Fracture simulation of hybrid Titanium-CF/PEEK laminates

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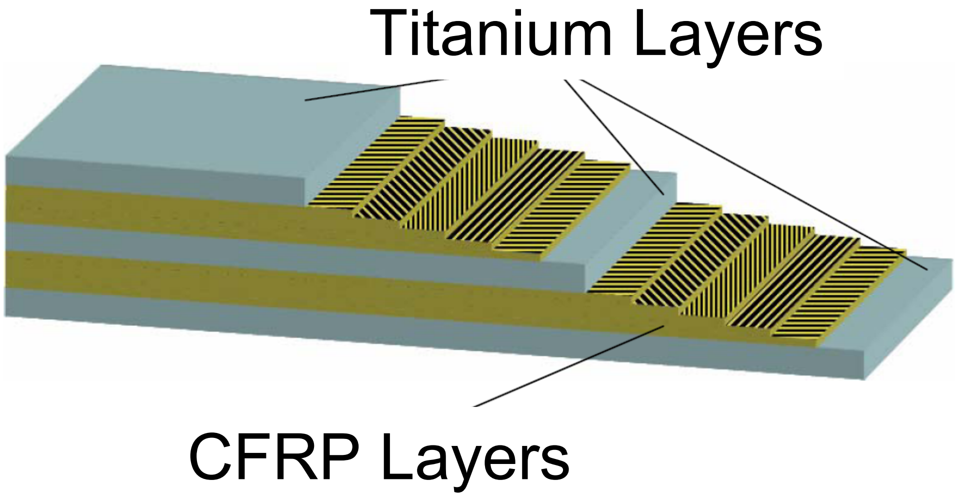
in der Helmholtz-Gemeinschaft

Outline

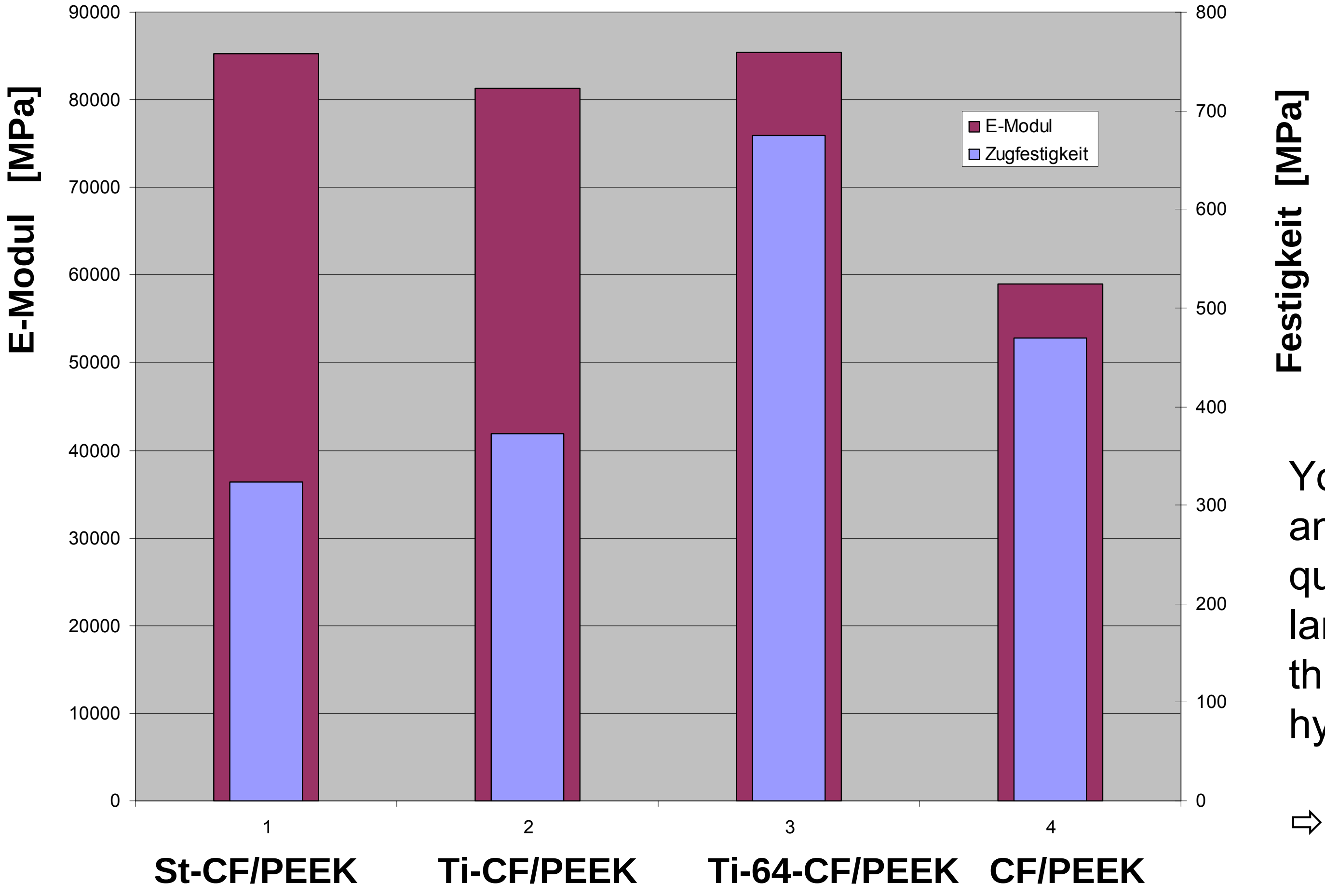
- Introduction
- Lamina and Interface (cohesive zone elements) modelling for CFRP (PEEK/AS4)
- Mixed Mode Bending (MMB) on unidirectional and multidirectional CFRP
  - Numerical Finite Element simulations
  - Experimental validation
- Outlook on numerical MMB simulation of multidirectional Ti/CFRP structures
- Summary and conclusion

Hybrid Ti-CFRP structure

- Hybrid Ti/CFRP layered structures combine advantageous properties for aerospace applications.
  - CFRP provides higher structural stiffness and resistance to fatigue effects.
  - Titanium protects the CFRP core from environmental effects and improves impact resistance.



Potential of different metals in hybrid laminates



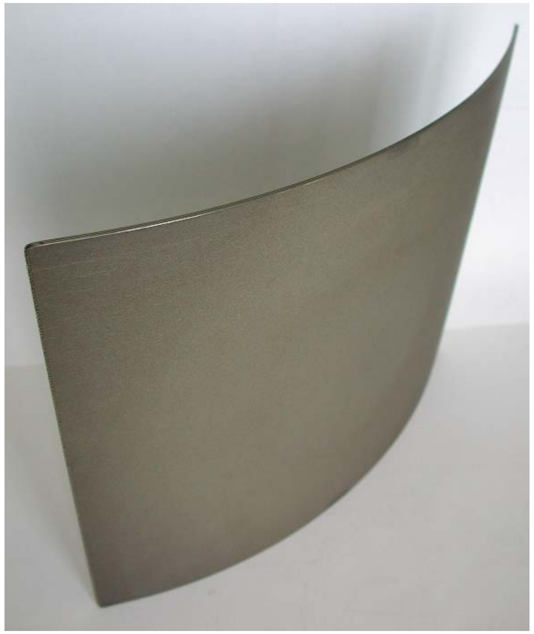
Young‘s Modulus and tensile strength of quasi-isotropic hybrid laminates of the same thickness and same hybrid density

⇨best: Ti-64-CF/PEEK

Thermoplastic CFRP-Matrix PEEK

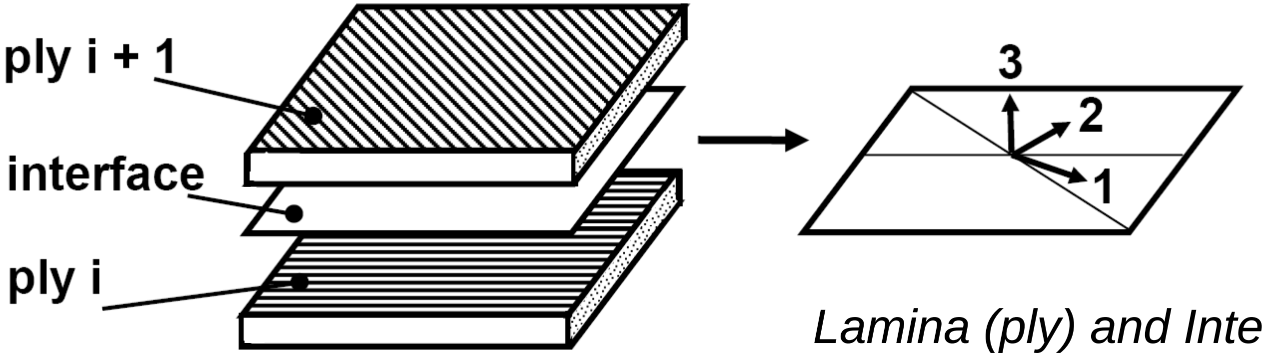
Advantages

- Good adhesion to metals
- Resistant up to 150°C (short term), 250°C (long term), respectively
- Easy to store, no expiry date of prepregs
- Environmentally friendly processing
- Formable by reheating
- Weldable
- Certified for aeronautic applications



Material models for CFRP-lamina and interlaminar interfaces

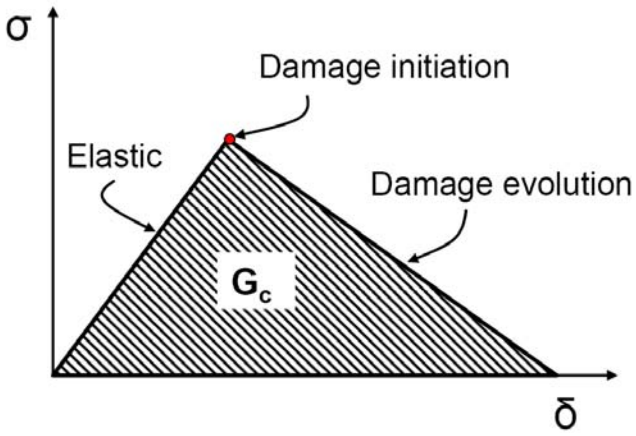
- Composite laminates exhibit complex damage states under mechanical loads as a result of:
  - **intralaminar** damage modes, i.e. matrix cracking, fiber rupture (orthotropic ply damage by Hashin's reinforced ply damage model)
  - **interlaminar** damage modes or delamination (out of plane damage by cohesive zone approach)



Lamina (ply) and Interface combination

Intralaminar ply damage model (Hashin, 1981)

Undamaged ply response:
orthotropic linear elastic material
under plane stress



$$d_{fiber,matrix,shear} = \frac{\delta_f(\delta-\delta_0)}{\delta(\delta_f-\delta_0)}$$

Damage initiation:

- Tensile fiber rupture
- Compressive fiber buckling/kinking
- Transverse tensile matrix cracks
- Transverse compressive & shear matrix crushing

Damage Evolution:
Based on the displacement & stress
for each of the 4 damage modes
⇨ 3 independent damage variables ***d***
⇨ effective density of micro-defects
degrading the material stiffness

$$\vec{\sigma} = \underbrace{\frac{1}{1-\nu_{12}\nu_{21}}\begin{pmatrix} \frac{E_{11}}{(1-d_f)} & E_{22}\nu_{12} & 0 \\ E_{11}\nu_{21} & \frac{E_{22}}{(1-d_m)} & 0 \\ 0 & 0 & \frac{G}{(1-d_s)} \end{pmatrix}}_{Stiffness\ matrix} \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \end{bmatrix}$$

Interlaminar damage: cohesive zone interface elements

Very thin intermediate glue material**:** a traction-separation description for separation under mixed mode is used.

Damage initiation:

Quadratic nominal stress criterion $$\sum_{i=n,s,t}\left(\frac{t_i}{t_i^{\,0}}\right)^2=1$$

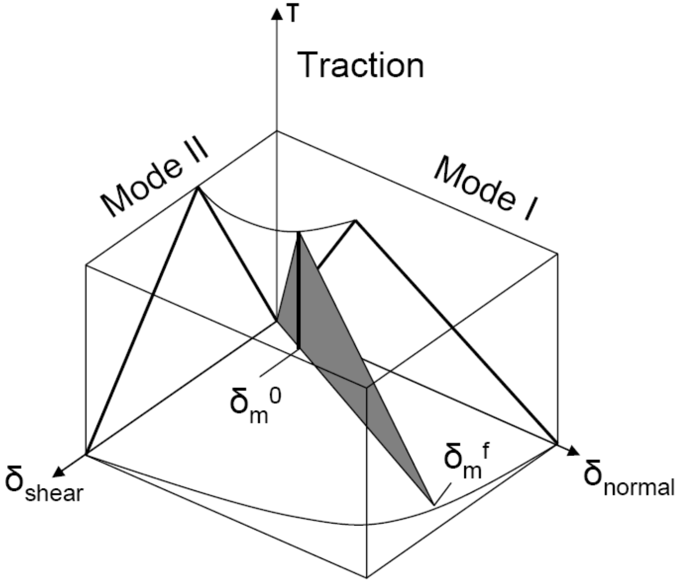
Damage Evolution:

Constitutive equation (if $\delta_n > 0$):

$$\begin{bmatrix}\tau_s\\ \tau_t\\ \tau_n\end{bmatrix}=\begin{pmatrix}(1-d)K & 0 & 0\\ 0 & (1-d)K & 0\\ 0 & 0 & (1-d)K\end{pmatrix}\begin{bmatrix}\delta_s\\ \delta_t\\ \delta_n\end{bmatrix}$$

K = initial stiffness of the interface

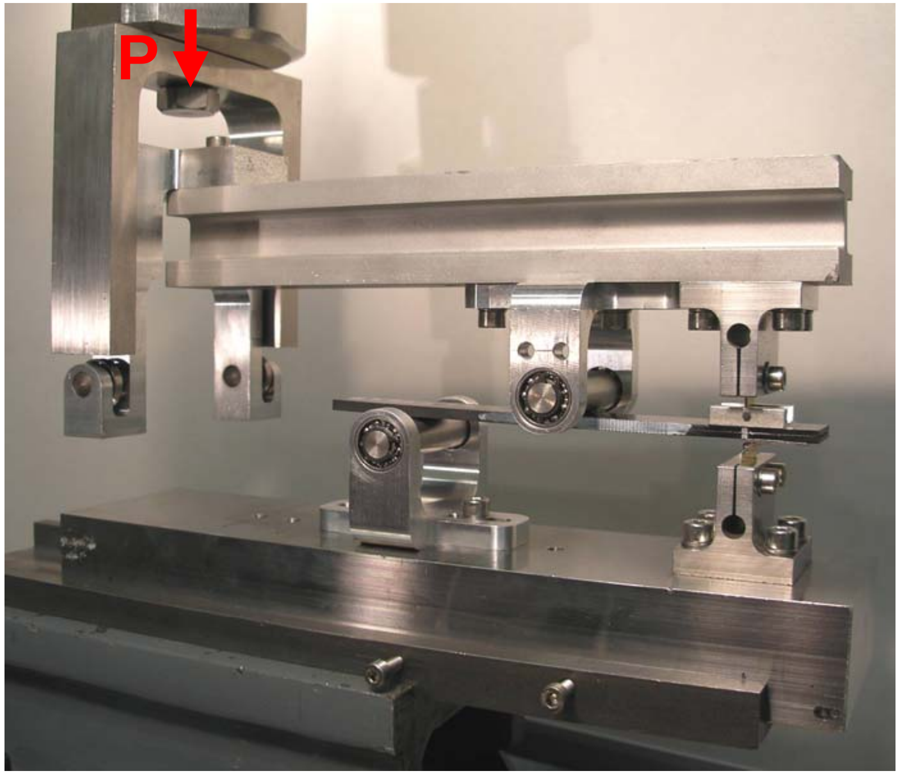
Damage parameter: $$d=\frac{\delta_m^{\,f}(\delta_m^{\max}-\delta_m^{\,0})}{\delta_m^{\max}(\delta_m^{\,f}-\delta_m^{\,0})}$$



$$G_{IC}+(G_{IIC}-G_{IC})\left(\frac{G_{II}}{G_T}\right)^{\eta}=G_C$$

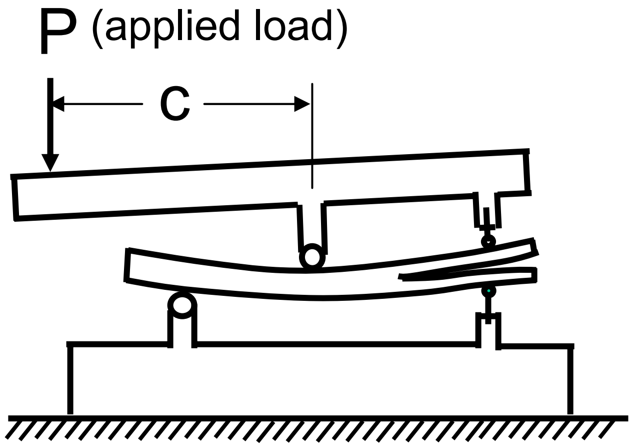
Energy based damage propagation criteria under mixed mode

Determination of material model parameters in mixed mode bending (MMB)



Specimen: 24-plies, AS4/PEEK
width=25 mm, length=150 mm, thickness=3.12 mm
Initial delamination length a_0=50 mm

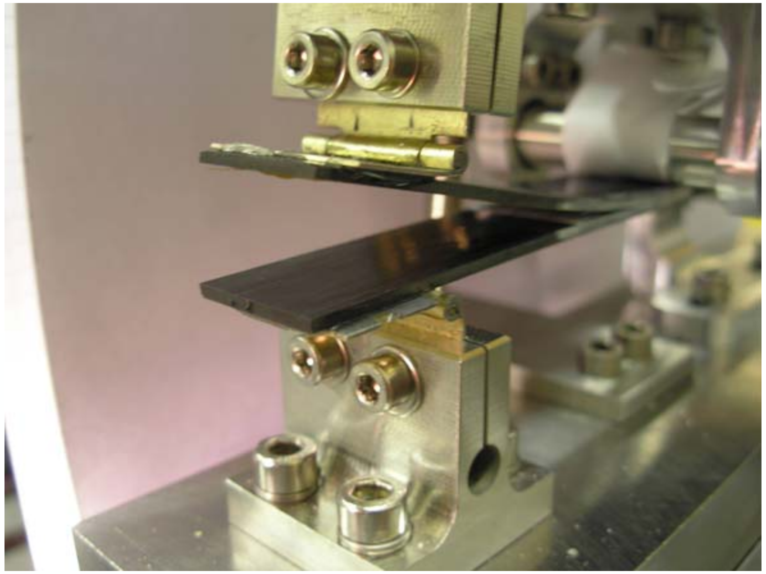
Superposition of mode I + mode II
Tests conducted by a single load, P.

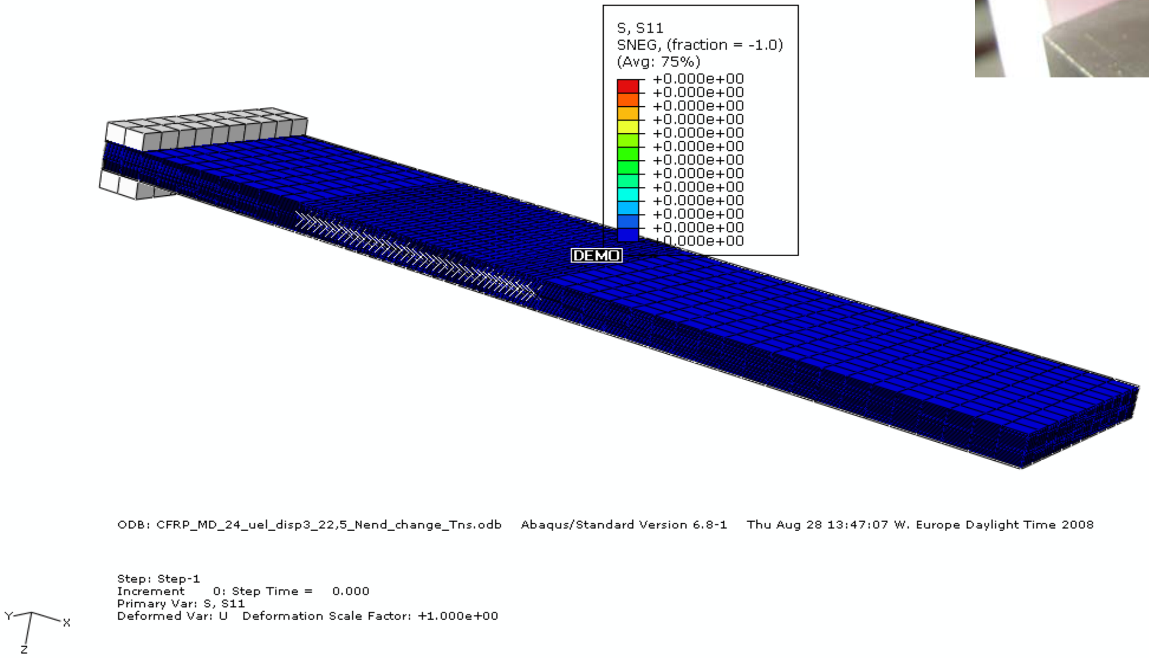


Result: G_I, G_{II}
(applied load (P), crack length (a), mode mixity (m), specimen geometry)

Simulation of the MMB experiment

- A <u>fully parametric model</u>
- Lamina: Hashin ply damage model, SC8R elements
- Interface: Cohesive elements (User defined elements)
- Load: Mixed mode
- Solver: ABAQUS implicit





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ODB: CFRP_MD_24_uel_disp3_22,5_Nend_change_Tns.odb    Abaqus/Standard Version 6.8-1    Thu Aug 28 13:47:07 W. Europe Daylight Time 2008

Step: Step-1
Increment     0: Step Time =    0.000
Primary Var: S, S11
Deformed Var: U   Deformation Scale Factor: +1.000e+00
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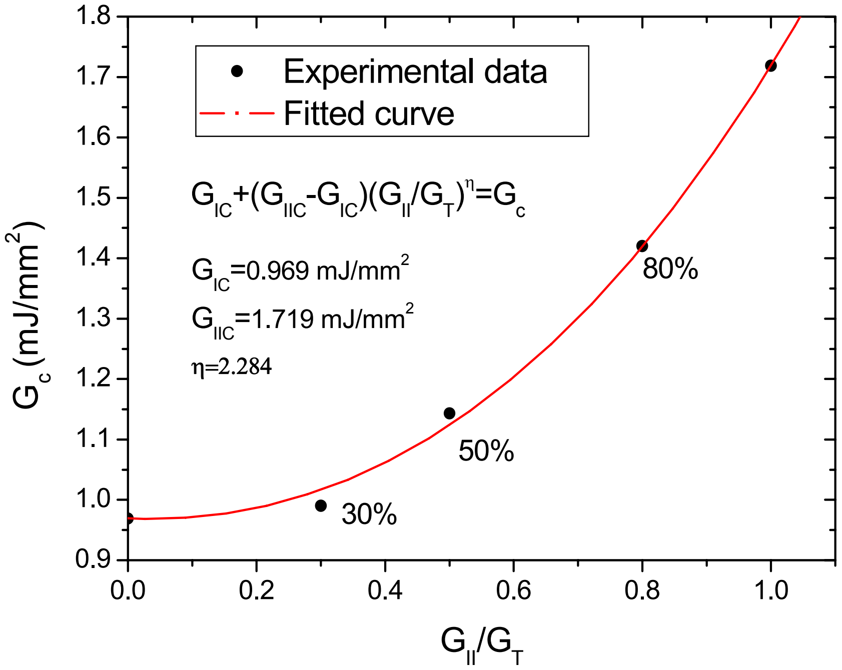
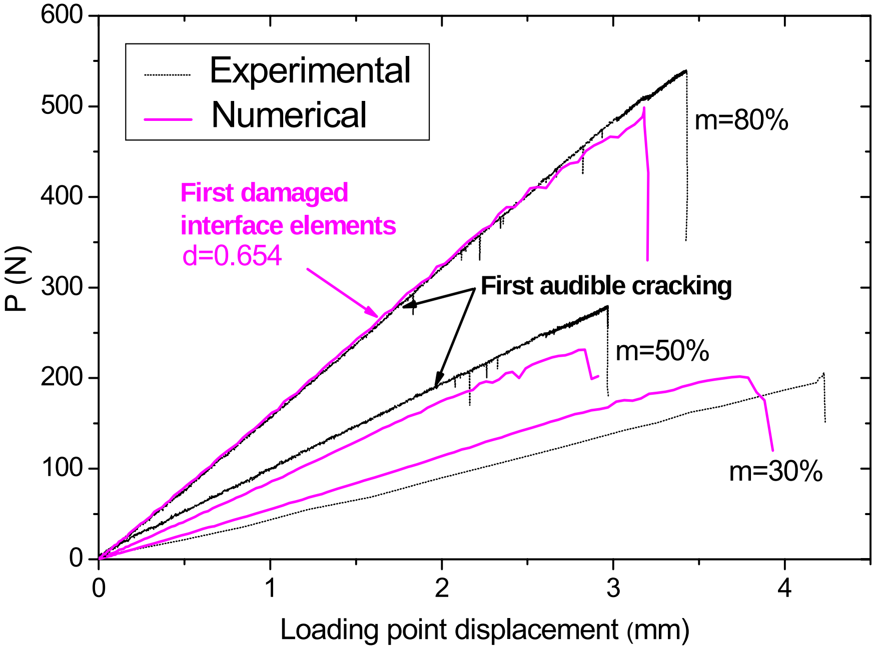
Comparison of numerical and experimental results on unidirectional CFRP-laminates





Experimental G_C values

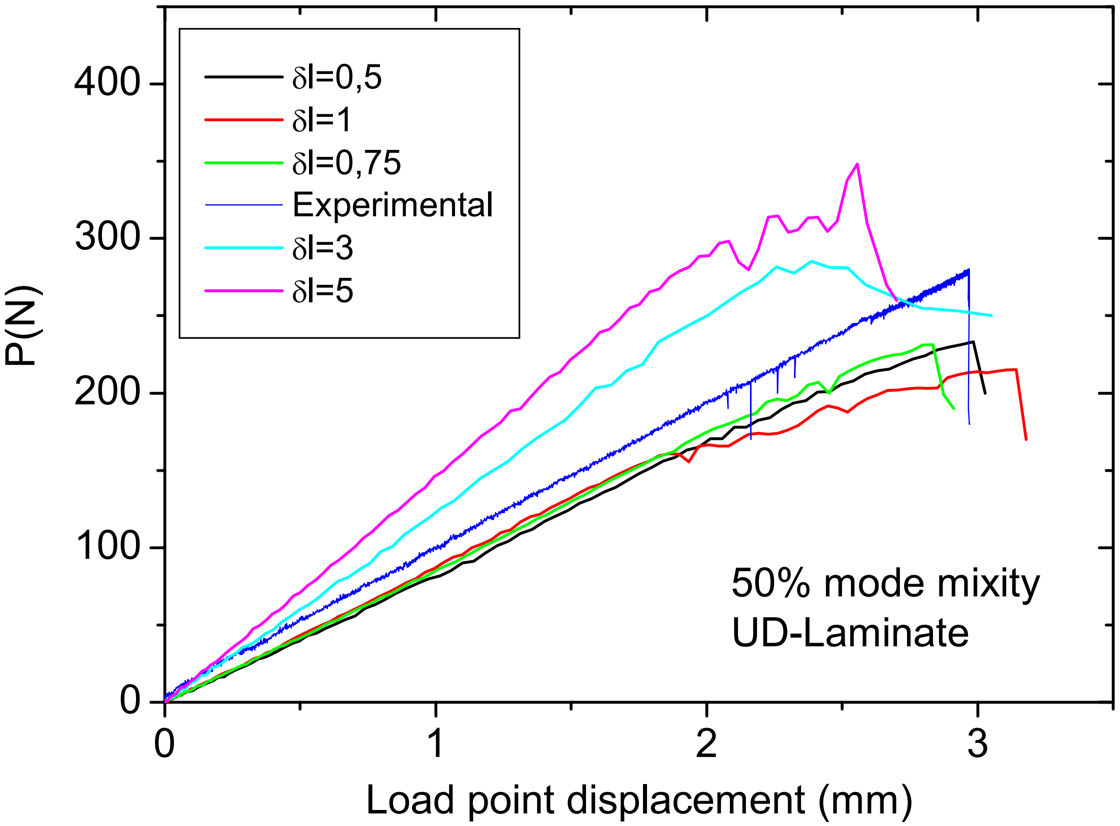
average from at least 2 experiments for each mode mixity

Fitted curve ⇨ Parameter η

Load displacement curves

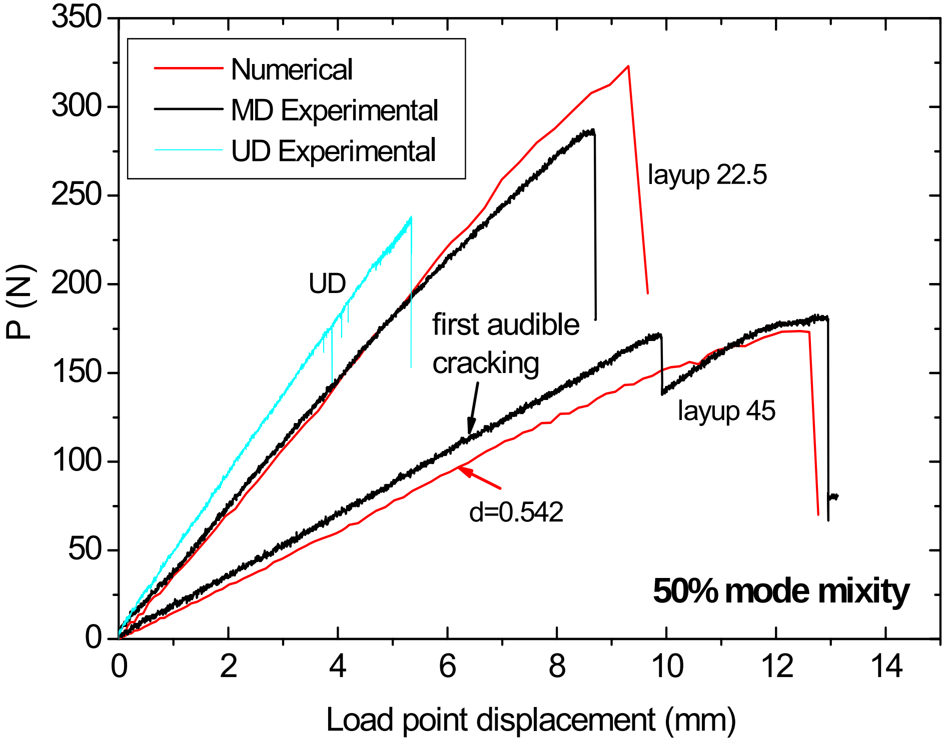
d = damage parameter of the
interface elements

Mesh dependence study on the numerical model



Mesh dependence study ⇨ stable results with a lenght of the cohesive interface elements of δl ≤ 1mm

Analytical, experimental, and numerical MMB results on multidirectional (MD) laminates



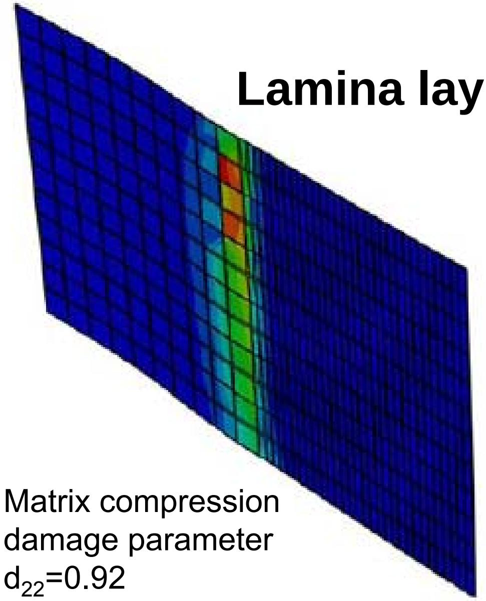
Lay-up	Analytical G_c (mJ/mm^2)	Experimental G_c (mJ/mm^2)
$(+22,5/-22,5)_{24}$	1,71	1,59
$+45/-45/0_3/-45/0/+45/0_2/+45/-45/\mathbf{d}/-45/+45/0_2/+45/0/-45/0_3/-45/+45$	1,92	1,73
UD	1,32	1,19

- ➢ Fracture toughness of MD laminates > UD fracture toughness
- ➢ Fiber angle orientation & stacking sequences ⇨ Global load- displacement response
- ➢ 45° layup ⇨ highest MMB interlaminar fracture toughness (45.7% increase)

Fracture behavior of UD and MD CFRP-laminates

Multidirectional laminates have higher resistance to through thickness fracture compared to UD laminates, owing to:

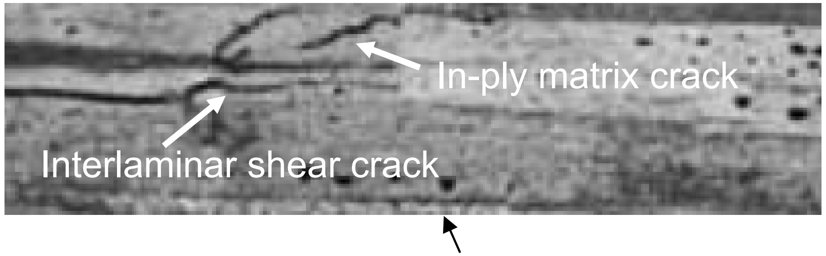
⇨crack jumping, fiber bridging, intraply energy absorption, curved crack fronts in the vicinity of fracture surfaces.



Matrix compression damage parameter d_{22}=0.92

Layer adjacent to delamination plane in a 45° MD-lay up

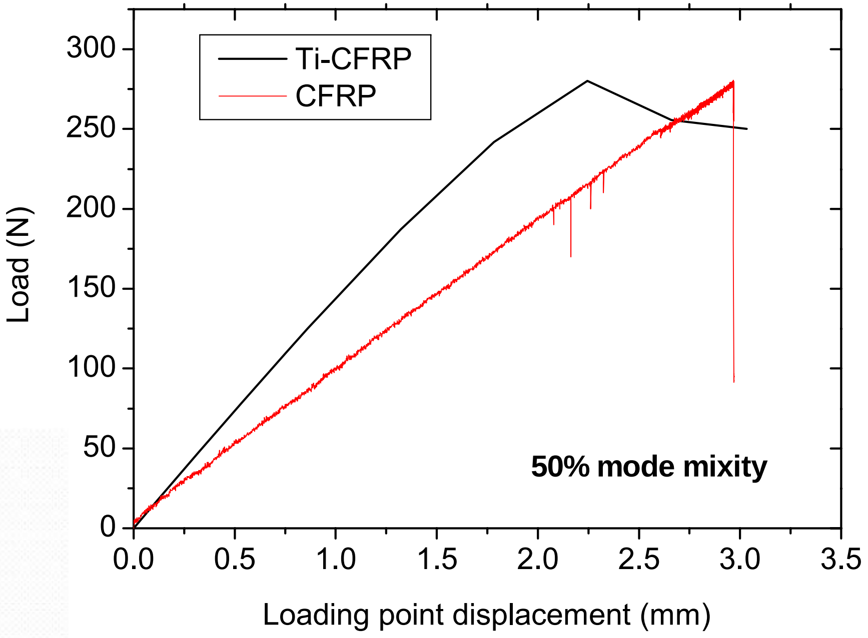
Curved crack front in 45° layup



Gilchrist M.D, Svensson N., Compos Sci and Tech. 1995; 55:195-207

Numeric simulation of MMB in Ti/CFRP-hybrid laminate

- 3 Ti – layers, 0.5 mm thick, Ti-6Al-4V, elastic-plastic properties
- 2 – CFRP-layers, 1.12 mm thick, PEEK/AS4, 8 plies each, lay up $[0/0]_{8s}$,
- between Ti and PEEK/AS4 interface: cohesive elements



ODB: Ti_CFRP_1_try1_elasticmetal.odb   Abaqus/Standard Version 6.8-1   Thu Oct 23 16:07:01 W. Europe Daylight Time 2008

Step: Step-1
Increment   0: Step Time =   0.000

Summary and conclusion

- The mixed mode interlaminar delamination of UD and MD PEEK/AS4 laminates can be modeled successfully with cohesive zone approach (UEL in ABAQUS).
- MMB simulations of UD and MD laminates give very close results to experiments
- MD laminates have higher mixed mode fracture toughness compared to UD laminates
- In MD laminates crack jumping from interface to the adjacent disoriented layer is observed
- Observed crack jumping, intraply damage, and curved crack front will rise the fracture toughness of MD laminates (~ 45%)
- The cohesive elements can be used in Ti/AS4-PEEK interface to further model the MMB damage in hybrid Ti/CFRP laminates

Acknowledgement

- Colleagues at DLR Stuttgart for manufacturing the CFRP lay-ups
- Herr H. Hinderlich for experimental support

Thank you for your Attention!