Fracture toughness of architected joints involving crack instabilities

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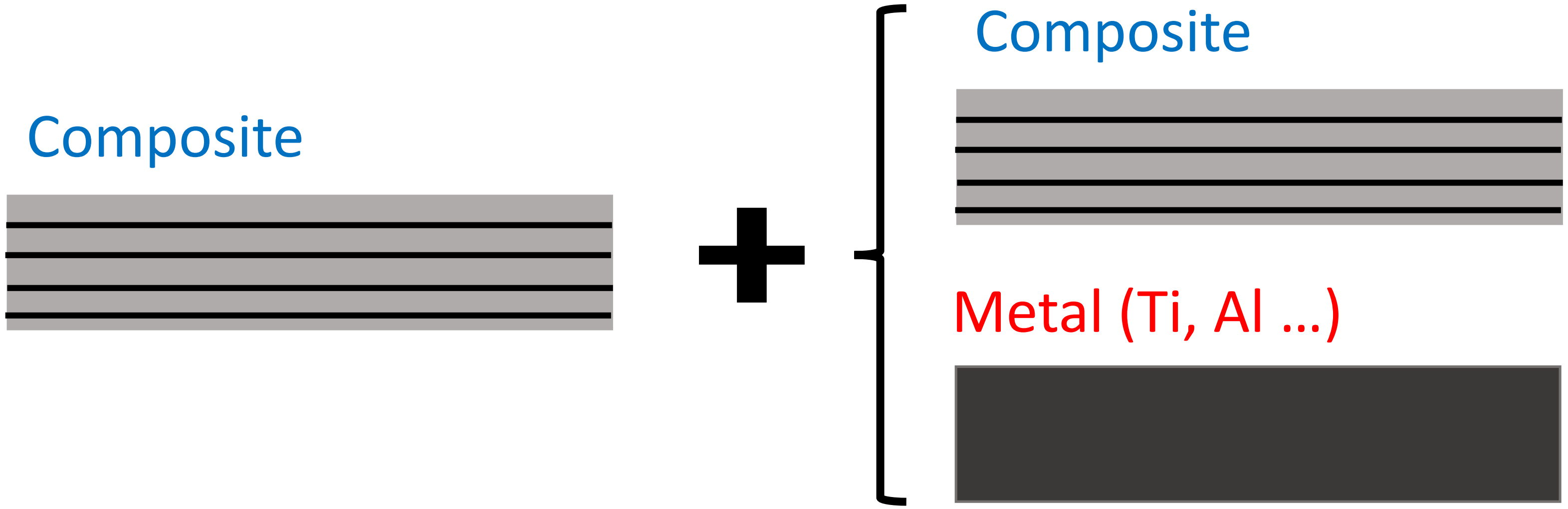
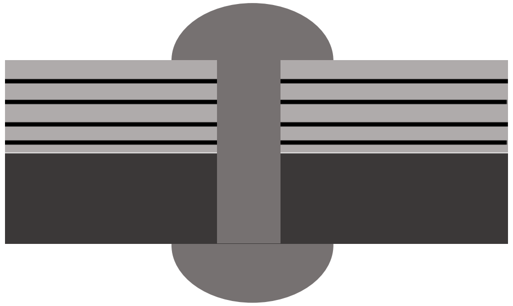
A380
Own the sky
A380 AIRBUS


Composite
+
Composite
Metal (Ti, Al …)

→ To bond

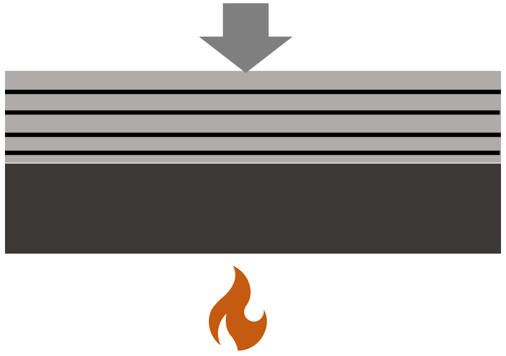
Joining techniques

Mechanical fastening



- × Drilling holes
  - → stress concentrations
  - →↓ structural integrity
- × Additional weight
- ✓ Control of components

Thermoplastic welding

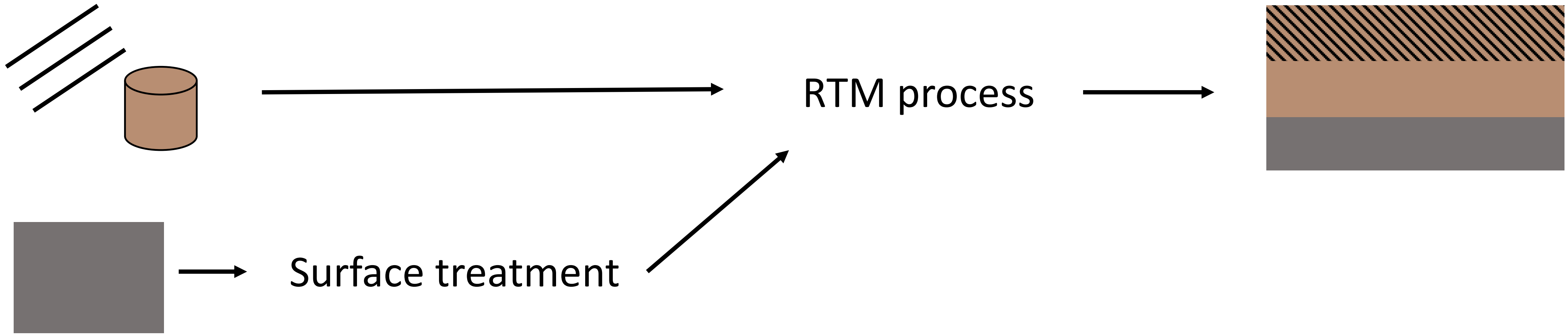


- × Only for TP composites
  - → TS = largest share
- ✓ High throughput

Adhesive bonding

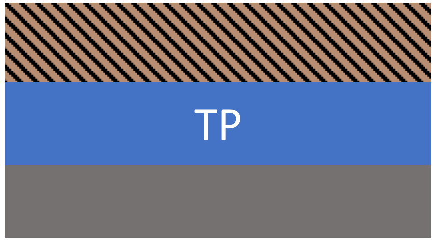
- ✓ Homogeneous stress transfer
- ✓ Lightweight
- × Low G_{Ic}
- × Time- & labor-intensive
- × Lack of non-destructive control

Time- and labor-intensive process ➔ Integrated manufacturing = Cocuring

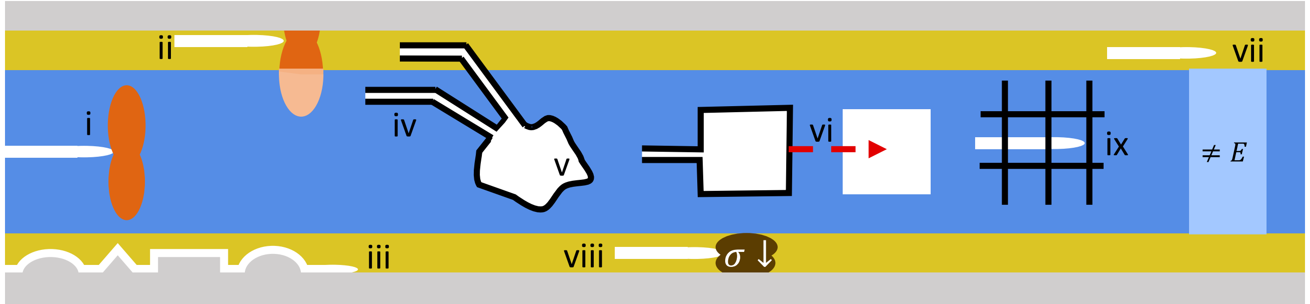


× Poor adhesion composite resin - metal

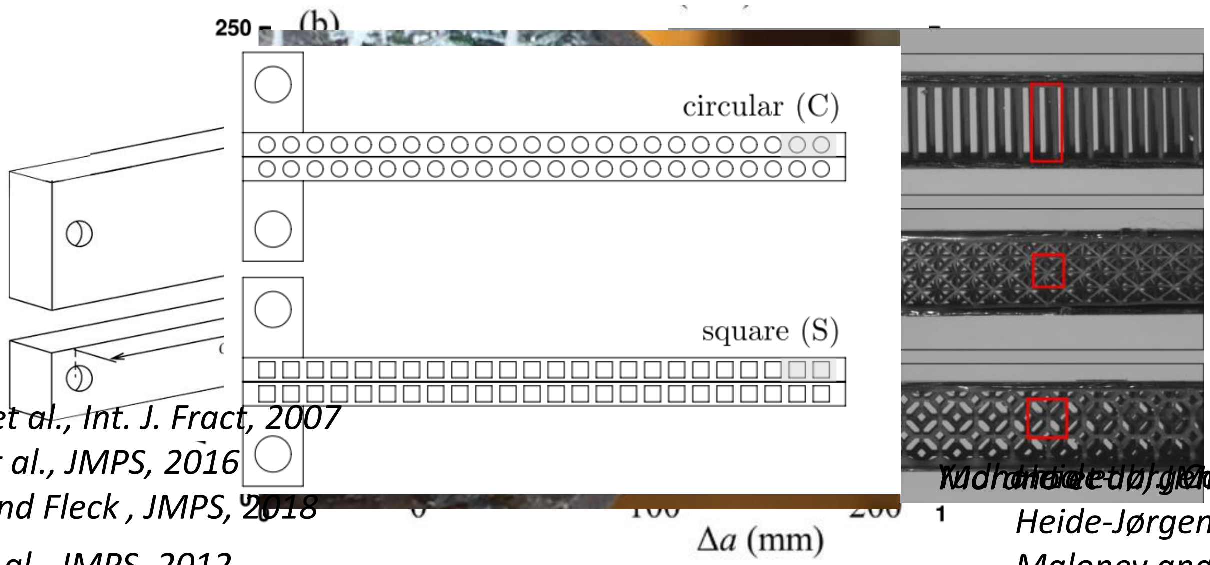
→ Addition of thermoplastic layer compatible with epoxy resin



Low G_{Ic} ➔ Toughening strategies



Plastic dissipation (i-ii)
Interface patterning (iii)
Crack deflection (iv)
Crack tip blunting (v)
Metamaterials (vi)
Bridging (ix)
Change of stiffness (vii-viii)



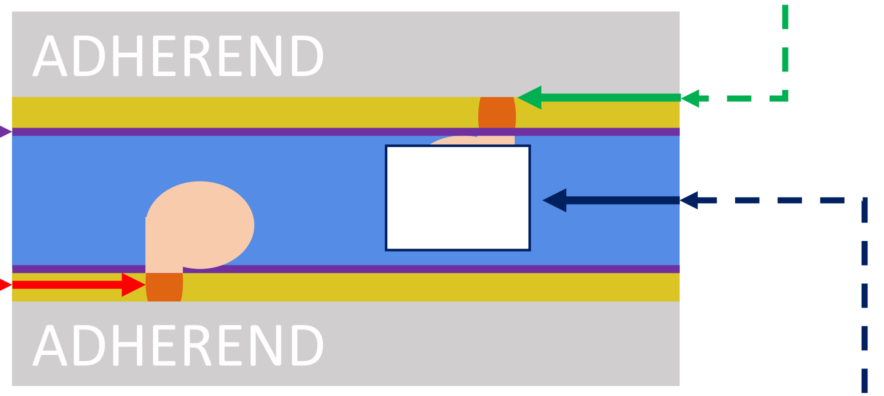
Zavattieri et al., Int. J. Fract, 2007
Cordisco et al., JMPS, 2016
Maloney and Fleck , JMPS, 2018
Martiny et al., JMPS, 2012

Heide-Jørgensen et al., JMPS, 2020
Heide-Jørgensen and Budzik, JMPS, 2018
Maloney and Fleck, JMPS, 2019

Tough architected joints + cocuring

✓ Bonding: tough interface TP-resin
- Semi IPNs (PEI, PES, PSU …)
- Reaction of functional groups (PA)

S1: Composite interface = C-fibres – resin interface
- No control
- ↑ G_{Ic}: plastic dissipation in TP if soft



S2: Resin layer
- Too thin for architecturing
- ↑ G_{Ic}: plastic dissipation in TP if soft

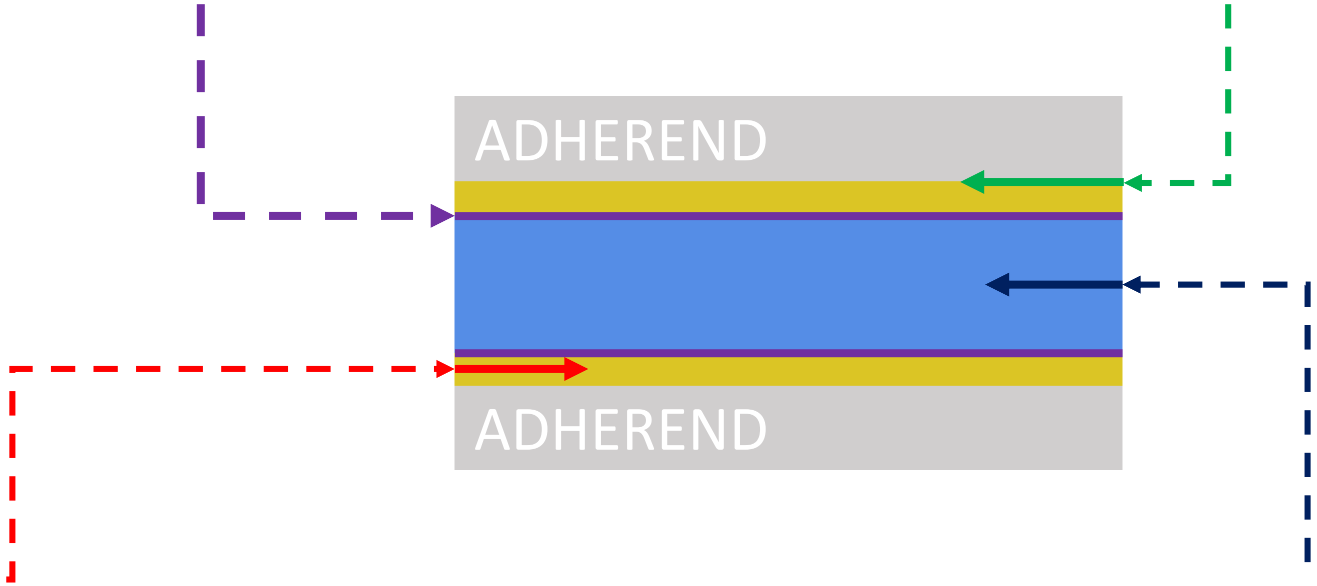
S3: TP film
- Architecturing

Toughest

Tough architected joints + cocuring

✓ Bonding: tough interface TP-resin interface

S1: Composite interface = C-fibres – resin interface



S2: Resin layer

S3: TP film

Dominant scenario = weakest

➔ deflection to trigger other mechanisms ➔ addition of cavities in the TP layer

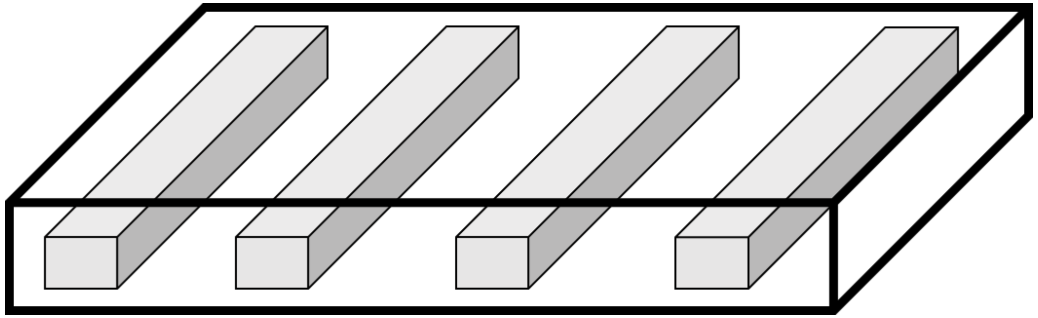
A thermoplastic film with some characteristics

(1) Good interactions with the epoxy resin

(2) Softer than the resin

(3) Contains cavities

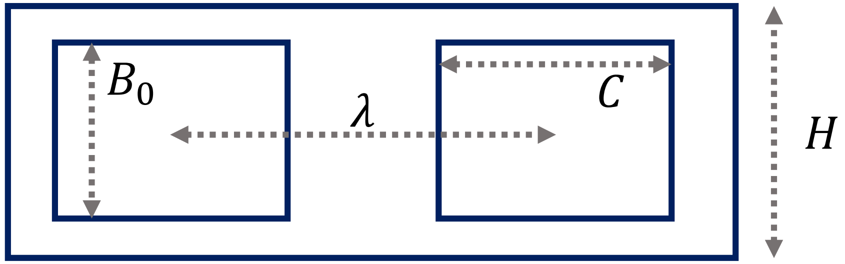
(4) Easy to manufacture ➔ 3D printing



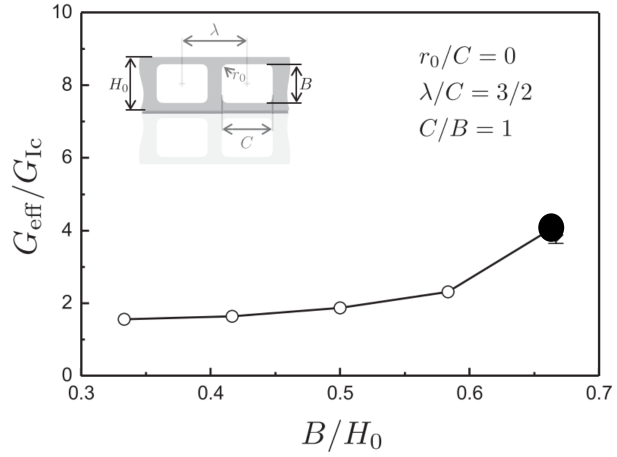
Dimensions of the cavities

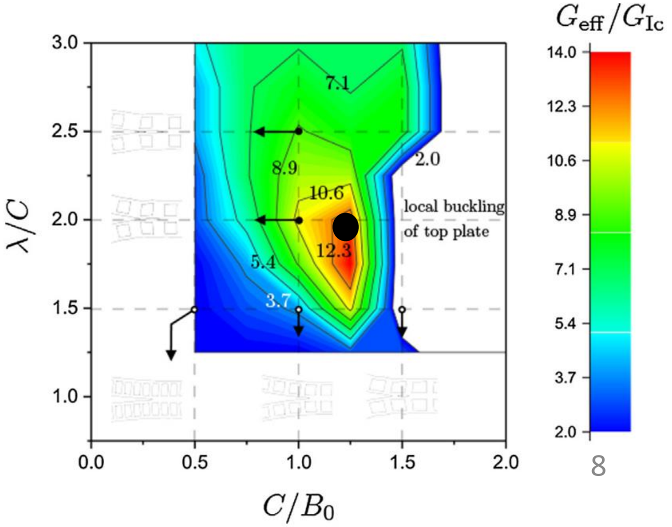
(1) Manufacturing constraint: depth of RTM mold → film thickness of 1 mm

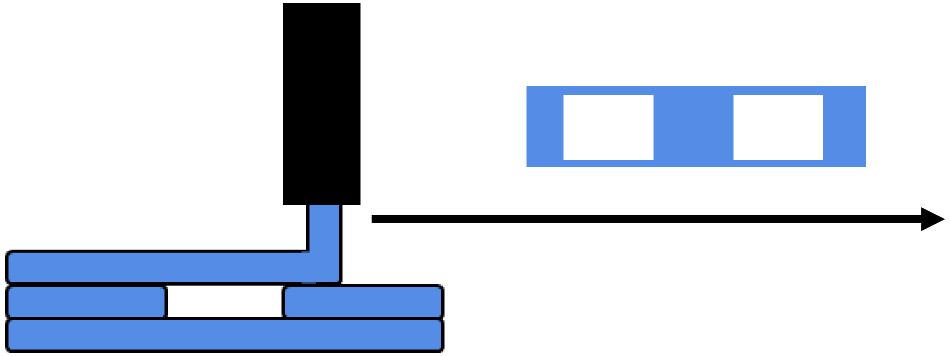
(2) Dimensions of cavities: parametric study of Morano et al.



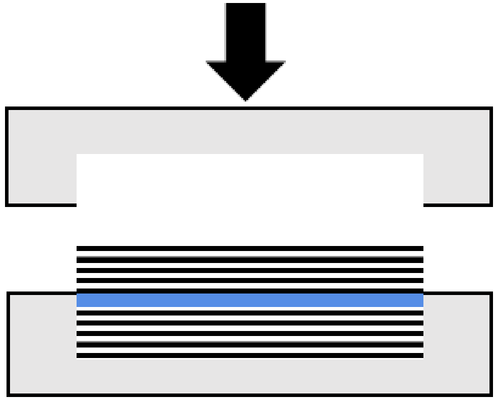
Morano et al., JMPS, 2020



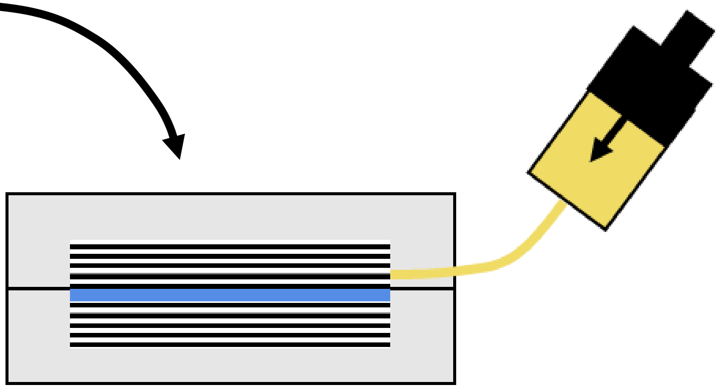


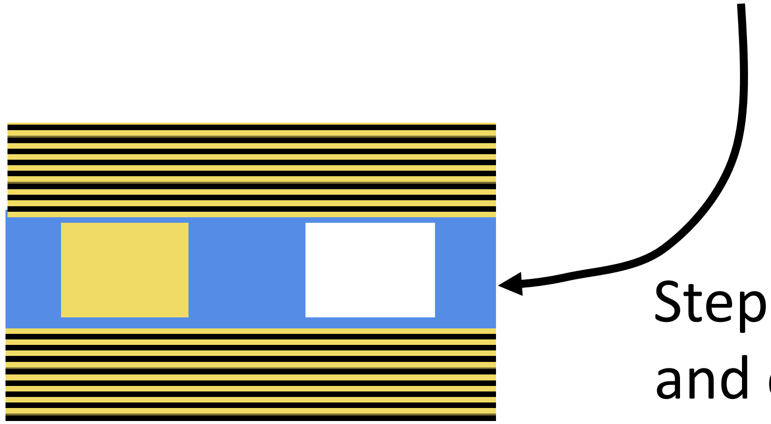


Step 1: 3D printing

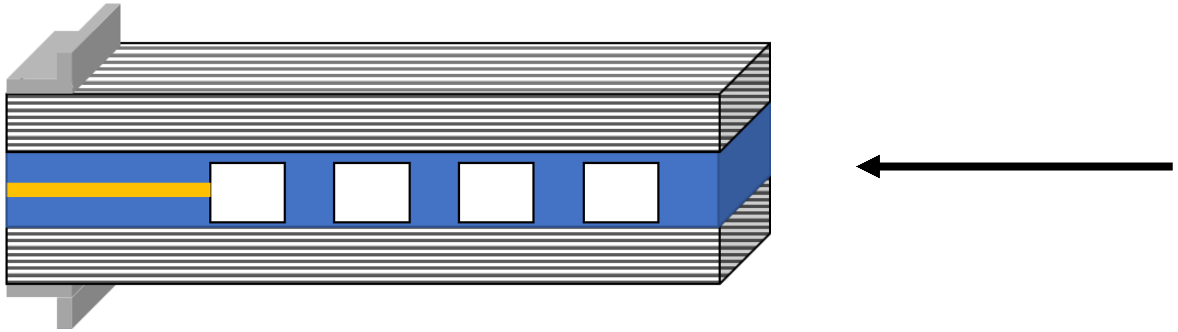


Step 2: stacking in RTM mould

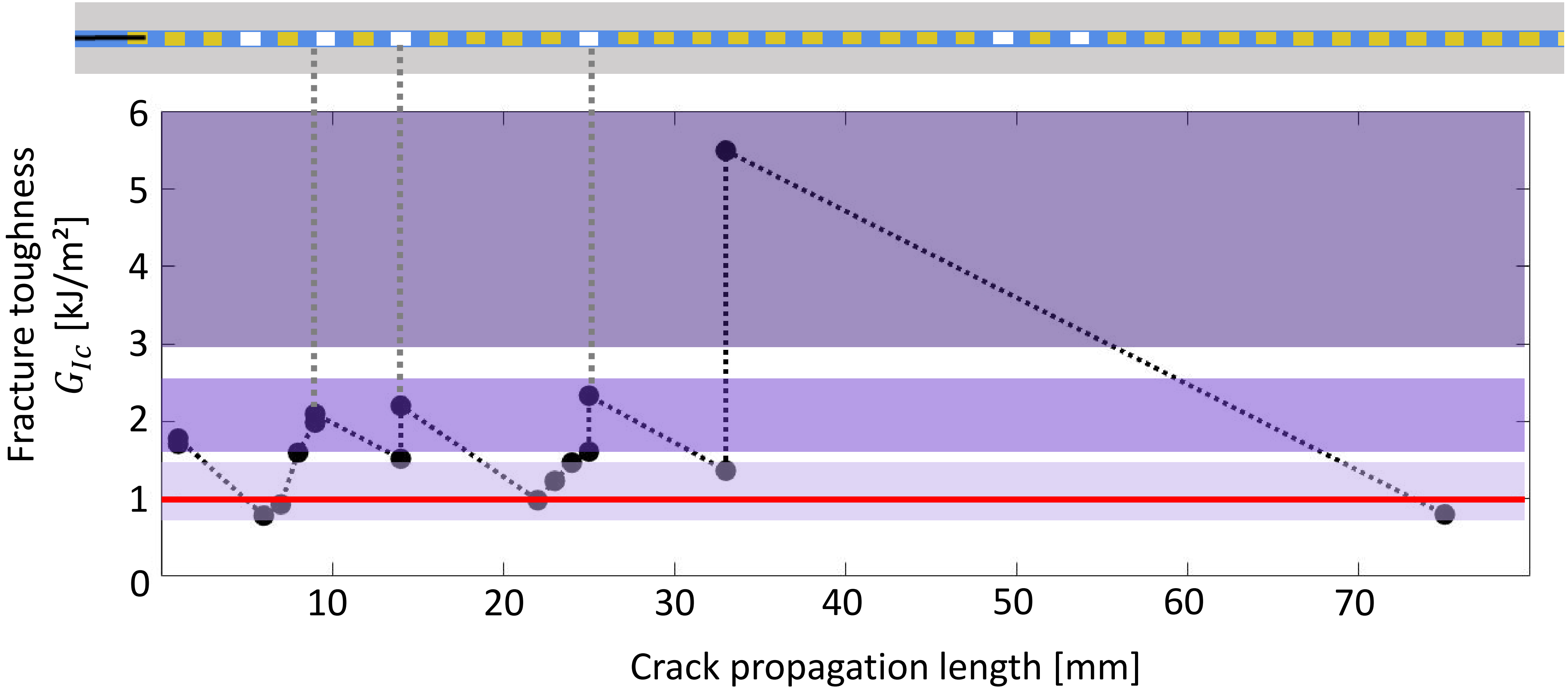




Step 3: resin injection and composite curing

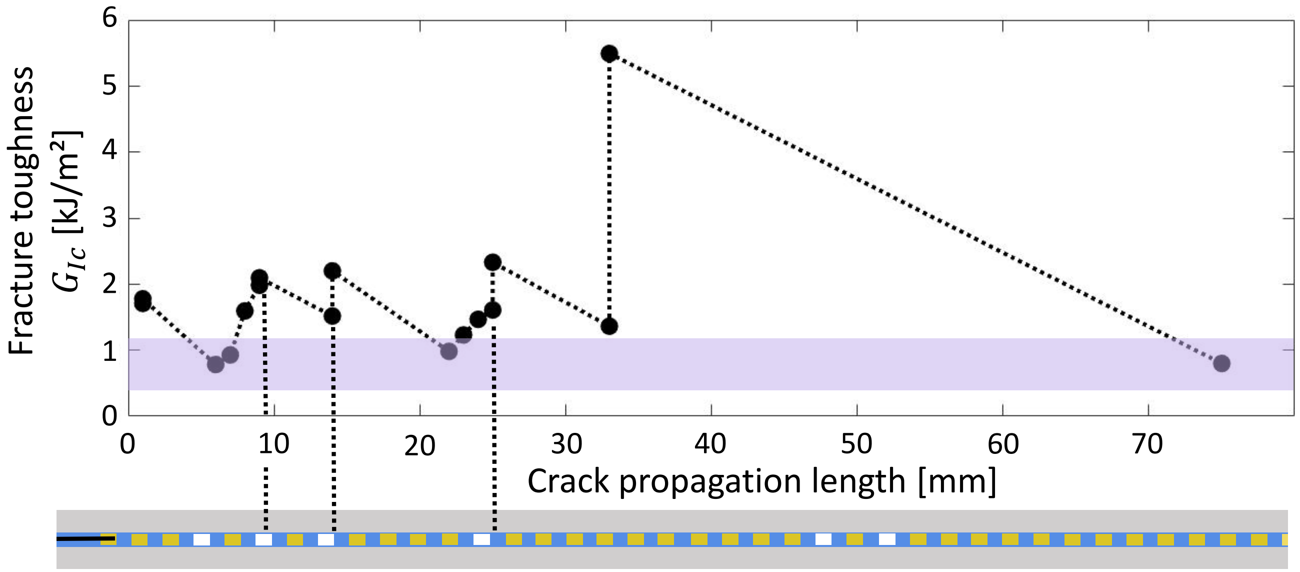


Step 4: DCB testing – mode I G_{Ic}

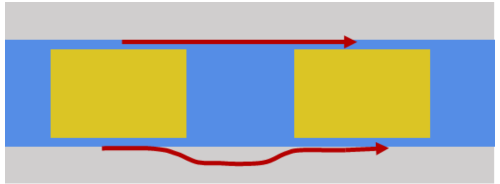


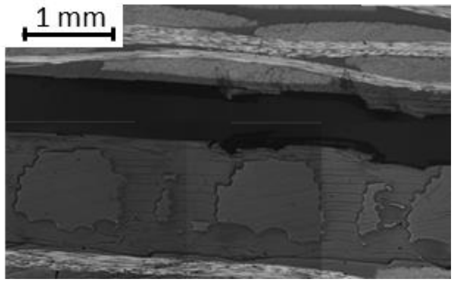
Stick-slip behavior → Identification of 3 G_{Ic} regimes

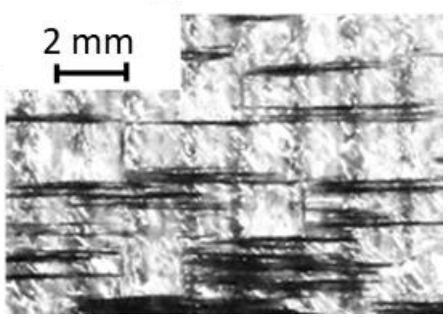
→ Crack instabilities

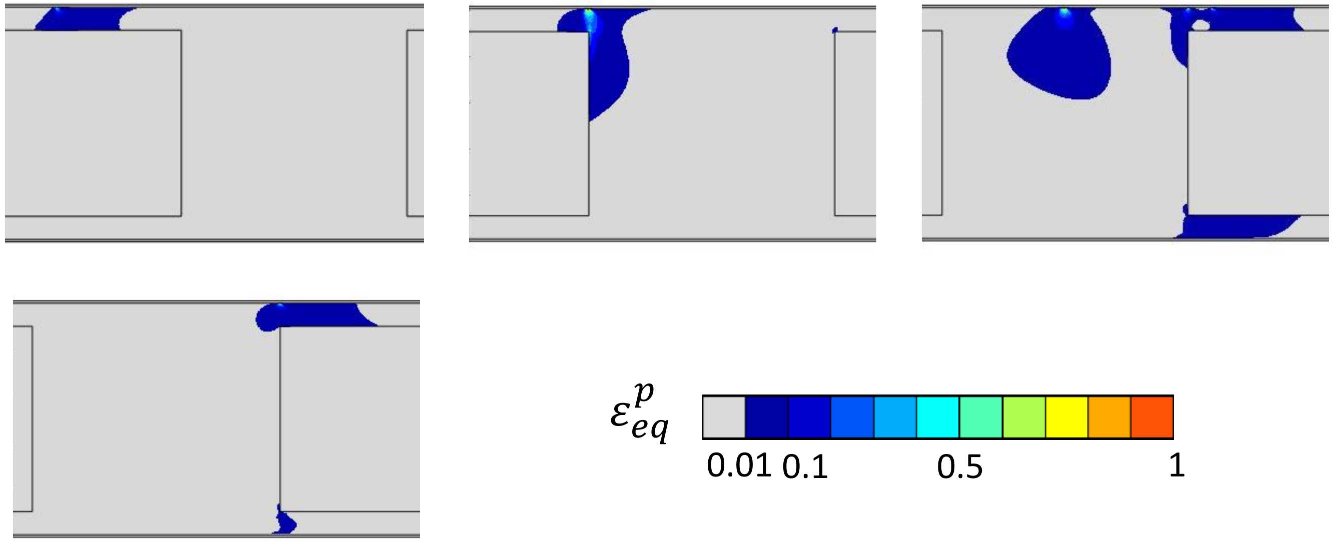


Regime (1): propagation at composite-Nylon interface: 600-1200 J/m²

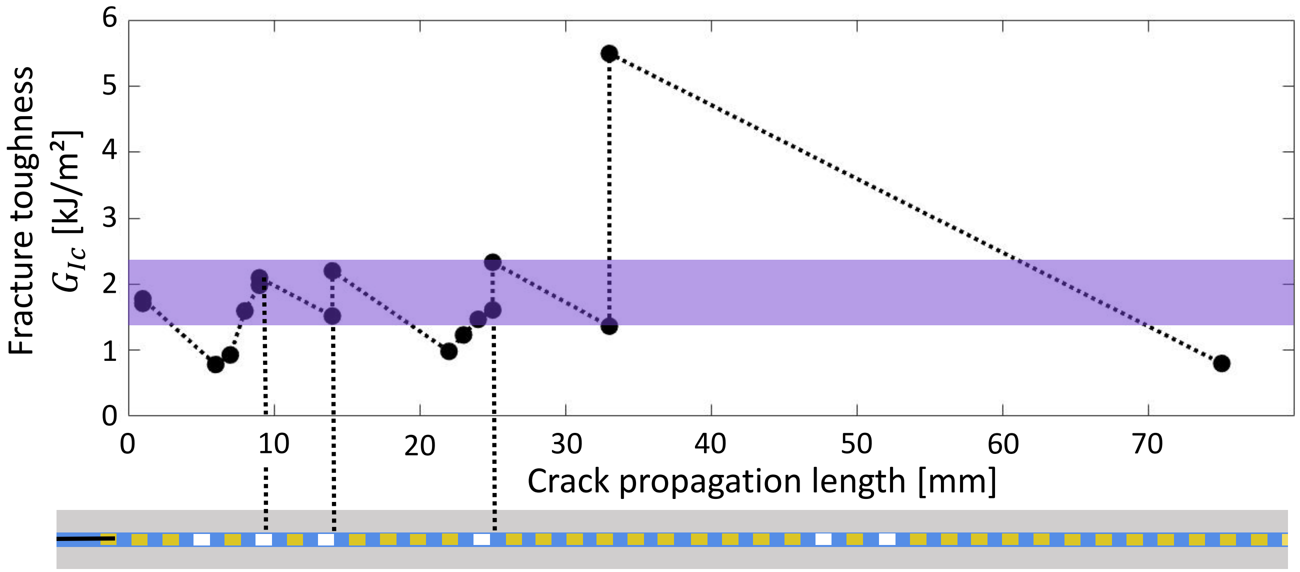








Architected film: dissipative layer
+ mechanical interlocking



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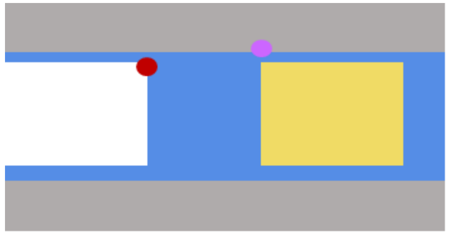
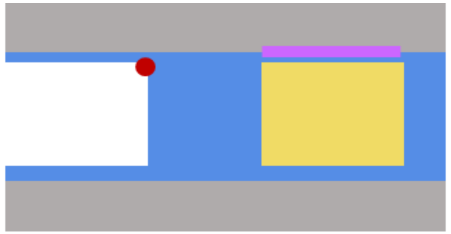
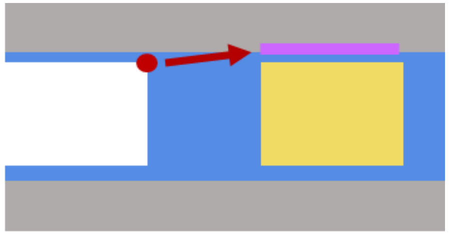
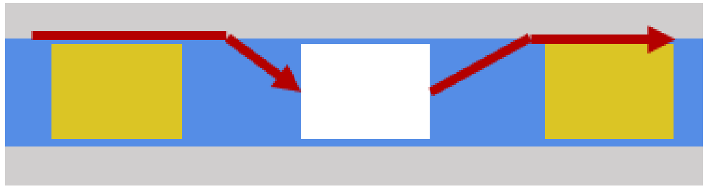
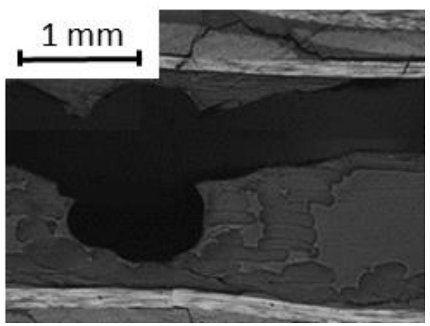


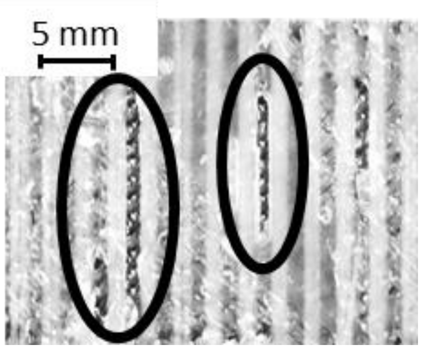
2)


3)


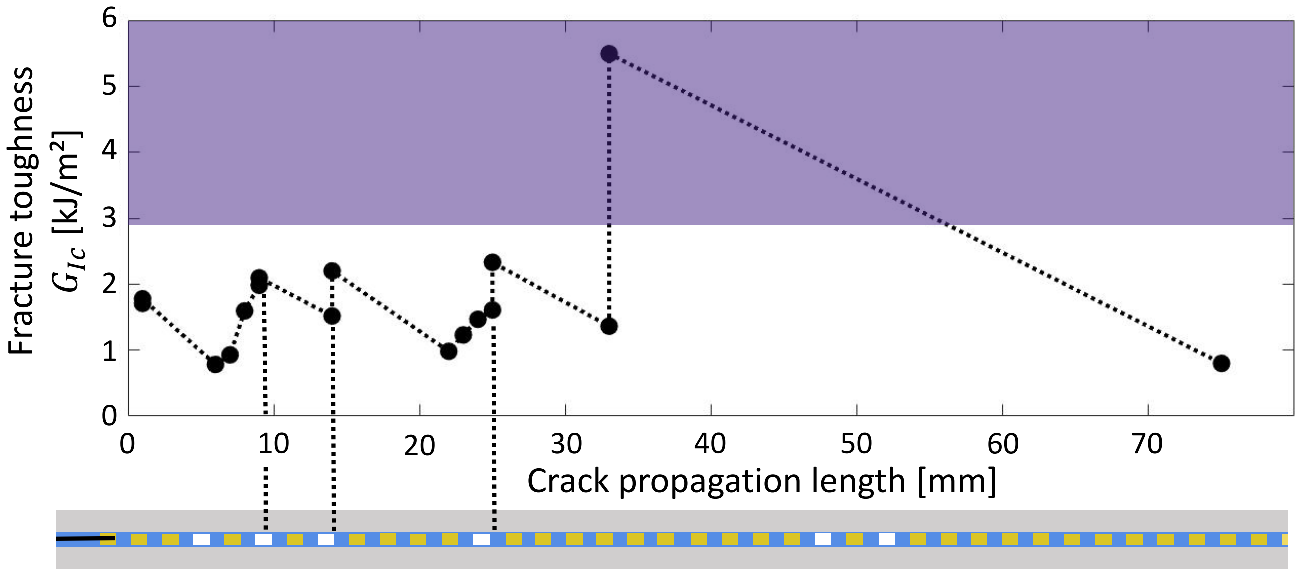
Regime (2): empty channel - deflection and re-initiation: 1500-2200 J/m²



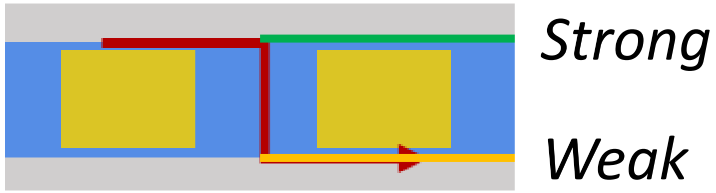


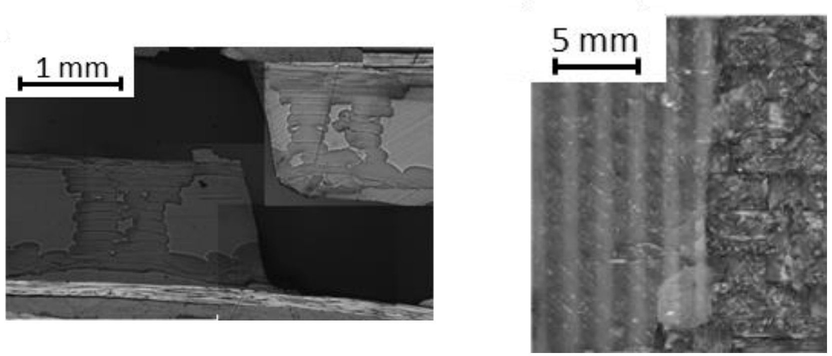


Empty channels: deflection + propagation in tough TP



Regime (3): propagation through Nylon > 3000 J/m²





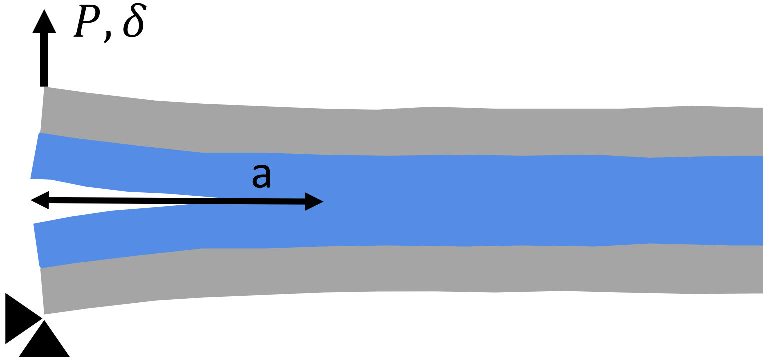
Controlling channel filling
→ different toughness regimes
→ **Triggering of different toughening mechanisms**

Change of regime associated with crack arrest or jumps

Local change in adherence?

Analytical model to consider the stick-slip behaviour

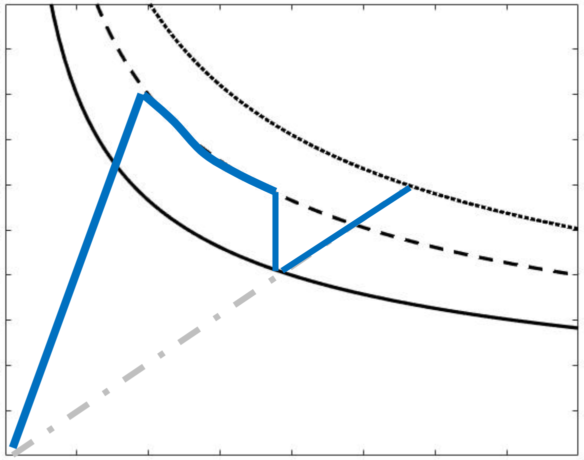
DCB → Euler-Bernoulli beams



$$G_{Ic} = \frac{P^2 a^2}{EBI} = \frac{3Eh^3\delta^2}{16a^4}$$

Stick-slip behavior: triggering of different mechanisms
- 3 regimes with 3 different G_{Ic}: $G_{Ic}^1 < G_{Ic}^2 < G_{Ic}^3$
- *a* at which we change of regimes are known (experiment)

Three scenarios



1. Steady-state: $G_{Ic} = ct$

$$P(\delta, G_i, a_i) = \left(\frac{EB^4h^3G_i}{27}\right)^{1/4} \frac{1}{\sqrt{\delta_i}}$$

2. Crack jump from a_i to a_{i+1}: $\delta_{i+1} = \delta_i$ and $G_i > G_{i+1}$

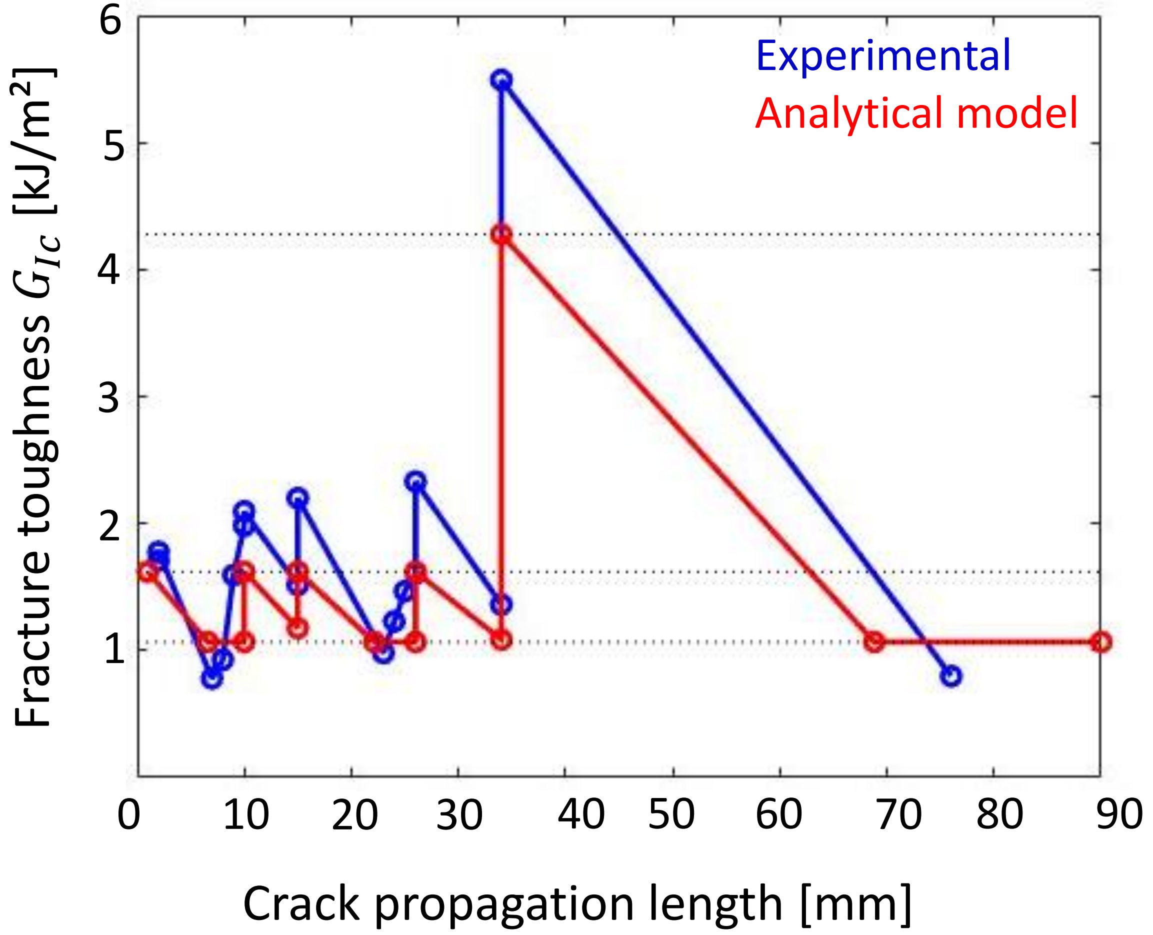
$$\Delta a = a_{i+1} - a_i = \left(\frac{3Eh^3}{16}\right)^{1/4} \sqrt{\delta_i}\left(\frac{1}{G_{i+1}^4} - \frac{1}{G_i^4}\right)$$

$$\Delta P = \left(\frac{EB^4h^3}{27}\right)^{1/4} \frac{1}{\sqrt{\delta_i}}\left(G_{i+1}^{1/4} - G_i^{1/4}\right)$$

3. Crack arrest $a_i = a_{i+1}$ and $G_i < G_{i+1}$

$$\delta_{i+1} = \delta_i\sqrt{\frac{G_{i+1}}{G_i}}$$

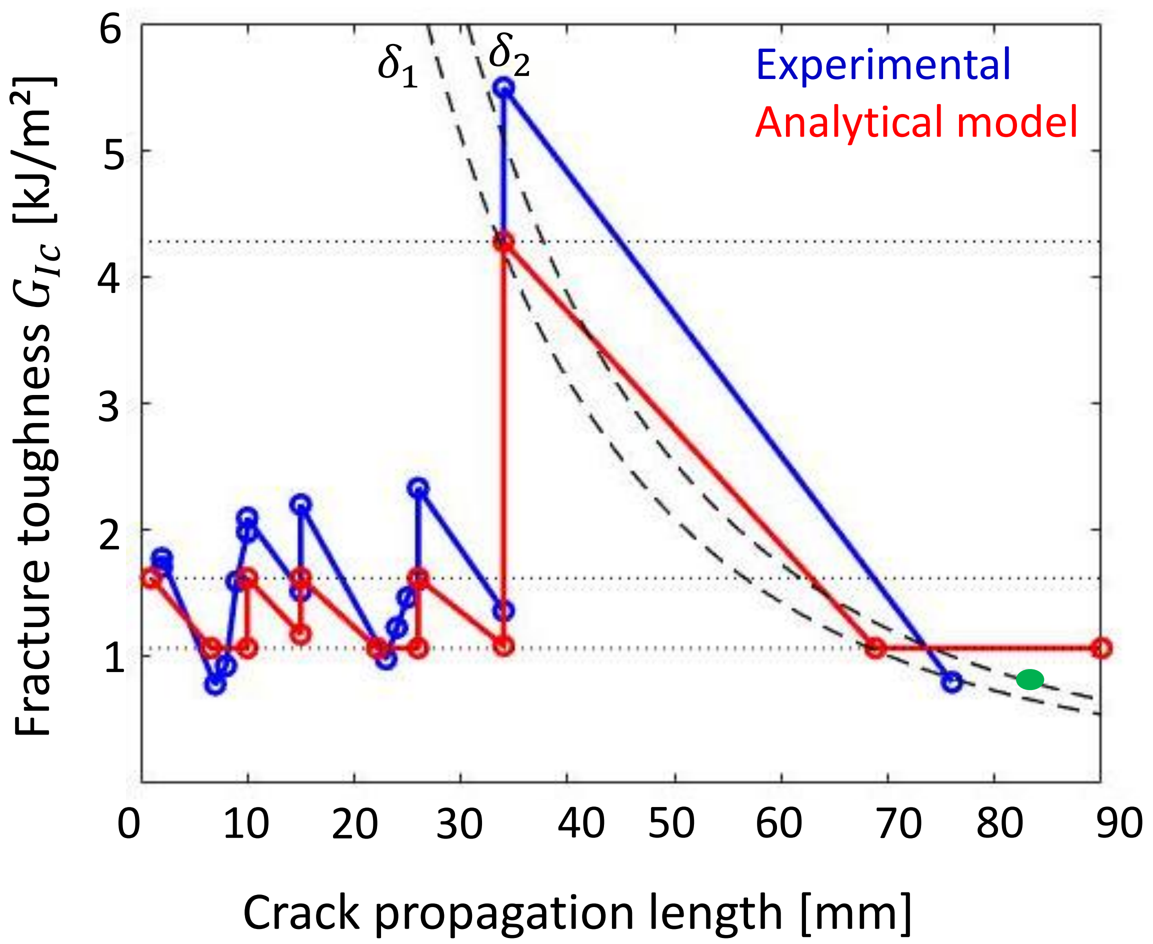
$$P_{i+1} = \left(\frac{EB^4h^3G_i}{27}\right)^{1/4} \sqrt{\frac{G_{i+1}}{\delta_i}}$$



Model

- Average fracture toughness for each regime
- Crack position for each event

✓ Capture the general trend of the R-curve



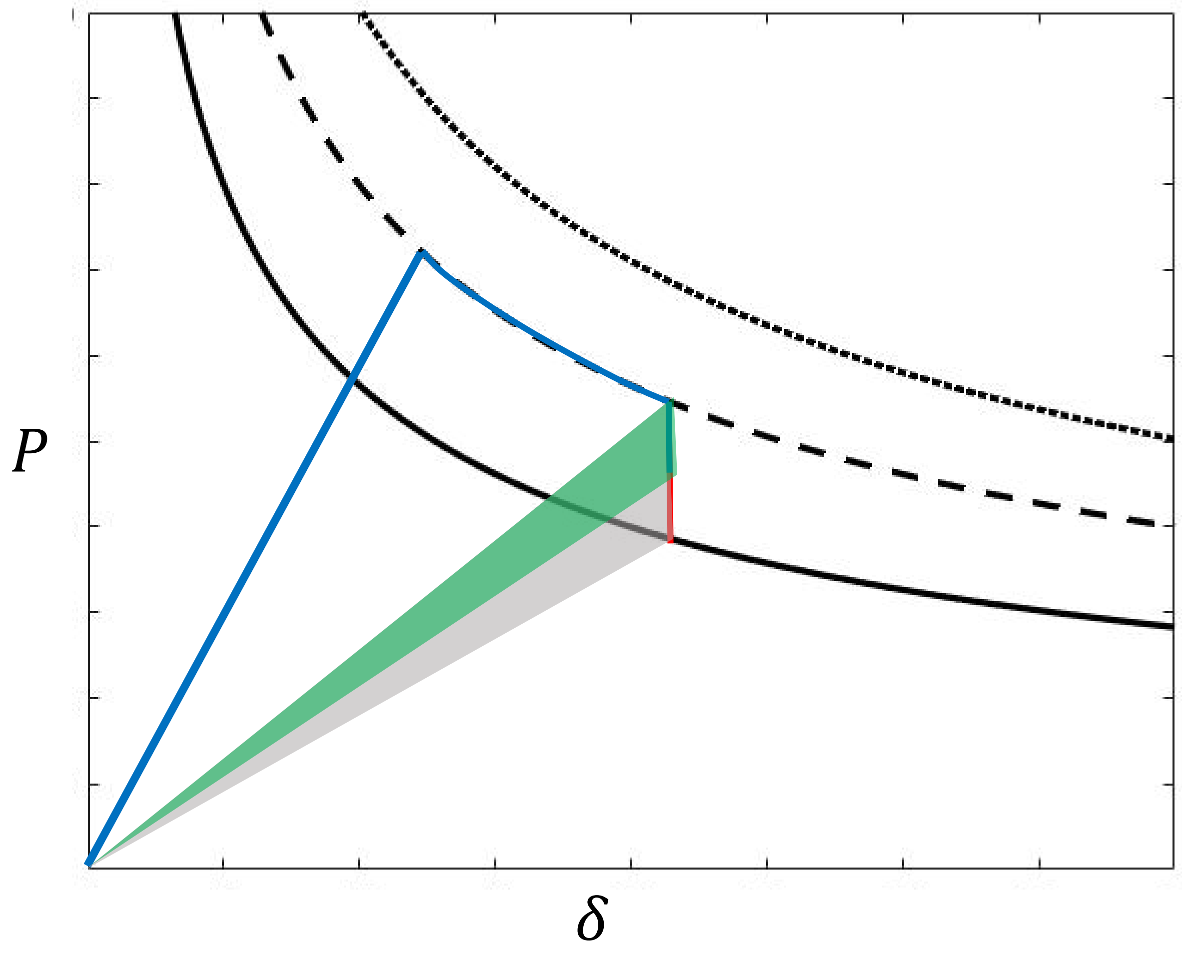
Model

- Average fracture toughness for each regime
- Crack position for each event

✓ Capture the general trend of the R-curve

× Overestimation of crack jump length

$$G_{Ic}(\delta) = \frac{3Eh^3\delta^2}{16a^4}$$



Equilibrium equation

$$dW = -\frac{1}{2}\Delta P\delta = G_c^1 \Delta a B$$

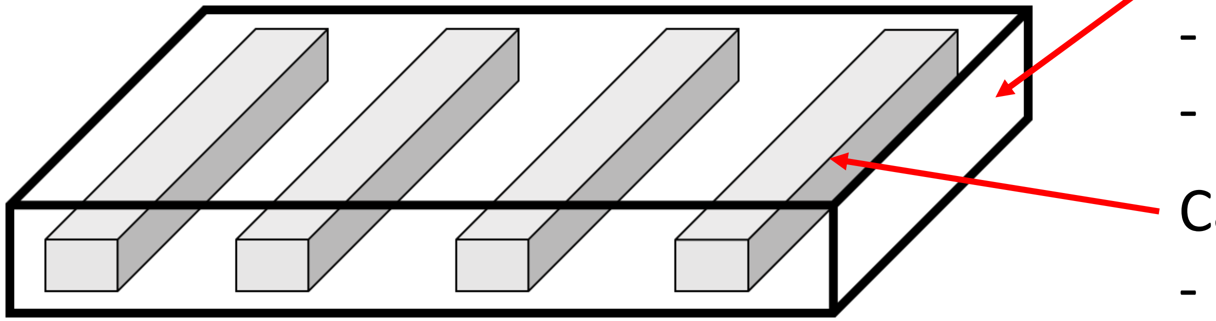
Modified equilibrium equation

$$dW = -\frac{1}{2}\Delta P\delta = G_c^1 \Delta a B - \text{others}$$

- Dissipation ahead of crack tip?
- Influence of kinetic energy?

Simple EB model fails to correctly predict the joint behavior

Initial objective: design of tough joints for single step bonding process



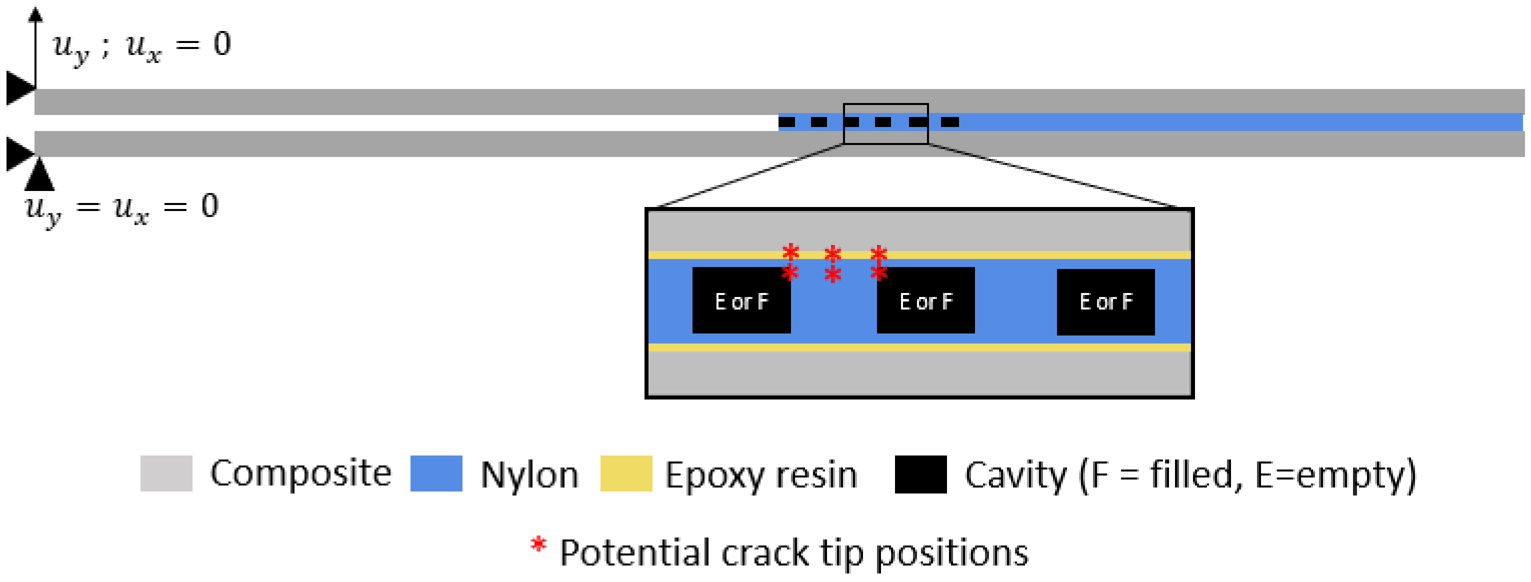
TP layer
- Compatible with epoxy → bonding
- Softer than resin: plastic dissipation

Cavities
- Control of filling → different failure mechanisms

G_{Ic} from 600 J/m² up to 5500 J/m²

Stick-slip behavior → not accurately captured by simple analytical model based on EB beam theory

➔ Need to consider dissipation phenomenon (to investigate)

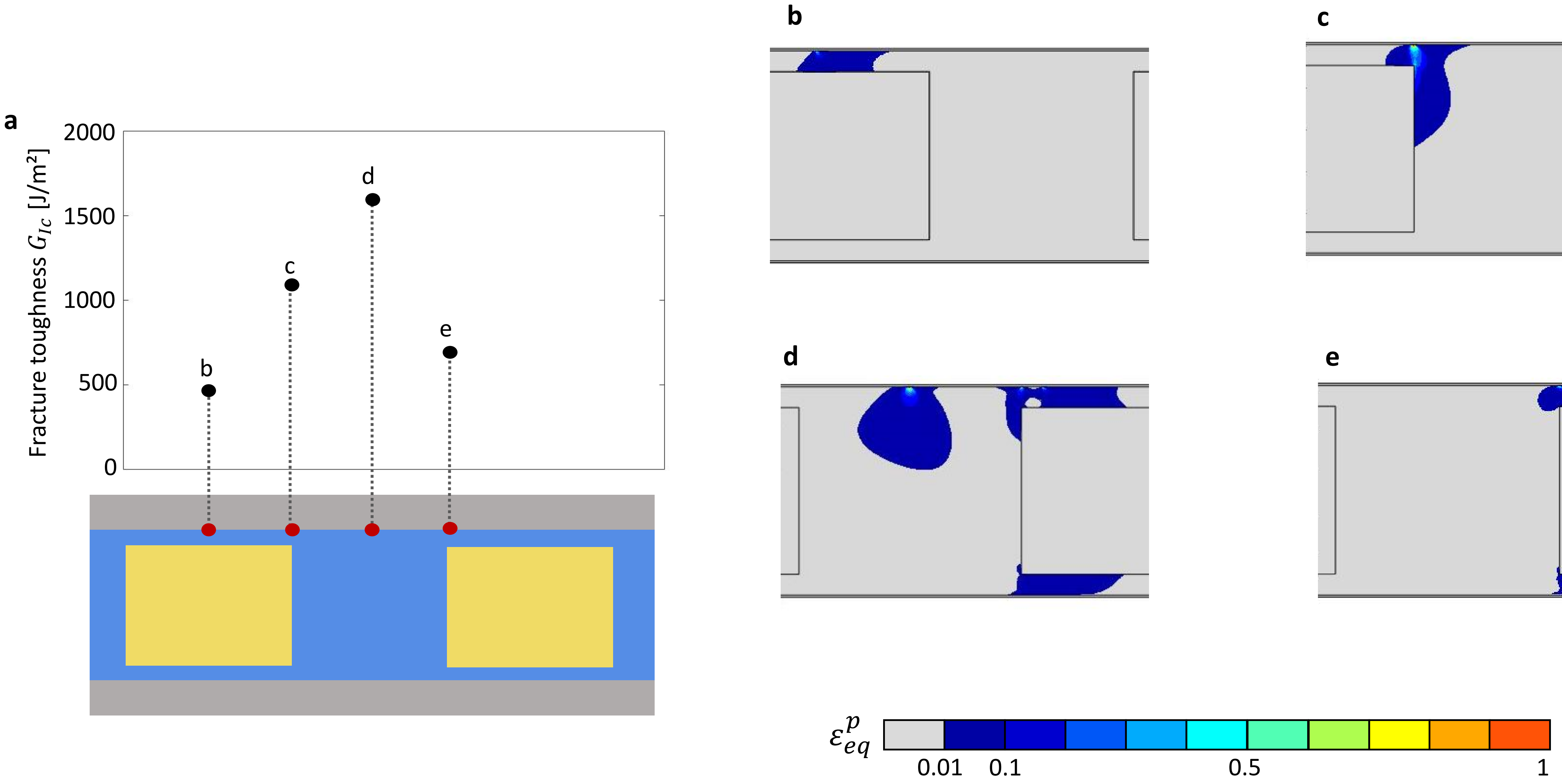


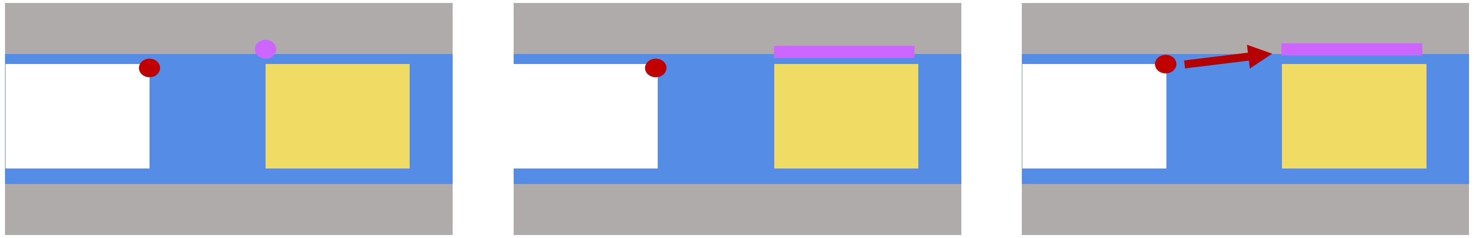
Material constitutive laws

- Composite: $E_{in} = 70\ GPa$ and $E_{out} = 3\ GPa$
- Resin: Drucker-Prager model for RTM6 *[Morelle et al., Mech. Time-Dependent Mat., 2017]*
- Nylon: properties from tensile tests

Failure criterion: $\boldsymbol{\sigma_c}$ at $\boldsymbol{d_c}$

- RTM6: 300 MPa, 10µm
- Interface: 50 MPa, 100 µm
- Nylon: 50 MPa, 200 µm


a
2000
1500
1000
500
0
Fracture toughness G_{Ic} [J/m^2]
b
c
d
e
b
c
d
e
ε_{eq}^{p}
0.01
0.1
0.5
1

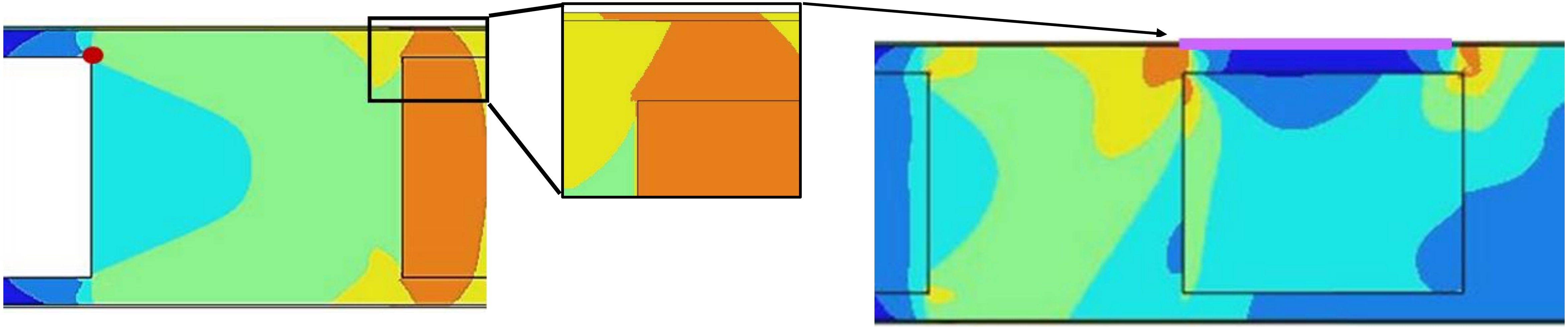


1) Secondary crack initiation

2) Secondary crack growth

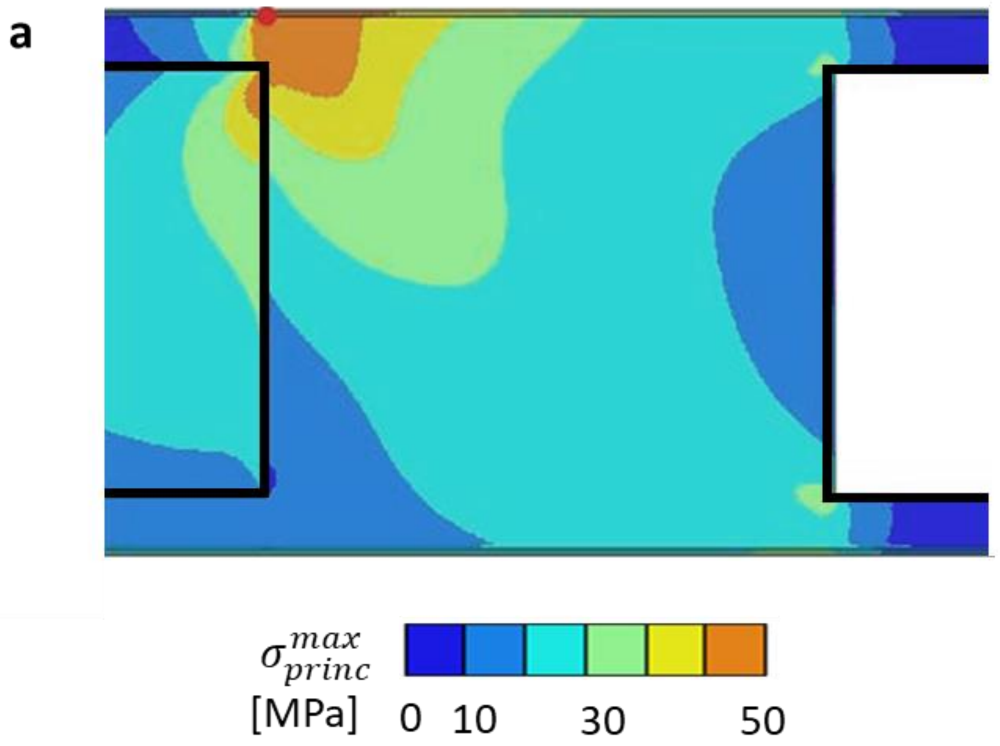
3) Crack interactions and main crack growth

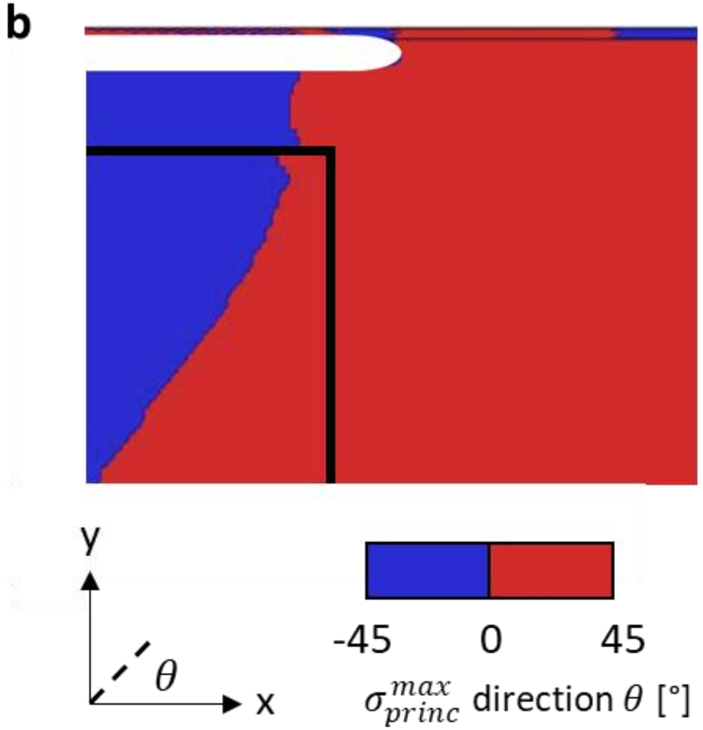
Secondary crack initiation

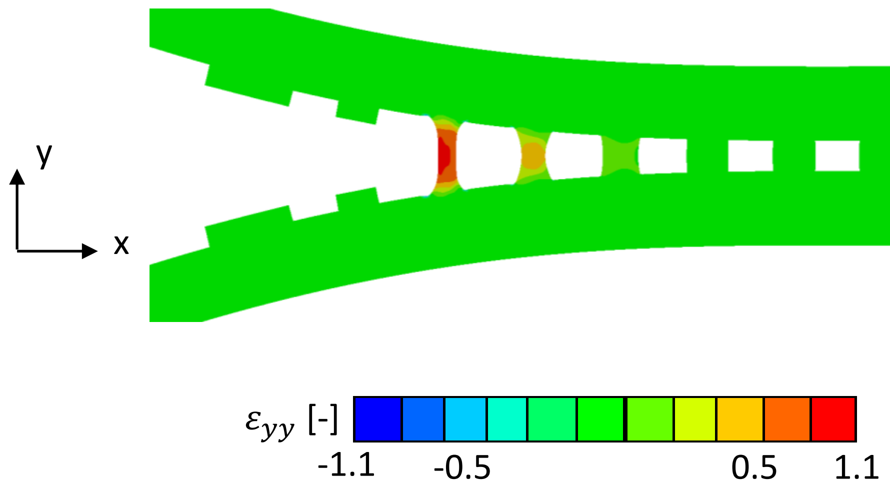


Composite Nylon Epoxy resin Cavity Propagation direction

Crack tip Secondary crack

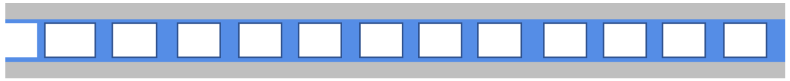

a
σ_{princ}^{max}
[MPa]
0 10 30 50

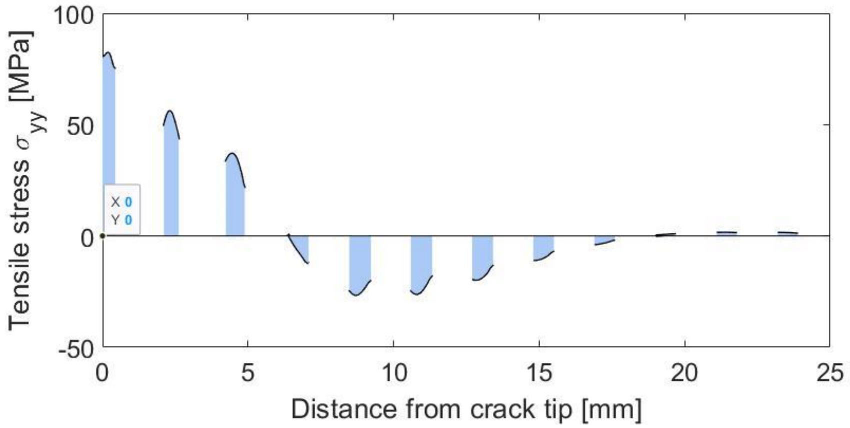

b
y
x
θ
-45 0 45
σ_{princ}^{max} direction θ [°]

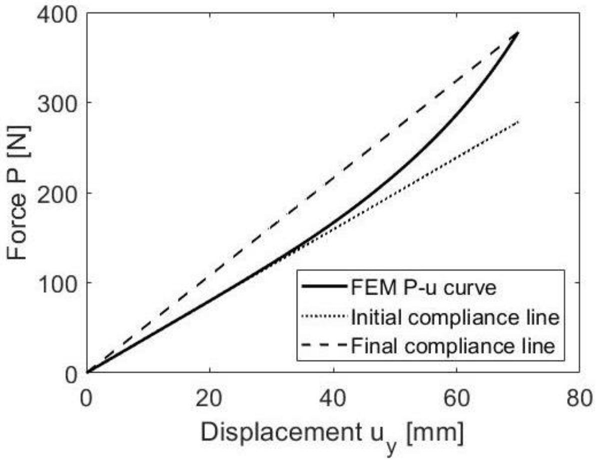


Load redistribution

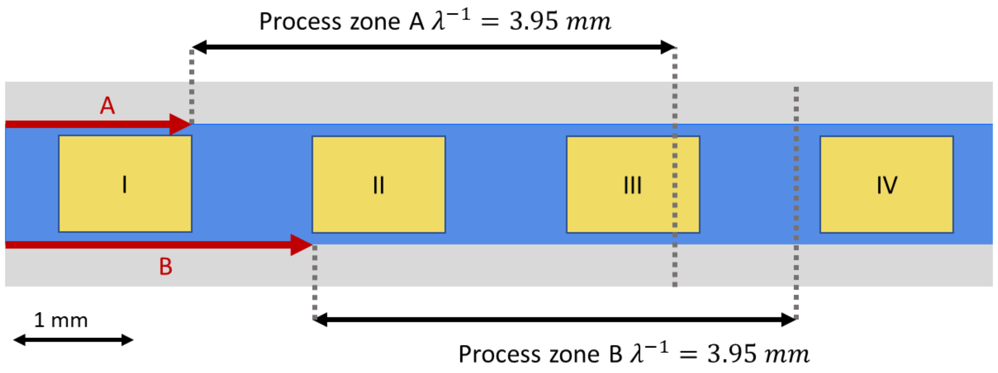
Stiffening



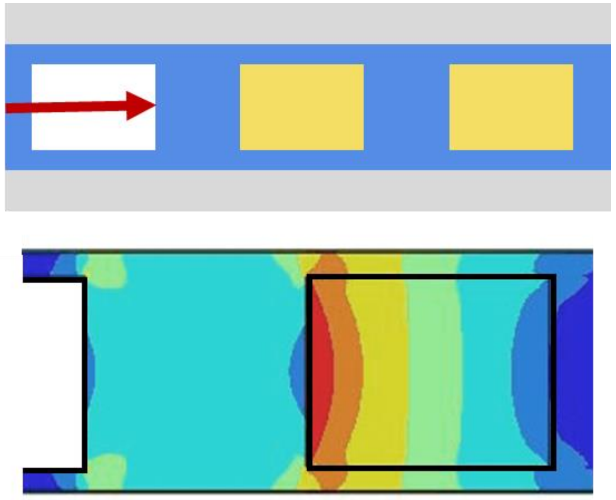


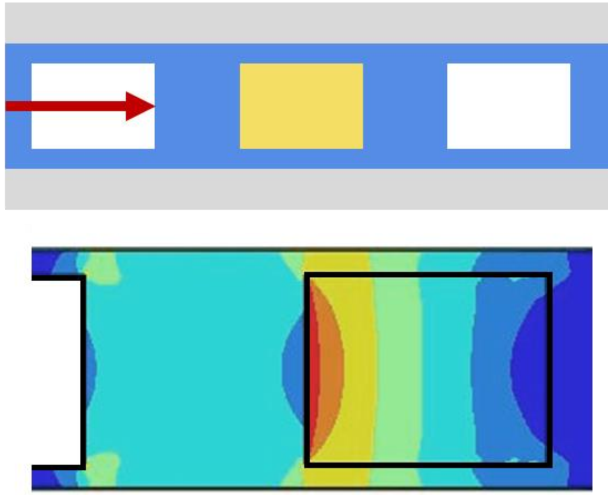


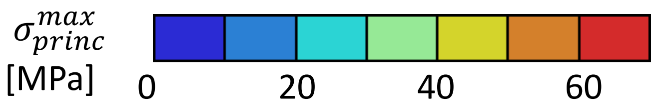
[Heide-Jorgensen et al., JMPS, 2020]
[Fulco et al., Extreme Mech. Let., 2023]

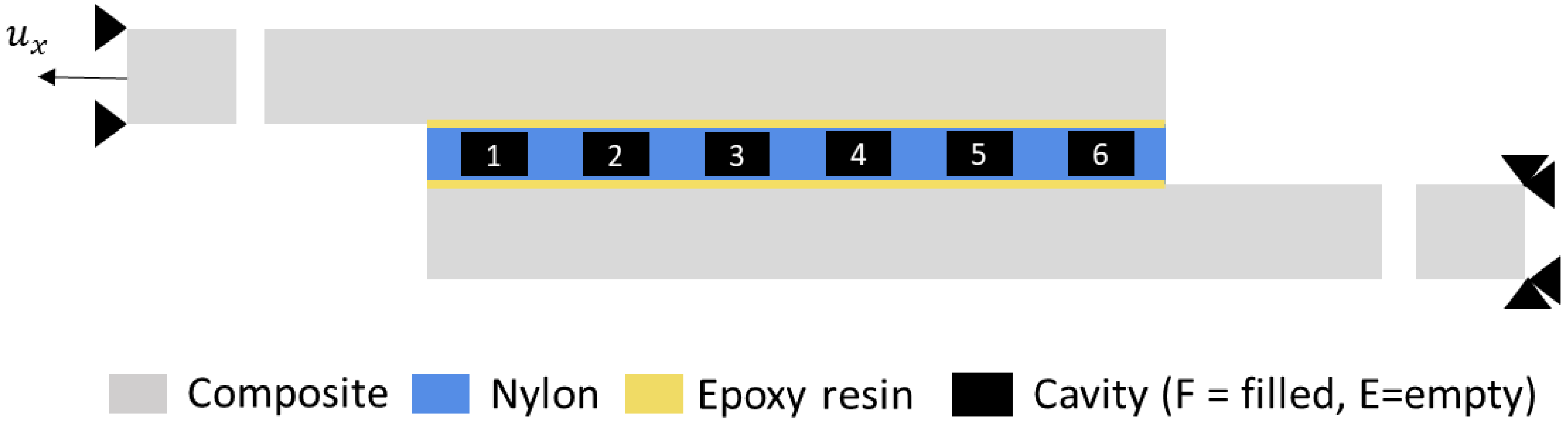


Shielding effect if III is empty








u_x
1
2
3
4
5
6
Composite
Nylon
Epoxy resin
Cavity (F = filled, E=empty)

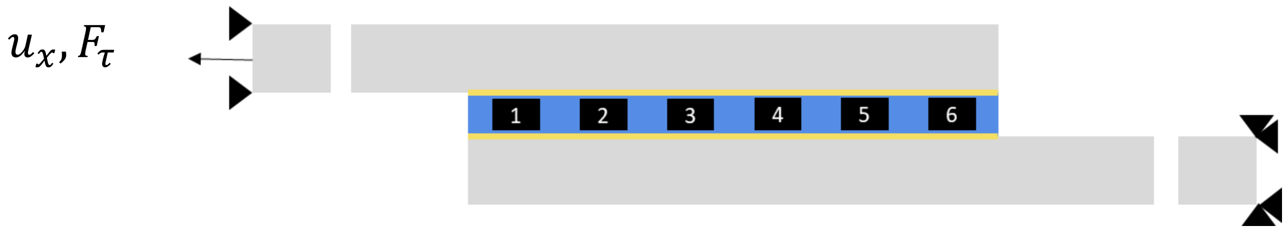
$\uparrow \tau^f$, μ
$\downarrow G_{Ic}$

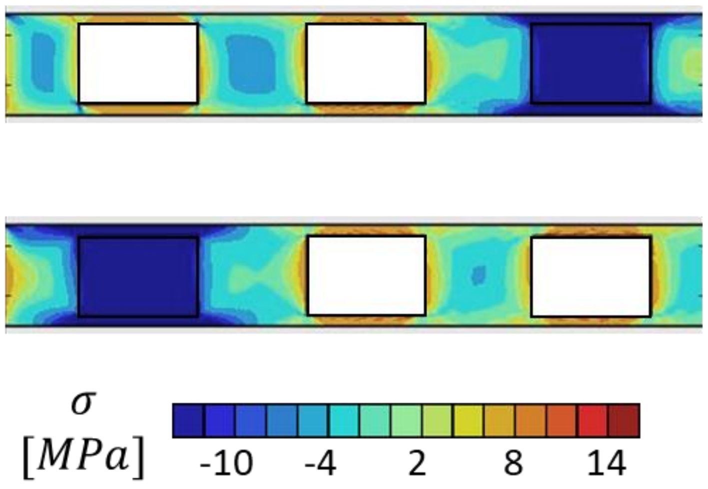
Amount of filled cavity	Configuration	Apparent shear modulus [MPa]	Strength [MPa]	Maximum G_{Ic} [kJ/m²]
0%	EEE	52	6	40
33%	FEE	138	9	16
	EFE	138	11	16
	EEF	137	12	16
66%	EFF	221	14	2.2
	FFE	222	12	2.2
	FEF	223	13	2.2
100%	FFF	306	14	1.5
Nylon	/	143	12	8.5 – 11.5
Resin	/	1070	20	0.09

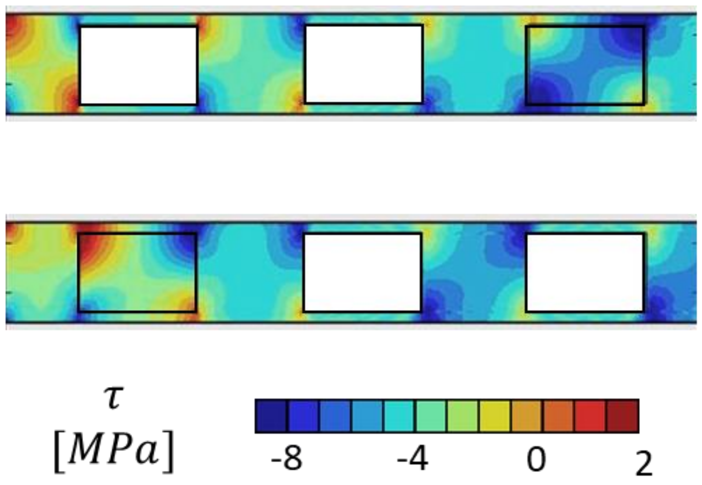
Increasing the amount of filled channels increases shear stiffness and strength, but decreases G_{Ic}

Amount of filled cavity	Configuration	Apparent shear modulus [MPa]	Strength [MPa]	Maximum G_{Ic} [kJ/m²]
0%	EEE	52	6	40
33%	FEE	138	9	16
	EFE	138	11	16
	EEF	137	12	16
66%	EFF	221	14	2.2
	FFE	222	12	2.2
	FEF	223	13	2.2
100%	FFF	306	14	1.5
Nylon	/	143	12	8.5 – 11.5
Resin	/	1070	20	0.09

An empty channel located at the joint edge increases the shear strength







Large peel stresses above the filled channel
➔ More detrimental

Larger shear stresses if the channel is empty

[Kumar et al., 2017]
[da Silva, INEGI, Porto]

Advantages	Disadvantages
Homogeneous stress transfer	Surface treatment dependence
Fatigue resistance (NA)	Harsh environments (NA)
Lightweight	Lack of non-destructive control
Impact resistance (NA)	Difficult to rework
Bonding of complex shapes	Slow process
Bonding of dissimilar materials (NA)	Toxic components
Durable (NA)	Low G_{Ic}
High throughput	
Decrease of cost	

Further improved by empty cavities (→ Lightweight)

Probably (→ Impact resistance (NA))

Flat film → issues when big t differences (→ Bonding of complex shapes)

Single step process instead of multiple steps process (→ High throughput)

Not needed (→ Surface treatment dependence)

If cavity is detected → crack arrest with high G_{Ic} (→ Lack of non-destructive control)

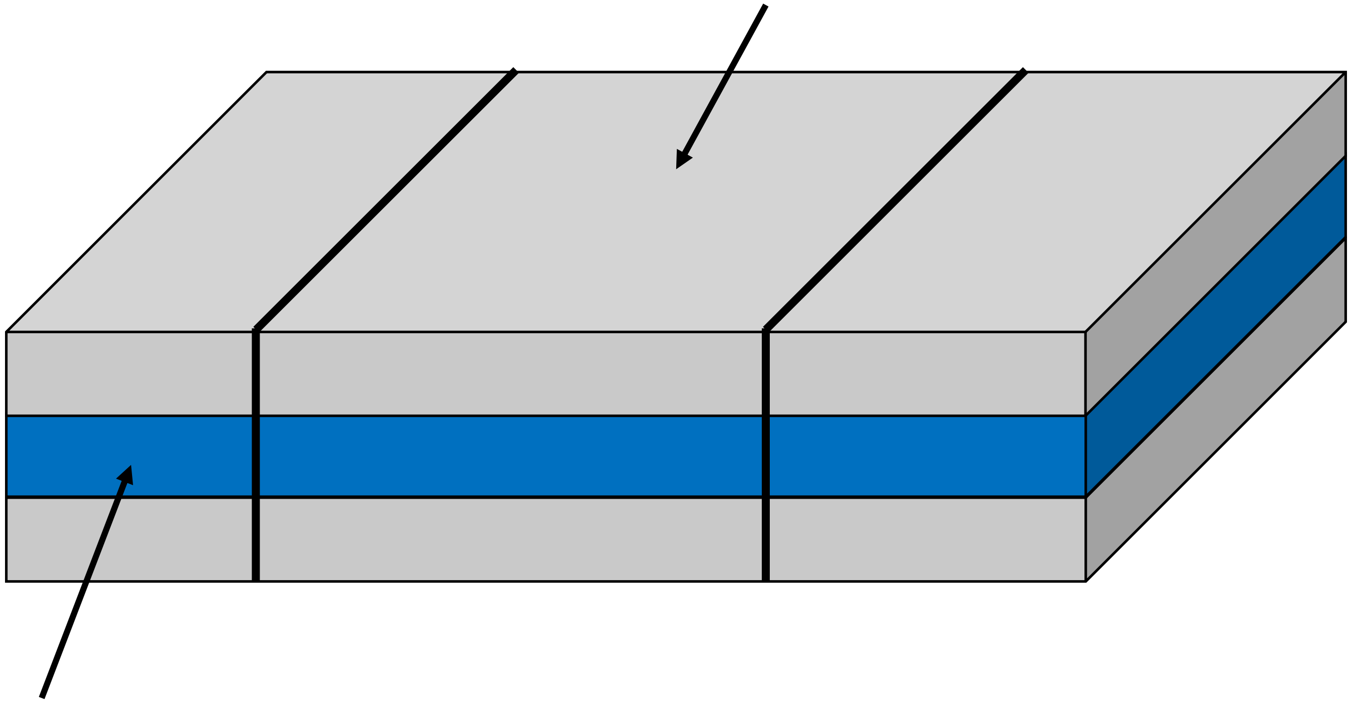
Single step process (→ Slow process)

Toughening (→ Low G_{Ic})

- Local control of properties by controlling the filling of the channels
- Application with ≠ requirements

- Integrated manufacturing: new strategy
- Need for potential applications

Toughness
→ Empty cavities



Strength and stiffness
→Filled cavities

Tuning of the joint local properties