One step closer to reliable failure prediction in composites - understanding the interaction between matrix cracking and delamination

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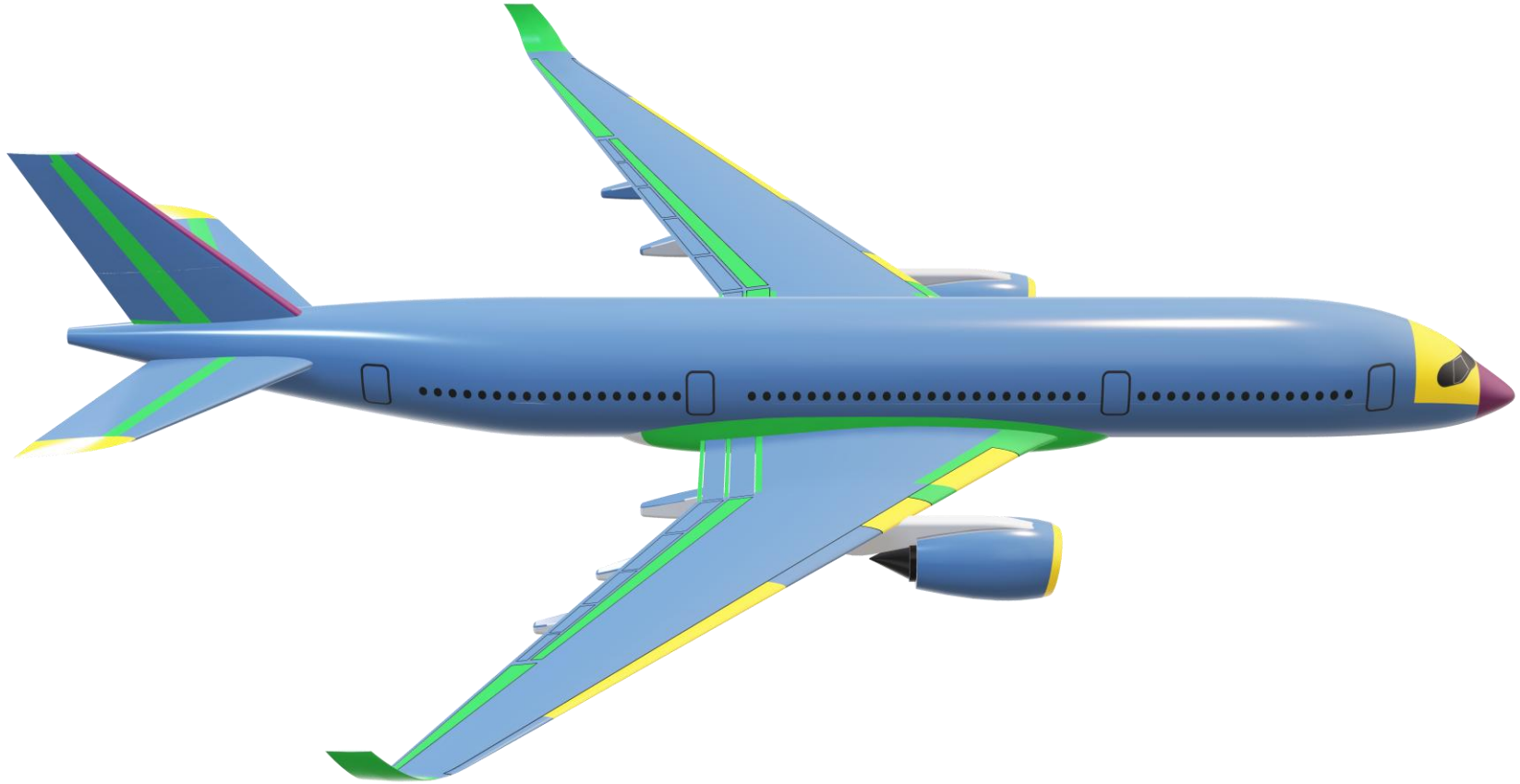
Technical University of Leoben

33rd Leoben-Conference
POLYMER ENGINEERING and Science

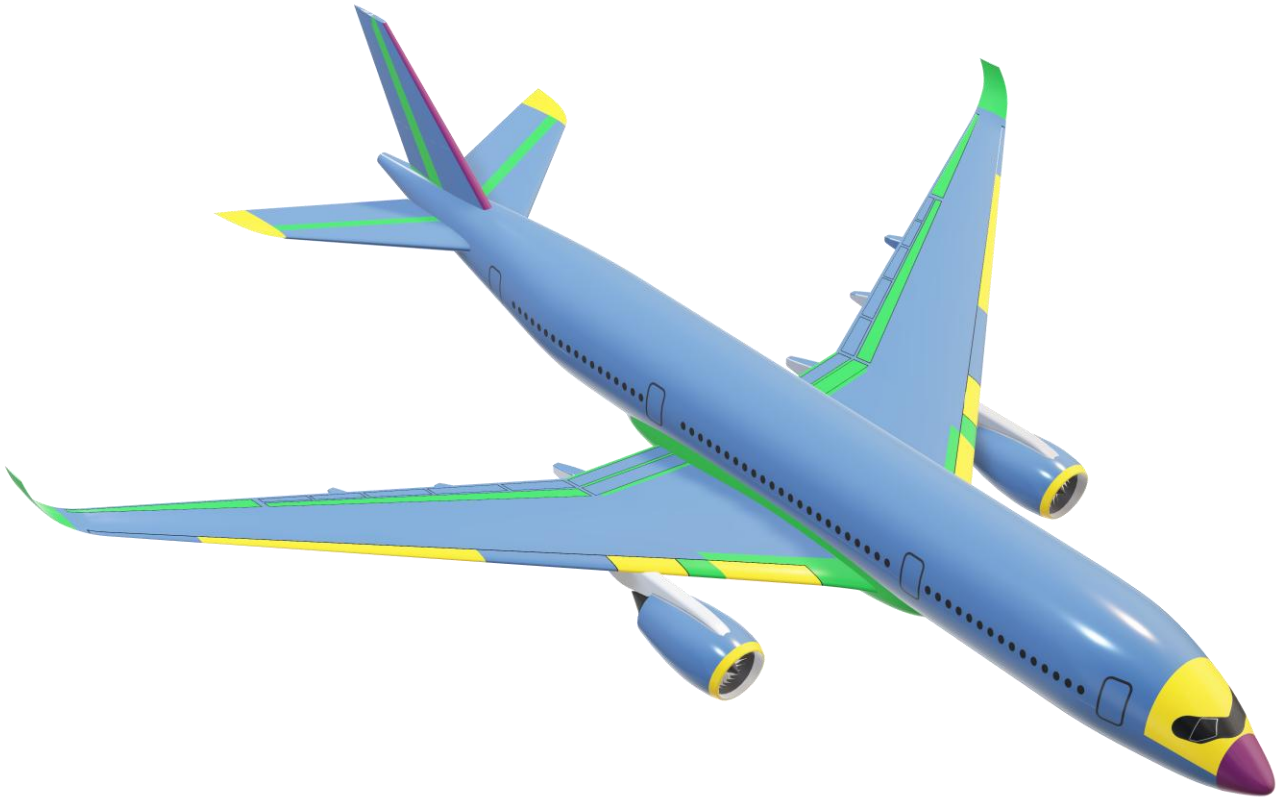
Move mountains

Motivation

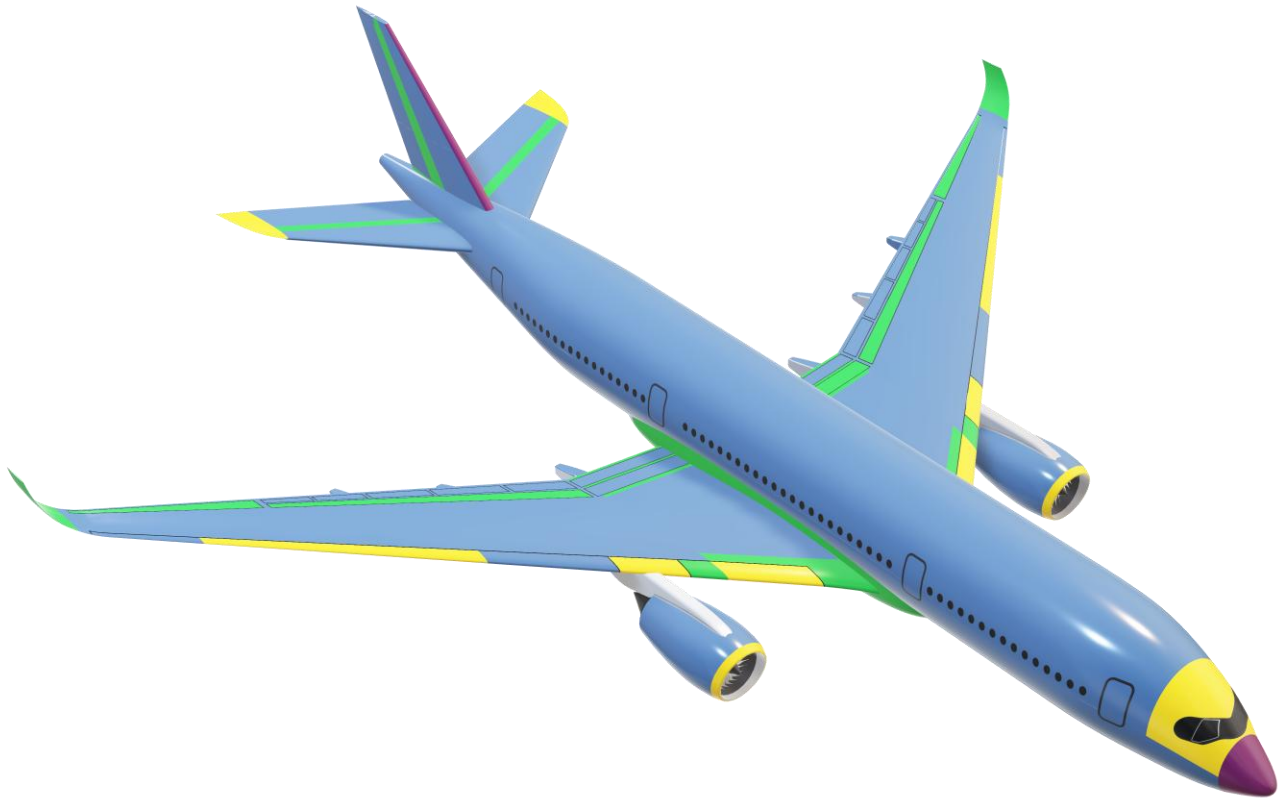
Motivation



Motivation



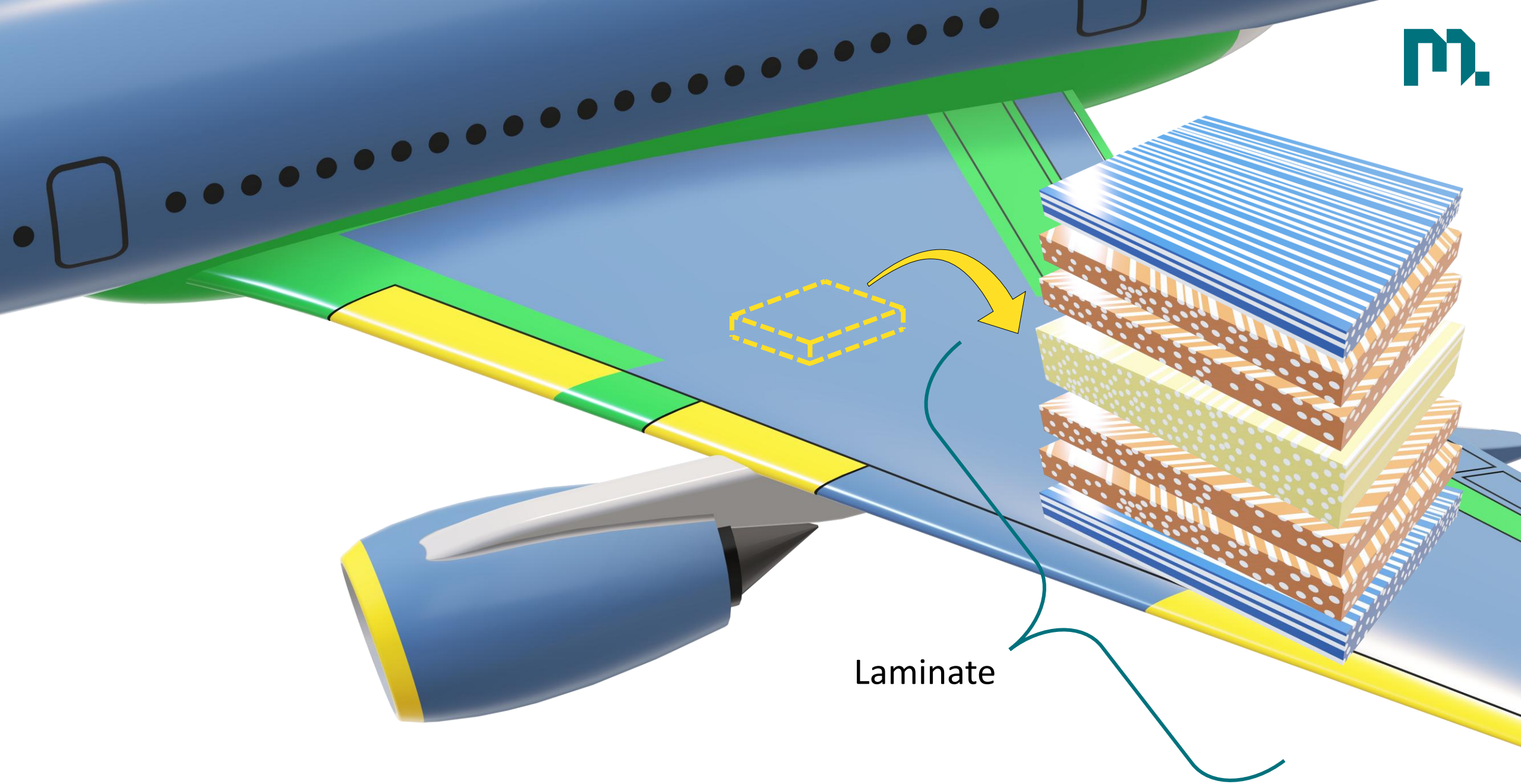
Motivation

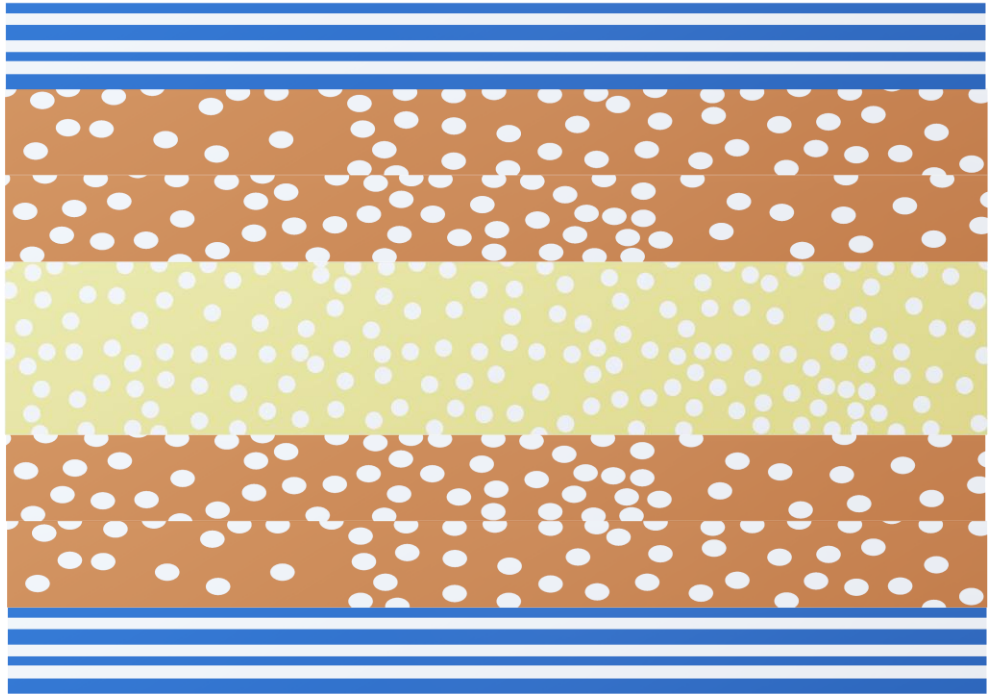


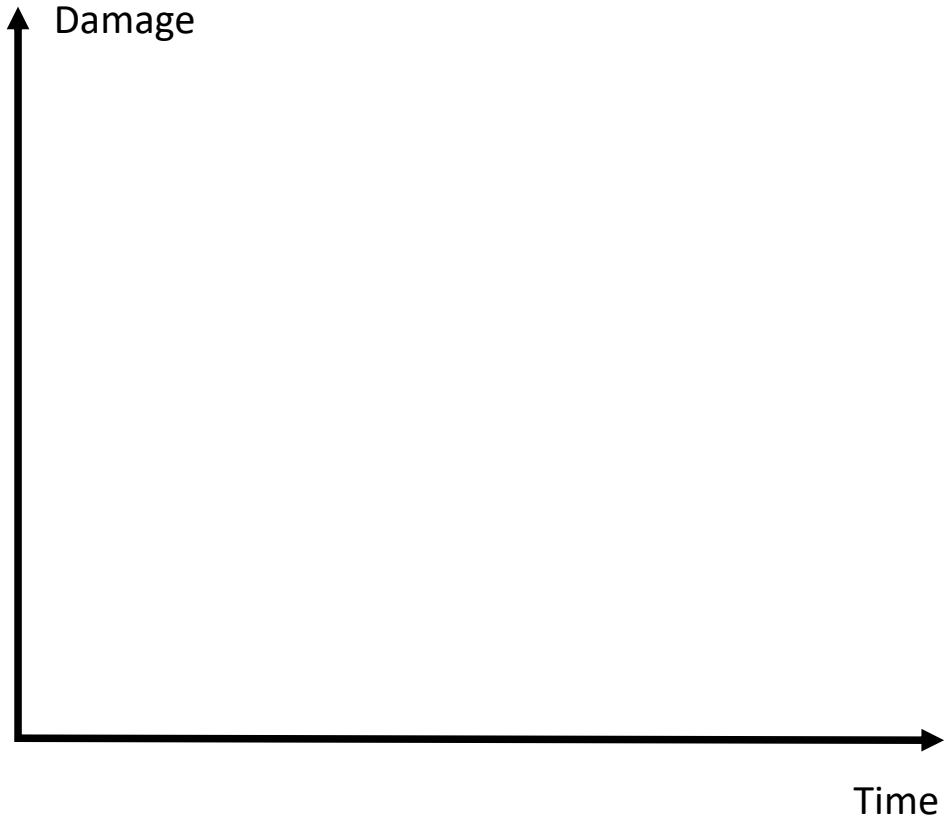
- CFRP Monolithic
- CFRP Sandwich
- Glass, Quartz Composite

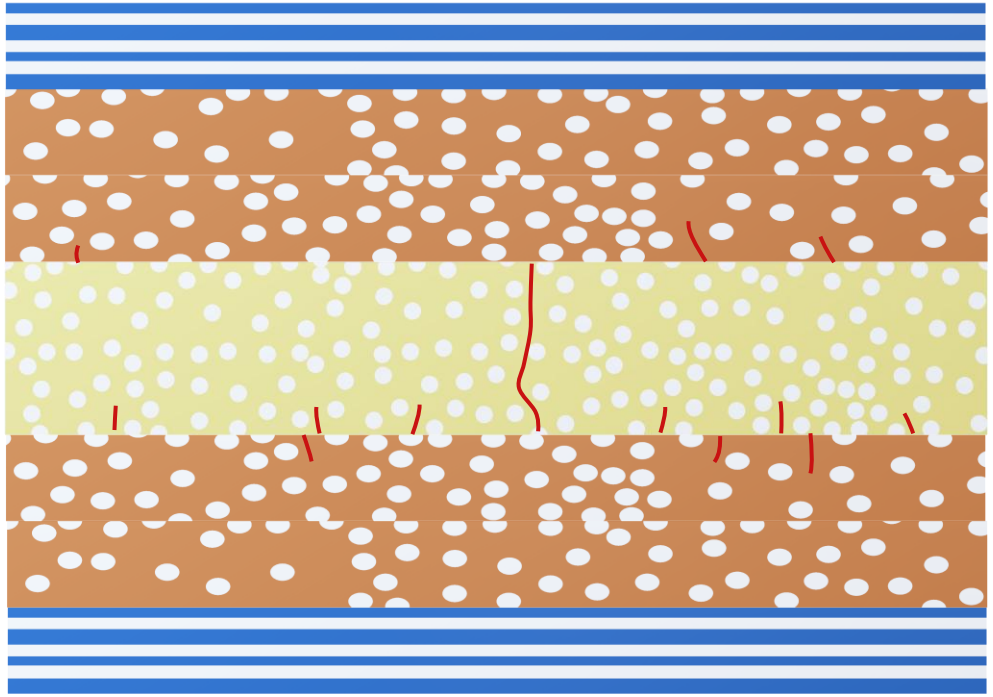
Composite

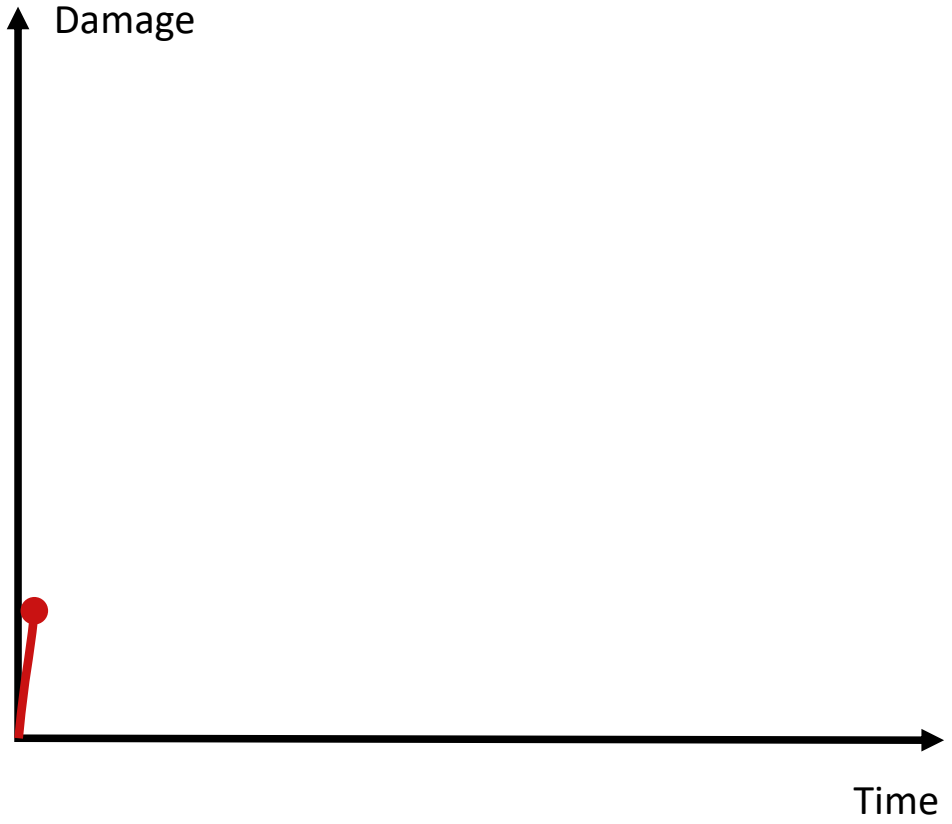
- Aluminum
- Titanium

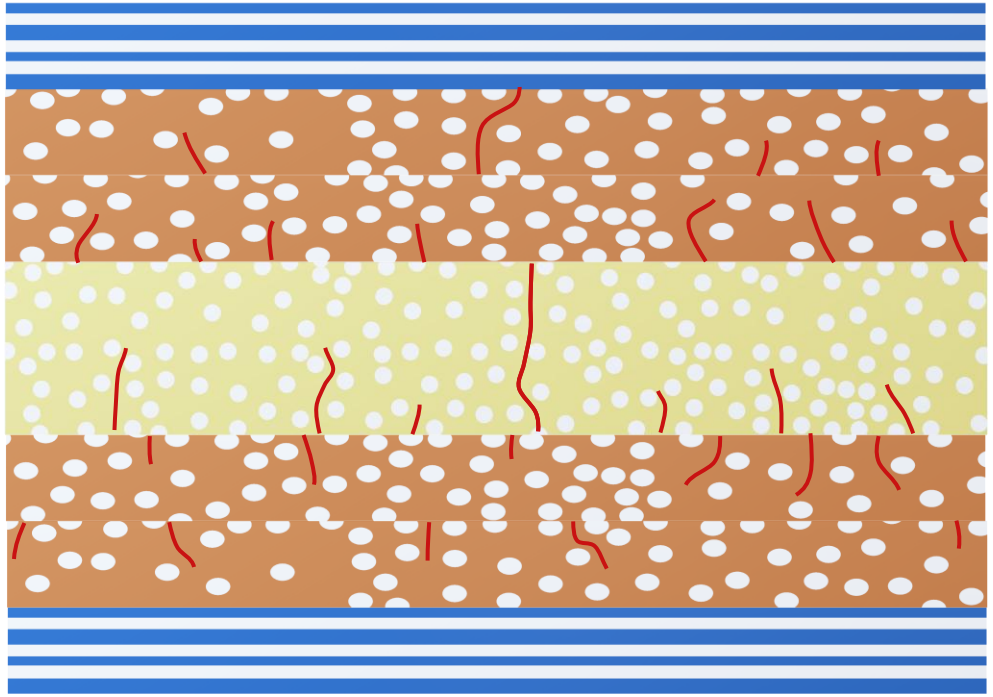

Laminate

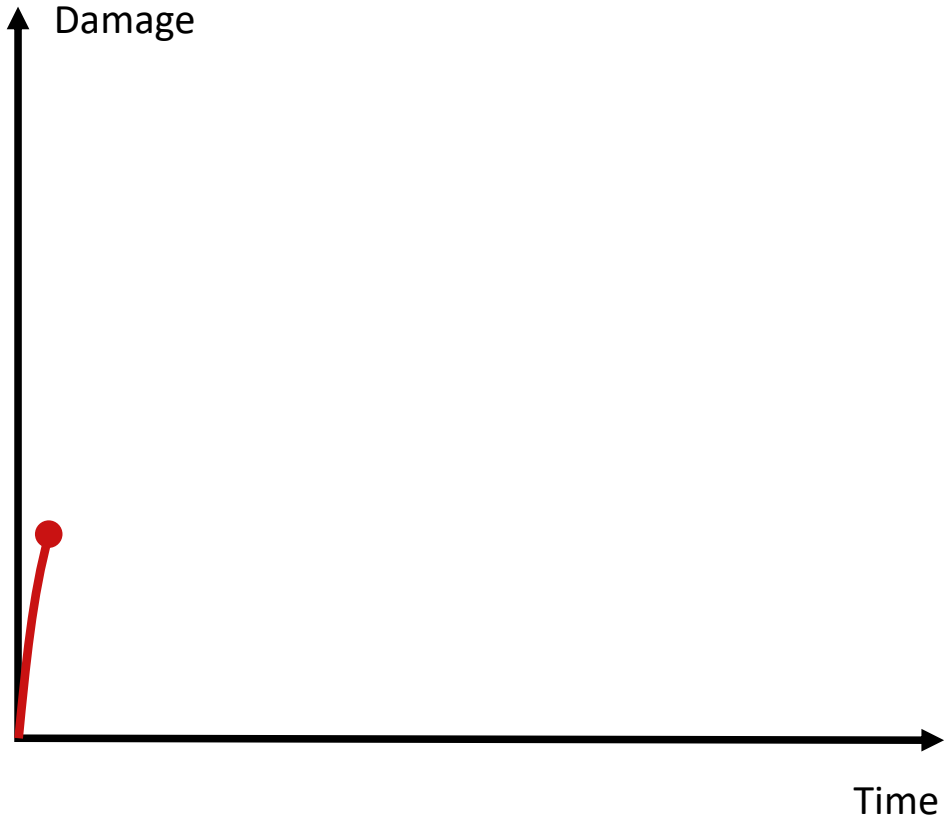


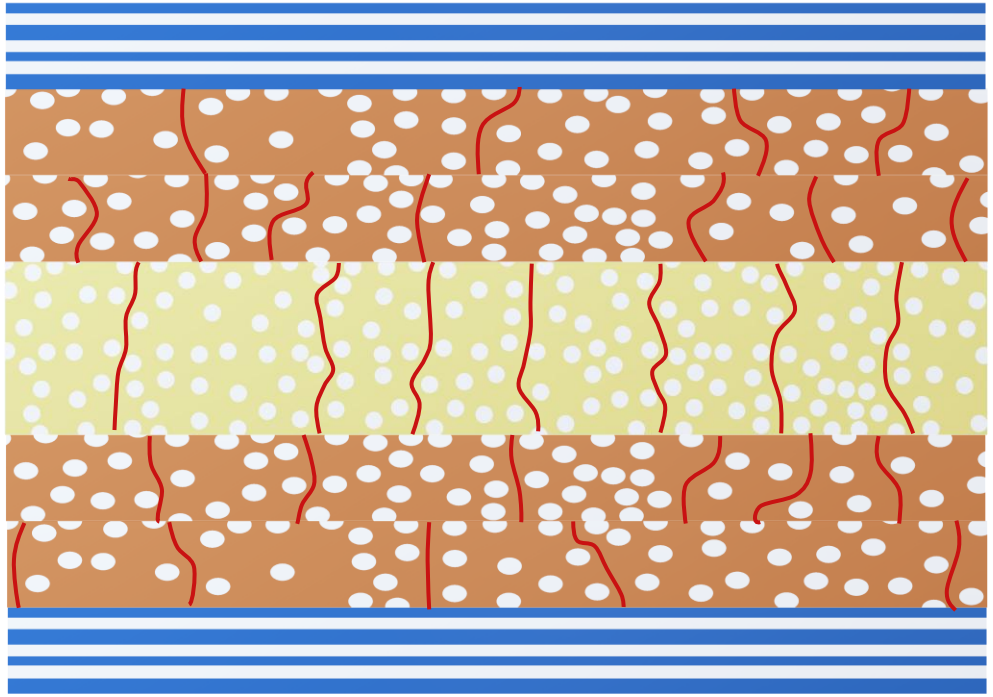

Damage
Time

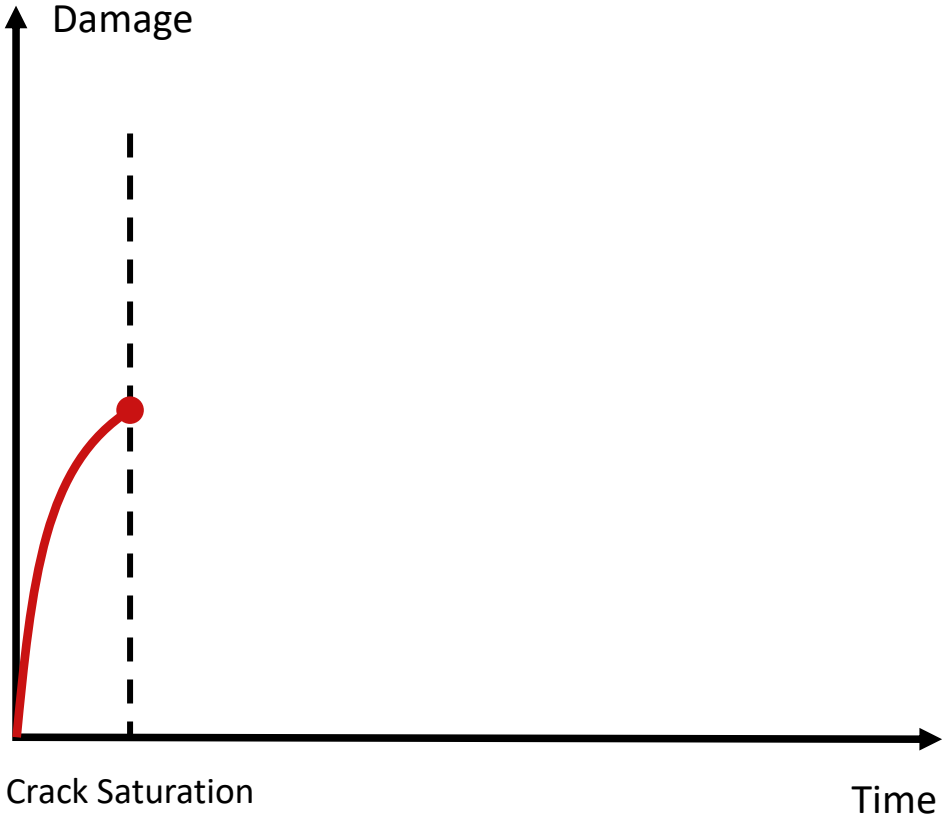


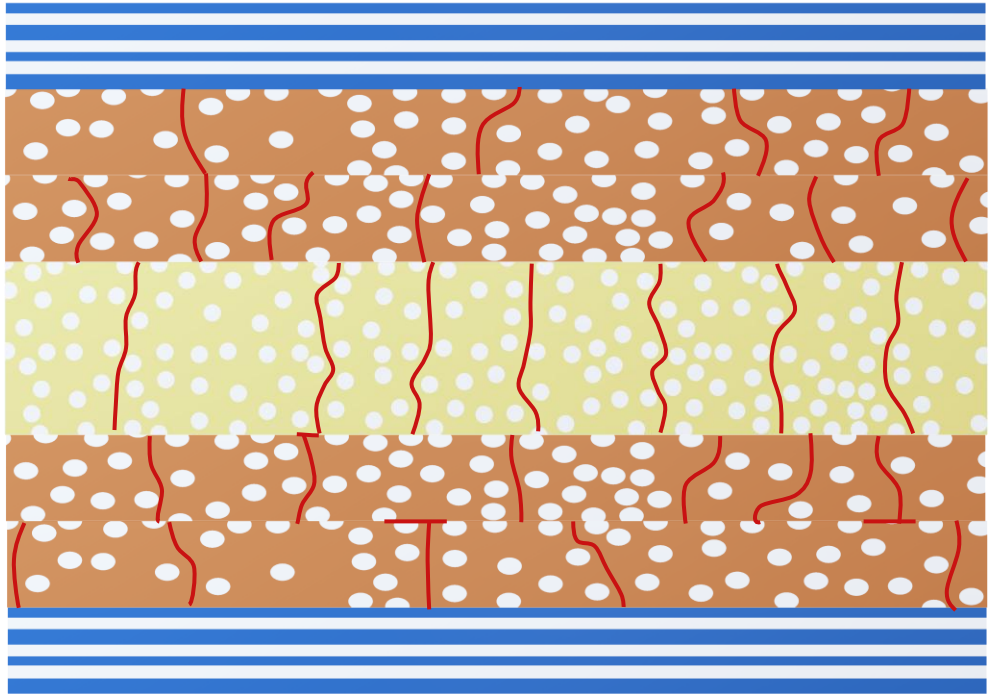

Damage
Time

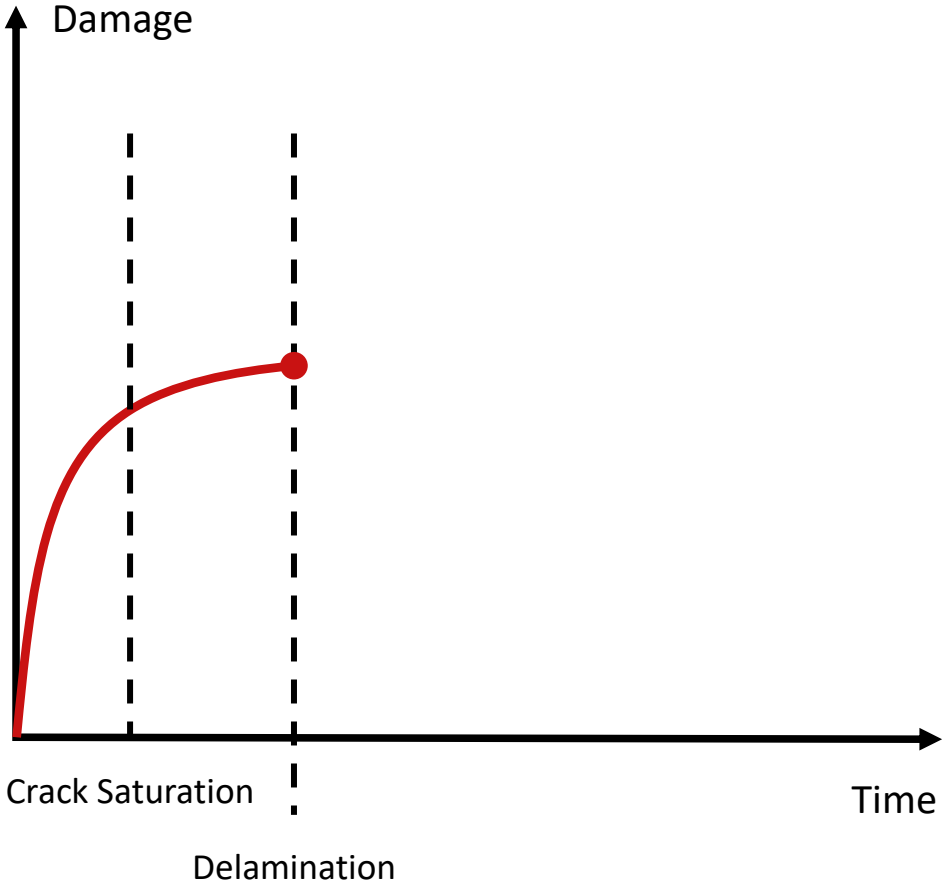


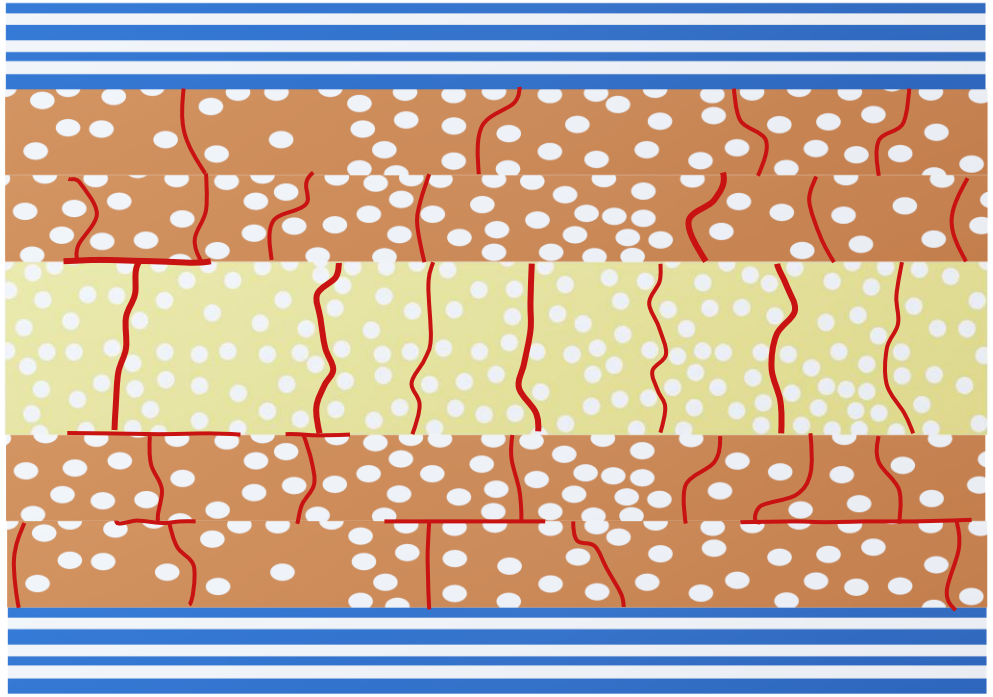

Damage
Time

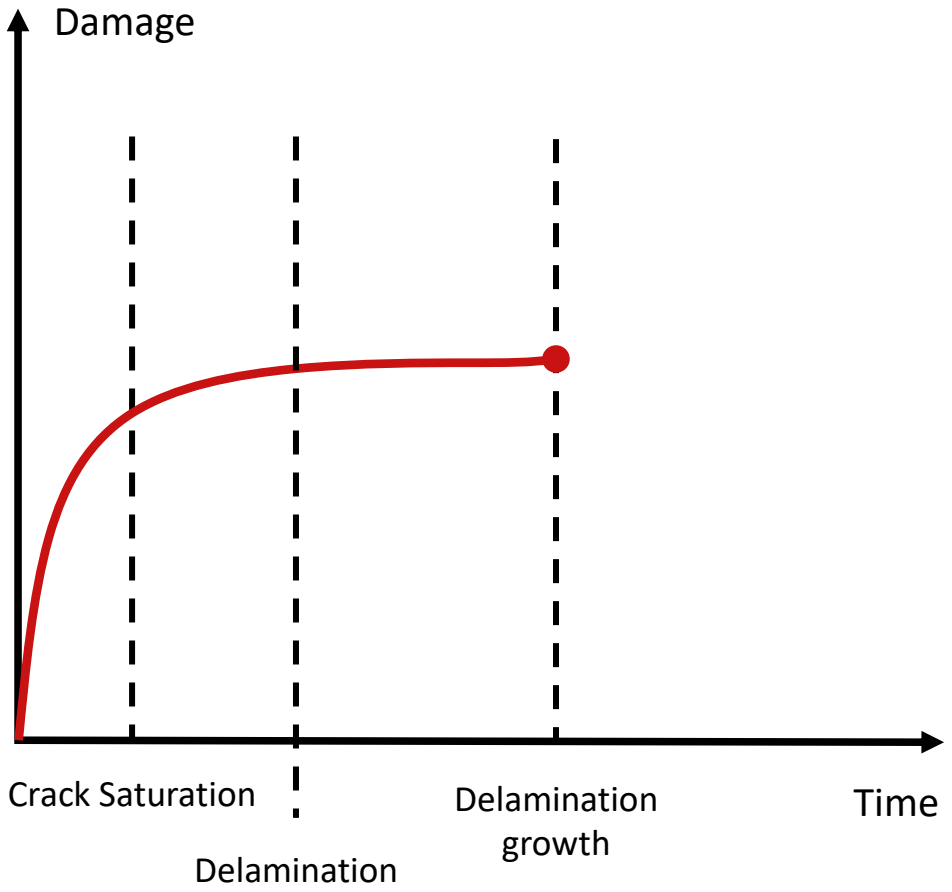


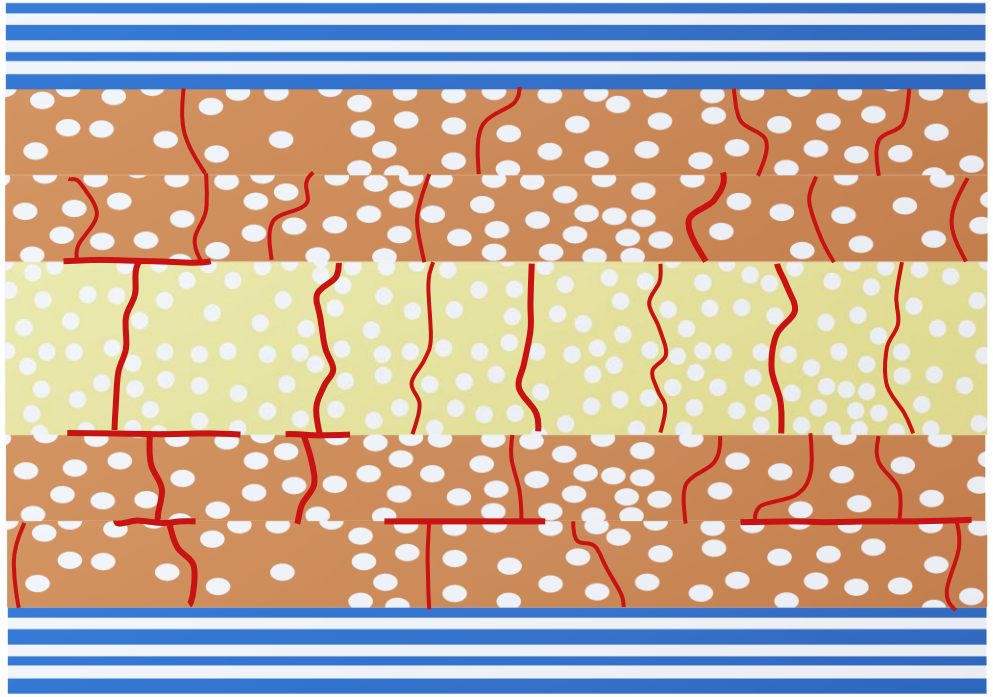

Damage
Crack Saturation
Time

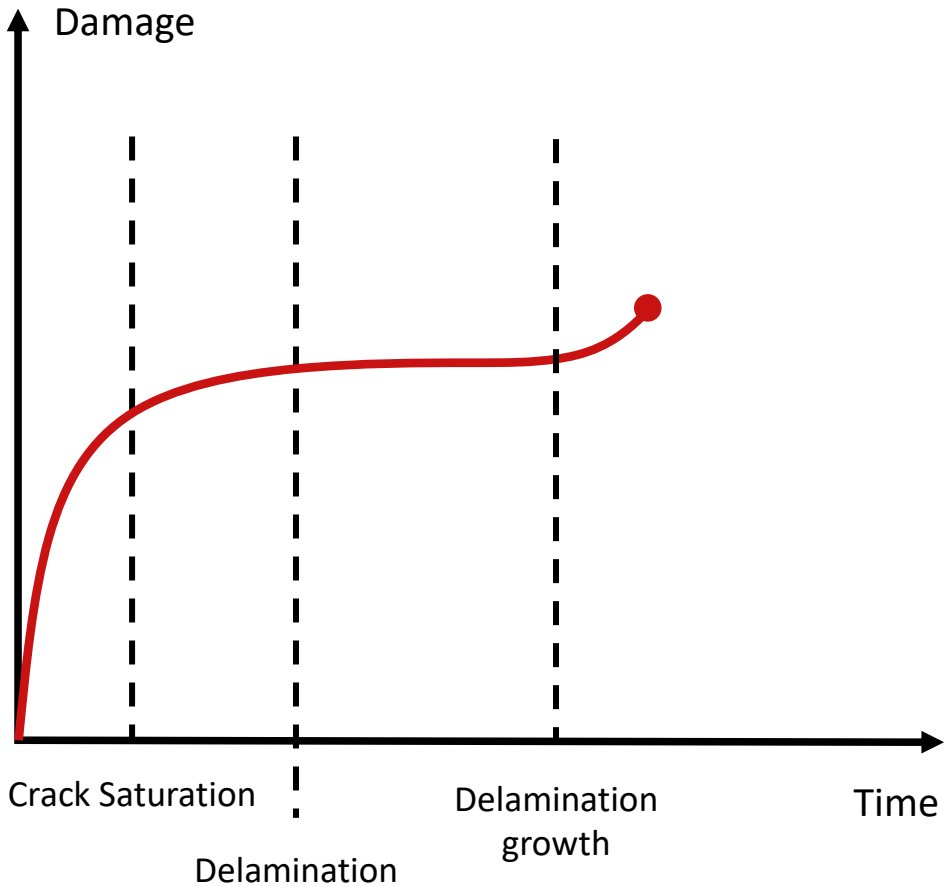


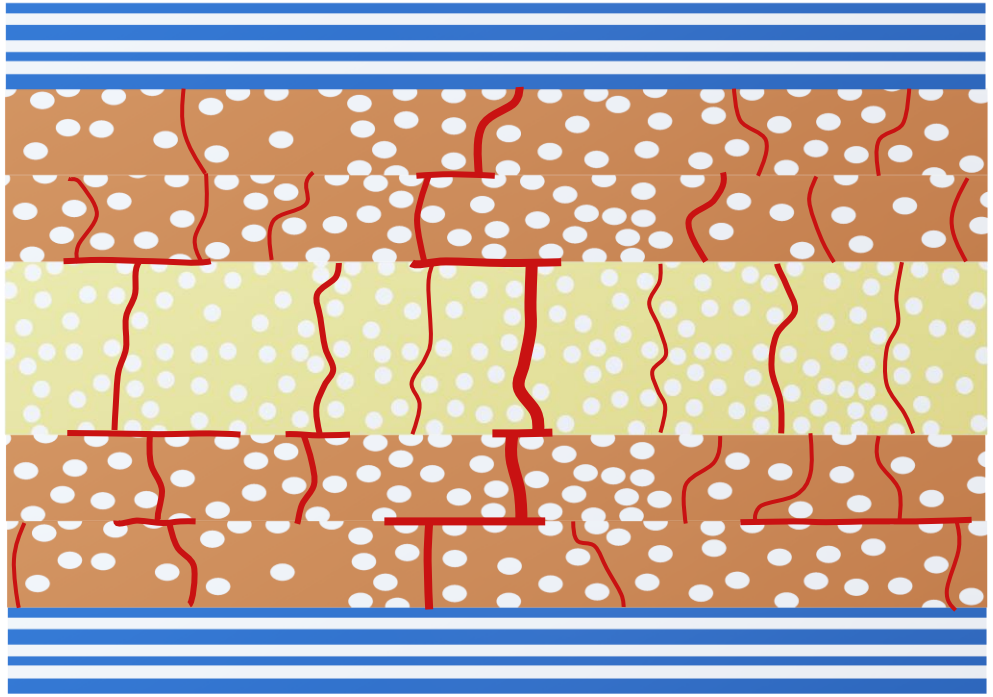

Damage
Crack Saturation
Time
Delamination

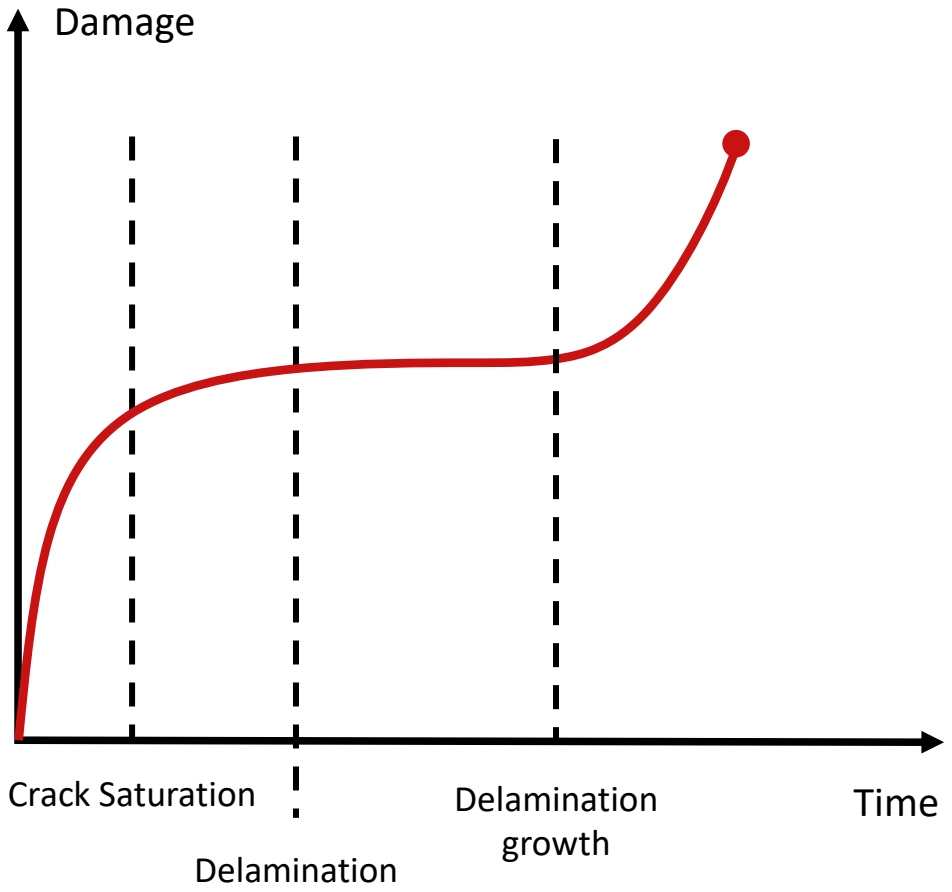


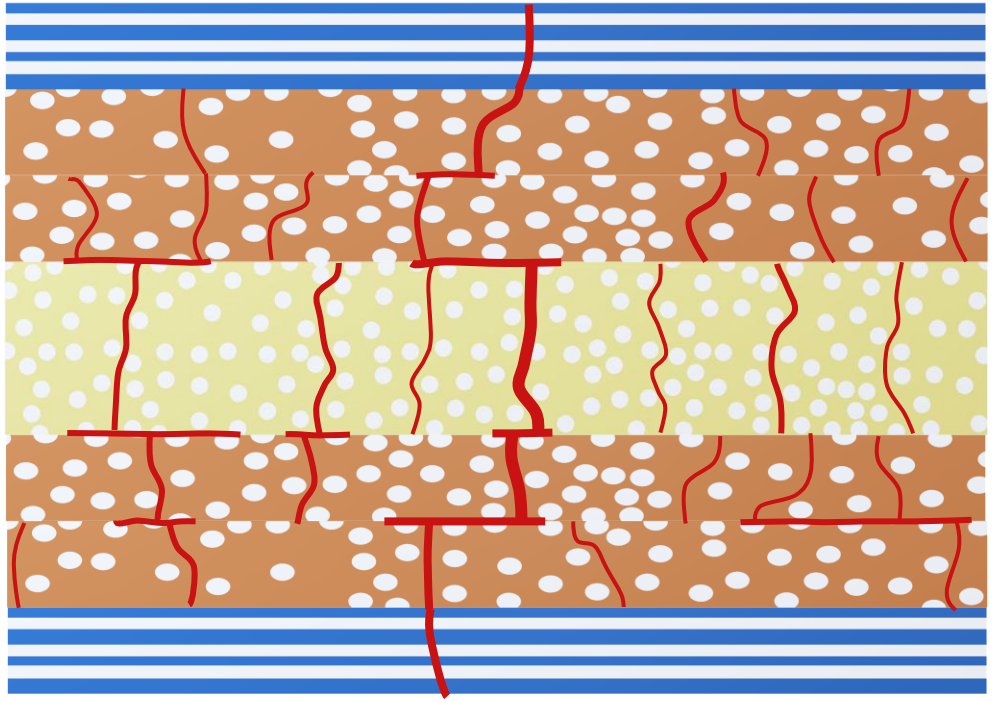

Damage
Crack Saturation
Delamination
Delamination growth
Time

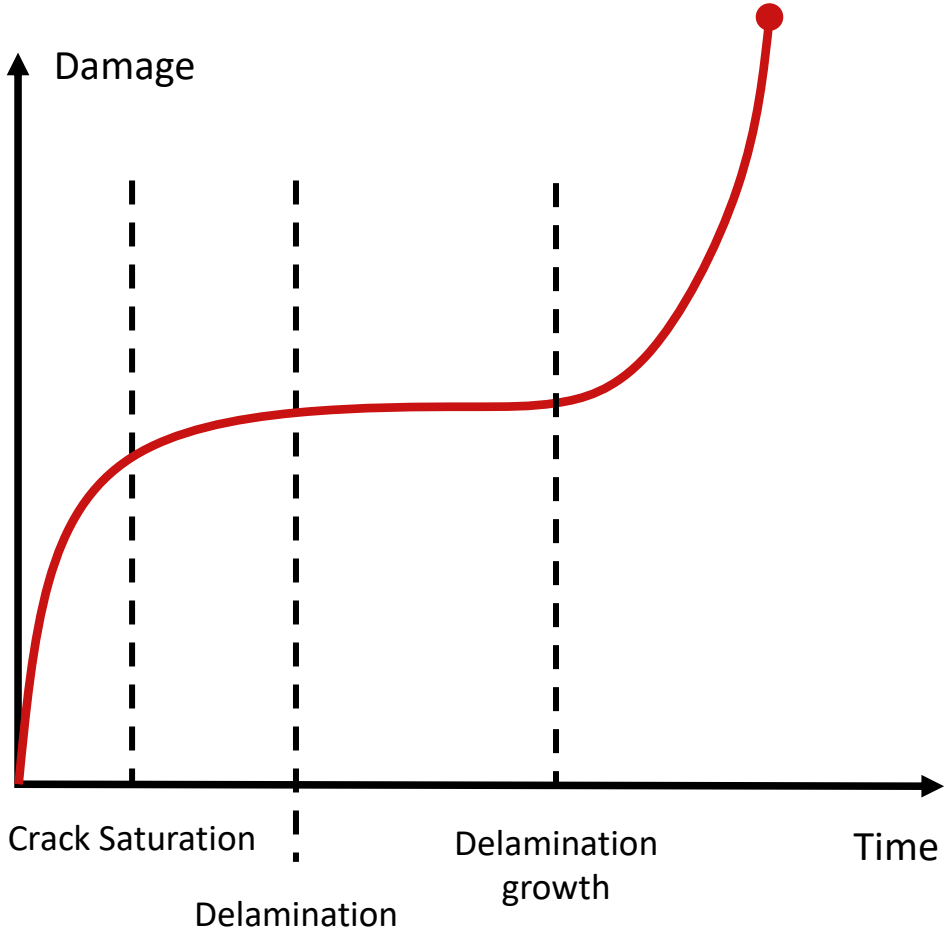


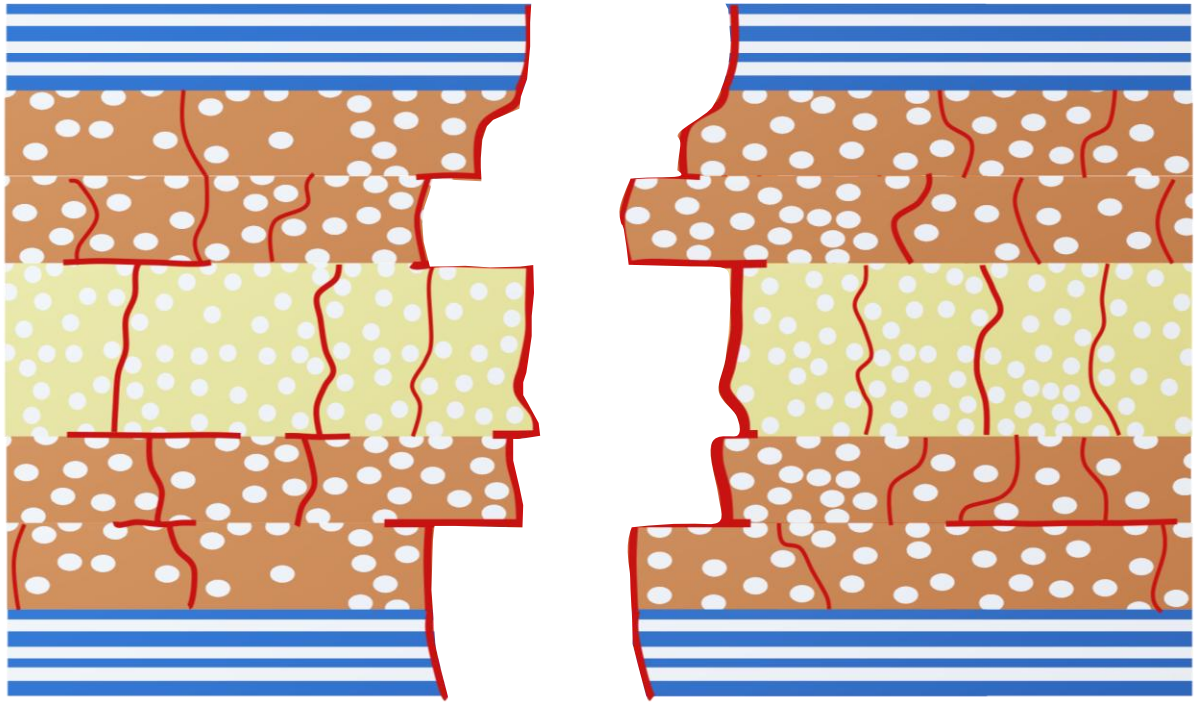

Damage
Crack Saturation
Delamination
Delamination growth
Time

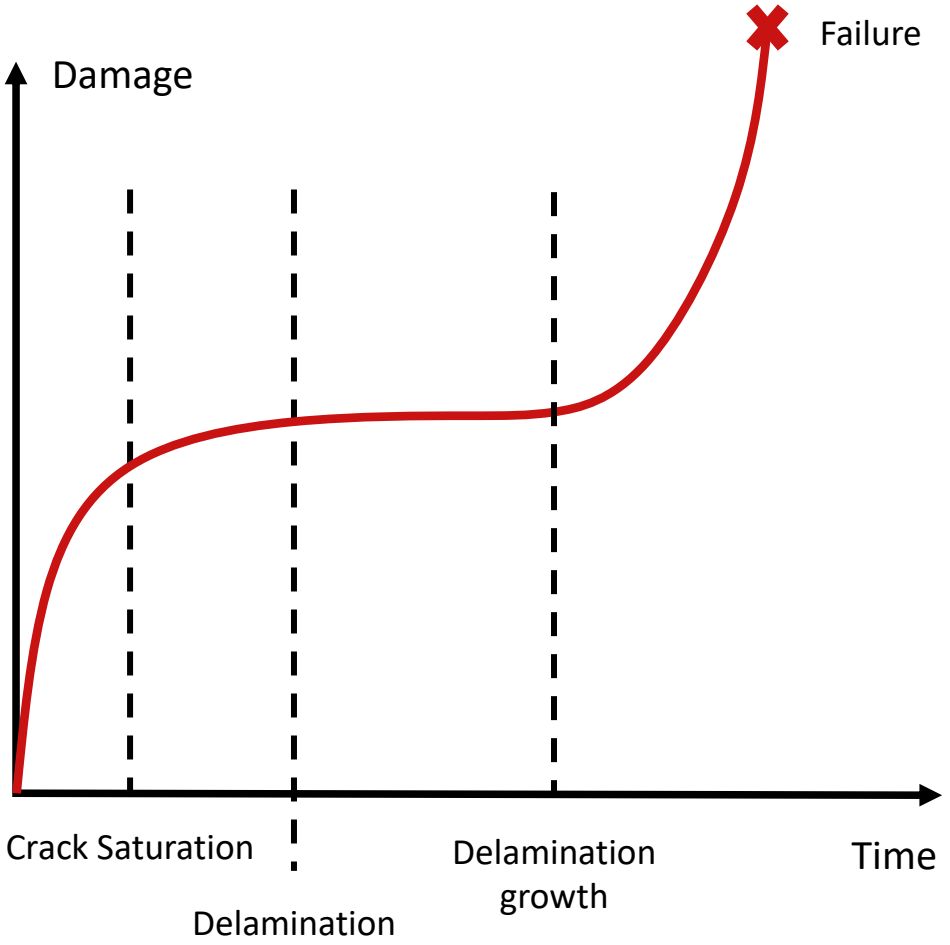


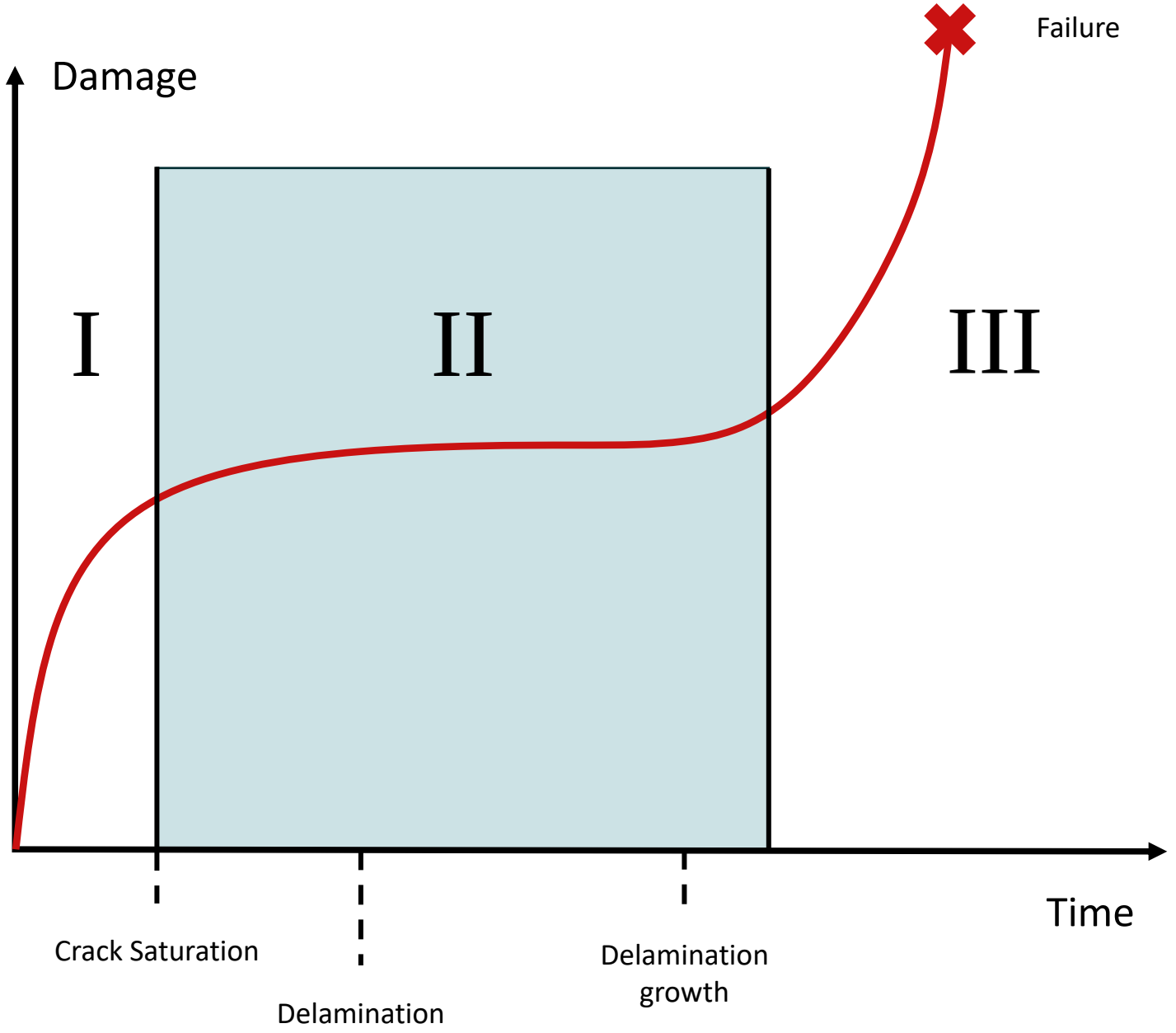

Damage
Crack Saturation
Delamination
Delamination growth
Time




Damage
Crack Saturation
Delamination
Delamination growth
Time




Failure
Damage
Crack Saturation
Delamination
Delamination growth
Time

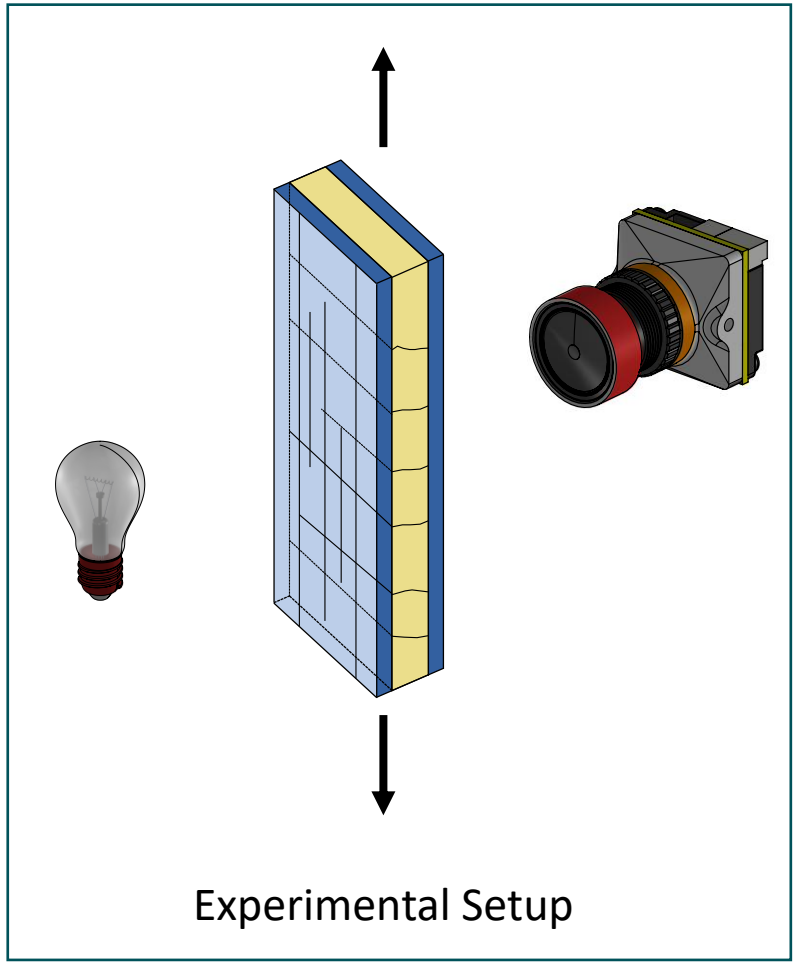

Failure
Damage
I
II
III
Time
Crack Saturation
Delamination
Delamination growth

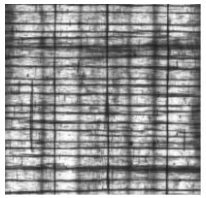
Motivation

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

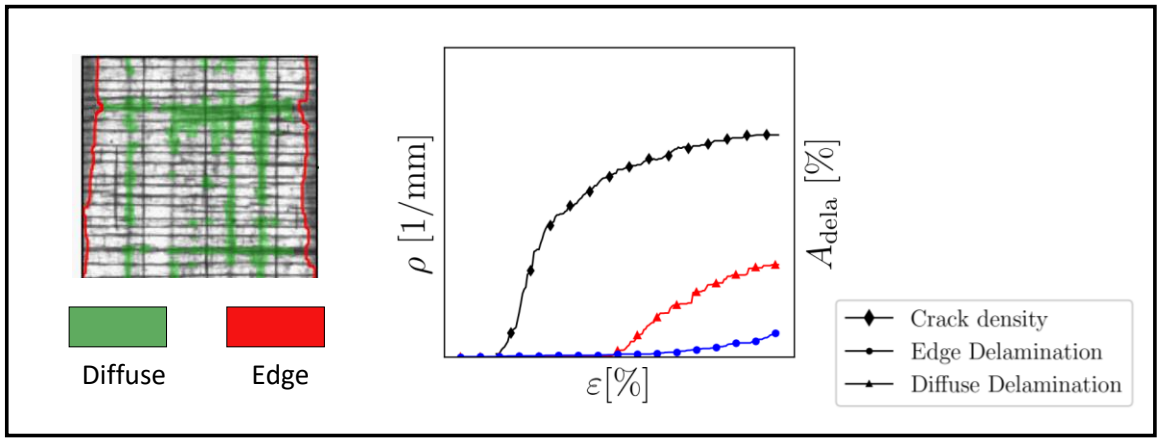
- Qualitatively
- Quantitively (?)

Experimentally, we observed…





DelaDect

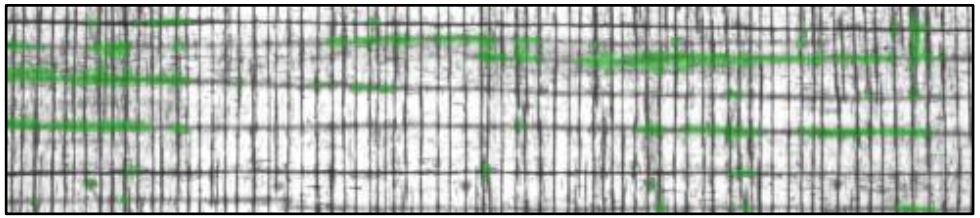


Results – Effect of t_{90}

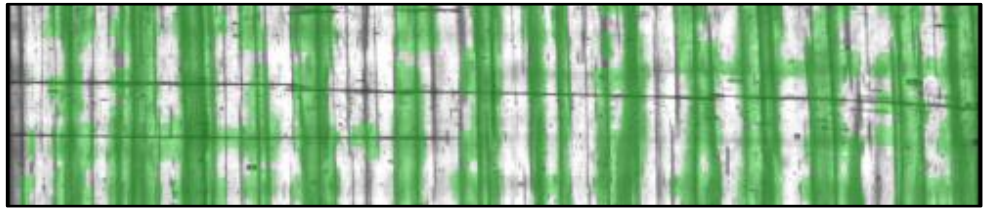
Delamination

Matrix cracks

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



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



Cross-ply Layup

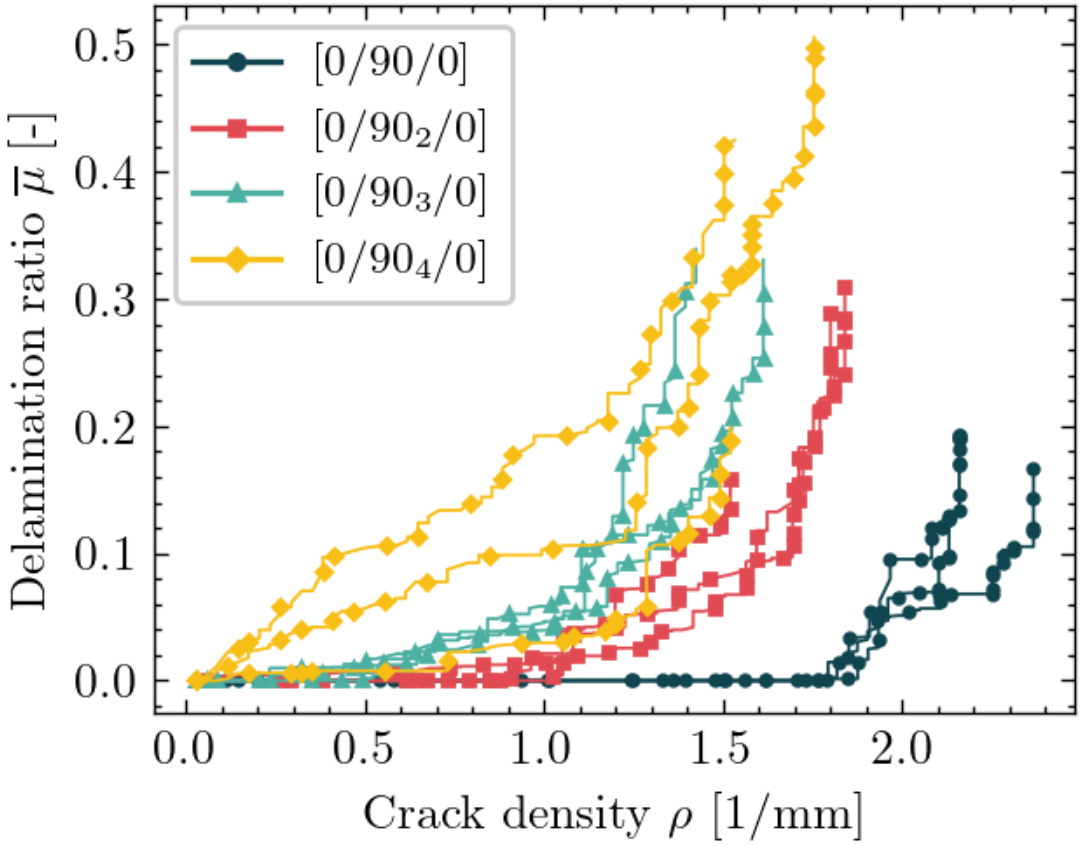
Relative Delamination:

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

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

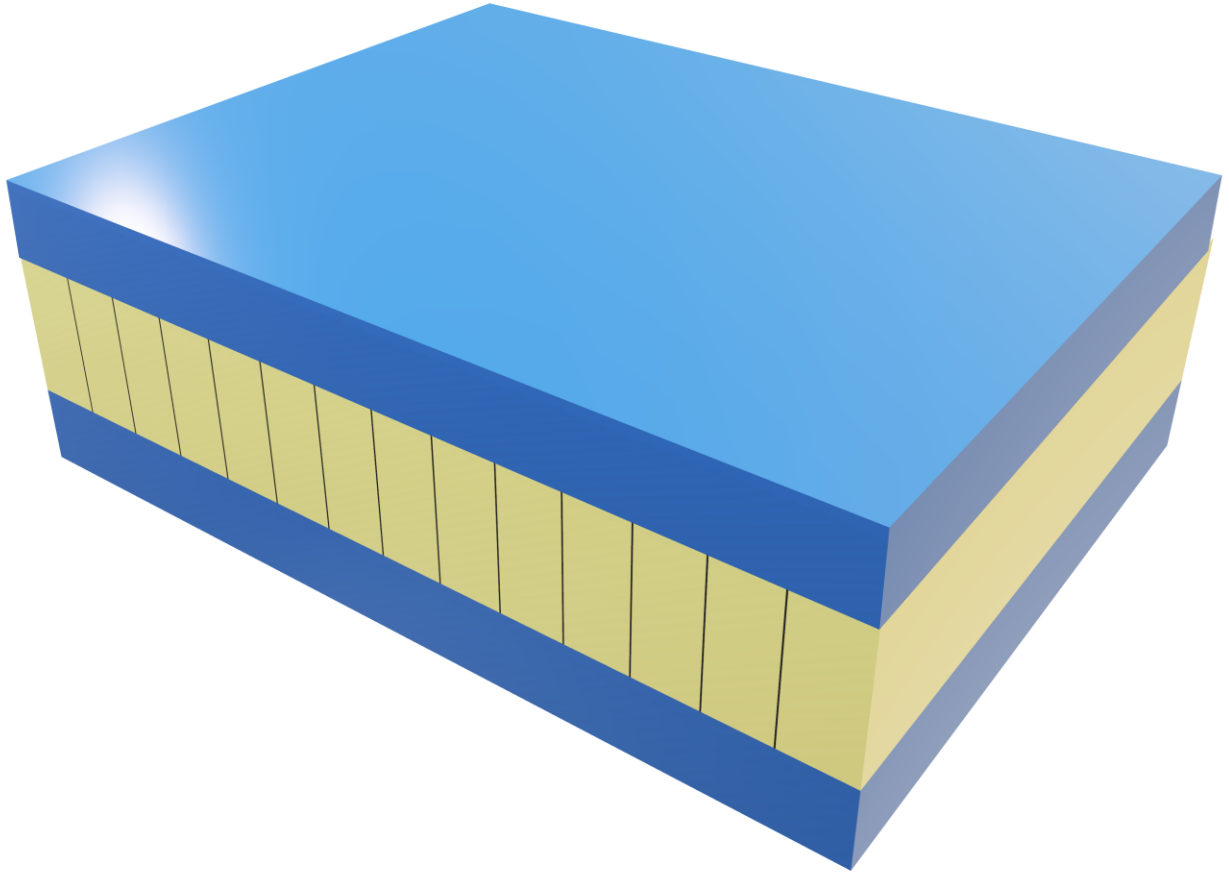
$$t_{90} \rightarrow \begin{cases} \rho \\ \bar{\mu} \end{cases} \quad ?$$

Results – Effect of t_{90}



So, fewer cracks → More delamination?

Modelling approach

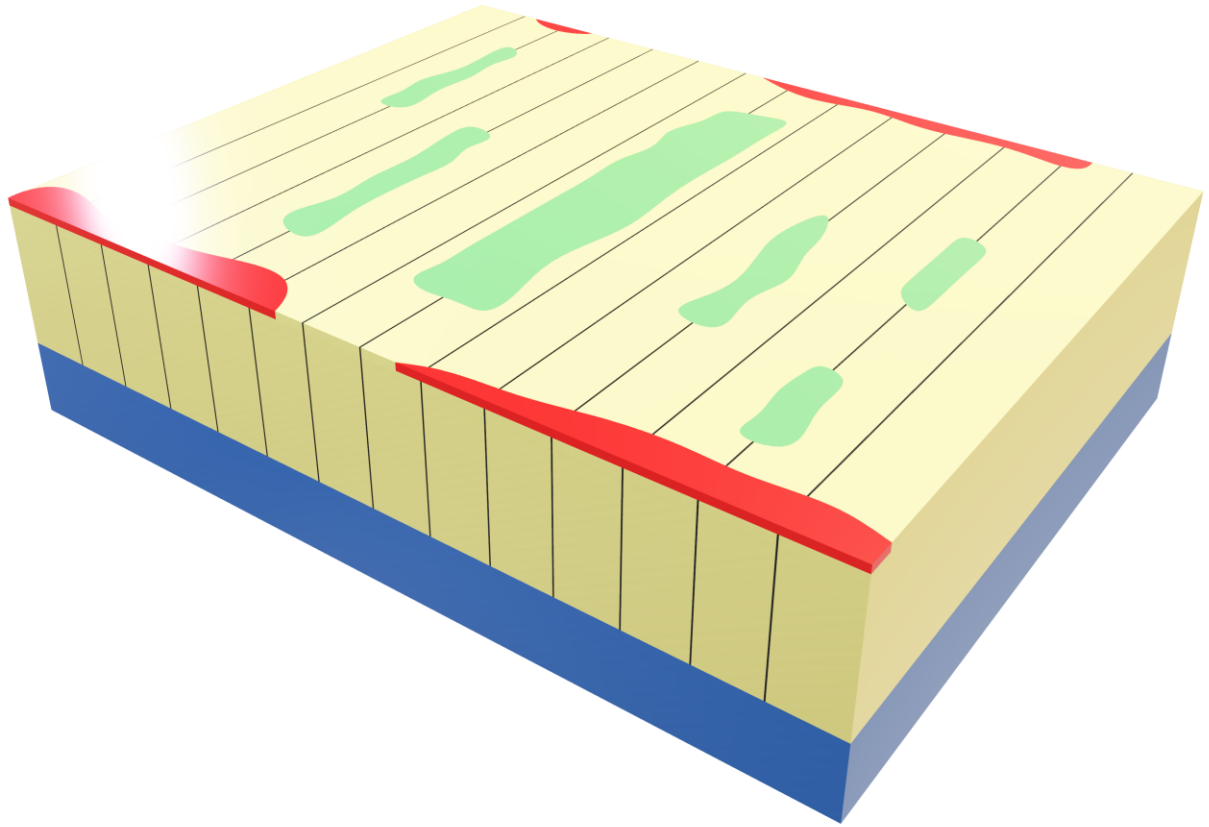


Cross-ply Layup

Modelling approach

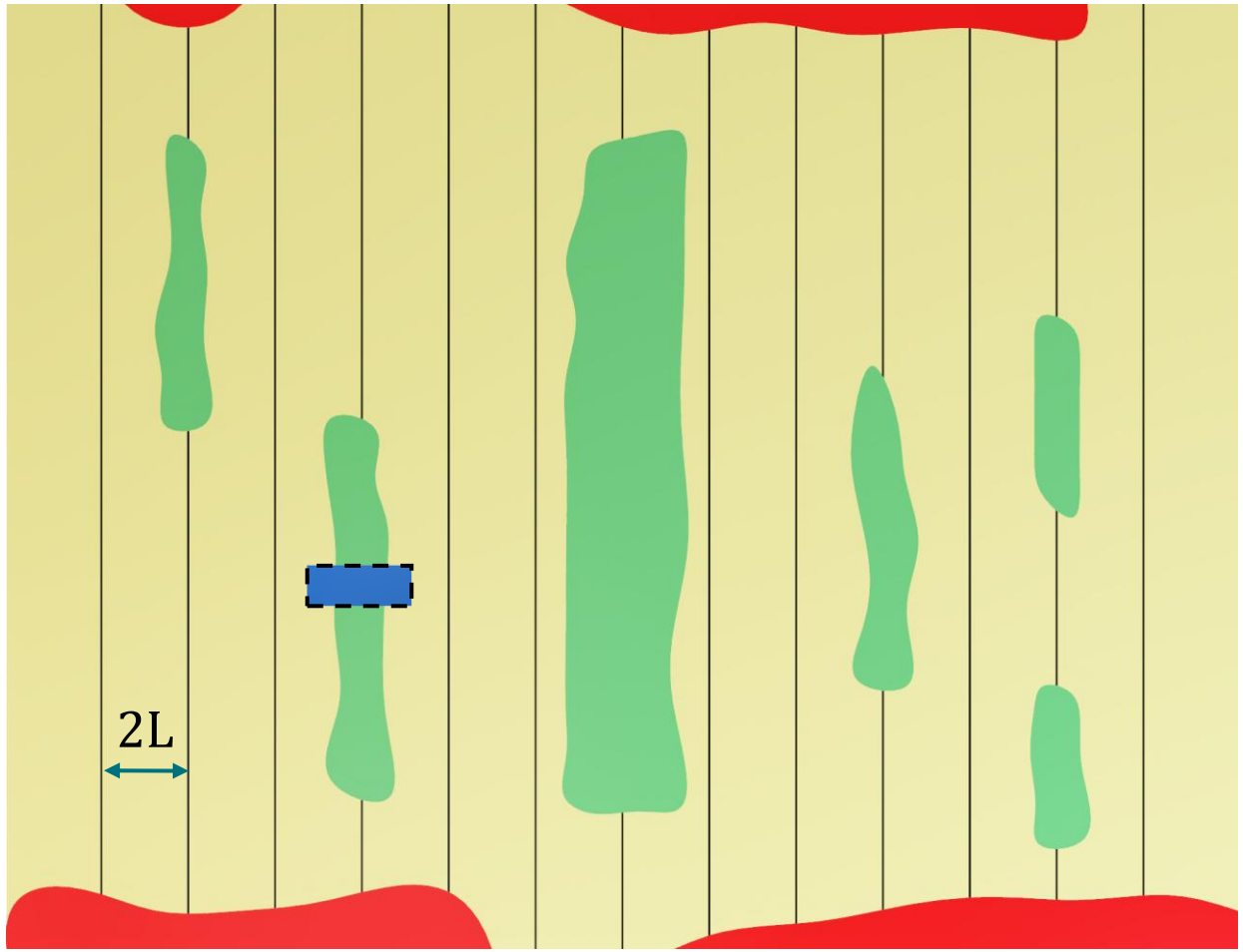
Delamination

Matrix cracks



Cross-ply Layup

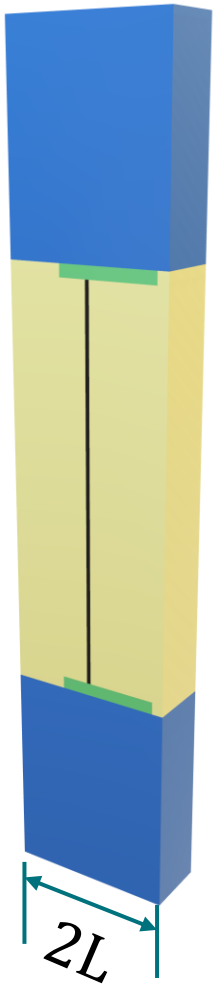
Modelling approach

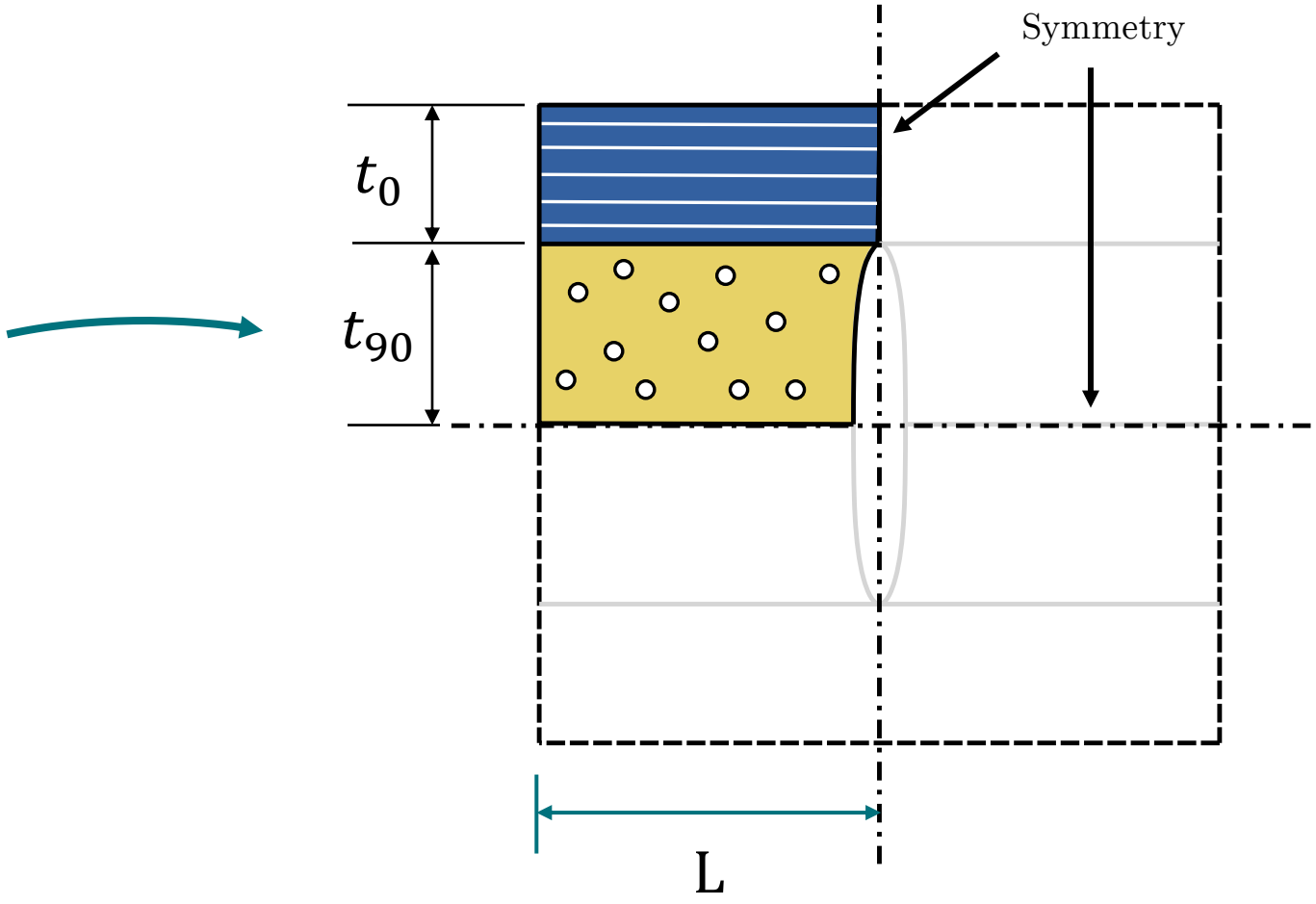


Delamination

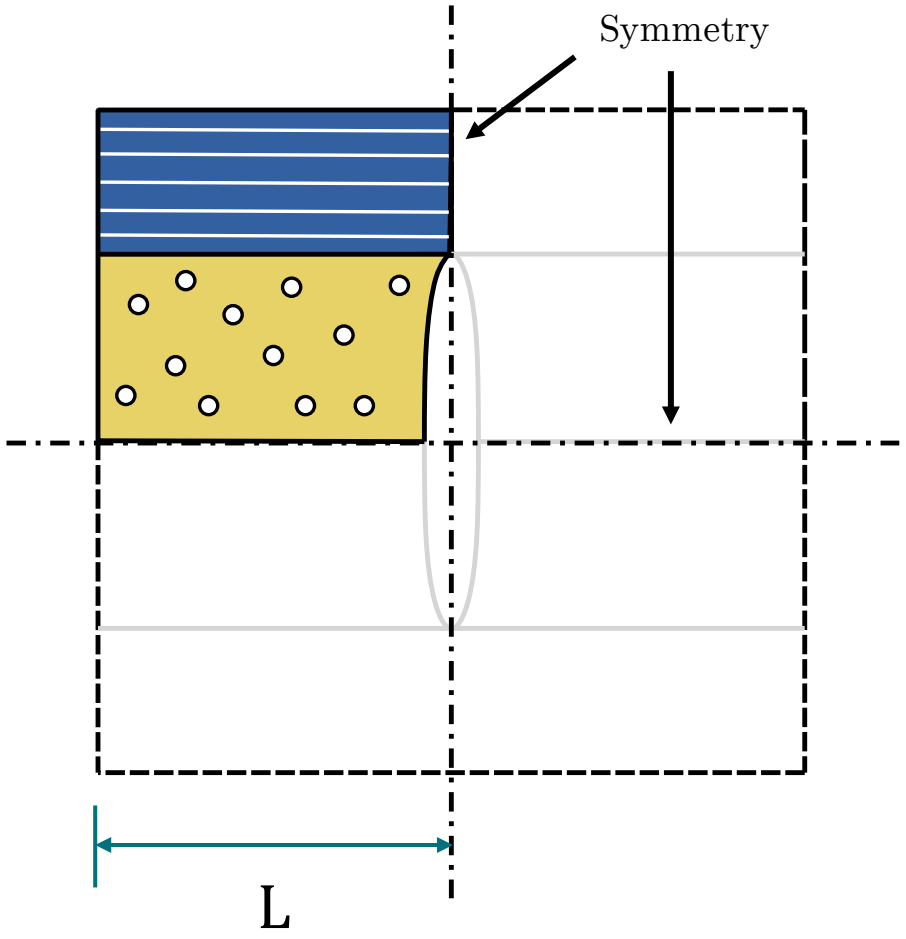
Matrix cracks

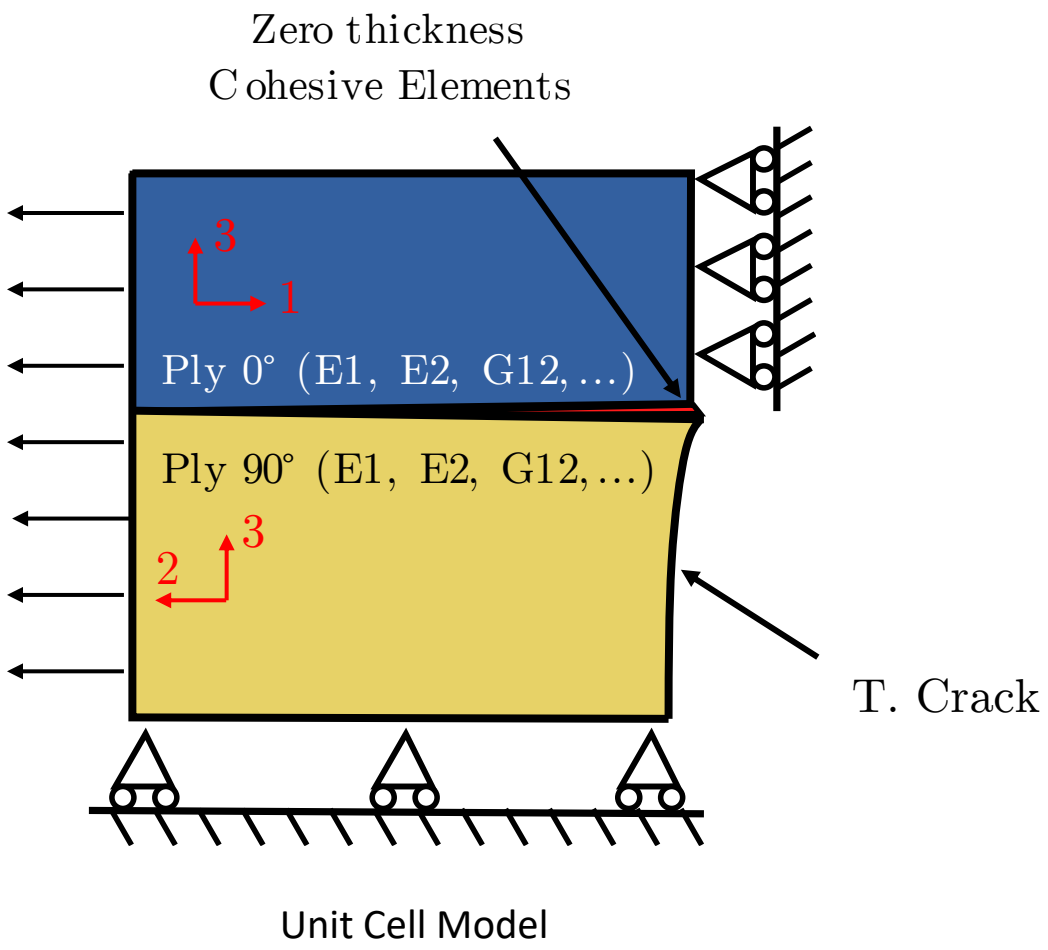
Modelling approach





Modelling approach





Unit Cell Model

Modelling approach

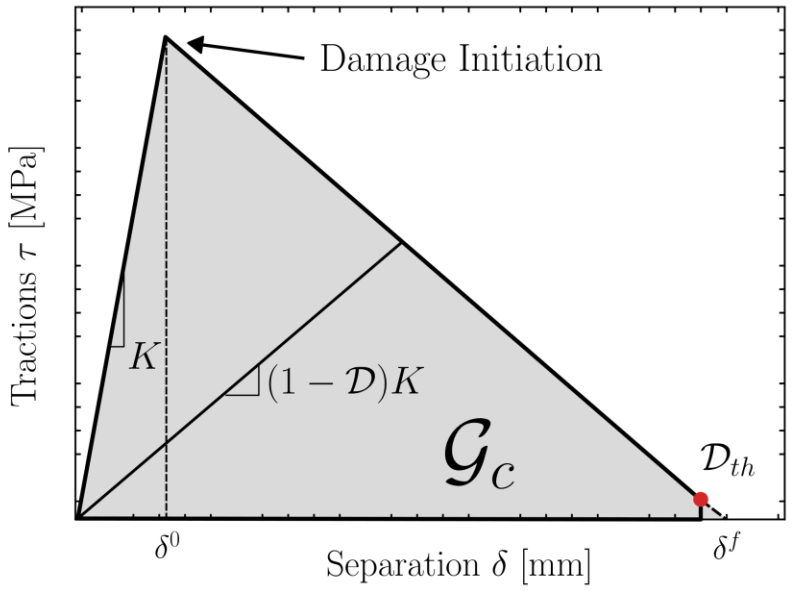
Cohesive Settings
Damage Initiation:

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

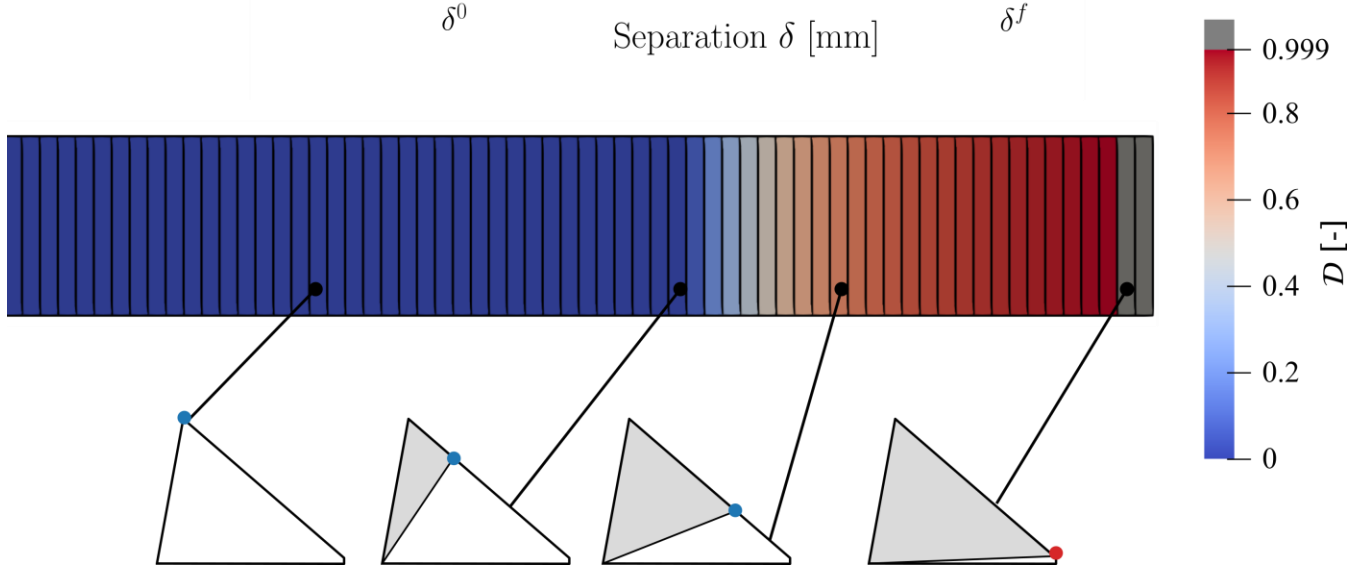
Damage Evolution: Linear

Mixed mode behavior: B-K Law

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

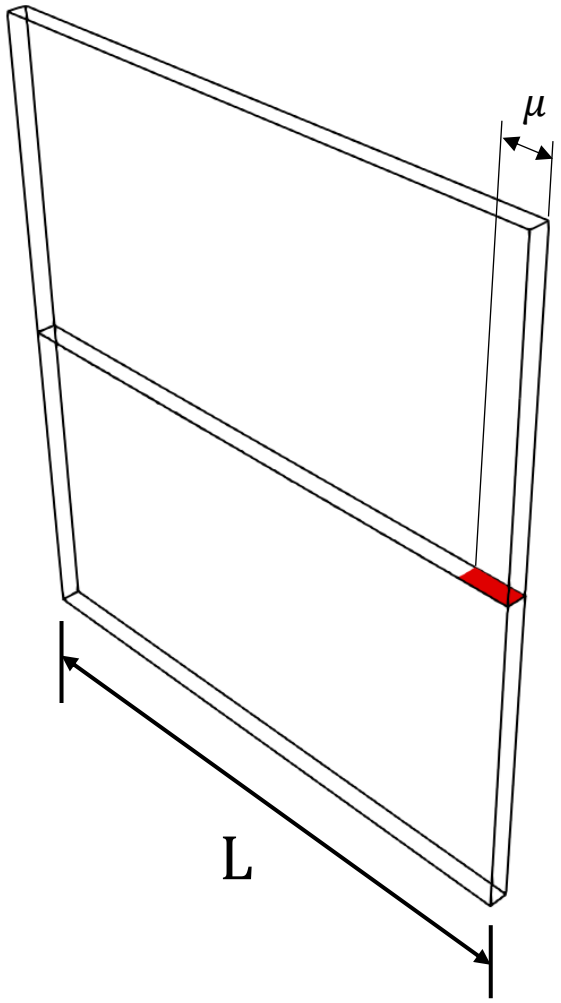


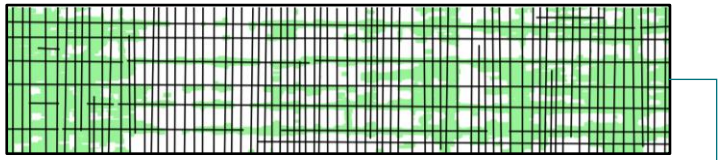
$\mathcal{D}$ corresponds to the degradation of the element



Modelling approach

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





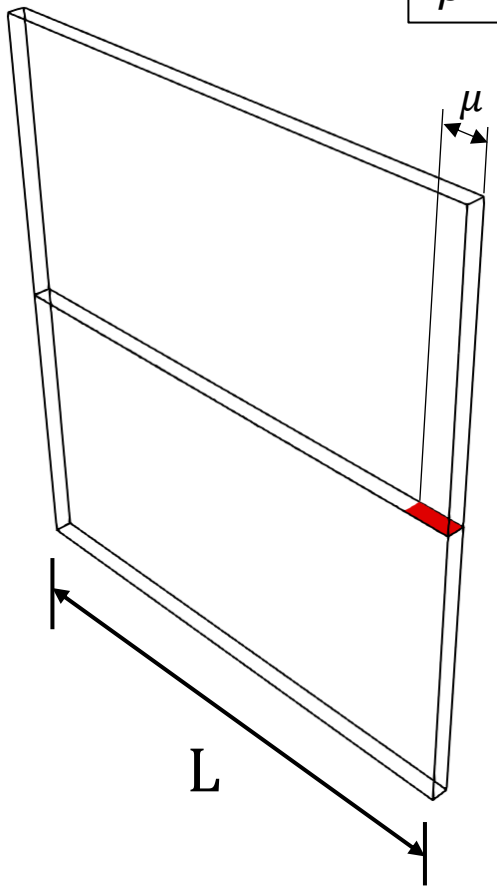
Relative Delamination:

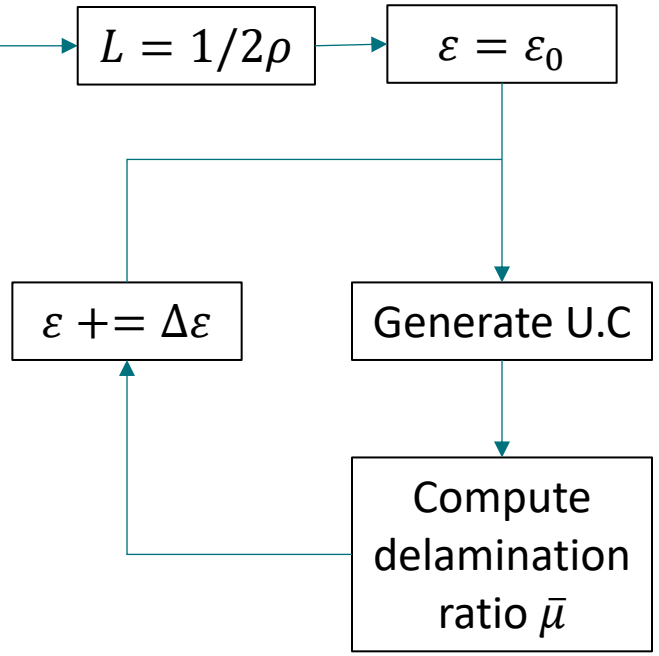
$$\bar{\mu} = \frac{\mu}{L} \Leftrightarrow \boxed{\bar{\mu} = \frac{A_{del}}{A_{specimen}}}$$

Crack Density:

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

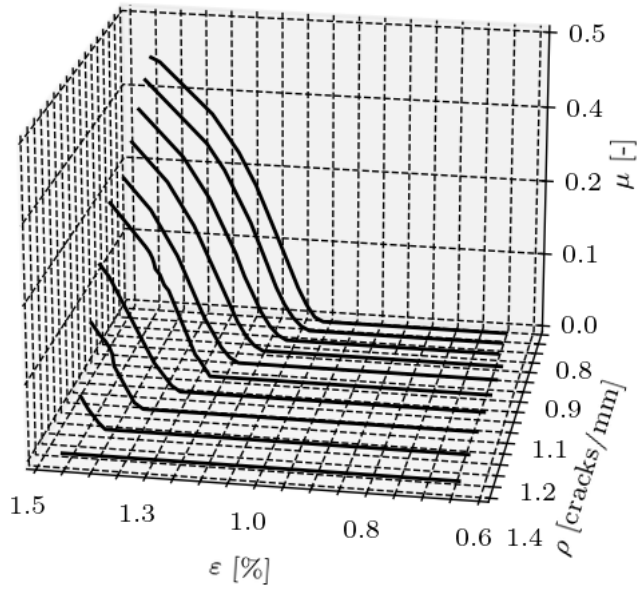
Parametric study





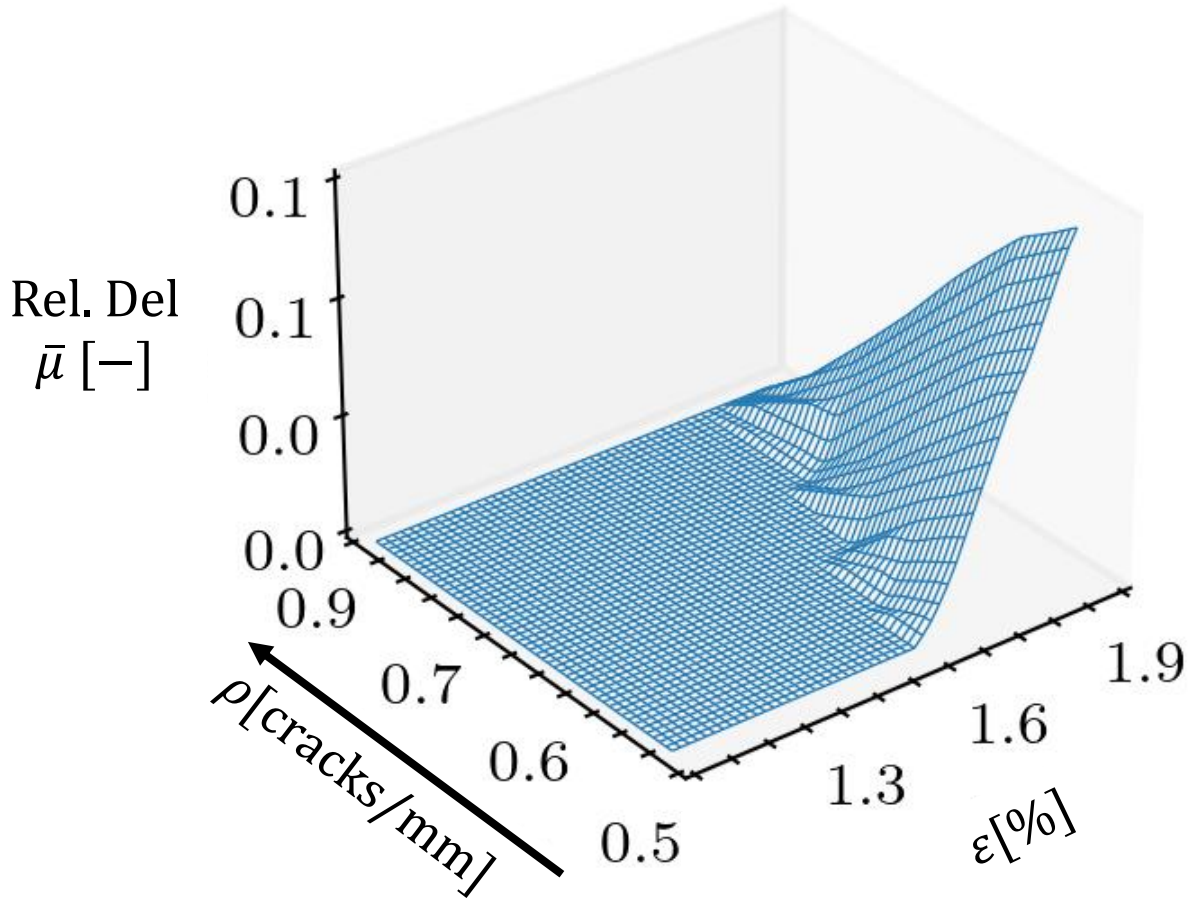
Same laminate, fixed dimensions and material properties.

Unit Cell for a fixed crack spacing/density

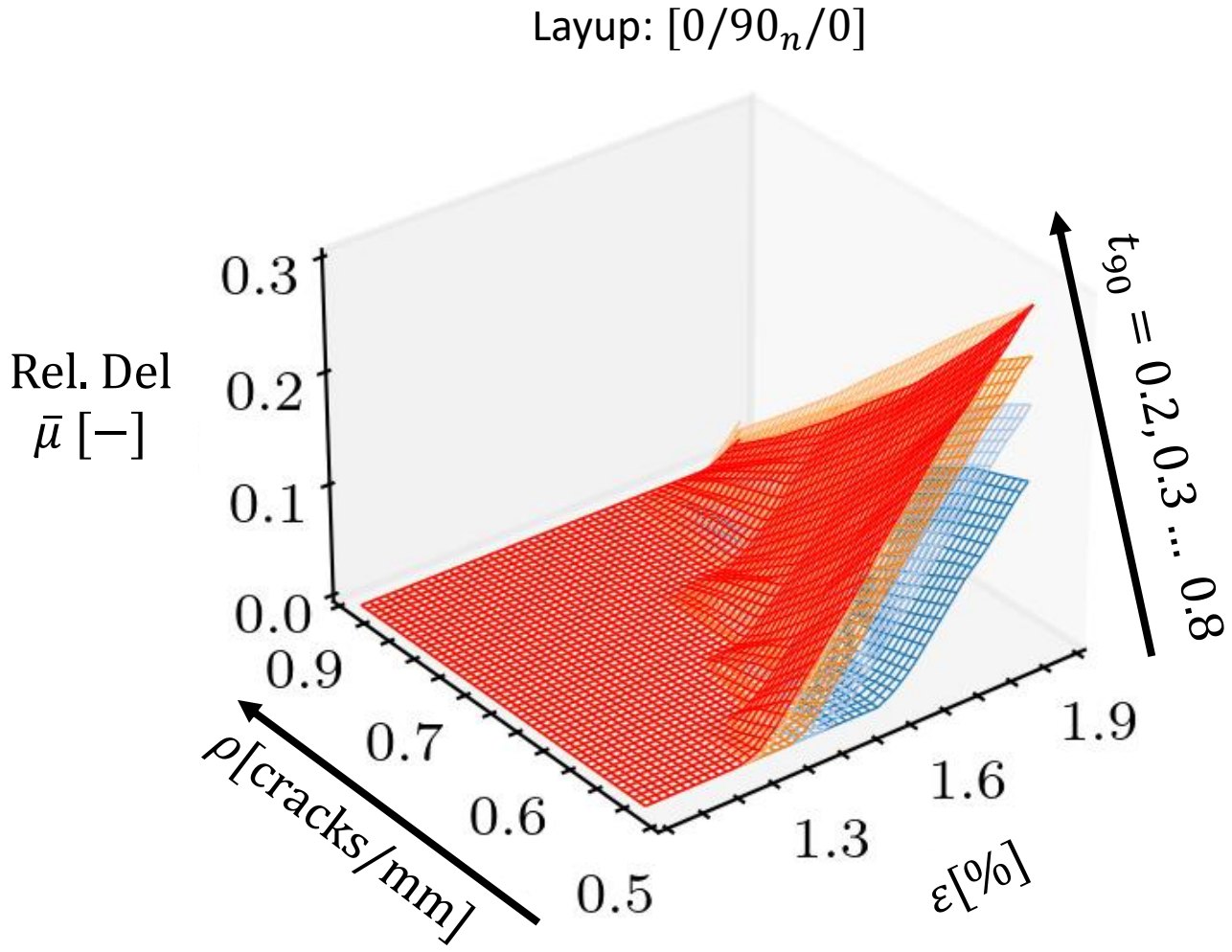


Results

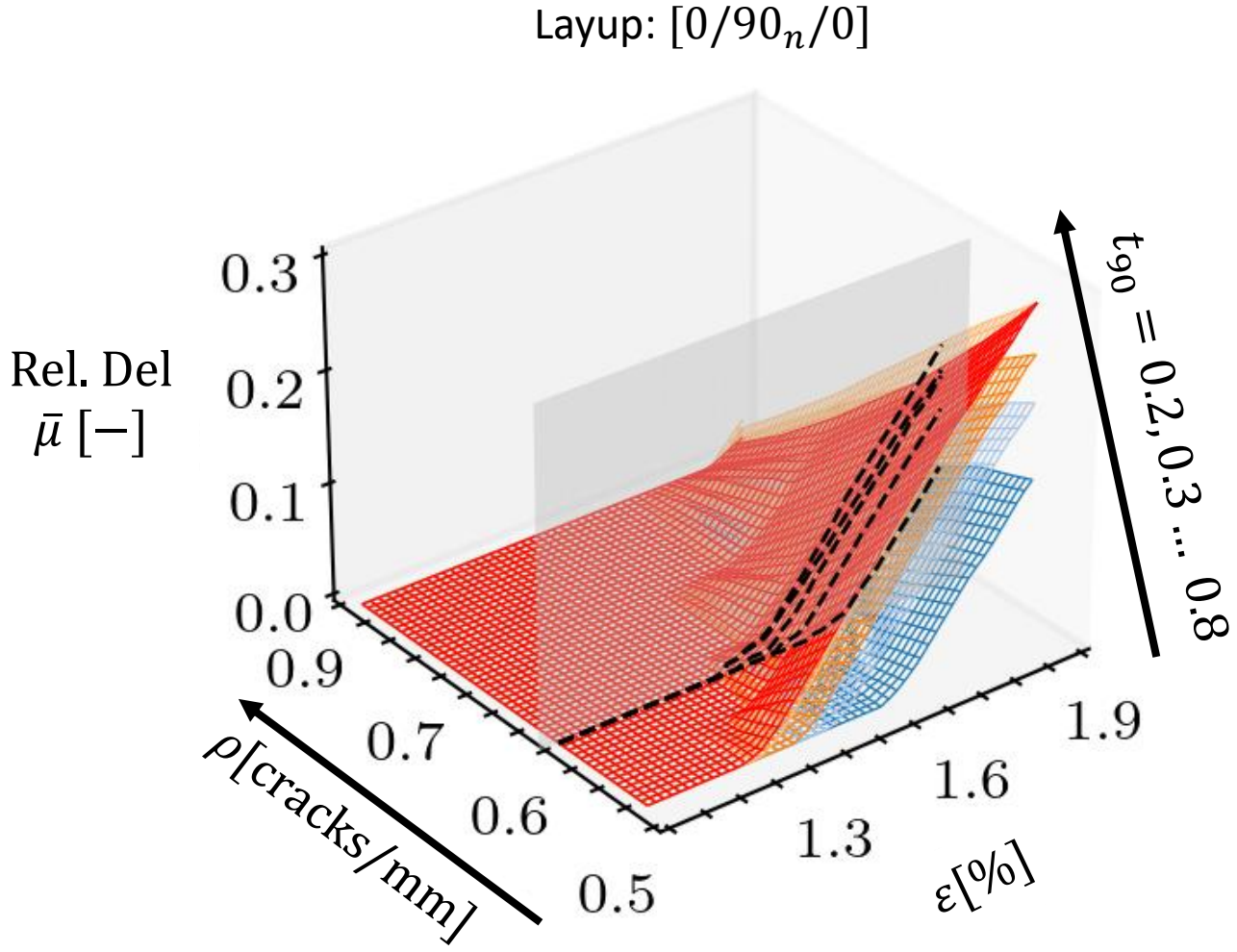
Layup: $[0/90_n/0]$



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]
1.9
1.6
1.3
ε[%]
$t_{90} = 0.2, 0.3 \ldots 0.8$

Results


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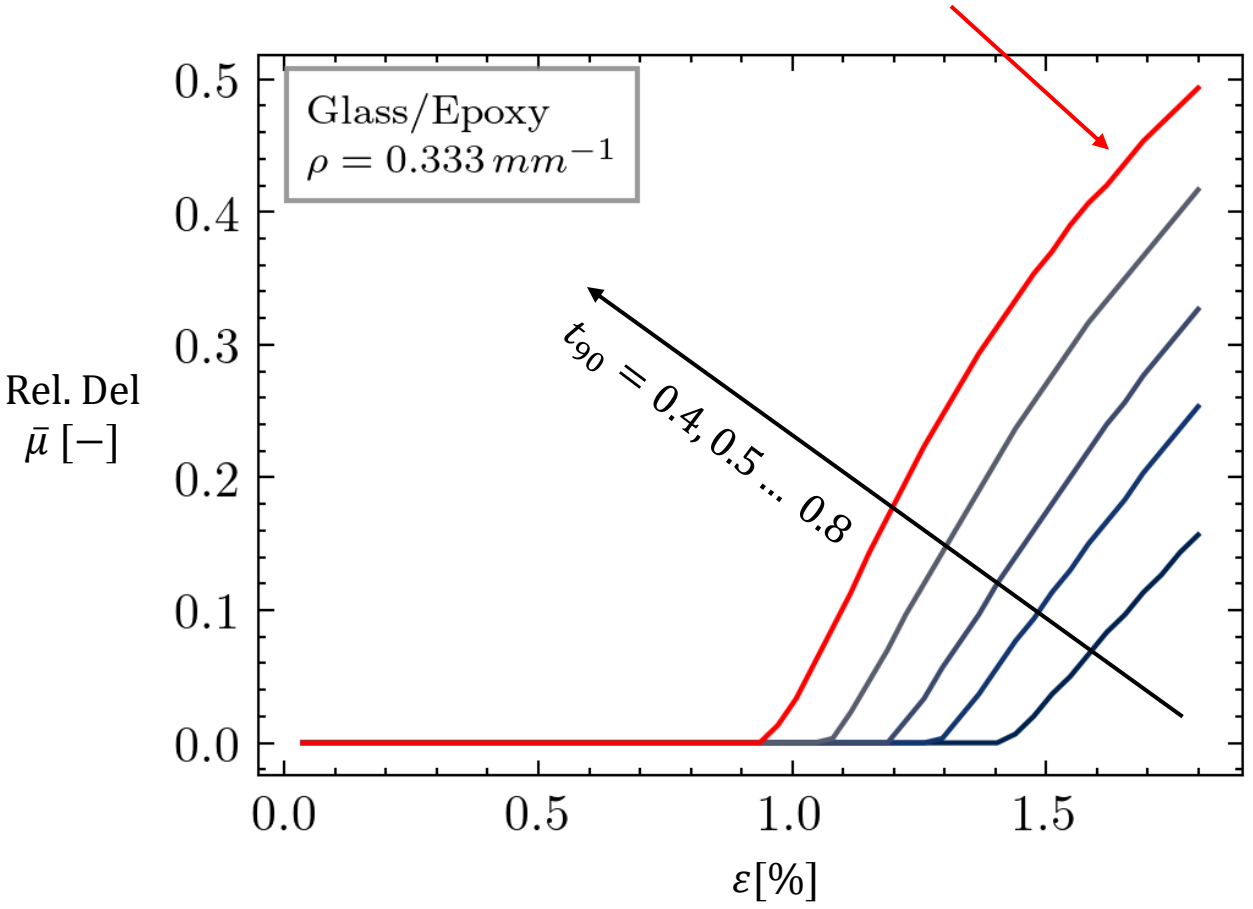
0.5
ρ[cracks/mm]
1.9
1.6
1.3
ε[%]
$t_{90} = 0.2, 0.3 \ldots 0.8$

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

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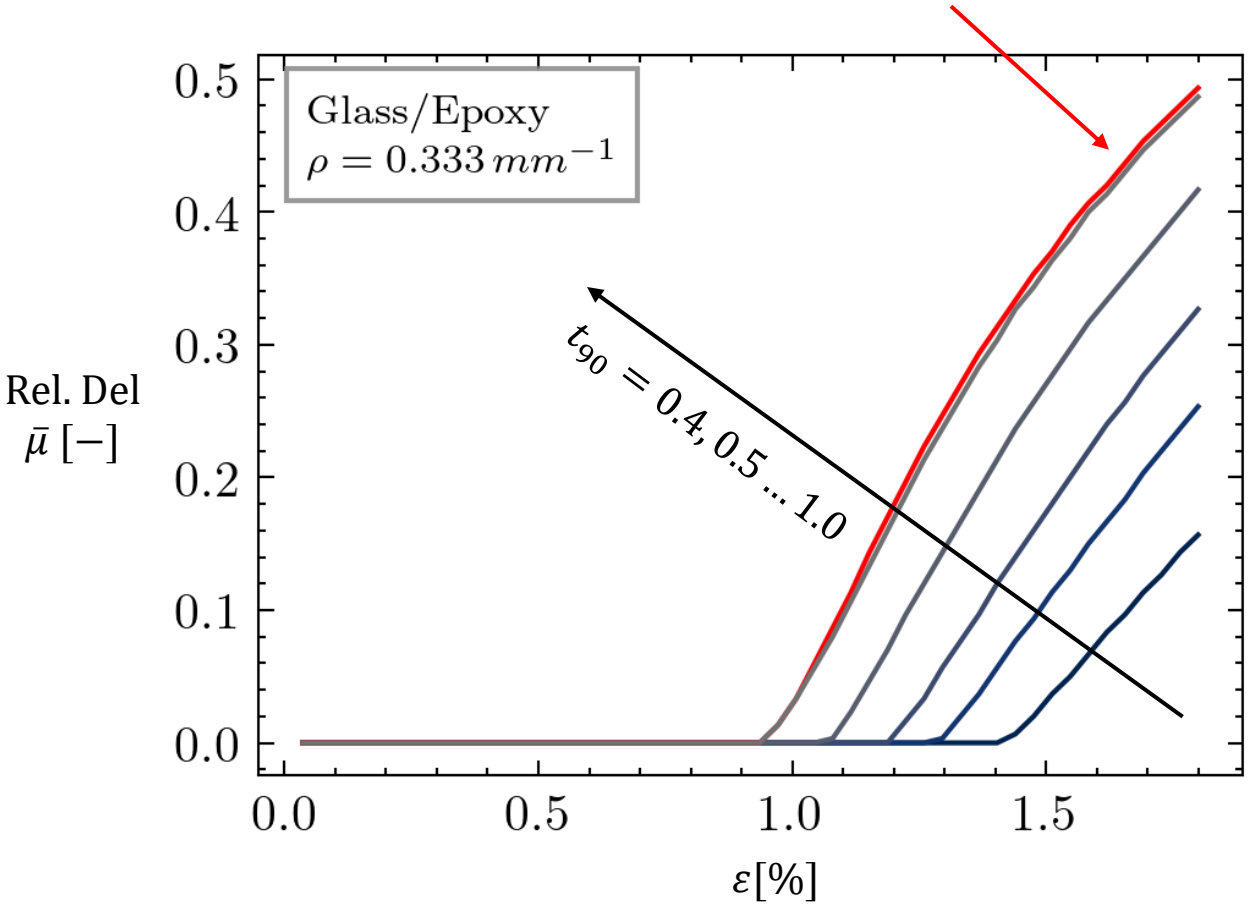

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Results

?

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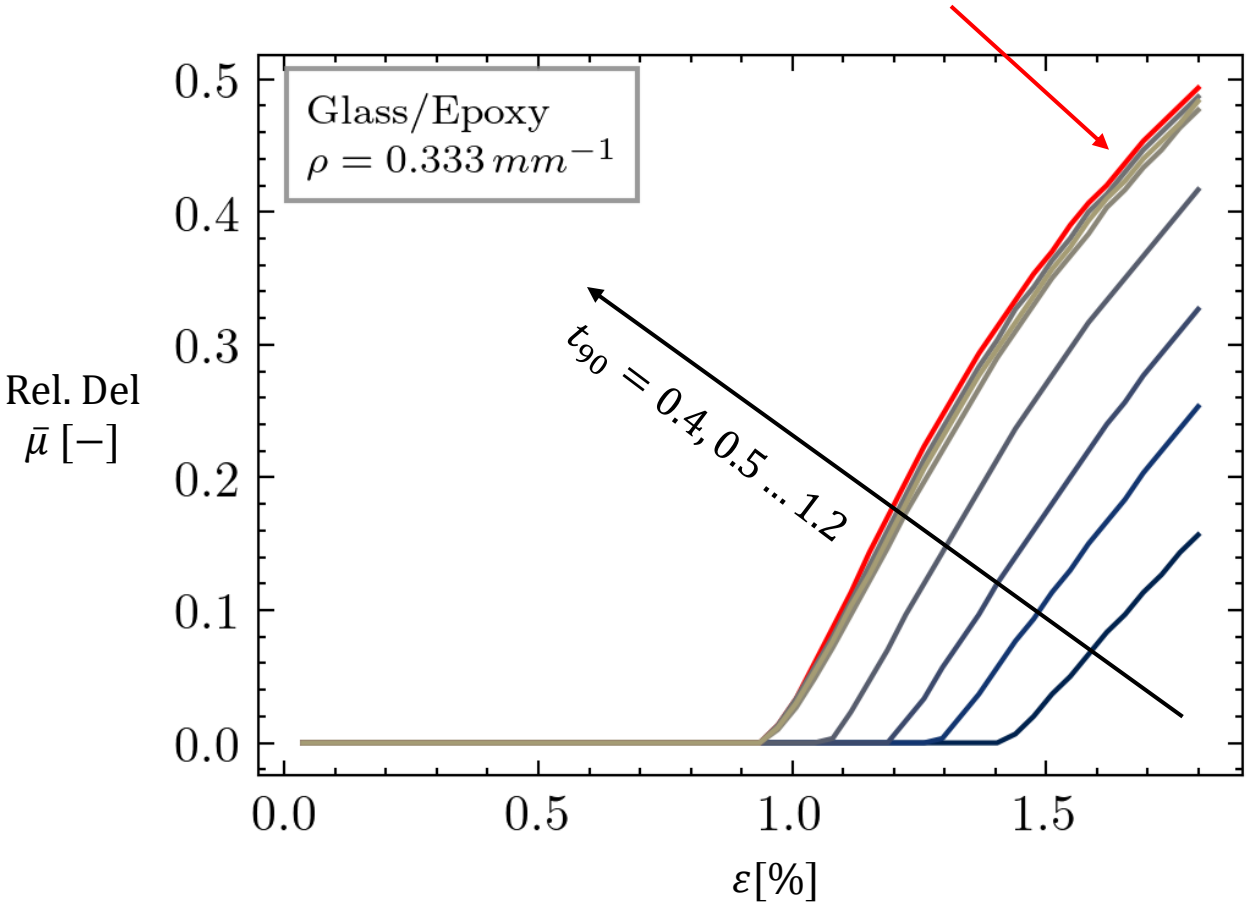

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Results

?

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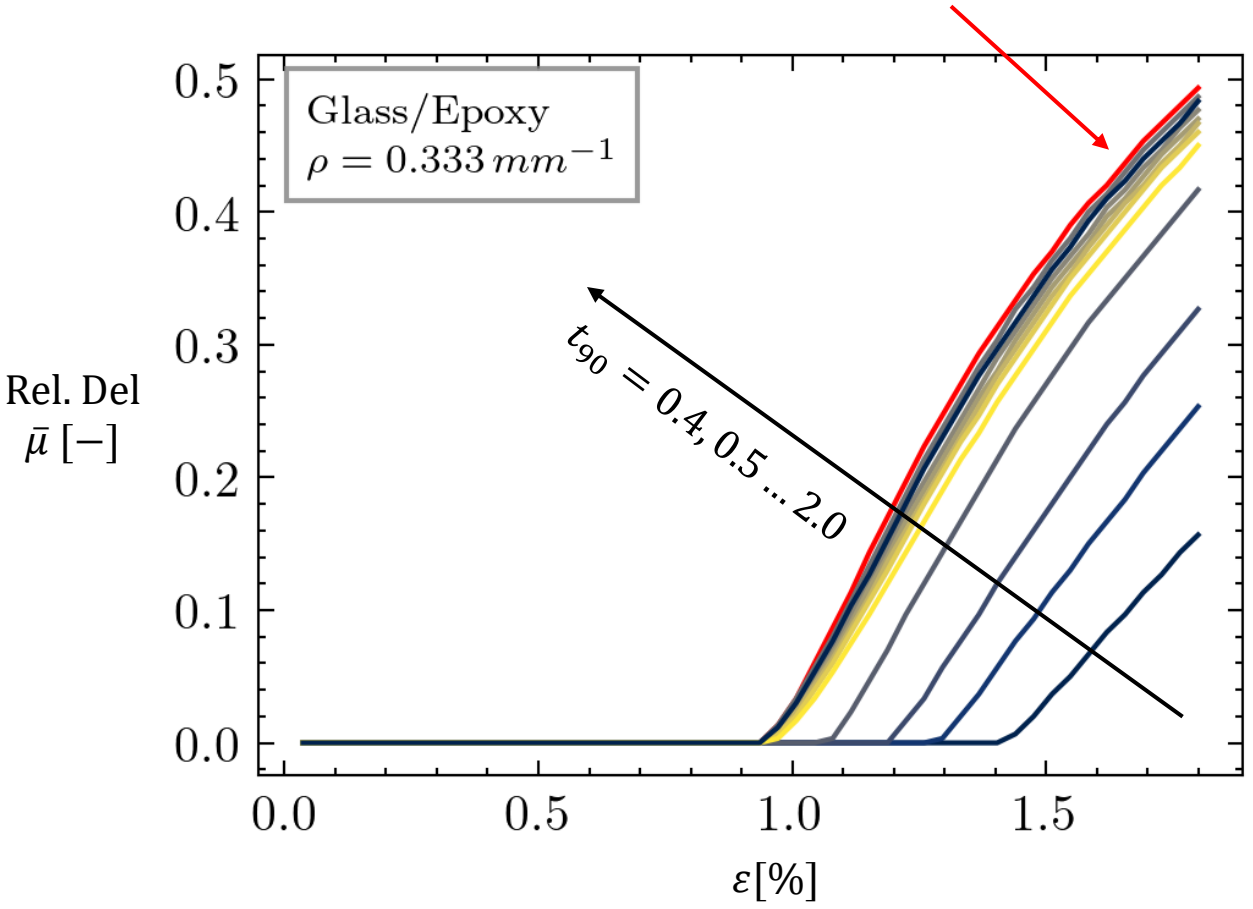

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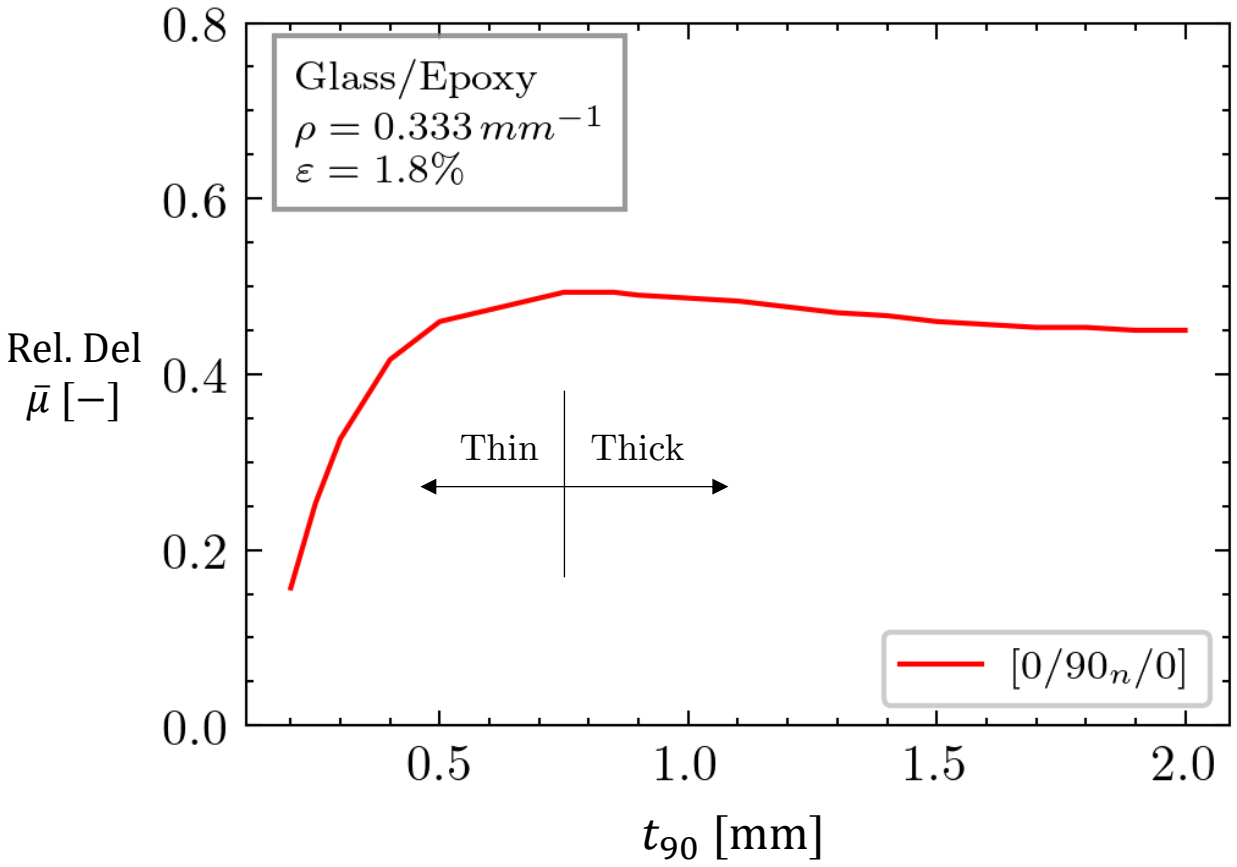
Outer Ply thickness = 0.8 mm

Results


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

Conclusions

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

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  - However, we cannot separate individual contributions

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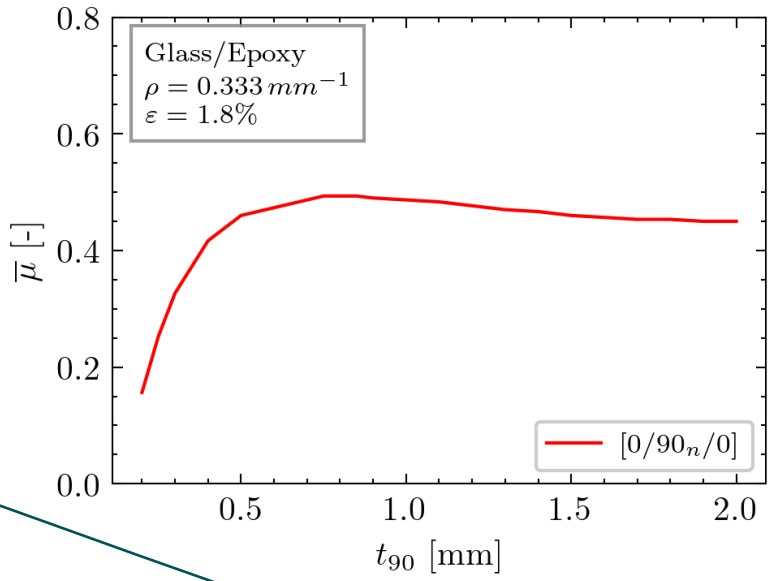
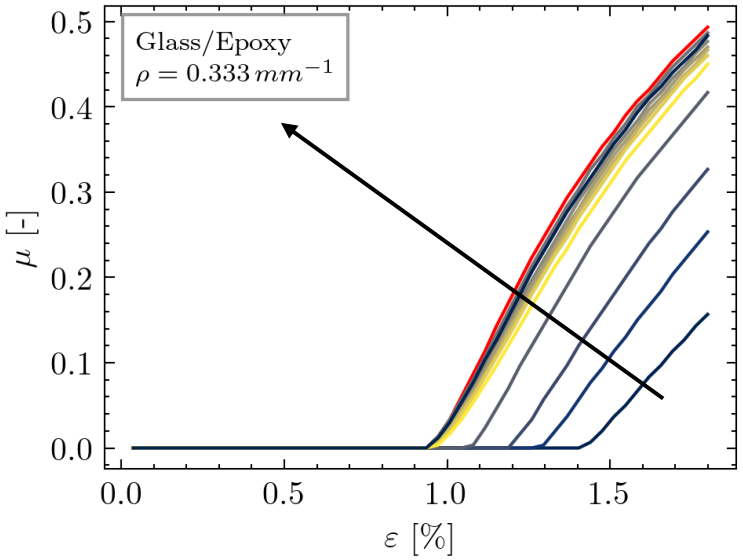
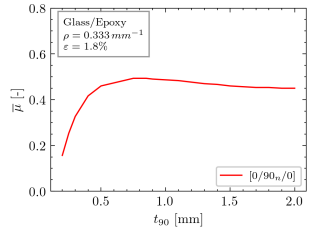


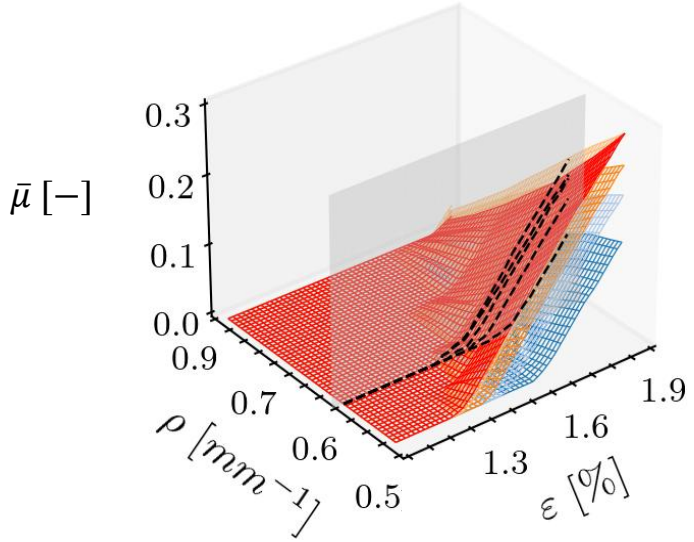


Conclusions

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
- $\rho \downarrow \rightarrow \bar{\mu} \uparrow$





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Thanks for your attention!

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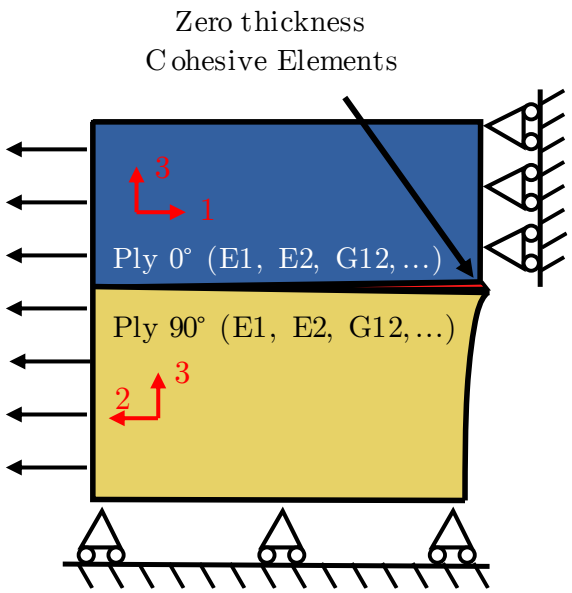
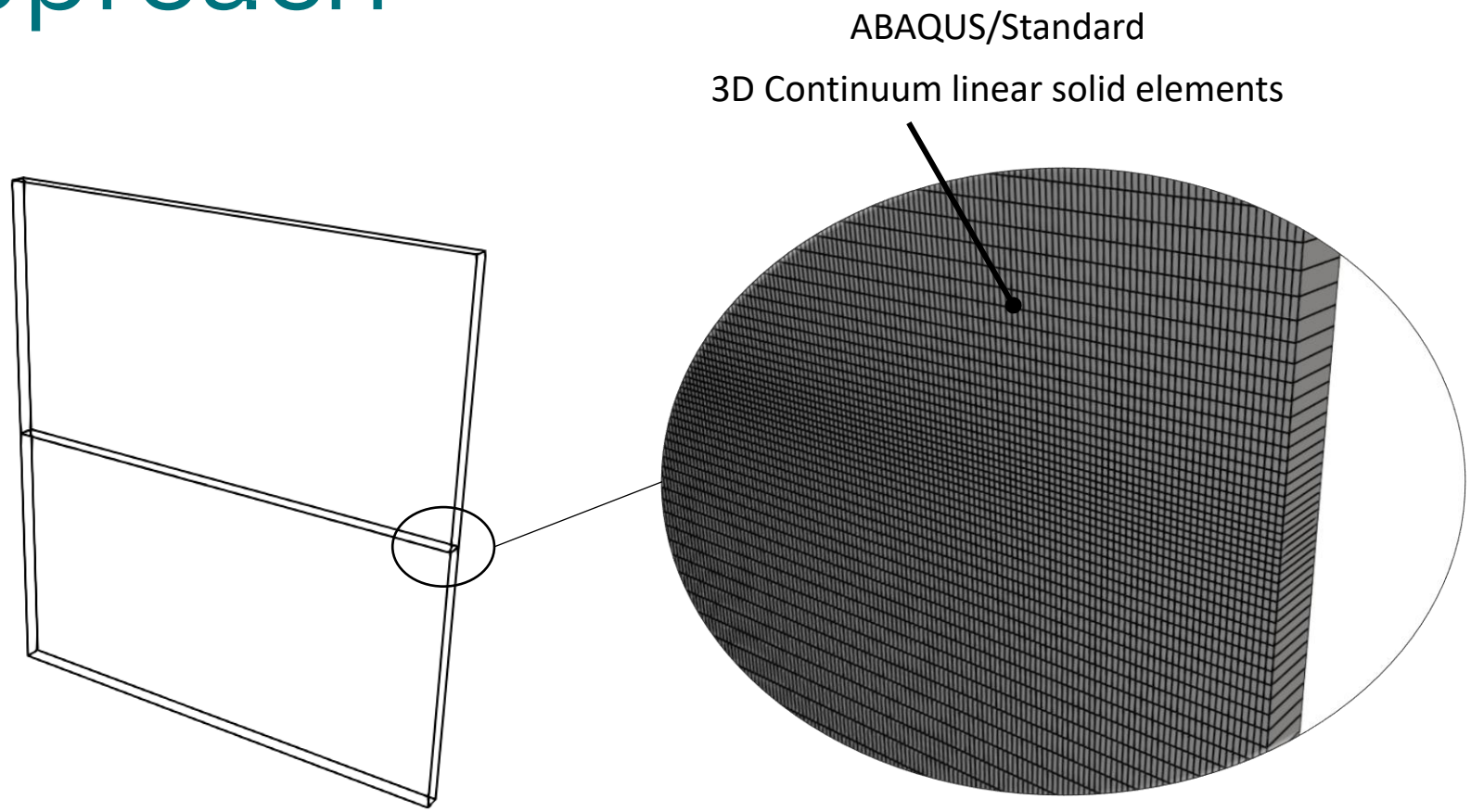
Backup Slides

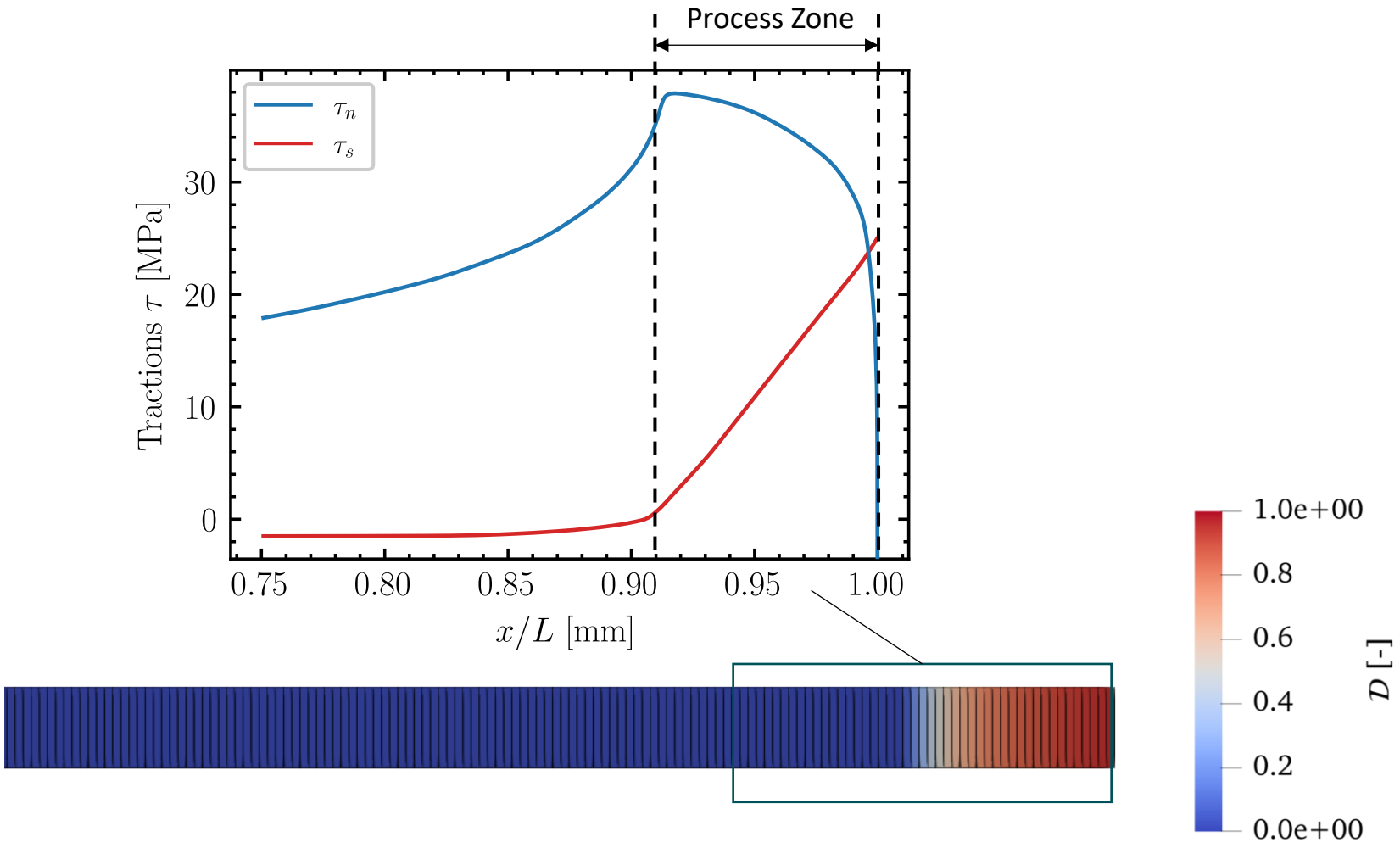
Modelling approach





Generalized plane strain model

Process Zone and Tractions



Material Properties - Elastic

GFRP:

E_1 [GPa]	E_2 [GPa]	v_{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]	v_{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