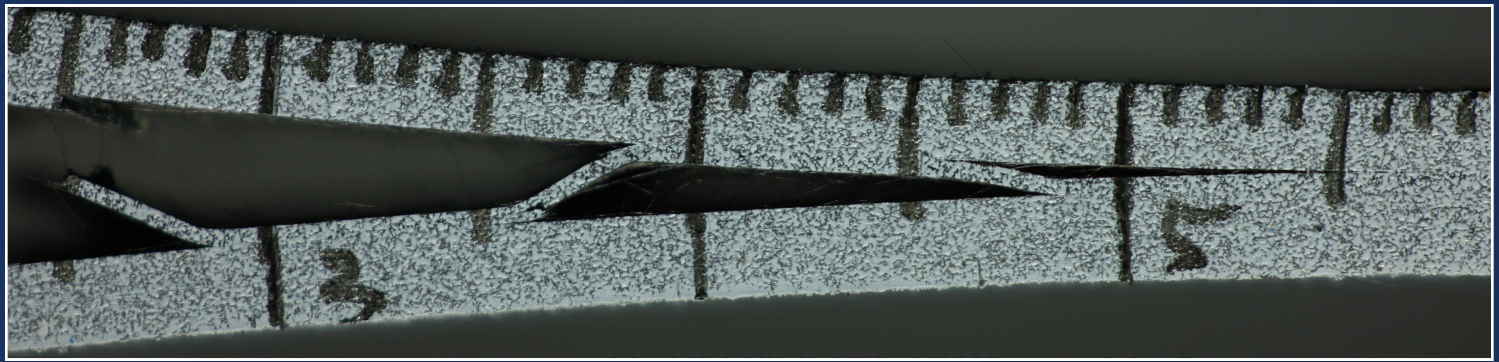
King Abdullah University of Science and Technology

Professor Gilles Lubineau

KAUST

Toughening Adhesive Joints
By Laser-Patterning induced Bridging



23rd International Conference of Composite Materials (ICCM23)

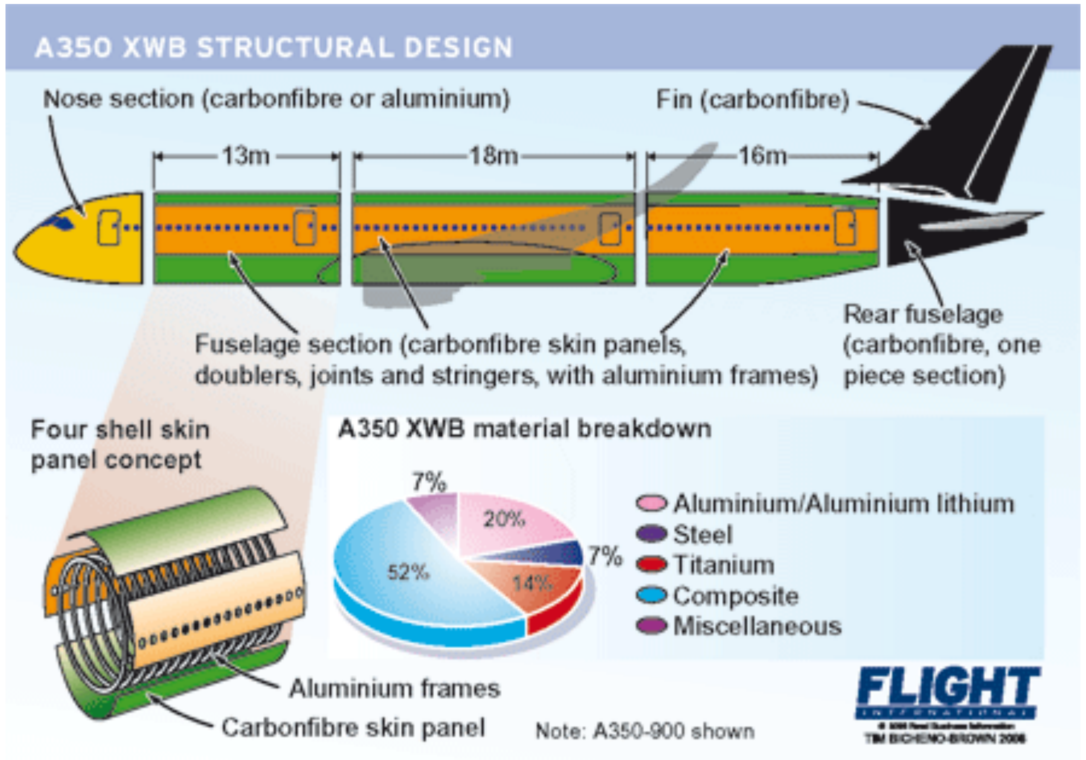
Belfast, 2023

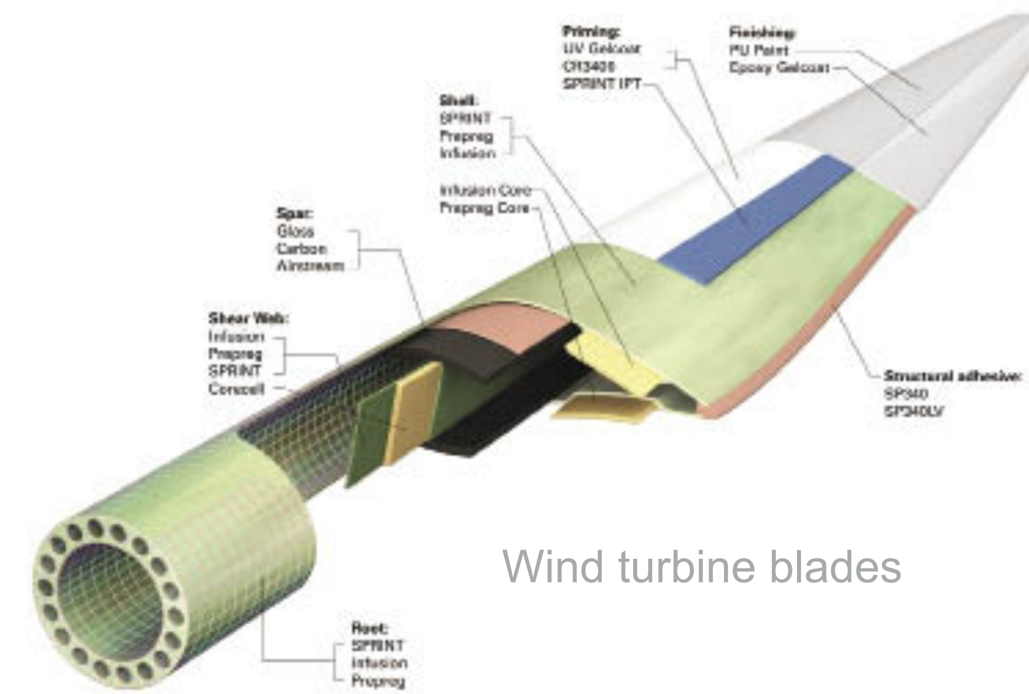
Mechanics of Composites for Energy and Mobility

Why bonding?

Introduction and motivation

High demand for lightweight materials





Wind turbine blades

Assembly between:

- metal to composite
- composite to composite

become increasingly important in:

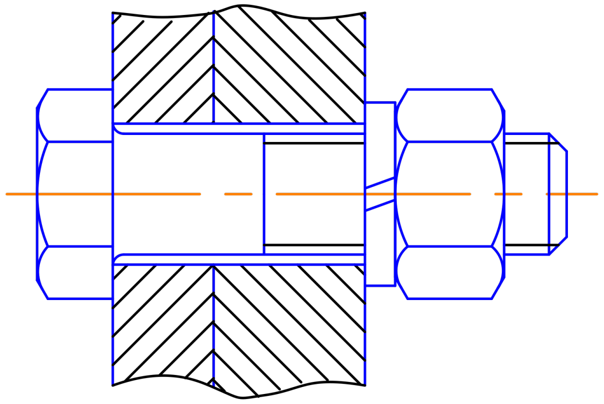
- aeronautic
- civil
- energy
- automotive

MP4-12C CFRP Passager MonoCell

Introduction and motivation

Need for alternative bonding strategies

Conventional fastening technologies using rivets or bolts are facing limitations



1) Technological:

a) stress concentrations

b) weight increase

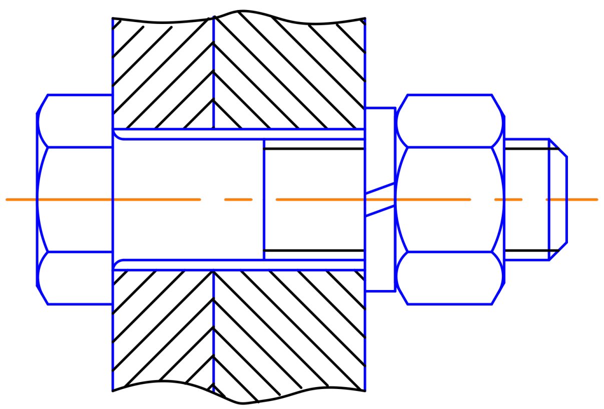
2) Economical: drilling requires extensive labor

3) Lifecycle: maintenance and repair

Introduction and motivation

Need for alternative bonding strategies

Conventional fastening technologies using rivets or bolts are facing limitations



1) Technological:

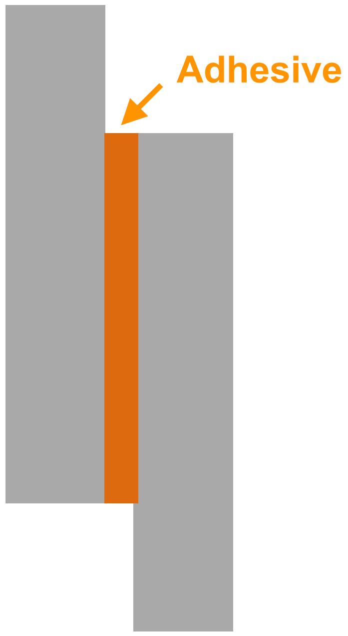
a) stress concentrations

b) weight increase

2) Economical: drilling requires extensive labor

3) Lifecycle: maintenance and repair

Adhesive bonding is attractive but:



1) Confidence is limited:

a) difficult to measure/inspect initial strength

b) brittle response

2) Performance is sensitive to adherent surface preparation

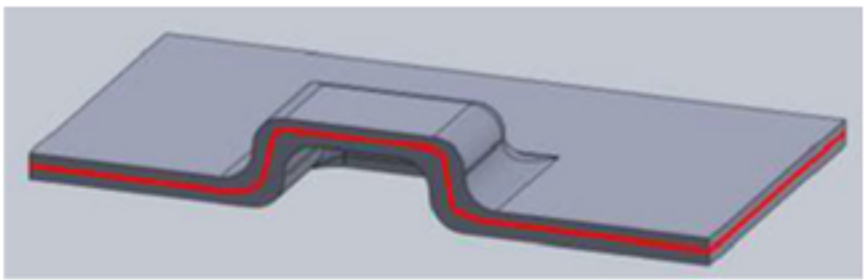
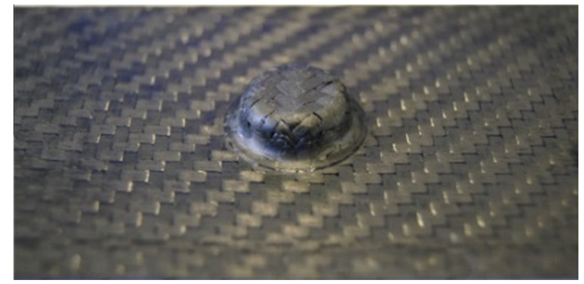
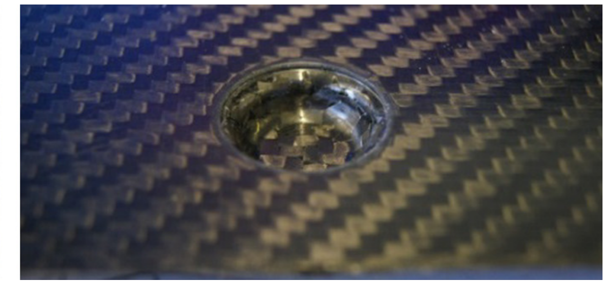
Mechanical treatments: operators introduce dissimilarities across treated surfaces

Chemical treatments: large volume of chemical waste, health, safety and ecological concerns (EU/200/53/EC)

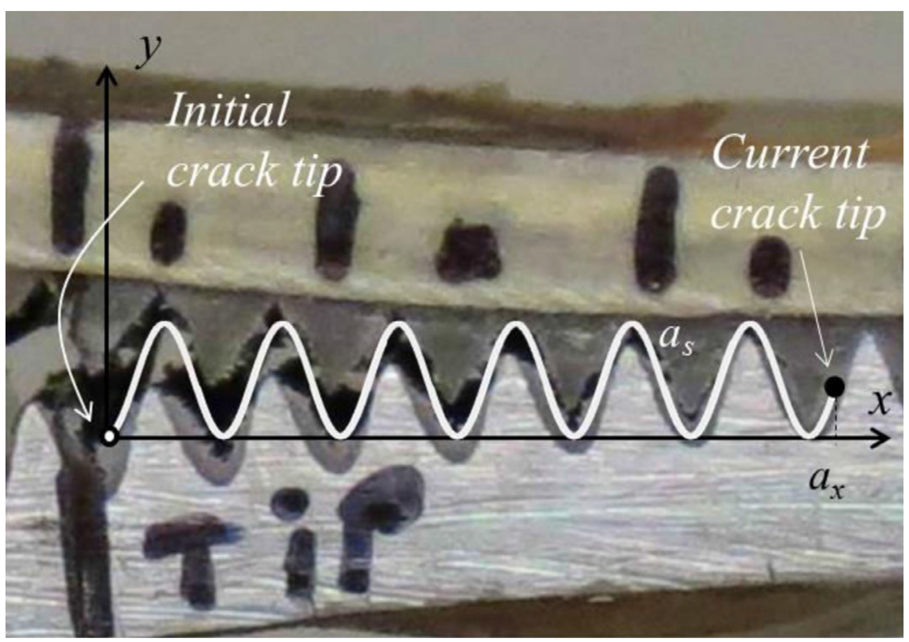
Introduction and motivation

Literature on crack arrest features

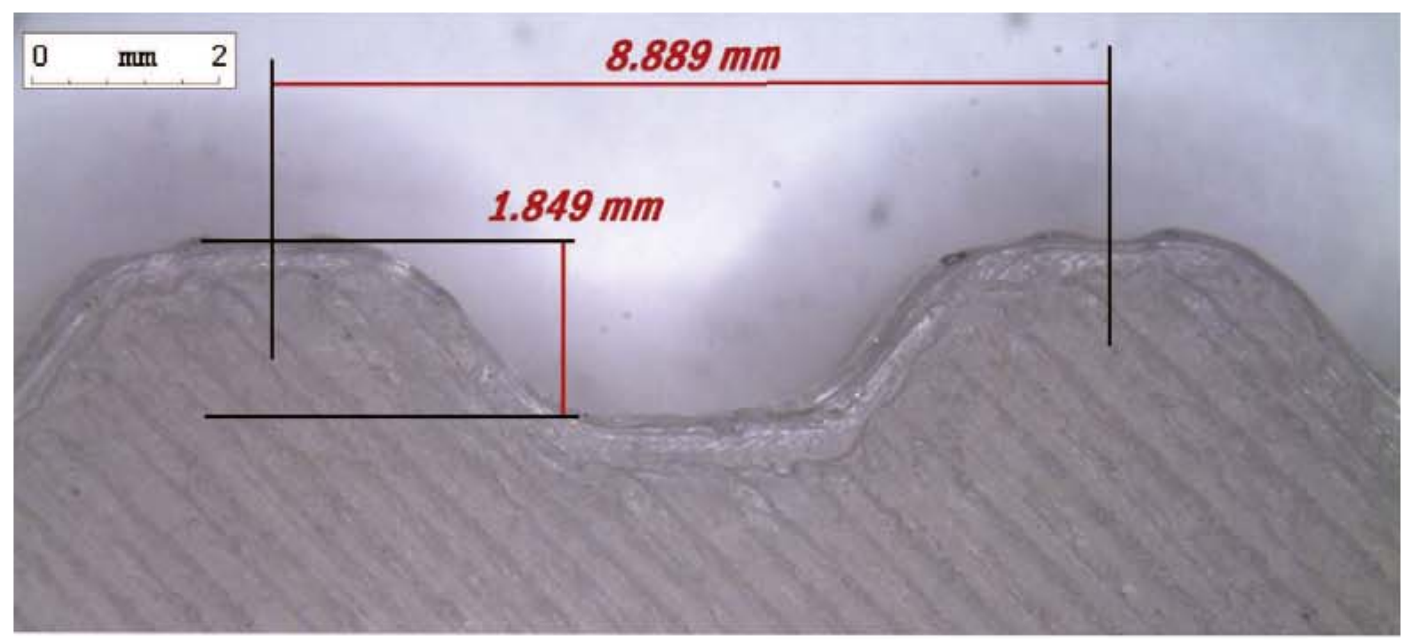
Strategy #1: corrugation of the substrate and mode-mixity

Tserpes, K. I., et al. "Crack stopping in composite adhesively bonded joints through corrugation." Theoretical and Applied Fracture Mechanics 83 (2016): 152-157.



Cordisco, F.A. et al. "Mode I fracture along adhesively bonded sinusoidal interfaces", IJSS (2016), (83), 45-64.



Garcia-Guzman L. et al. "Fracture resistance of 3D printed…" Composite Structures (2018), (188), 173-184.

Introduction and motivation

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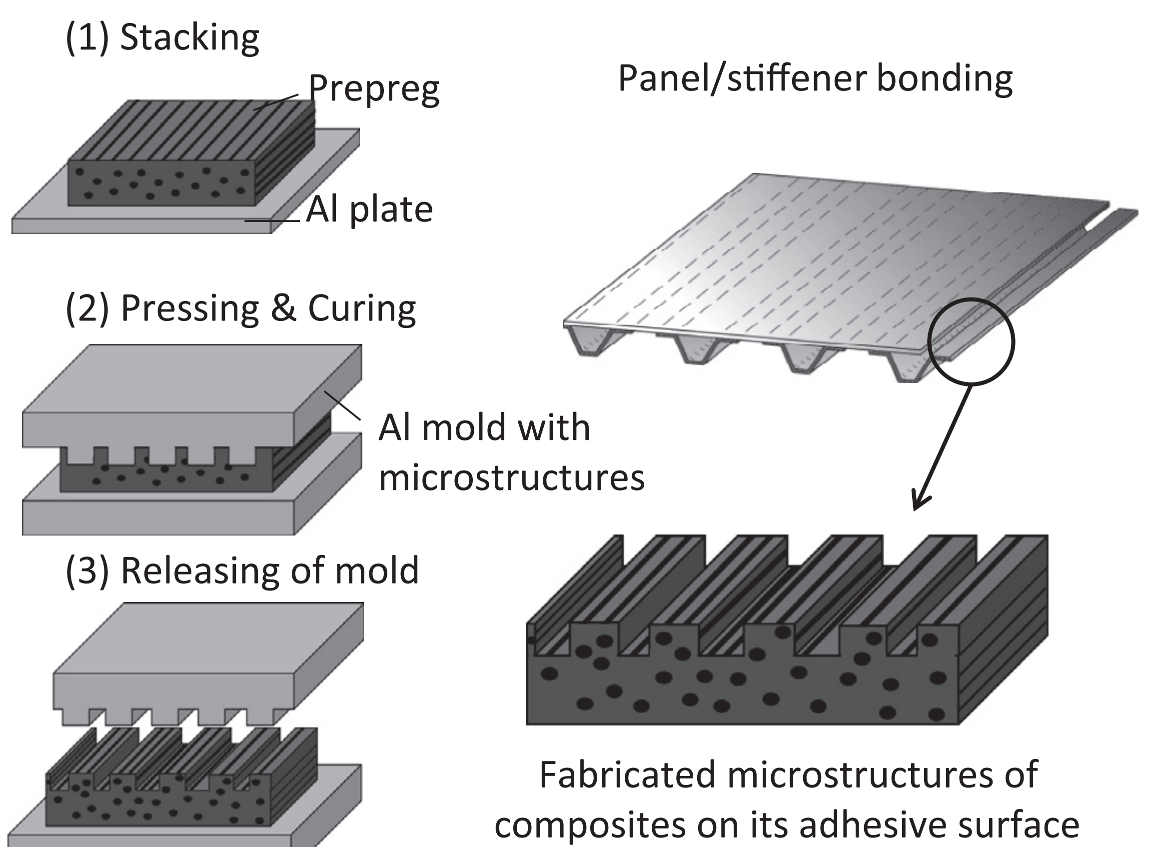
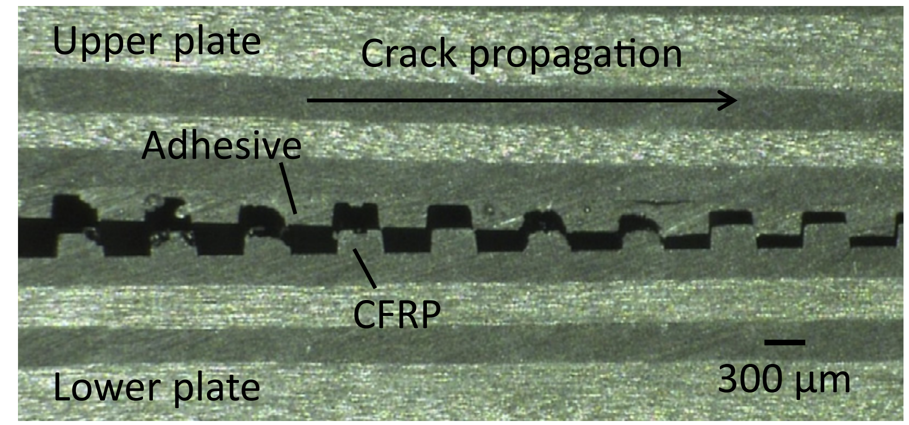
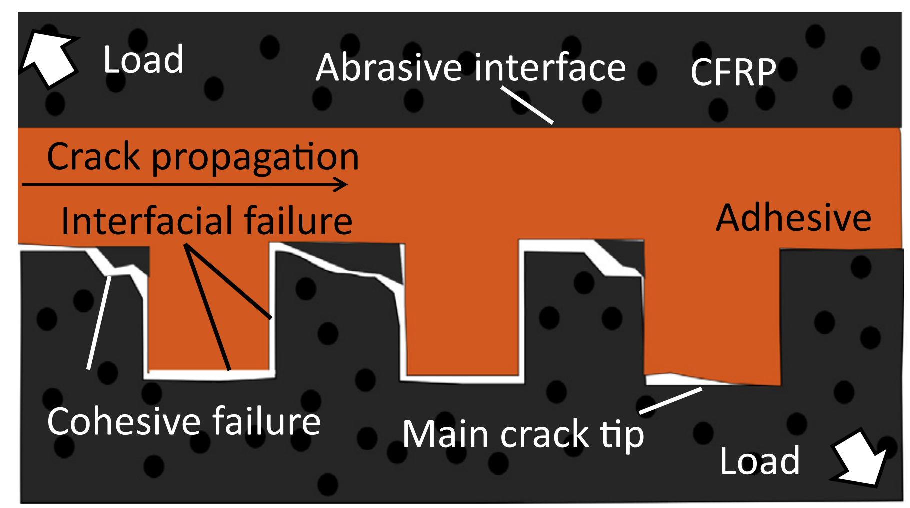


Fig. 1. Schematic illustration of in-mold surface modification by imprint lithography for composite materials.



(a)



Yukimoto, Y. et al. “Effects of mixed-mode ration and step-shaped micro pattern…” ,Composites: Part A, (2015), (69), 139-149.

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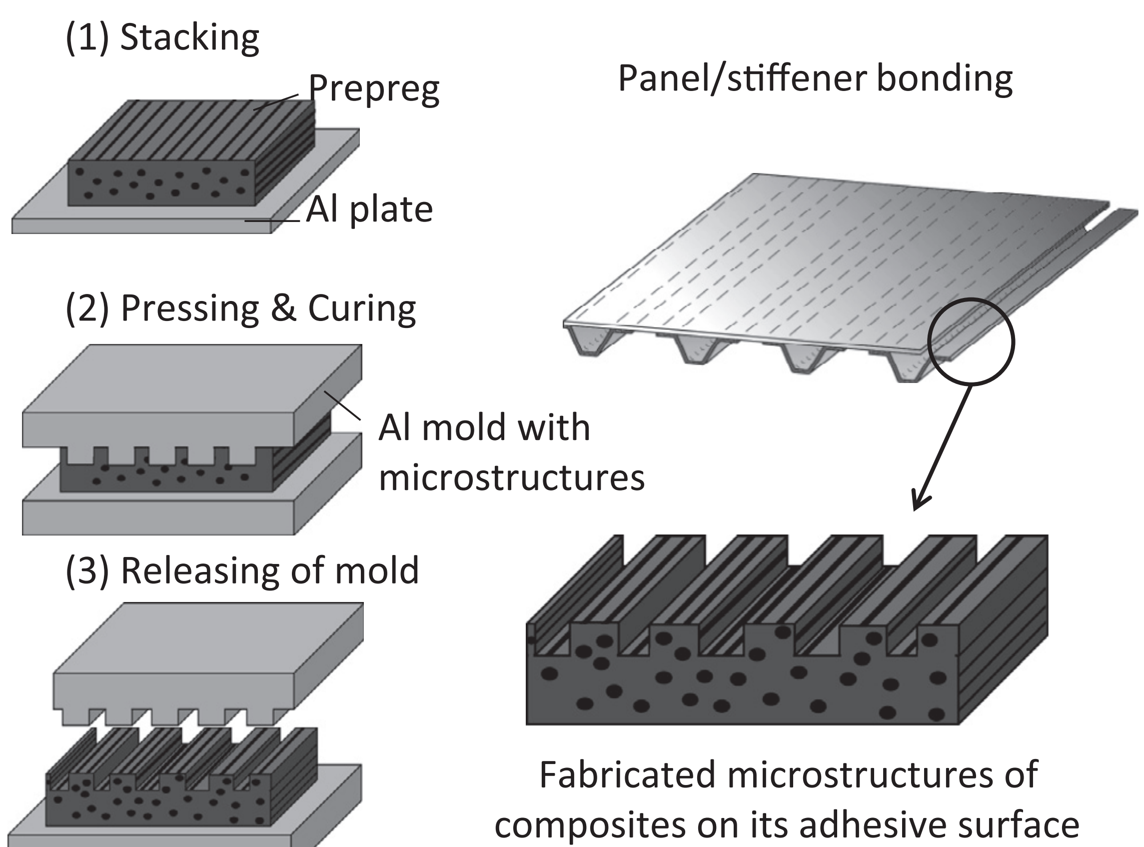

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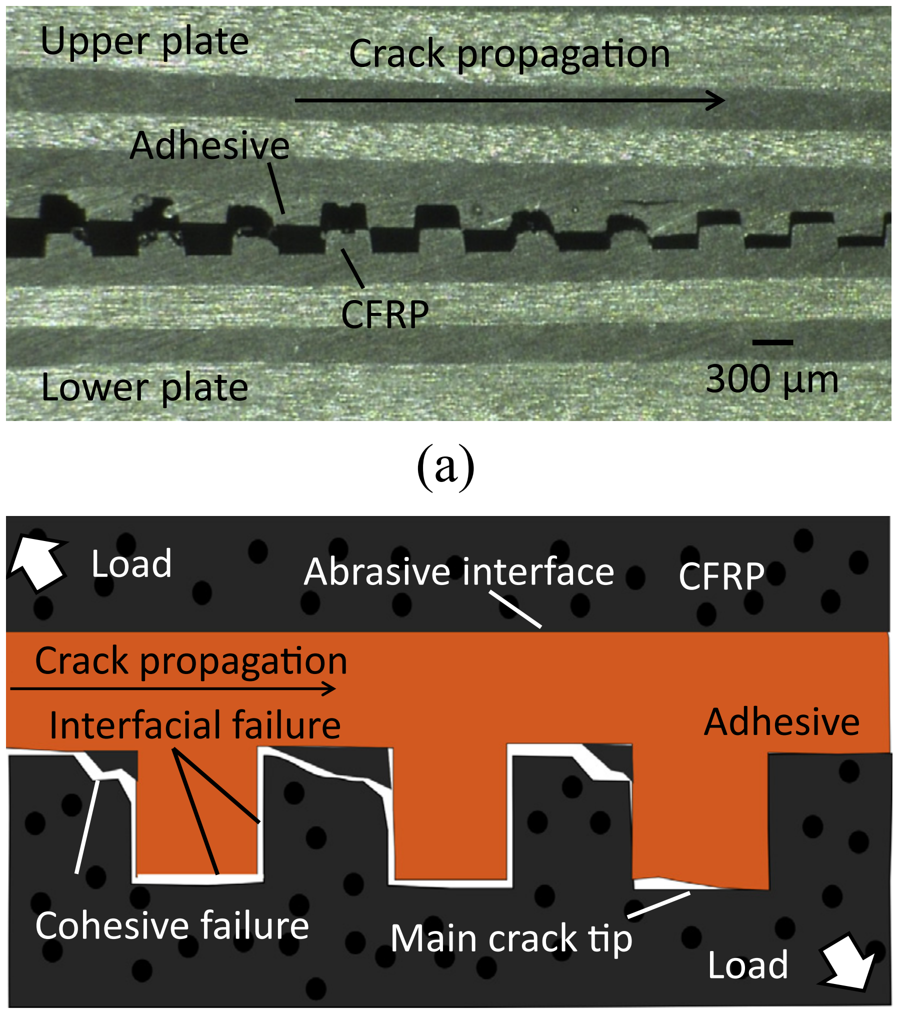

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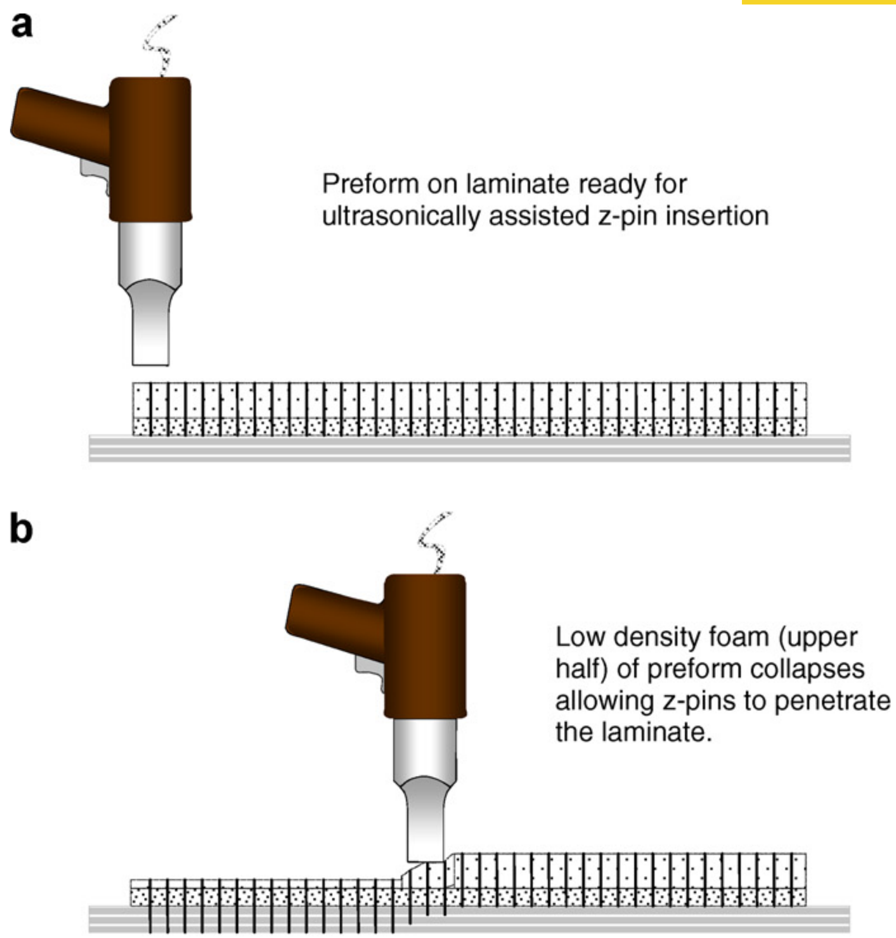
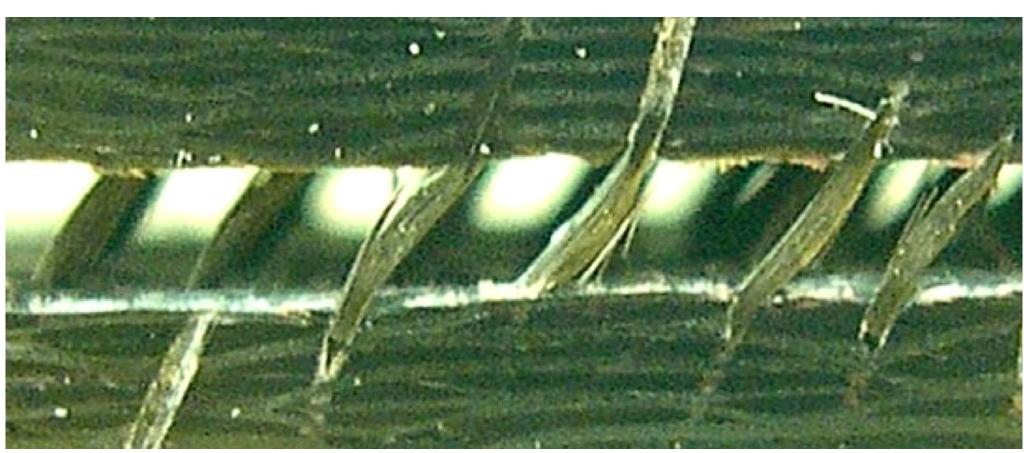
Efficient,
but strong perturbation of the substrates (cost, global performance, qualification?…)

Introduction and motivation

Literature on crack arrest features

Strategy #2: pinning / stitching





Mouritz. “Review of z-pinned composite laminates” *Composites: Part A* (2007), (38), 2383-2397.

Cartie et al. . “3D reinforcement of stiffener-to-skin T-joints by Z-pinning and tufting” *Engineering Fracture Mechanics* (2006), (73), 2532-2540.

Introduction and motivation

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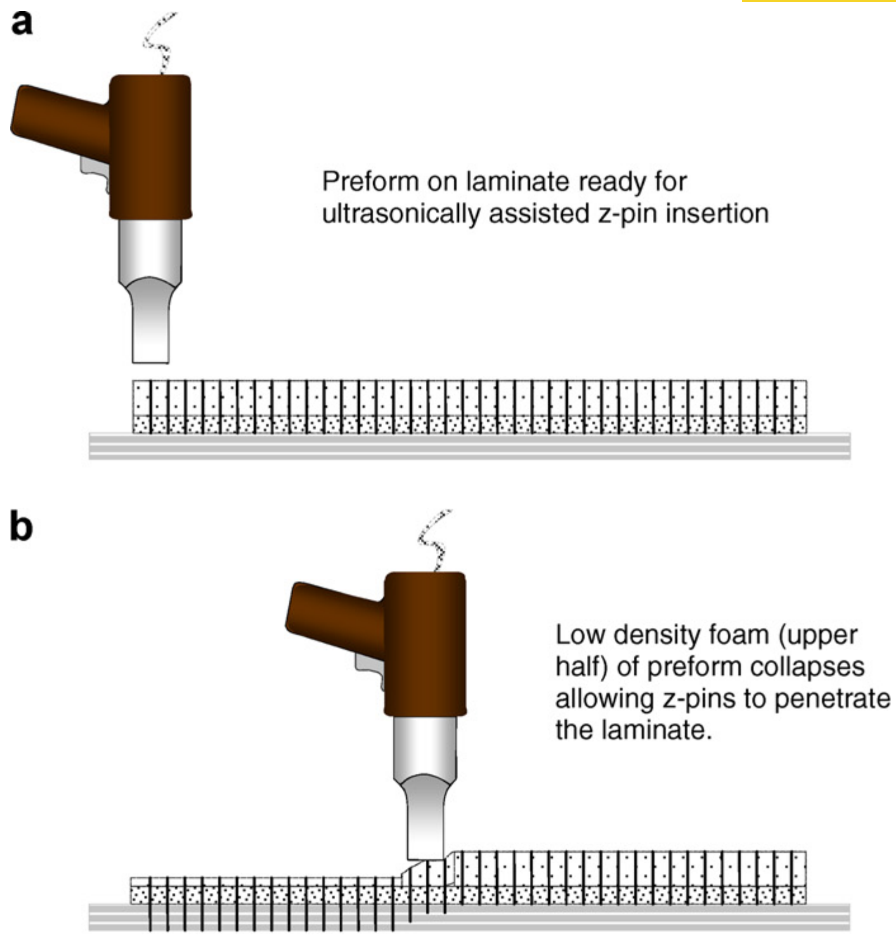
Mechanics of Composites for Energy and Mobility

Strategy #2: pinning / stitching



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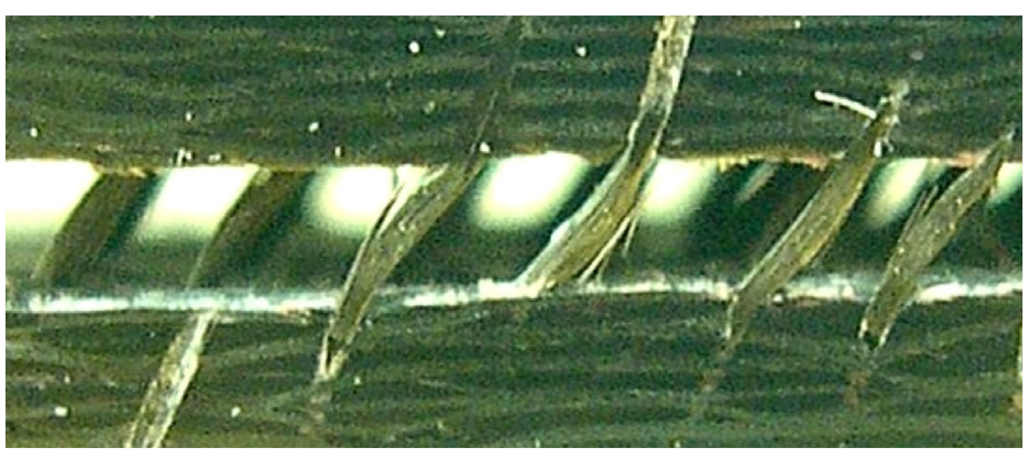

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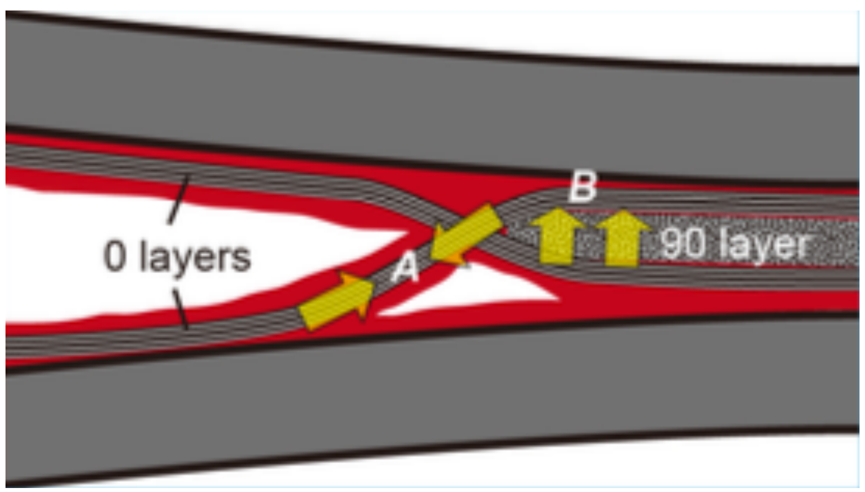
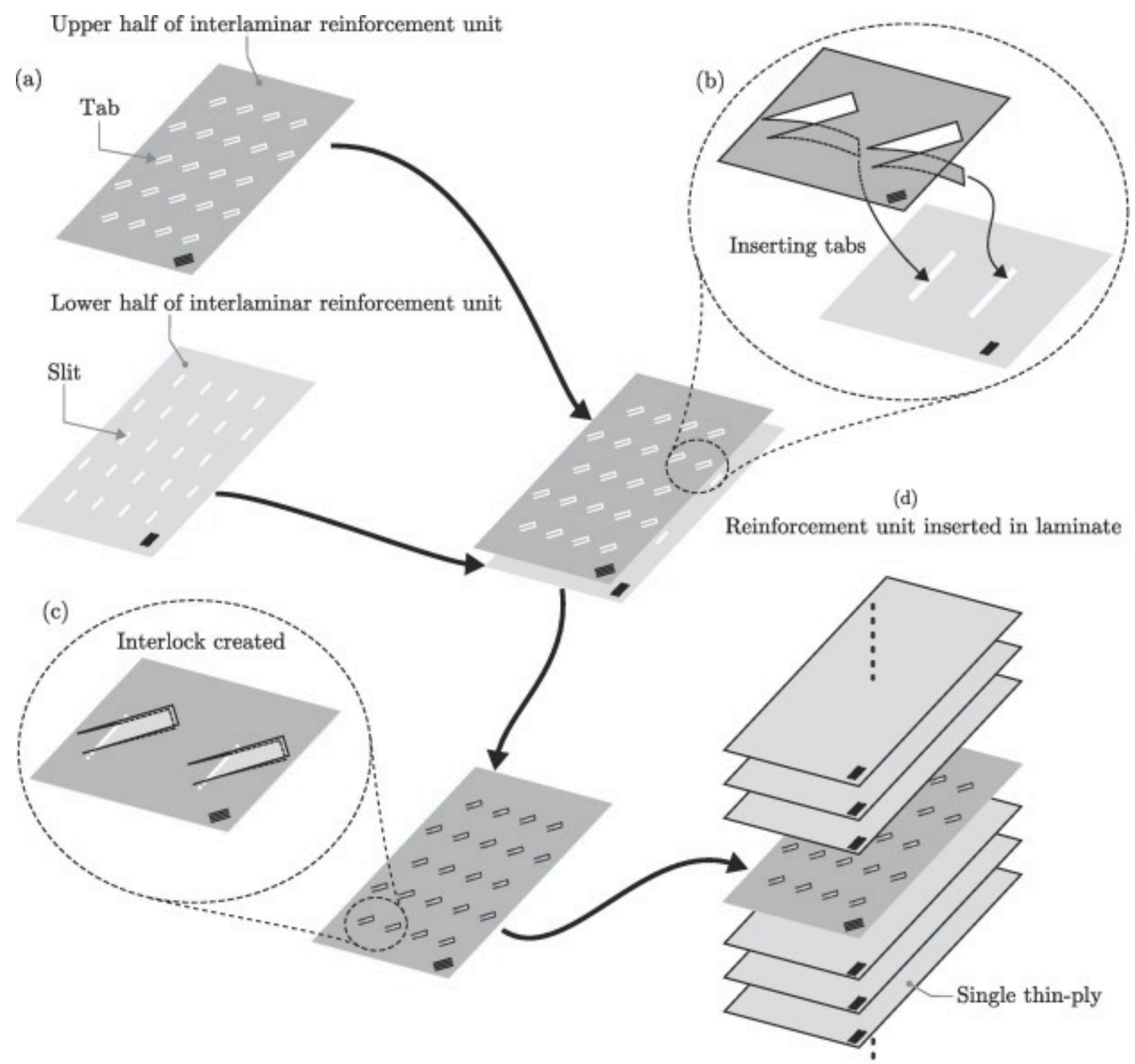
Perturbation of fiber arrangement,
Integrity of the substrate?

Strategy #3: interlocks



S. Minakuchi, *et al*. “Arresting fatigue crack in composite bonded joint using interlocked fiber feature." 21st *ICCM proceeding* (2017)

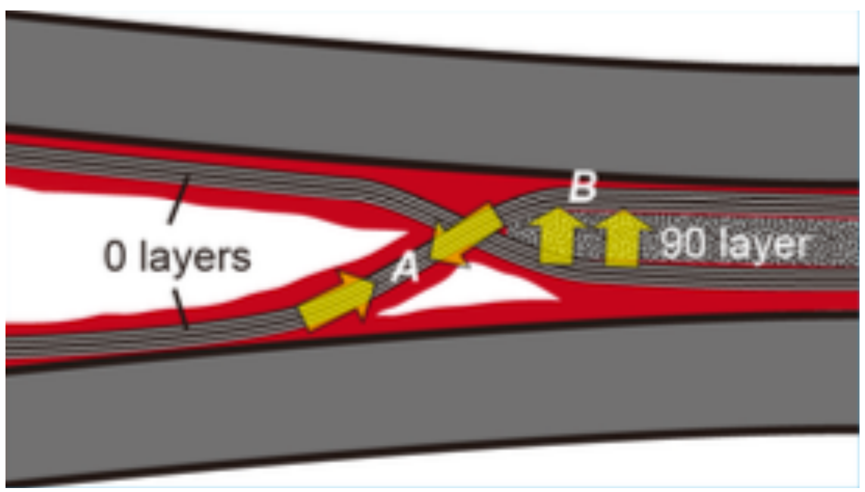


Pascoe, Pimenta and Pinho. “Interlocked interlaminar thin-ply CFRP reinforcements.” *Composite Structures* 238, (2020)

Introduction and motivation

Literature on crack arrest features

Strategy #3: interlocks



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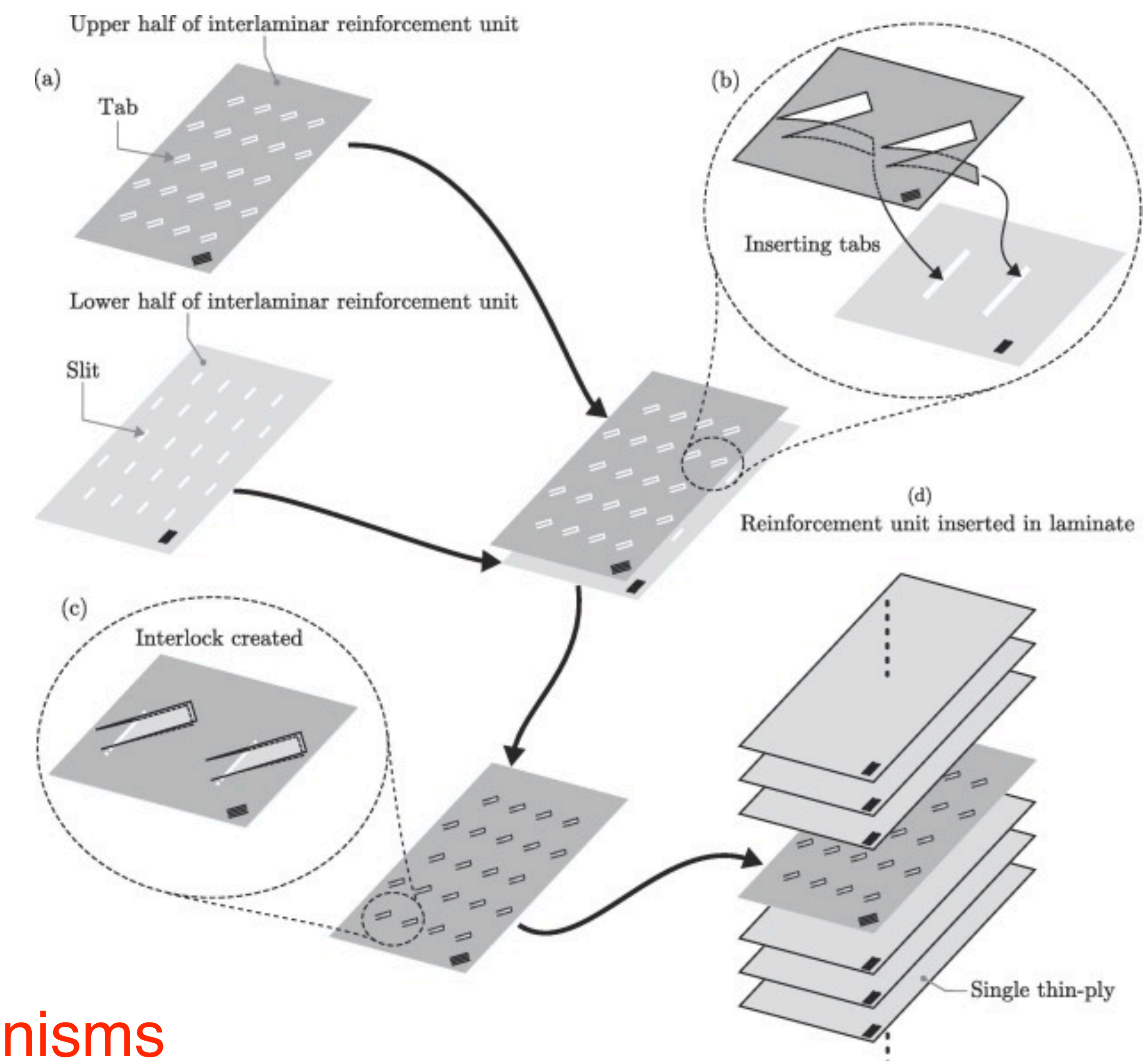


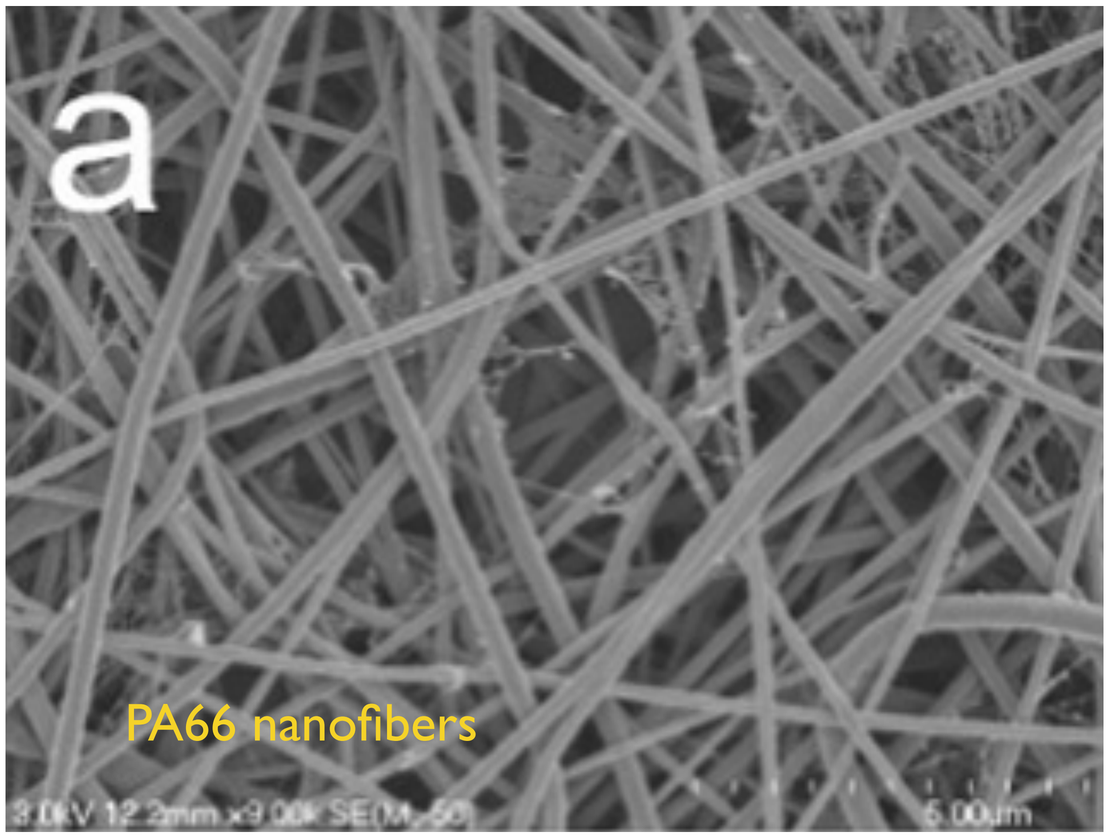
Integrity of the substrate?
Introduction of other damage mechanisms

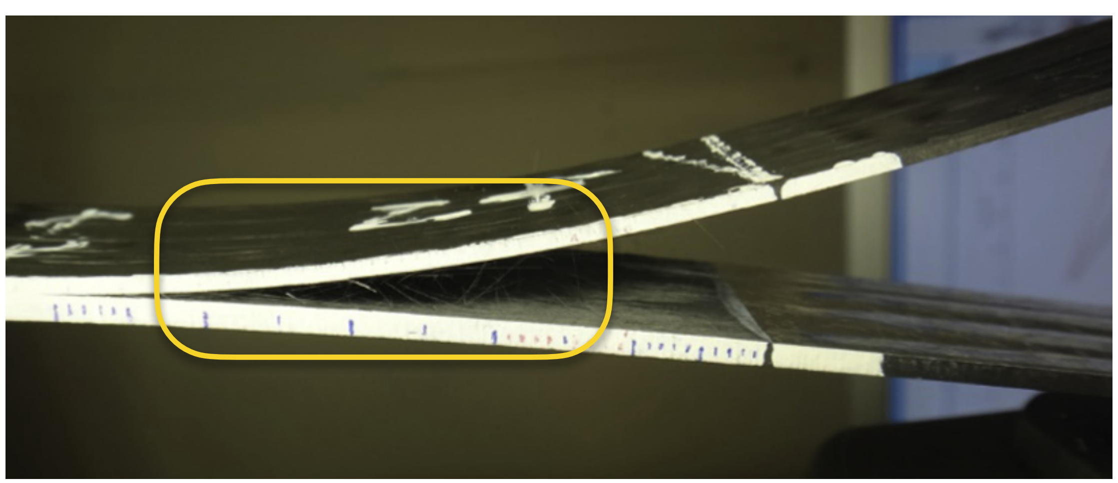
Pascoe, Pimenta and Pinho. "Interlocked interlaminar thin-ply CFRP reinforcements." *Composite Structures* 238, (2020)

Introduction and motivation

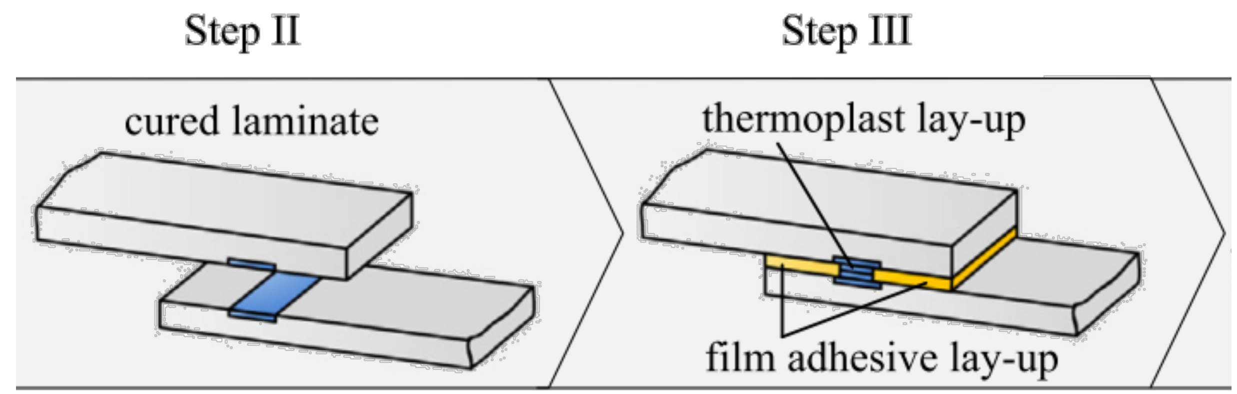
Literature on crack arrest features

Strategy #4: hybrid materials (thermoset/thermoplastics)





Beckermann, G. And Pickering, K. "…fracture toughness of composite laminated interleaved with electrospun nanofibre veils…", Composites: Part A, 72 (2015): 11-21.

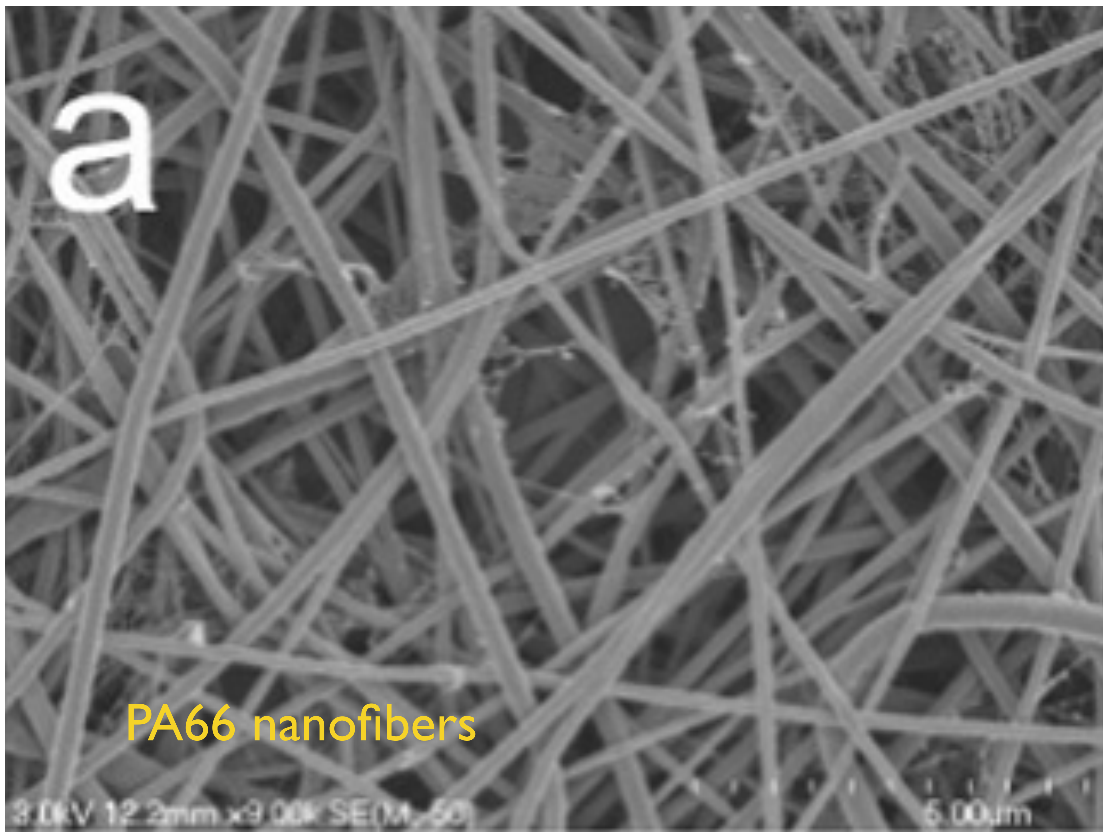


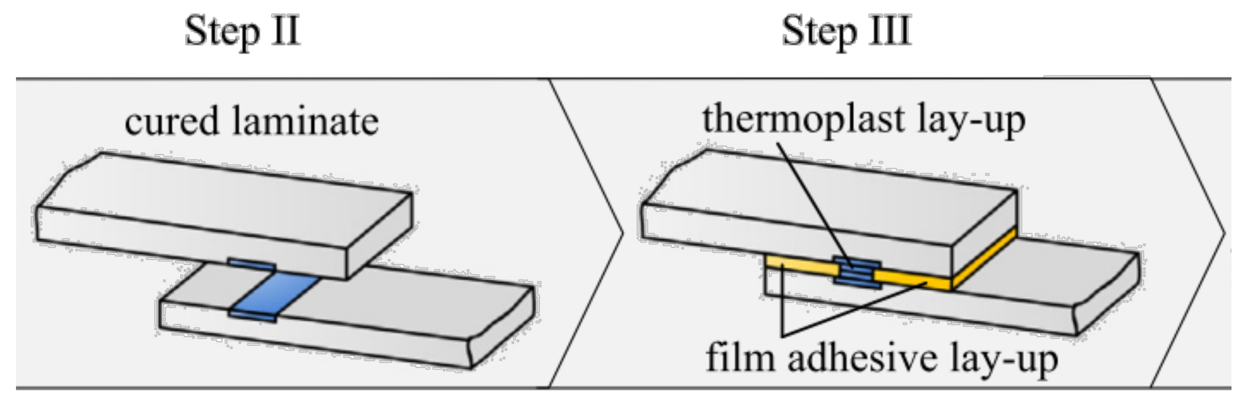
Löbel, T., et al. "A hybrid bondline concept for bonded composite joints." International Journal of Adhesion and Adhesives 68 (2016): 229-238.

Introduction and motivation

Literature on crack arrest features

Strategy #4: hybrid materials (thermoset/thermoplastics)





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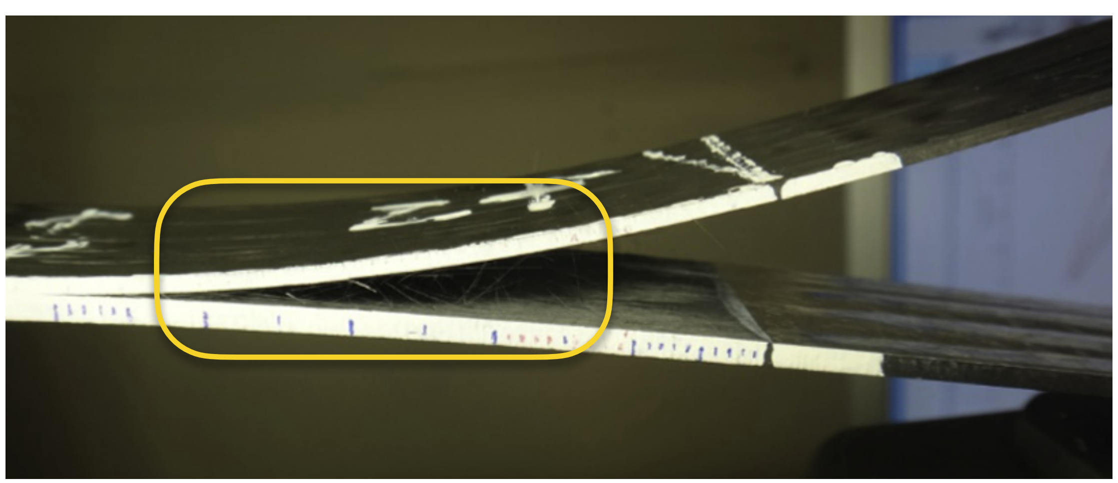

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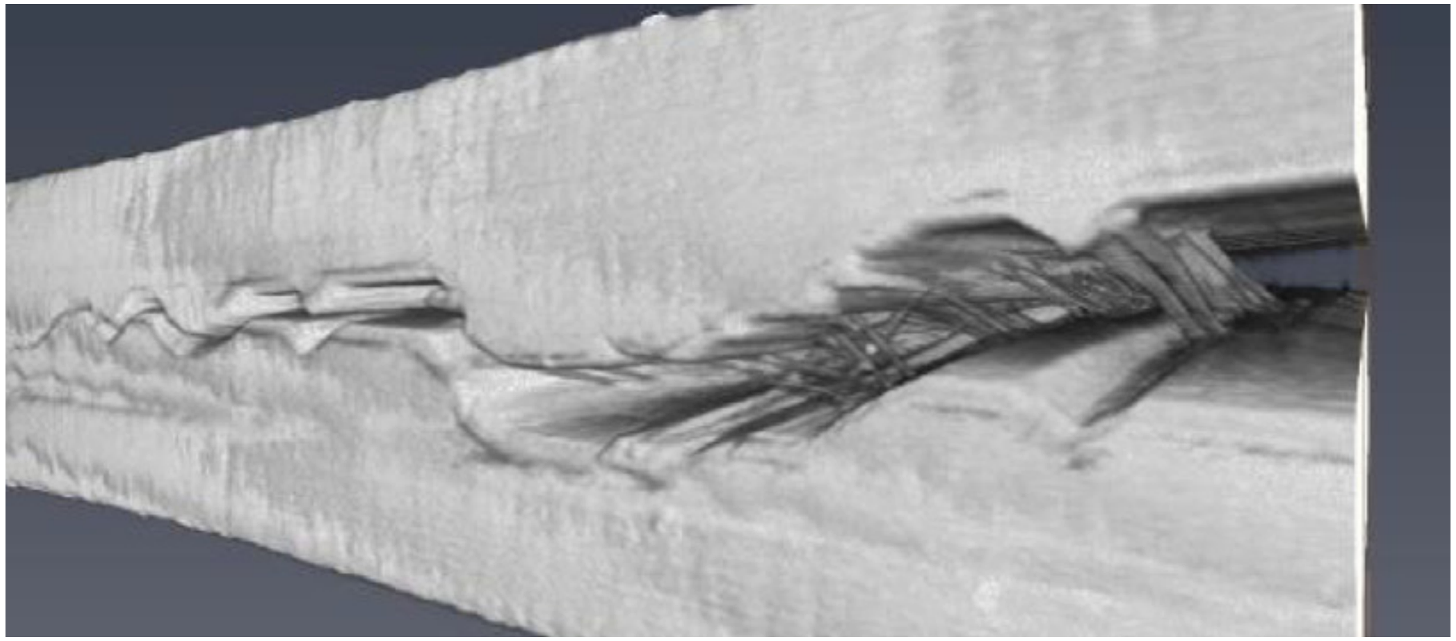
Promising path for toughening

How to make it more efficient?
Better integration?

Introduction and motivation

Literature on crack arrest features

Our strategy: promoting long-range bridging and non-local toughening



P. Hu et al. "An experimental study on the influence of intralaminar damage on interlaminar delamination properties of laminated composites ", Composites: Part A, (131), 2020, 105783

Introduction and motivation

Literature on crack arrest features

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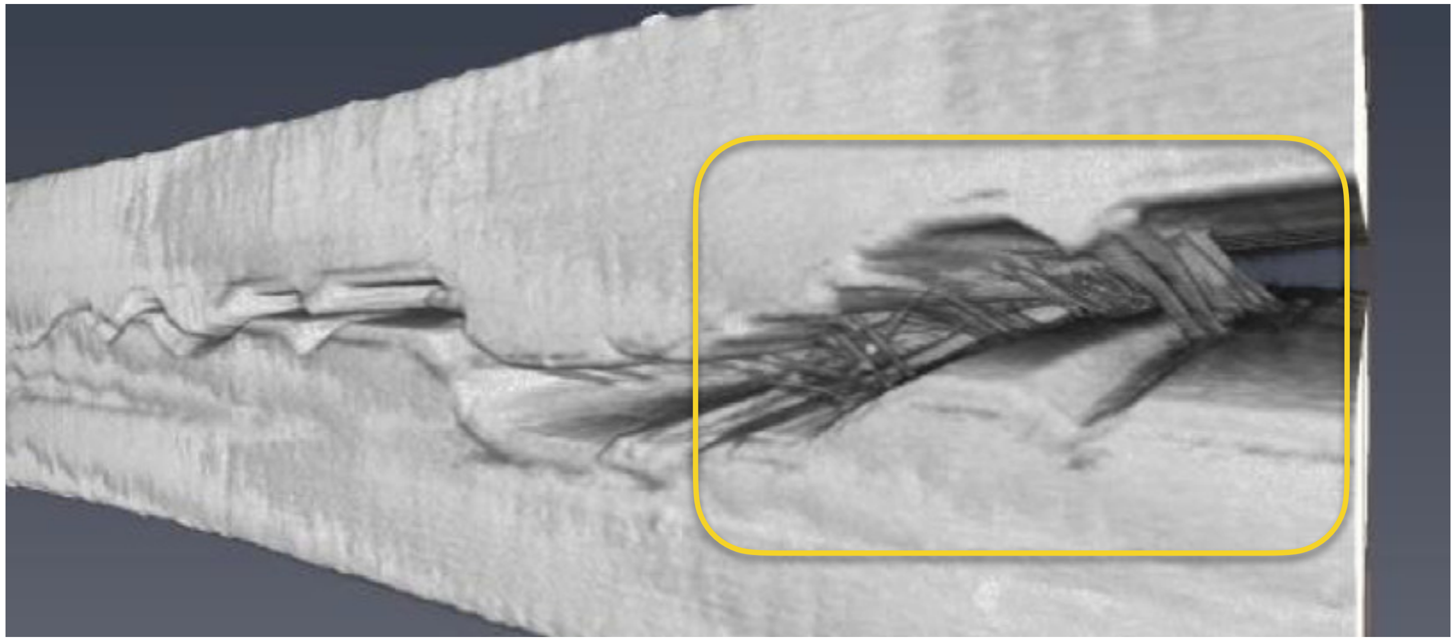

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Three challenges:

Three challenges:

- (#1) Improve the intrinsic performance of adhesive joints?

Three challenges:

- (#1) Improve the intrinsic performance of adhesive joints?

- (#2) Change the failure from brittle to progressive by design?

Three challenges:

- (#1) Improve the intrinsic performance of adhesive joints?
- (#2) Change the failure from brittle to progressive by design?
- (#3) Without compromising the substrate / All-in-adhesive concept.

Our strategy: promoting long-range bridging and non-local toughening

- (1) by structuring the adhesive/substrate interface

Introduction and motivation

Towards next generation bonding

Our strategy: promoting long-range bridging and non-local toughening

- (1) by structuring the adhesive/substrate interface

- (2) by structuring an hybrid adhesive

(2a)

Additive approach

Introduction and motivation

Towards next generation bonding

Mechanics of Composites for Energy and Mobility

Our strategy: promoting long-range bridging and non-local toughening

- (1) by structuring the adhesive/substrate interface

- (2) by structuring an hybrid adhesive

(2a)

Additive approach

(2b)

Subtractive approach

Path #1:

Structuring
the adhesive/substrate
interface

Introduction and motivation

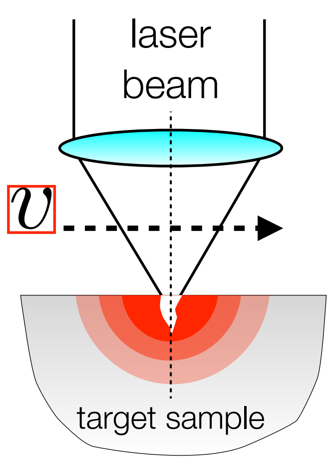
A refresh on laser treatments

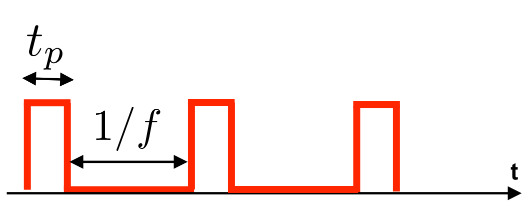
Metal to Metal (example: copper)	Metal to CFRP	CFRP to CFRP

Laser irradiation: promising ecological alternative/suited to industrial automation

- large amount of energy over short time scale and spatially confined region
- fast and controllable processing
- infrared-range light source

Laser processing

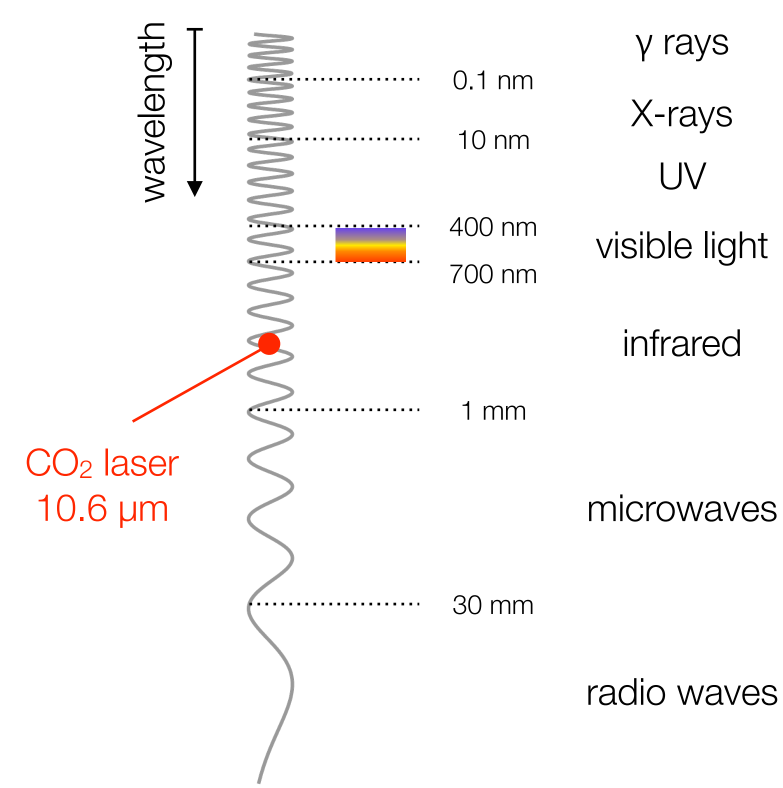




UNIVERSAL Laser Systems PLS6.75

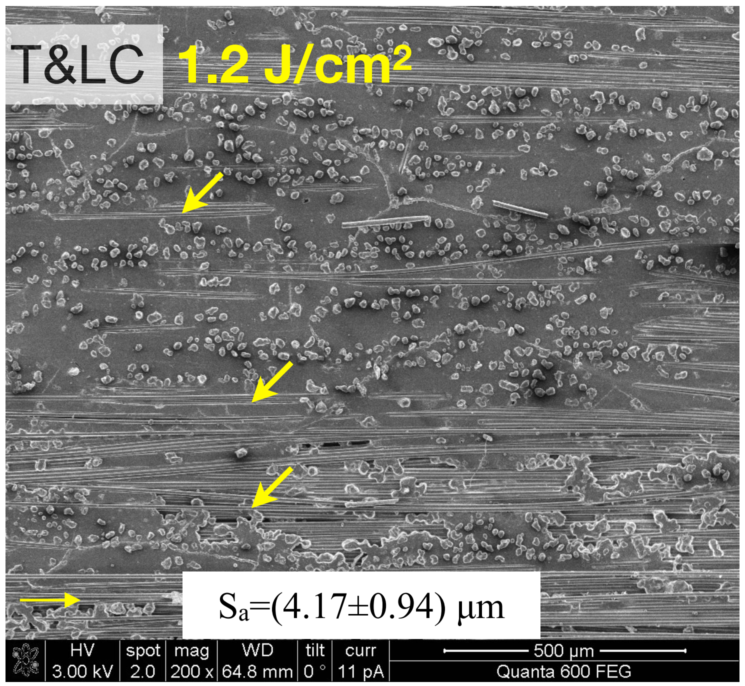
$$F = \frac{P_{ave}}{f \cdot A_s} = \frac{P_{ave}}{v \cdot PPI \cdot A_s}$$

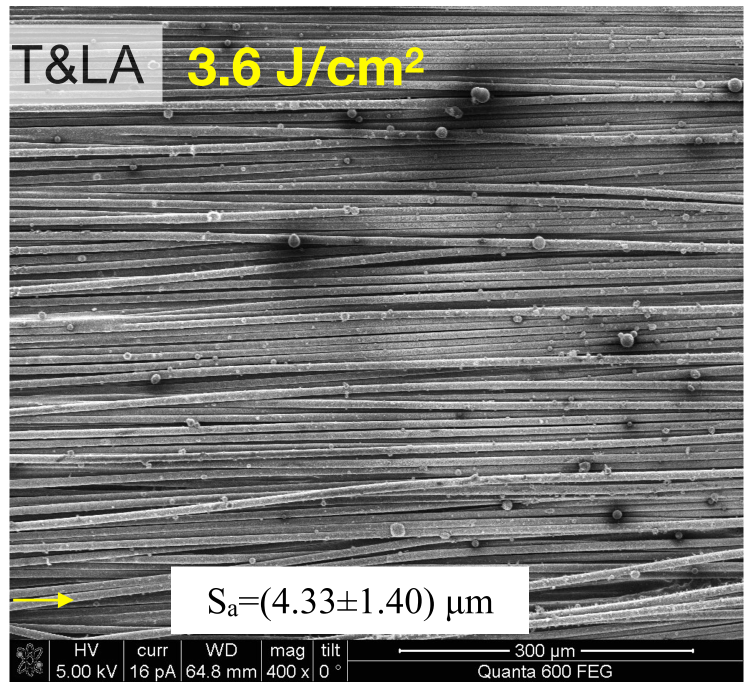
Electromagnetic spectrum

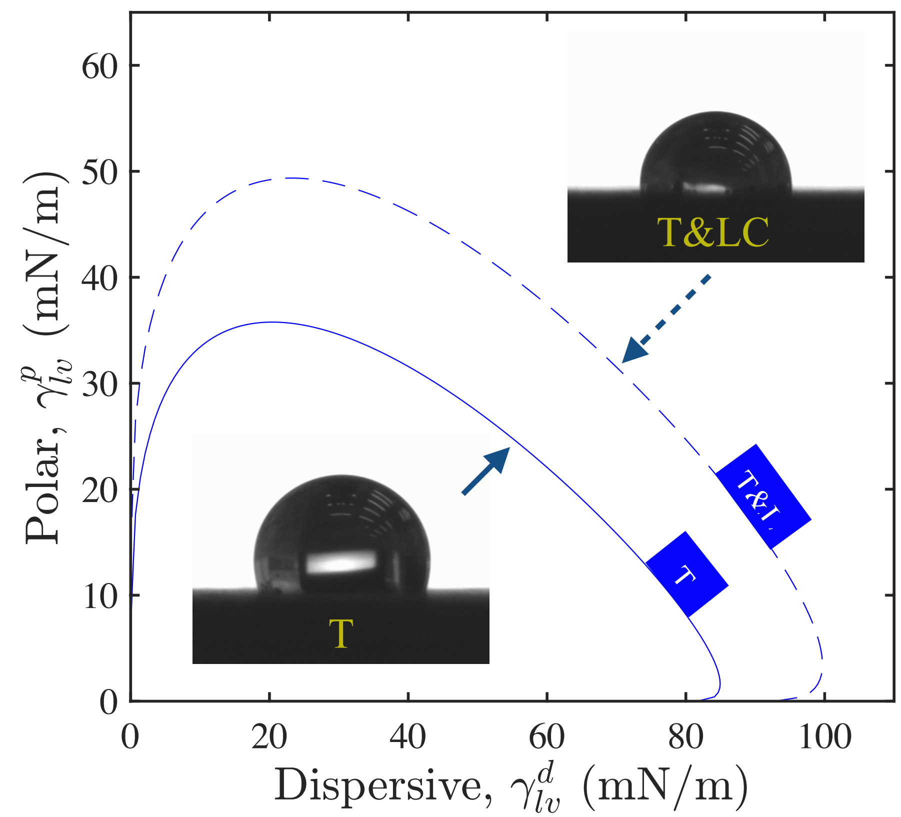


Tailoring morphology using laser treatments

Teflon, Peel ply, Sandblasting, Sanding and Lasers





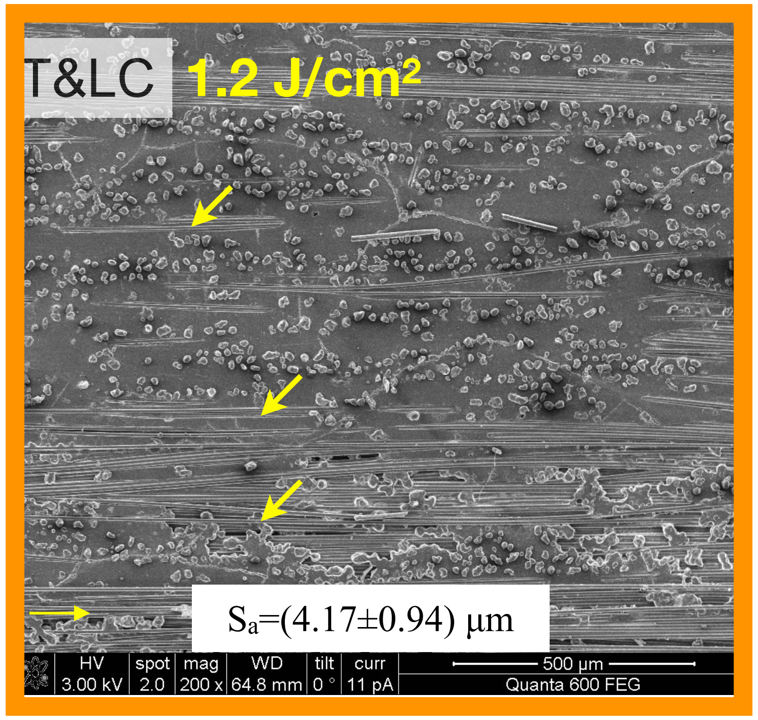


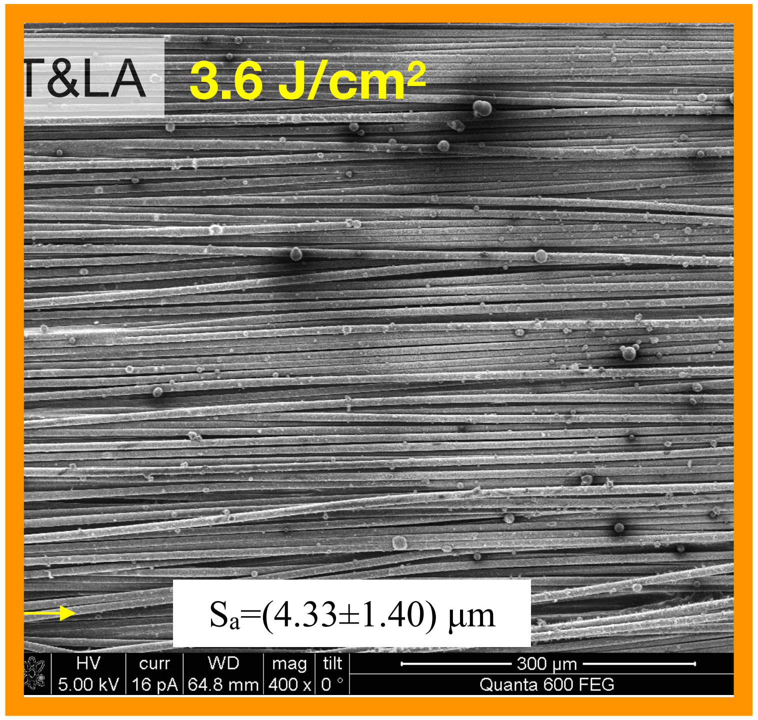
Laser treatment can modify

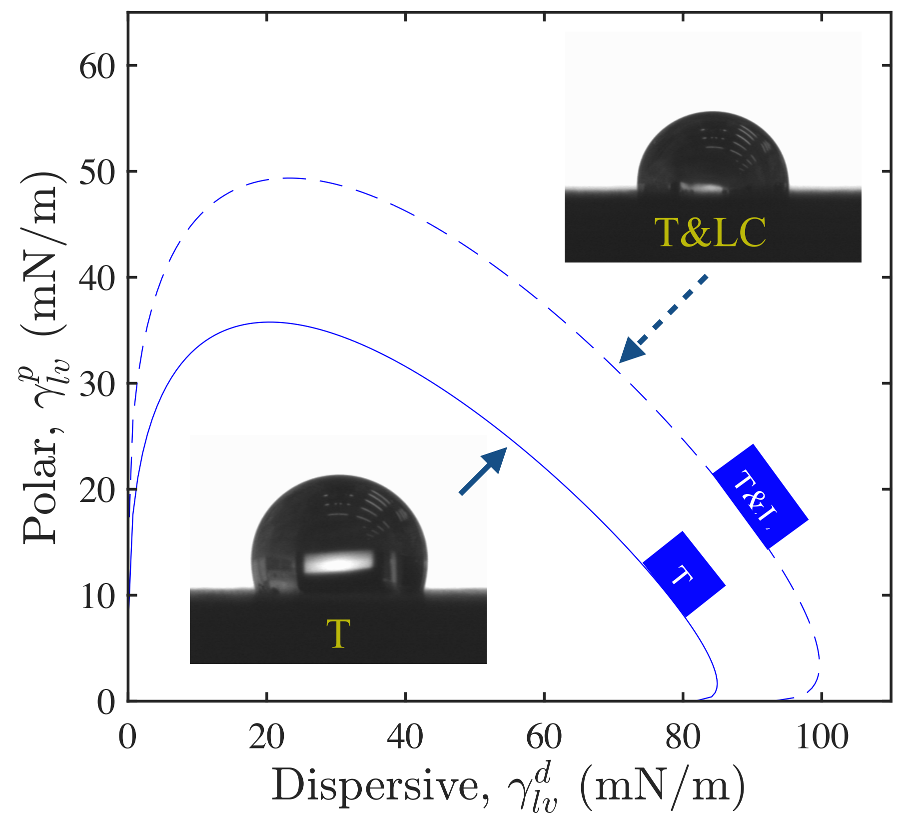
- the local morphology (including roughness, exposure of fibers)
- interlocking low-scale features,
- wetting properties

Tailoring morphology using laser treatments

Teflon, Peel ply, Sandblasting, Sanding and Lasers







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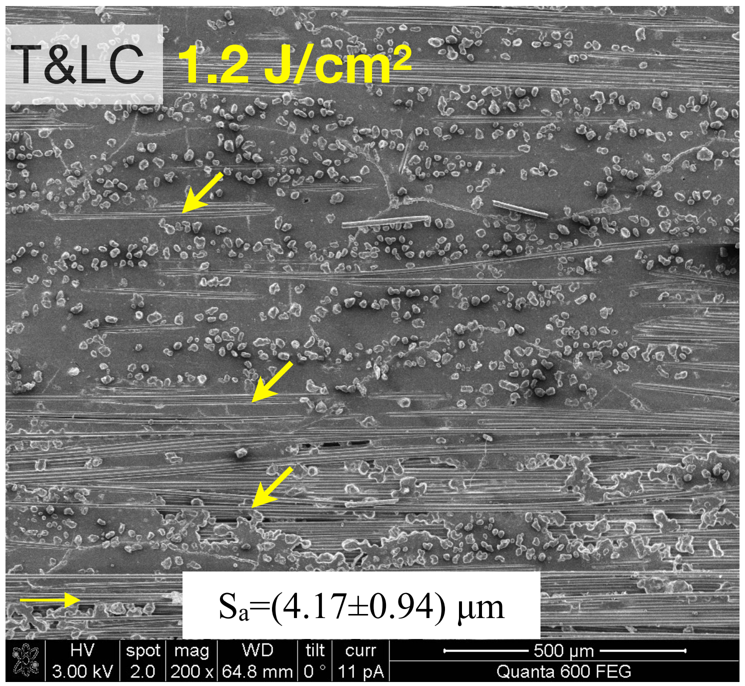

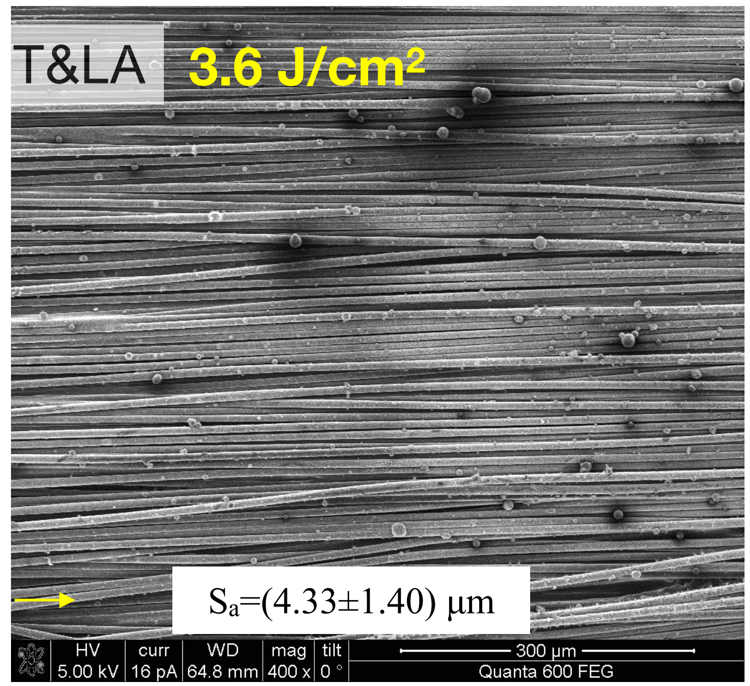

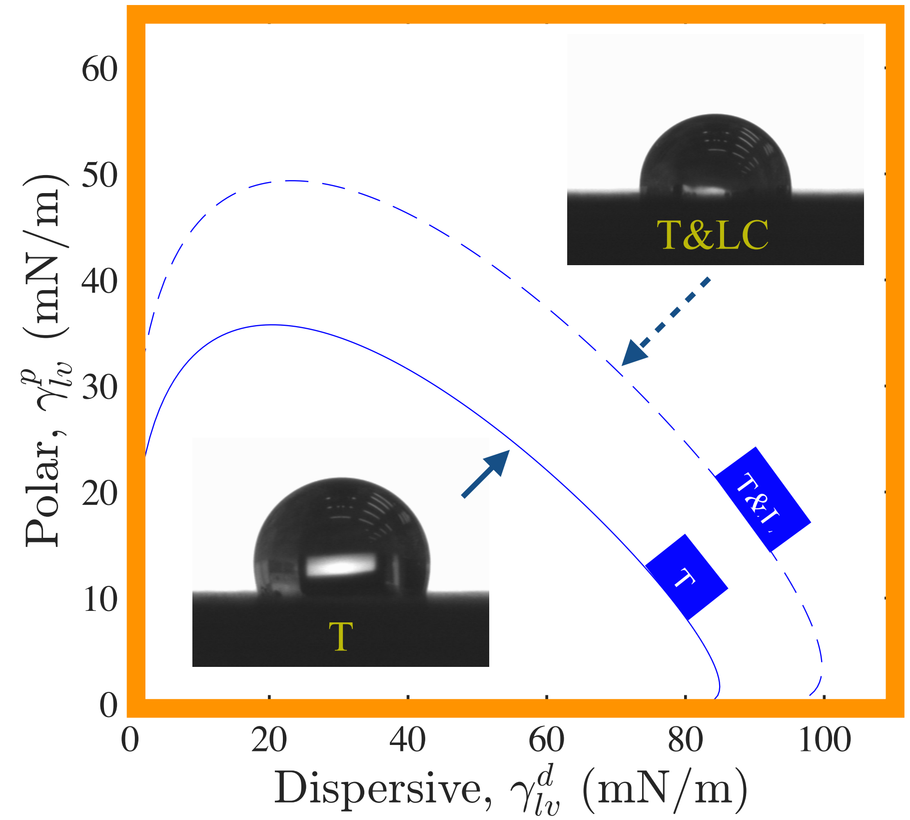

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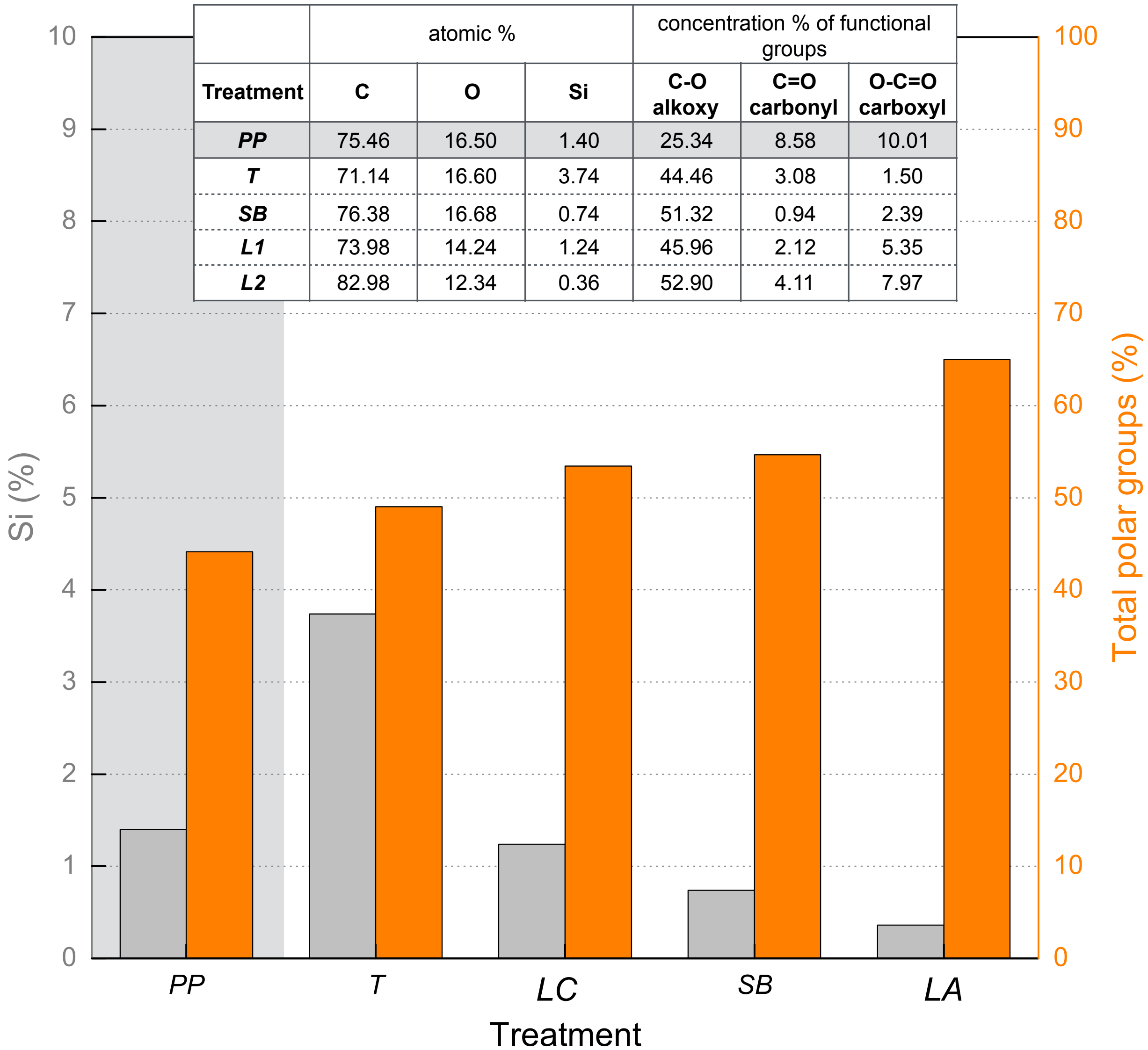
Chemistry of treated surfaces

From removal of contaminants to increased toughness



	atomic %			concentration % of functional groups		
Treatment	**C**	**O**	**Si**	**C-O alkoxy**	**C=O carbonyl**	**O-C=O carboxyl**
PP	75.46	16.50	1.40	25.34	8.58	10.01
T	71.14	16.60	3.74	44.46	3.08	1.50
SB	76.38	16.68	0.74	51.32	0.94	2.39
L1	73.98	14.24	1.24	45.96	2.12	5.35
L2	82.98	12.34	0.36	52.90	4.11	7.97

Laser can be used to remove contaminants and taylor surface functionalization.

Chemistry of treated surfaces

From removal of contaminants to increased toughness

	atomic %			concentration % of functional groups		
Treatment	C	O	Si	C-O alkoxy	C=O carbonyl	O-C=O carboxyl
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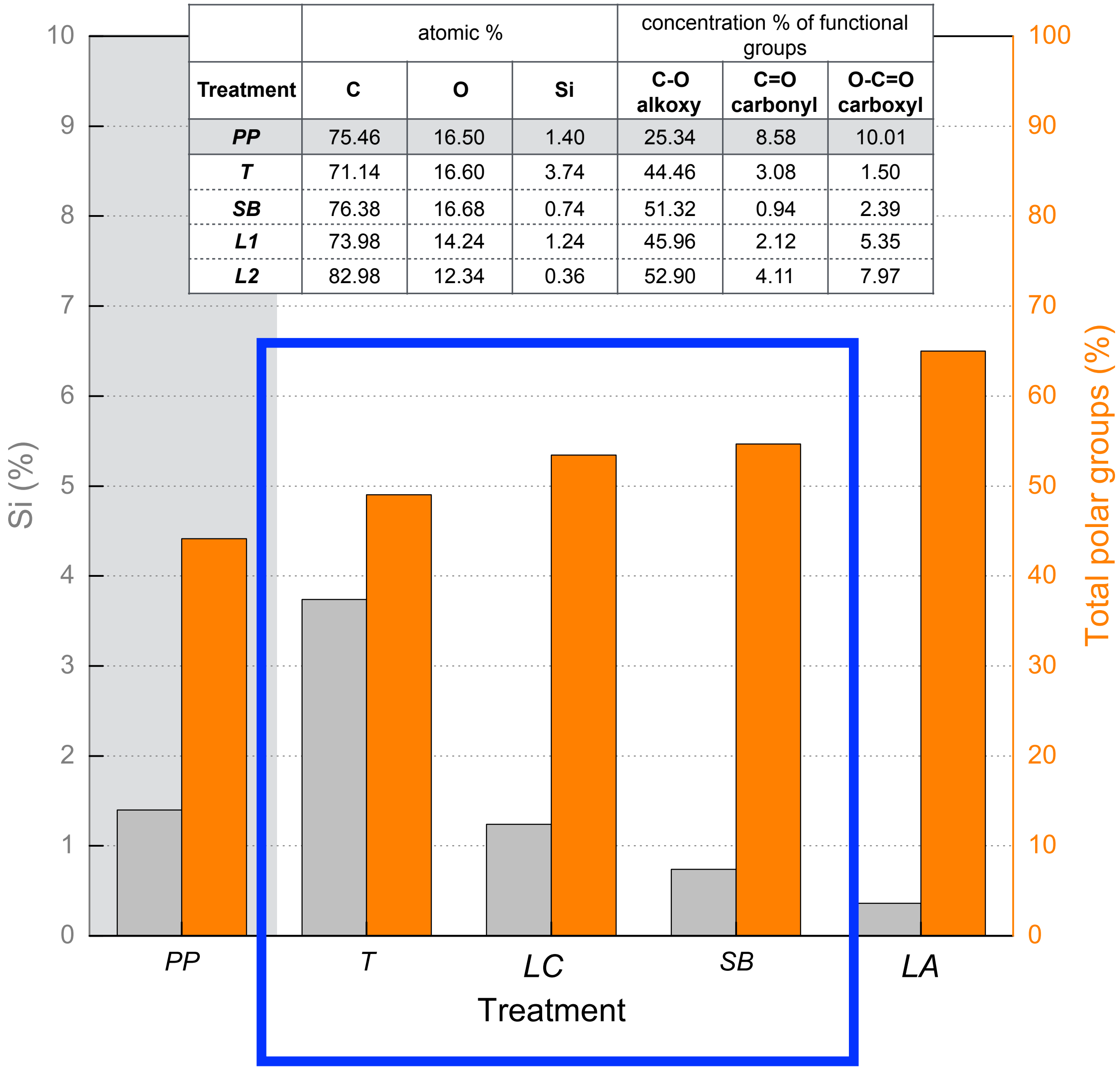
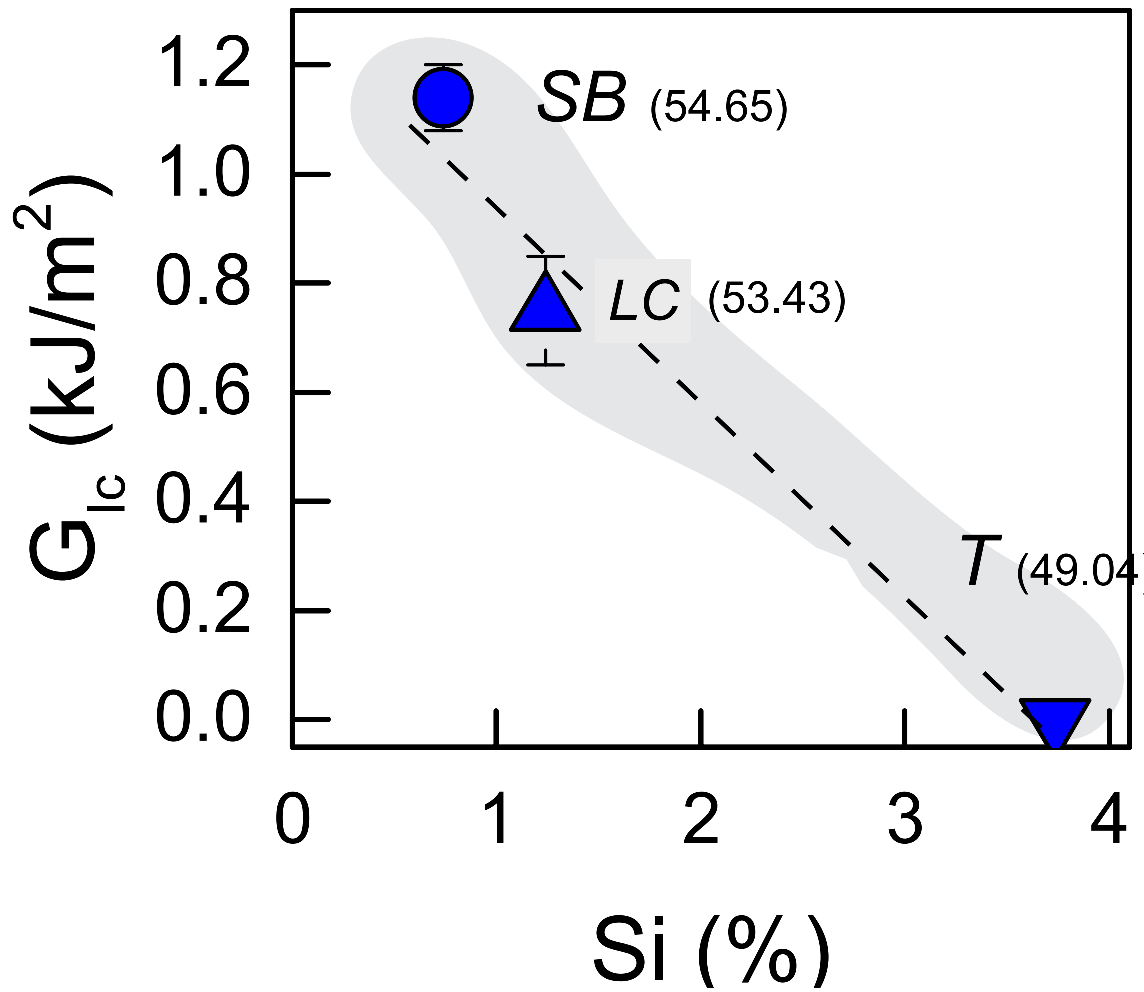




(1) Removal of Silicon contaminant originating from technical fabrics

(2) Increase in the density of functional polar groups promoting adhesion

Laser can be used to remove contaminants and taylor surface functionalization.

Mechanics of Composites for Energy and Mobility

Controlling fiber bridging by selective patterning

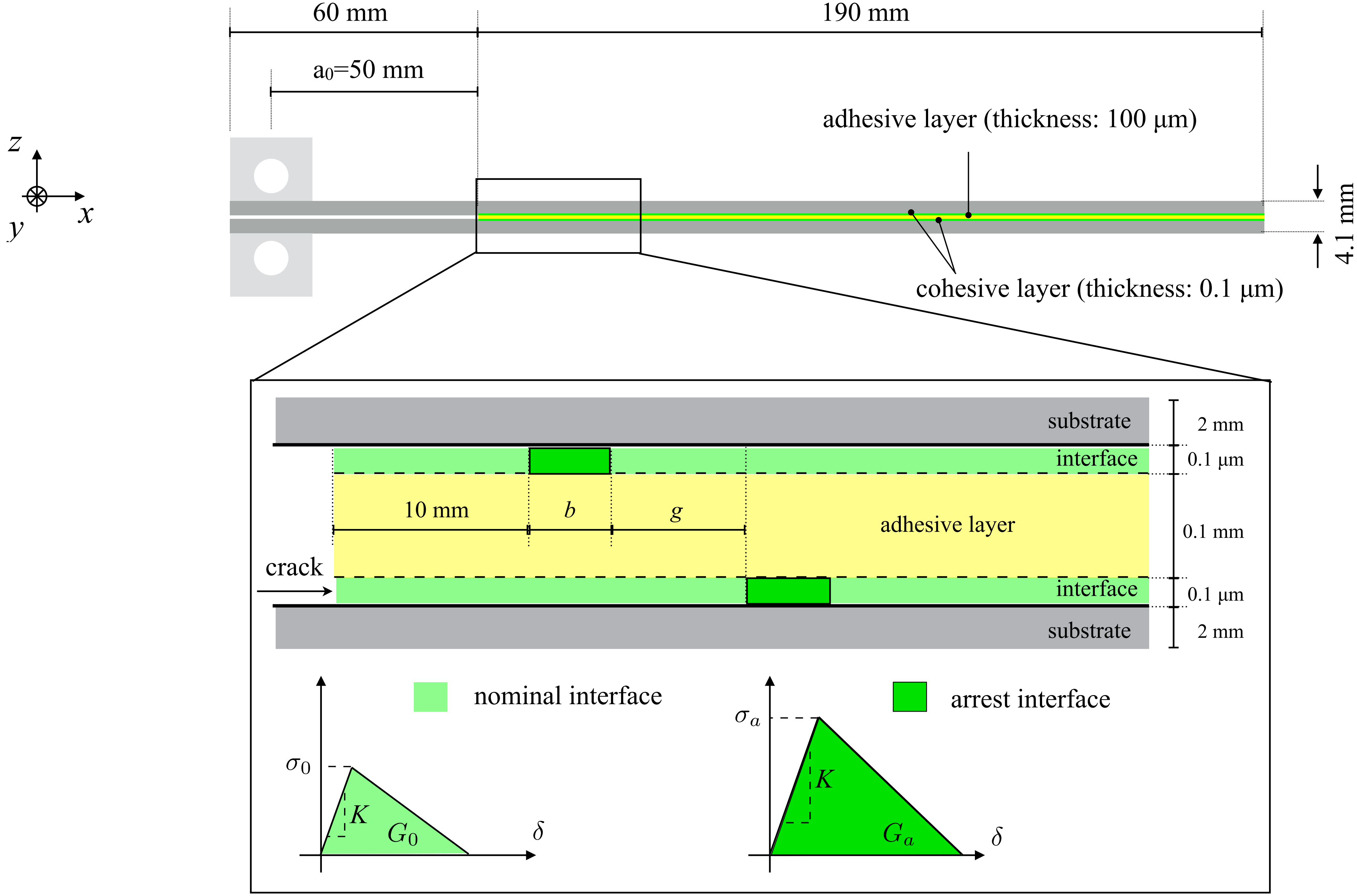
1. Numerical study
2. Experimental verification
3. Role of Randomness

Simulating a crack-arrest feature

Heterogeneous interface properties

Mechanics of Composites for Energy and Mobility

Objective: to understand how contrast in interface properties can trigger ligaments

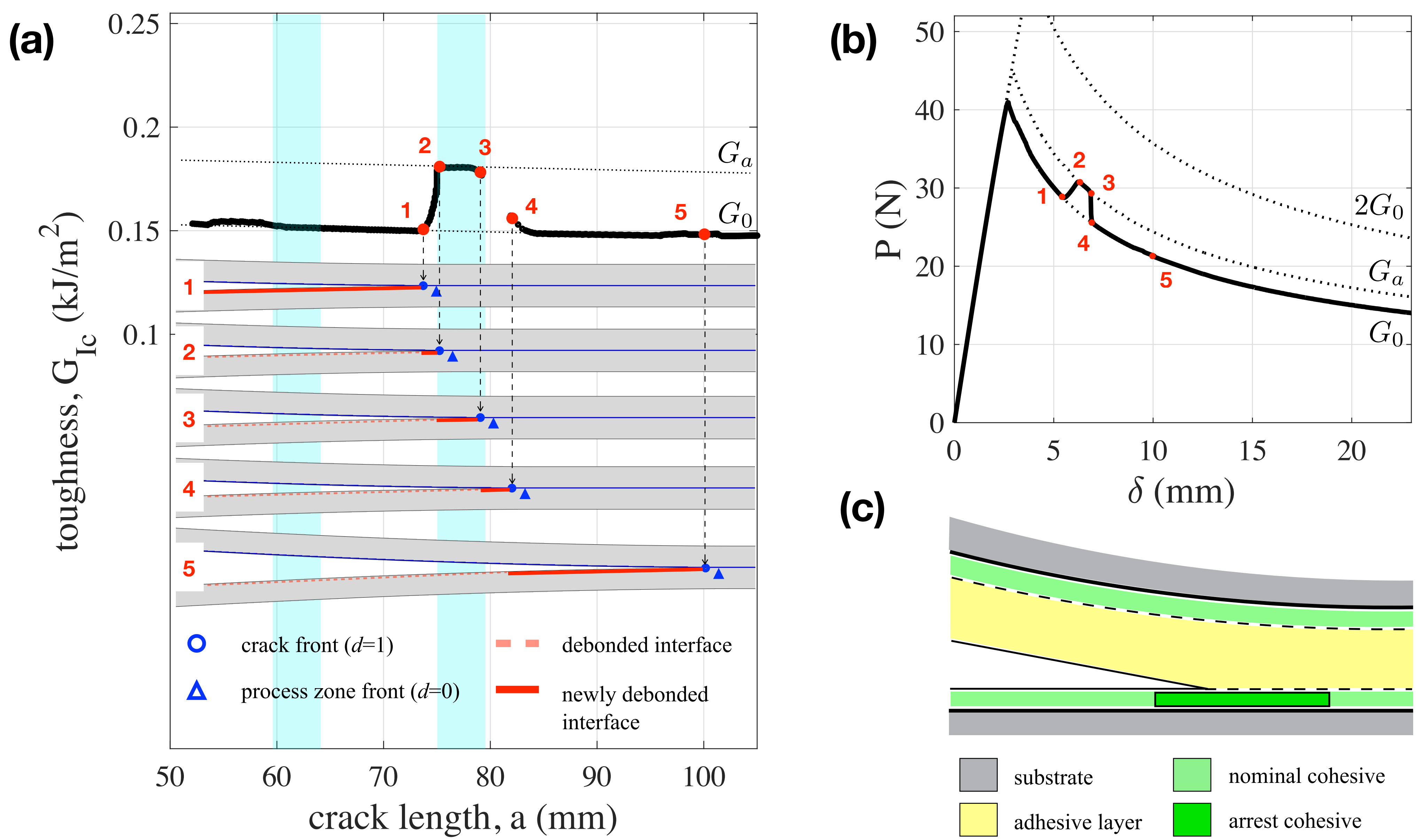


- 2D DCB joints are simulated using two layers of ABAQUS built-in cohesive elements
- Arrest features with different properties are investigated to understand how ligaments are created

Typical responses

Depending on interface and ligament properties…

Case 1: crack stayed on the bottom interface and no ligament was triggered

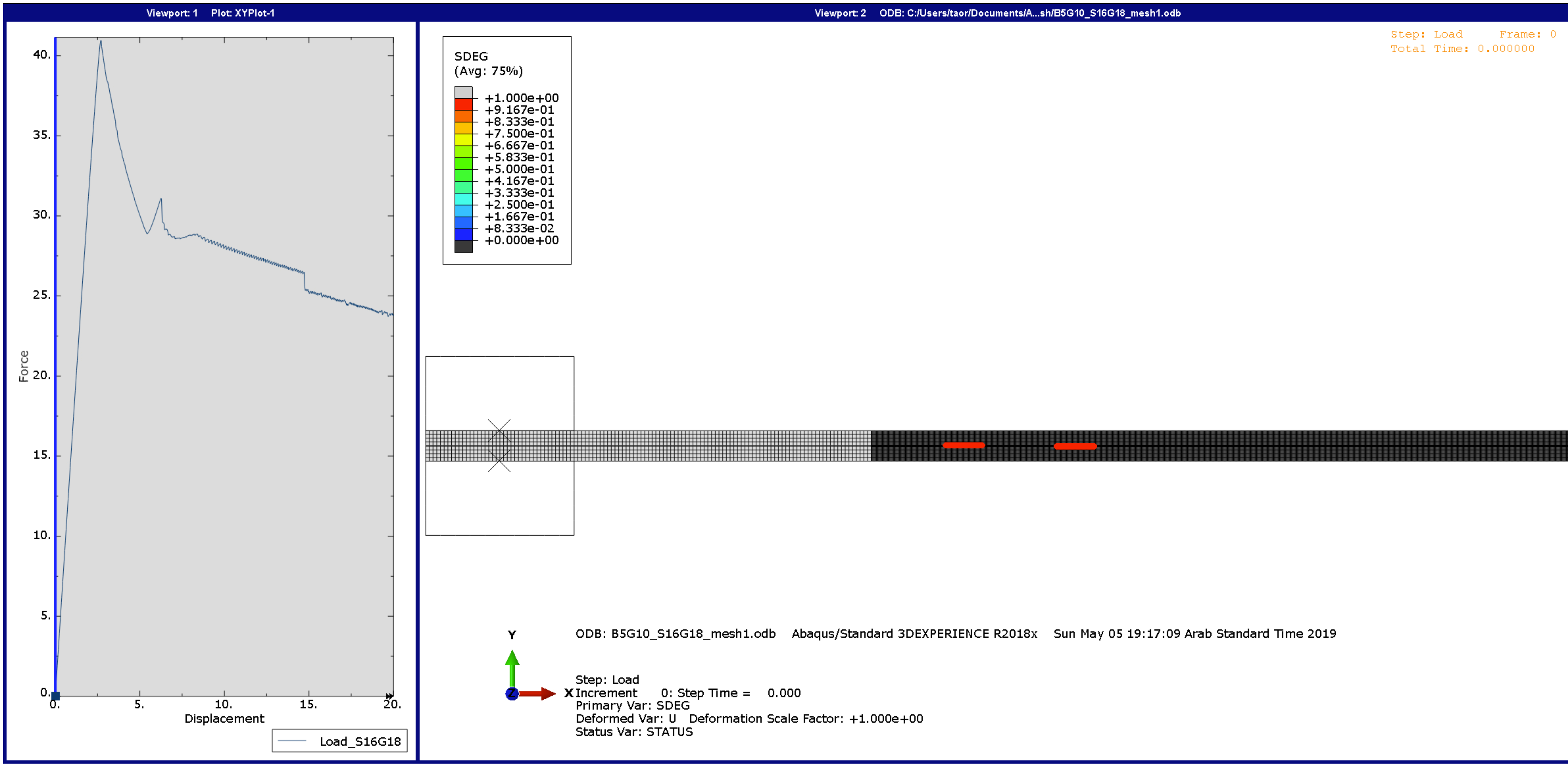


Typical responses

Depending on interface and ligament properties…

Mechanics of Composites for Energy and Mobility

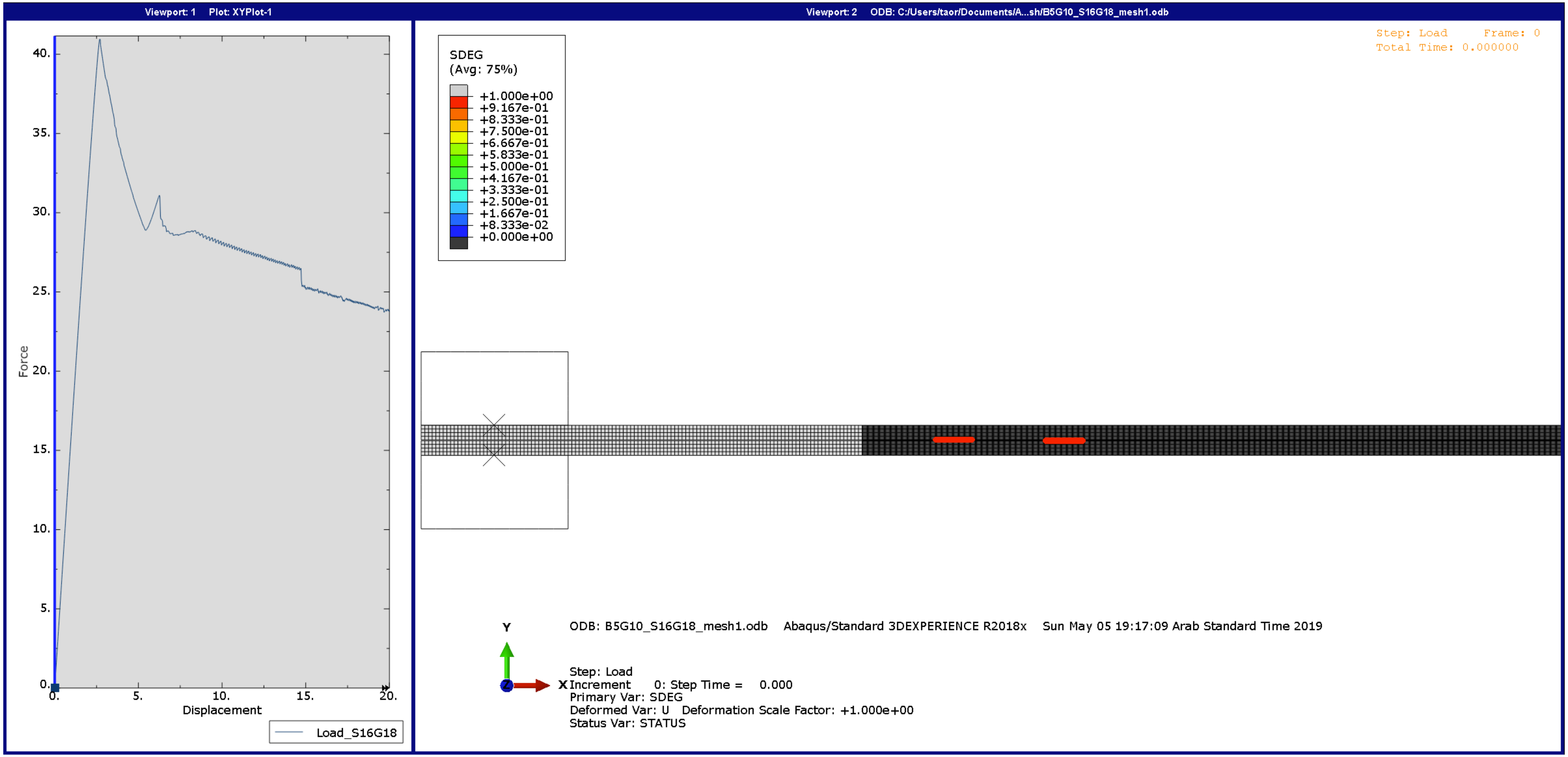
Case 2a: transition of delaminated interfaces but non-broken ligament



Typical responses

Depending on interface and ligament properties…

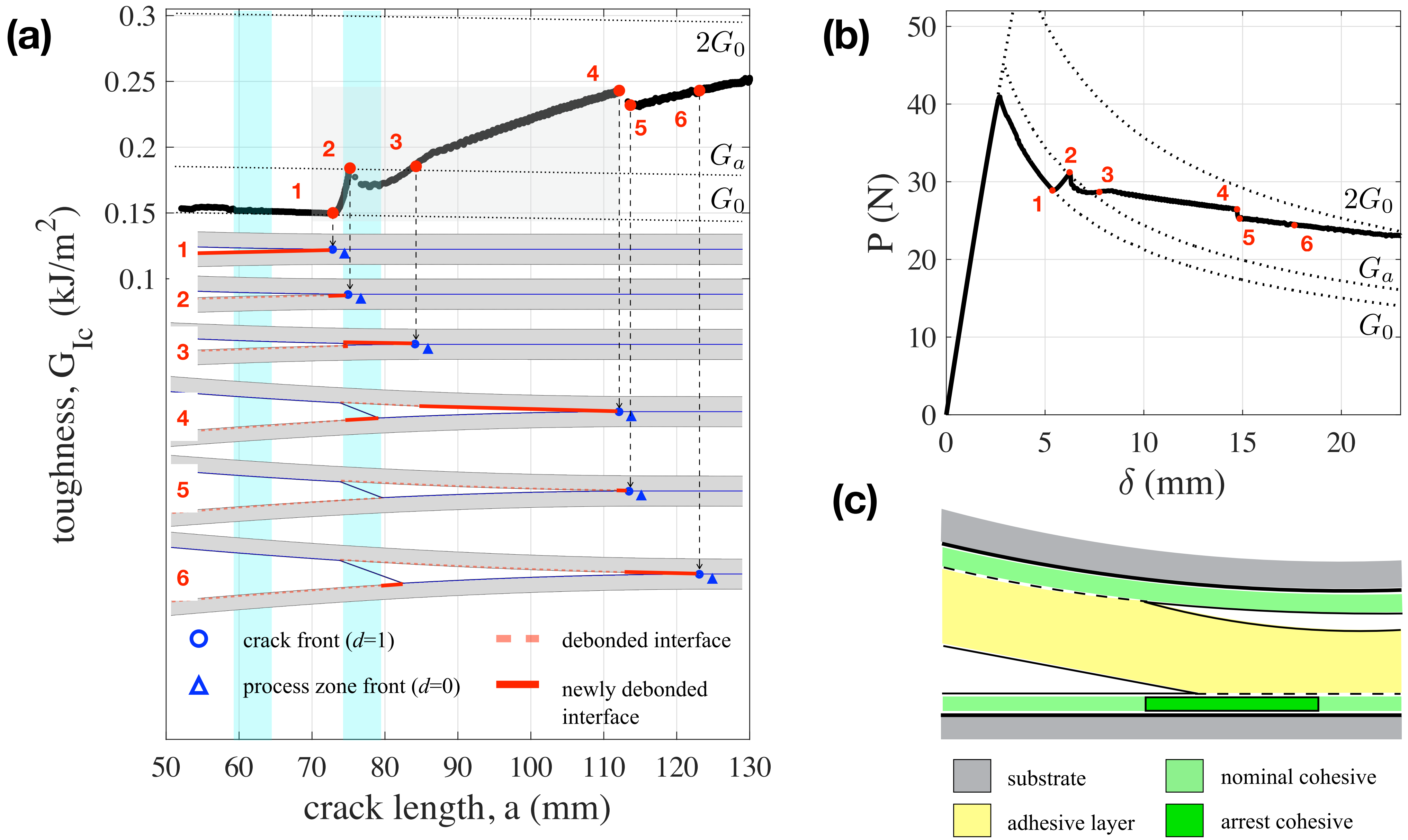
Case 2a: transition of delaminated interfaces but non-broken ligament



Typical responses

Depending on interface and ligament properties…

Case 2a: transition of delaminated interfaces but non-broken ligament

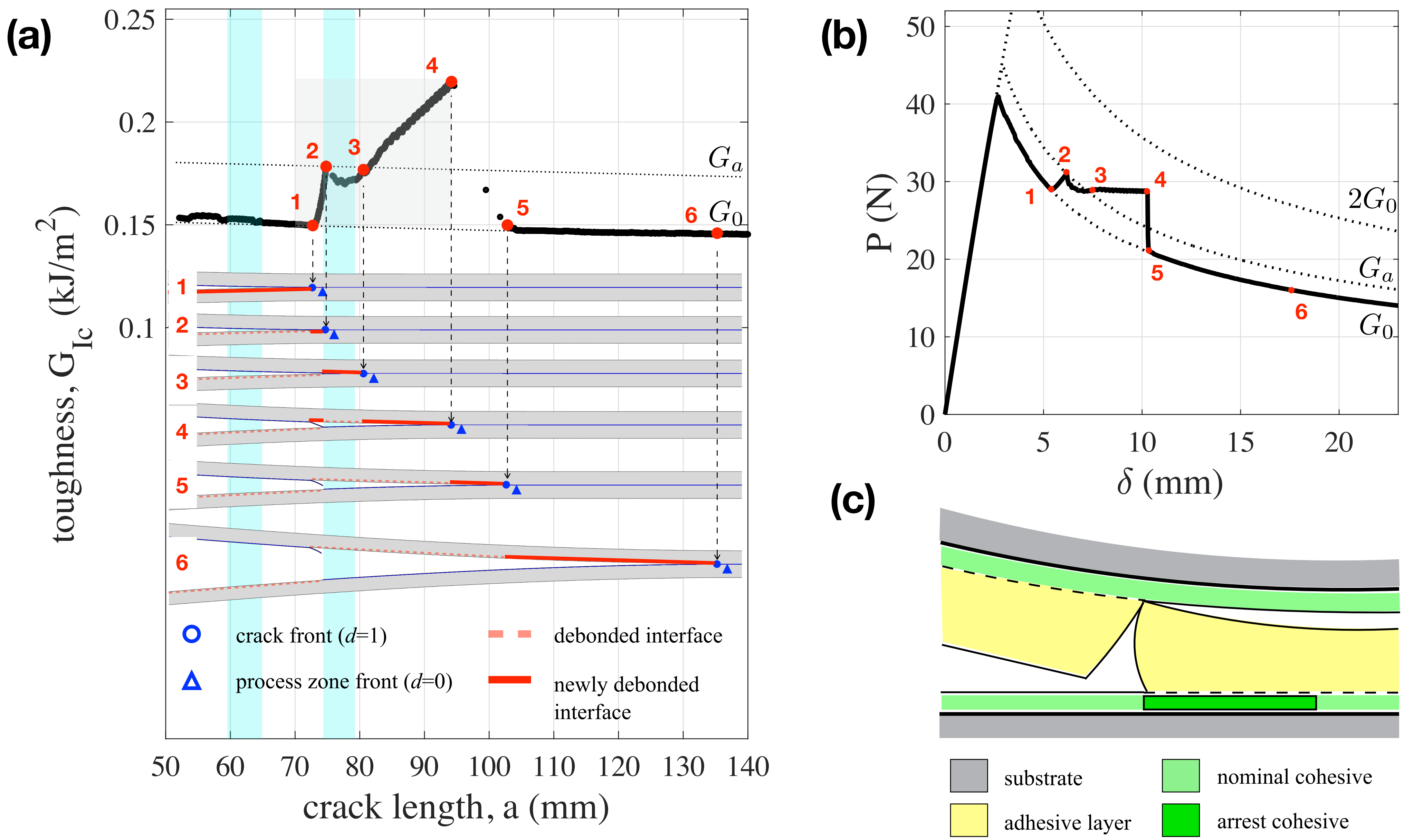


- adhesive ligament detached from the arrest interface
- ligament was not break during the whole process
- after point 5, both **two interfaces detached, and thus dissipated energy approached $2G_0$**

Typical responses

Depending on interface and ligament properties…

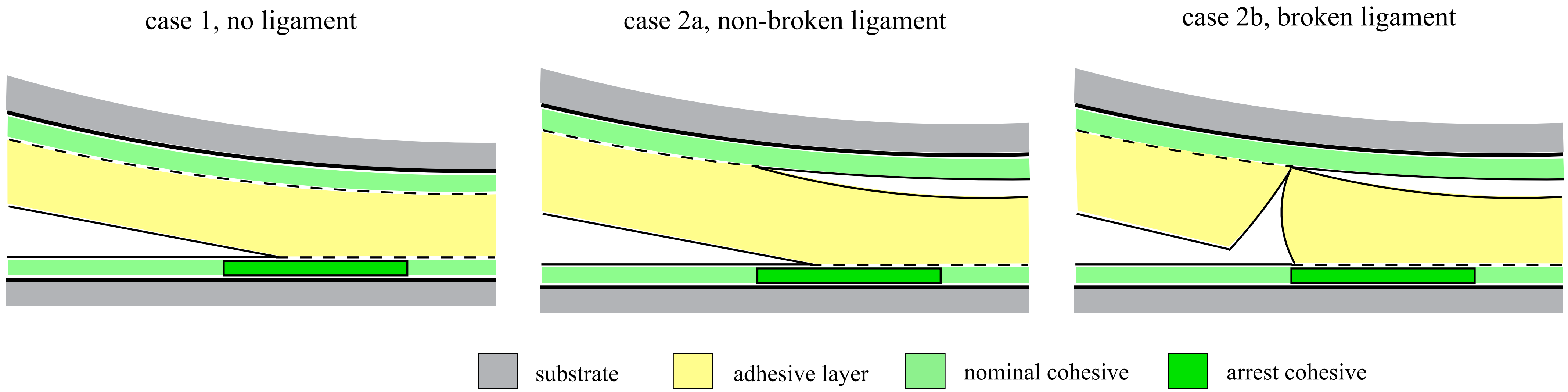
Case 2a: transition of delaminated interfaces and breakage of ligament

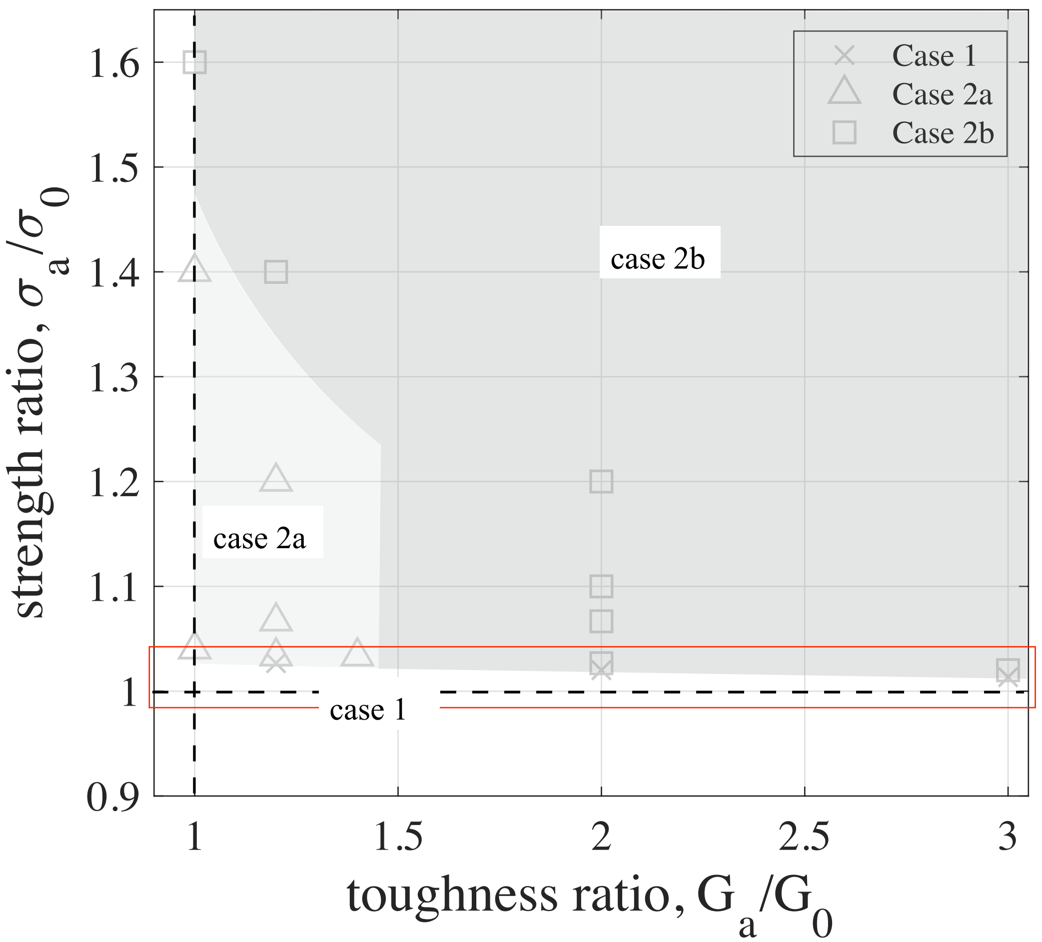


- adhesive ligament propagated back along the top interface before point 4
- after point 5, **ligament broke and the delamination occurred on the top interface**

Scenario depends on properties contrast

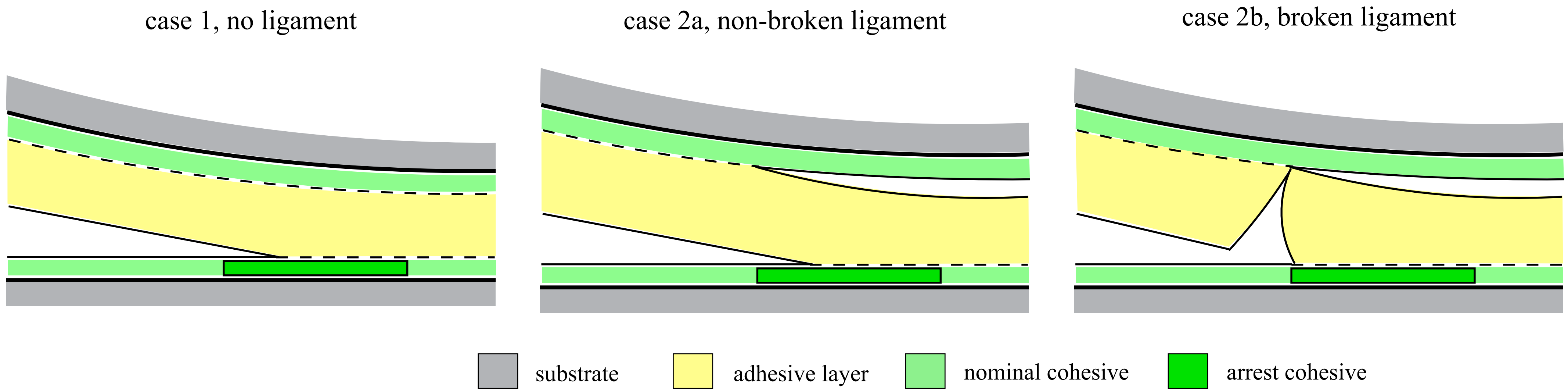
Strength contrast play a major role

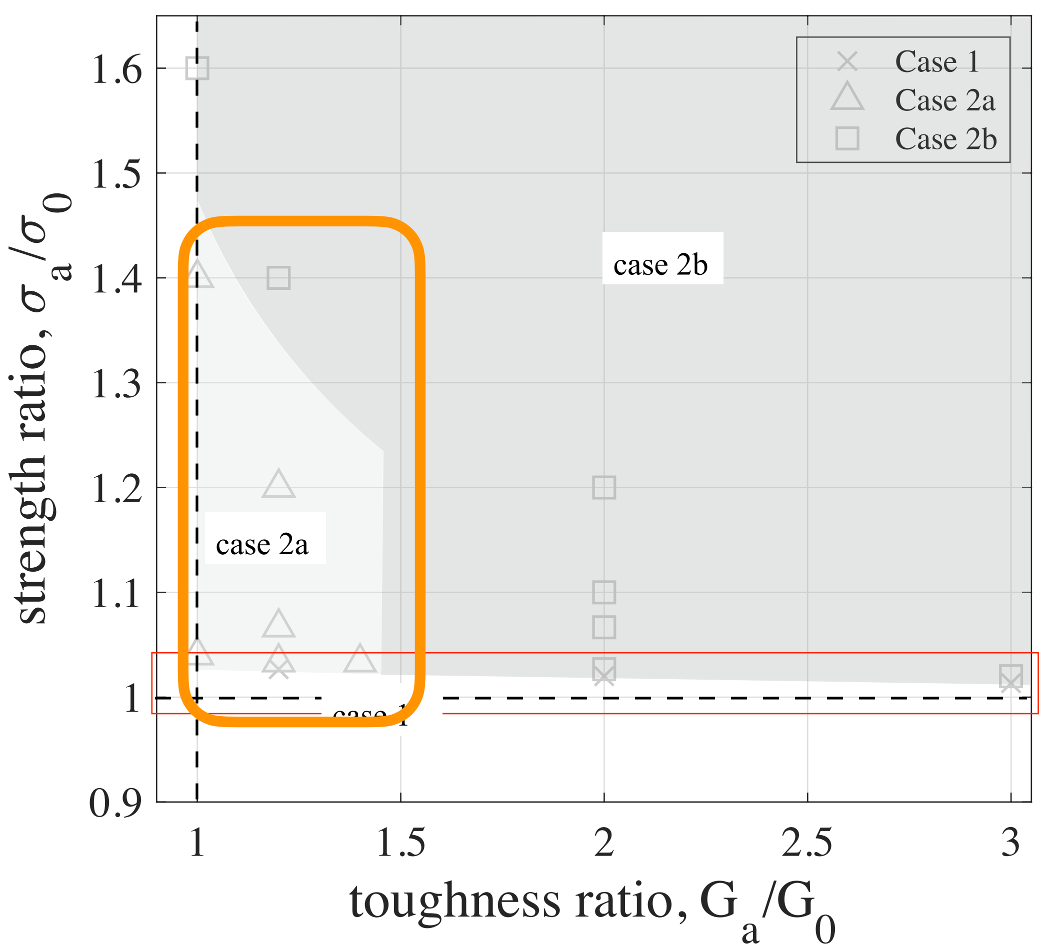




Scenario depends on properties contrast

Strength contrast play a major role





- smaller toughness ratio ($G_a/G_0<1.4$) and small strength ratio ($\sigma_a/\sigma_0<1.5$) led to non-broken ligament

- careful design of interface contrast properties can lead to drastically improved performance

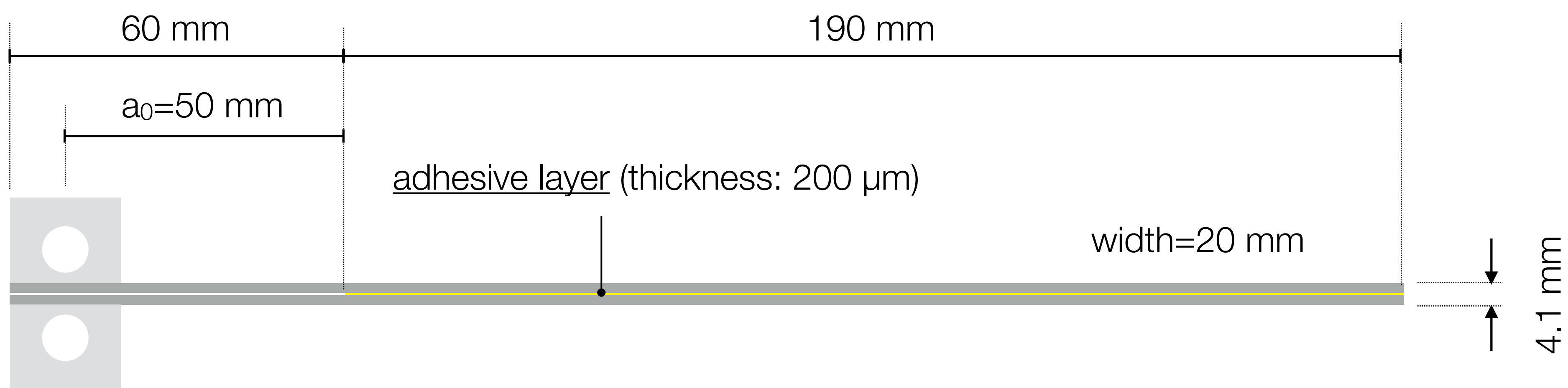
Controlling fiber bridging by selective patterning

1. Numerical study
2. **Experimental verification**
3. Role of Randomness

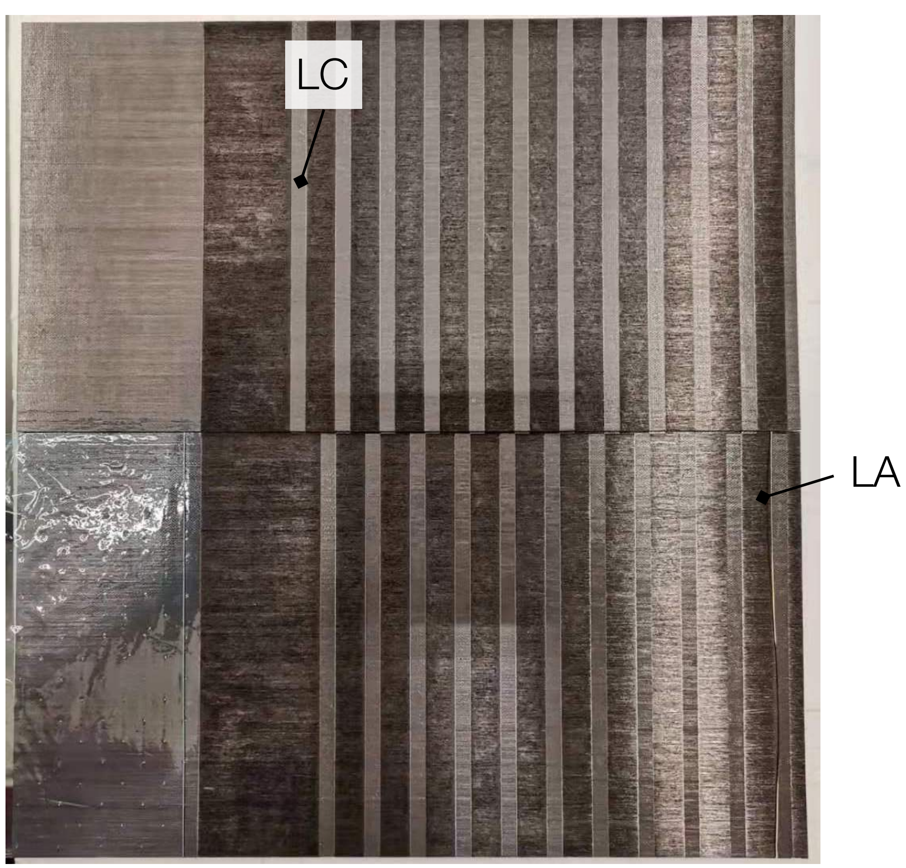
Experimental investigations - Multiple ligaments

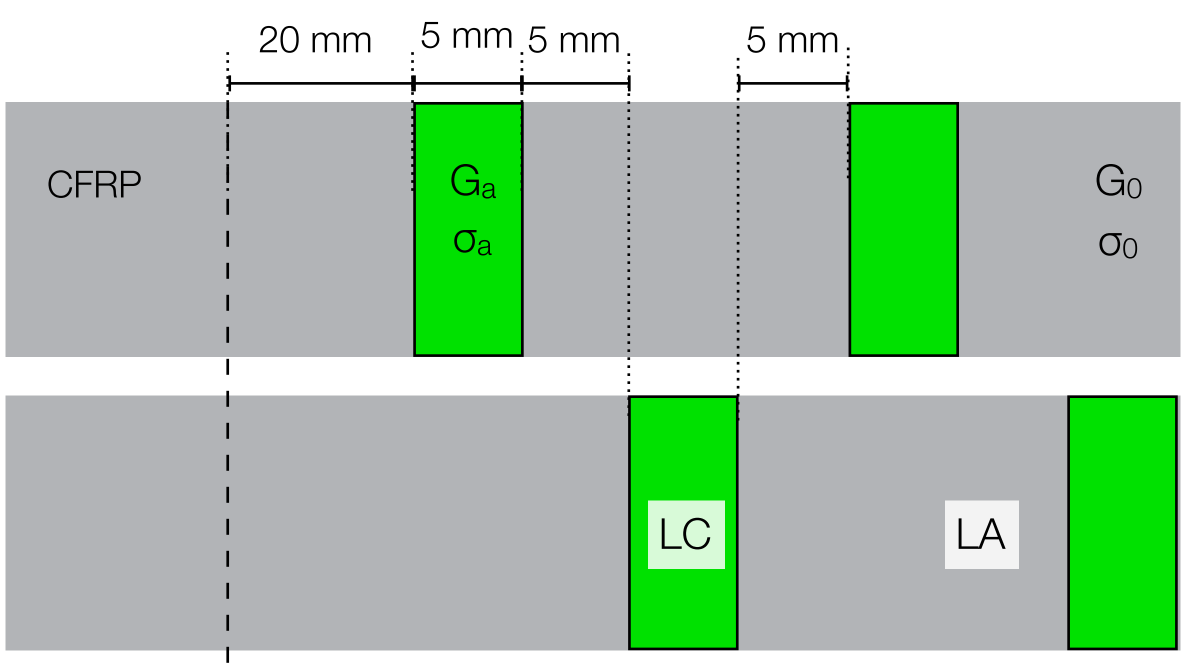
Plate preparation

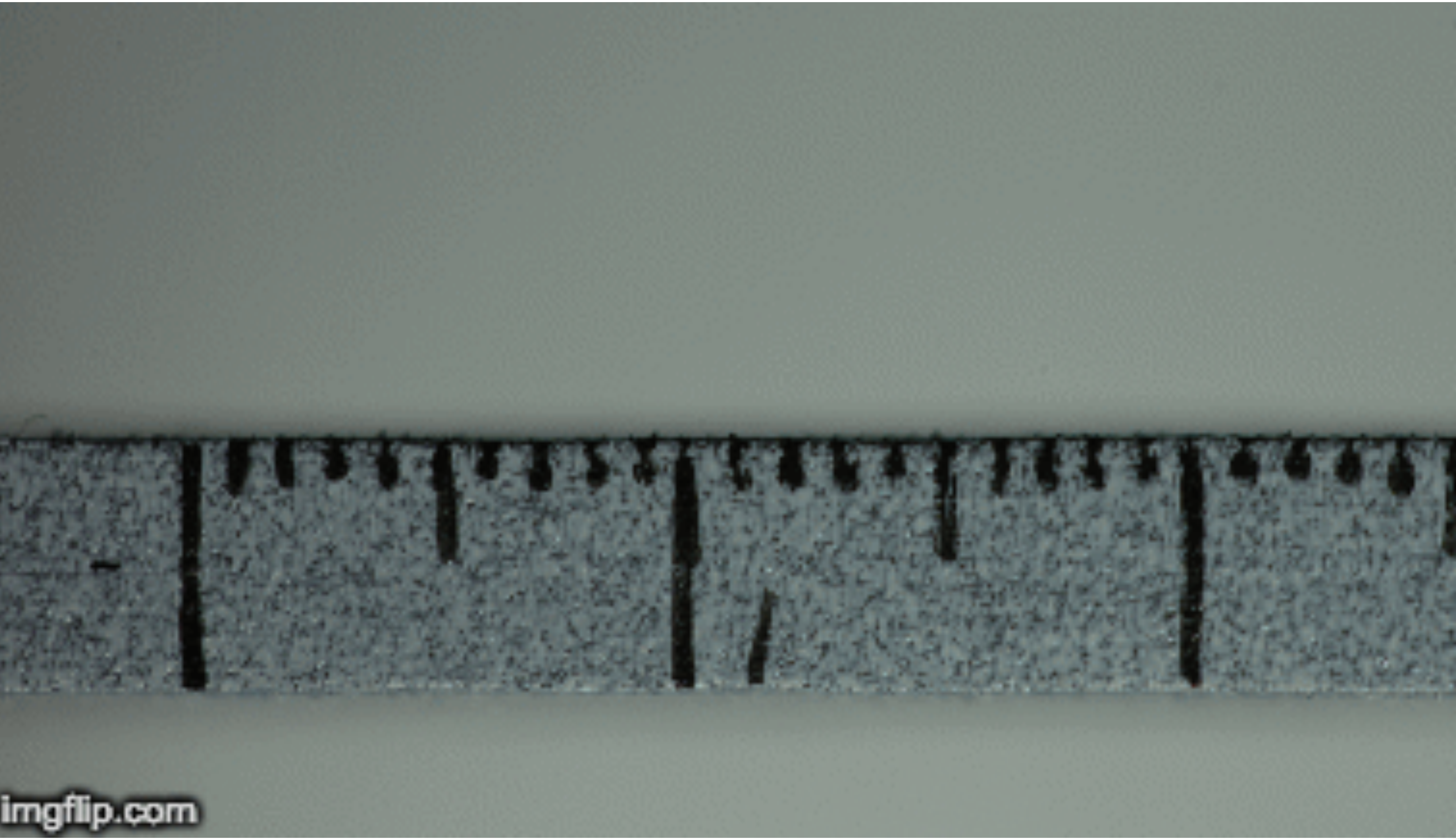
- UD $[0]_8$ CFRP, nominal thickness t=2 mm
- uniform surface treatment: T&LC/LA patterning



B5G5



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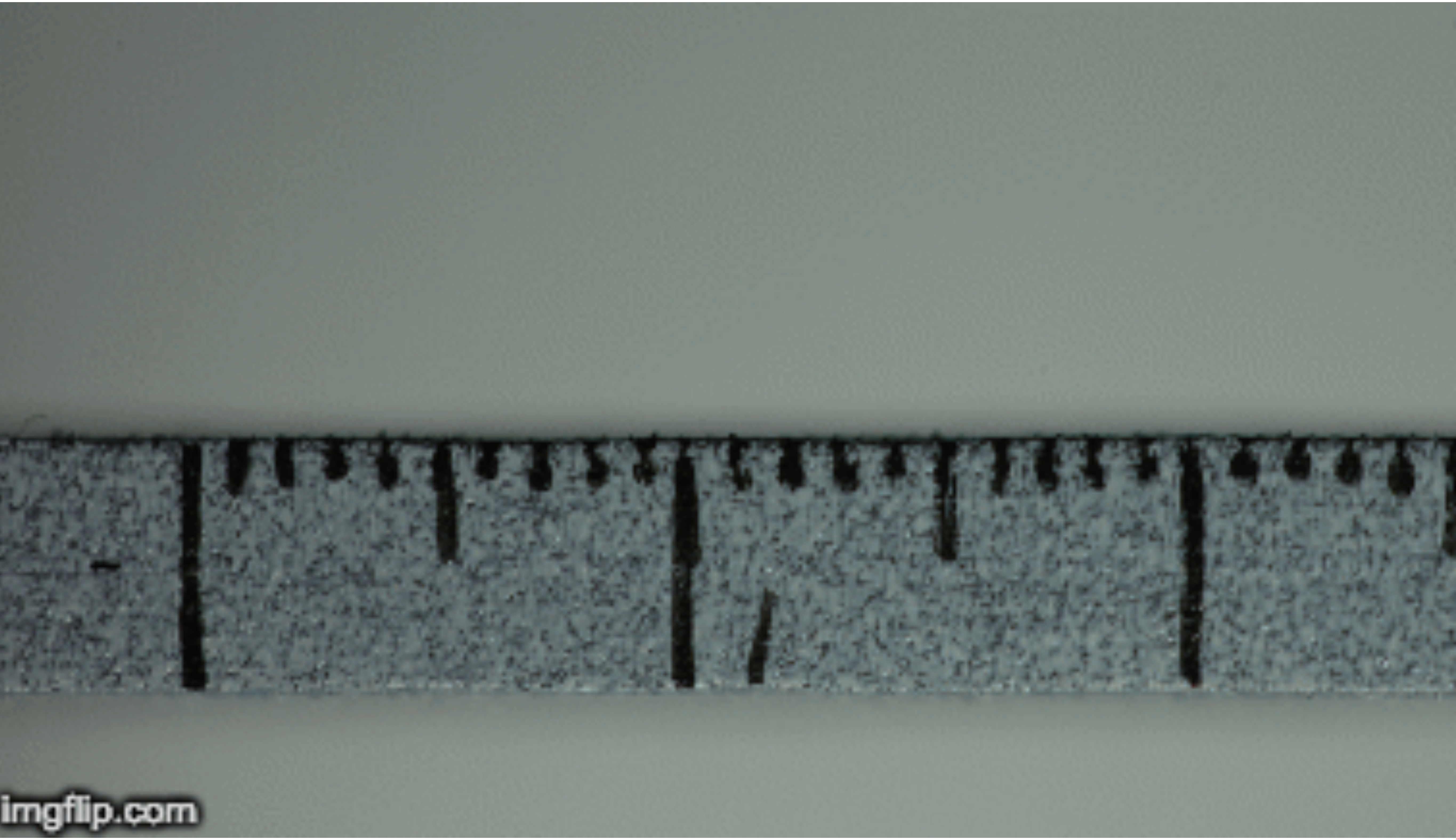
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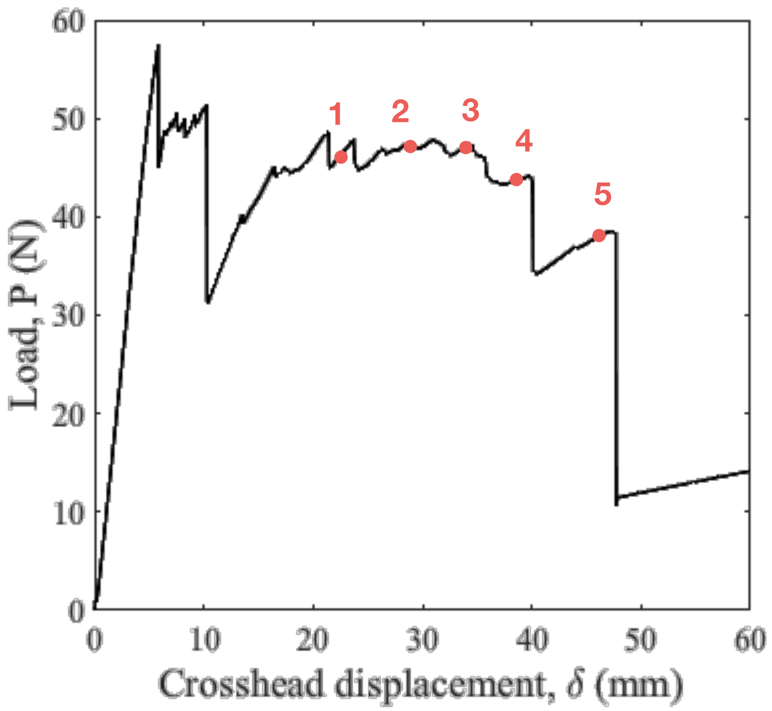
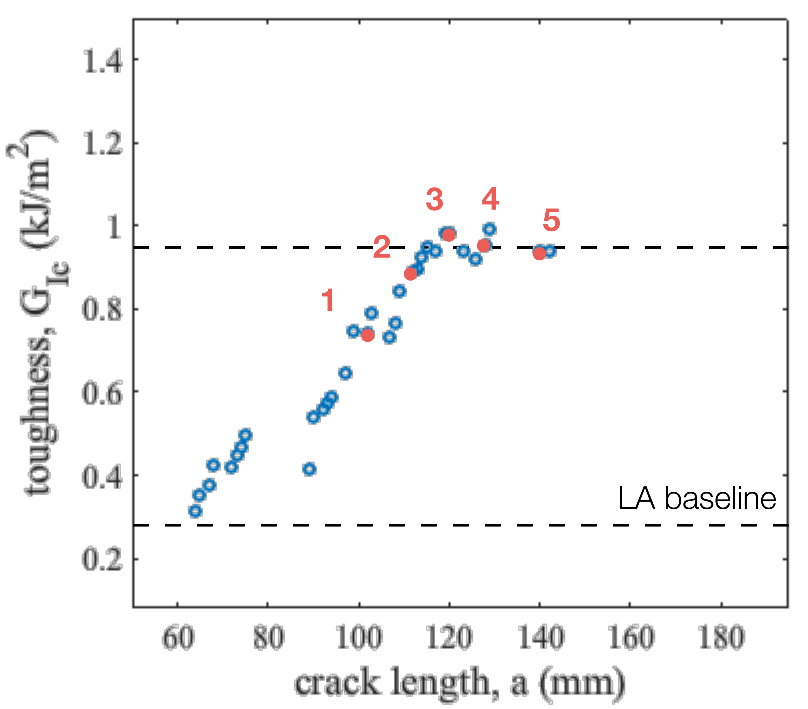
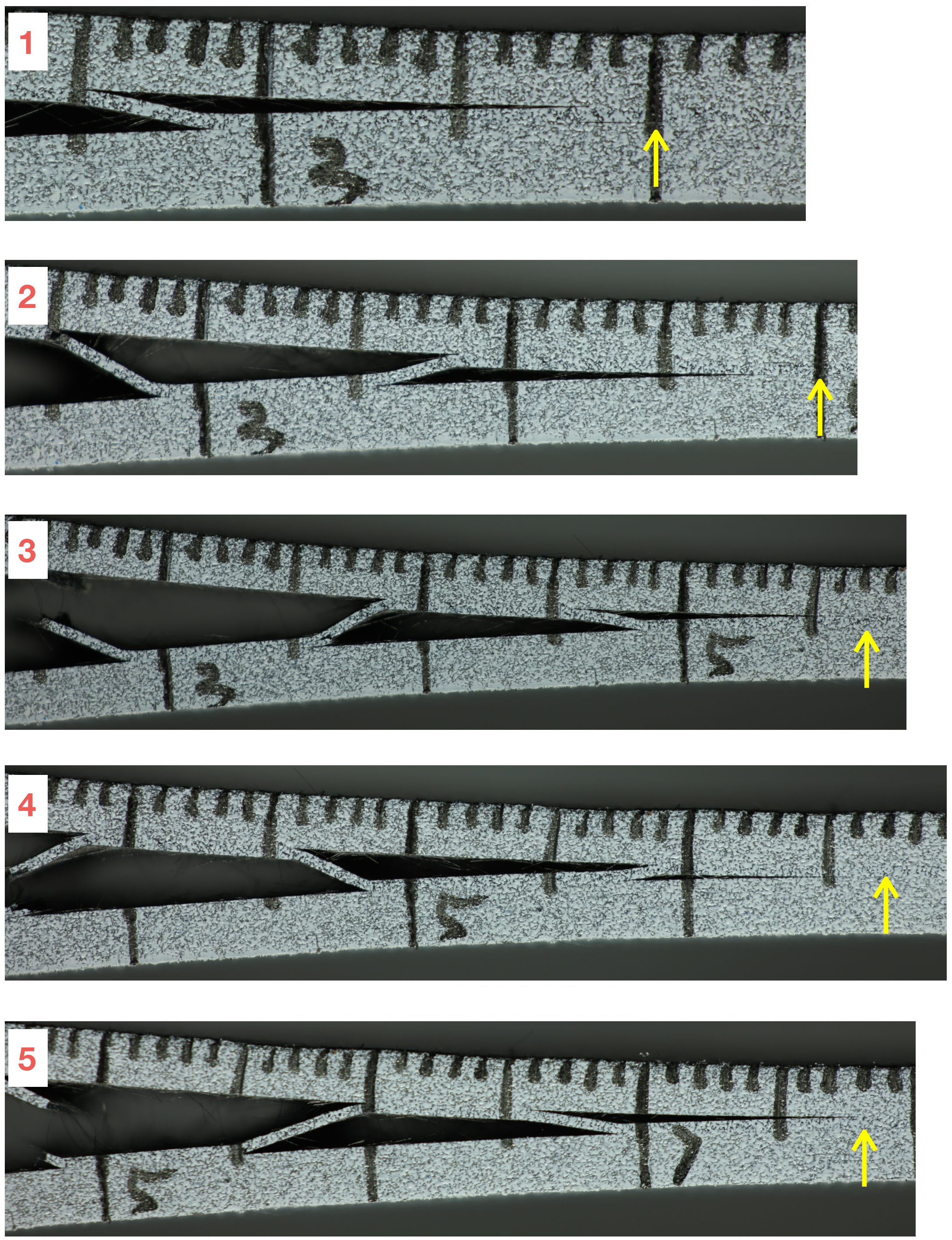
Experimental investigations - Multiple ligaments

DCB results

- DCB tests with the surface patterning clearly showed the triggering of adhesive ligaments
- The enhancement was **more than three times** when adhesive ligament was triggered

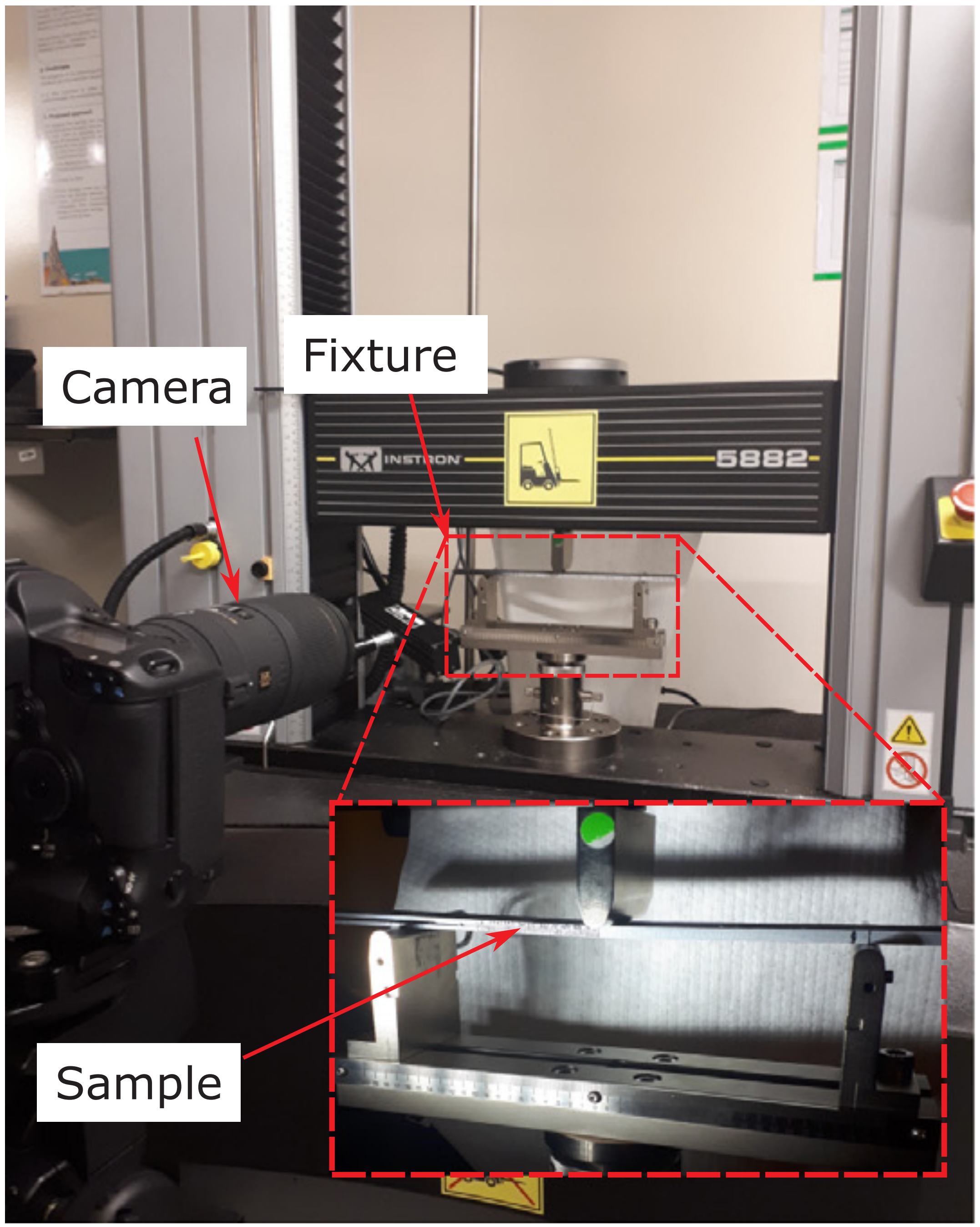


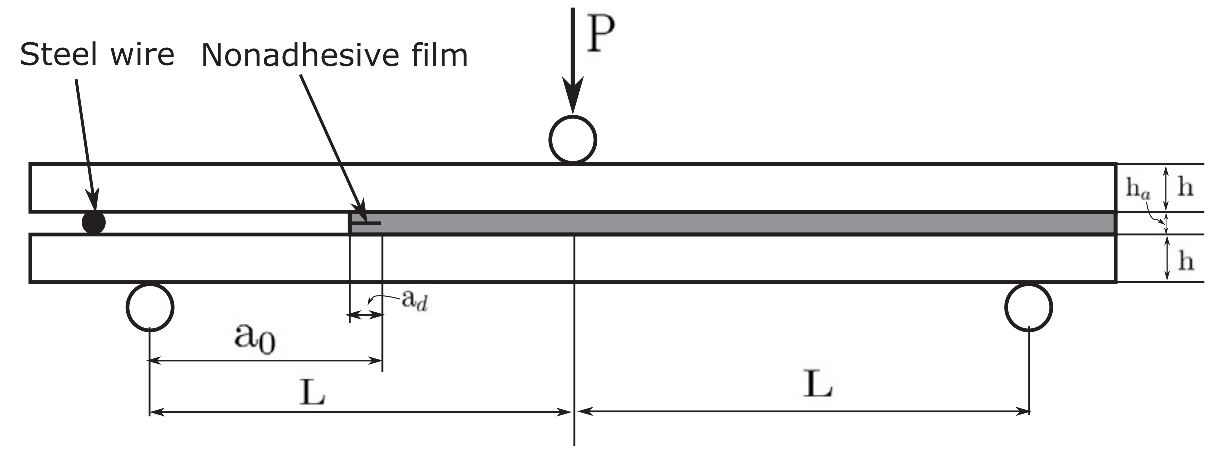


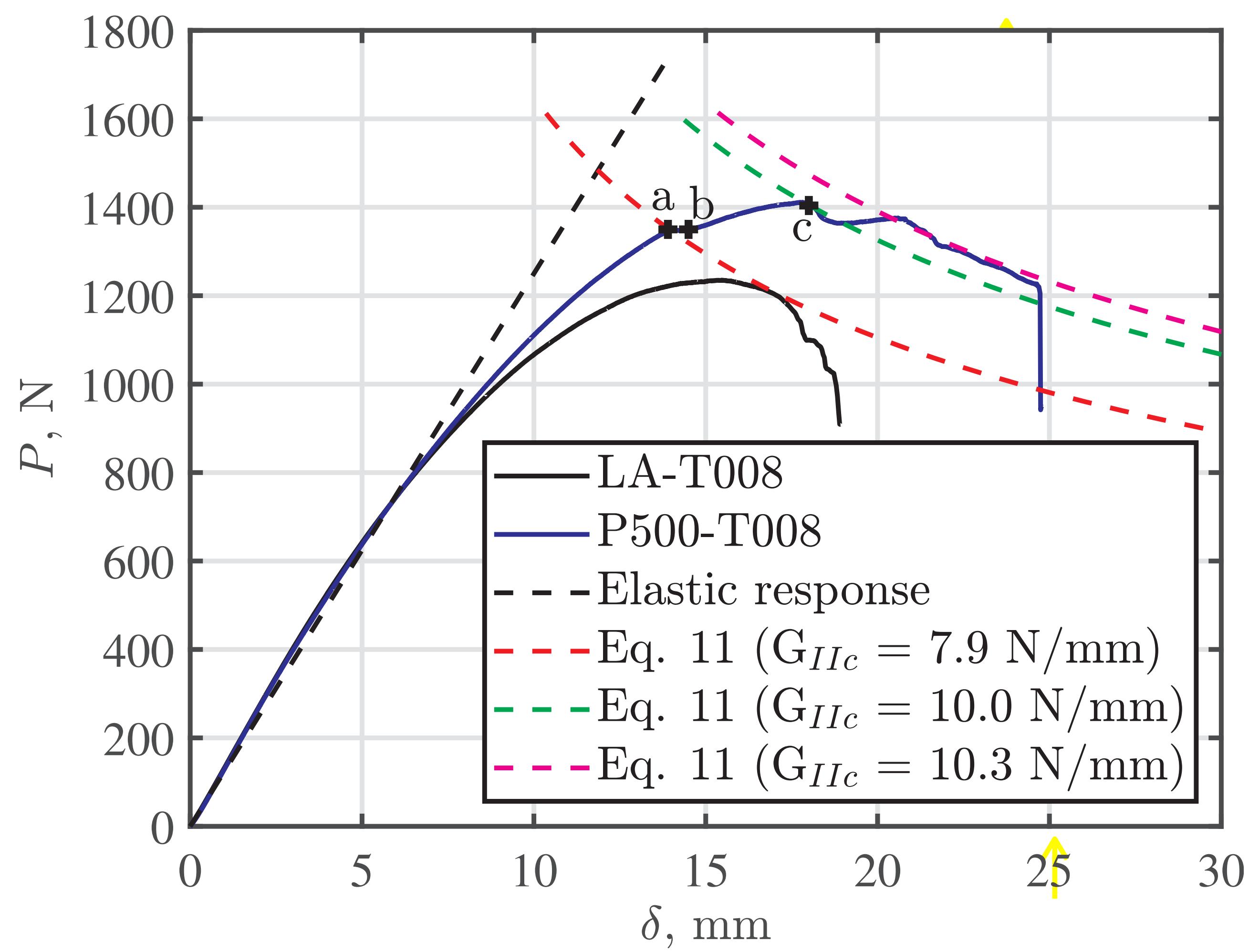


Experimental investigations

Mode II Results








Mechanics of Composites for Energy and Mobility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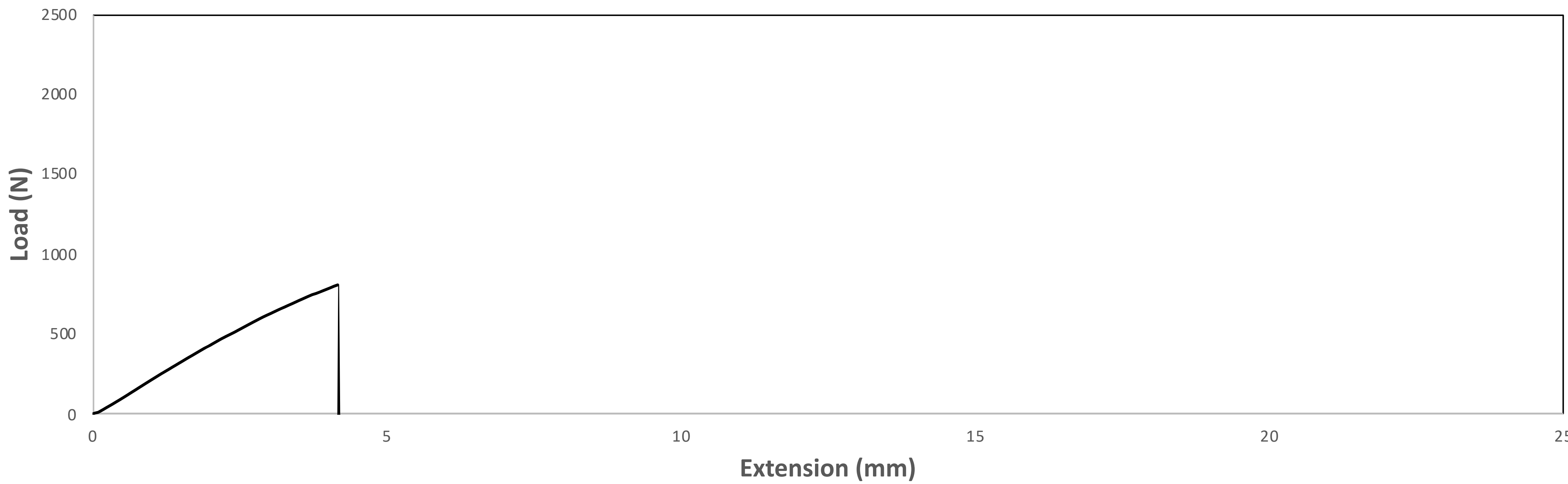
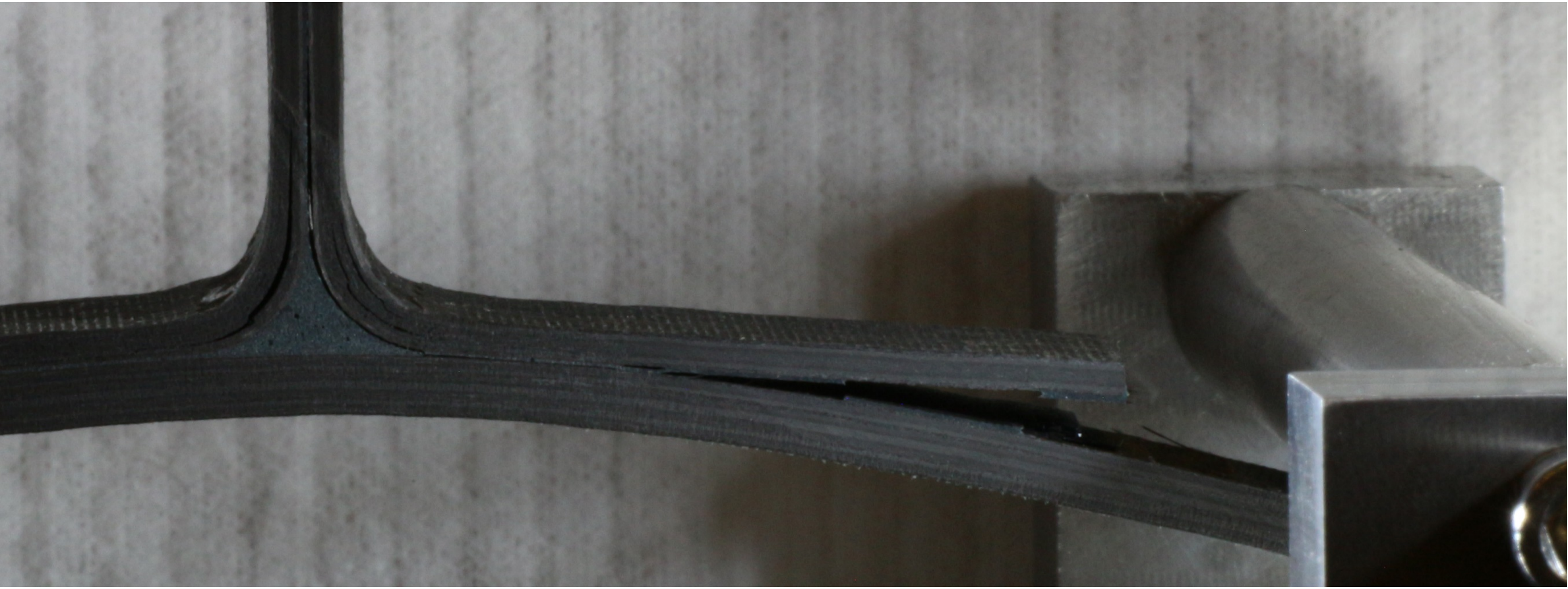
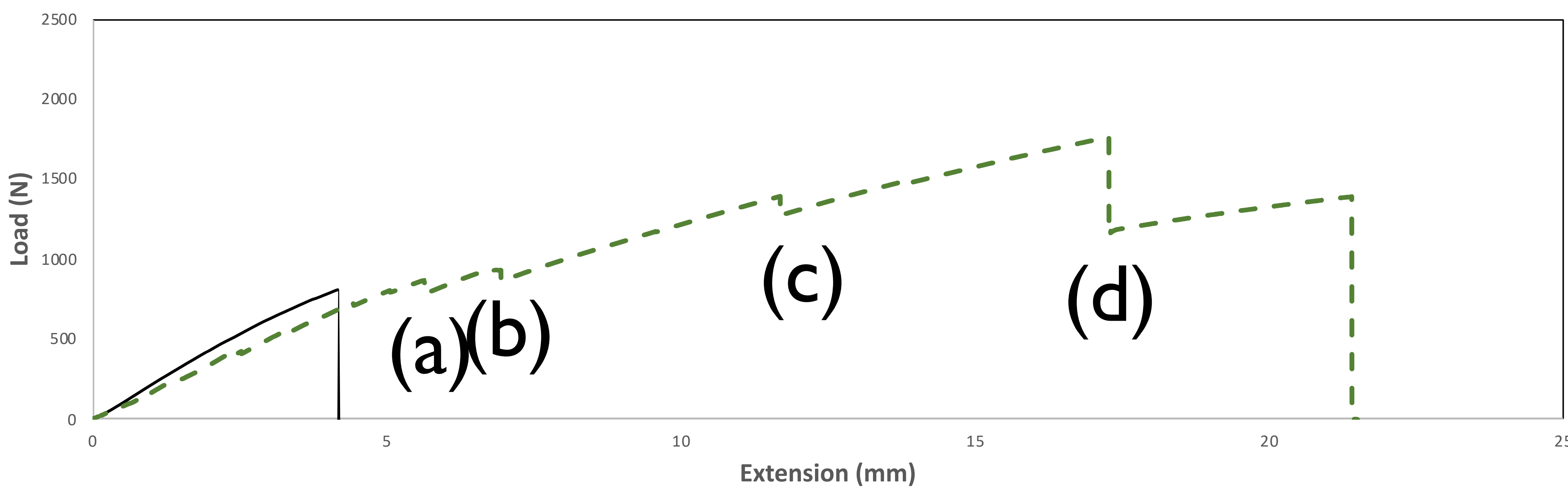
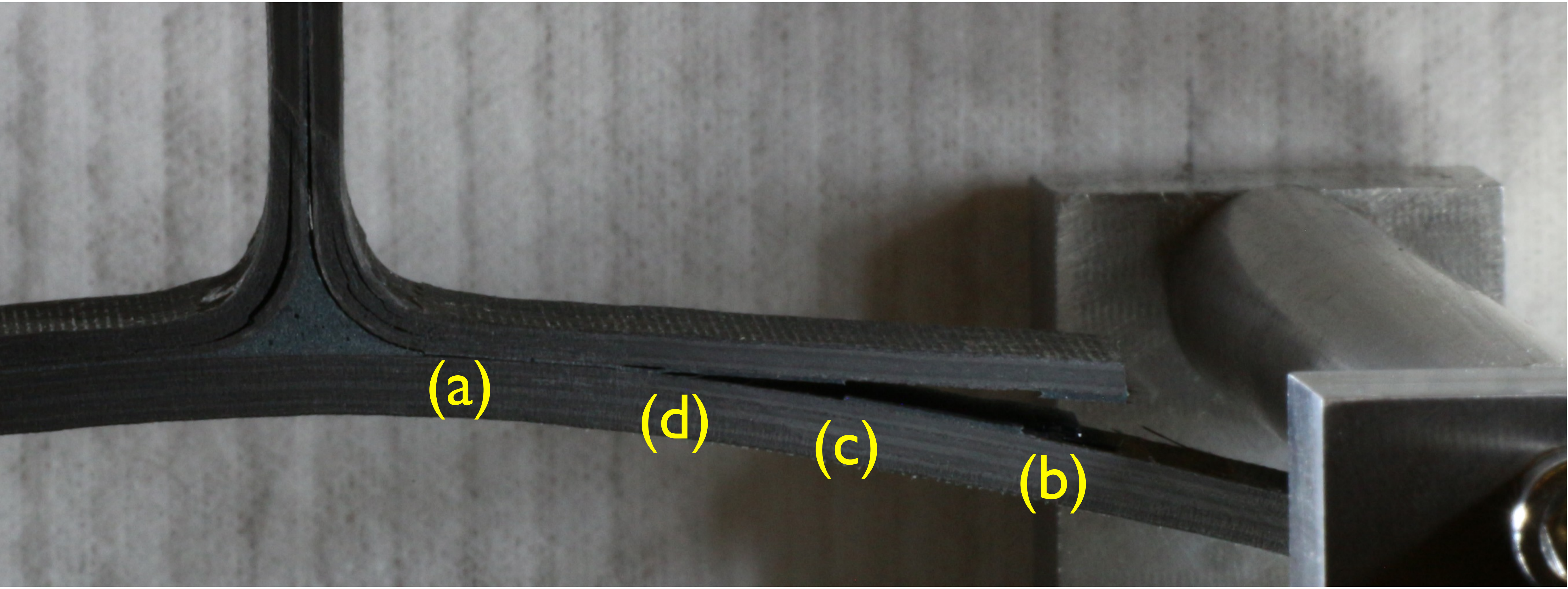
Experimental investigations - T-joints





Experimental investigations - T-joints





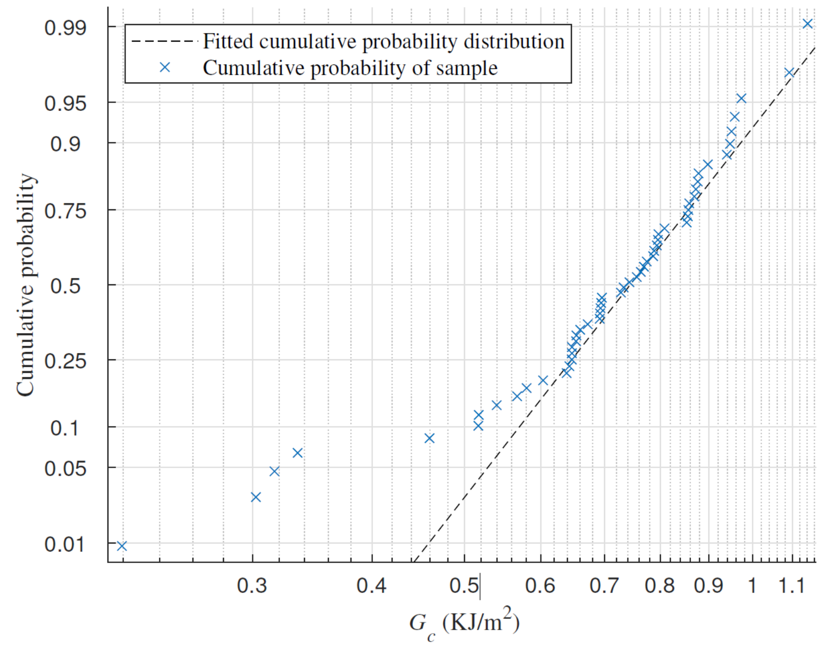
Mechanics of Composites for Energy and Mobility

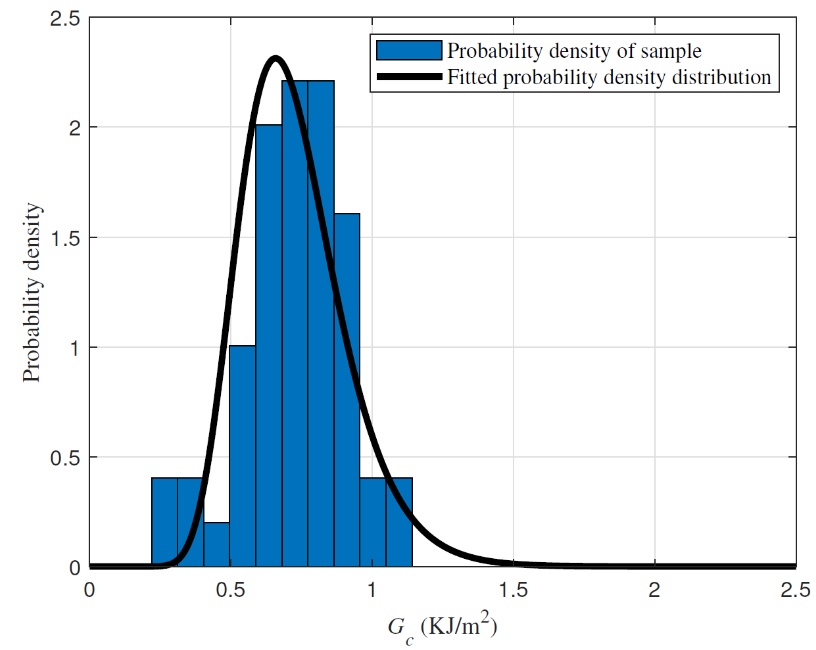
Controlling fiber bridging by selective patterning

1. Numerical study
2. Experimental verification
3. **Role of Randomness**

Role of Randomness- modeling strategy

Stochastic interface model

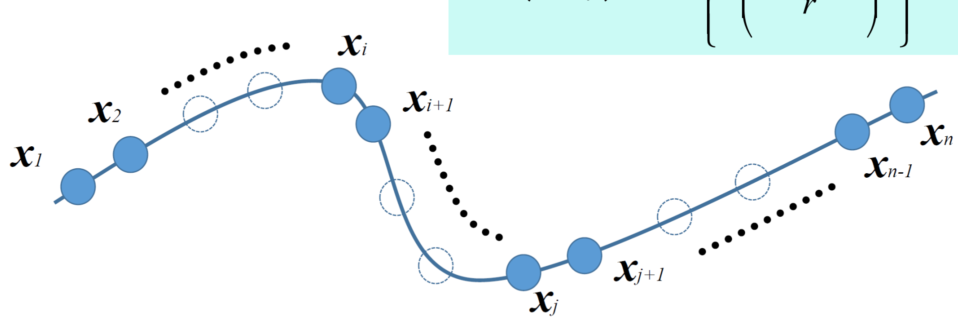


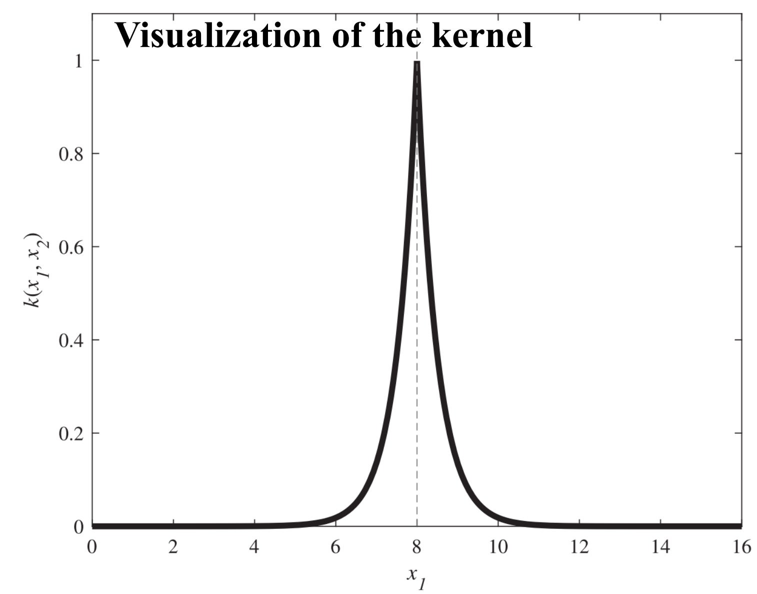


- Maximum Likelihood Estimation proves the applicability of a lognormal distribution of interface properties.

Kernel function

$$k\left(\mathbf{x}_i, \mathbf{x}_j\right) = \exp\left\{-\left(\frac{\left|\mathbf{x}_i - \mathbf{x}_j\right|}{r}\right)^{\alpha}\right\}$$

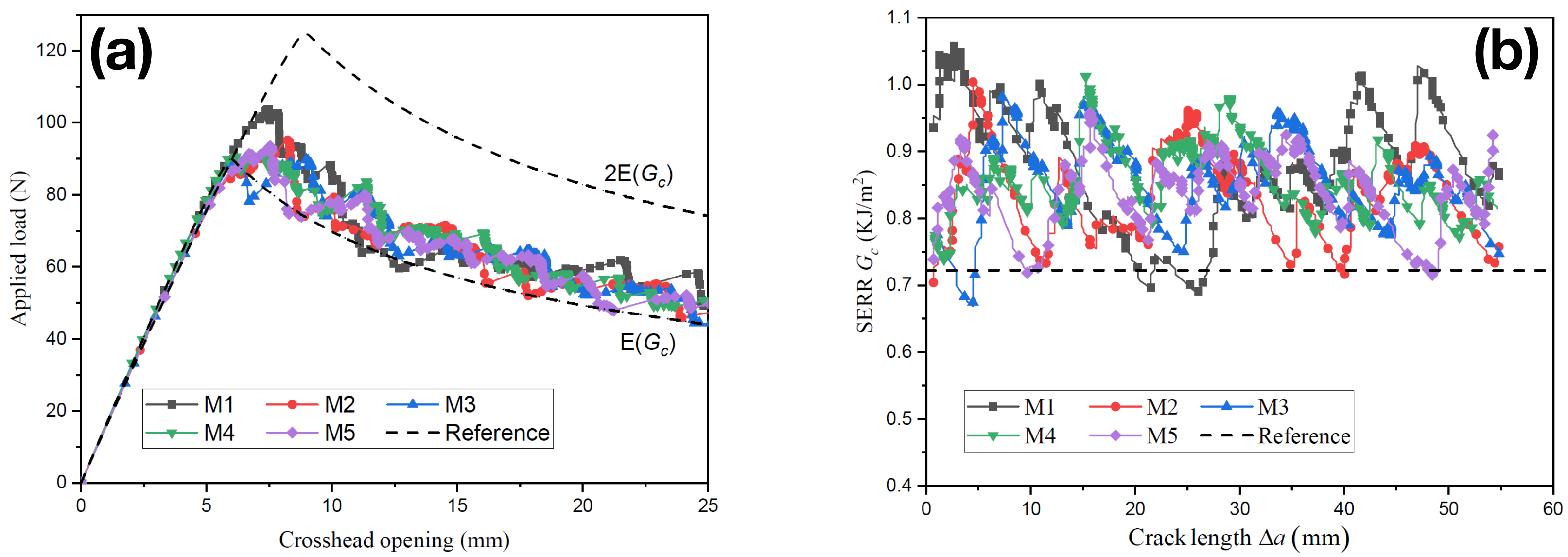




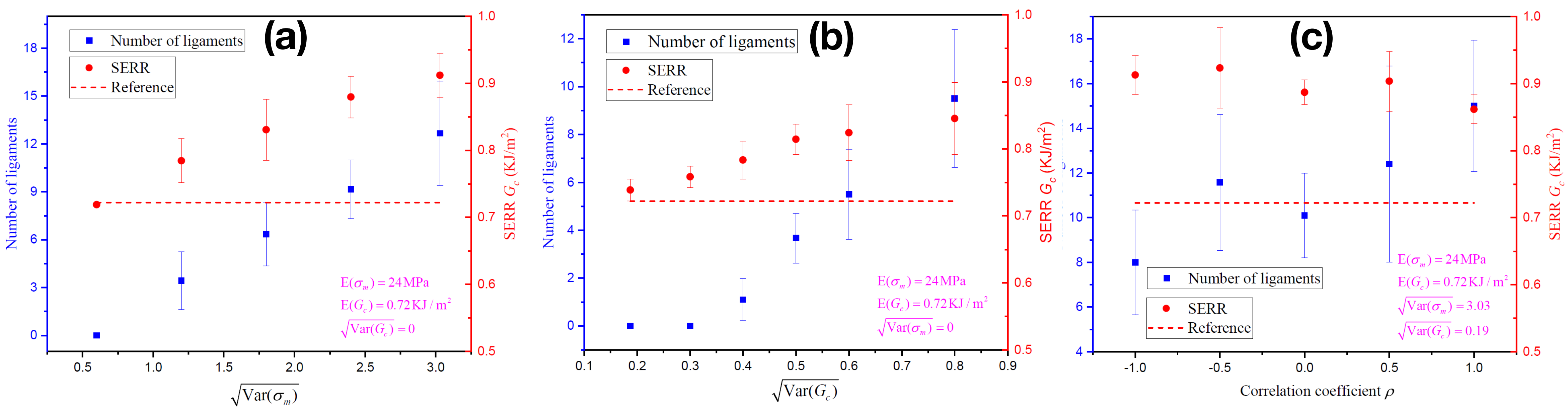
- Gaussian process is suitable for describing the spatial correlation of the Napierian logarithm of interface properties of the local adhesion.

Role of Randomness- Results

Effect of stochastic properties



- The spatially distributed stochastic properties significantly influence the debonding behaviors of joints **by** triggering the mechanisms of crack-tip transfer and ligament bridging.

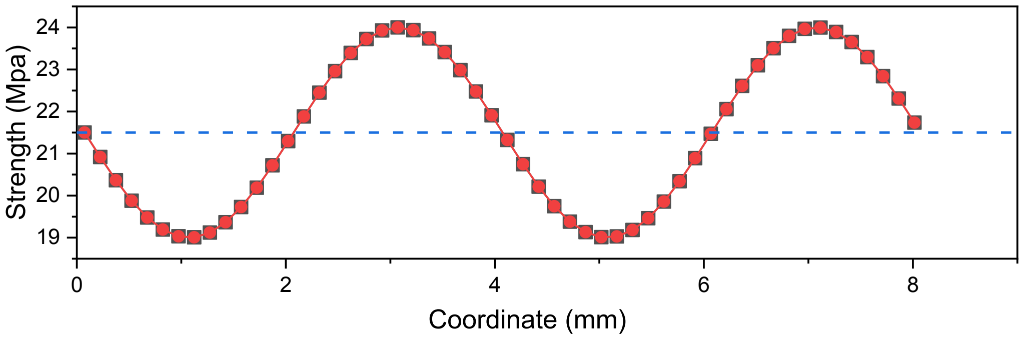


- Greater standard deviations of the critical traction σm and toughness Gc tend to build up more ligaments, which provide more extrinsic dissipation and significantly influence the effective toughness of joints,

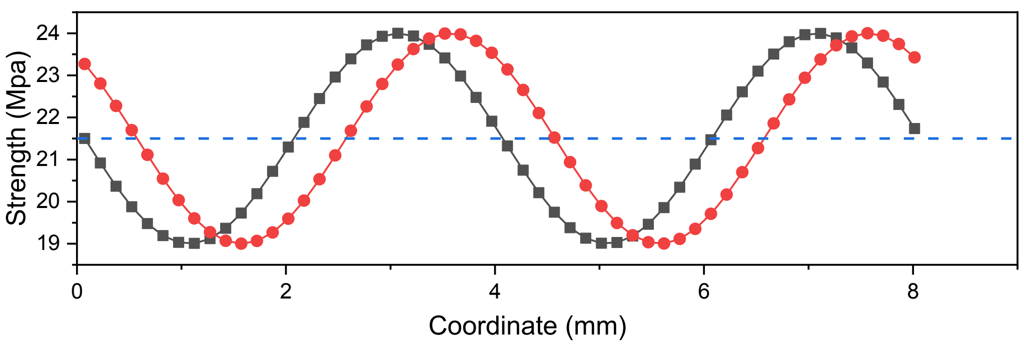
Role of Correlation- Results

Effect of correlation between top and bottom interfaces

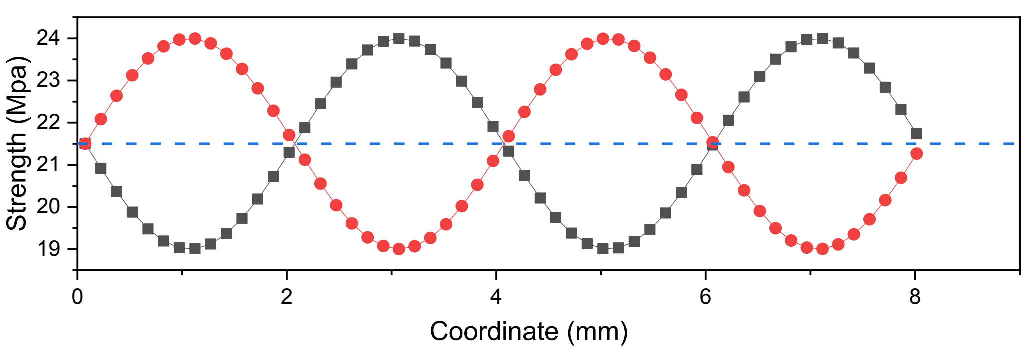
Mechanics of Composites for Energy and Mobility



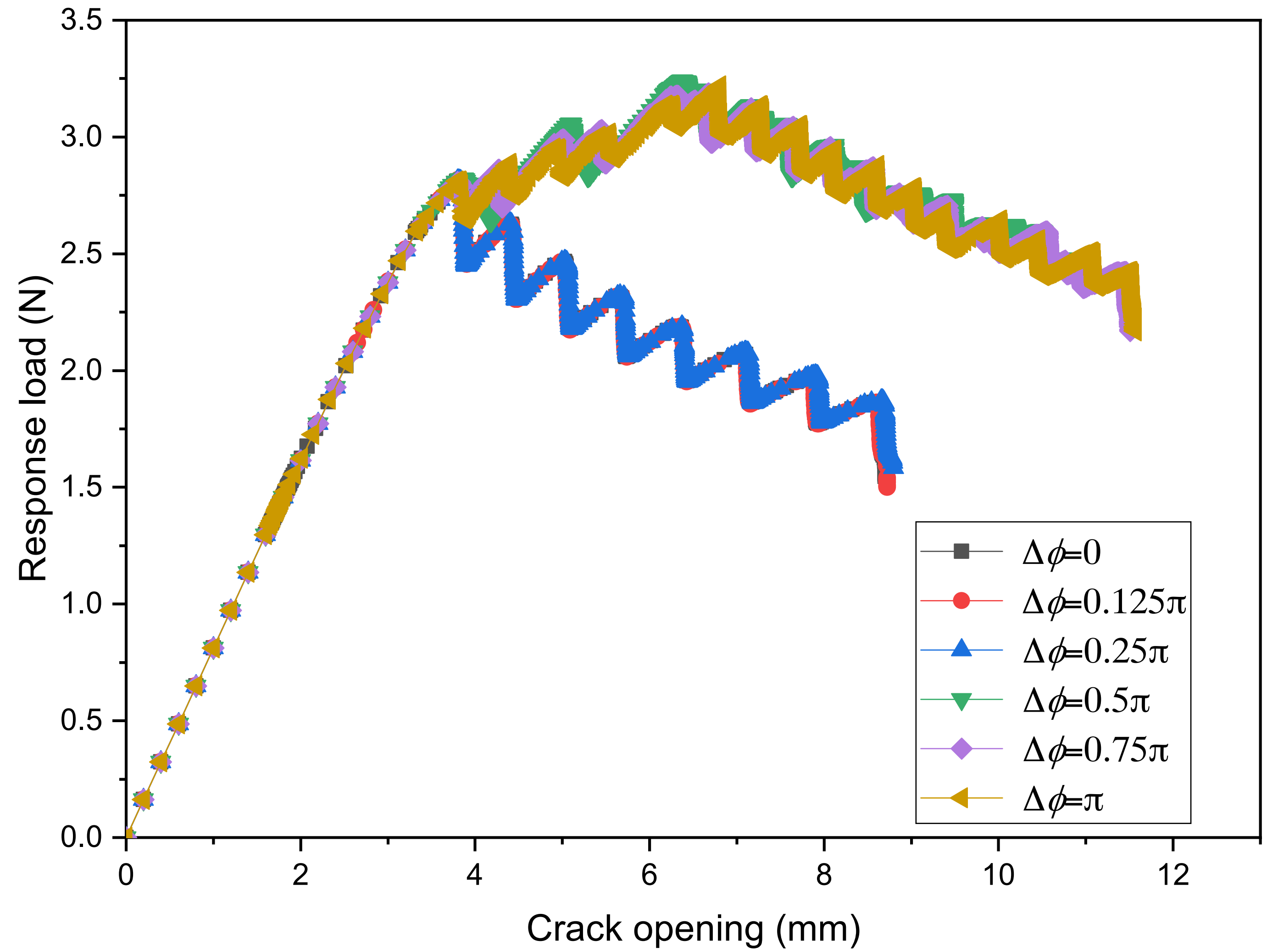
(a) Δϕ=0



(c) Δϕ=0.25π



(f) Δϕ=π



(a) P-δ curves

- **Phase contrast required between top and bottom substrates.**
- **Very flexible constraints for processing**

Conclusion

Conclusions and Future?

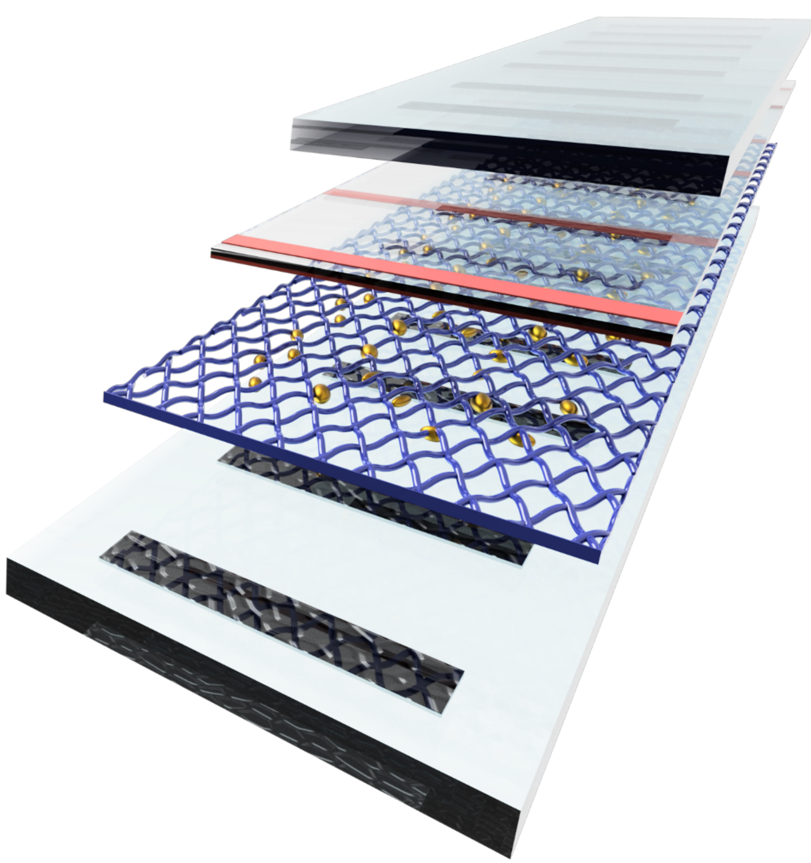
Mechanics of Composites for Energy and Mobility

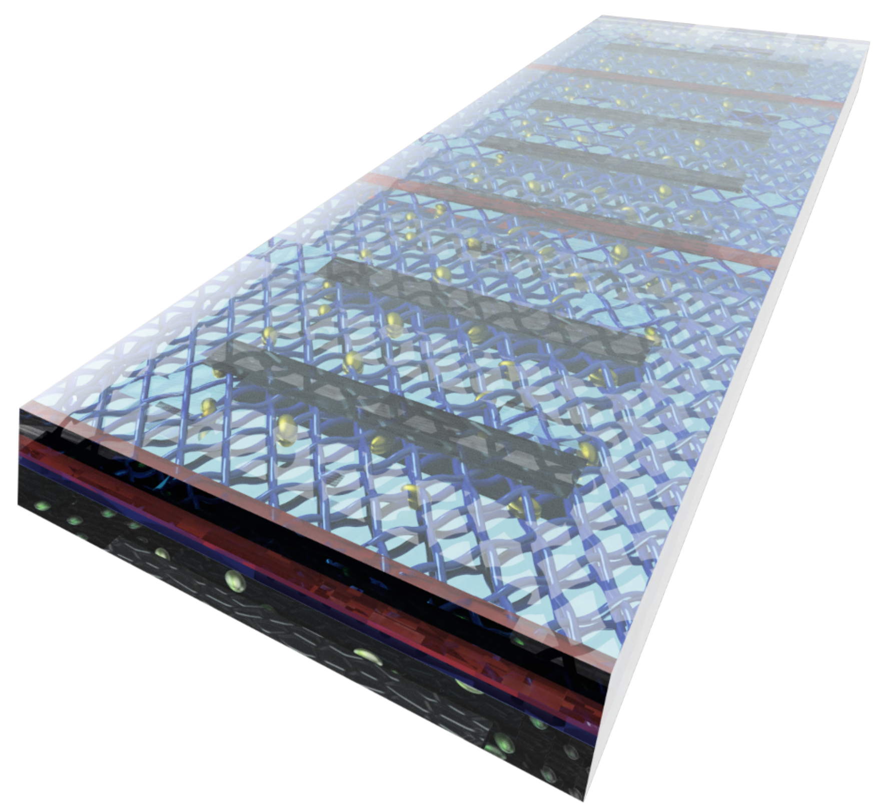
Various approaches for manipulating the failure of secondary bonding have been presented:

(1) Introduction of heterogeneity on the adhesive/substrate interface
(2a) Introduction of additive heterogeneities in the interfaces
(2b) Introduction of sacrificial cracks in the interface

All of these are compatible with a "All-in-adhesive" concept

Towards integration in a highly-engineered adhesive system





Related publications

C. Morano, R. Tao, M. Alfano, and G. Lubineau (2021). **Effect of Mechanical Pretreatments on Damage Mechanisms and Fracture Toughness in CFRP/Epoxy Joints**. *Materials*, 14(6), 1512.

R. Tao, X. Li, A. Yudhanto, M. Alfano and G. Lubineau (2020). **Laser-based interfacial patterns enable toughening of CFRP/epoxy joints through bridging of adhesive ligaments.** *Composites Part A: Applied Science and Manufacturing*, 139, 106094*.*

R. Tao, X. Li, A. Yudhanto, M. Alfano and G. Lubineau (2020). **On controlling interfacial heterogeneity to trigger bridging in secondary bonded composites: an efficient strategy to introduce crack-arrest features.** *Composites Science and Technology,* 188, 107964*.*

R. Tao, M. Alfano and G. Lubineau (2019). **In situ analysis of interfacial damage in adhesively bonded composite joints subjected to various surface pretreatments.** *Composites Part A: Applied Science and Manufacturing,* 116, 216-223.

R. Tao, Marco Alfano, and Gilles Lubineau (2018). **Laser-based surface patterning of composite plates for improved secondary adhesive bonding.** *Composites Part A: Applied Science and Manufacturing,* 109 84-94.

A. Wagih, R. Tao, A. Yudhanto, G. Lubineau (2020). **Improving mode II fracture toughness of secondary bonded joints using laser patterning of adherends**. *Composites Part A: Applied Science and Manufacturing*, 134, 105892.

A. Wagih, G. Lubineau (2021). **Enhanced mode II fracture toughness of secondary bonded joints using tailored sacrificial cracks inside the adhesive.** *Composites Science and Technology*, 204, 108605.

A. Wagih, R.Tao, G. Lubineau (2021). **Bio-inspired adhesive joint with improved interlaminar fracture toughness.** *Composites Part A: Applied Science and Manufacturing*, Under review.

A. Yudhanto, M. Almulhim, F. Kamal, R. Tao, L. Fatta, M. Alfano, G. Lubineau (2020). **Enhancement of fracture toughness in secondary bonded CFRP using hybrid thermoplastic/thermoset bondline architecture.** *Composite Science and Technology*, 199,108346.

A. Yudhanto, M. Alfano, G. Lubineau (2021). **Surface preparation strategies in secondary bonded thermoset-based composite materials: A review.** *Composites Part A: Applied Science and Manufacturing*, 147, 106443.

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P. Hu, D. Pulungan, R. Tao, G. Lubineau (2020). **An experimental study on the influence of intralaminar damage on interlaminar delamination properties of laminated composites.** *Composites Part A*, 131, 105783.

P. Hu, D. Pulungan, G. Lubineau (2020). **An enriched cohesive law using plane-part of interfacial strains to model intra/inter laminar coupling in laminated composites.** *Composites Science and Technology*, 200, 108460.

P. Hu, D. Pulungan, R. Tao, G. Lubineau (2021). **Influence of curing processes on the development of fiber bridging during delamination in composite laminates.** *Submitted to Composites Part A.*

Li, X., Tao, R., Alfano, M., & Lubineau, G. (2020). **How variability in interfacial properties results in tougher bonded composite joints by triggering bridging.** *International Journal of Solids and Structures*, 191, 87-98.

Li, X., Tao, R., Yudhanto, A., & Lubineau, G. (2020). **How the spatial correlation in adhesion properties influences the performance of secondary bonding of laminated composites.** *International Journal of Solids and Structures*, 196, 41-52.

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Thank you

gilles.lubineau@kaust.edu.sa

https://composites.kaust.edu.sa/

@gilleslubineau

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