Interaction of matrix cracking and diffuse delamination in cross-ply composites

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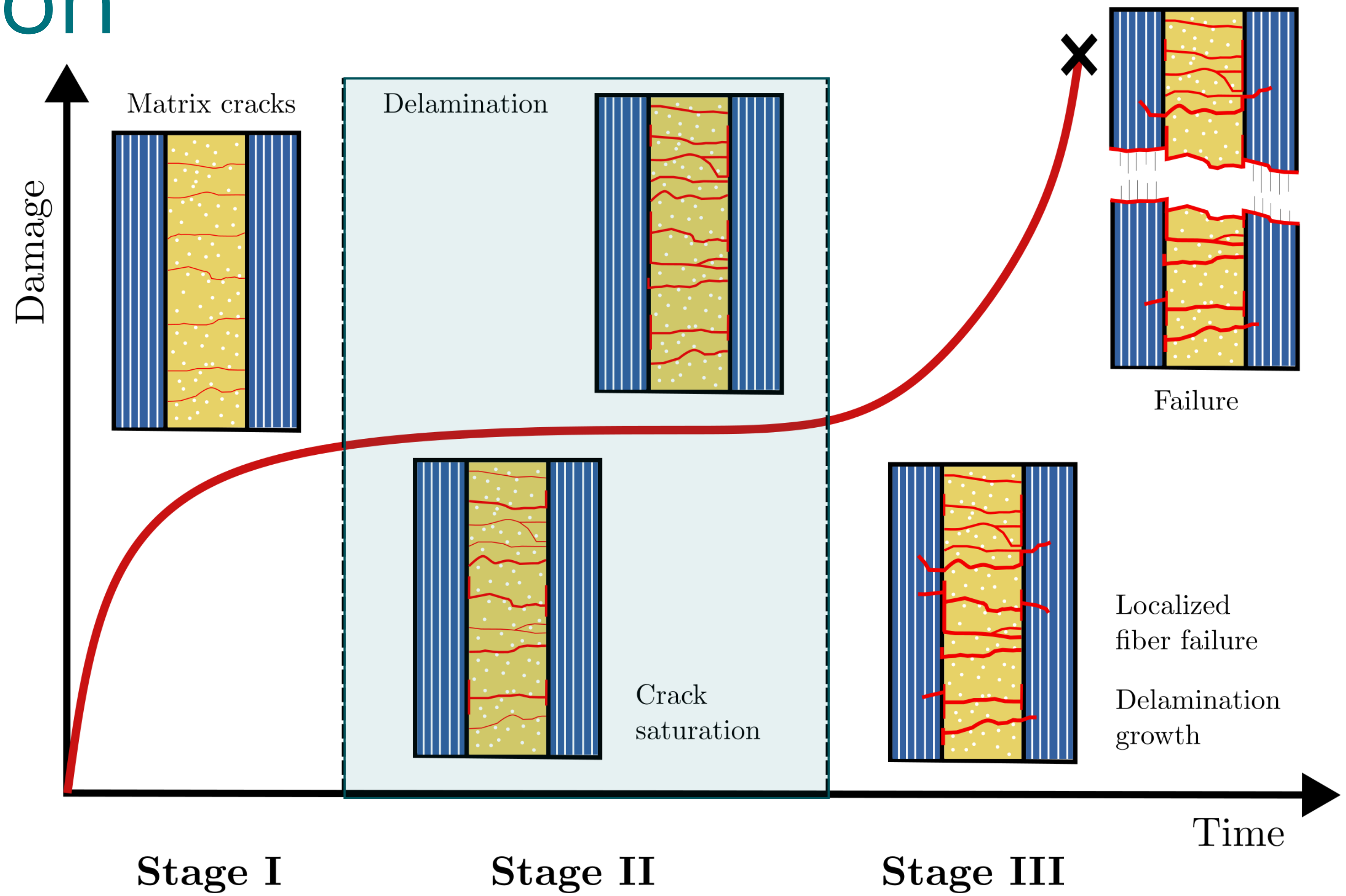
ECCOMAS

Composites 2025

Move mountains

Motivation



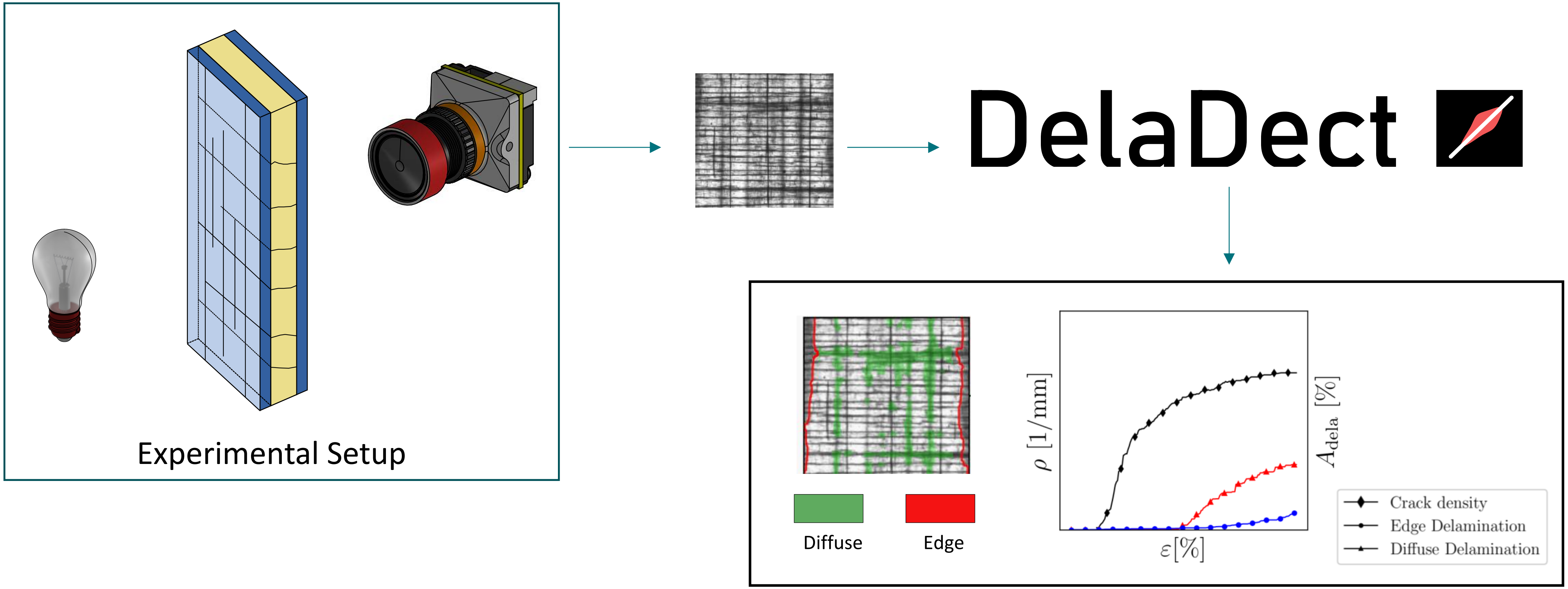
- The damage history from Stage I also influences Stage II, so both stages need to be modelled.

Motivation

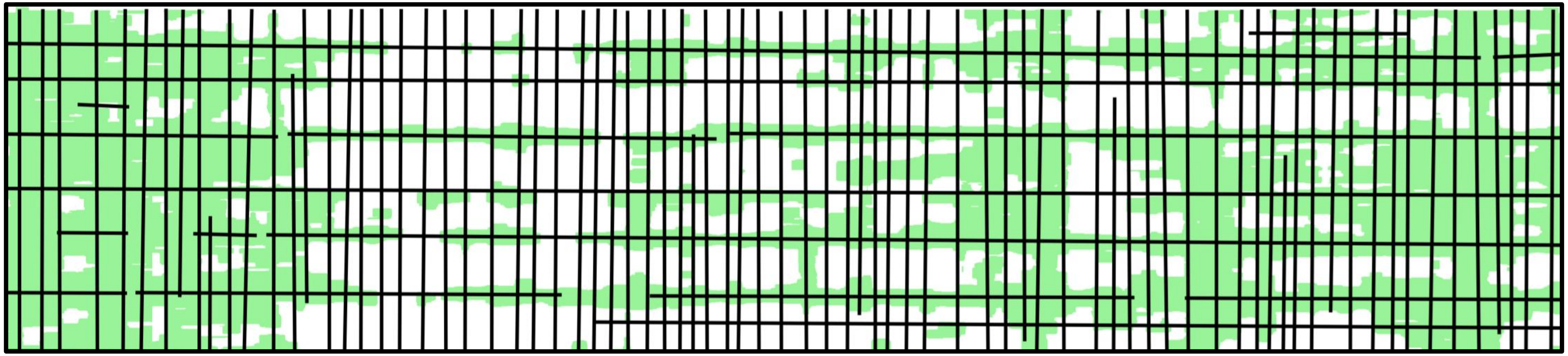
How does matrix cracking influence the onset and progression of delamination in laminates?

- → Qualitatively
- → Quantitively (?)

Experimentally, we observed…



Modelling approach



Delamination

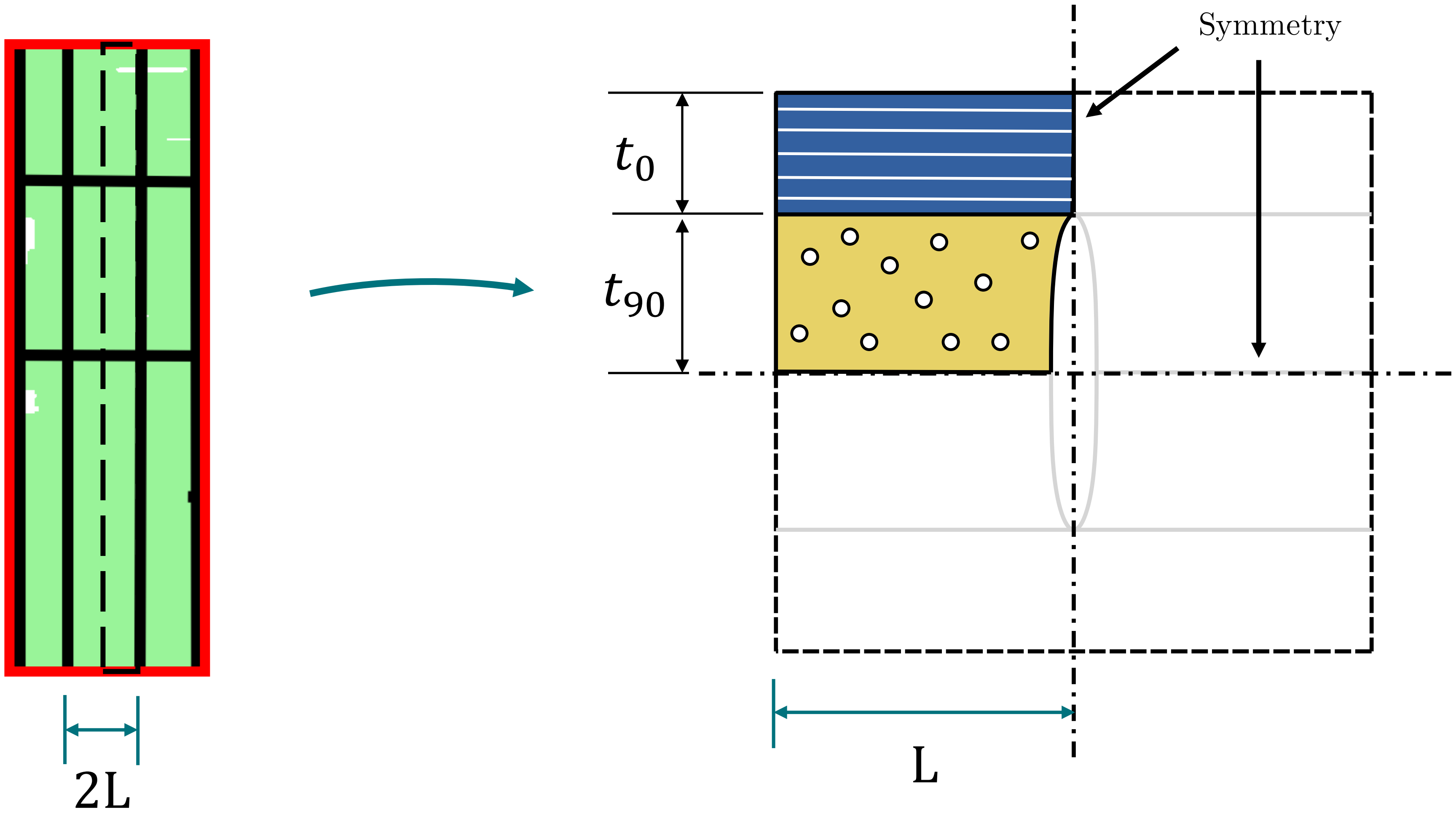
Matrix cracks

Glass/Epoxy

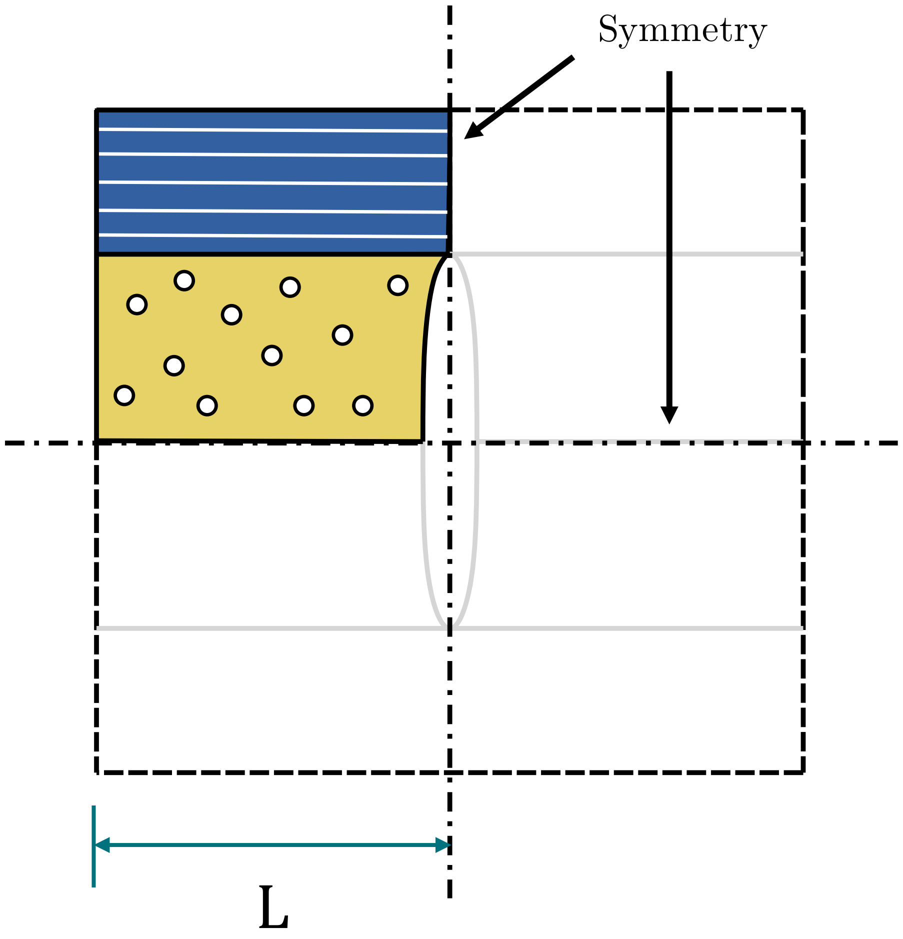
Cross-ply [0/90_3/0]

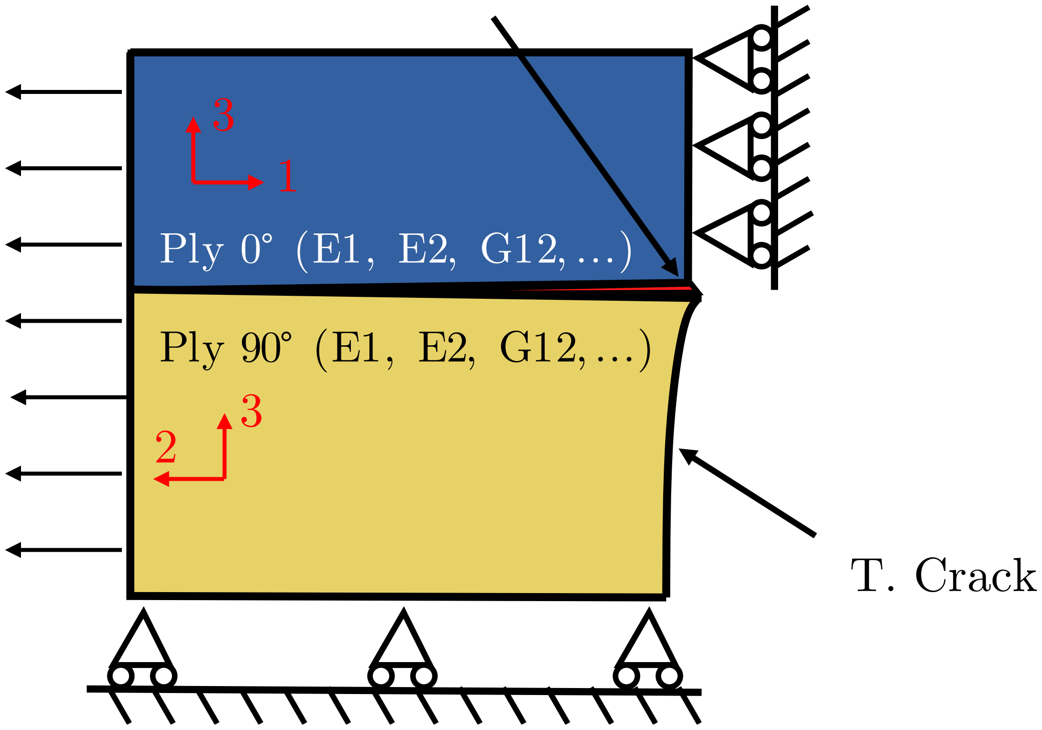
Ply thickness = 0.8 mm

Modelling approach



Modelling approach





Unit Cell Model

Modelling approach

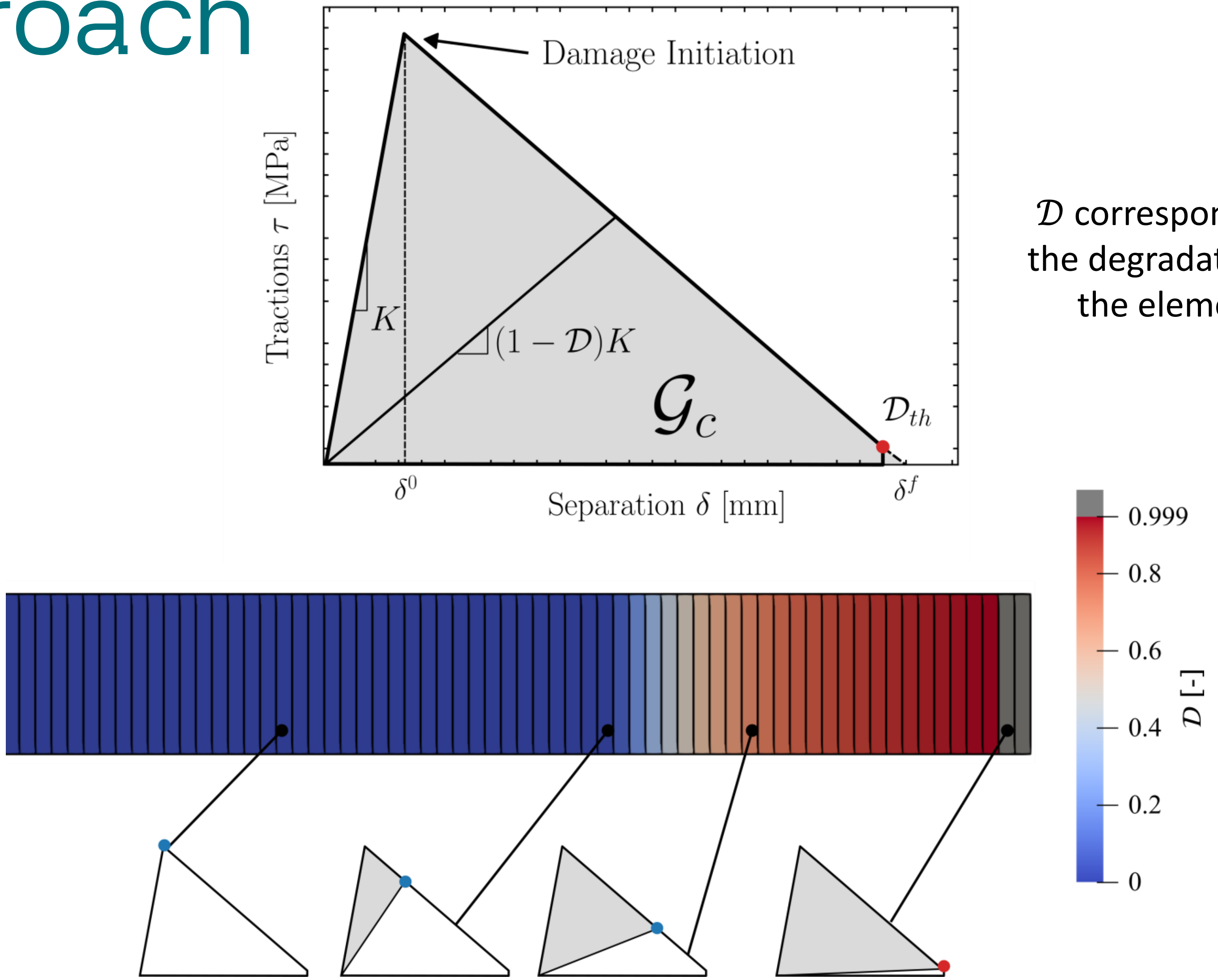
Cohesive Settings
Damage Initiation:

$$\left\{\frac{\langle \tau_n \rangle}{\tau_n^0}\right\}^2 + \left\{\frac{\tau_s}{\tau_s^0}\right\}^2 = 1$$

Damage Evolution: Linear

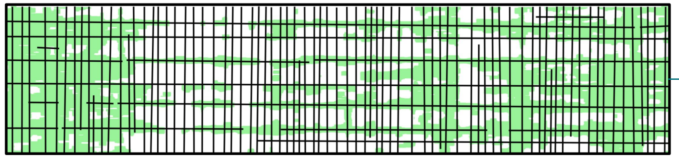
Mixed mode behavior: B-K Law

$$\mathcal{G}_{\mathrm{C}} = \mathcal{G}_{\mathrm{IC}} + (\mathcal{G}_{\mathrm{IIC}} - \mathcal{G}_{\mathrm{IC}}) \left(\frac{\mathcal{G}_{\mathrm{II}}}{\mathcal{G}_{\mathrm{T}}}\right)^{\eta}$$



$\mathcal{D}$ corresponds to the degradation of the element

Modelling approach

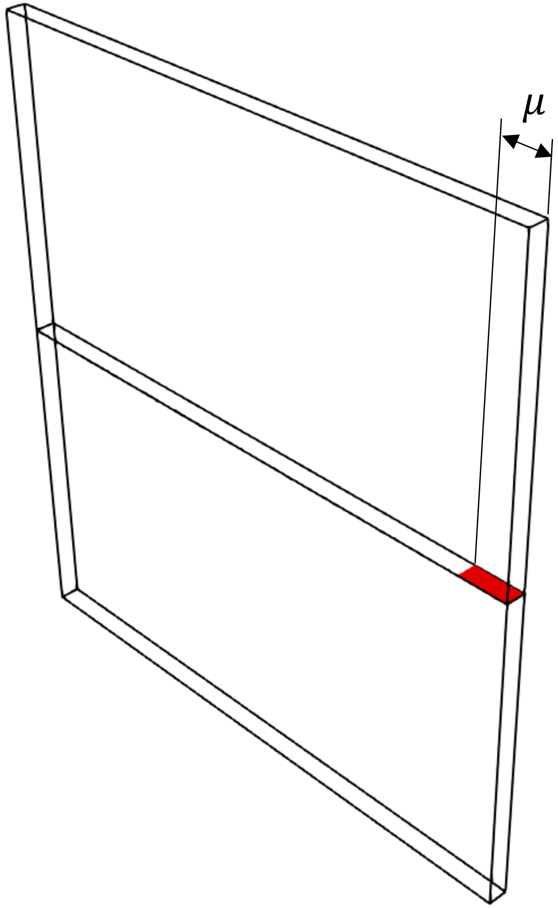


Relative Delamination:

$$\bar{\mu} = \frac{\mu}{L} \Leftrightarrow \bar{\mu} = \frac{A_{del}}{A_{specimen}}$$

Crack Density:

$$\rho = \frac{1}{2L}$$

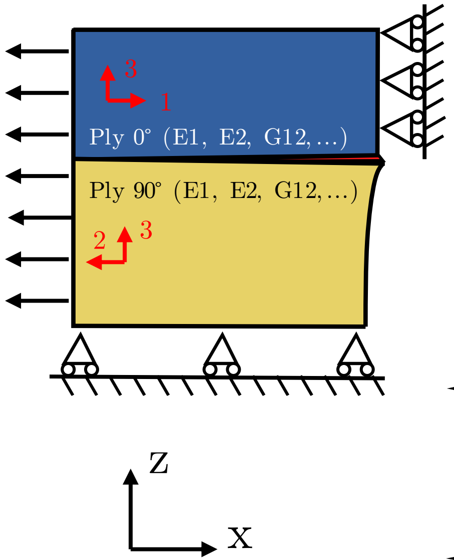


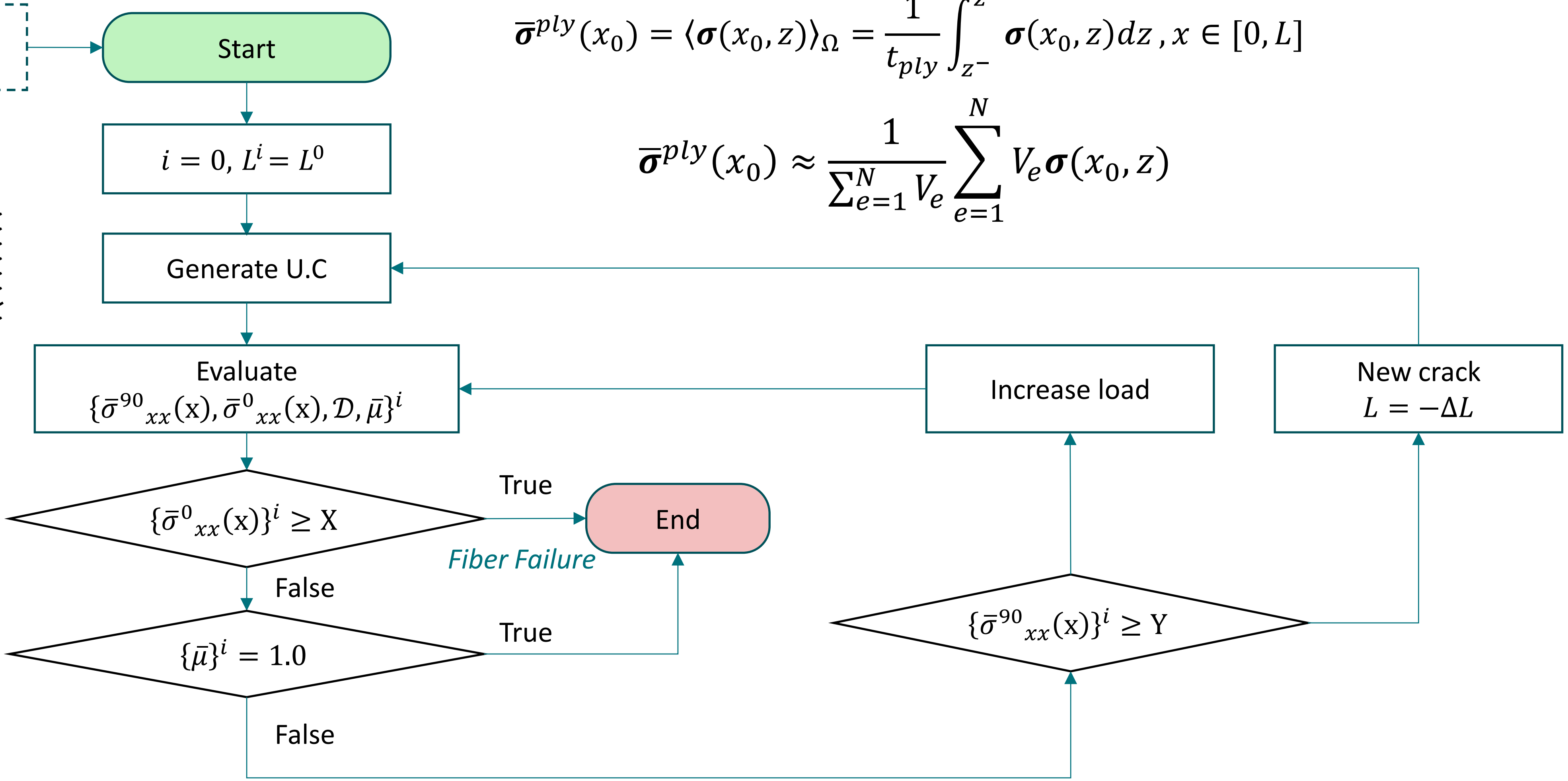
Once the element reaches the damage threshold $\mathcal{D}_{th}$, it is considered to be delaminated.

Methodology – Crack evolution

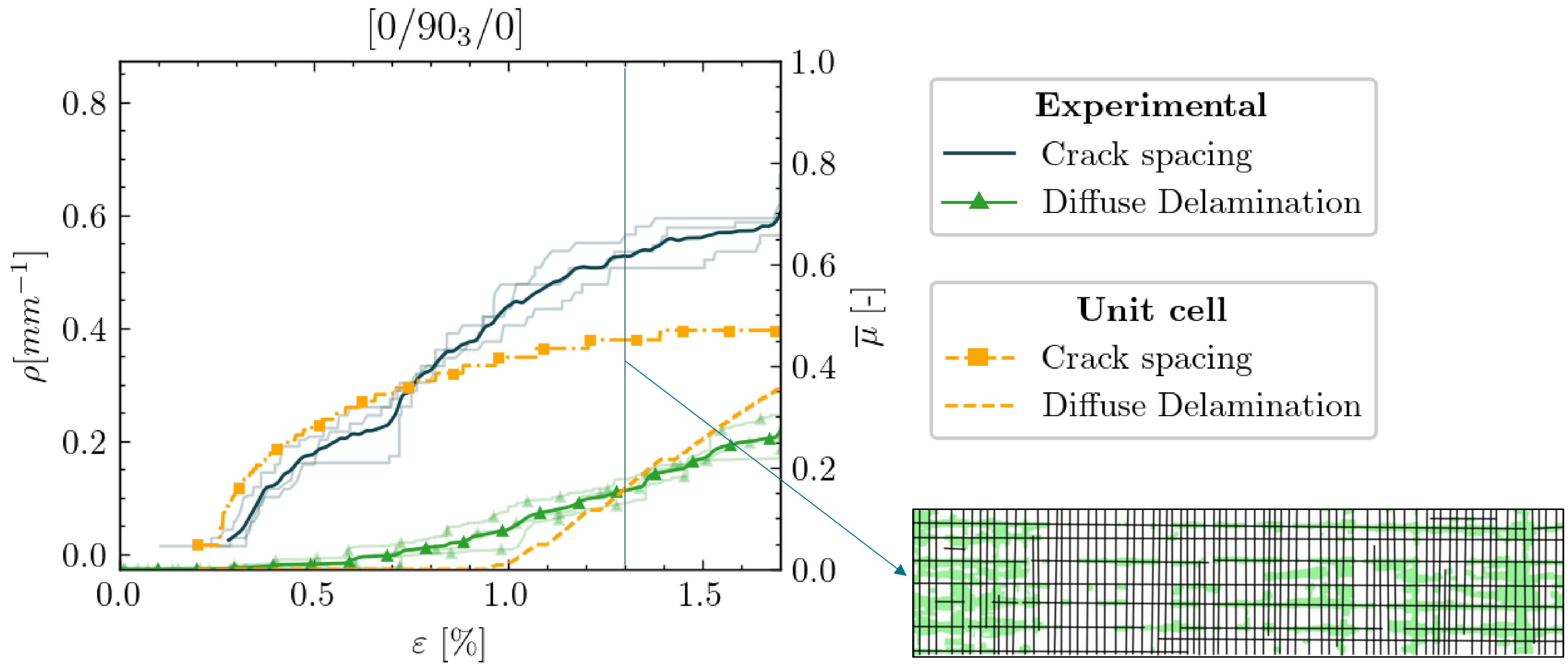
$$\bar{\boldsymbol{\sigma}}^{ply}(x_0) = \langle \boldsymbol{\sigma}(x_0, z) \rangle_\Omega = \frac{1}{t_{ply}} \int_{z^-}^{z^+} \boldsymbol{\sigma}(x_0, z)\, dz \,, x \in [0, L]$$

$$\bar{\boldsymbol{\sigma}}^{ply}(x_0) \approx \frac{1}{\sum_{e=1}^{N} V_e} \sum_{e=1}^{N} V_e \boldsymbol{\sigma}(x_0, z)$$





Results – Damage progression

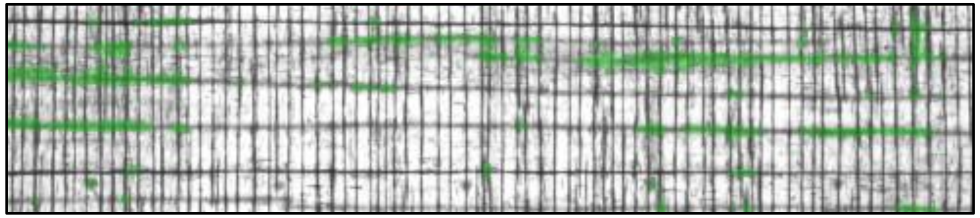


Results – Effect of t_{90}

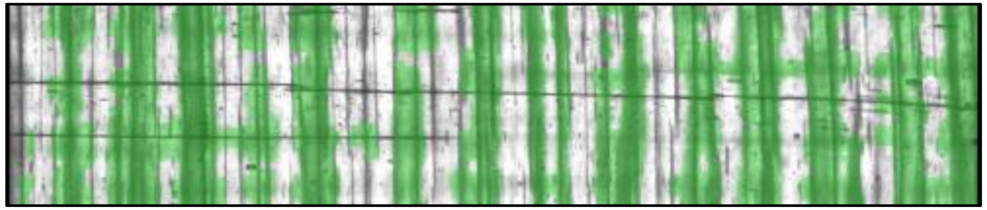
Delamination

Matrix cracks

[0/90/0] , $t_{90} = 0.8$ mm



[0/90$_4$/0] , $t_{90} = 3.6$ mm



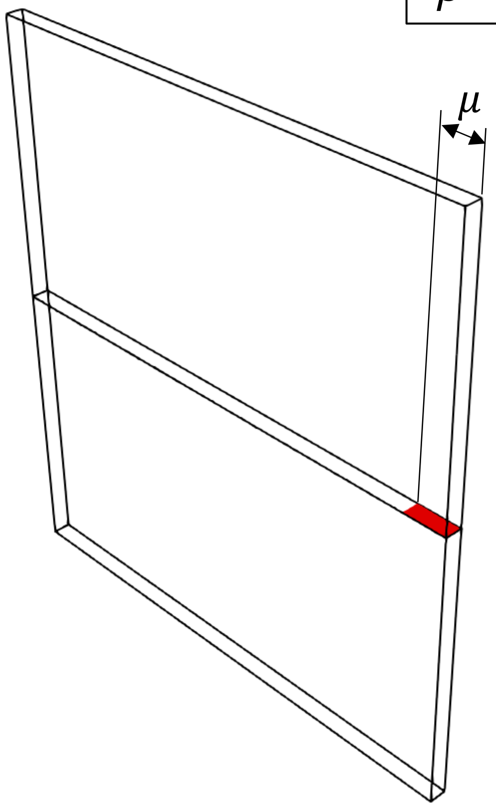
$t_{90} \rightarrow \rho \rightarrow \mu$

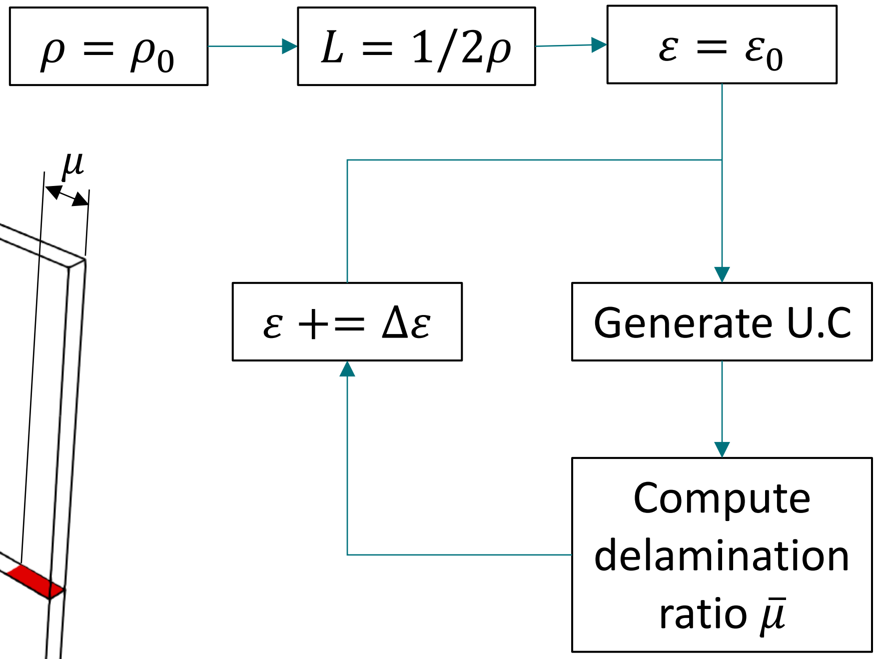
$$t_{90} \rightarrow \begin{cases} \rho \\ \mu \end{cases}$$

?

Experimentally, we cannot decouple all these parameters

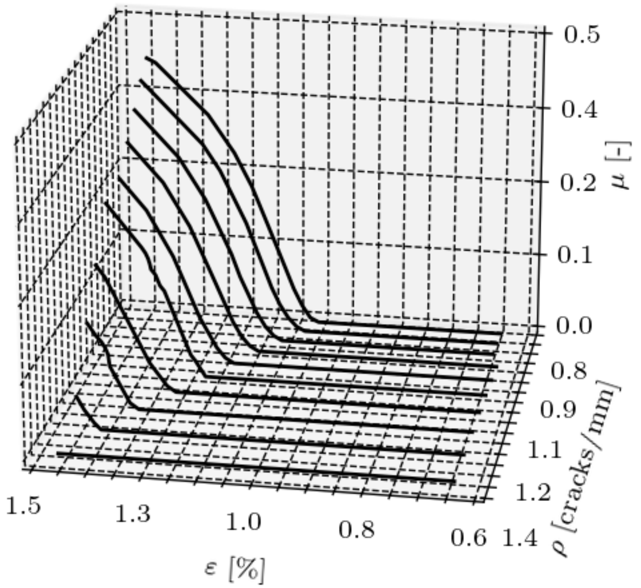
Parametric study





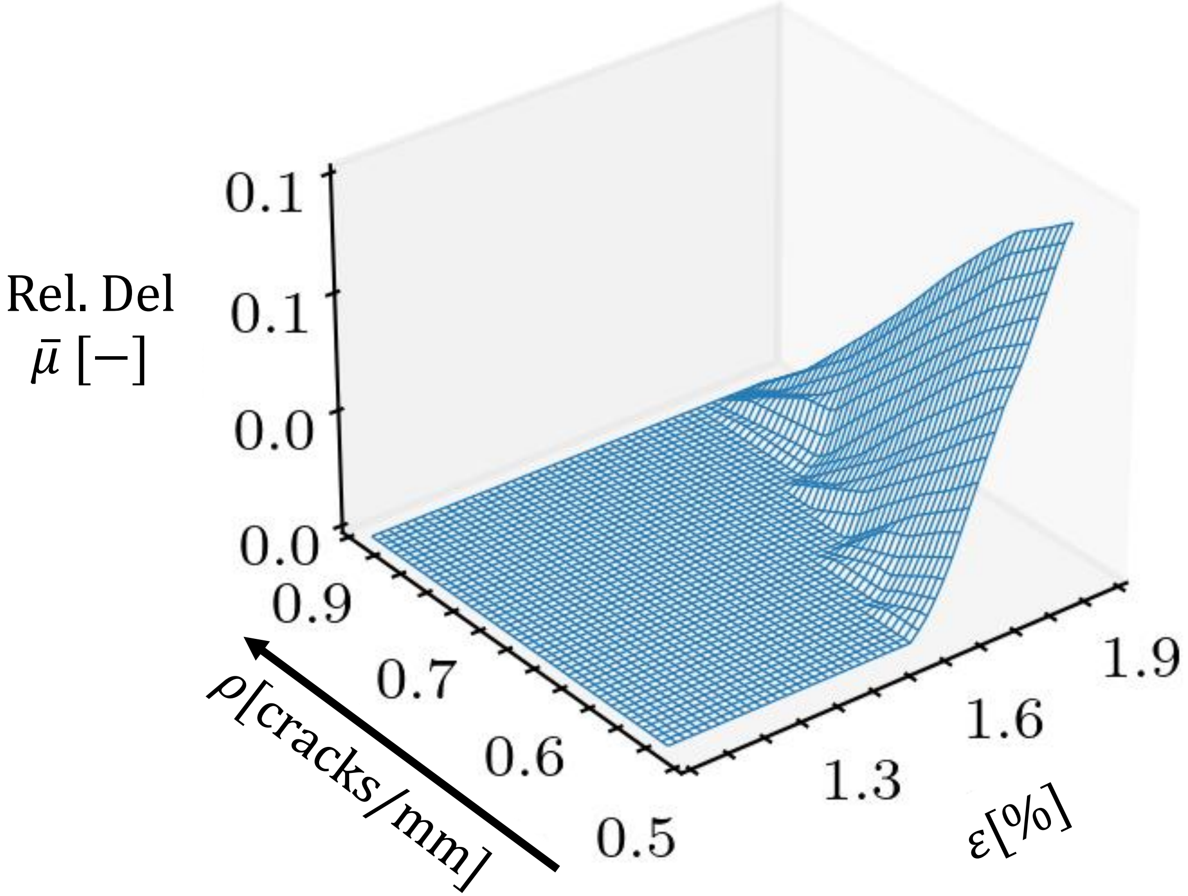
Same laminate, fixed dimensions and material properties.

Unit Cell for a fixed crack spacing/density



Results

Layup: $[0/90_n/0]$



Results

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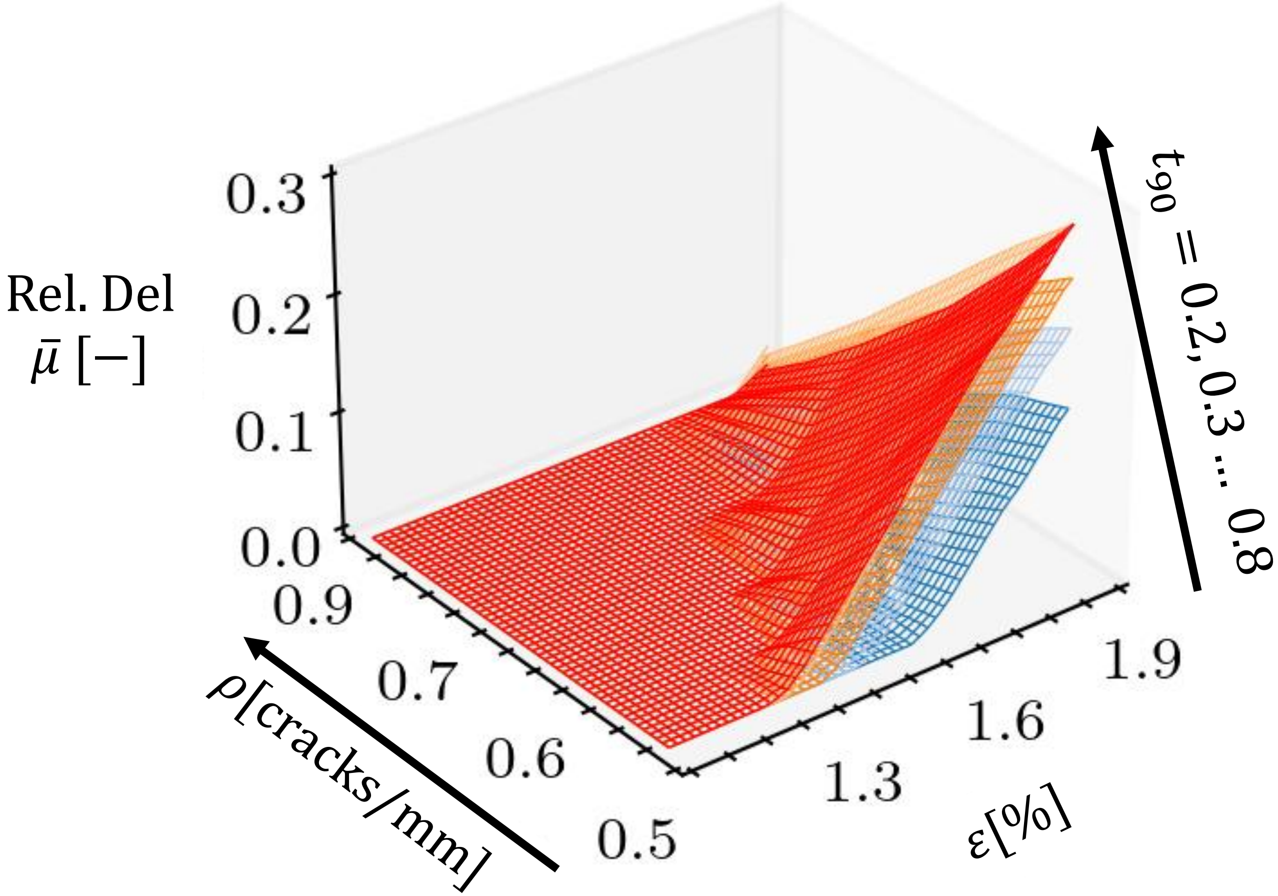
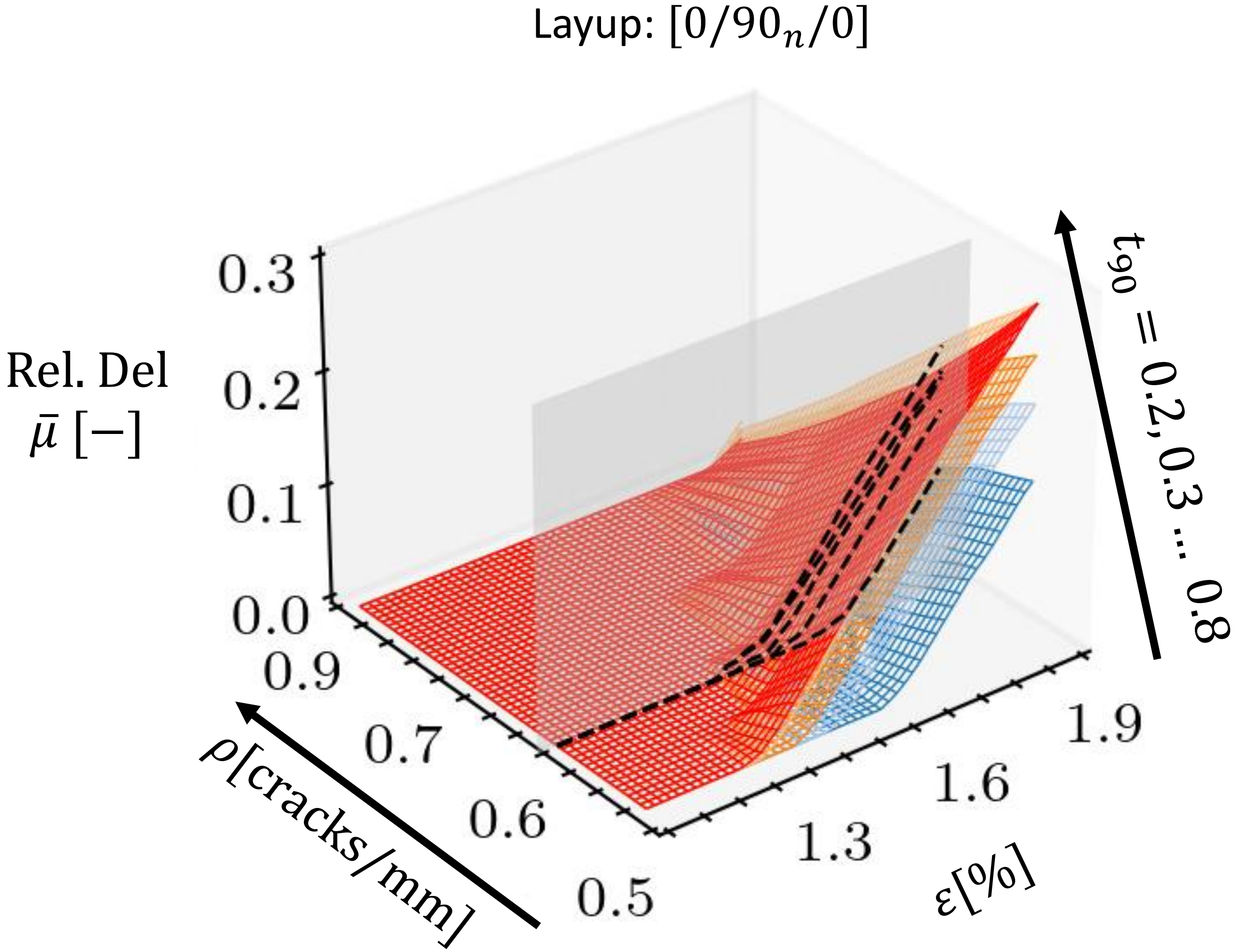


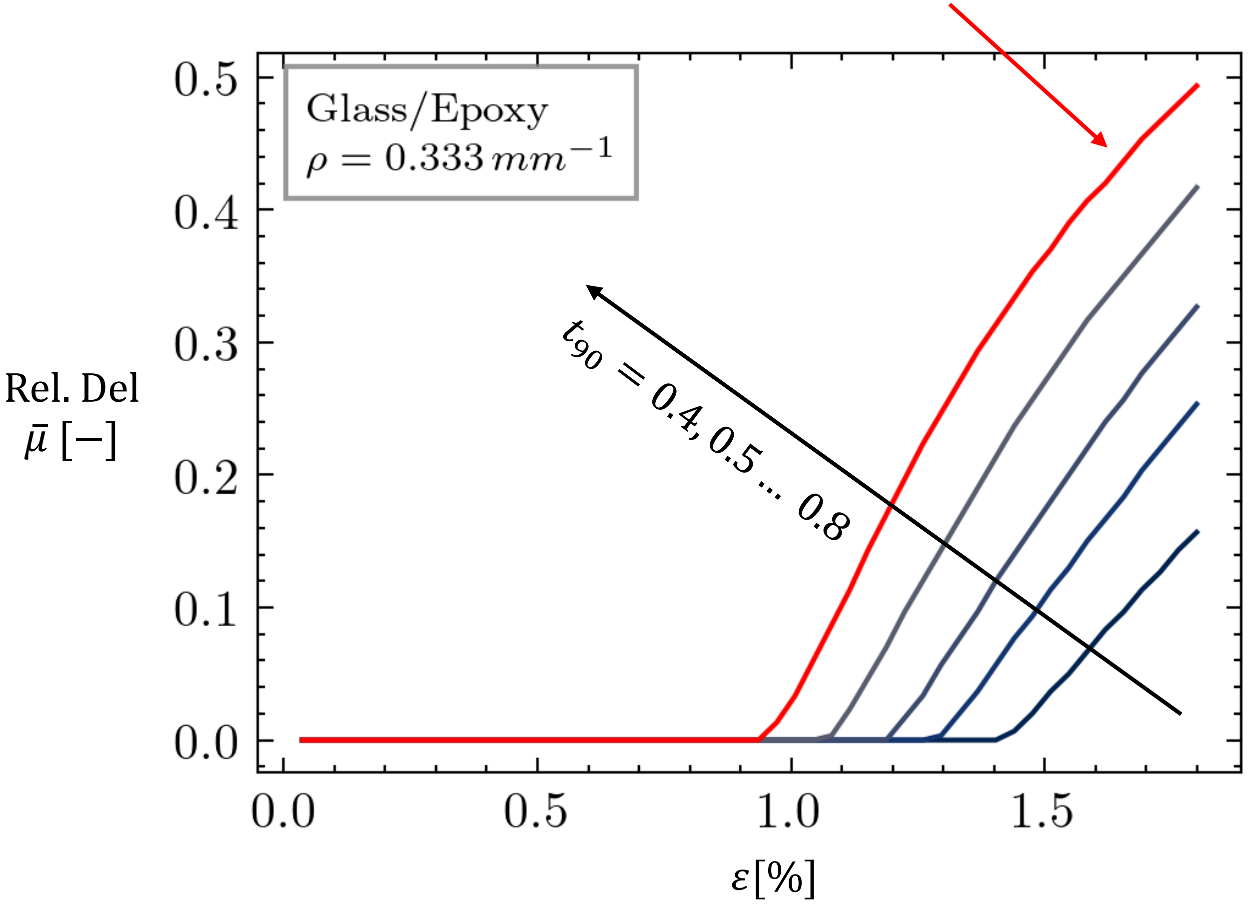
Results



Layup: $[0/90_n/0]$
Rel. Del
$\bar{\mu}$ [−]
0.3
0.2
0.1
0.0
0.9
0.7
0.6
0.5
ρ[cracks/mm]
1.3
1.6
1.9
ε[%]
t_{90} = 0.2, 0.3 … 0.8

Results

$$\rho = Const$$
$$t_{90} \uparrow \rightarrow \bar{\mu} \uparrow$$



Glass/Epoxy

Cross-ply $[0/90_n/0]$

Outer Ply thickness = 0.8 mm

Results

$$\rho = Const$$
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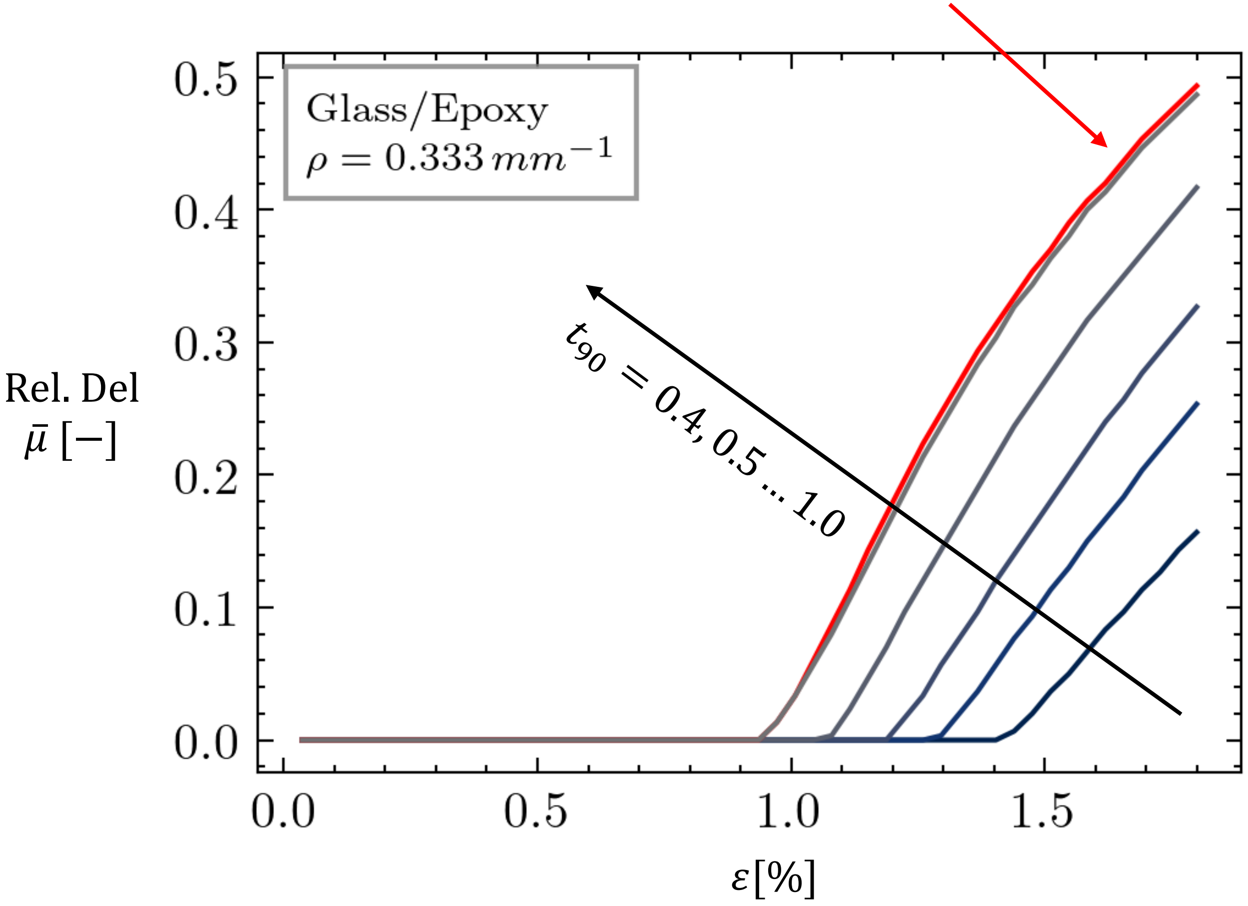

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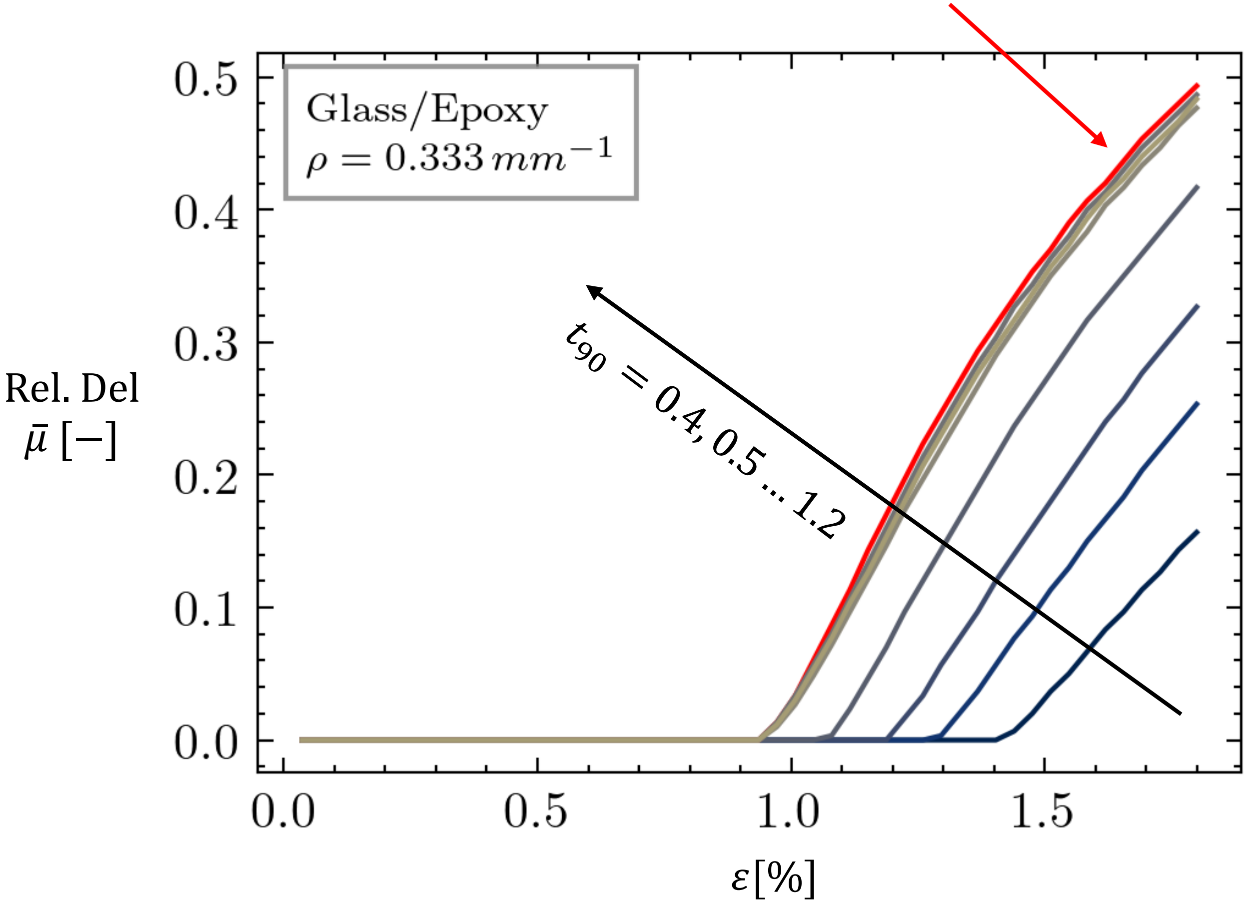

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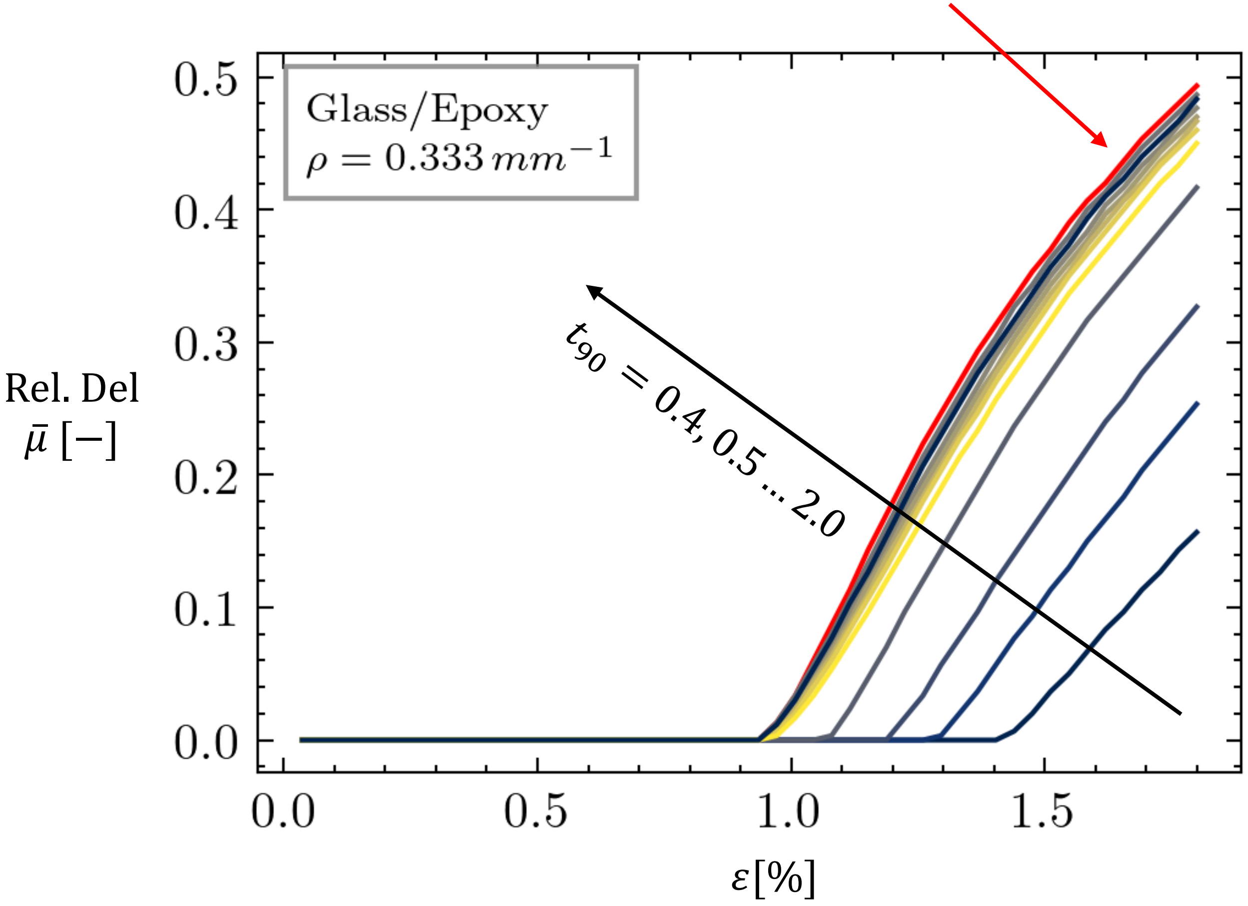

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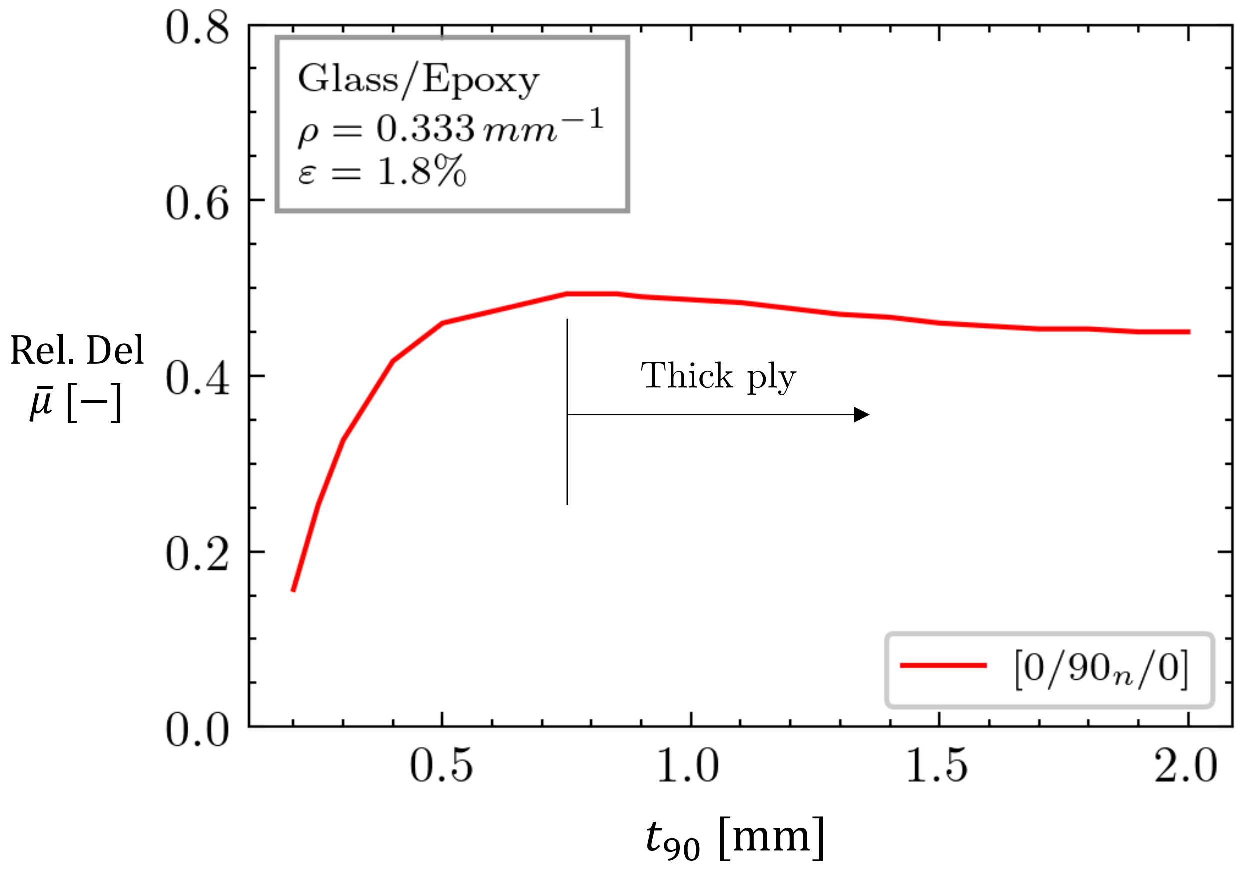
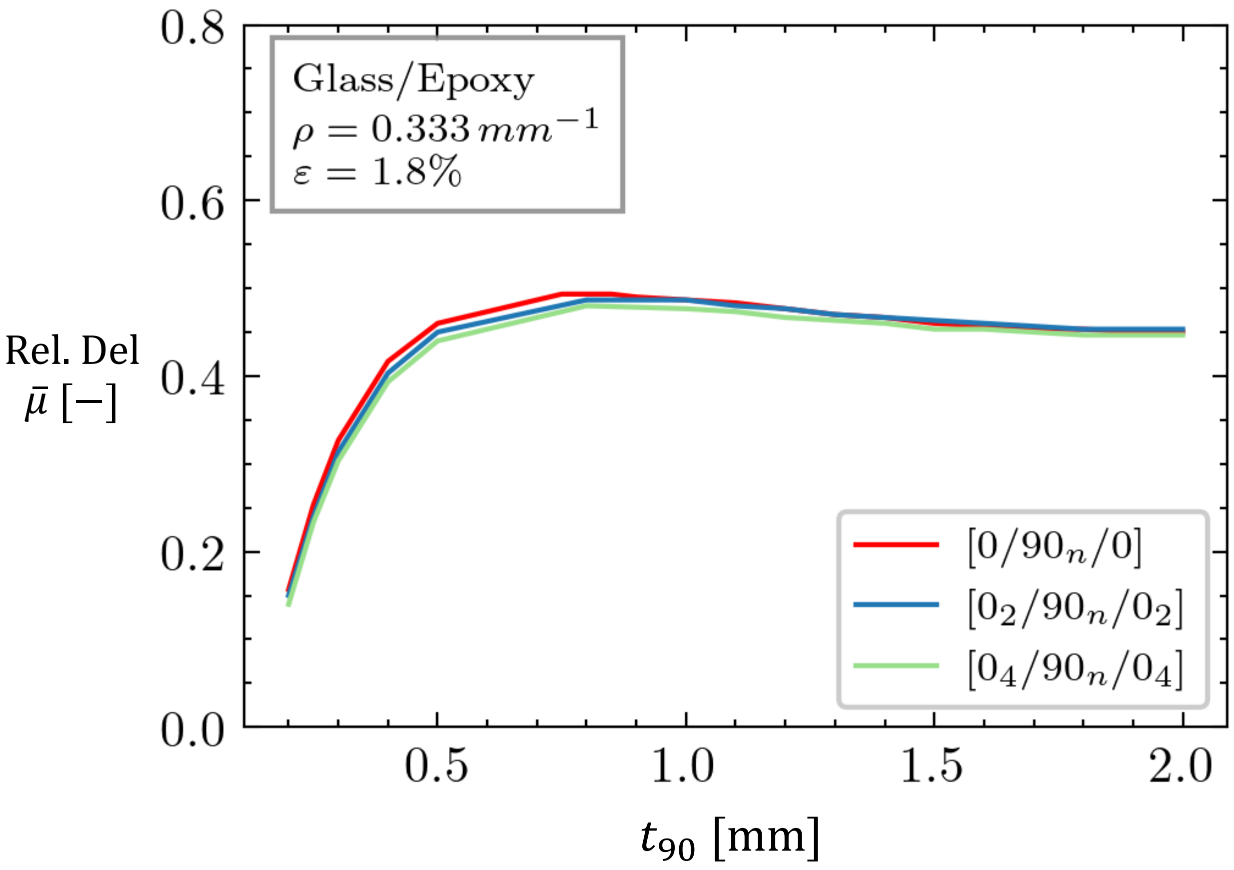

Glass/Epoxy
$\rho = 0.333\,mm^{-1}$
$\varepsilon = 1.8\%$
Thick ply
$[0/90_n/0]$
Rel. Del
$\bar{\mu}$ [−]
t_{90} [mm]
0.0
0.2
0.4
0.6
0.8
0.5
1.0
1.5
2.0

Results



Glass/Epoxy
$\rho = 0.333\,mm^{-1}$
$\varepsilon = 1.8\%$
Rel. Del
$\bar{\mu}$ [−]
0.8
0.6
0.4
0.2
0.0
0.5
1.0
1.5
2.0
t_{90} [mm]
$[0/90_n/0]$
$[0_2/90_n/0_2]$
$[0_4/90_n/0_4]$

Conclusions

How does matrix cracking influence the onset and progression of delamination in laminates?

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→ Experimentally there's a link between cracking, inner ply thickness and delamination

→ However, we cannot separate individual contributions

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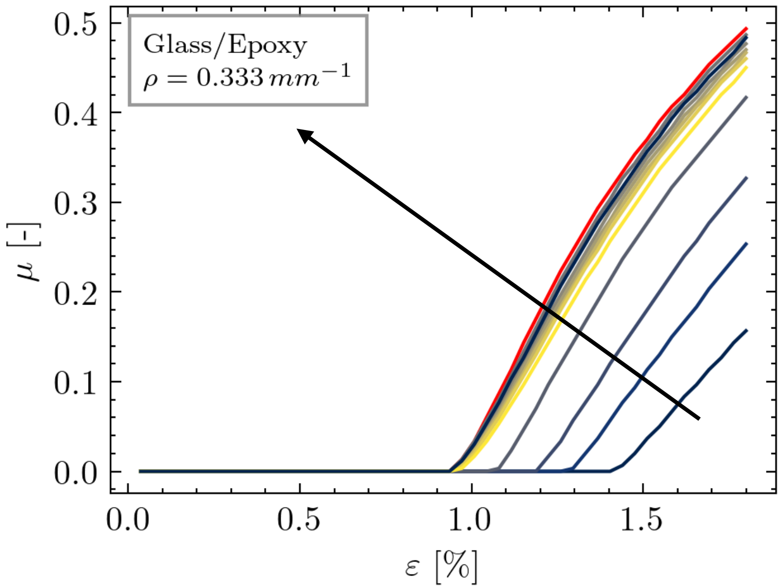
→ Experimentally there's a link between cracking, inner ply thickness and delamination

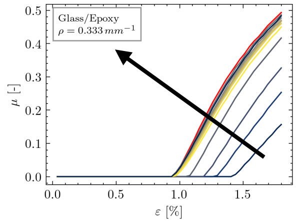
→ There's a "**thin/thick ply concept**" for diffuse delamination

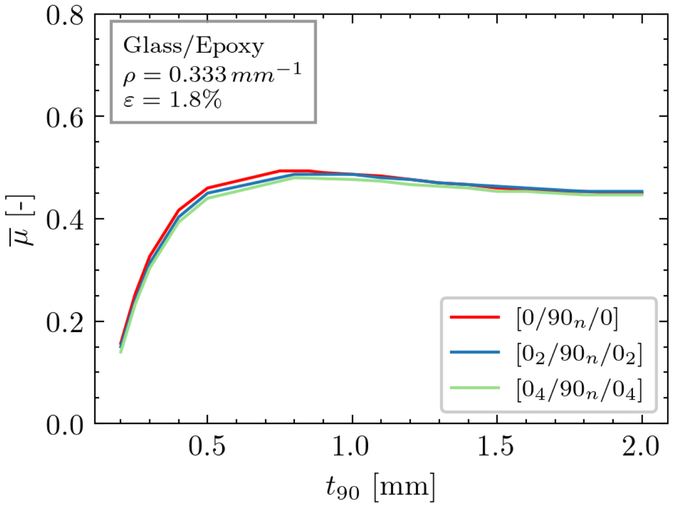


Conclusions

How does matrix cracking influence the onset and progression of delamination in laminates?

- Experimentally there's a link between cracking, inner ply thickness and delamination
- There's a "**thin/thick ply concept**" for diffuse delamination
- The **outer ply** thickness seems to play no role for diffuse delamination

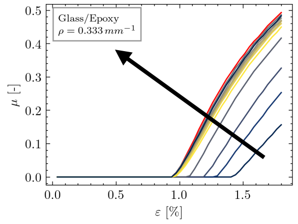


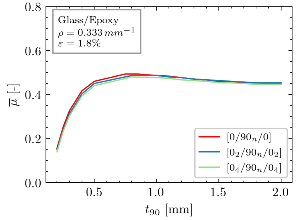


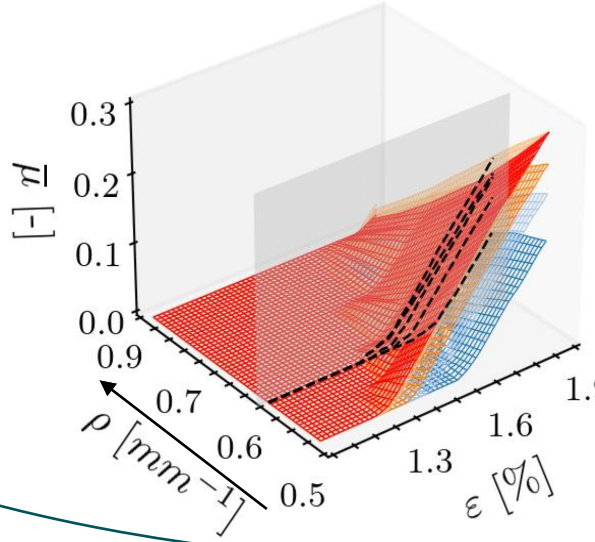
Conclusions

How does matrix cracking influence the onset and progression of delamination in laminates?

- Experimentally there's a link between cracking, inner ply thickness and delamination
- There's a "**thin/thick ply concept**" for diffuse delamination
- The **outer ply** thickness seems to play no role for diffuse delamination
- $\rho \downarrow \rightarrow \ \bar{\mu} \uparrow$







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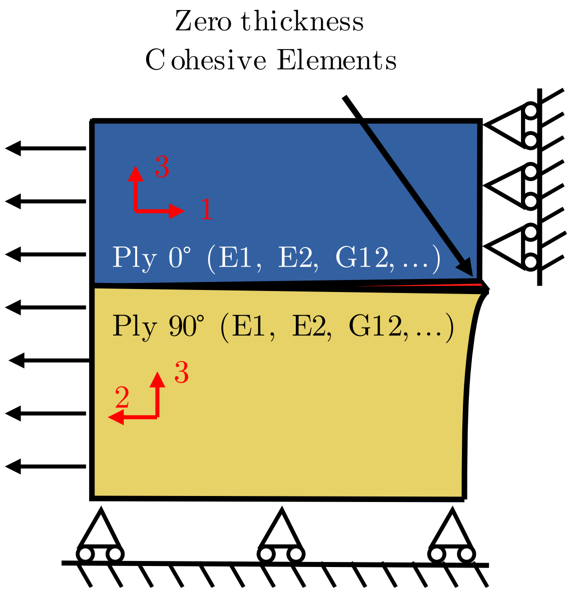
Thanks for your attention!

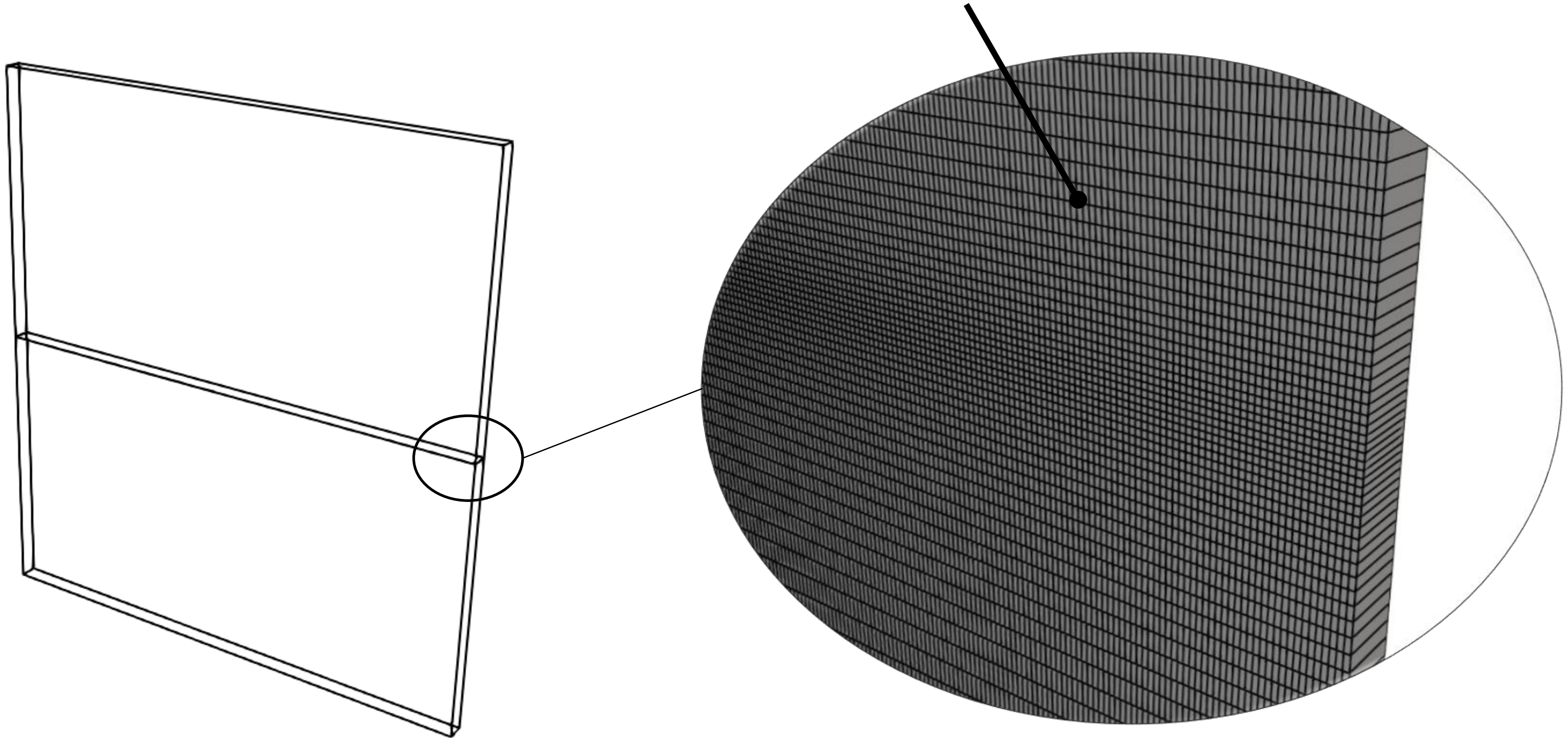
Backup Slides

Modelling approach



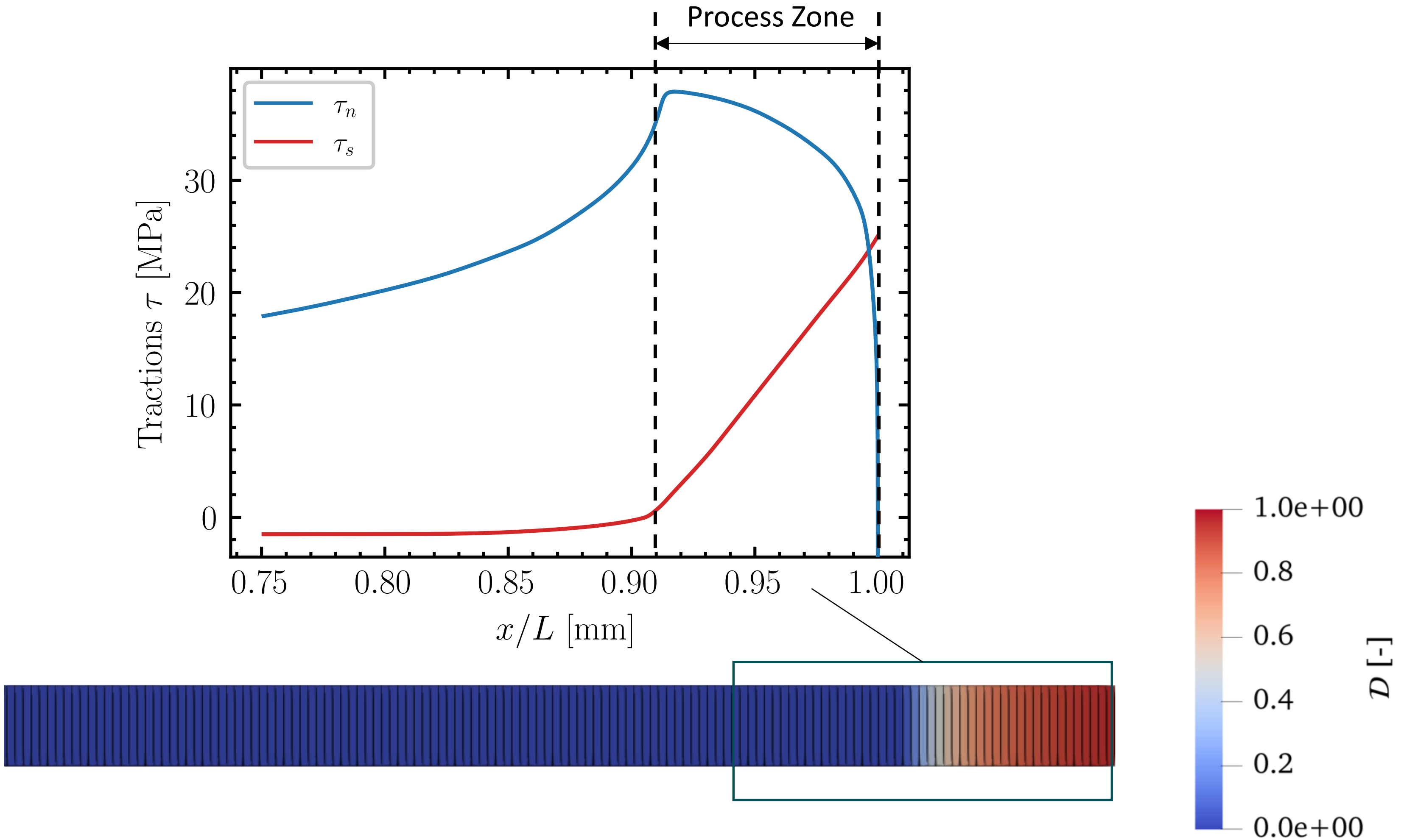
ABAQUS/Standard

3D Continuum linear solid elements



Generalized plane strain model

Process Zone and Tractions



Material Properties - Elastic

GFRP:

E_1 [GPa]	E_2 [GPa]	ν_{12} [-]	G_{12}[GPa]
50.4	14.3	0.296	3.2

X_T[MPa]	X_C[MPa]	Y_T[MPa]	Y_C[MPa]	S_{12} [MPa]
1490	973	36	127	38

CFRP:

E_1 [Gpa]	E_2 [GPa]	ν_{12} [-]	G_{12} [GPa]
123.5	7.3	0.351	3.3

X_T [MPa]	X_C[MPa]	Y_T [MPa]	Y_C[MPa]	S_{12} [MPa]
1858	874	38	131	52

Material Properties - Cohesive

GFRP:

t_n[MPa]	t_s[MPa]	G_{Ic}[N/mm]	G_{IIc}[N/mm]
36	38	0.202	2.566

CFRP:

t_n[MPa]	t_s[MPa]	G_{Ic}[N/mm]	G_{IIc}[N/mm]
38	52	0.186	0.786

Interface Stiffness:

K_{nn} [N/mm]	K_{ss} [N/mm]	K_{ss} [N/mm]
1E6	1E6	1E6

Material Properties – BK Law fit