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Certification of Discontinuous Composite Material Forms for Aircraft Structures

Marco Salviato, Jinkyu Yang, Mark Tuttle
University of Washington

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Research team

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Cindy Ashforth, Ph.D.

Industry mentors:

William Avery, Ph.D. (Boeing)

Bruno Boursier, Ph.D. (Hexcel)

Introduction

Aviationweek.com

Avstop.com

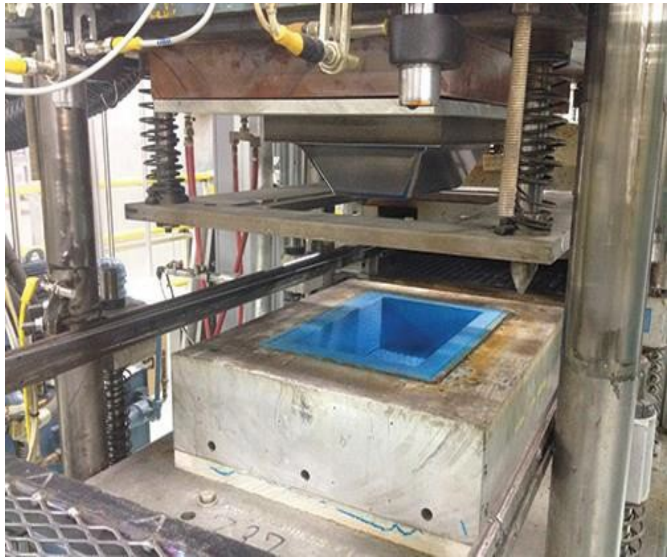
compositestoday.com

Made of composites?

Aviationweek.com

Introduction

Platelet-based random morphology



Thermoset DFC
(Hexcel)

Thermoplastic DFC
(Tencate)

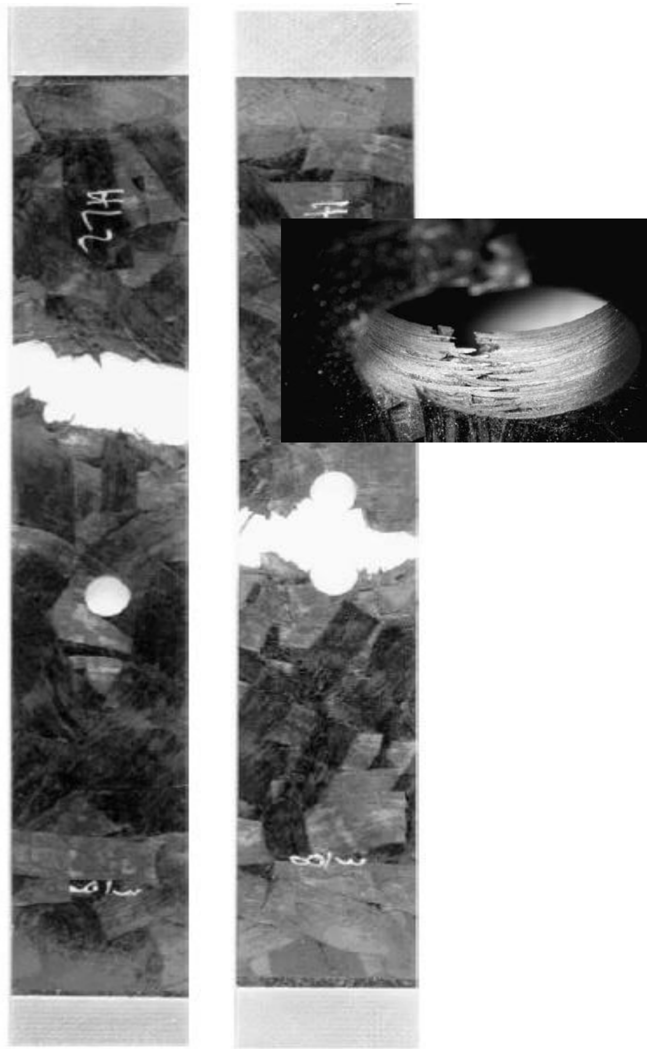
Current challenges:

Lack of design guidelines for the DFCs with the presence of notches or holes

Conventional application of DFC

Hexmc parts, Hexcel

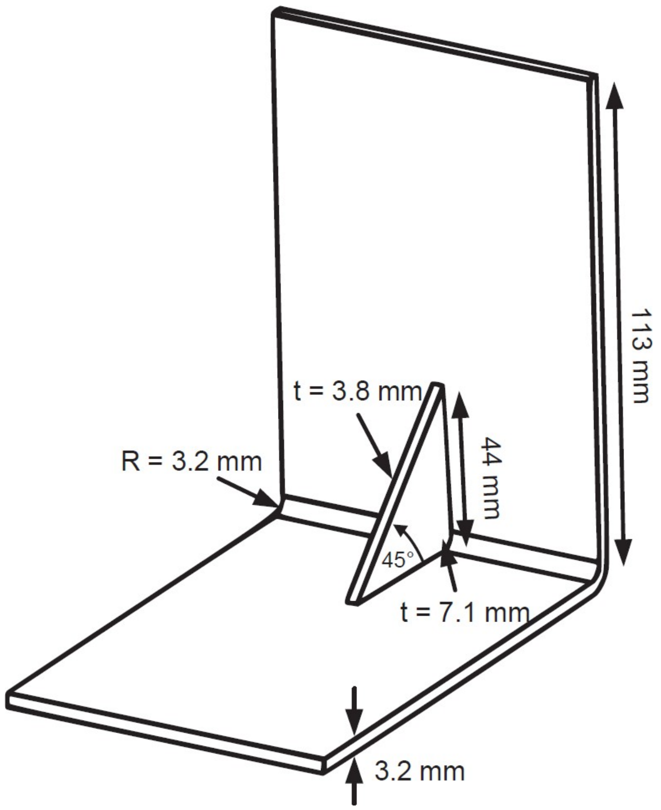
Qian, 2011



Feraboli, 2009

Current challenges:

Lack of acceptance/rejection criteria for defected DFC components



Landry, PhD dissertation, McGill, 2015

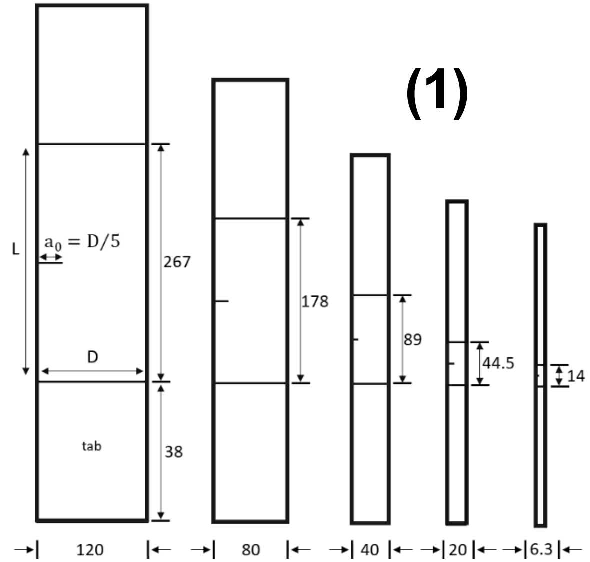
Objectives:

(1) To develop an *experimental protocol for the characterization of fracture toughness of DFCs*

(2) To investigate the *effects of material morphology* (e.g. platelet size and distribution) and *geometrical features* (e.g. structure thickness and notch radius) *on the fracture behavior*

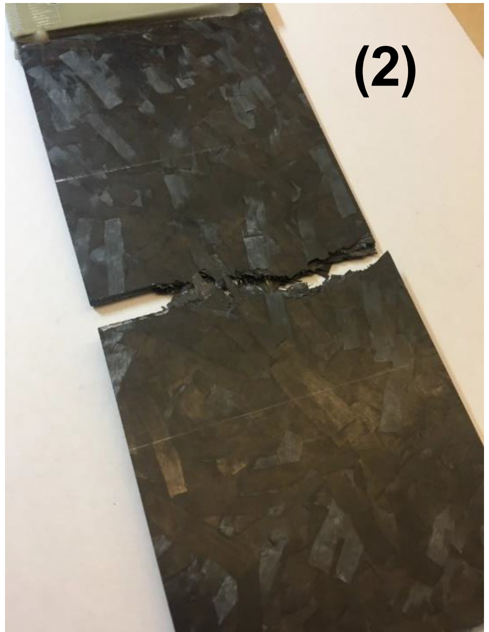
(3) To *formulate certification guidelines for DFC parts subject to intra-laminar defects or featuring sharp notches*

(1)



Size effect test, law

(2)

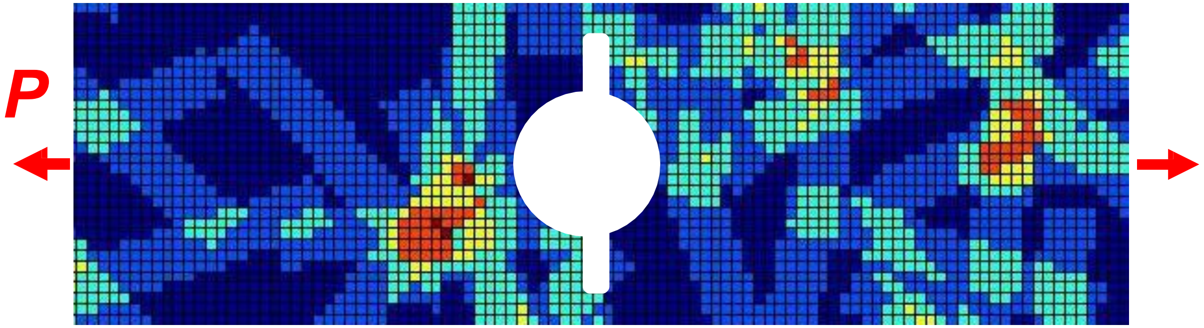


Platelet size:
75×12 mm

50×8 mm

25×4 mm

(3)

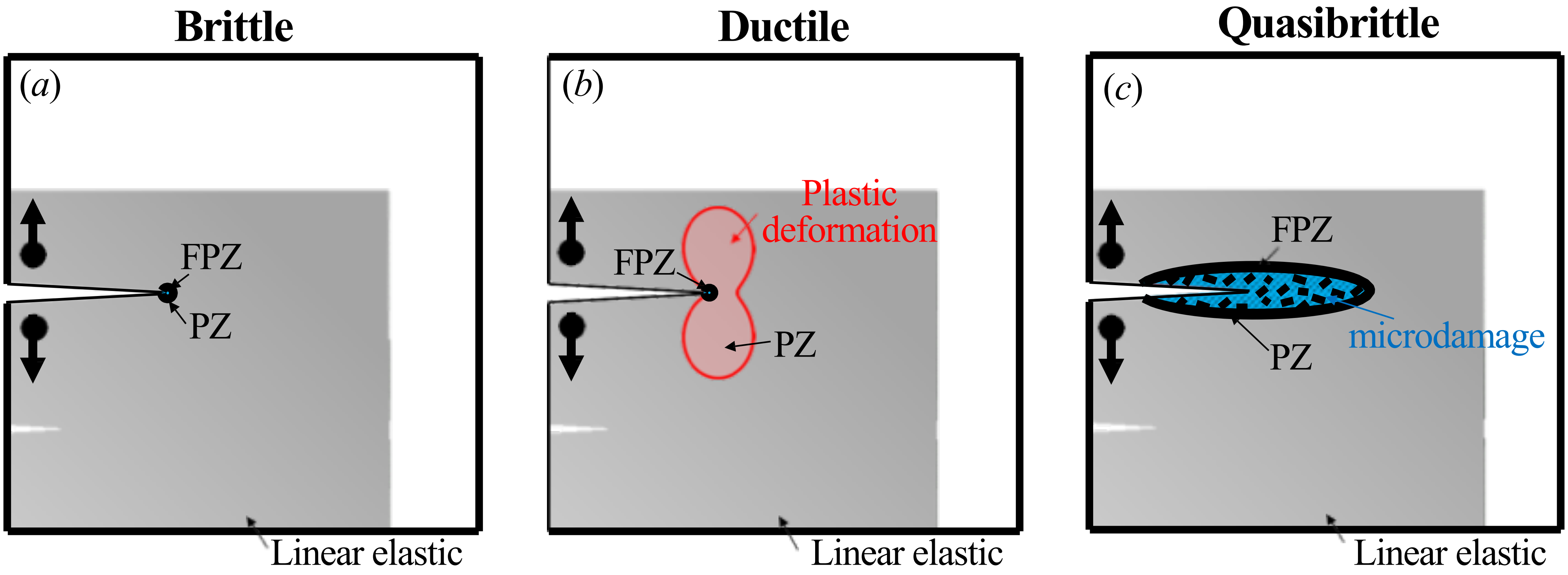


Quasi-brittle fracture behavior of DFCs

Effect of the characteristics dimension on the nominal strength

*FPZ = Fracture process zone

*PZ = Plastic zone



Bazant, 1998

FPZ is large in DFC

Size effect law

Let's define the nominal stress in the specimen as:

$$\sigma_N = P/(tD) \qquad P = \text{applied load} \quad D = \text{width} \quad t = \text{thickness} \tag{1}$$

the following expression holds for the initial fracture energy:

$$G_f(\alpha) = \frac{\sigma_N^2 D}{E^*} g(\alpha) = \frac{\sigma_N^2 D}{E^*} g(\alpha_0 + c_f/D) \tag{2}$$

$\alpha = a/D$

$E* =$ effective modulus

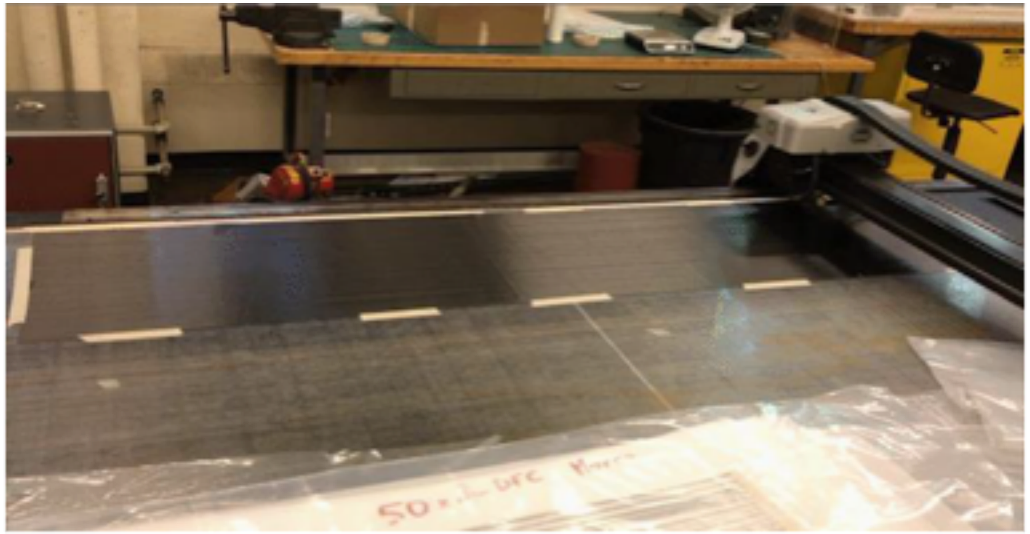
$g =$ dimensionless energy release rate

By expanding g in Taylor Series, retaining only 1st order terms and re-arranging:

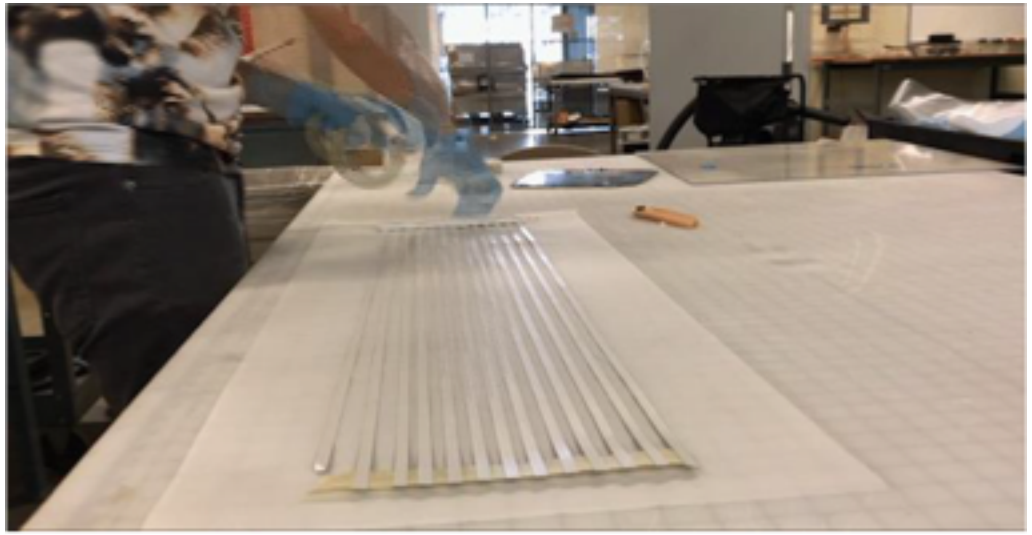
$$\sigma_N = \sqrt{\frac{E^* G_f}{D g(\alpha_0) + c_f g'(\alpha_0)}} \tag{3}$$

Bažant's Size Effect Law (SEL) for quasi-brittle materials (extended to DFCs)

Specimen preparation



1) Cut into strips

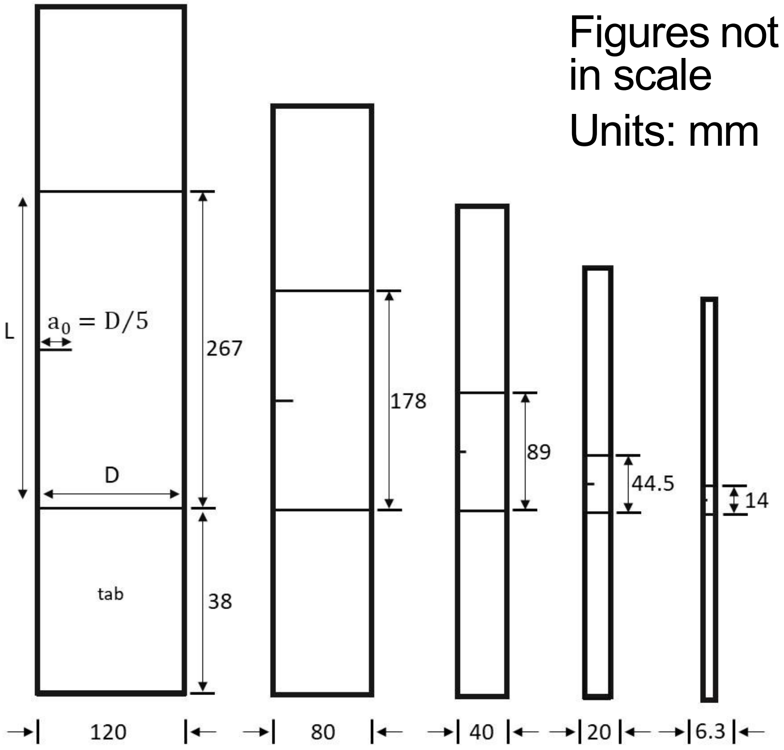


2) Remove backing tape

3) Cross-cut the strips

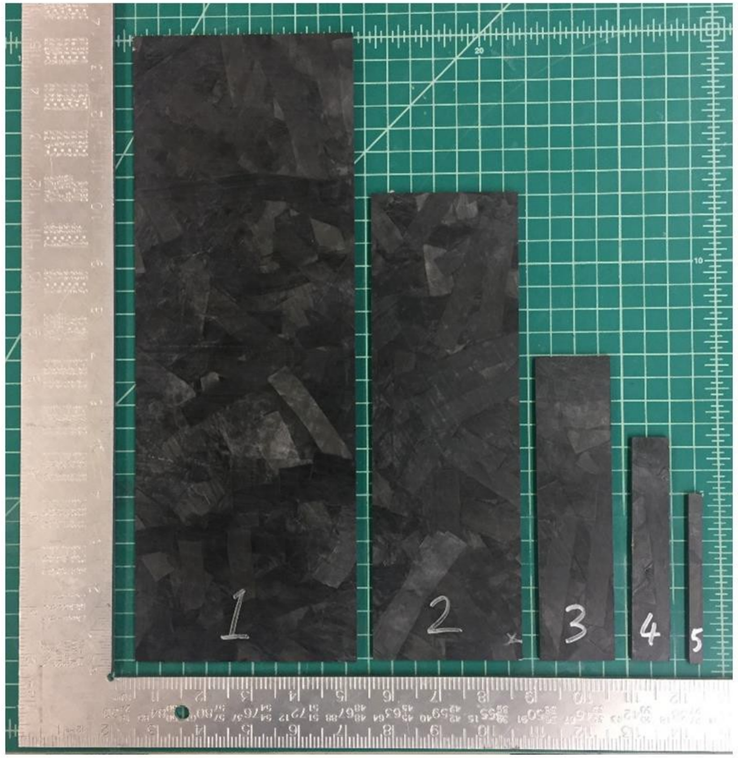
4) Distribute platelets randomly

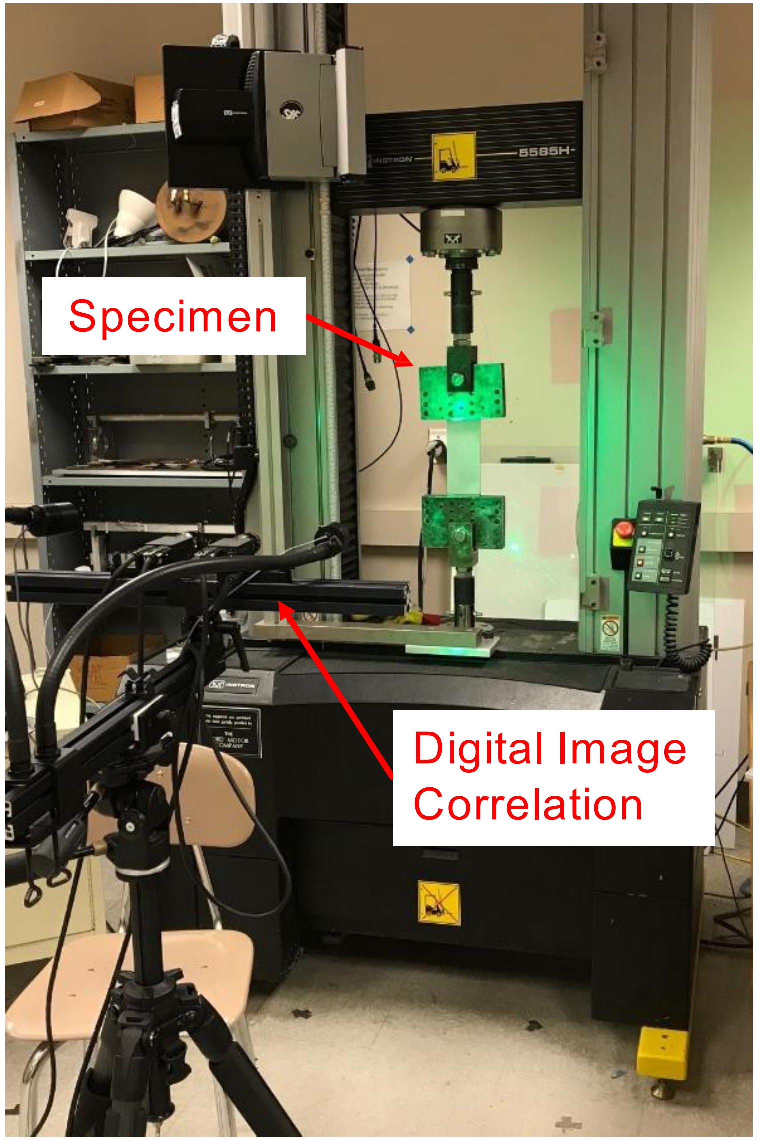
Specimen geometry



Figures not in scale

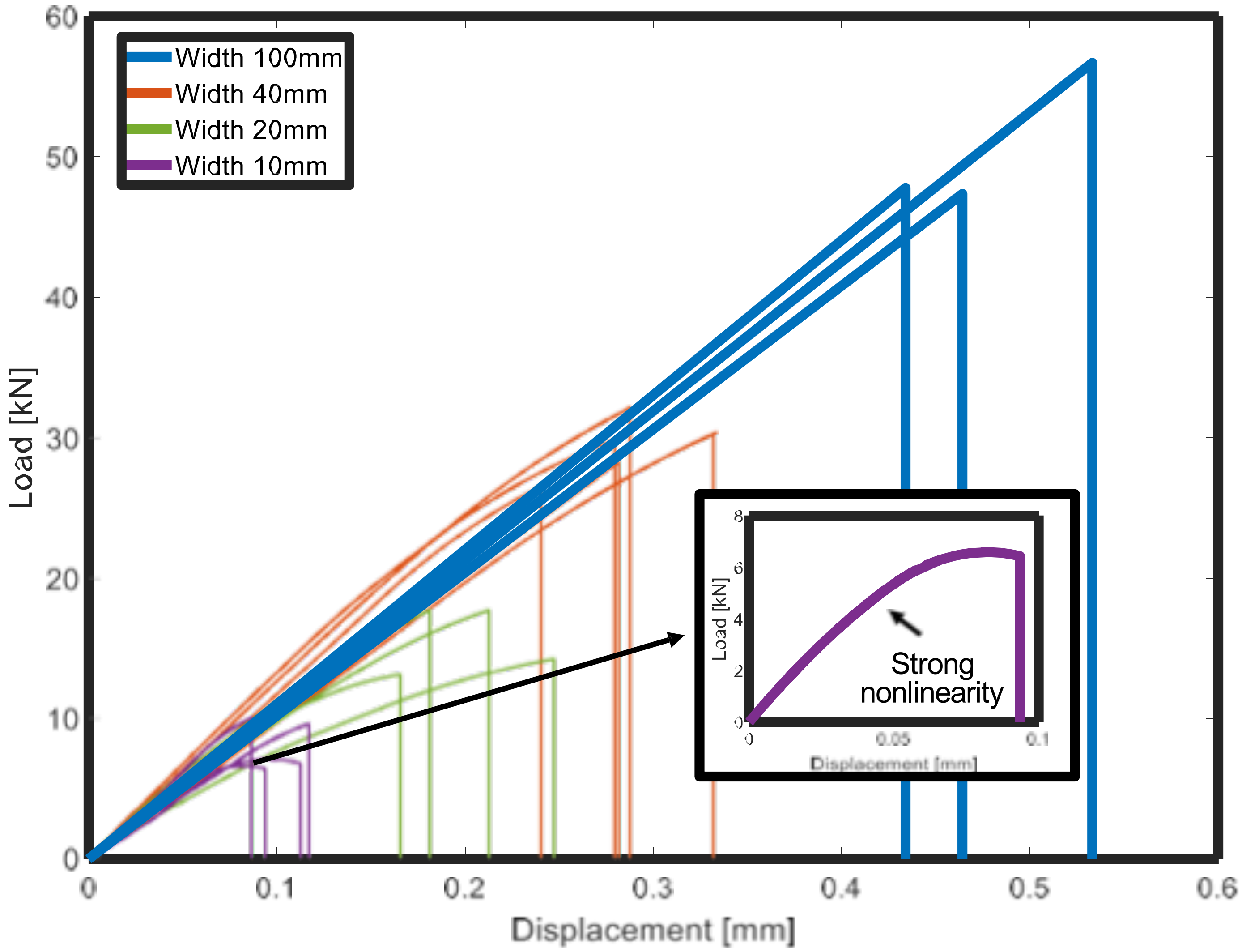
Units: mm





- Coupon sizes are proportionally scaled in width, gauge length, and crack length
- Thickness is constant = 3.3 mm

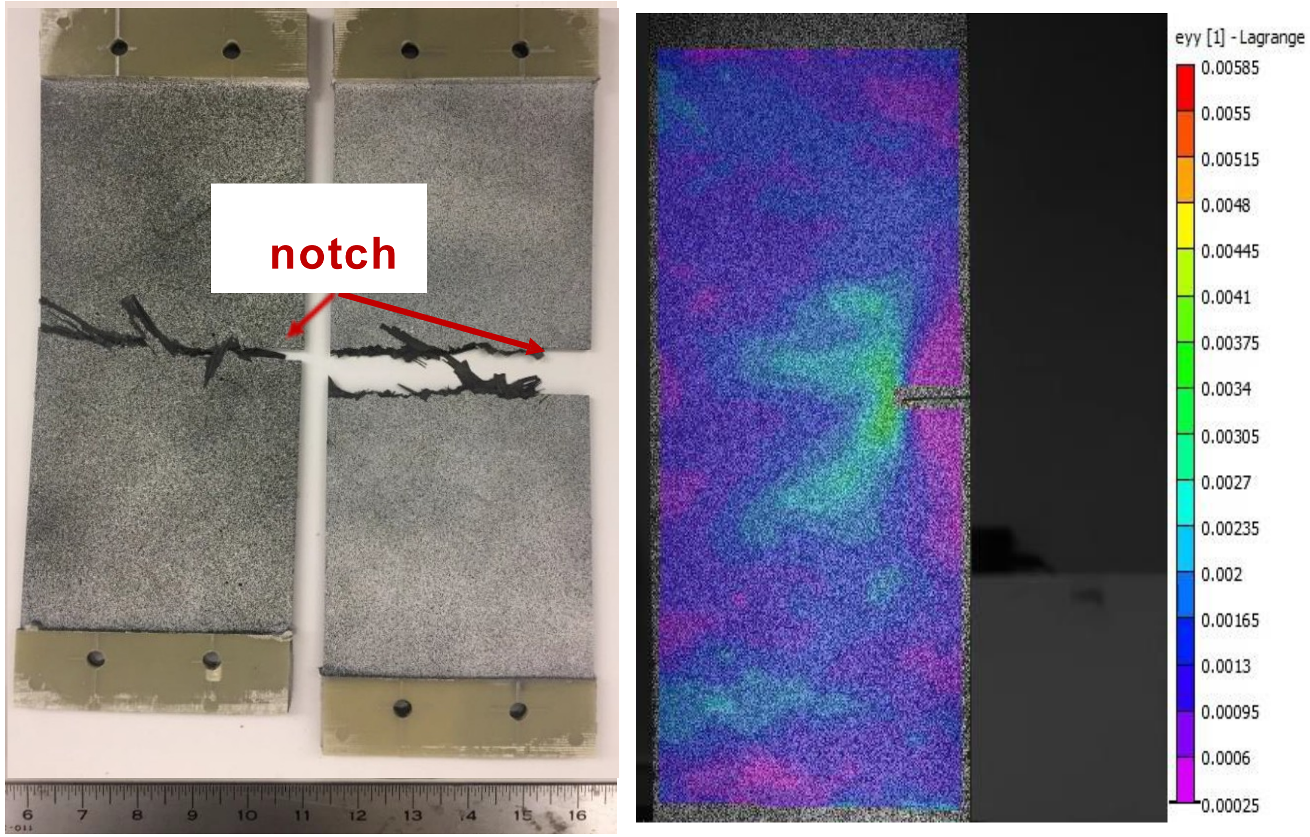
Typical Force and Displacement curves



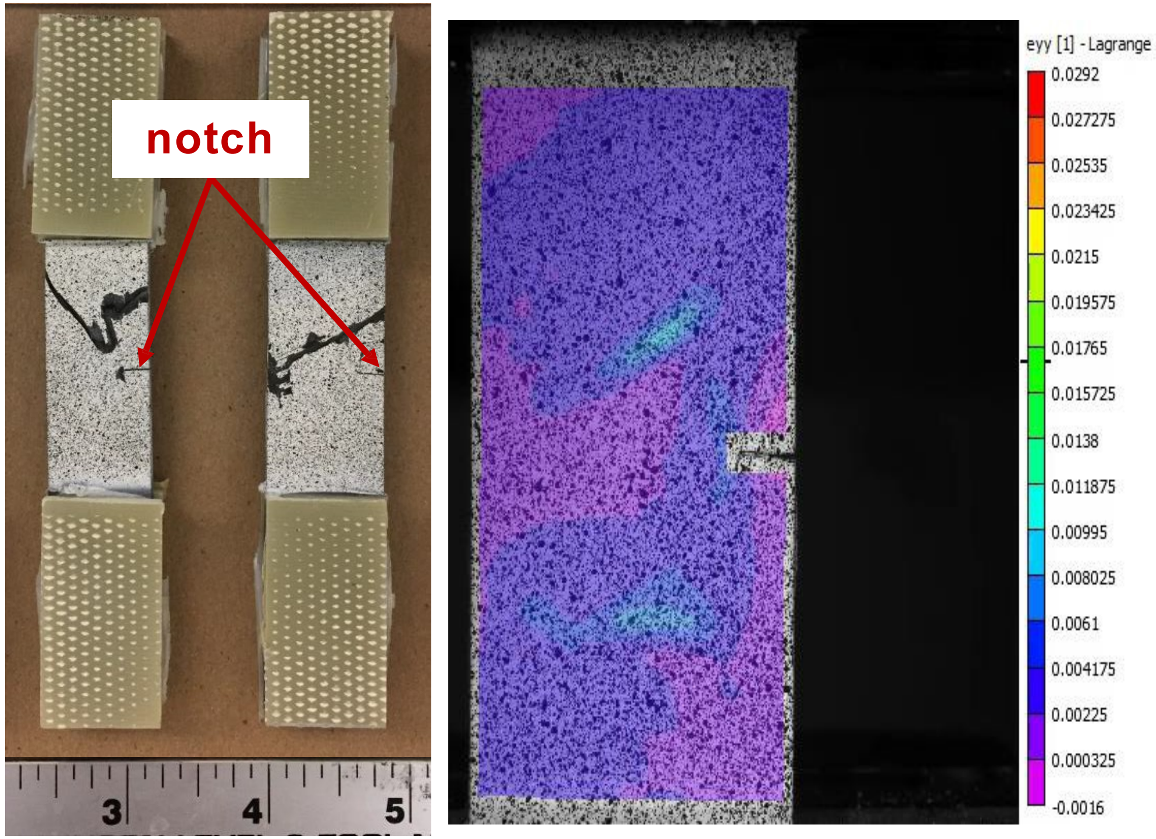
1. As the specimen size increases, the nonlinearity of the slope decreases.
2. Decreasing nonlinearity of the slope represents increased brittleness of the material behavior.
3. the brittleness/ductility of the material depends not only on the material property but also on the structure size.

Result 2: Fracture surfaces and DIC

Platelet size of 75×12 mm



Width = 120 mm



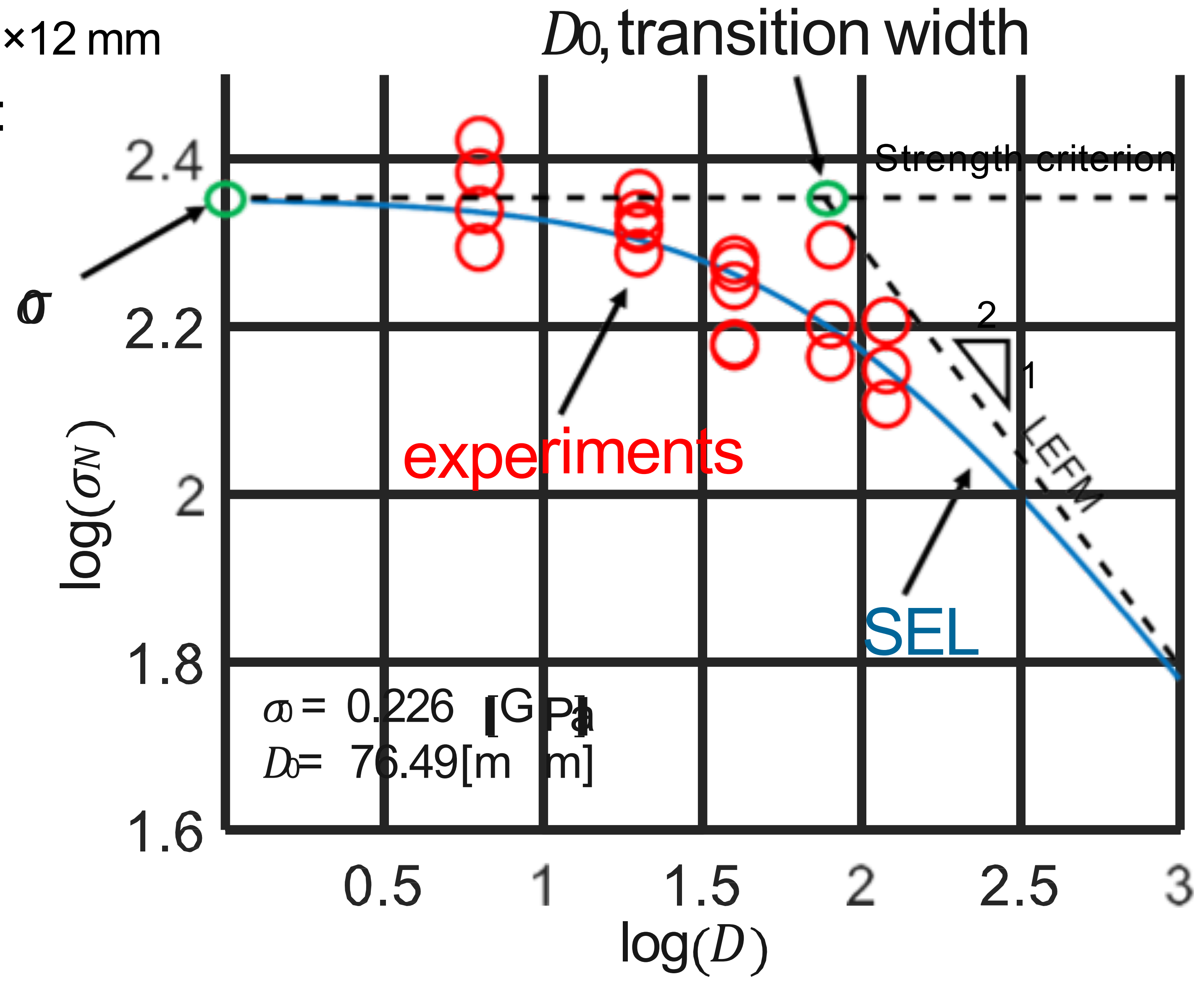
Width = 20 mm

Result 3: Size effect curve

Platelet size of 75×12 mm

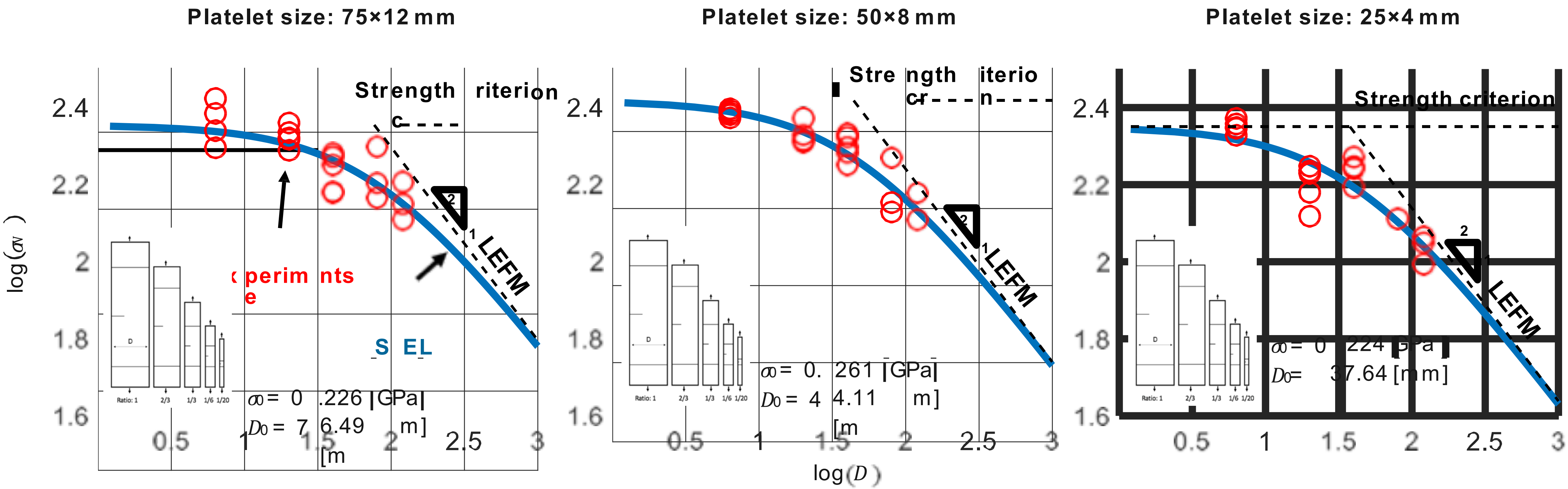
Size effect law:

$$\sigma_N = \frac{\sigma_0}{\sqrt{1+D/D_0}}$$



DFCs are well fitted using the size effect law

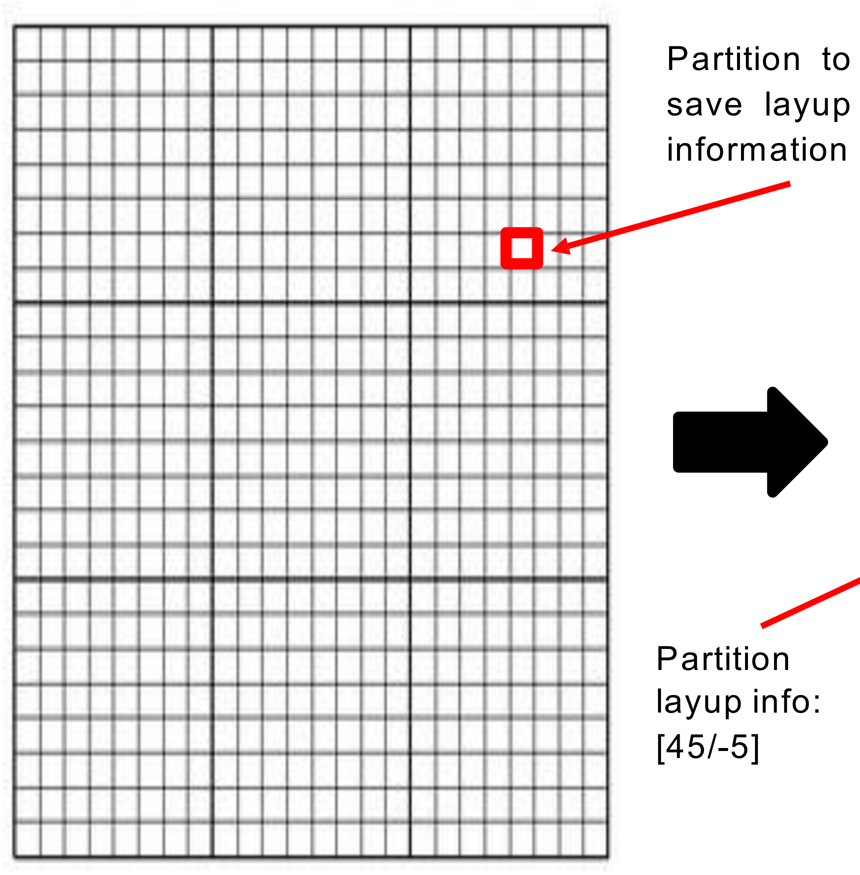
Result 3: Size effect curves



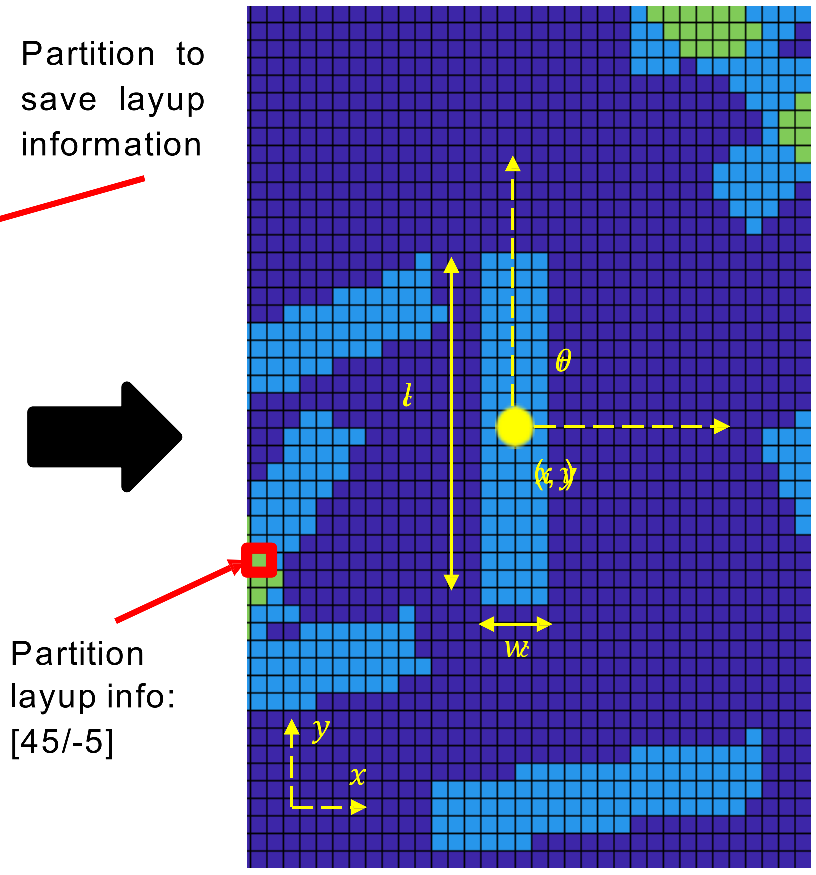
1. DFC shows a strong size effect.
    a) we can clearly observe the transition from the strength to energy driven fracture.
    b) Neither strength nor LEFM can predict the behavior of the DFC.
    c) The notch insensitivity is observed when the specimen size is moving away from LEFM region (or when the width is below the transition width, D_0).
2. The platelet size has a strong effect in fracturing behavior of DFC
    a) Smaller the platelet size, the DFC behaves more brittle manner

Microstructure generation

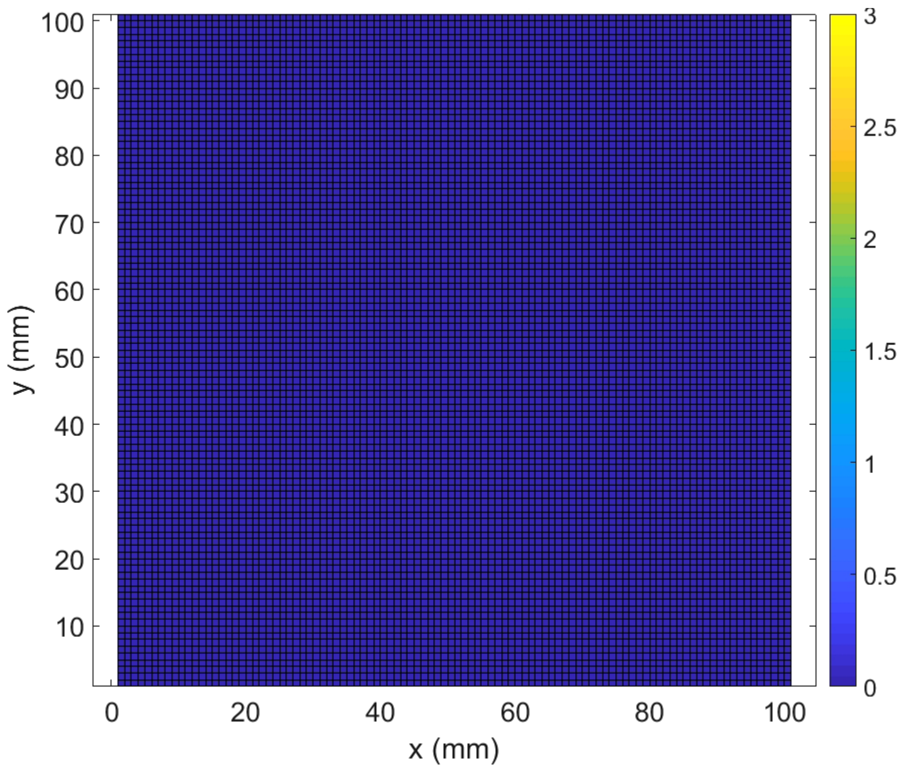
- Finite element model is based on stochastic laminate analogy [Tuttle, 2010, Selezneva, 2015]
- Platelet center point and its orientation is randomly chosen



Partition generation

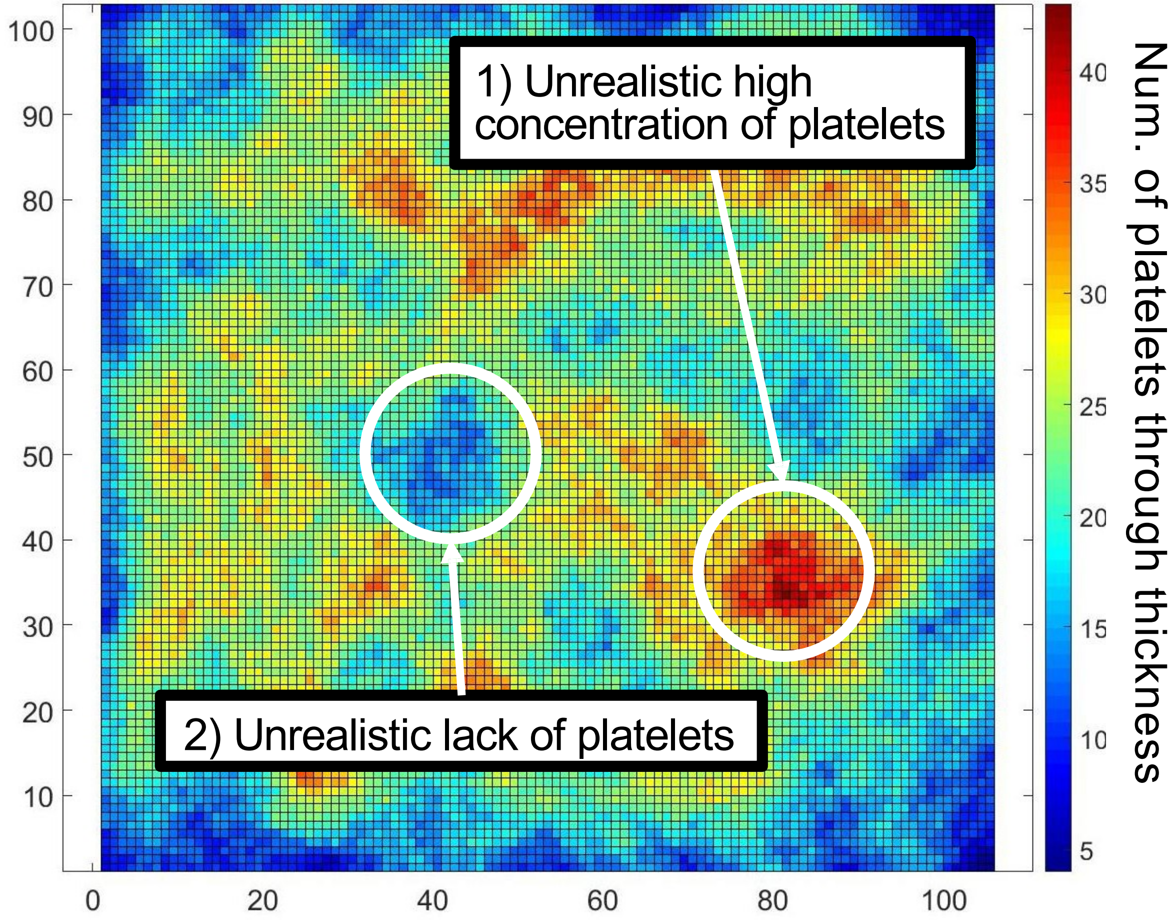


Random platelet generation



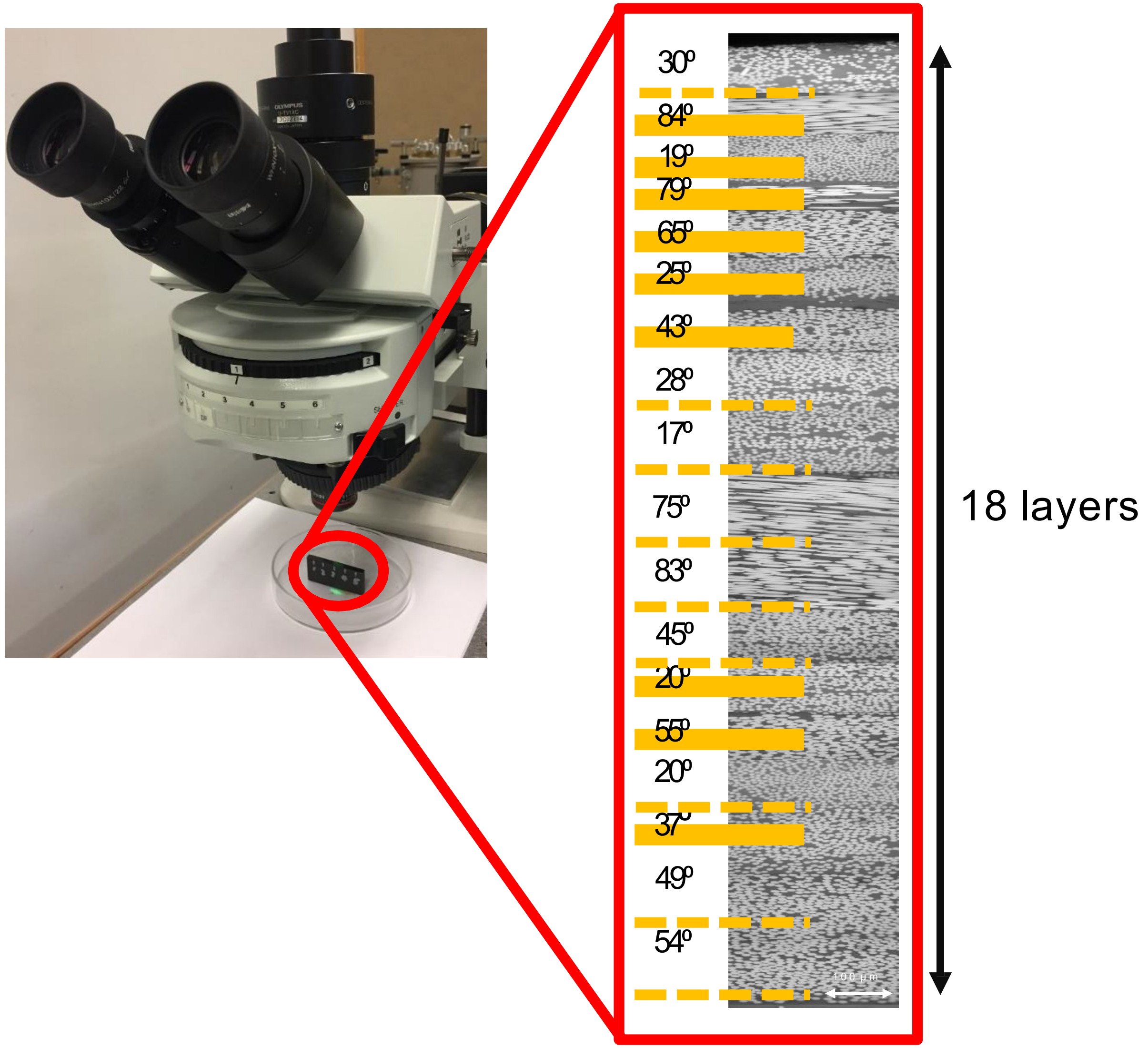
Example of platelet generation

Problem with platelet distribution algorithm

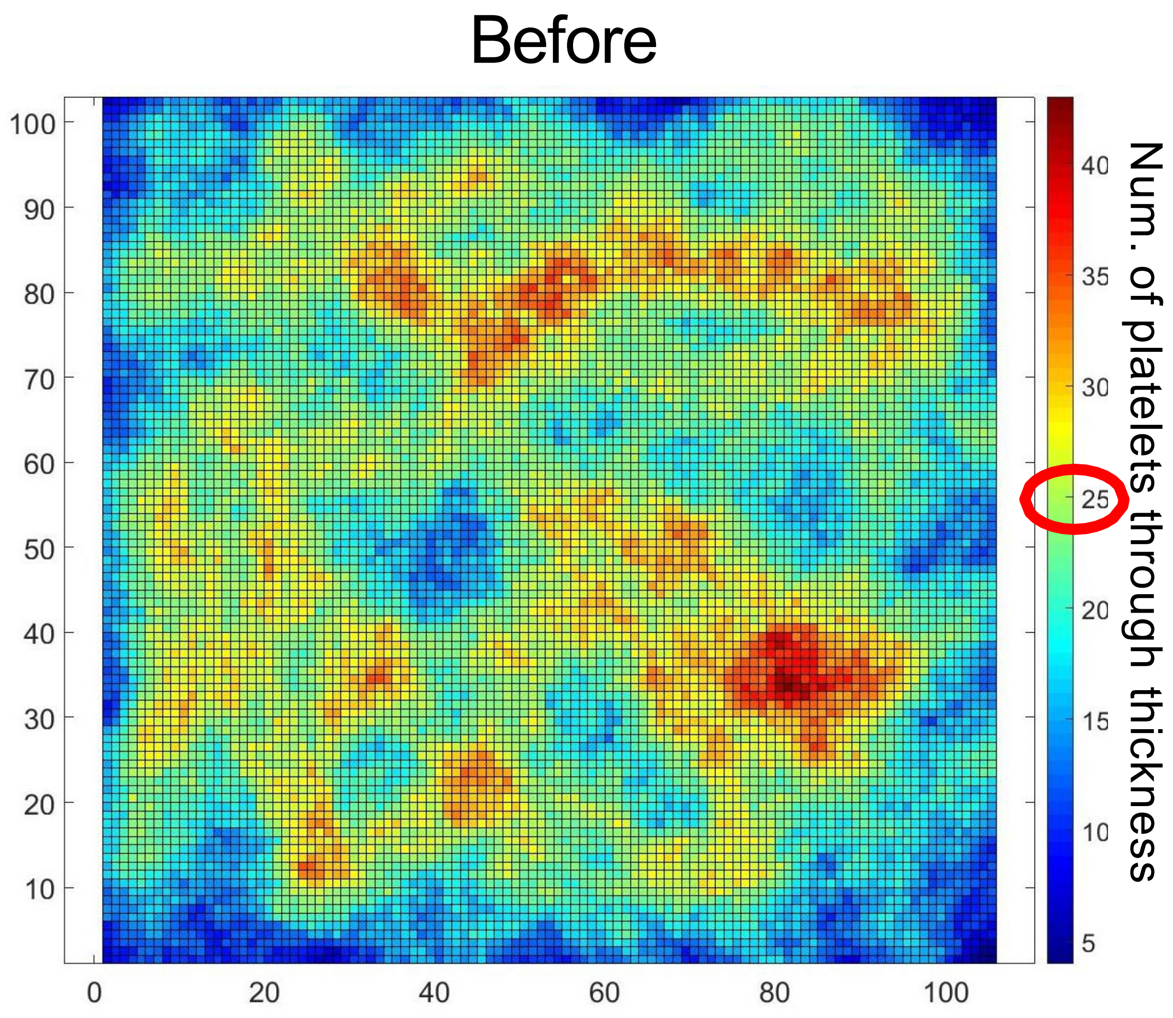


*target average number of platelets through thickness = 25

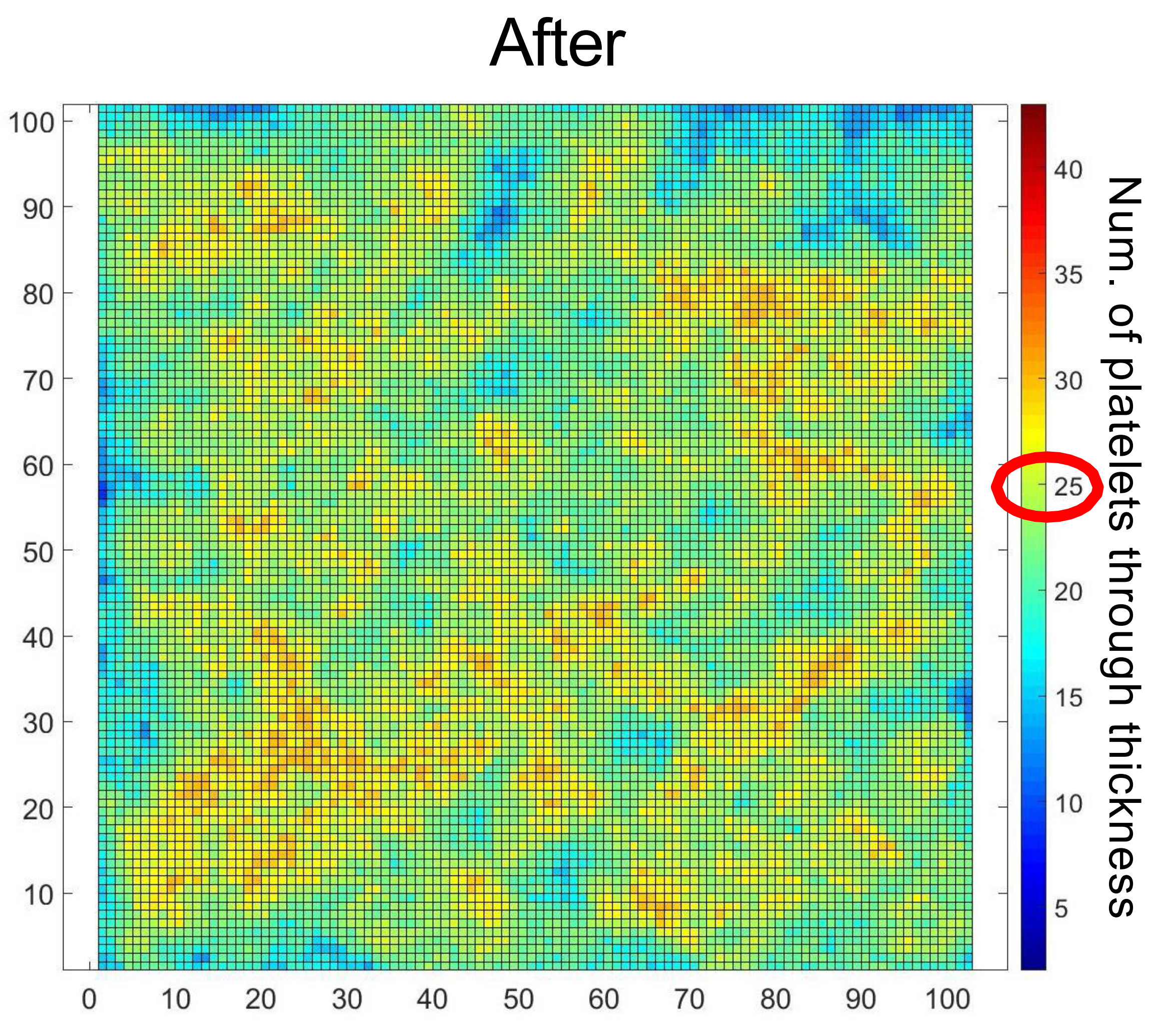
We observed total of 90 cross-sections to measure the distributions



Calibrated platelet distribution algorithm



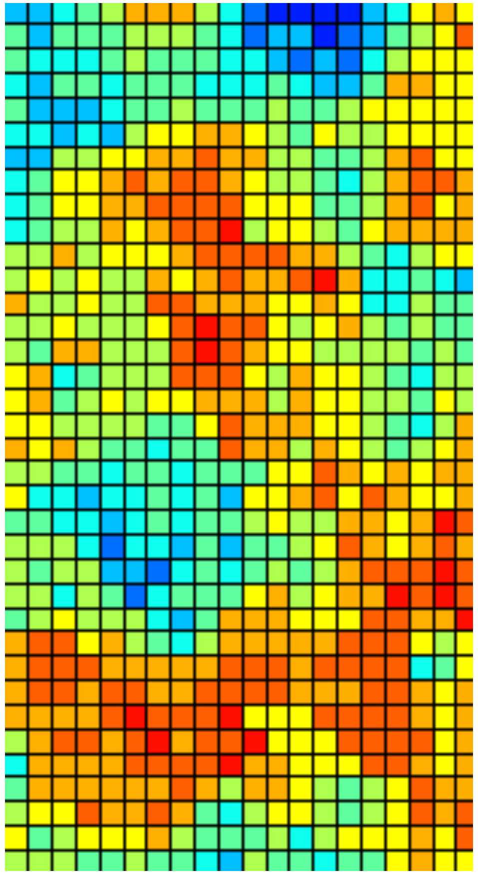
*target average number of platelets through thickness = 25



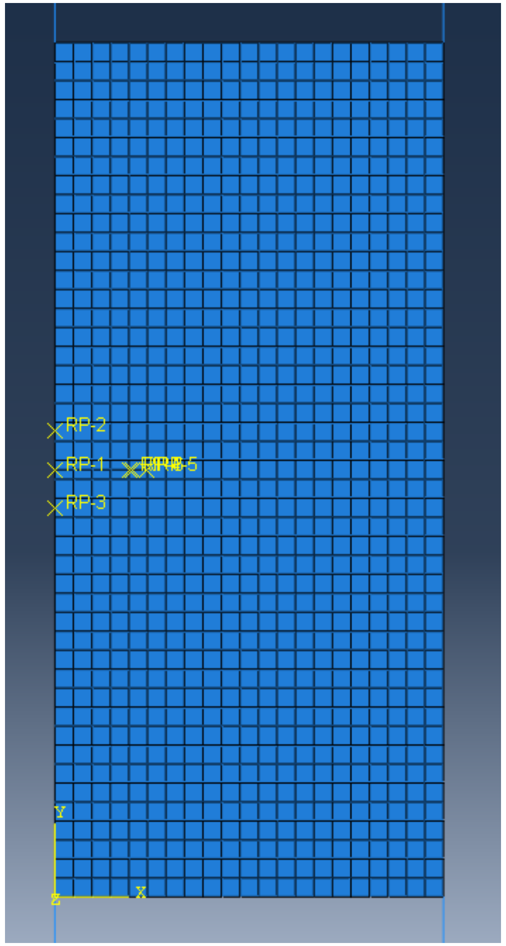
No high concentrations nor lack of platelets

Microstructure is imported to Abaqus

S8R Belytschko-Tsay shell element is used



Matlab



Abaqus

Use CLT on each partition

Obtained from FEM

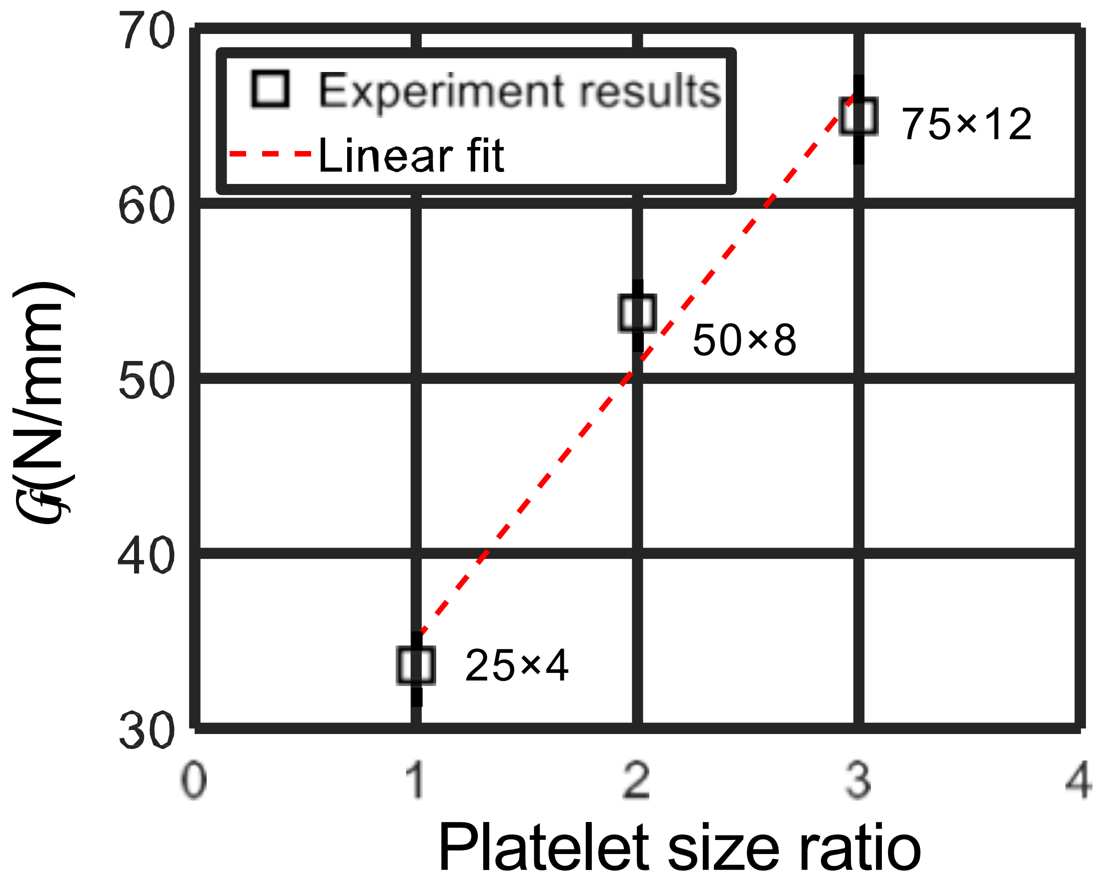
	$g(\alpha_0)$	$g'(\alpha_0)$
25×4 mm	0.93 ± 0.07	5.51 ± 1.20
50×8 mm	0.93 ± 0.11	5.60 ± 0.75
75×12 mm	0.88 ± 0.03	4.79 ± 0.67
QI layup	0.761	4.29

$$G_f = \frac{g(\alpha_0)}{E^* A} \quad [3]$$

Intra-laminar mode I fracture energy of DFC

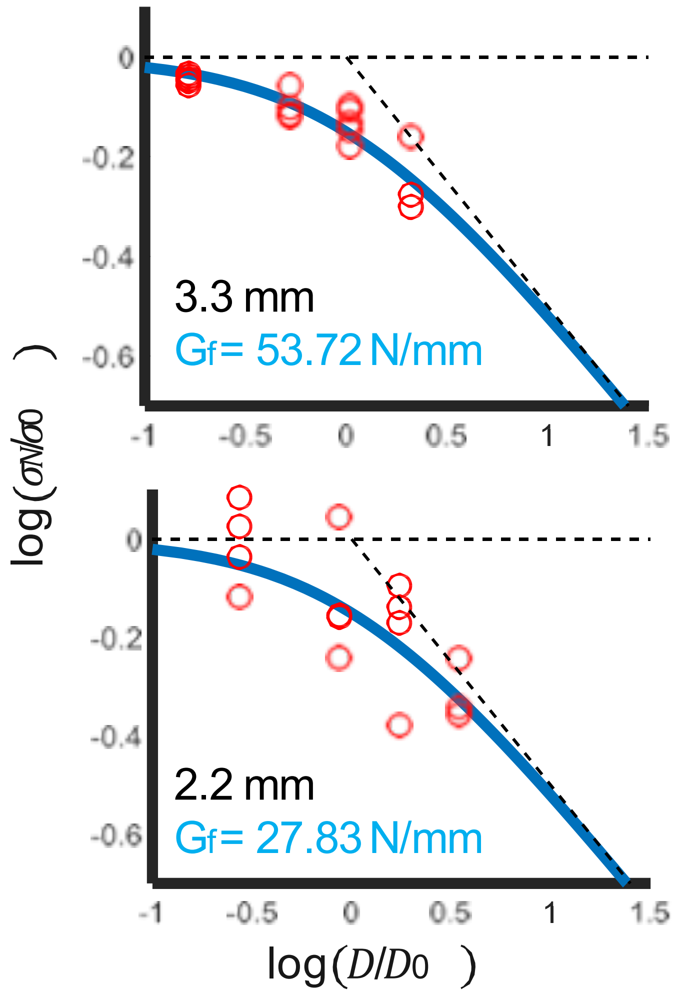
Size effect law: $\sigma_N = \sqrt{\dfrac{E^* G_f}{D g(\alpha_0) + c_f g'(\alpha_0)}}$

	Effective FPZ length, c_f (mm)	Fracture energy, G_f (N/mm)
25×4 (mm)	6.55 ± 1.07	33.59 ± 2.86
50×8 (mm)	7.43 ± 0.83	53.72 ± 6.14 Δ59.9%
75×12 (mm)	14.2 ± 1.85	64.98 ± 2.79 Δ93.5%

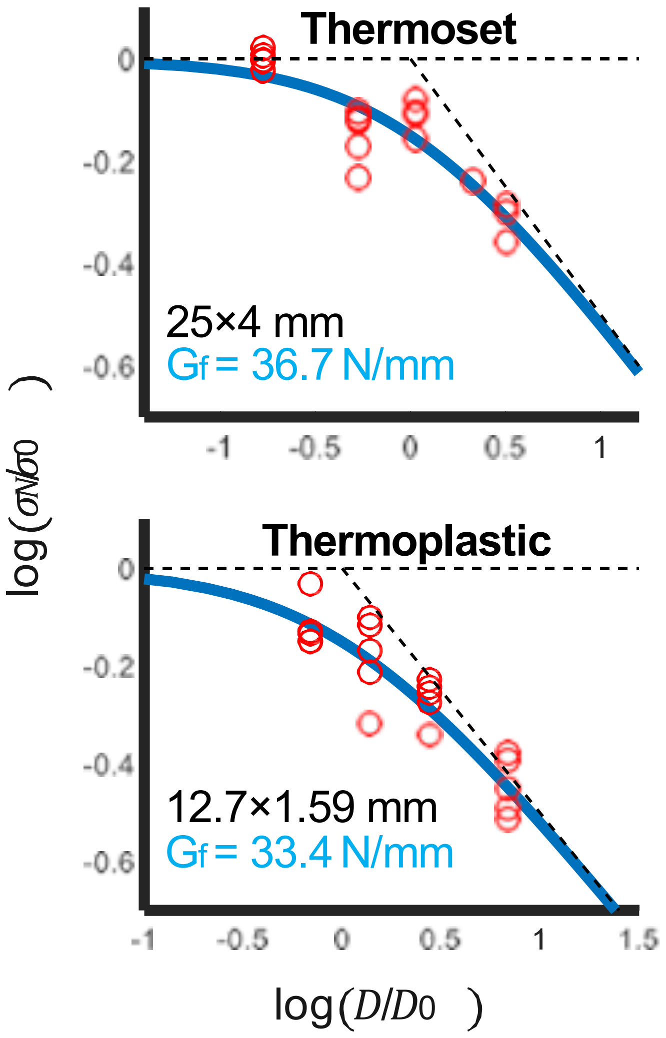


Ongoing/future work

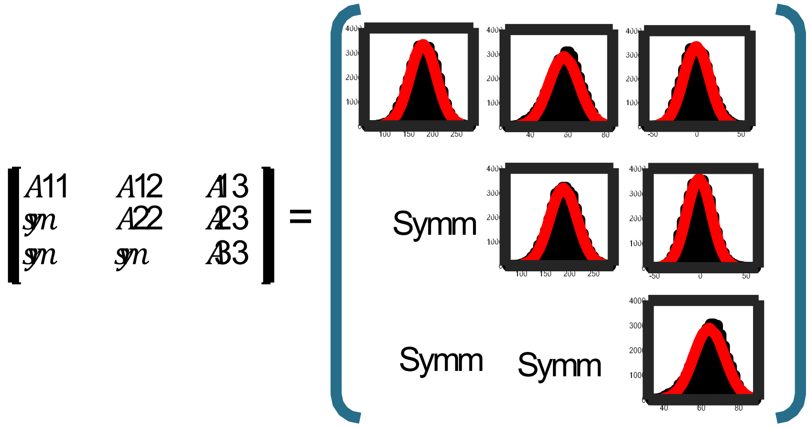
Thickness size effect

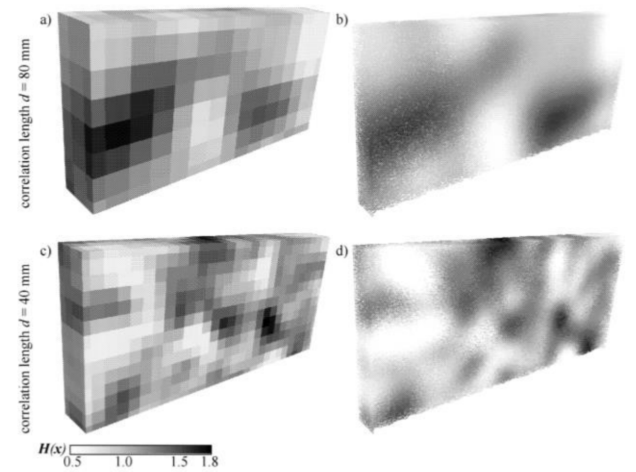


Thermoset vs. Thermoplastic



Stochastic homogenized model



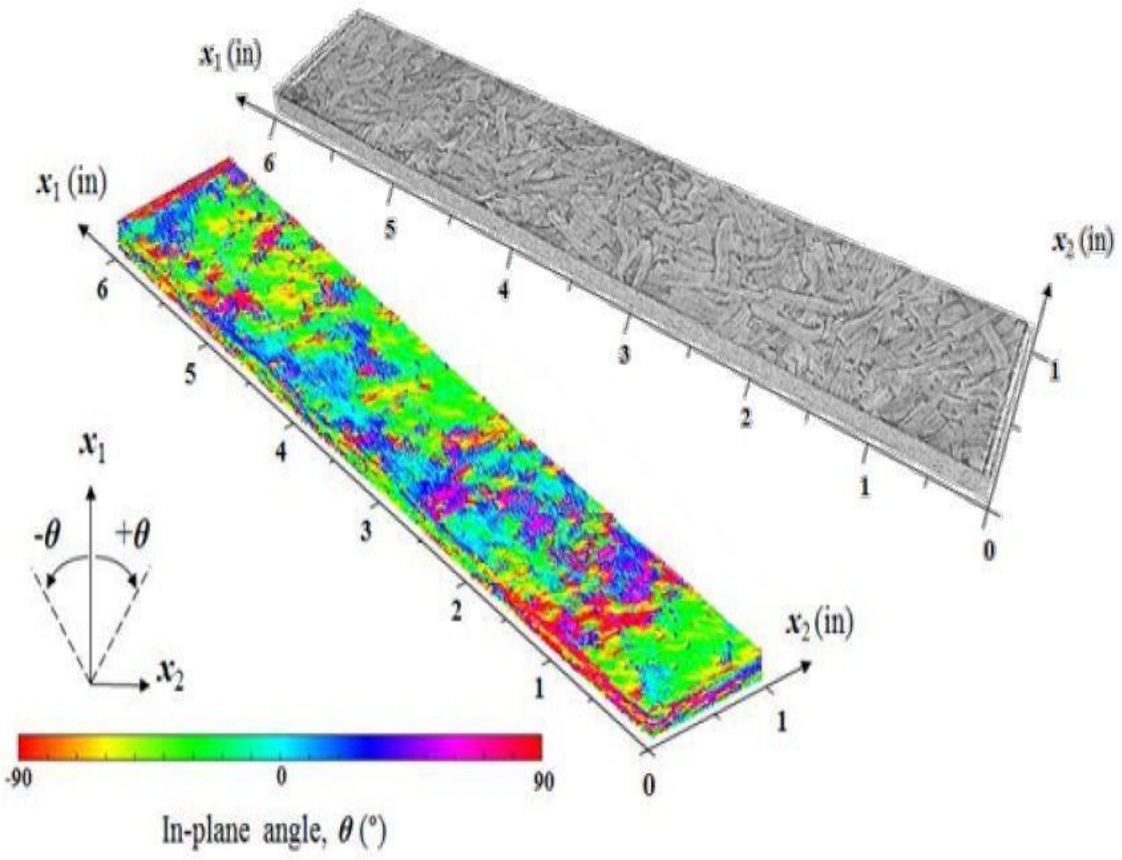


Autocorrelated random field of elastic properties based on Karhunen –Loeve expansion

(5) micro-CT scan and local fiber orientation

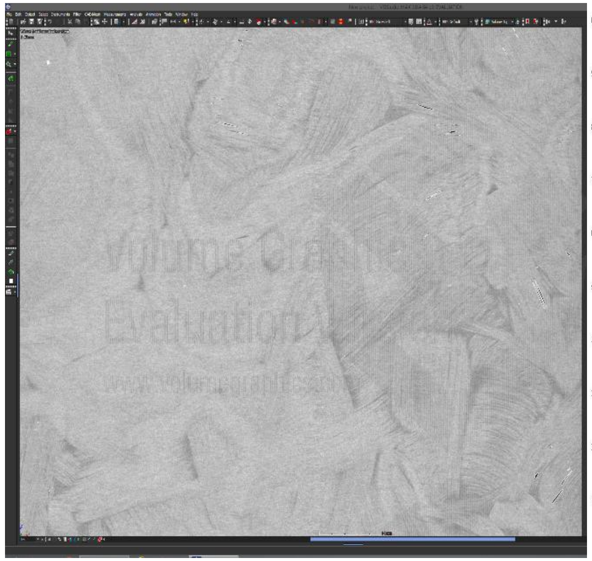
(1) Determine local fiber orientations

(2) Obtain defect size and locations

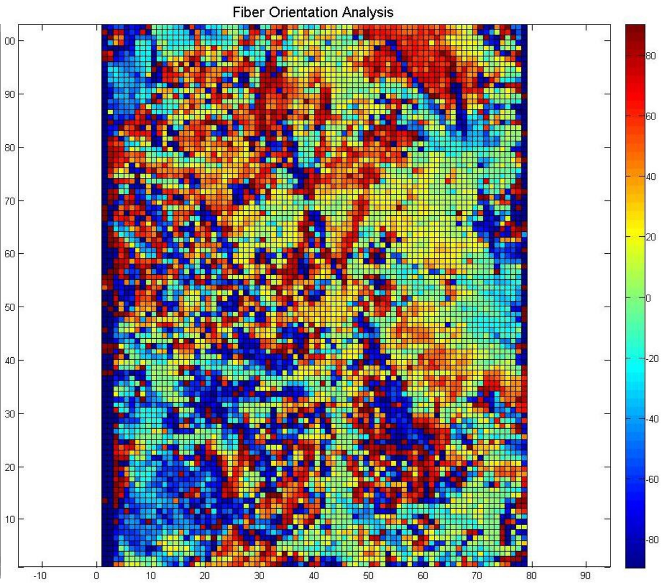


Denos (Purdue DFC project), 2017

Current UW progress



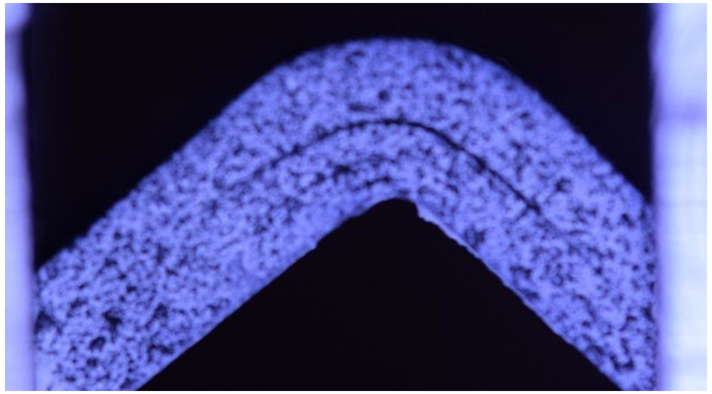
UW micro CT scan

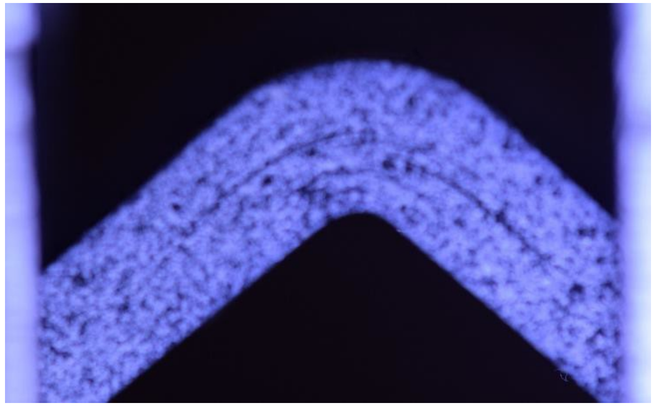


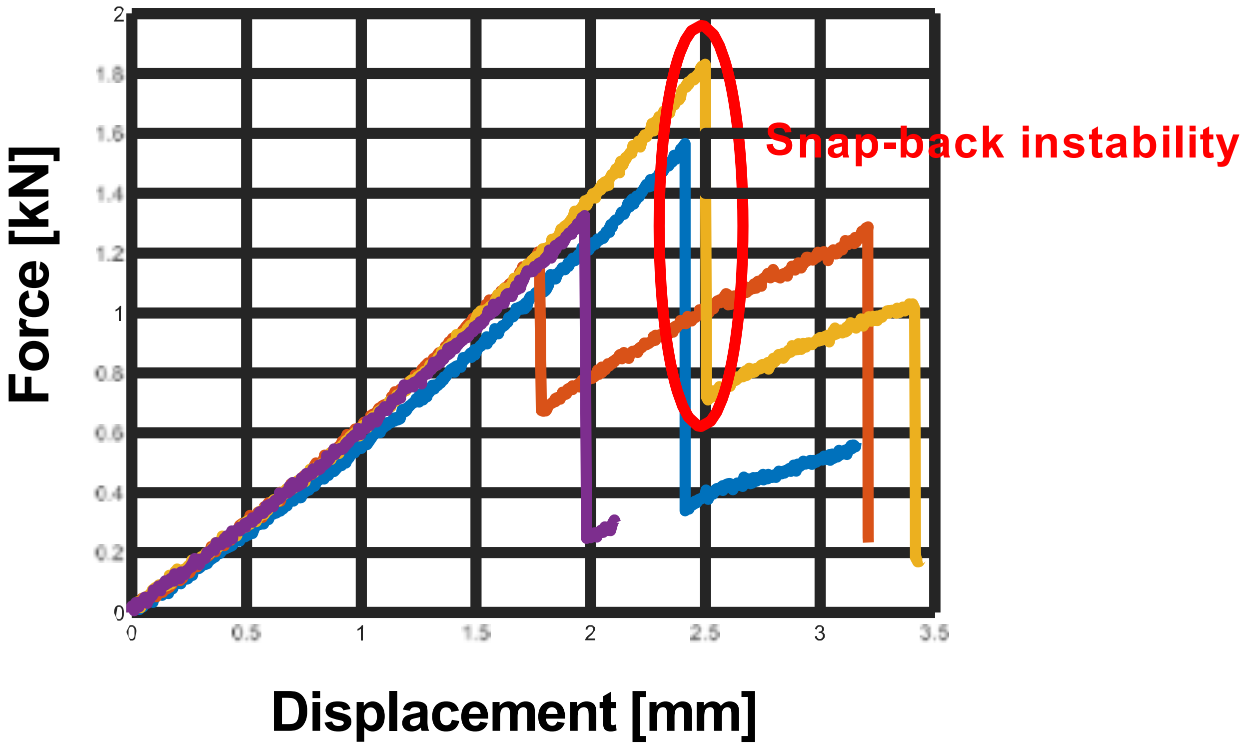
Local fiber orientation analysis in progress

- Training on the operating micro-CT scanner is completed.
- We are now in a progress of how to obtain the local fiber orientations using the post processing program.

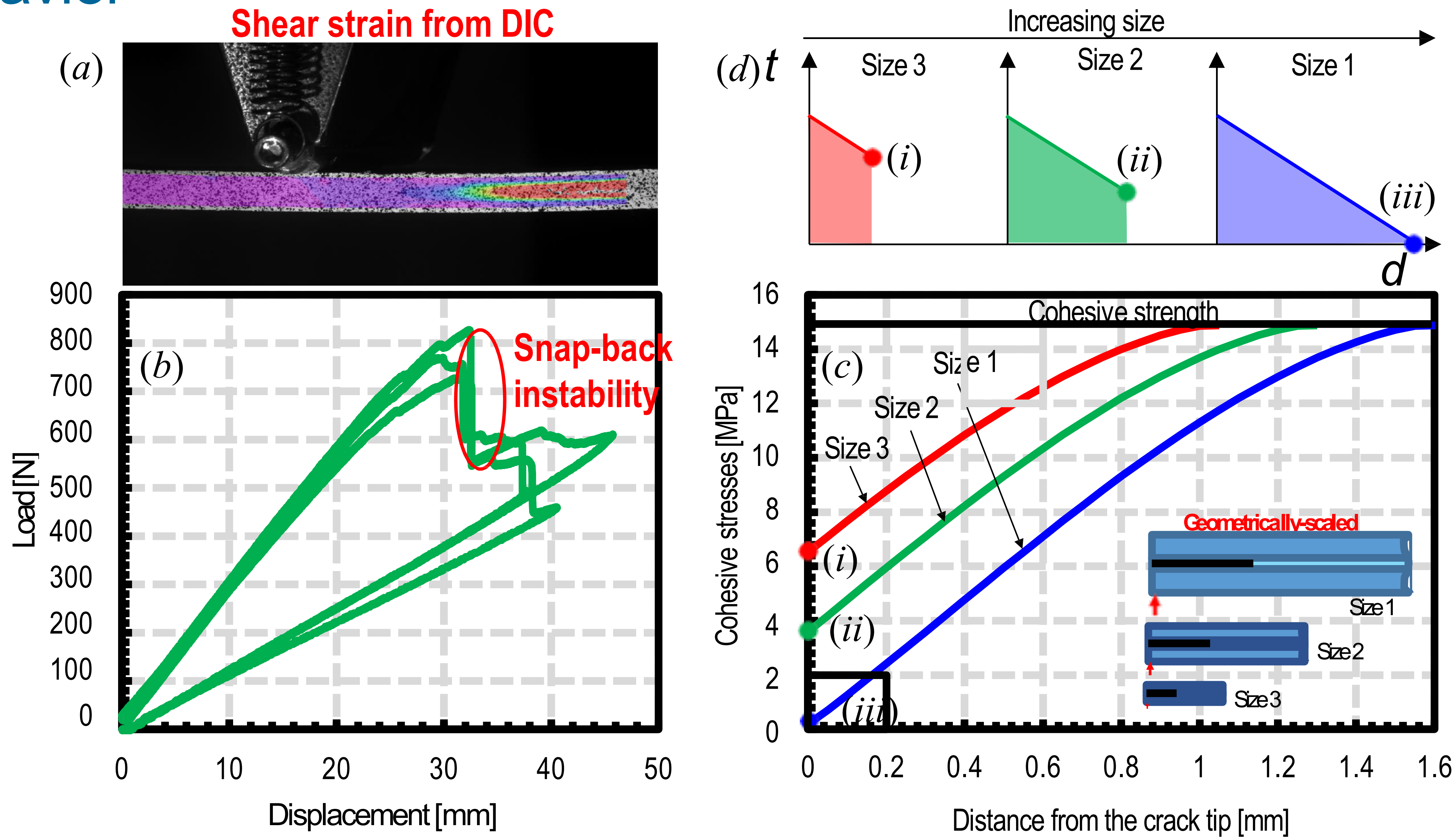
Ongoing/future work: Investigation of inter-laminar fracture behavior







Ongoing/future work: Investigation of inter-laminar fracture behavior



Summary

1. We developed and validated an experimental protocol for the characterization of the fracture energy in DFCs.
2. The approach is based on size effect. Size effect testing is a simple and accurate method to characterize the fracture energy of the DFC.
3. The size effect law can be used a design/certification guideline for DFCs to identify critical defect sizes.
4. The larger platelets provide higher G_f (75×12 mm is 93.5% higher than 25×4 mm). The fracture energy increases linearly with the platelet size in the size range investigated.
5. Preliminary results show a significant thickness effect on the fracture energy. A 1/3 reduction of the thickness leads to roughly a 50% decrease of the fracture energy

Looking forward

Benefit to aviation:

1. Novel experimental framework for characterization of the fracture toughness of DFCs;
2. Investigation of platelet size effect and thickness effect on fracturing behavior
3. Development of certification guidelines for defected DFC structures and its validation (in progress)
4. Construction of a database of fracture energy for both thermosets and thermoplastic DFCs

Future needs:

1. Better understanding on inter-laminar fracturing behavior;
2. Investigation on the use of failure probability theory to capture the significan randomness of material behavior
3. Investigation of the correlation between local platelet morphology in real components and fracturing behavior

Acknowledgements

FAA Technical monitor: Ahmet Oztekin, Cindy Ashforth, Larry Ilcewicz
Industry Monitor: William Avery, Bruno Boursier

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