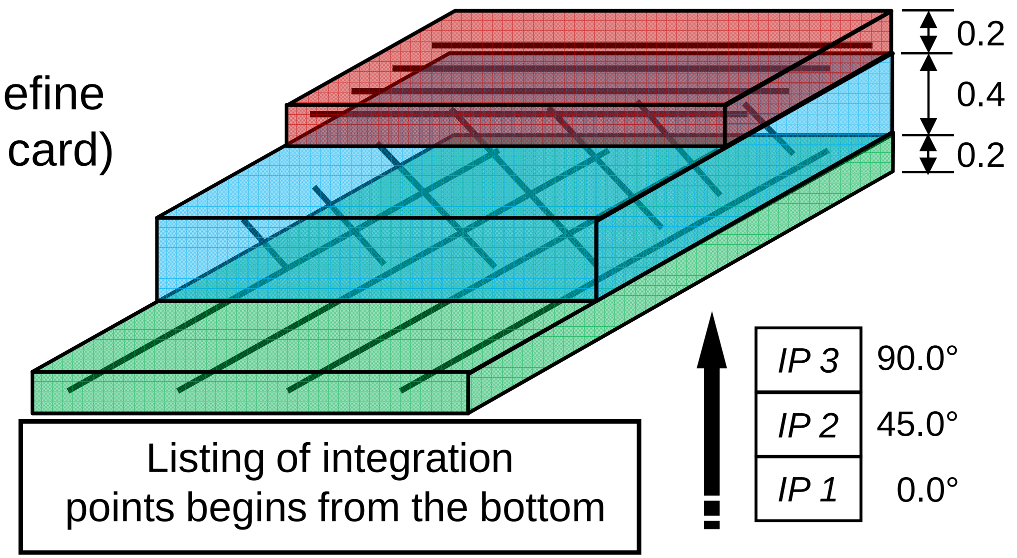
layered thin shell definition with *PART_COMPOSITE(_TSHELL)

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

`*PART_COMPOSITE(_TSHELL)`

	1	2	3	4	5	6	7	8
Card 1	PID	ELFORM	SHRF	NLOC	MAREA	HGID	ADOPT	
	28	2	0.0	0.0				
Card 2	MID1	THICK1	BETA1		MID2	THICK2	BETA2	
	1	0.2	0.0		2	0.4	45.0	
Card 3	MID3	THICK3	BETA3		MID4	THICK4	BETA4	
	3	0.2	90.0					
...								

add as many cards are necessary to define the whole layup (define two layers per card)



layered thin shell definition with *PART_COMPOSITE(_TSHELL)

- need *SECTION_(T)SHELL-keyword card to define ELFORM
- different material models allowed

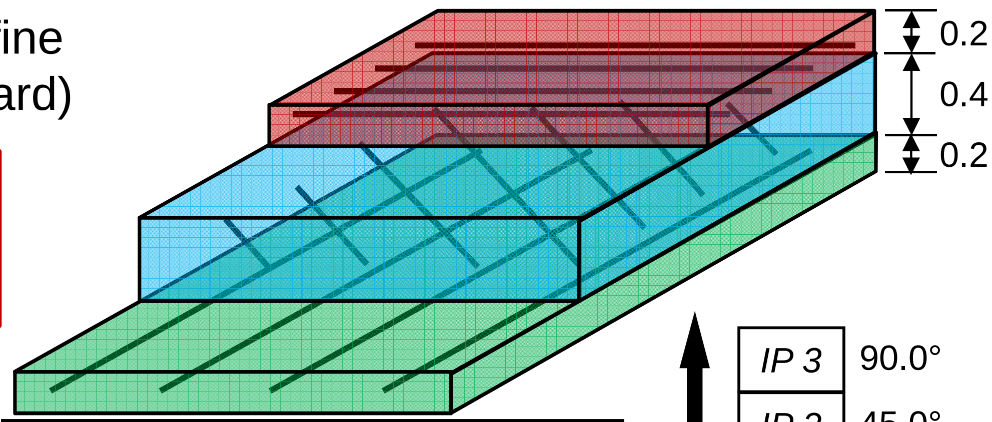
***ELEMENT_(T)SHELL_COMPOSITE**

	1	2	3	4	5	6	7	8	9	10
Card 1	EID	PID	N1	N2	N3	N4	N5	N6	N7	N8

	1	2	3	4	5	6	7	8
Card 2	MID1	THICK1	BETA1		MID2	THICK2	BETA2	
	1	0.2	0.0		2	0.4	45.0	
Card 3	MID3	THICK3	BETA3		MID4	THICK4	BETA4	
	3	0.2	90.0					
...								

add as many cards are necessary to define the whole layup (define two layers per card)

Now it is possible to define different „Lay-ups“ within the same PART

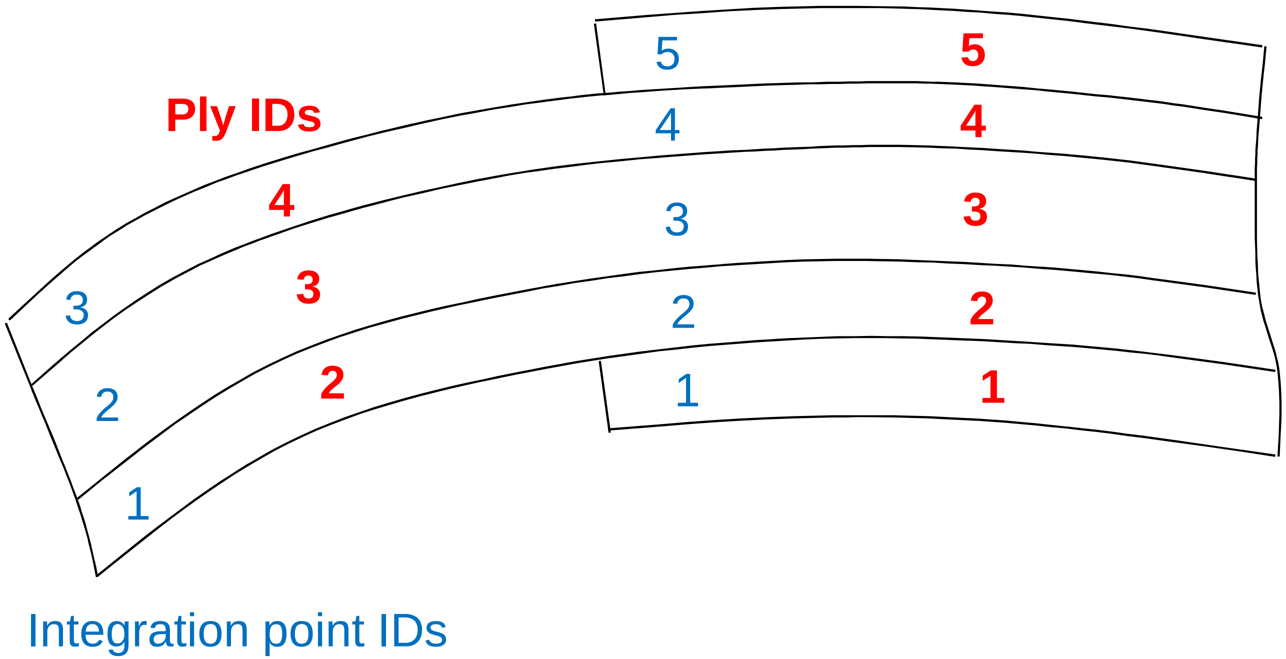


Listing of integration points begins from the bottom

IP 3	90.0°
IP 2	45.0°
IP 1	0.0°

Outlook: ply based modeling with *ELEMENT_(T)SHELL_COMPOSITE8

- definition of a Ply ID will allow an easier post-processing
- new LS-PrePost versions will support ply based modeling
- separate binary file for post-processing of composite parts



some remarks

- extra history variables

  many composite material models have extra history variables that help to track modes of failure in each integration point (see material documentation in the LS-DYNA Keyword User’s Manual for details). A list of history variables is given here:

  http://www.dynasupport.com/howtos/material/history-variables

  NEIPS (shells) or NEIPH (solids) in *DATABASE_EXTENT_BINARY should be set to the number of extra history variables needed. For example, if you want to track the damage parameters (6 extra history variables) in *MAT_054, set NEIPS=6.

- output of stresses and strains in the local material coordinate system (IPs)
  → set CMPFLG=1 in *DATABASE_EXTENT_BINARY

	binout	d3plot	
		global	local *)
CMPLFG=0	Element KOS	Global KOS	Element KOS
CMPFLG=1	Material KOS	Material KOS	undefined

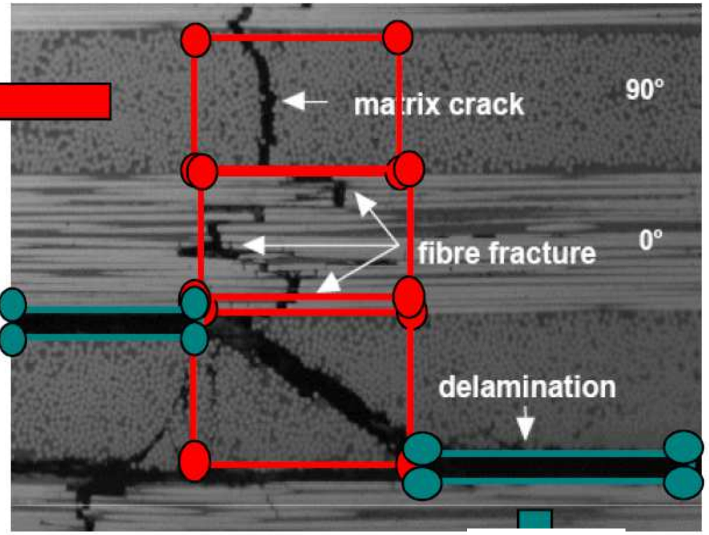
*) Formerly LSPP did not know about INN (information not written to d3plot), so transfromation from Global KOS → Element KOS might not be correct.
This is fixed with LS-DYNA Version R7 and later and newer LSPP versions (4.1).

Material models for intralaminar failure

available since R7.0

***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):

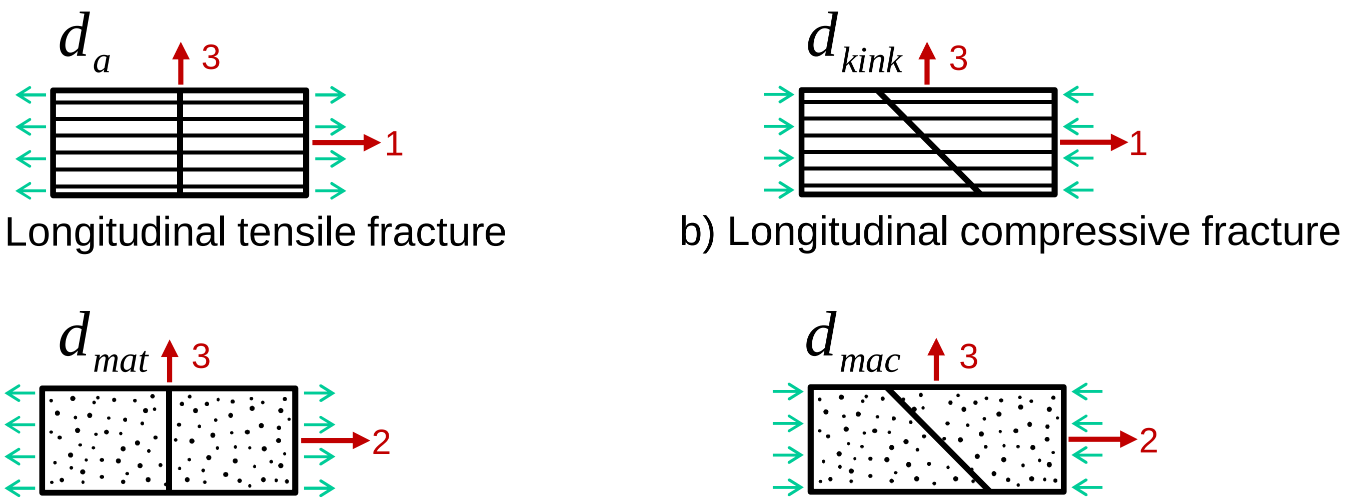
- constitutive law

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

4 damage parameter

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

- 4 failure criteria



a) Longitudinal tensile fracture

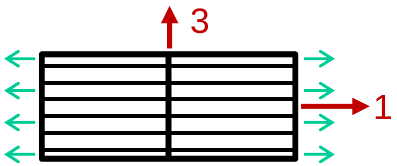
b) Longitudinal compressive fracture

c) Transverse fracture with α=0°

d) Transverse fracture with α=53°

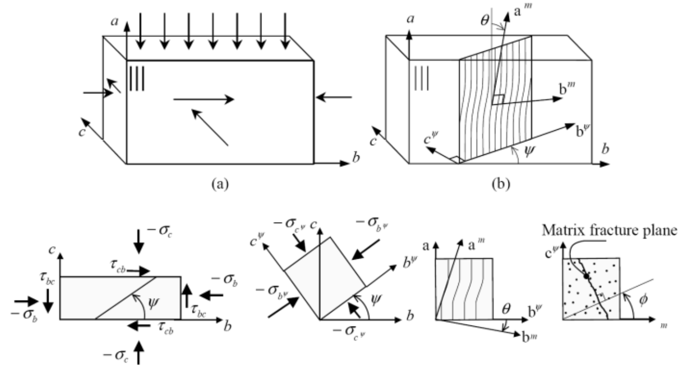
*MAT_261 (*MAT_LAMINATED_FRACTURE_DAIMLER_PINHO):

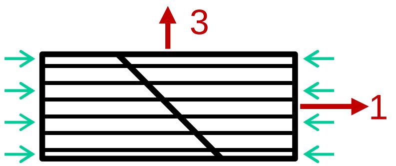
- physically based failure criteria
- continuum damage model



a) Tensile fibre mode (maximum stress)

$$e_f^2 = \left(\frac{\tilde{\sigma}_{11}}{X_T}\right)^2 - 1$$





b) Compressive fibre mode (3D-kinking model)

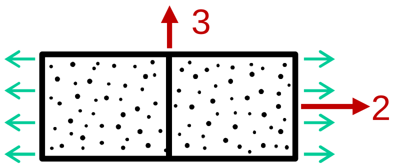
$$e_c^2 = \left(\frac{\tau_T}{S_T - \mu_T \sigma_n}\right)^2 + \left(\frac{\tau_L}{S_L - \mu_L \sigma_n}\right)^2 - 1 \qquad (\sigma_n \le 0)$$

$$e_c^2 = \left(\frac{\sigma_n}{Y_T}\right)^2 + \left(\frac{\tau_L}{S_L}\right)^2 + \left(\frac{\tau_T}{S_T}\right)^2 - 1 \qquad (\sigma_n > 0)$$

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

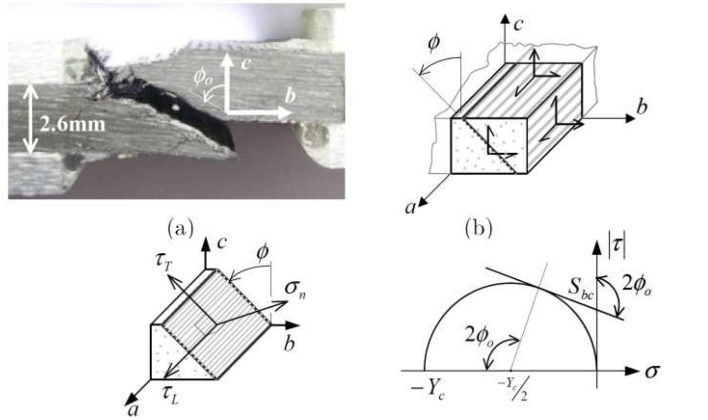
$$\tau_T = -\frac{\tilde{\sigma}_{b^m} - \tilde{\sigma}_{c^\psi}}{2}\sin(2\phi) + \tilde{\sigma}_{b^m c^\psi}\cos(2\phi)$$

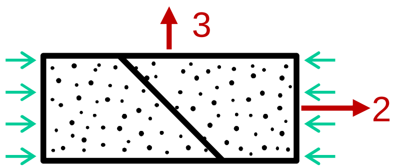
$$\tau_L = \tilde{\sigma}_{a^m b^m}\cos(\phi) + \tilde{\sigma}_{c^\psi a^m}\sin(\phi)$$



c) Tensile matrix mode (transf. fracture plane)

$$e_m^2 = \left(\frac{\sigma_n}{Y_T}\right)^2 + \left(\frac{\tau_T}{S_T}\right)^2 + \left(\frac{\tau_L}{S_L}\right)^2 - 1$$





d) Compressive matrix mode (transf. fracture plane)

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

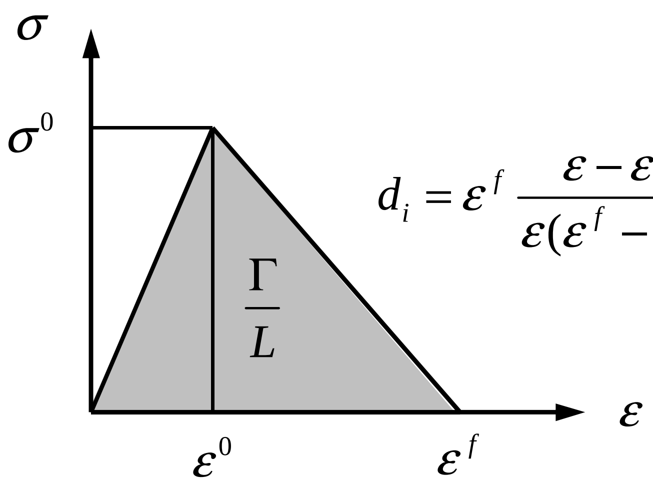
ϕ_0 : *fracture plane for pure compression*

ϕ : *fracture plane under general loading*

***MAT_261** (*MAT_LAMINATED_FRACTURE_DAIMLER_PINHO):

- linear damage laws

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



$$d_i = \varepsilon^f \frac{\varepsilon - \varepsilon^0}{\varepsilon(\varepsilon^f - \varepsilon^0)}$$

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

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

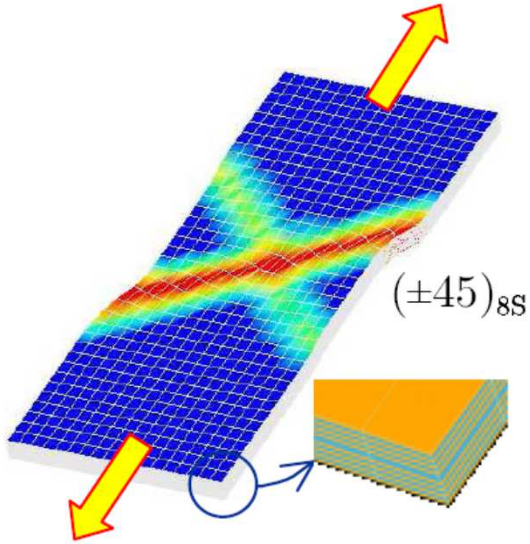
$L :$

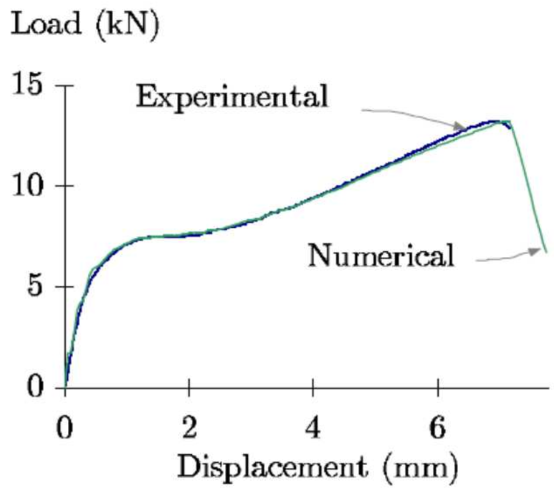
internal (characteristic) length for objectivity (localization!)

Material models for intralaminar failure

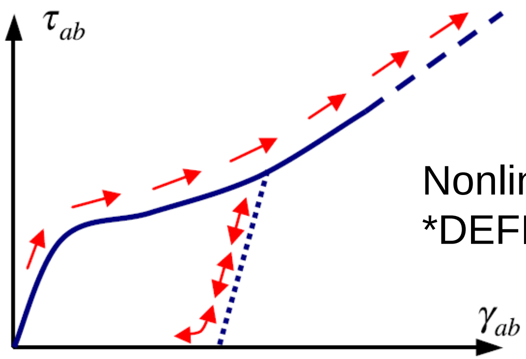
***MAT_261** (*MAT_LAMINATED_FRACTURE_DAIMLER_PINHO):

- in-plane shear behavior

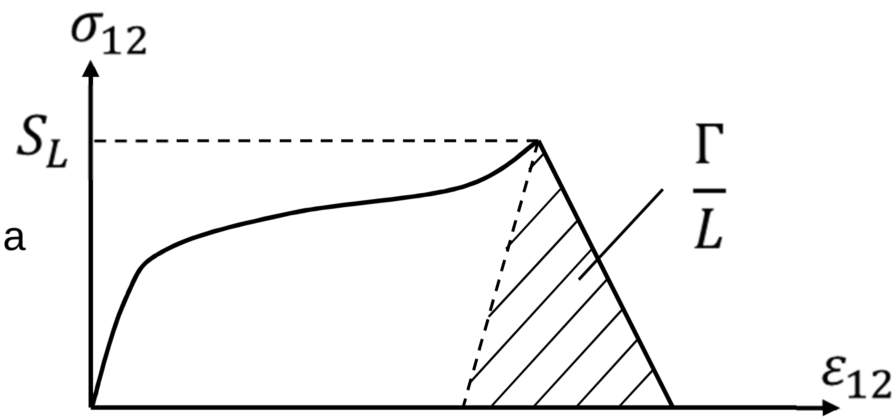




1D plasticity formulation with combined isotropic/kinematic hardening – coupled with linear damage model



Nonlinearity defined via
*DEFINE_CURVE



Material models for intralaminar failure

*MAT_261 (*MAT_LAMINATED_FRACTURE_DAIMLER_PINHO):

		1	2	3	4	5	6	7	8
elastic, orthotropic parameters	Card 1	MID	RO	EA	EB	EC	PRBA	PRCA	PRCB
	Card 2	GAB	GBC	GCA	AOPT	DAF	DKF	DMF	EFS
material coos	Card 3	XP	YP	ZP	A1	A2	A3		
	Card 4	V1	V2	V3	D1	D2	D3	MANGLE	
model parameter	Card 5	ENKINK	ENA	ENB	ENT	ENL			
	Card 6	XC	XT	YC	YT	SL			
	Card 7	FIO	SIGY	LCSS	BETA	PFL	PUCK	SOFT	

DAF: flag to control failure of an IP based on longitudinal (fiber) tensile failure

DKF: flag to control failure of an IP based on longitudinal (fiber) compressive failure

DMF: flag to control failure of an IP based on transverse (matrix) failure

EFS: Max. effect. Strain for element layer failure. A value of unity would equal 100% strain

ENKINK: Facture toughness for longitudinal (fiber) compressive failure mode

ENA: Facture toughness for longitudinal (fiber) tensile failure mode

ENB: Facture toughness for intralaminar matrix tensile failure

ENT: Fracture toughness for intralaminar matrix transverse shear failure

ENL: Fracture toughness for intralaminar matrix longitudinal shear failure

XC: longitudinal compressive strength

XT: longitudinal tensile strength

YC: transverse compressive strength

YT: transverse tensile strength

SL: longitudinal shear strength

FIO: fracture angle in pure transverse compression (in degrees, default=53.0)

SIGY: In-plane shear yield stress

LCSS: Load curve ID which defines the non-linear in-plane shear-stress as a function of in-plane shear-strain

BETA: hardening parameter for in-plane shear plasticity

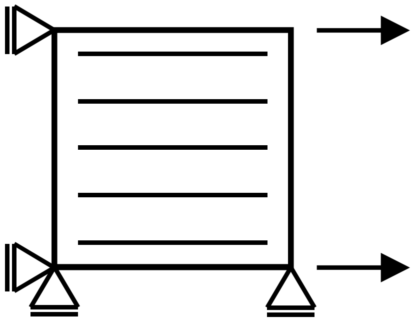
PFL: Percentage of layer which must fail before crashfront is initiated.

PUCK: flag to post-process Puck's inter-fiber-failure criterion

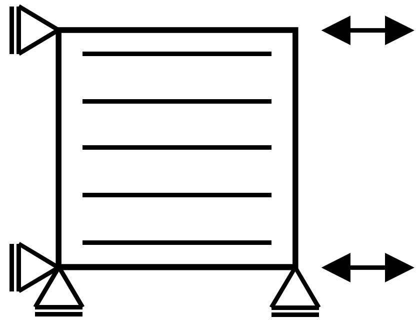
SOFT: reduction factor for strength in crashfront elements

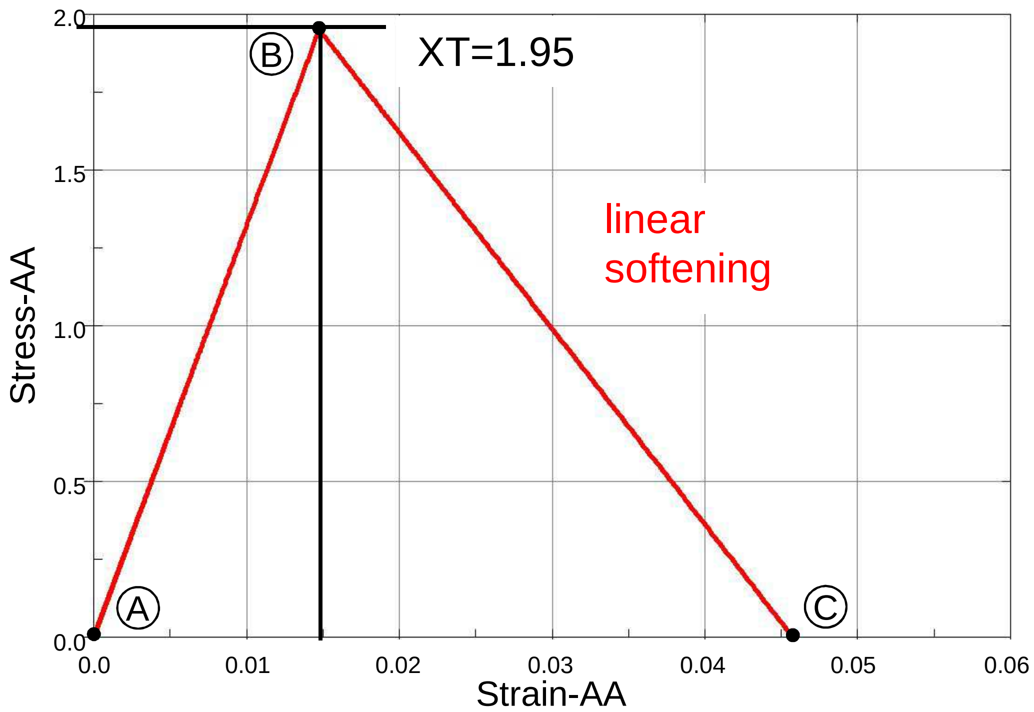
***MAT_261** (*MAT_LAMINATED_FRACTURE_DAIMLER_PINHO):

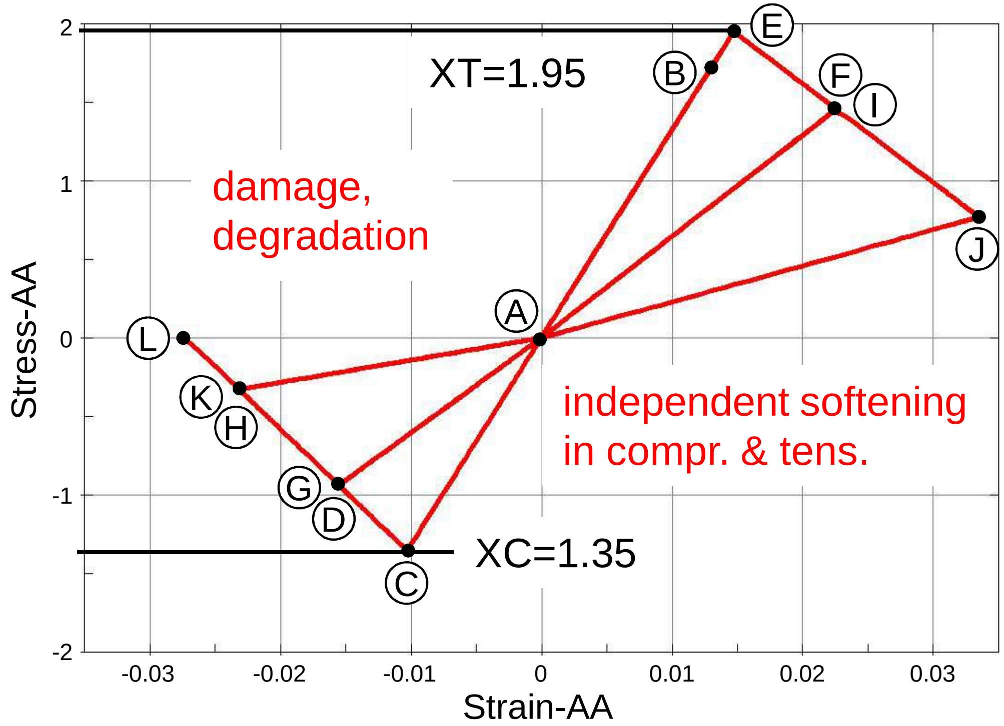
- 1-Element-Test, Single-Layer (‘SHELL’, ELFORM=2)



Material Parameter:
EA= 132.0 [kN/mm²]
XT= 1.95 [kN/mm²]
XC= 1.35 [kN/mm²]
ENA=0.05 [kN/mm]
ENKINK=0.02 [kN/mm]
EFS=0.05

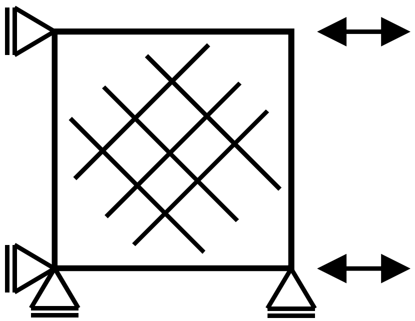




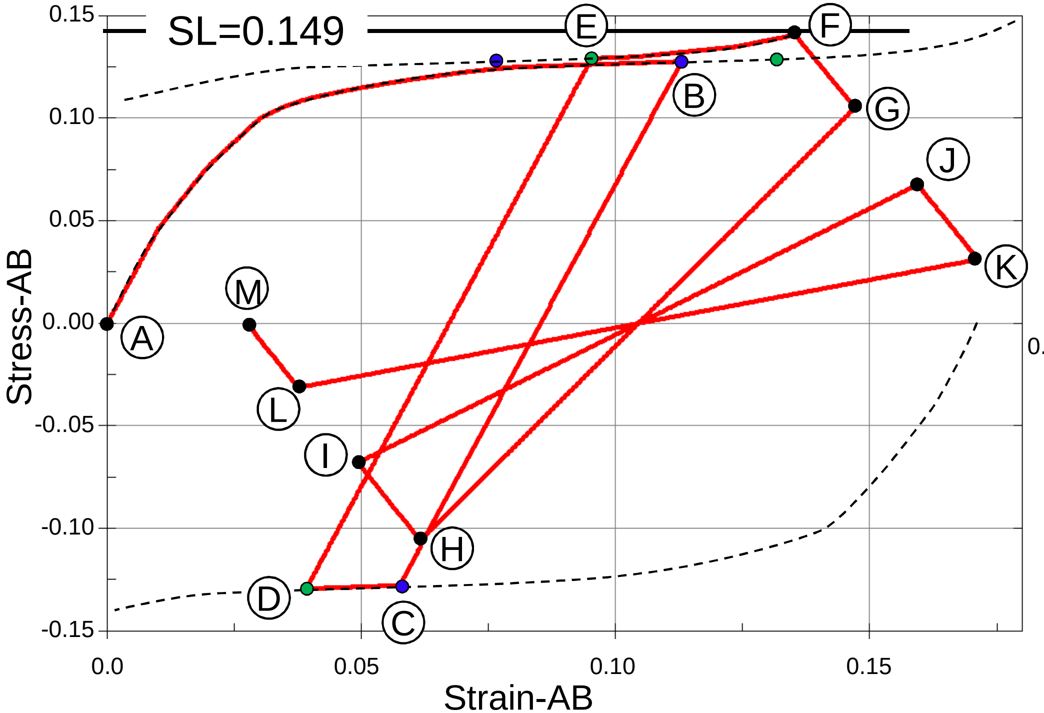


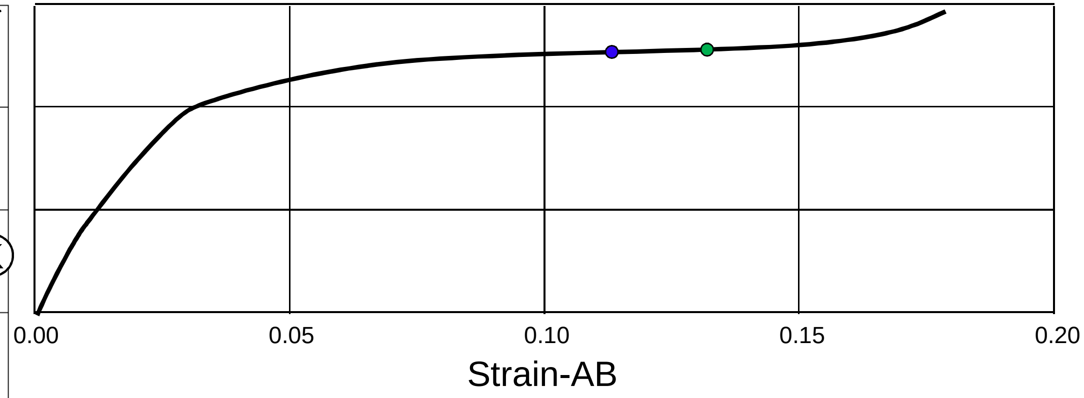
***MAT_261** (*MAT_LAMINATED_FRACTURE_DAIMLER_PINHO):

- 1-Element-Test, Single-Layer (‘SHELL’, ELFORM=2)
- Cyclic test with a +/-45° layup (A-M)



Material Parameter:
GAB= 4.6 [kN/mm²]
ENT= 0.006 [kN/mm]
ENL= 0.006 [kN/mm]
SL= 0.149 [kN/mm²]





shear non-linearity with *DEFINE_CURVE

***MAT_261** (*MAT_LAMINATED_FRACTURE_DAIMLER_PINHO):

- Extra History Variables (→ set NEIPS in *DATABASE_EXTENT_BINARY)

SHELLS / TSHELLS / SOLIDS		
1	fa	damage activation function: fiber ternsile mode
2	fkink	damage activation function: fiber compressive mode
3	fmat	damage activation function: matrix mode
5	da	damage variable: fiber tension
6	dkink	damage variable: fiber compression
7	dmat	damage variable: transverse direction
9	dam	damage parameter (SOFT)
10	fmt_p	Puck‘s inter-fiber-failure criterion: tensile matrix mode
11	fmc_p	Puck‘s inter-fiber-failure criterion: compressive matrix mode
12	theta_p	Puck‘s inter-fiber-failure criterion: angle of fracture plane

fa, fkink, fmat:	0→1-elastic;	1-failure criterion reached	
da; dkink; dmat:	0-elastic;	1-fully damaged	
dam:	-1-intact;	0-failed;	10e-8-crashfront
fmt_p; fmc_p, theta_p:	0→1-elastic;	1-failure criterion reached	

Material models for intralaminar failure

***MAT_262** (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):

- constitutive relation

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

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

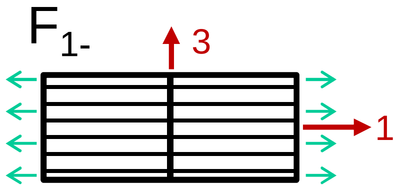
5 damage variables

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

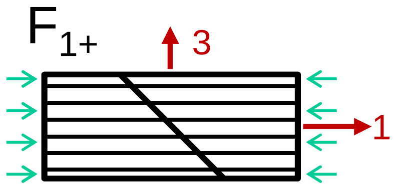
$$d_1 = d_{1+}\frac{\langle \sigma_{11} \rangle}{|\sigma_{11}|} + d_{1-}\frac{\langle -\sigma_{11} \rangle}{|\sigma_{11}|}$$

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

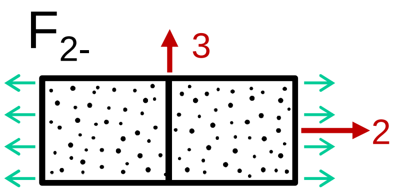
- 4 failure criteria (LaRC03/04)



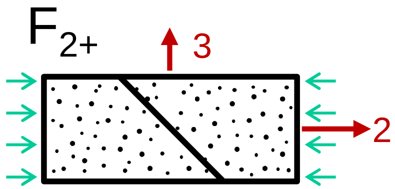
a) Longitudinal tensile fracture



b) Longitudinal compressive fracture



c) Transverse fracture with α=0°



d) Transverse fracture with α=53°

damage activation functions

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

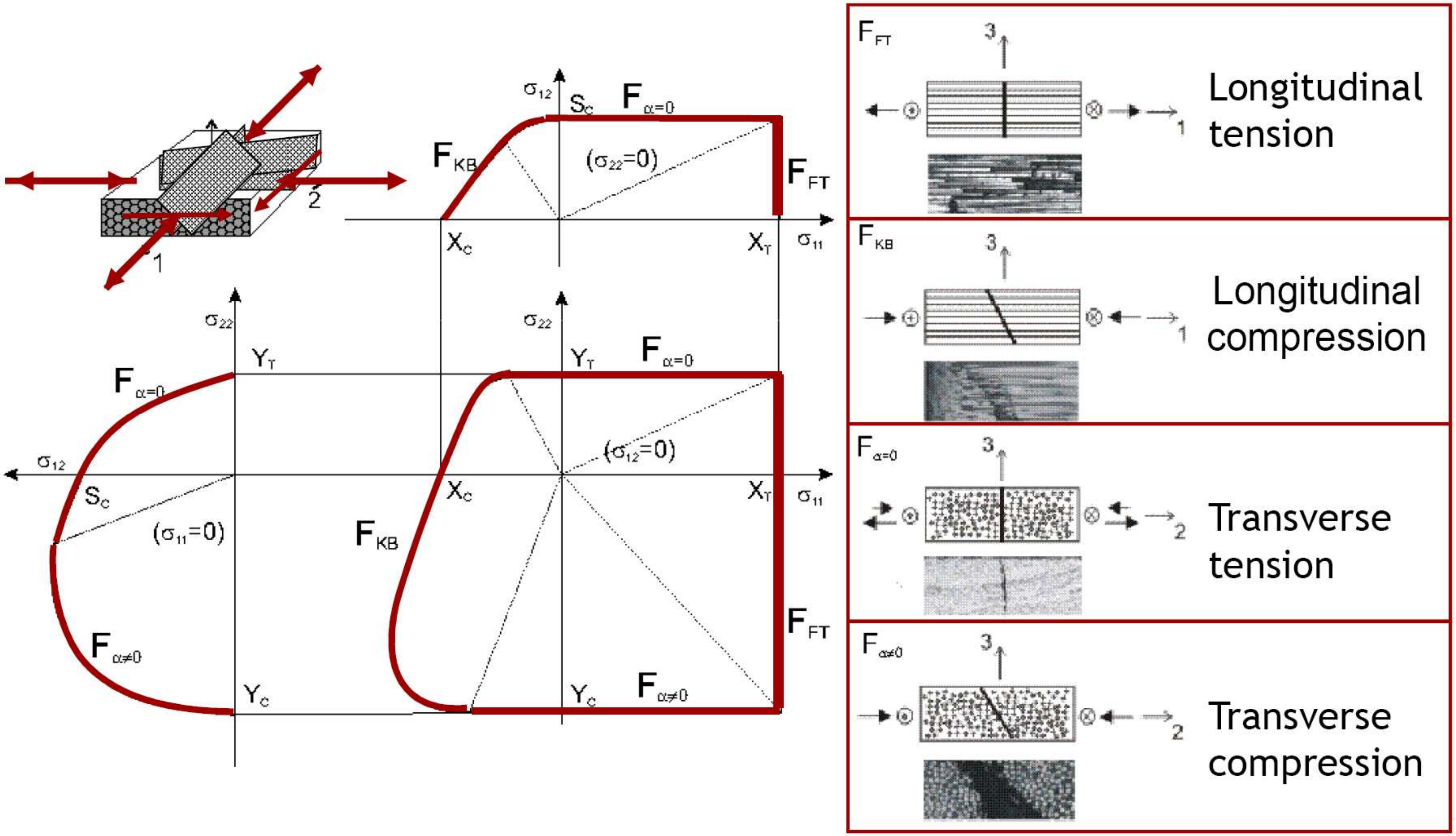
$$F_{2-} = \phi_{2-} - r_{2-} \leq 0$$

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

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

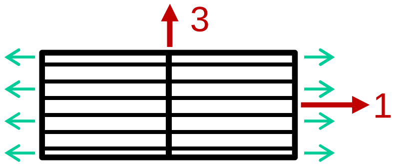
***MAT_262** (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):

- failure surface (assembly of 4 sub-surfaces)



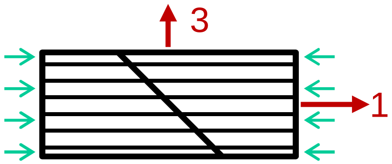
***MAT_262** (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):

- physically based failure criteria
- continuum damage model



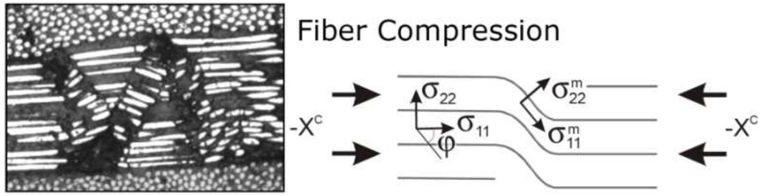
a) Tensile fibre mode
(maximum strain – LaRC04)

$$\phi_{1+} = \frac{\tilde{\sigma}_{11} - \nu_{12}\tilde{\sigma}_{22}}{X_T}$$



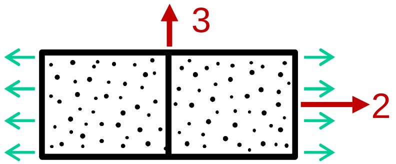
b) Compressive fibre mode (LaRC03)
(transf. fracture plane)

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



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

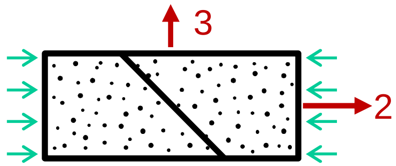
$$\tilde{\sigma}_{12}^{m} = (\tilde{\sigma}_{22} - \tilde{\sigma}_{11})\sin(\varphi^C)\cos(\varphi^C) + \left|\tilde{\sigma}_{12}\right|\left(\cos^2(\varphi^C) - \sin^2(\varphi^C)\right)$$



c) Tensile matrix mode
(LaRc04)

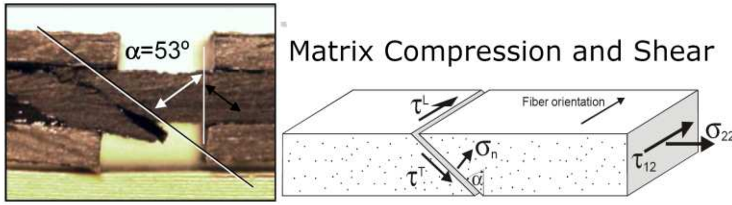
$$\phi_{2+} = \sqrt{(1-g)\frac{\tilde{\sigma}_{22}}{Y_T} + g\left(\frac{\tilde{\sigma}_{22}}{Y_T}\right)^2 + \left(\frac{\tilde{\sigma}_{12}}{S_L}\right)^2} \quad (\tilde{\sigma}_{22} \geq 0)$$

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



d) Compressive matrix mode (LaRC04)
(transf. fracture plane)

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



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

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

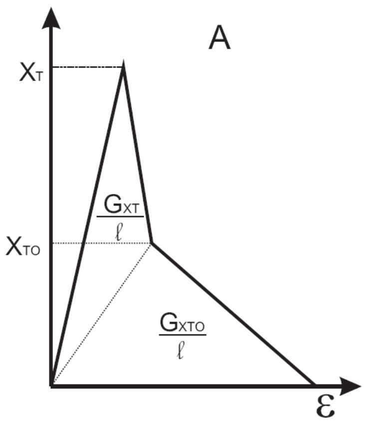
***MAT_262** (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):

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

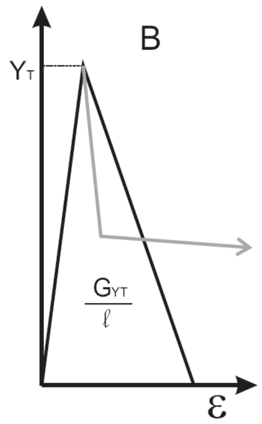
compression:	$r_{1-/2-}^{n+1} = \max\left\{1, r_{1-/2-}^{n}, \phi_{1-/2-}^{n+1}\right\}$
tension:	$r_{1+/2+}^{n+1} = \max\left\{1, r_{1+/2+}^{n}, r_{1-/2-}^{n+1}, \phi_{1+/2+}^{n+1}\right\}$

no damage due to crack (tension); crack closure

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

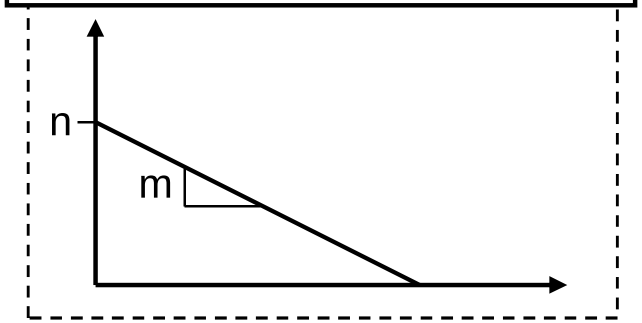


bi-linear in fiber direction



linear in transverse direction

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

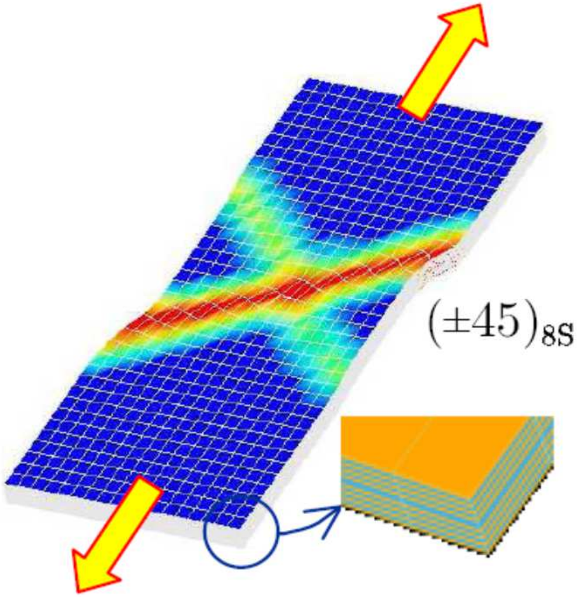


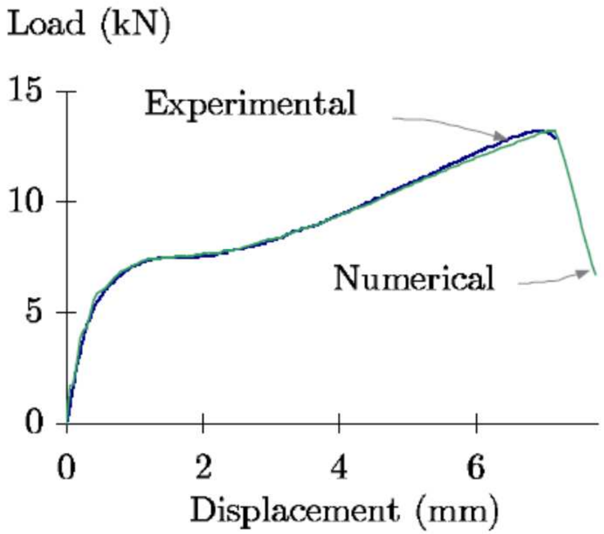
$G_{XT}, G_{XC}, G_{YT}, G_{YC}, G_{SL}$

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

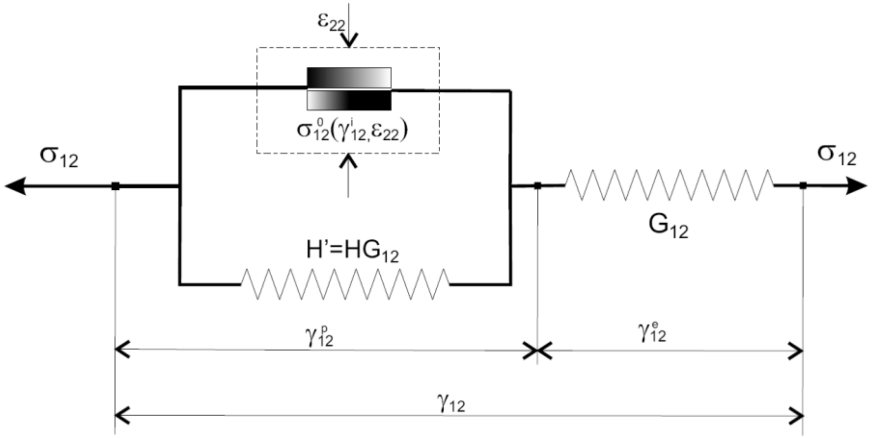
ℓ : internal (characteristic) length for objectivity (lokalization!)

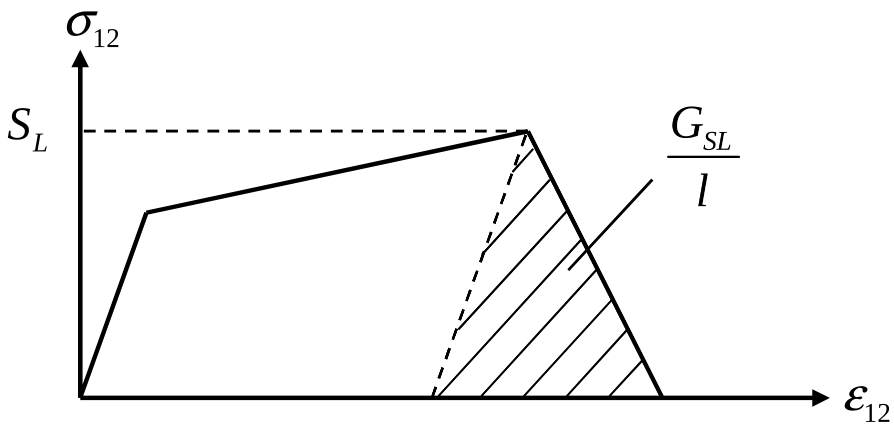
***MAT_262** (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):





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





*MAT_262 (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):

		1	2	3	4	5	6	7	8
elastic, orthotropic parameters	Card 1	MID	RO	EA	EB	EC	PRBA	PRCA	PRCB
	Card 2	GAB	GBC	GCA	AOPT	DAF	DKF	DMF	EFS
material coos	Card 3	XP	YP	ZP	A1	A2	A3		
	Card 4	V1	V2	V3	D1	D2	D3	MANGLE	
model parameter	Card 5	GXC	GXT	GYC	GYT	GSL	GXCO	GXTO	
	Card 6	XC	XT	YC	YT	SL	XCO	XTO	
	Card 7	FIO	SIGY	ETAN	BETA	PFL	PUCK	SOFT	

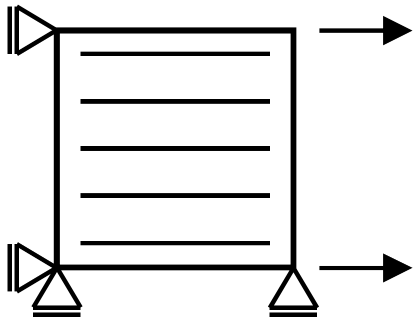
DAF: flag to control failure of an IP based on longitudinal (fiber) tensile failure
DKF: flag to control failure of an IP based on longitudinal (fiber) compressive failure
DMF: flag to control failure of an IP based on transverse (matrix) failure
EFS: Max. effect. Strain for element layer failure. A value of unity would equal 100% strain
GXC: Facture toughness for longitudinal (fiber) compressive failure mode
GXT: Facture toughness for longitudinal (fiber) tensile failure mode
GYC: Fracture toughness for transv. compr. fail.
GYT: Fracture toughness for transv. tens. fail.
GSL: Fracture toughness for in-plane shear fail.
GXCO: Frac. tough. long. compr. fail. bi-lin. damage
GXTO: Frac. tough. long. tens. fail. bi-lin. damage

XC: longitudinal compressive strength
XT: longitudinal tensile strength
YC: transverse compressive strength
YT: transverse tensile strength
SL: shear strength ab-plane
XCO: long. compr. strength at inflection point
XTO: long. tens. strength at inflection point
FIO: fracture angle in pure transverse compression (in degrees, default=53.0)
SIGY: In-plane shear yield stress
ETAN: tangent modulus for in-plane shear plasticity
BETA: hardening parameter for in-plane shear plasticity
PFL: Percentage of layer which must fail before crashfront is initiated.
PUCK: flag to post-process Puck's inter-fiber-failure criterion
SOFT: reduction factor for strength in crashfront elements

*MAT_262 (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):

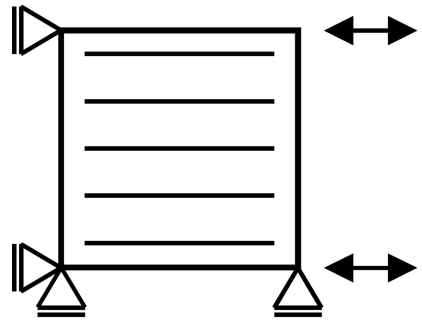
- 1-Element-Test, Single-Layer ('SHELL', ELFORM=2)

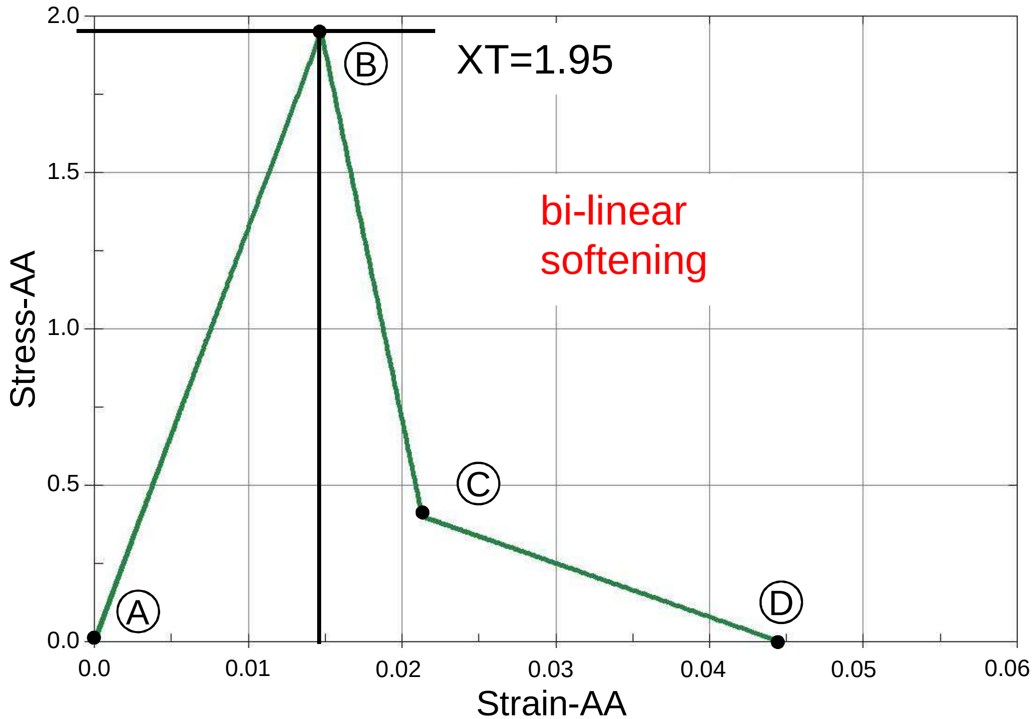
fiber tensile load (A-D)

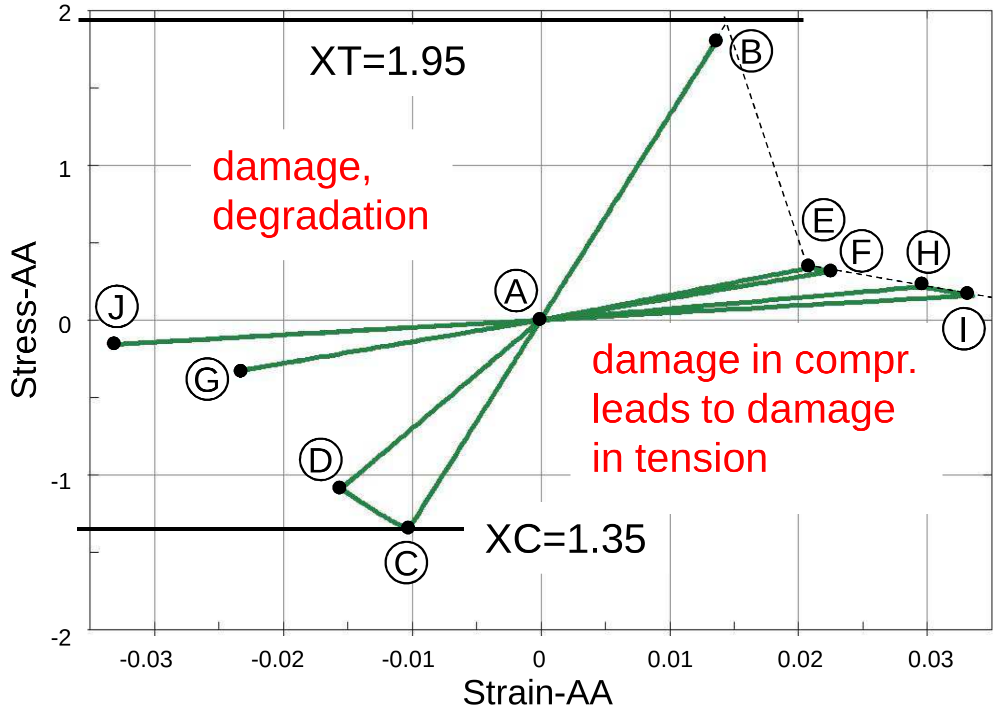


Material Parameter:
EA= 132.0 [kN/mm²]
XT= 1.95 [kN/mm²]
XC= 1.35 [kN/mm²]
GXT/GXC=0.015 [kN/mm]
GXTO/GXCO=0.01 [kN/mm]
XTO/XCO=0.4 [kN/mm²]

fiber cyclic load (A-K)

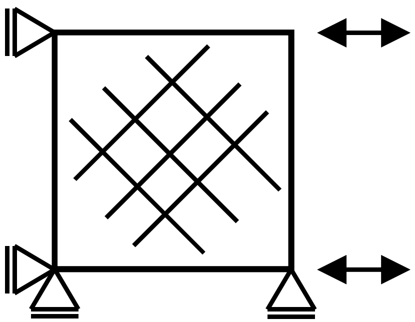




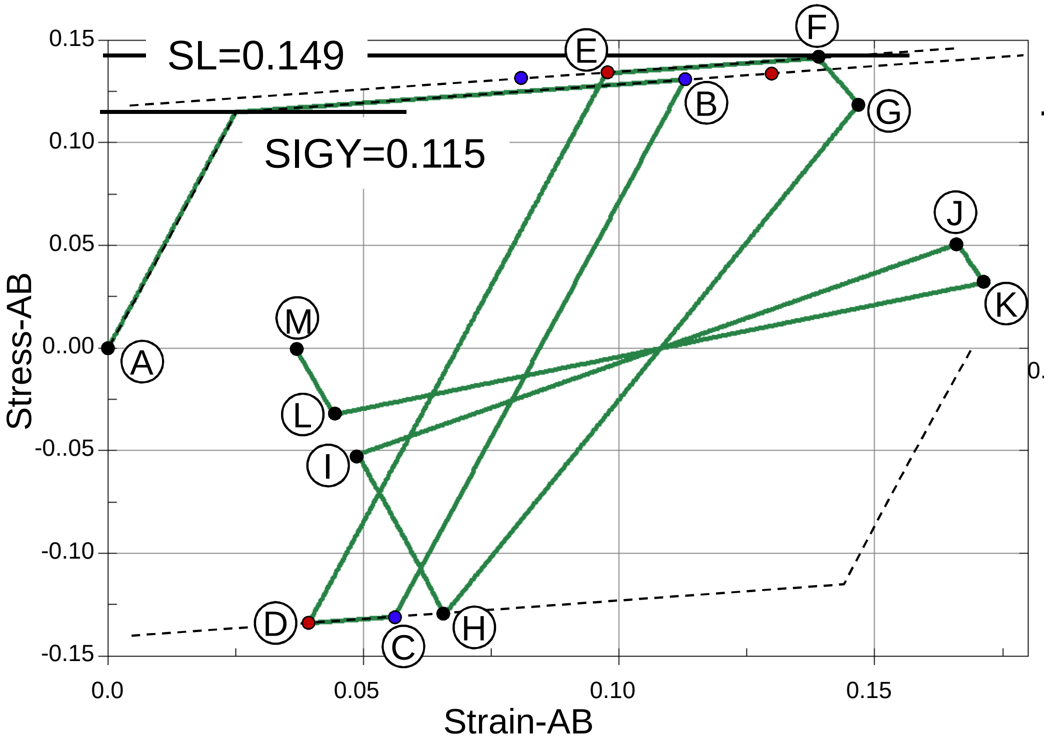


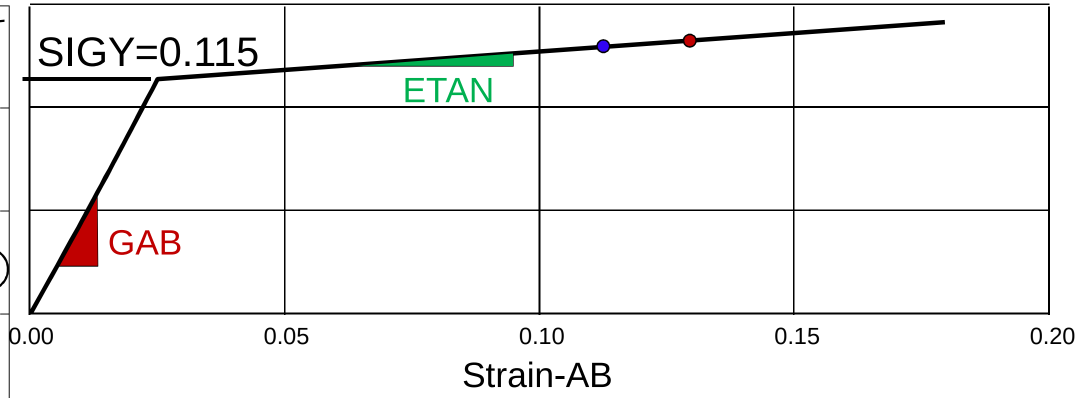
***MAT_262** (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):

- 1-Element-Test, Single-Layer (‘SHELL’, ELFORM=2)
- Cyclic test with a +/-45° layup (A-M)



Material Parameter:
GAB= 4.6 [kN/mm²]
GSL= 0.006 [kN/mm]
SIGY= 0.115 [kN/mm²]
ETAN= 0.18 [kN/mm²]
SL= 0.149 [kN/mm²]





***MAT_262** (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO):

- Extra History Variables (→ set NEIPS in *DATABASE_EXTENT_BINARY)

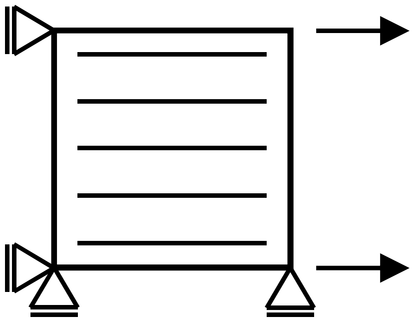
SHELLS / TSHELLS / SOLIDS		
1	Φ_{1+}	damage activation function: fiber ternsile mode
2	Φ_{1-}	damage activation function: fiber compressive mode
3	Φ_{2+}	damage activation function: tensile matrix mode
4	Φ_{2-}	damage activation function: compressive matrix mode
5	d_{1+}	damage variable: fiber tension
6	d_{1-}	damage variable: fiber compression
7	d_2	damage variable: transverse direction
8	d_6	damage variable: in-plane shear
9	dam	damage parameter (SOFT)
10	fmt_p	Puck's inter-fiber-failure criterion: tensile matrix mode
11	fmc_p	Puck's inter-fiber-failure criterion: compressive matrix mode
12	theta_p	Puck's inter-fiber-failure criterion: angle of fracture plane

Φ_i:	0→1-elastic;	1-failure criterion reached	
d_i:	0-elastic;	1-fully damaged	
dam:	-1-intact;	0-failed;	10e-8-crashfront
fmt_p; fmc_p, theta_p:	0→1-elastic;	1-failure criterion reached	

comparison between different material models

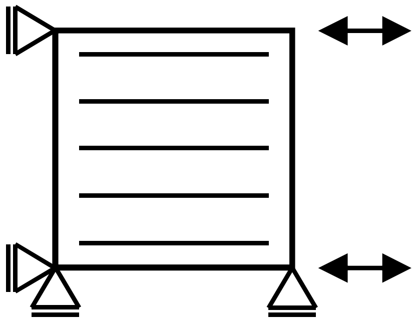
- 1-Element-Test, Single-Layer ('SHELL', ELFORM=2)

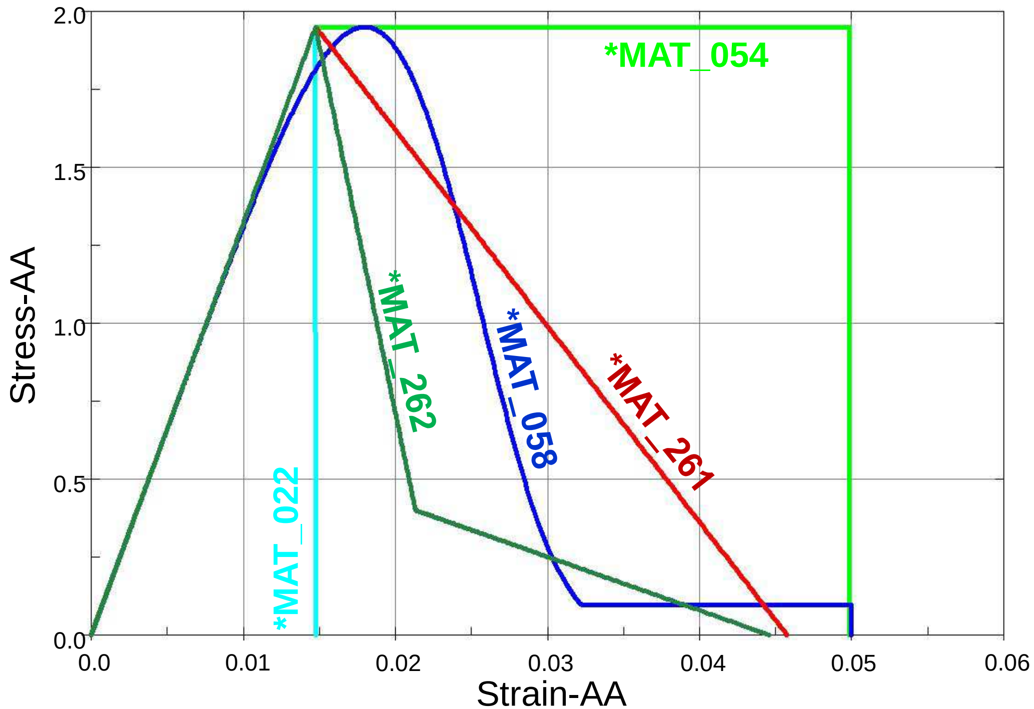
fiber tensile load (A-E)

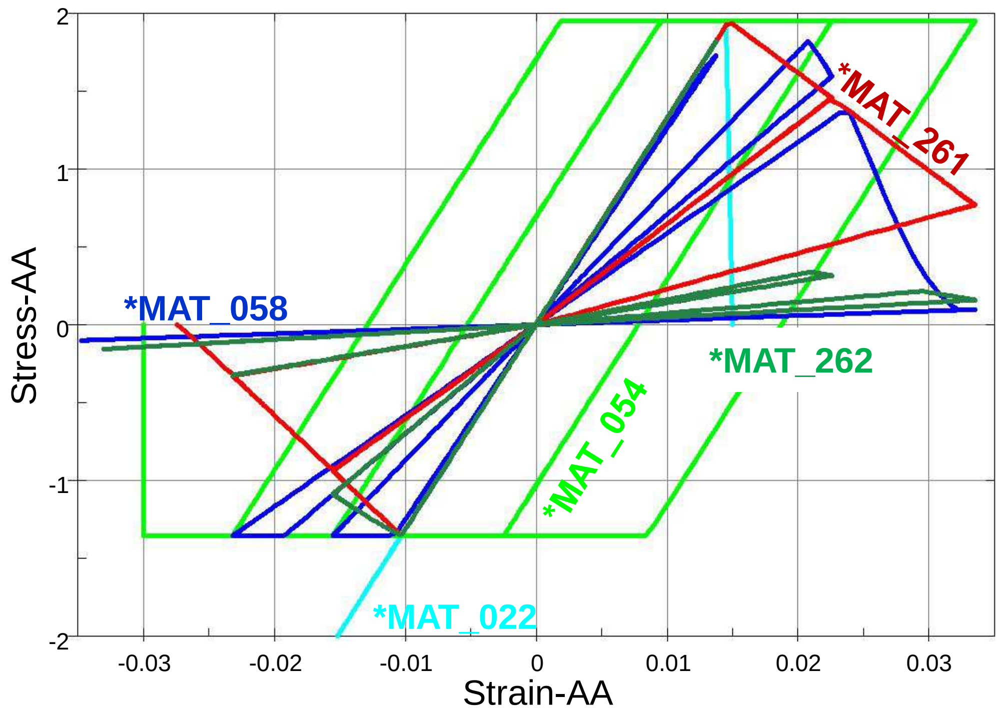


Material Parameter:
EA= 132.0 [kN/mm²]
XT= 1.95 [kN/mm²]
XC= 1.35 [kN/mm²]
… (model dependent)

fiber cyclic load (A-K)

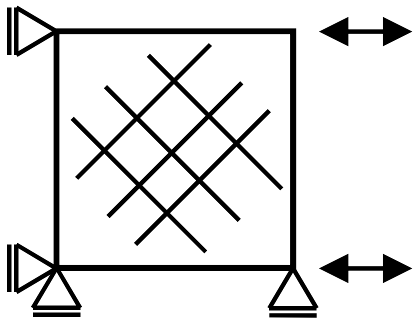


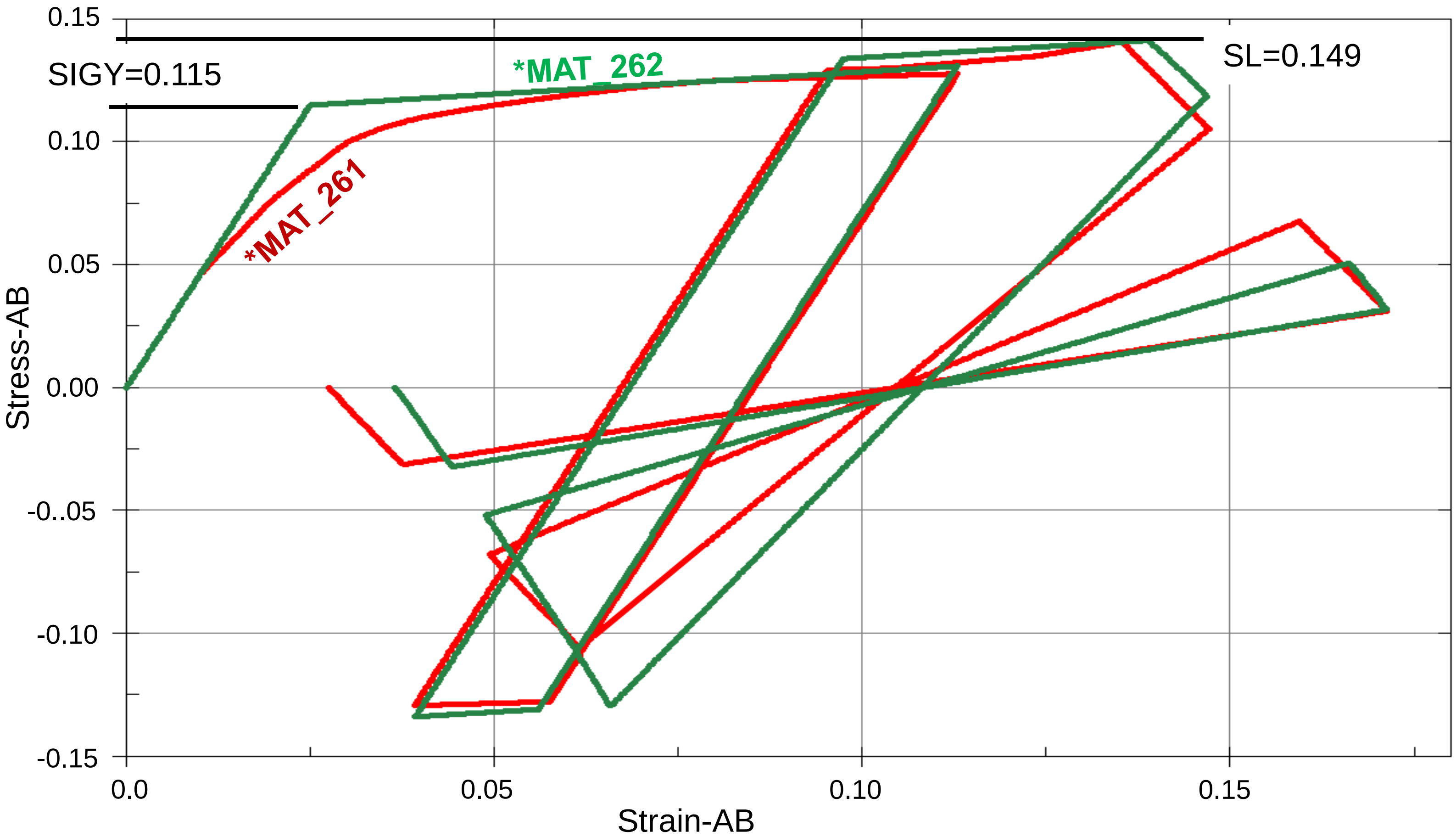




comparison of the new material models (in-plane shear)

- 1-Element-Test, Single-Layer (‘SHELL’, ELFORM=2)
- Cyclic test with a +/-45° layup (A-M)





*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

summary

***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

available since R7.0

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

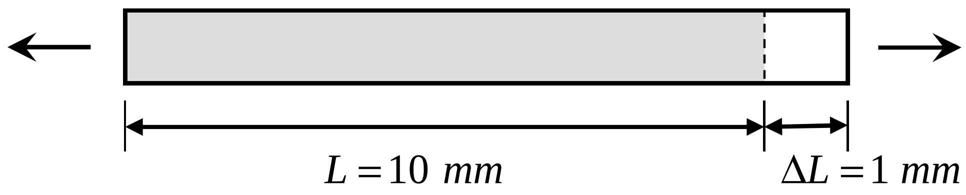
***MAT_262: (*MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO)** (together with Daimler AG)

✓ 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

available since R7.0

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

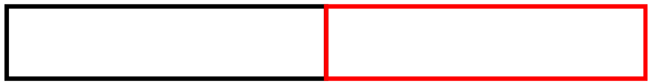
Problem der Objektivität (Pinho und Camanho gleichermassen) – 1D-Beispiel



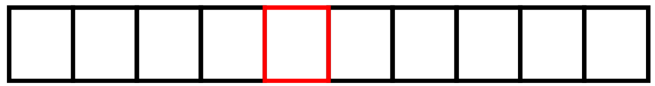
$$\varepsilon_{ges}^{el} = \frac{\Delta L}{L} = 0{,}1$$

(vereinfacht mit Ingenieurdehnungen)

FE-Diskretisierung

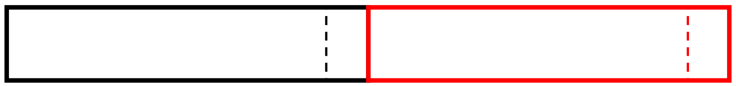


2 Elemente

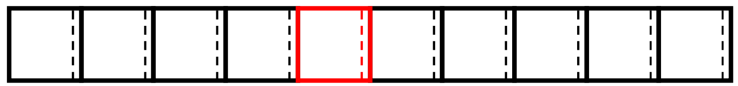


10 Elemente

Elastische Verformung

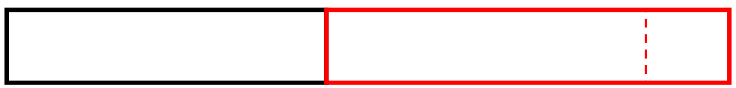


$$\varepsilon_{ges}^{el} = \frac{\Delta L}{L} = 0{,}1 \quad \Rightarrow \quad \varepsilon_{ele}^{el} = \frac{\Delta L / 2}{L / 2} = 0{,}1$$

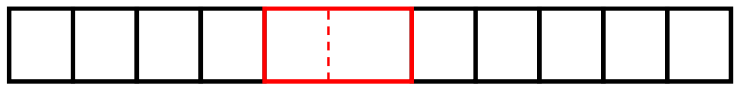


$$\varepsilon_{ges}^{el} = \frac{\Delta L}{L} = 0{,}1 \quad \Rightarrow \quad \varepsilon_{ele}^{el} = \frac{\Delta L / 10}{L / 10} = 0{,}1$$

Lokalisierung (Verformung in einem Element)

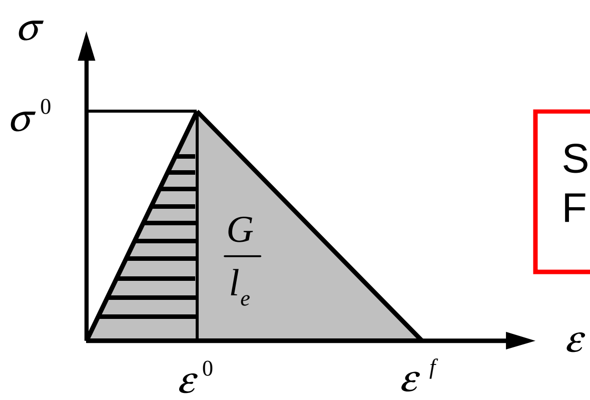


$$\varepsilon_{ges}^{el} = \frac{\Delta L}{L} = 0{,}1 \quad \Rightarrow \quad \varepsilon_{ele}^{el} = \frac{\Delta L}{L / 2} = 0{,}2$$



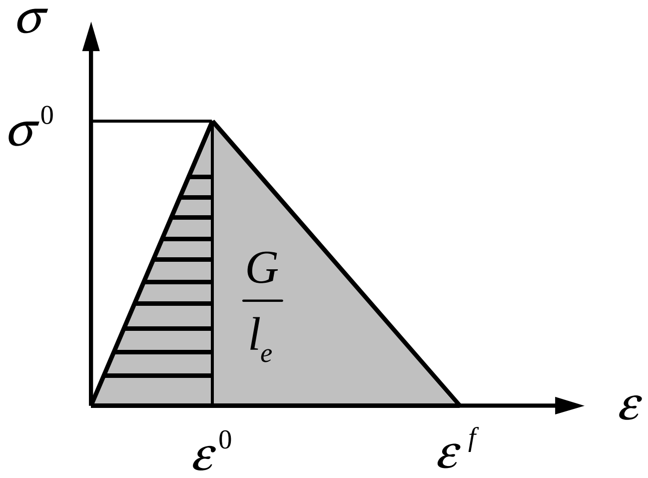
$$\varepsilon_{ges}^{el} = \frac{\Delta L}{L} = 0{,}1 \quad \Rightarrow \quad \varepsilon_{ele}^{el} = \frac{\Delta L}{L / 10} = 1{,}0$$

Spannungen aus lokaler $\sigma - \varepsilon$-Beziehung



Skalierung mit charakteristischer FE-Elementlänge

Problem der Objektivität (Pinho und Camanho gleichermassen)



- Gesamte Bruchenergie:

$$\frac{G}{l_e} = \frac{1}{2}\varepsilon^f \sigma^0 \rightarrow \varepsilon^f = \frac{2G}{l_e \sigma^0} \rightarrow l_e = \frac{2G}{\sigma^0 \varepsilon^f}$$

- Kriterium: $\varepsilon^f \geq \varepsilon^0$

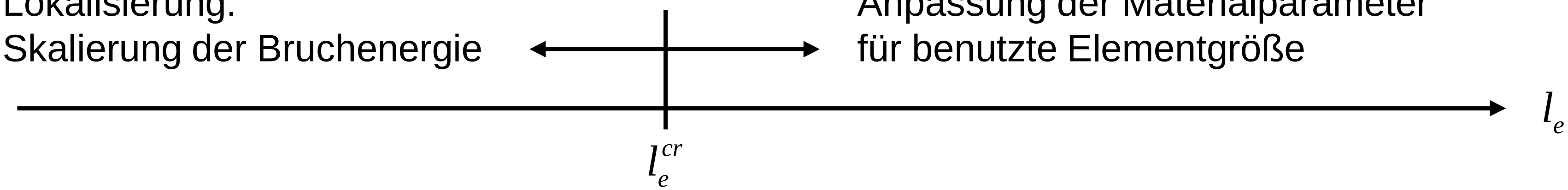
Daraus ergibt sich eine kritische, maximale Elementgröße

$$l_e^{cr} = \frac{2G}{\sigma^0 \varepsilon^0}$$

Diese ist Abhängig von den Materialparametern und liegt meist < 1mm!

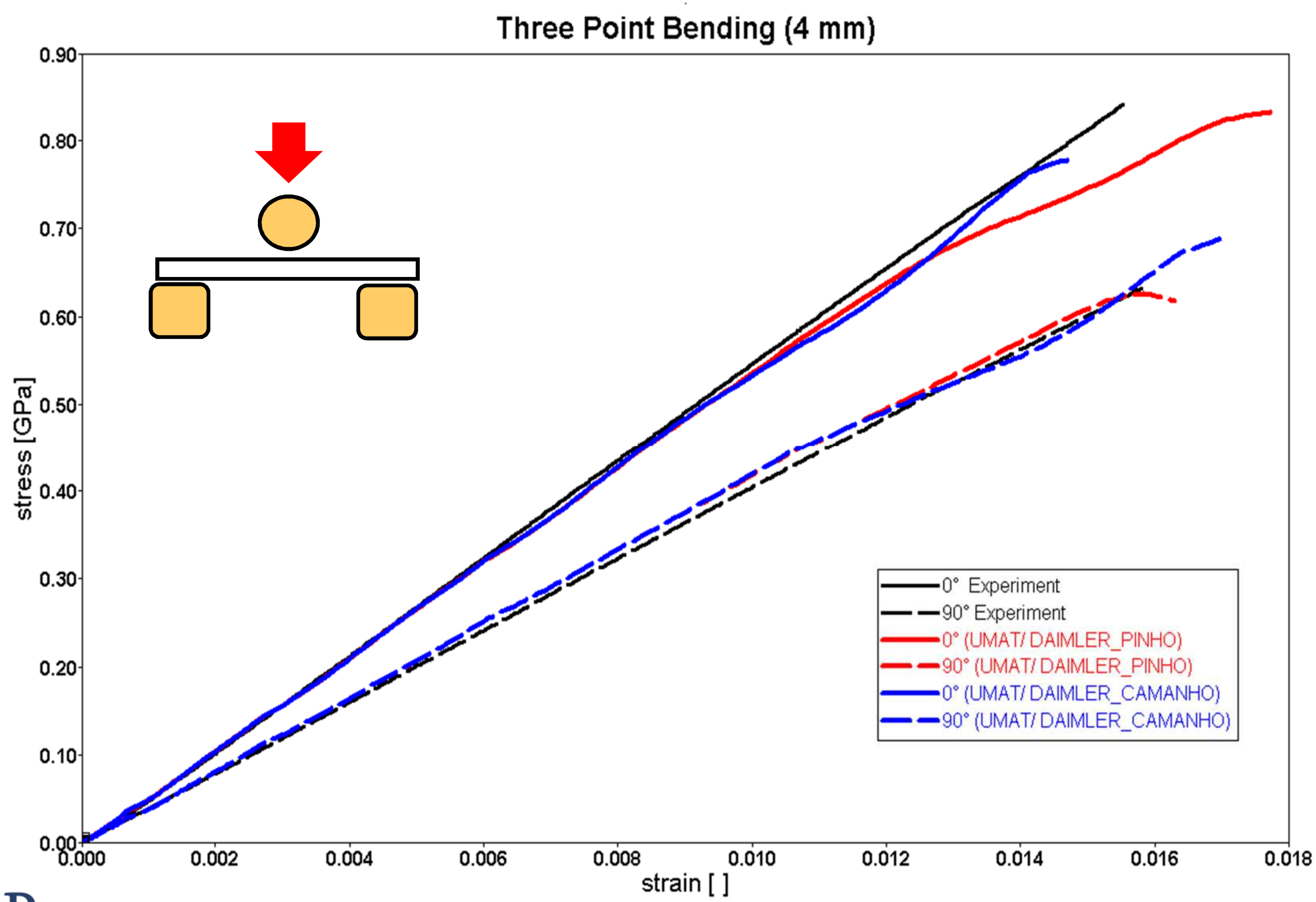
Lokalisierung:
Skalierung der Bruchenergie

Anpassung der Materialparameter
für benutzte Elementgröße



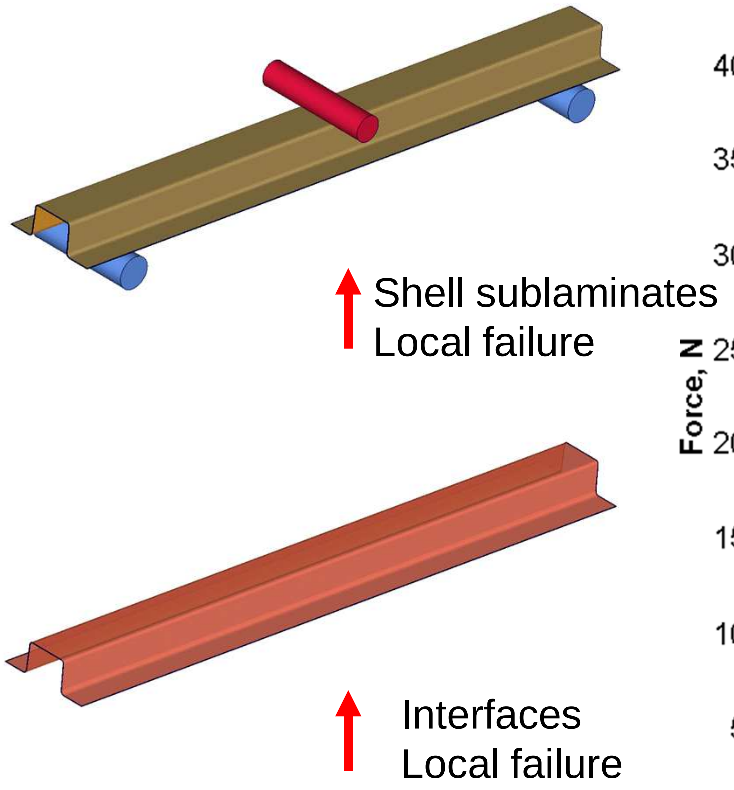
three point bending of flat specimen

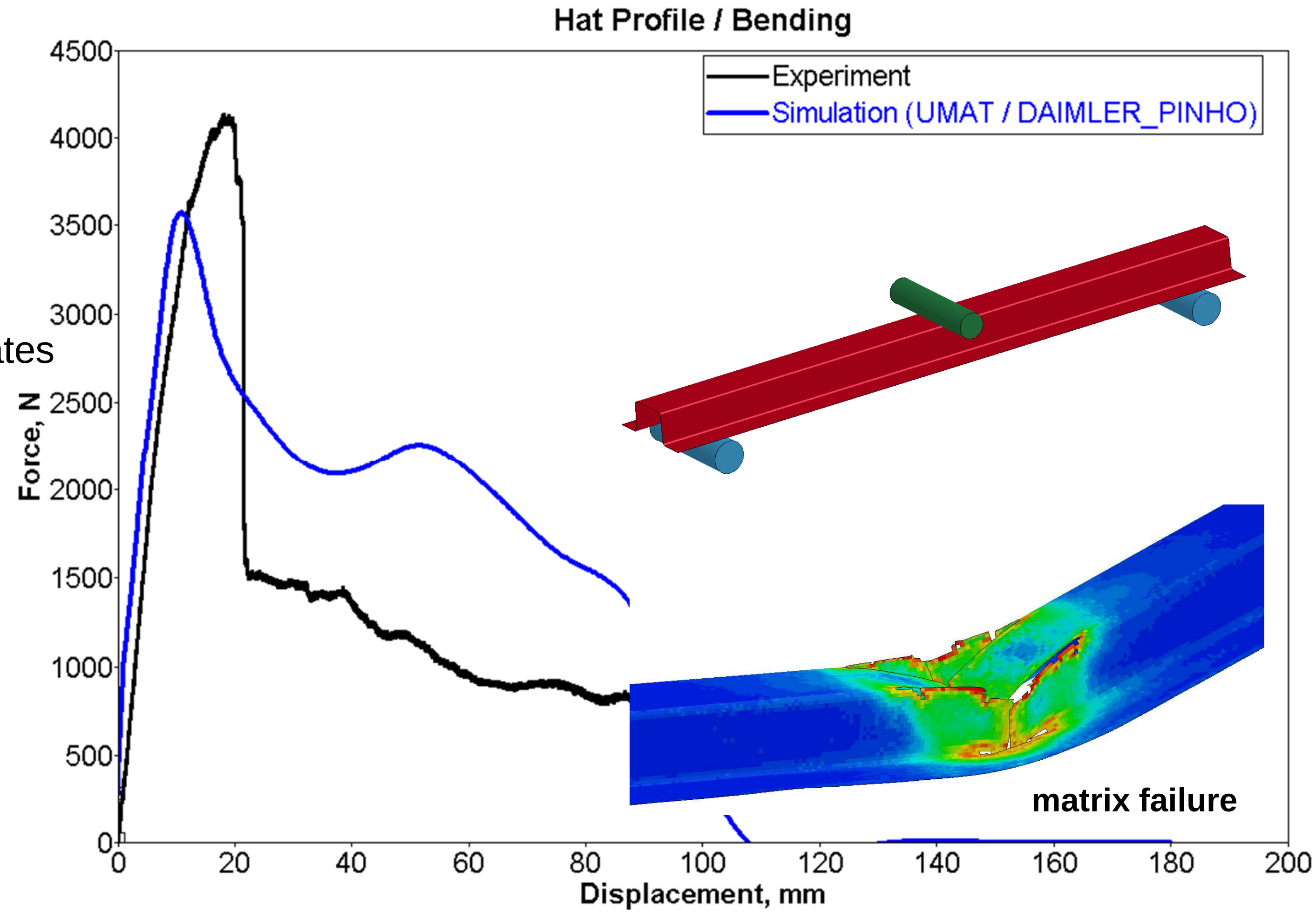
- single shell with a thickness of 4mm / carbon fibers in epoxy resin
  - $[0\ ]_{5s}$ (fibers in longitudinal direction of the plate)
  - $[90\ ]_{5s}$ (fibers in transverse direction of the plate)



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]





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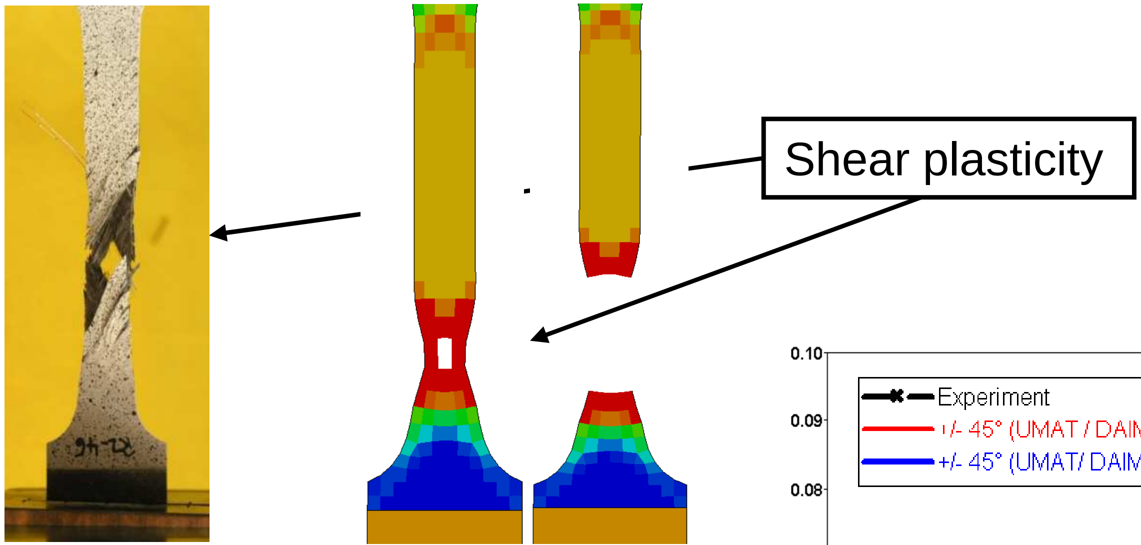
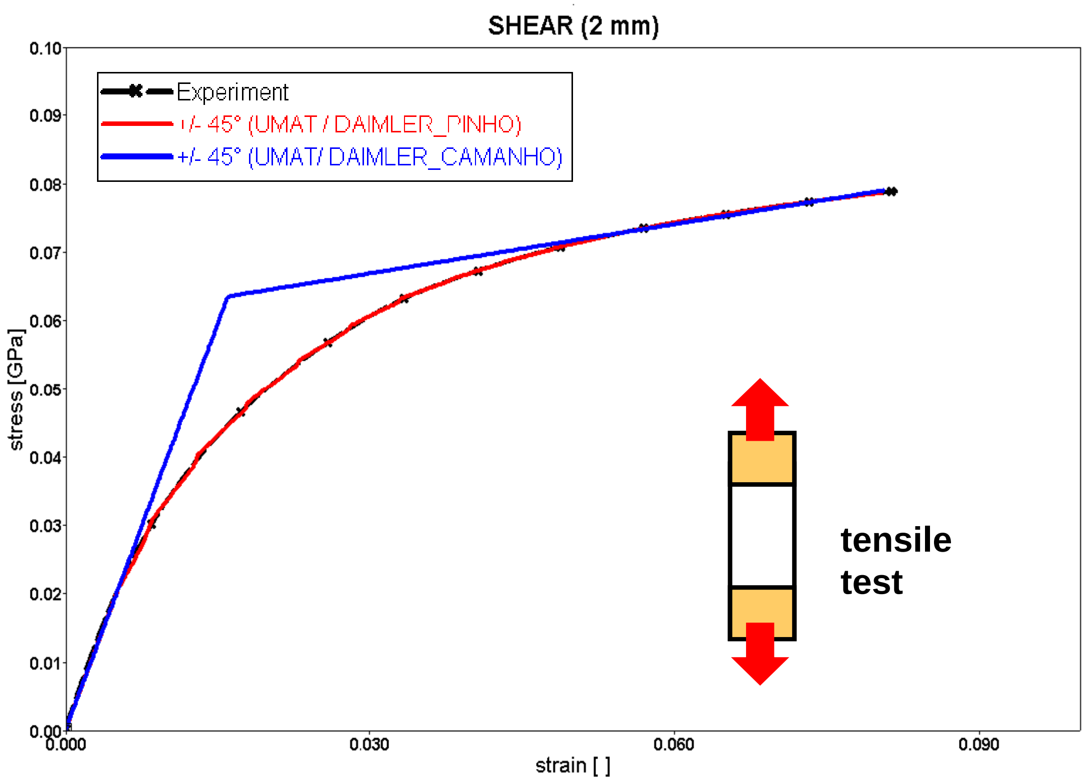
FEUP Faculdade de Engenharia

shear specimen

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



Experiment Simulation

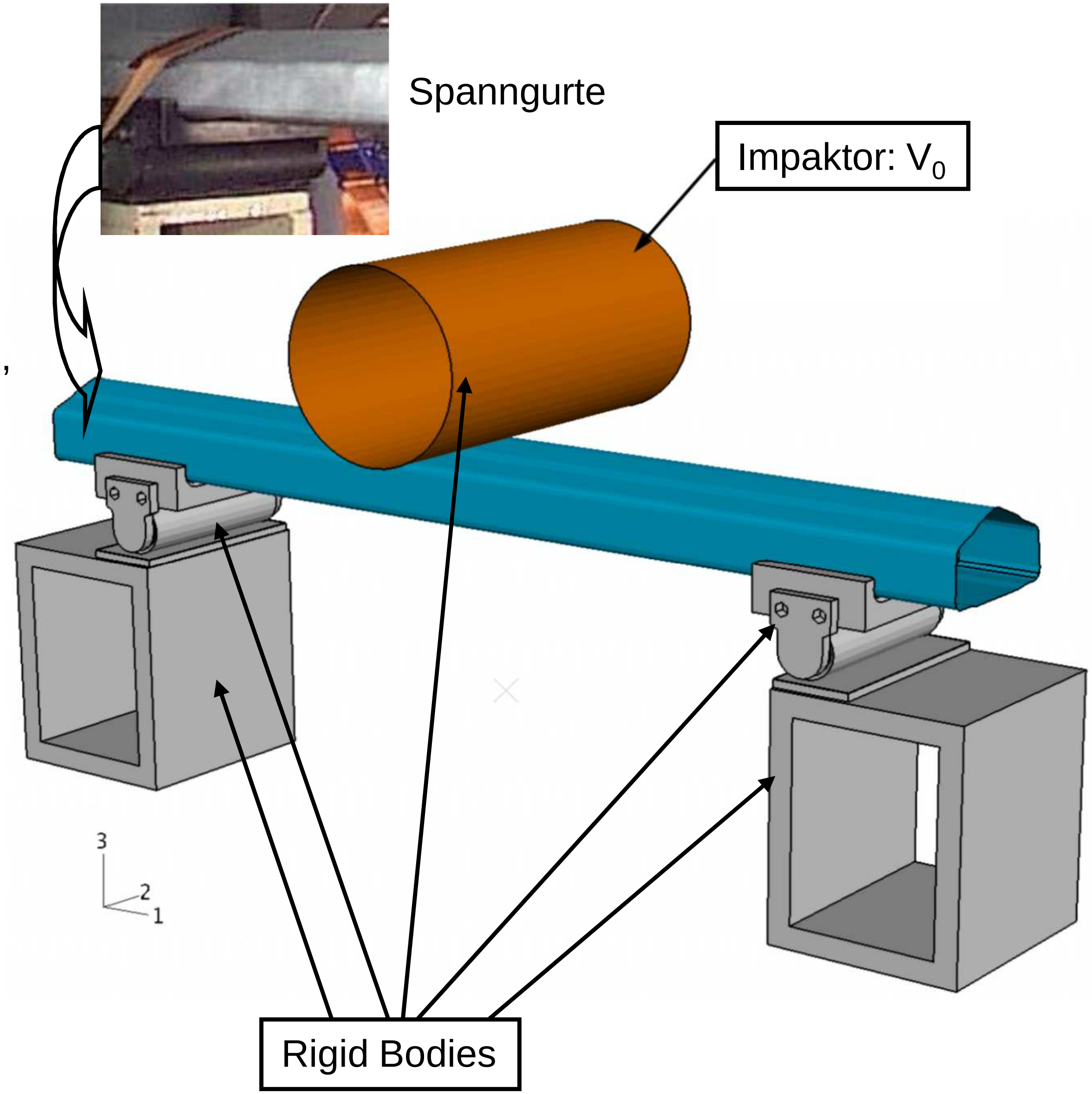


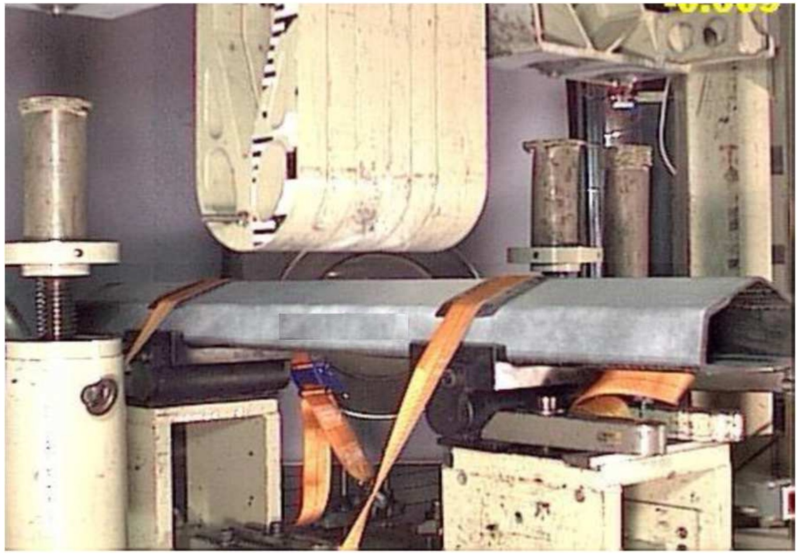
DAIMLER

Universidade do Porto FEUP Faculdade de Engenharia

3-Punkt-Biegung

- Auflager und Impaktor als starre Körper
- Spanngurte durch vorgespannte Balken
- Schweller mit geschichteten Schalenelementen (12 Schichten, *ELFORM=2*) und Materialmodell nach P. Camanho

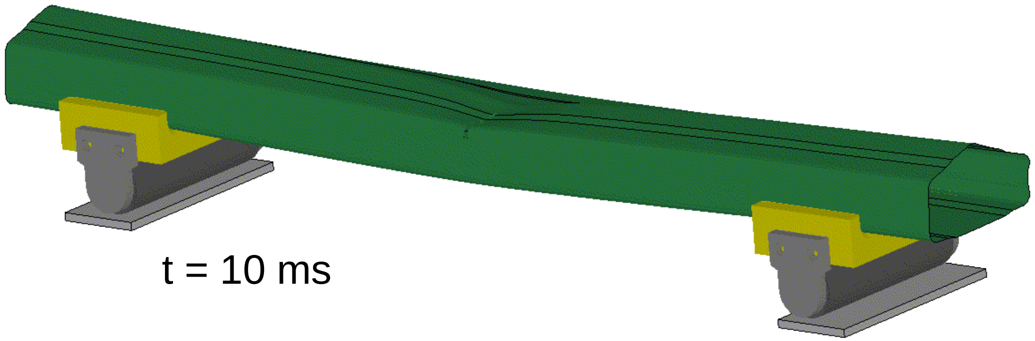




Preliminary results

3-Punkt-Biegung

LS-DYNA mit Materialmodell
nach P. Camanho (UserMat)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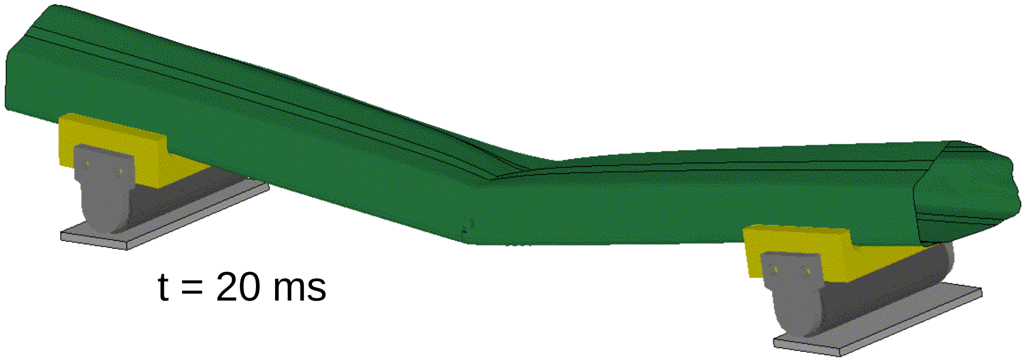
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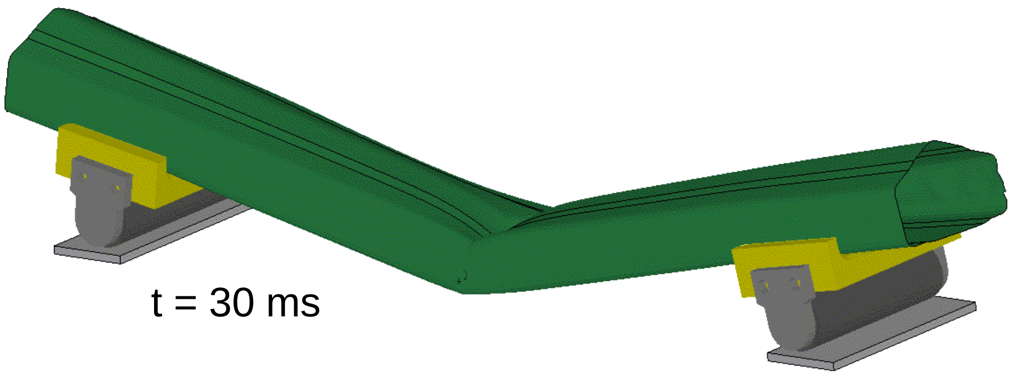
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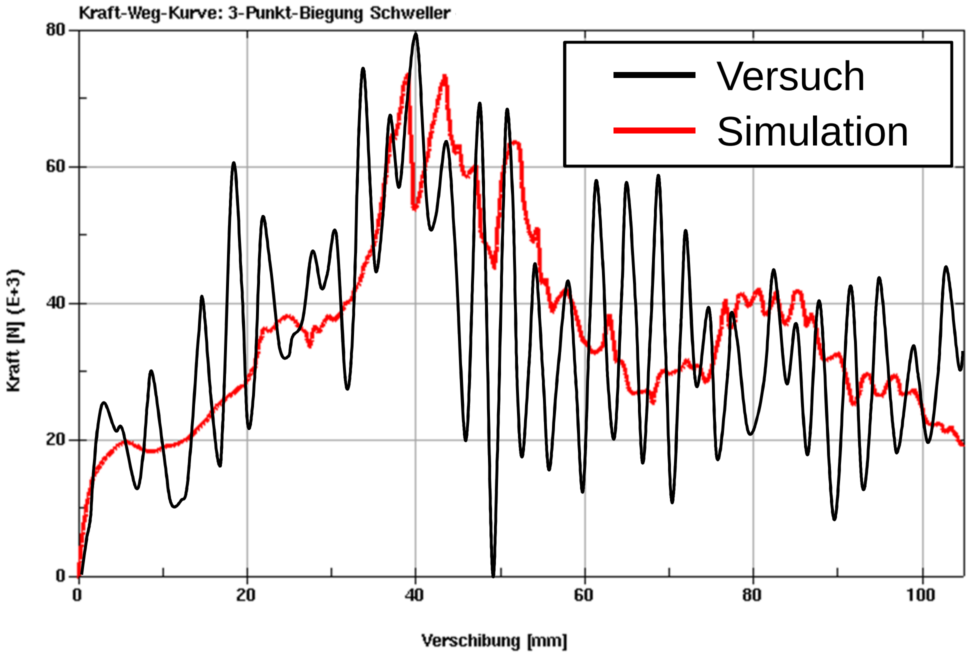

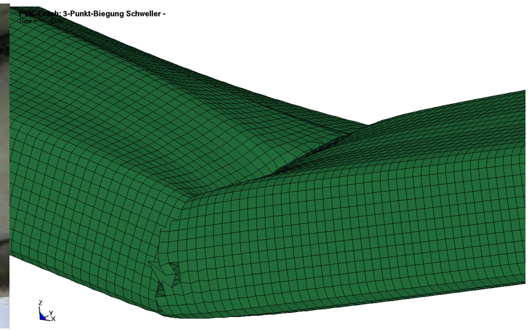

Summary

- 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

available since R7.0

- 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:
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Thank you!