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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Larry Ilcewicz, Ph.D.

Cindy Ashforth, Ph.D.

Industry mentors:

William Avery, Ph.D. (Boeing)

Bruno Boursier, Ph.D. (Hexcel)

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Introduction

Aviationweek.com

Avstop.com

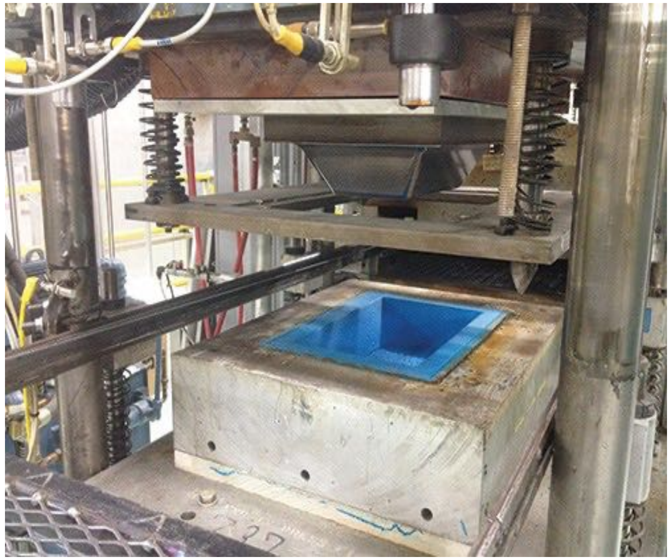
compositestoday.com

Made of composites?

Aviationweek.com

Introduction

Platelet-based random morphology



Thermoset DFC

(Hexcel)

Thermoplastic DFC

(Tencate)

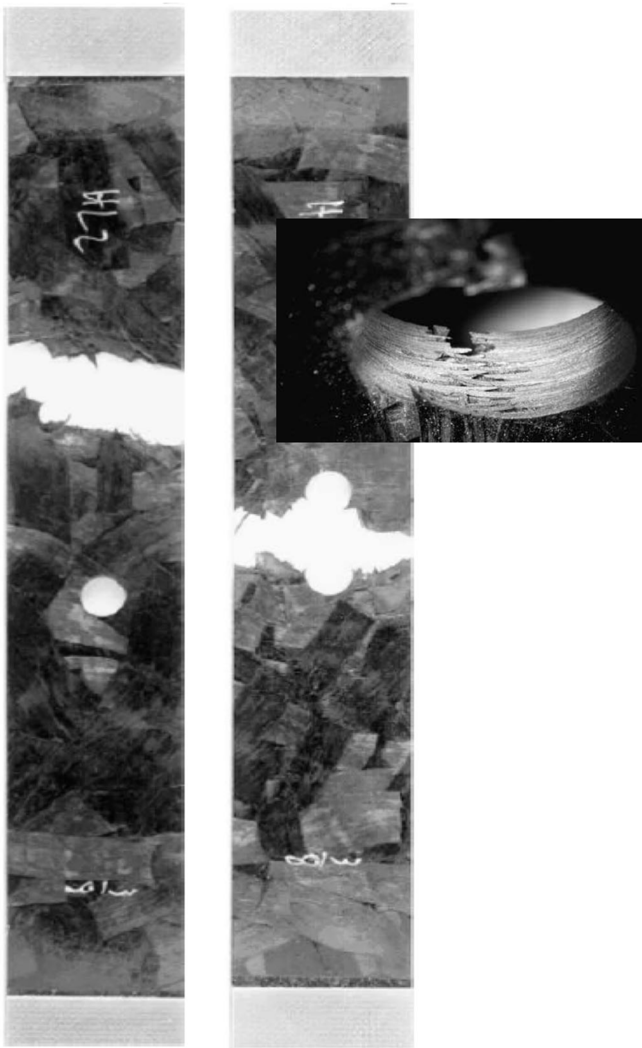
Current challenges:

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

Conventional application of DFC

Hexmc parts, Hexcel

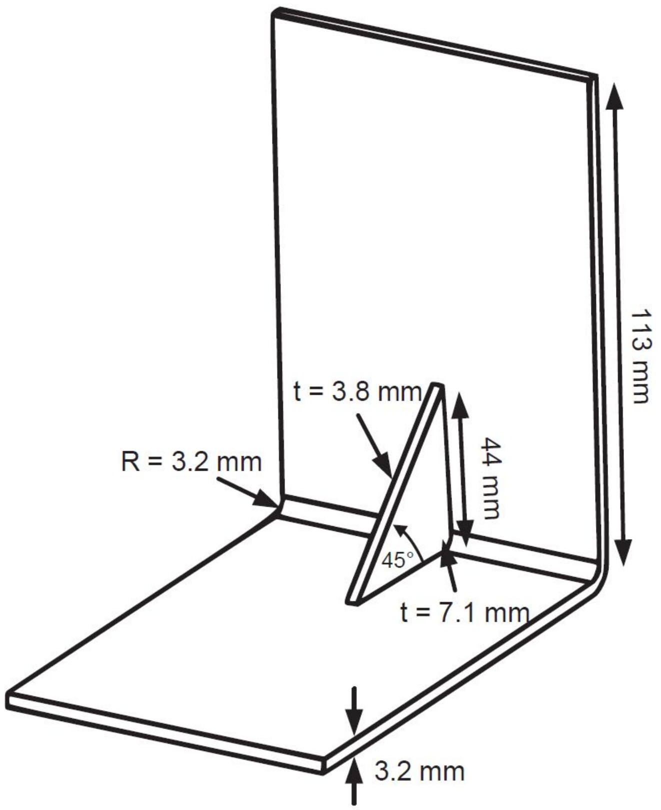
Qian, 2011



Feraboli, 2009

Current challenges:

Lack of acceptance/rejection criteria for defected DFC components

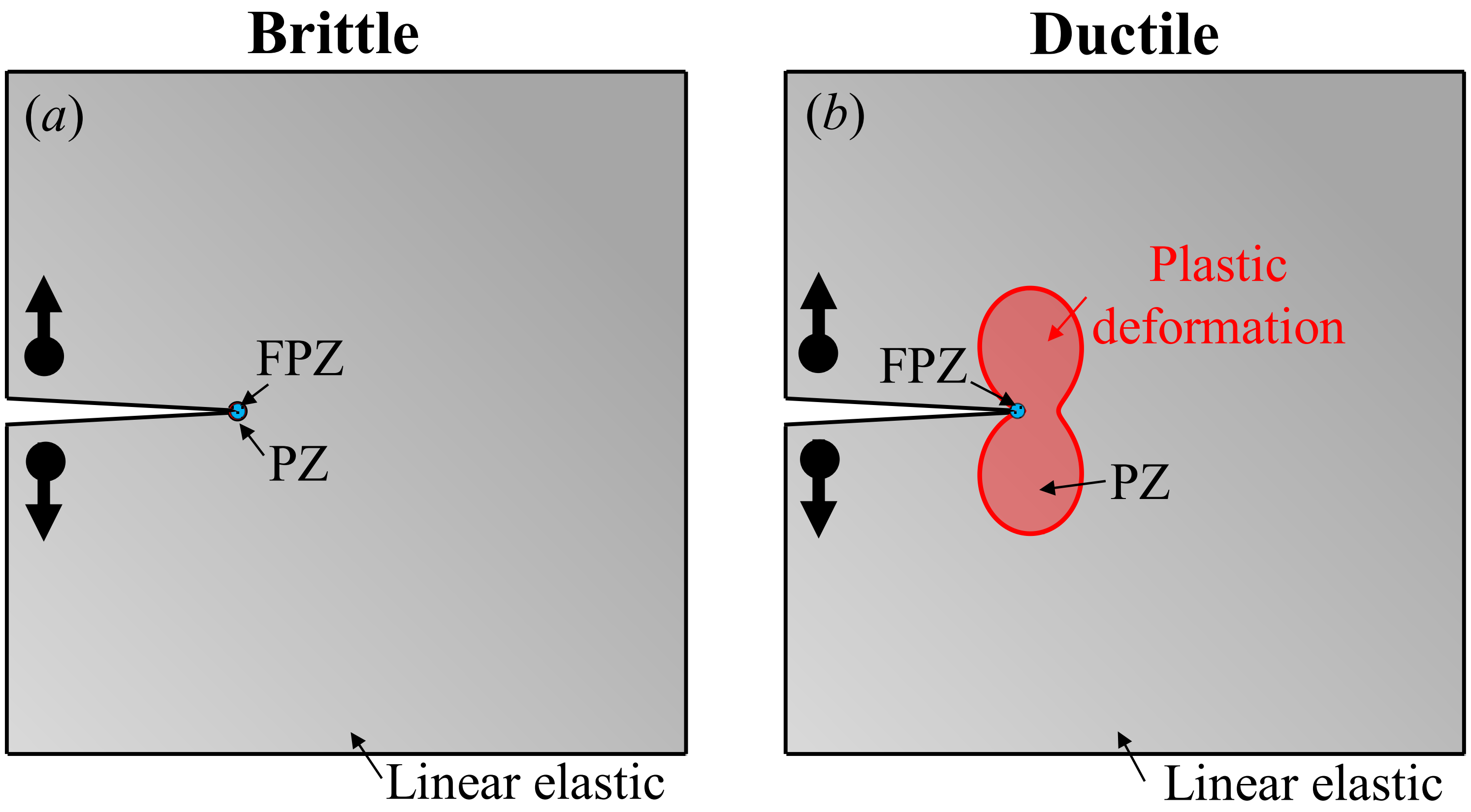


Landry, PhD dissertation, McGill, 2015

Quasi-brittle fracture behavior of DFCs

Effect of the characteristics dimension on the nominal strength

*FPZ = Fracture process zone
*PZ = Plastic zone

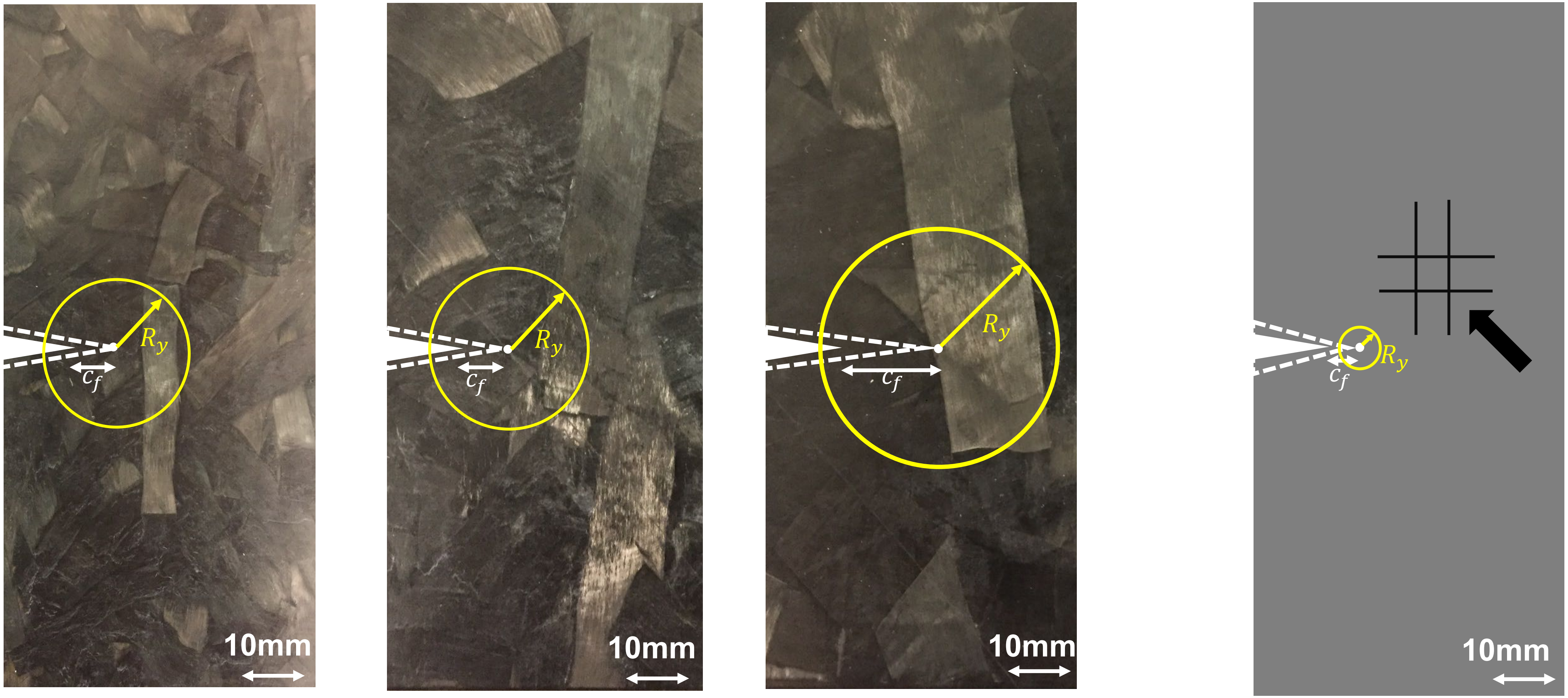


Bazant, 1998

FPZ is large in DFC

Fracture Process Zone in DFCs

Salviato et al. Comp Sci Tech, 2016



Platelet size: 25×4 mm
Thickness: 3.3 mm
c_f **= 6.55 mm,** R_y **= 8.85 mm**

Platelet size: 50×8 mm
Thickness: 3.3 mm
c_f **= 7.43 mm,** R_y **= 10.87 mm**

Platelet size: 75×12 mm
Thickness: 3.3 mm
c_f **= 14.16 mm,** R_y **= 17.95 mm**

Carbon twill 2×2
Thickness: 1.9 mm
c_f **= 1.81 mm,** R_y**= 5.01 mm**

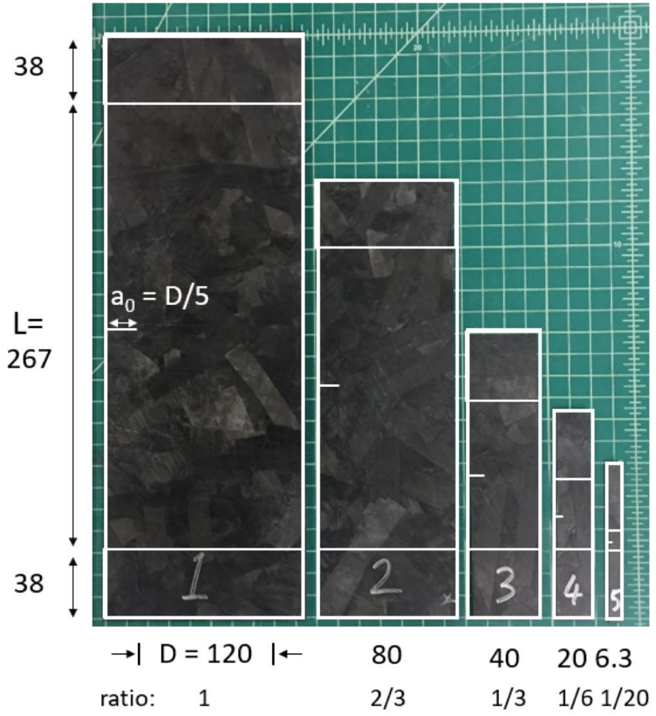
Objectives:

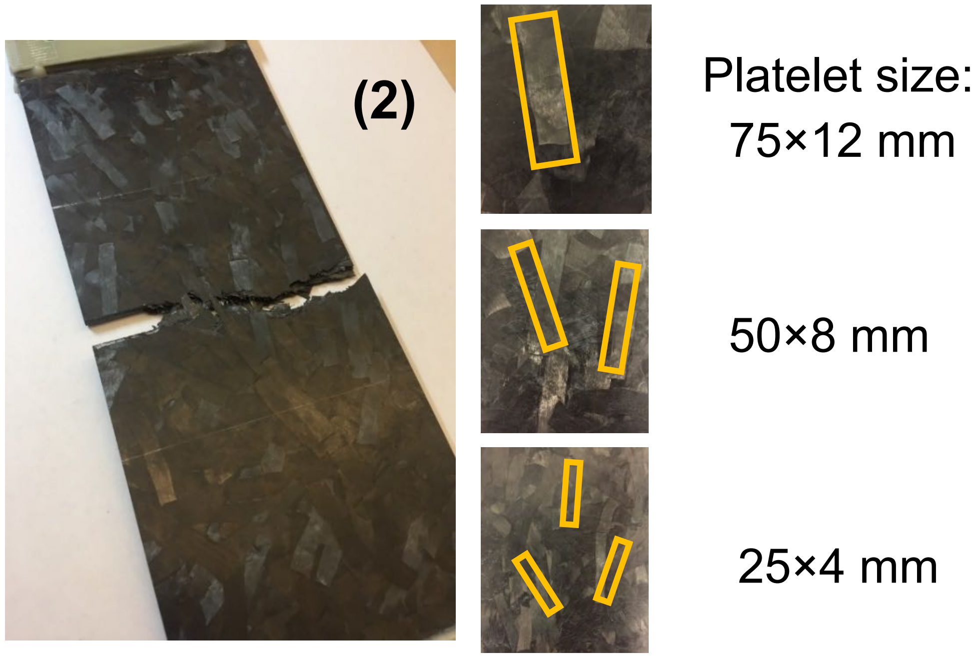
(1) To develop an *experimental protocol for the characterization of fracture toughness of DFCs*

(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*

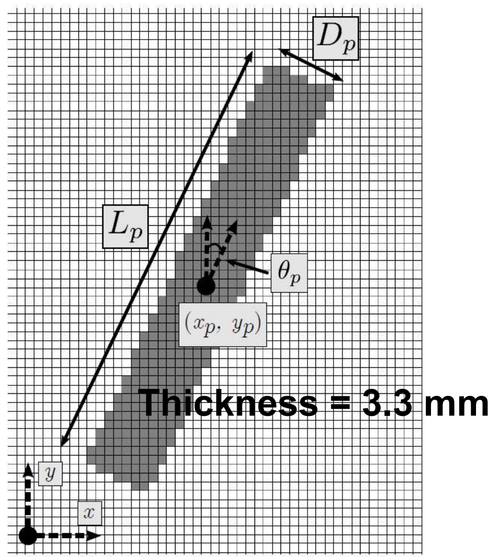
(3) To *formulate certification guidelines and computational tools for DFC parts subject to intra-laminar defects or featuring sharp notches*

(1)

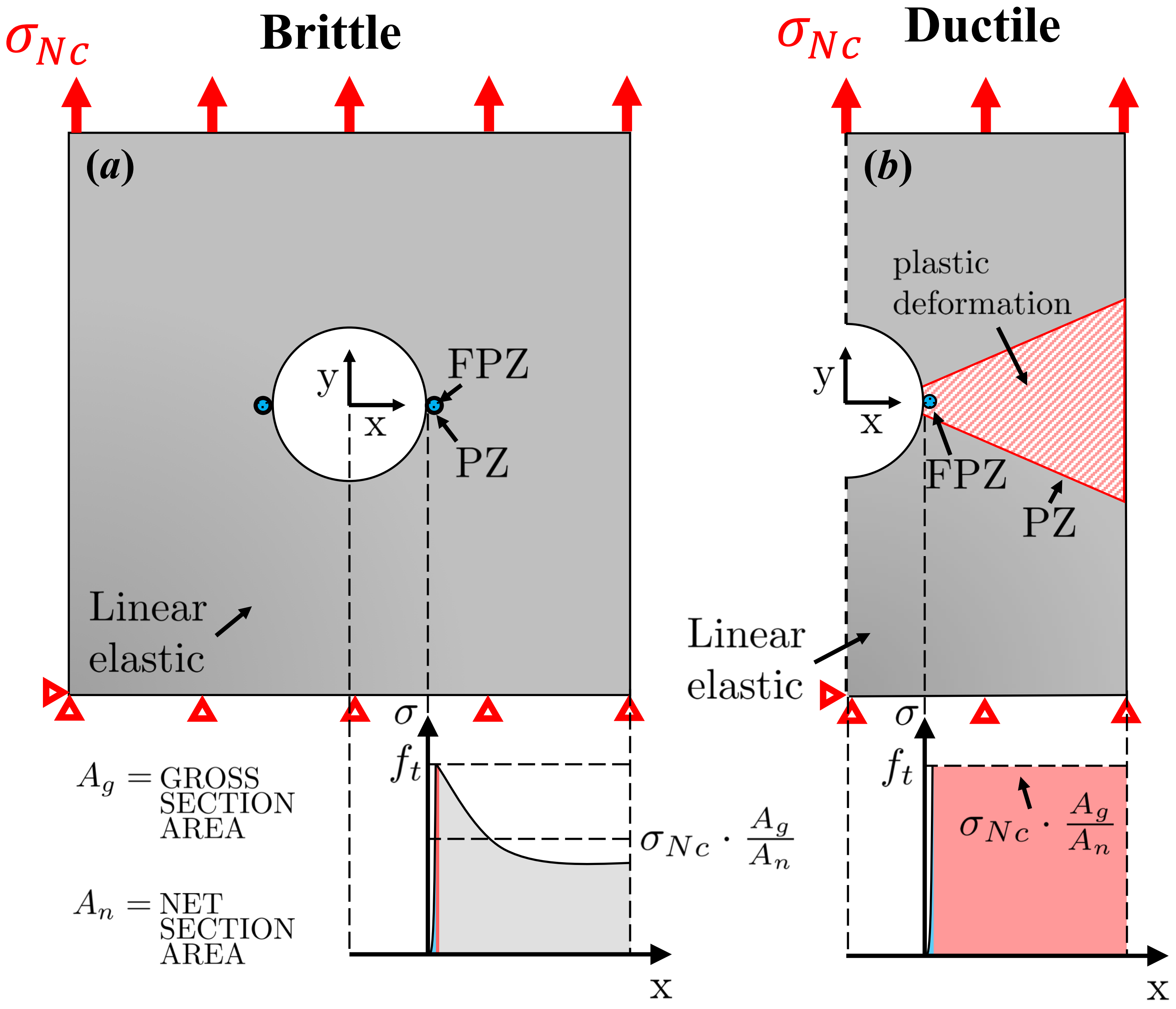




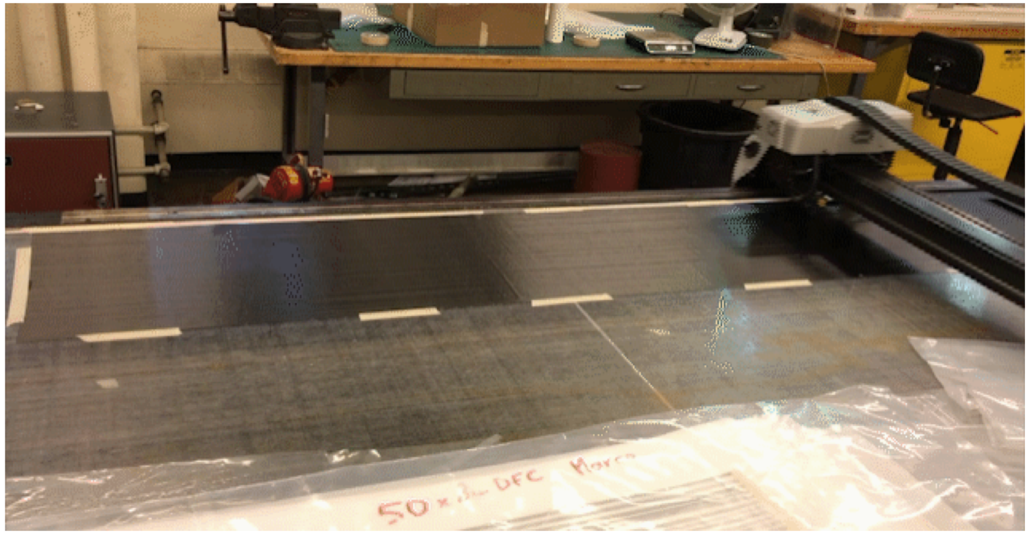
(3)



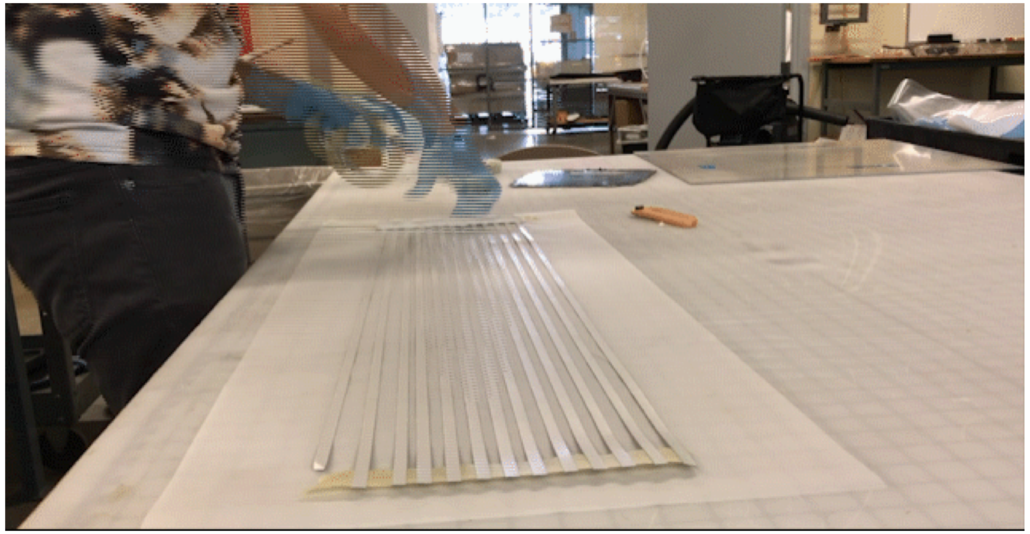
Quasi-brittle behavior of notched DFC structures



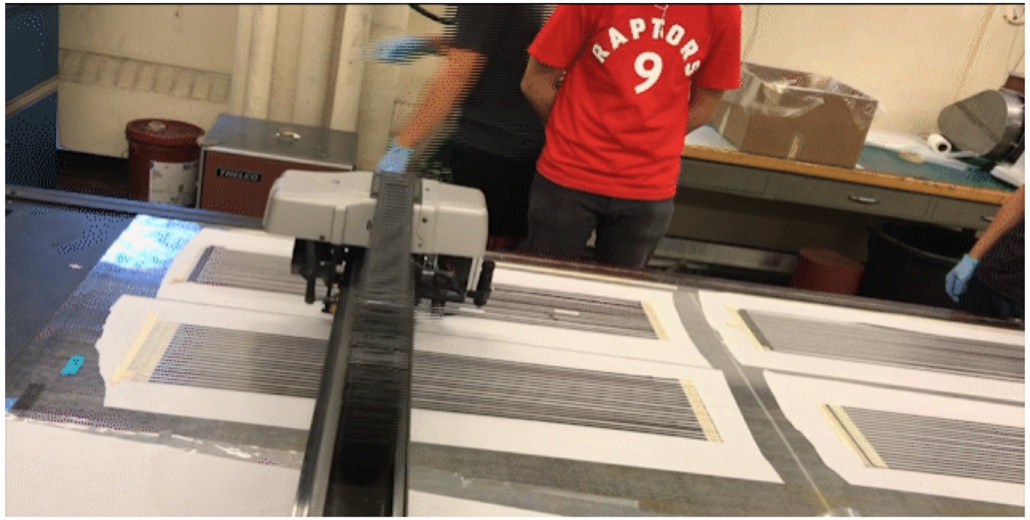
Specimen preparation



1) Cut into strips



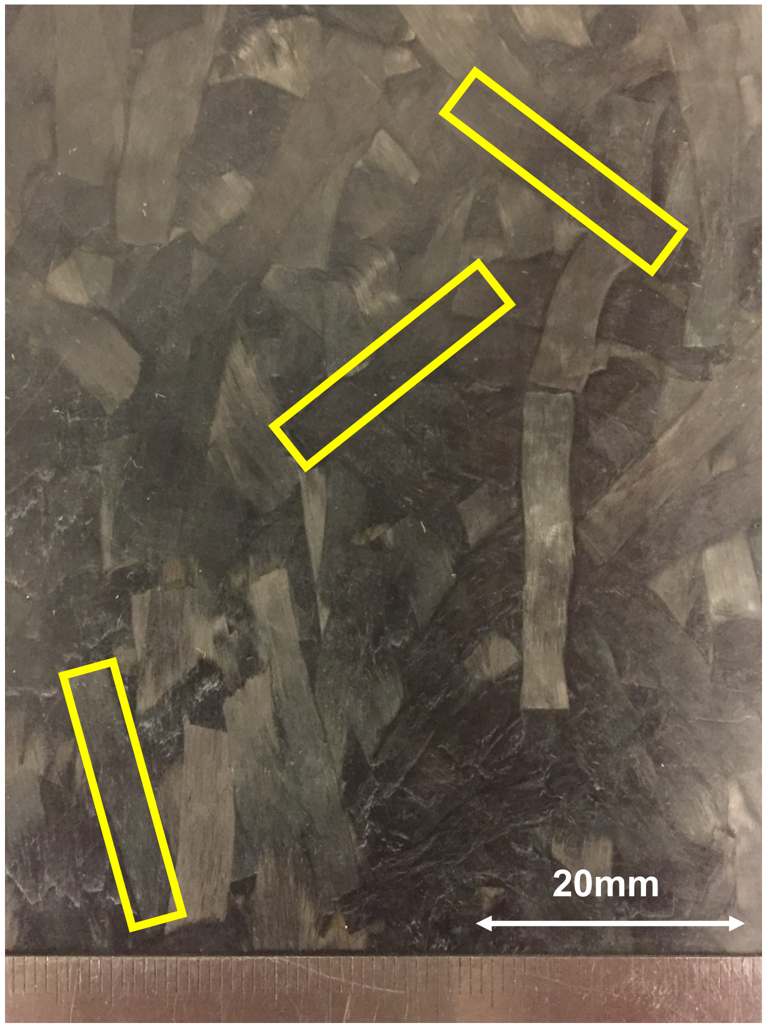
2) Remove backing tape



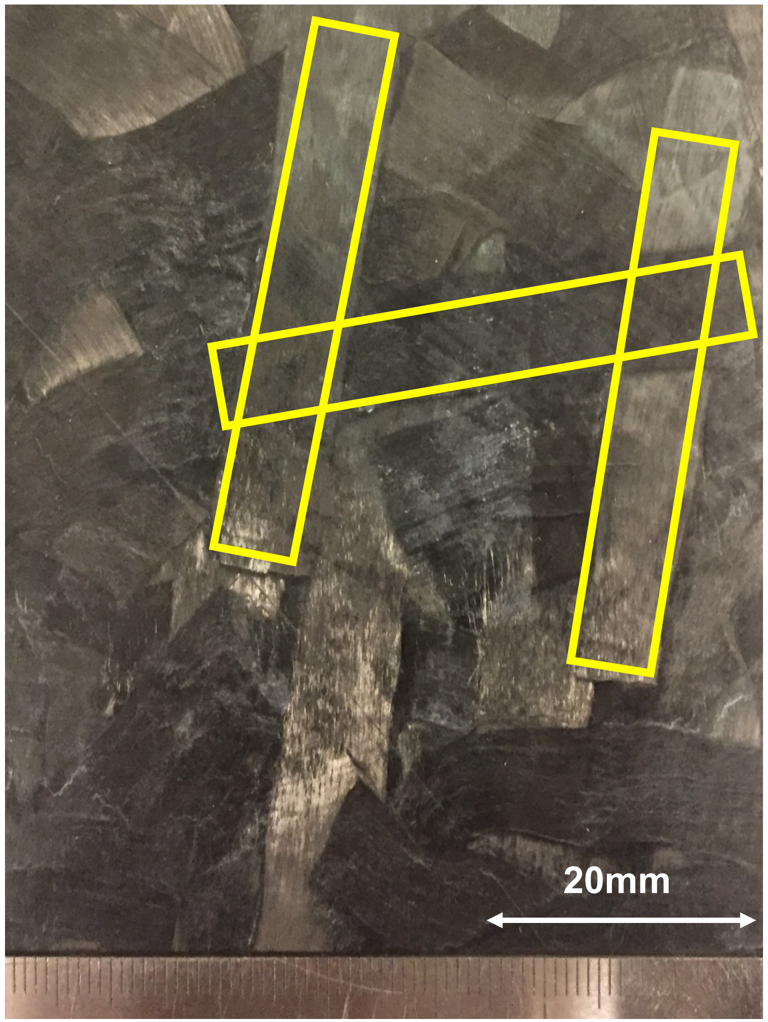
3) Cross-cut the strips

4) Distribute platelets randomly

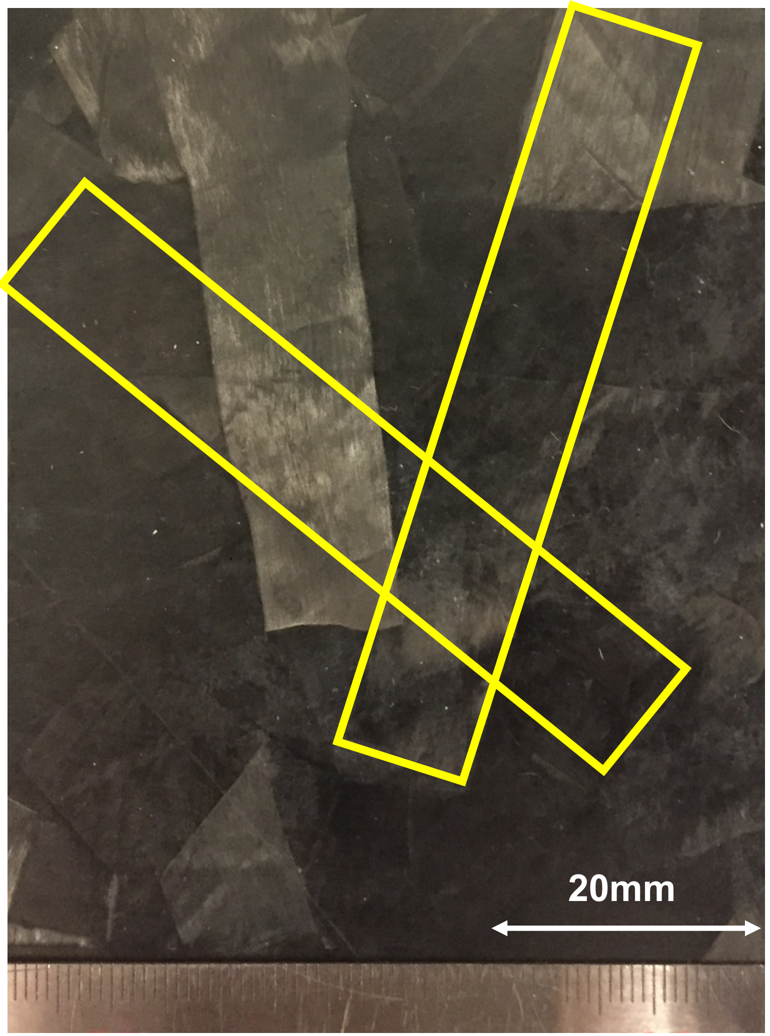
Investigated Platelet Sizes



25×4 mm



*50×8 mm



75×12 mm

*platelet size is commonly used in commercial products

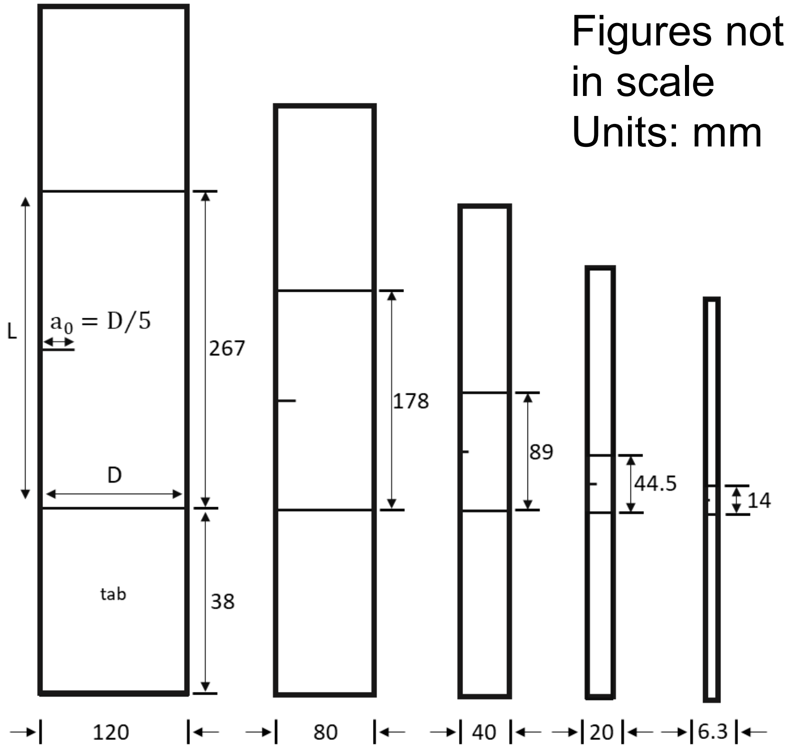
Feraboli et al. J. Reinf Plast and Comps, 2009, Boursier et al. SAMPE, 2010

Summary of Platelets Sizes and Thicknesses Investigated

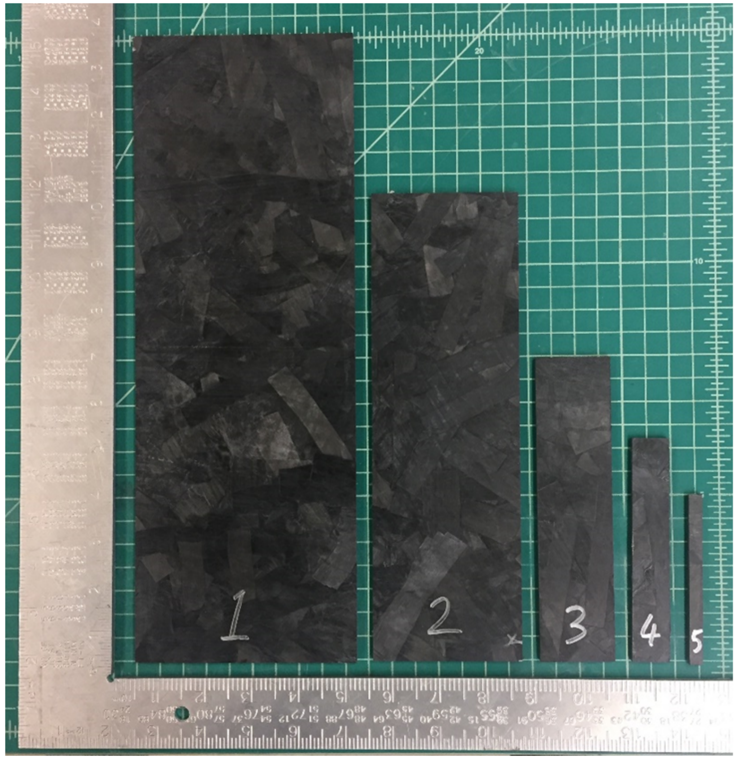
	Platelet size effect study			Thickness effect study			Platelet size effect study	
	Thermoset						Thermoplastic	
Size	75×12 mm, T = 3.3 mm	50×8 mm, T = 3.3 mm	25×4 mm, T = 3.3 mm	50×8 mm, T = 4.4 mm	50×8 mm, T = 2.1 mm	50×8 mm, T = 1.1 mm	12.7×12.7 mm, T = 3.8 mm	12.7×1.58 mm, T = 3.8 mm
1	3	2	3	*-	*-	*-	5	5
2	3	3	3	7	5	5	7	6
3	9	6	9	9	8	7	5	6
4	8	7	7	11	9	9	14	8
5	4	9	7	11	10	9	-	-
Total1	**27**	**27**	**29**	**38**	**32**	**30**	**31**	**25**
Total2	**239**							

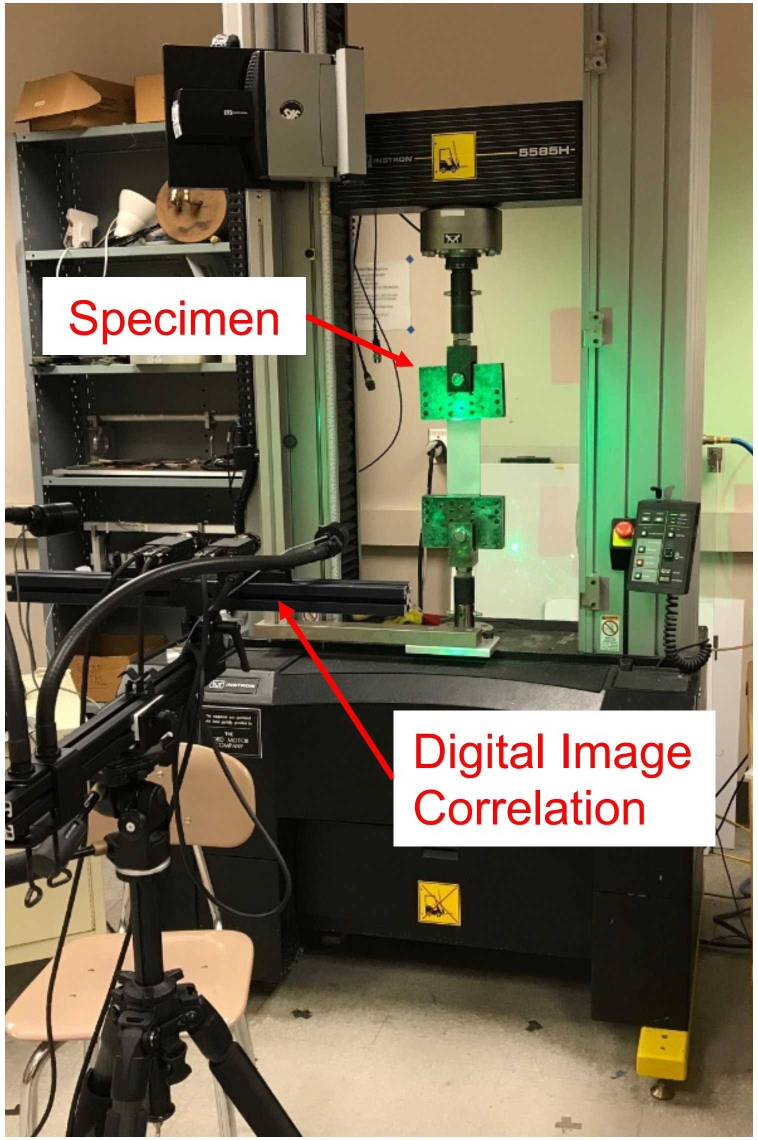
*** Coupon is well within the LEFM region, no need to test it.**

Specimen geometry



Figures not in scale
Units: mm



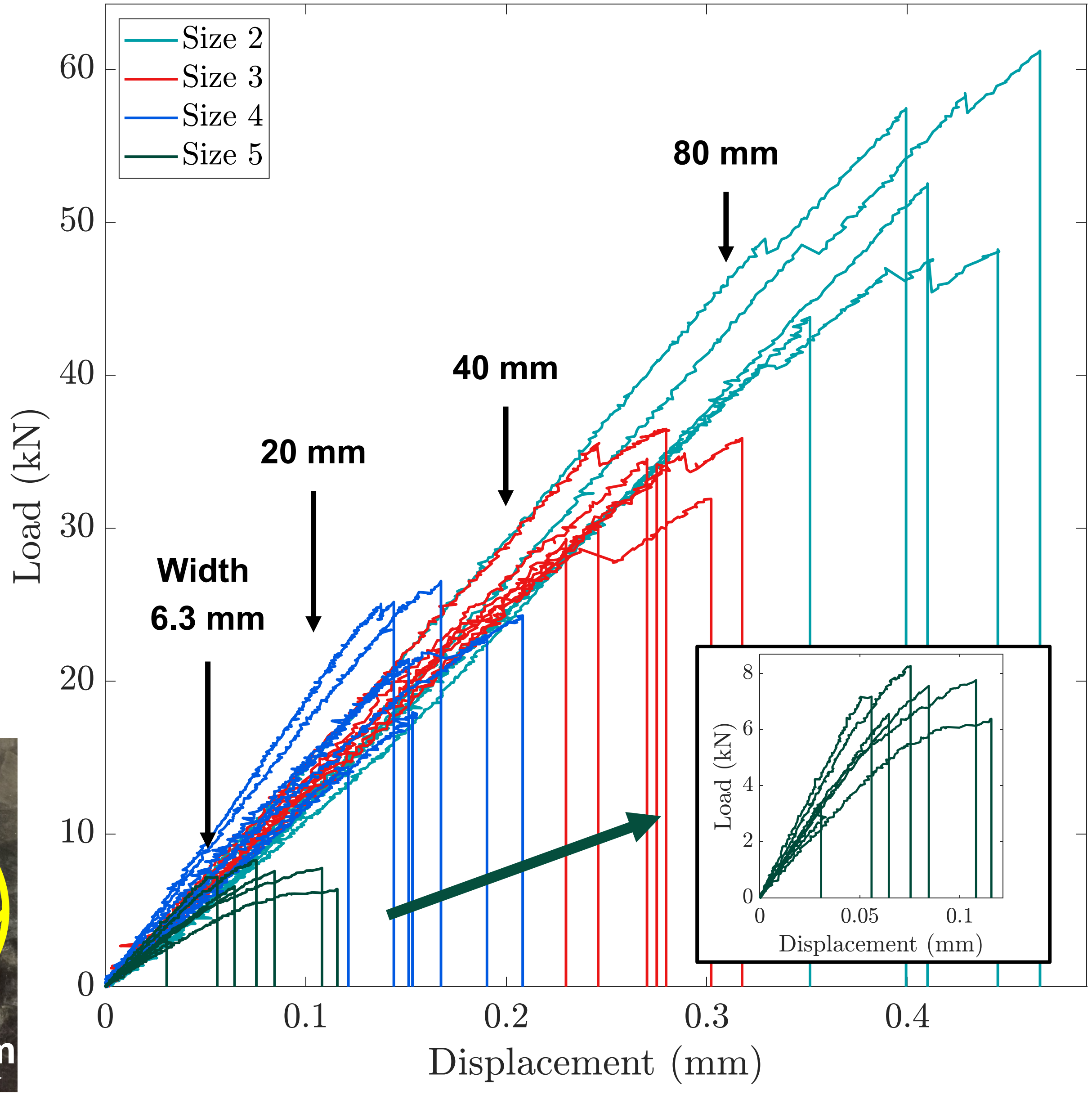


- Coupon sizes are proportionally scaled in width, gauge length, and crack length
- Thickness is constant = 3.3 mm

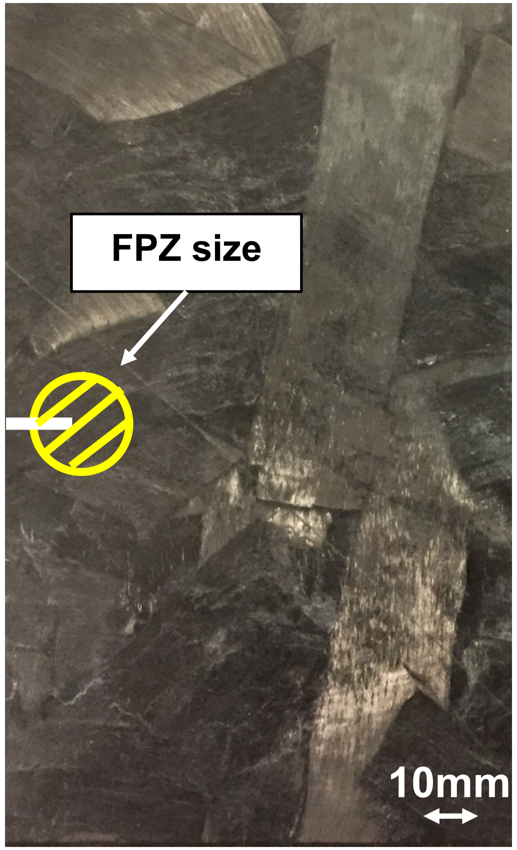
Typical Force and Displacement curves

20 mm

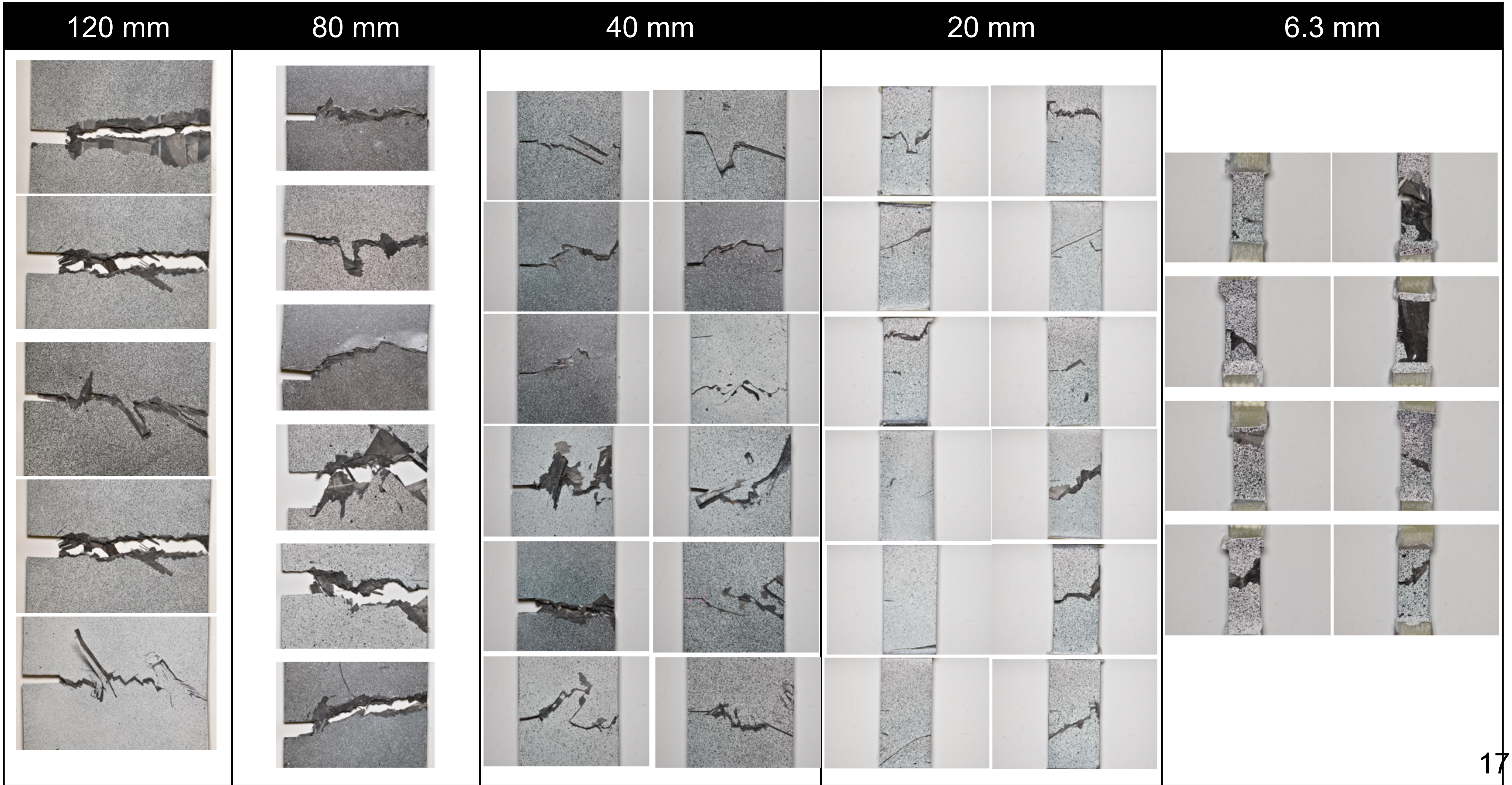
FPZ size



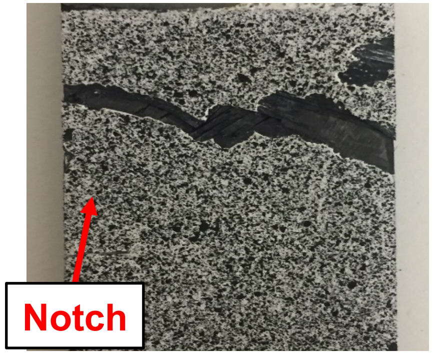
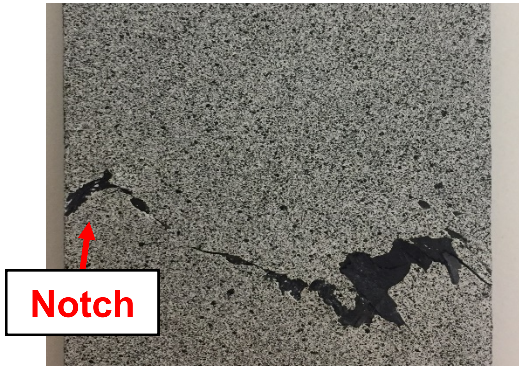
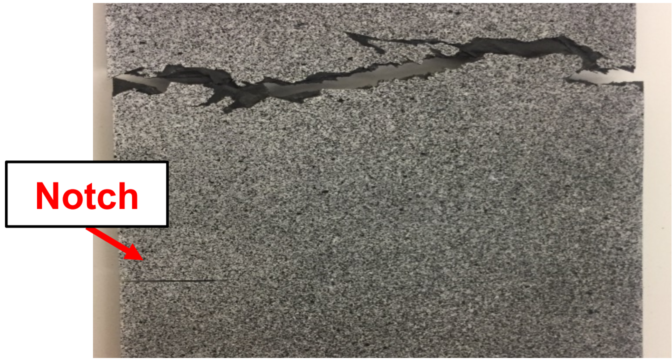
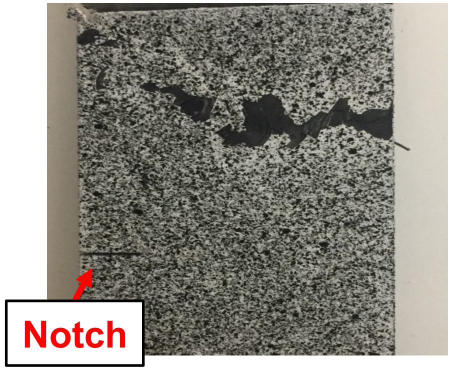
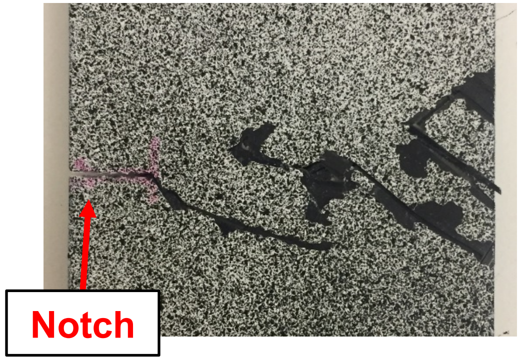
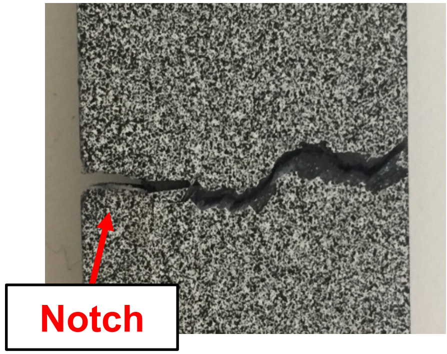
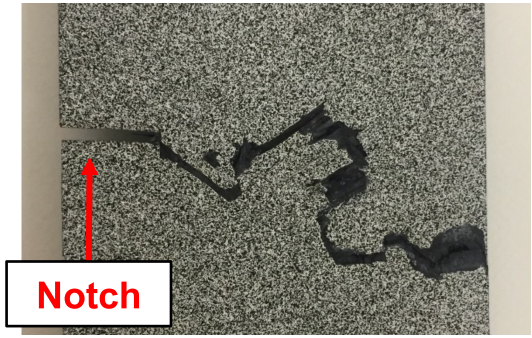
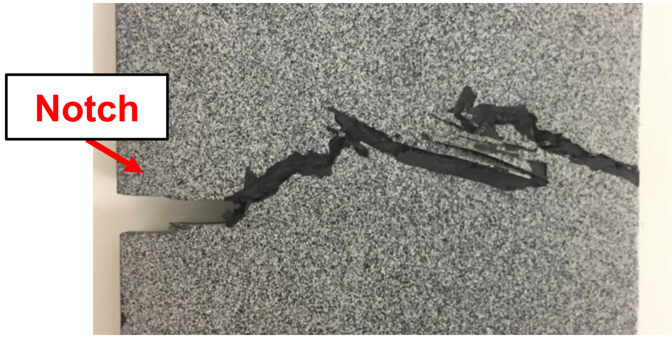
80 mm



Typical Fracture Surfaces (50 x 8 mm platelets)

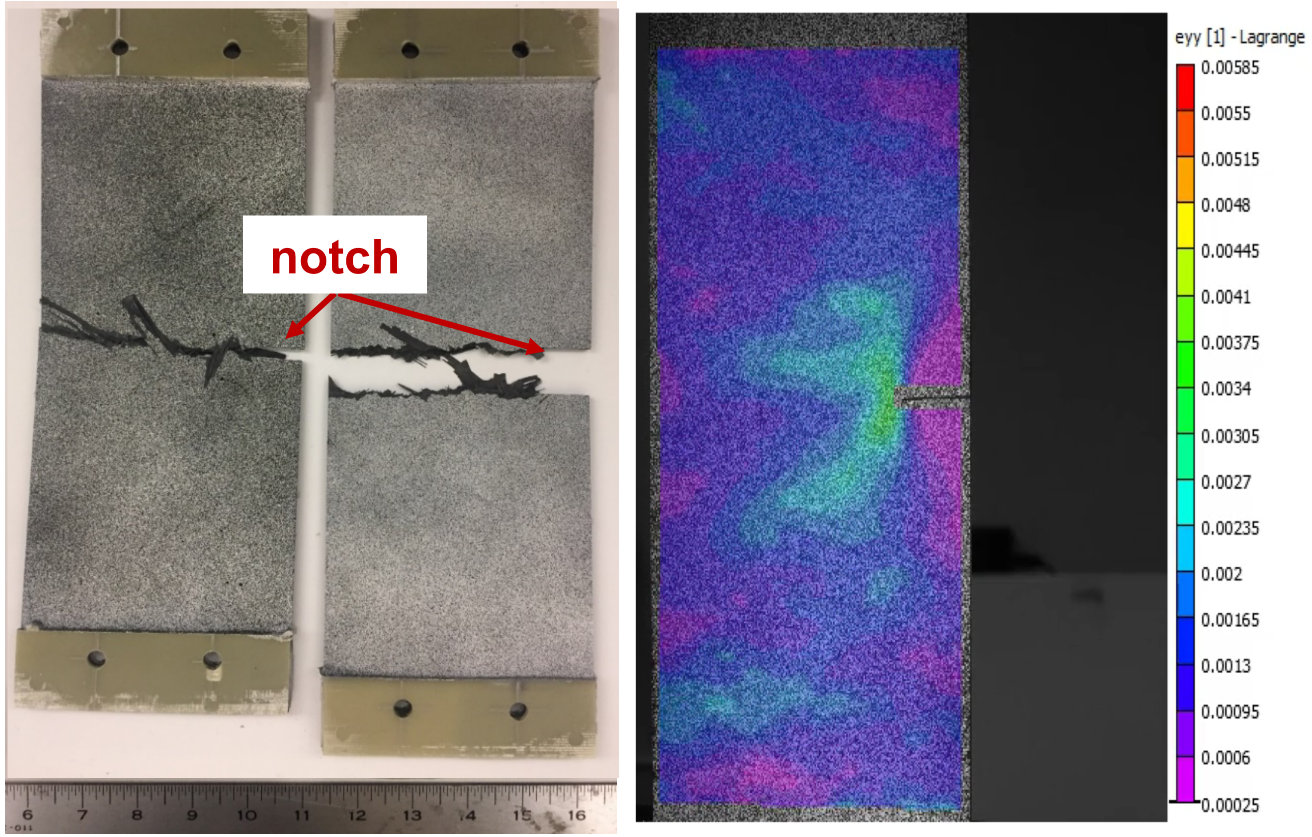


Fracture Surfaces (50 x 8 mm platelets) – thickness effect

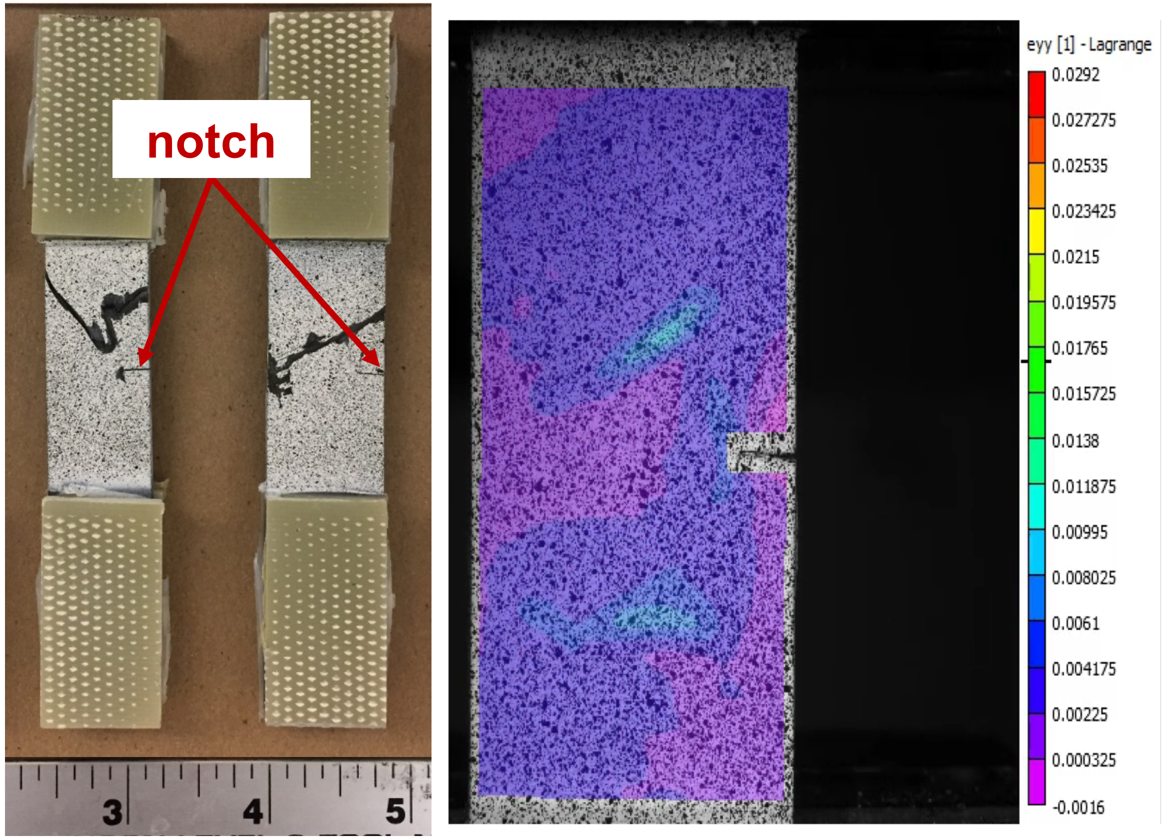
	D = 20 mm	D = 40 mm	D = 120 mm
1.1 mm			
2.2 mm			
4.1 mm			

Result: Fracture surfaces and DIC

Platelet size of 75×12 mm



Width = 120 mm



Width = 20 mm

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:

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

$\alpha = a/D$

$E* = \text{effective modulus}$

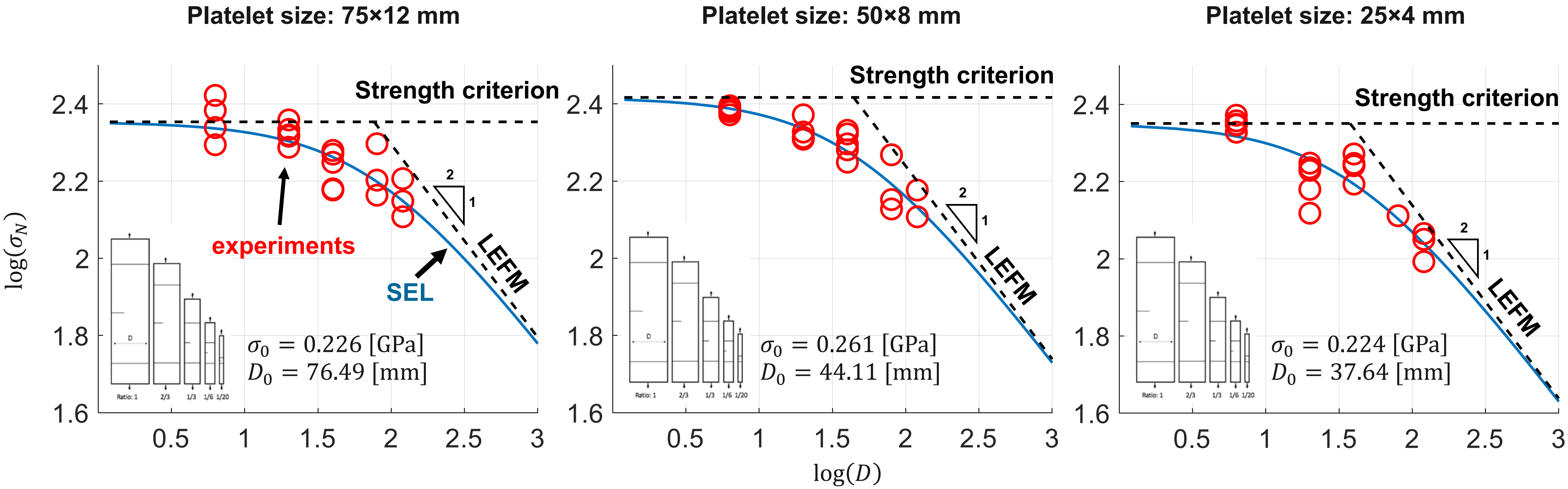
$g = \text{dimensionless energy release rate}$

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

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

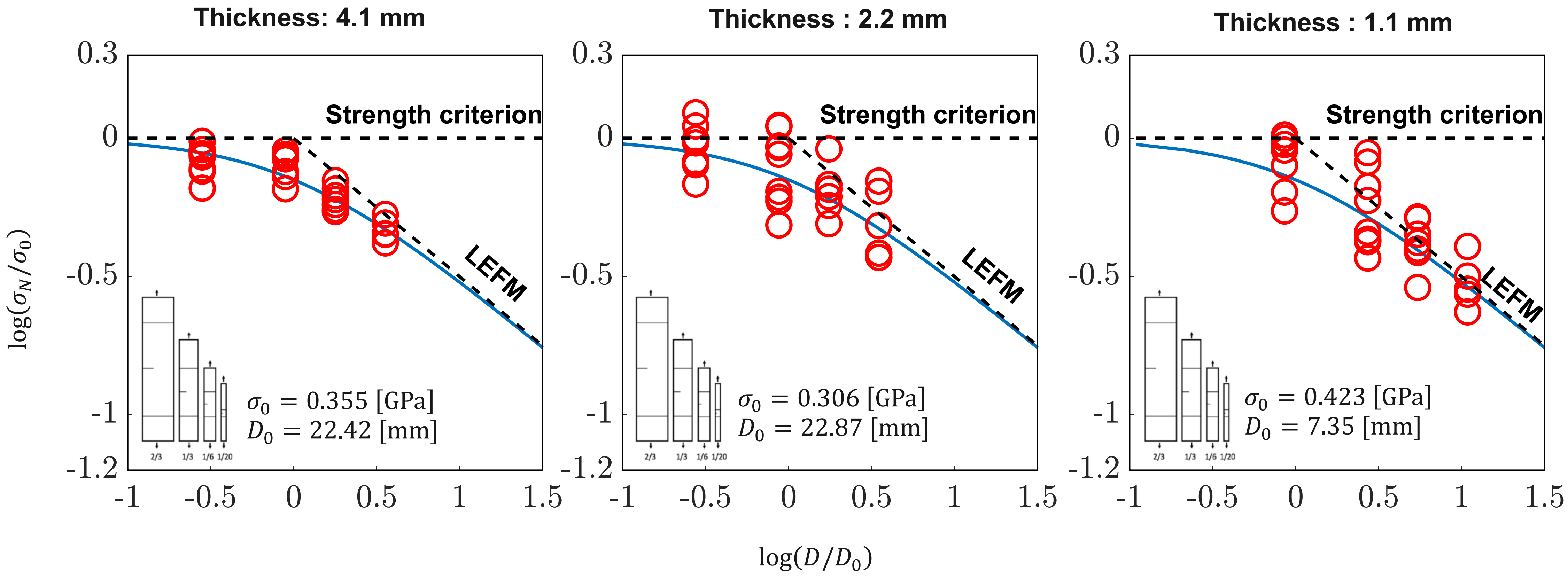
Bažant's Size Effect Law (SEL) for quasi-brittle materials (extended to DFCs)

Result: Size effect curves – (varying platelet size)

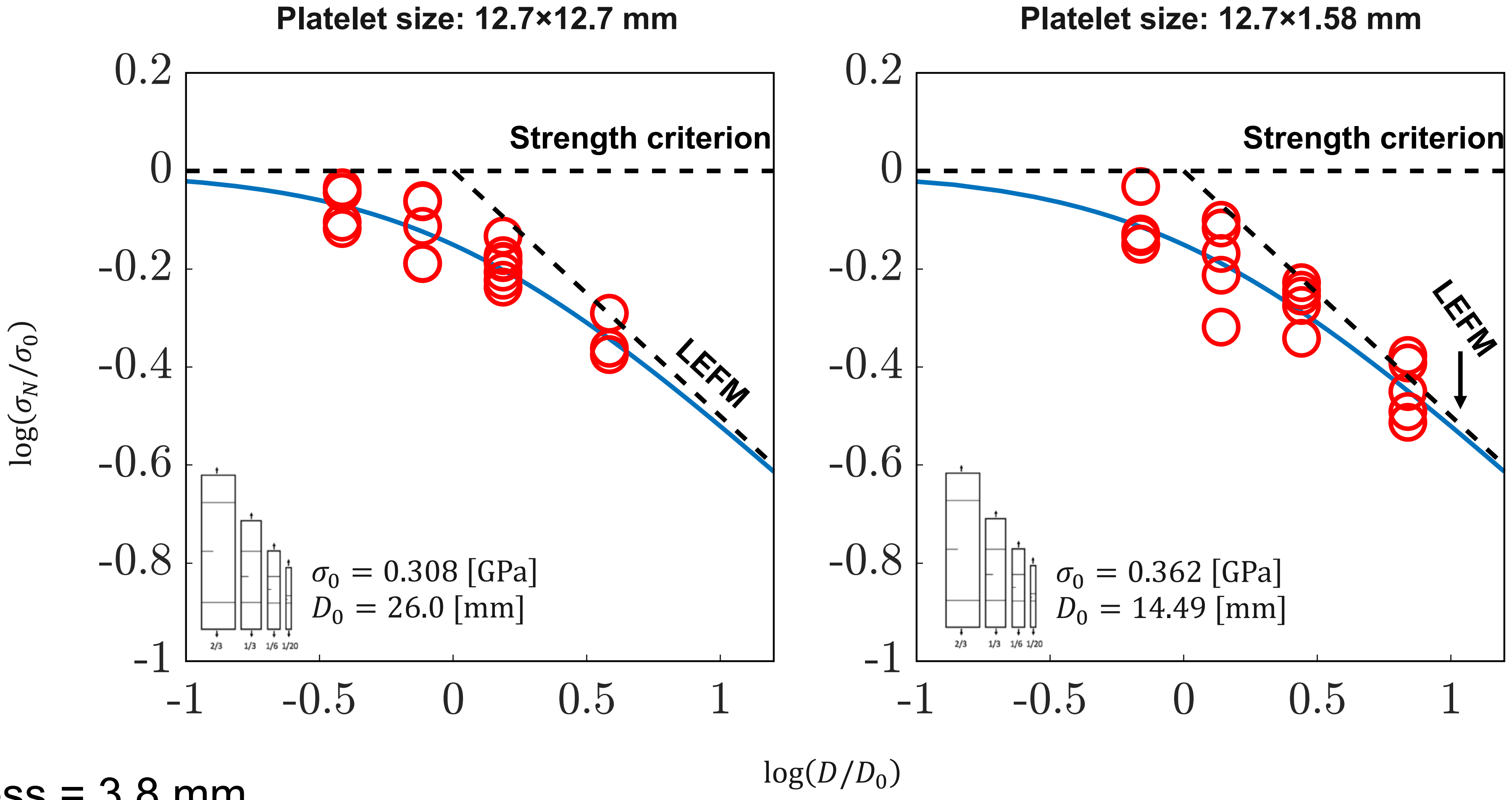


1. DFC shows a strong size effect.
   a) we can clearly observe the transition from the strength to energy driven fracture.
   b) Neither strength nor LEFM can predict the behavior of the DFC.
   c) The notch insensitivity is observed when the specimen size is moving away from LEFM region (or when the 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

Result: Size effect curves – (varying thickness)



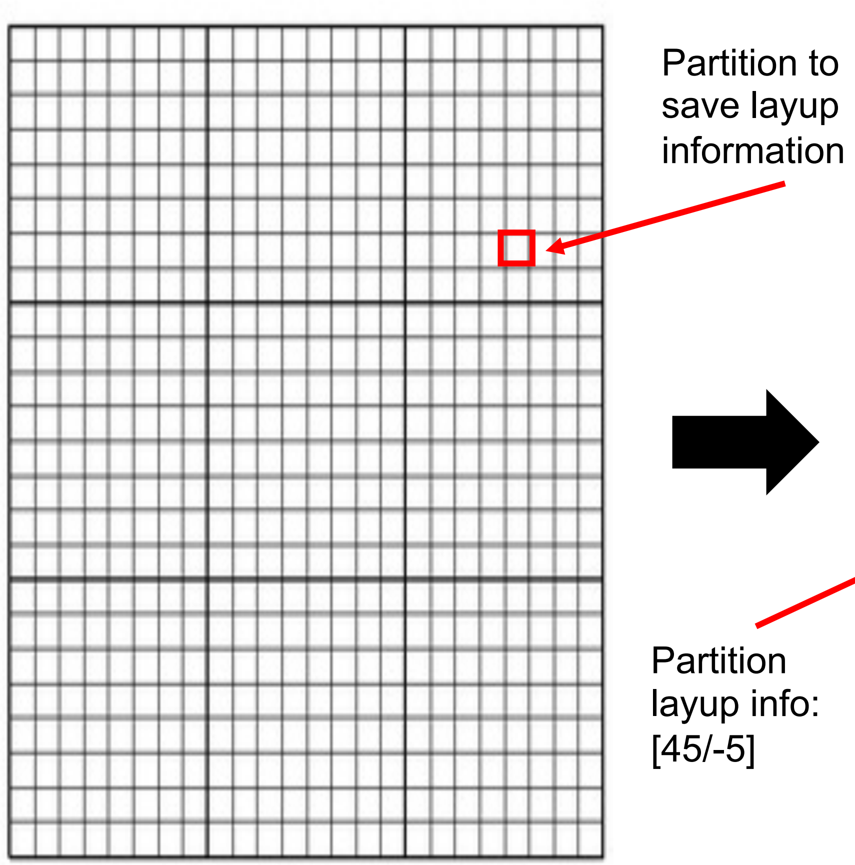
Result: Size effect curves – (thermoplastics)



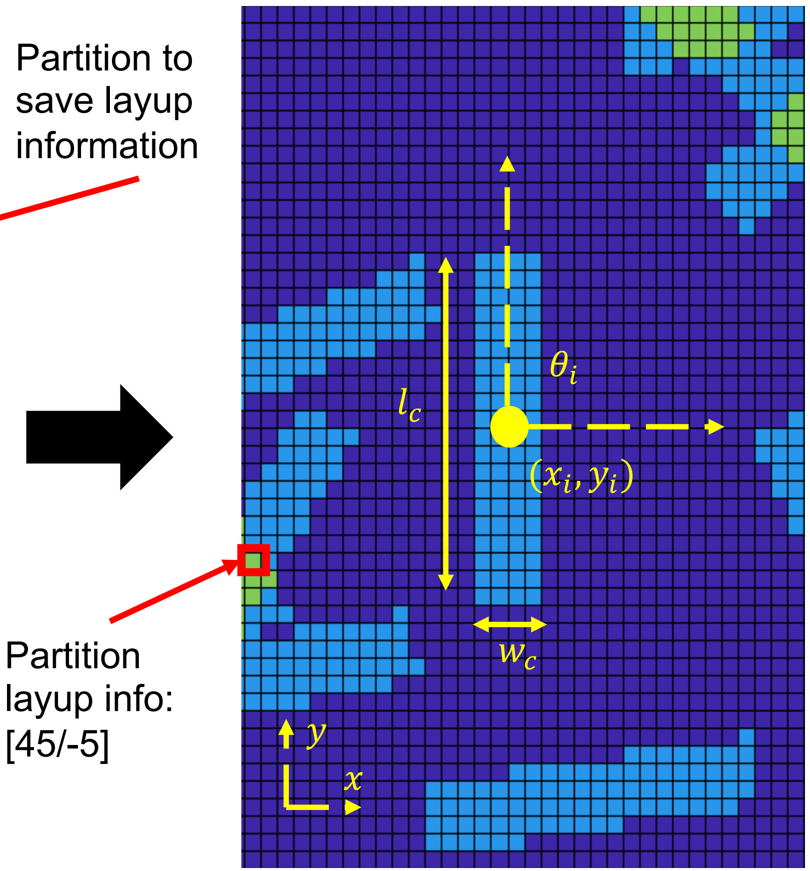
*Thickness = 3.8 mm

Microstructure generation

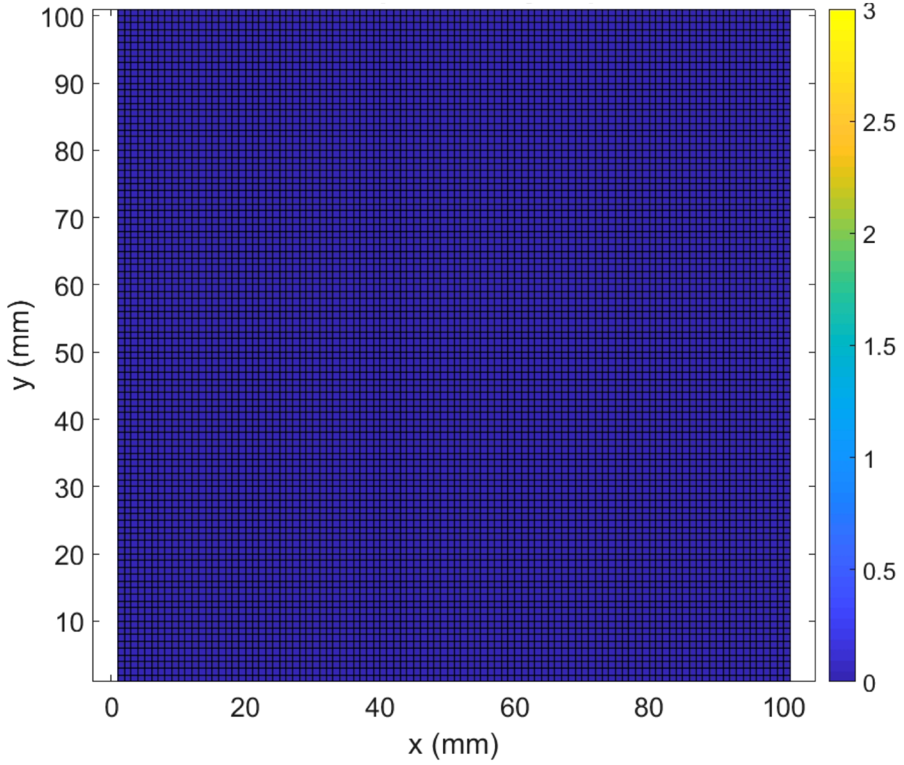
- Finite element model is based on stochastic laminate analogy [Tuttle, 2010, Selezneva, 2015]
- Platelet center point and its orientation is randomly chosen



Partition generation

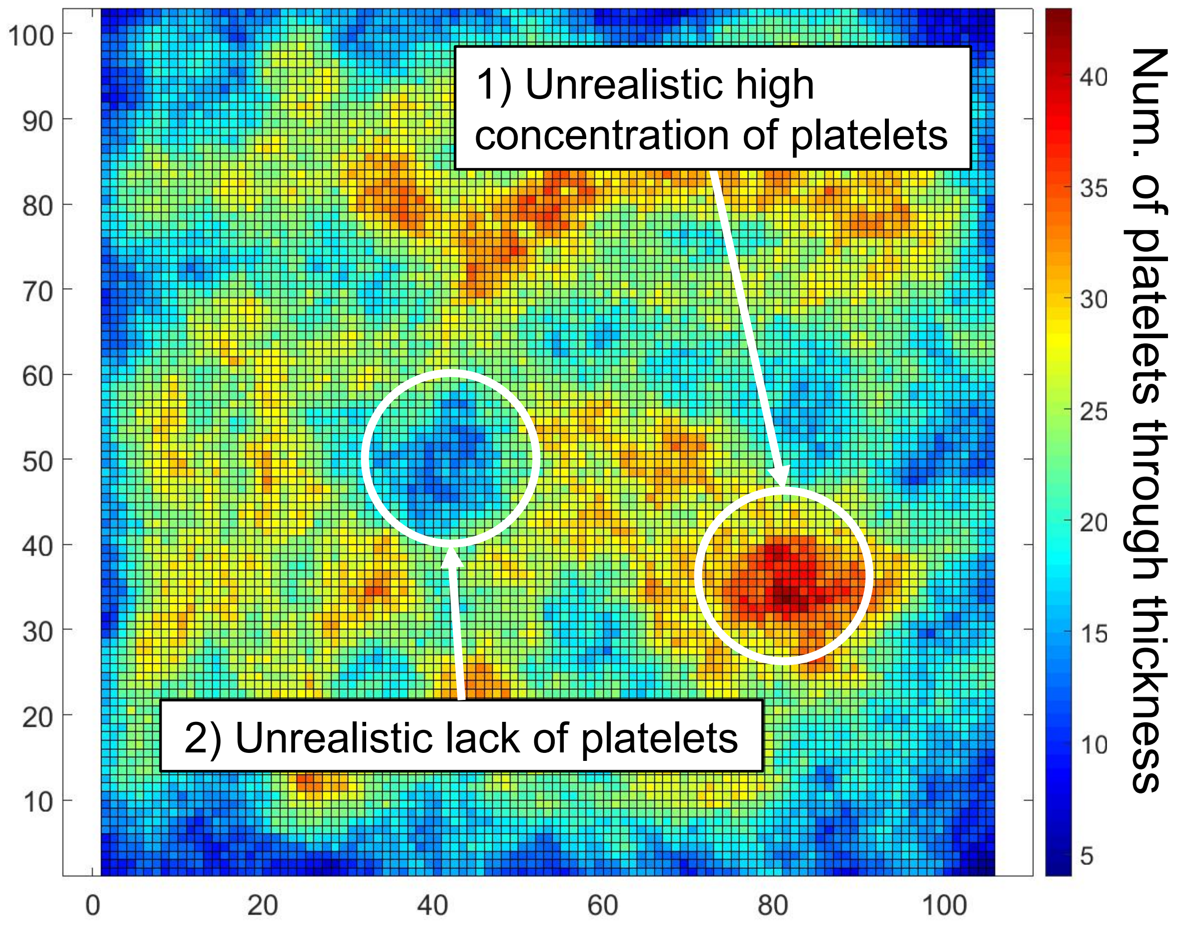


Random platelet generation



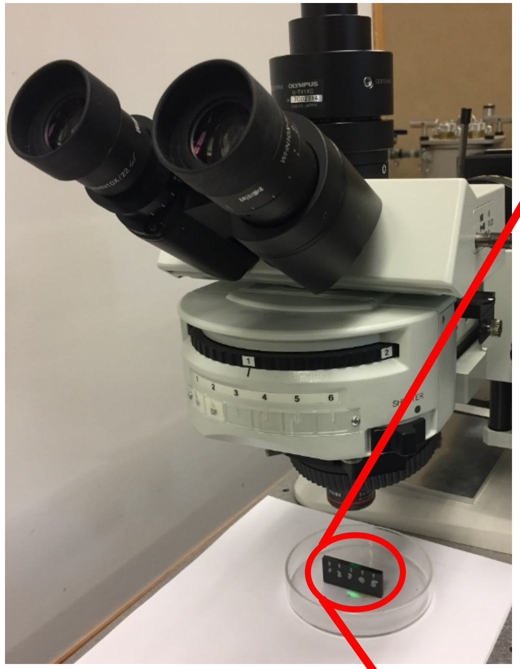
Example of platelet generation

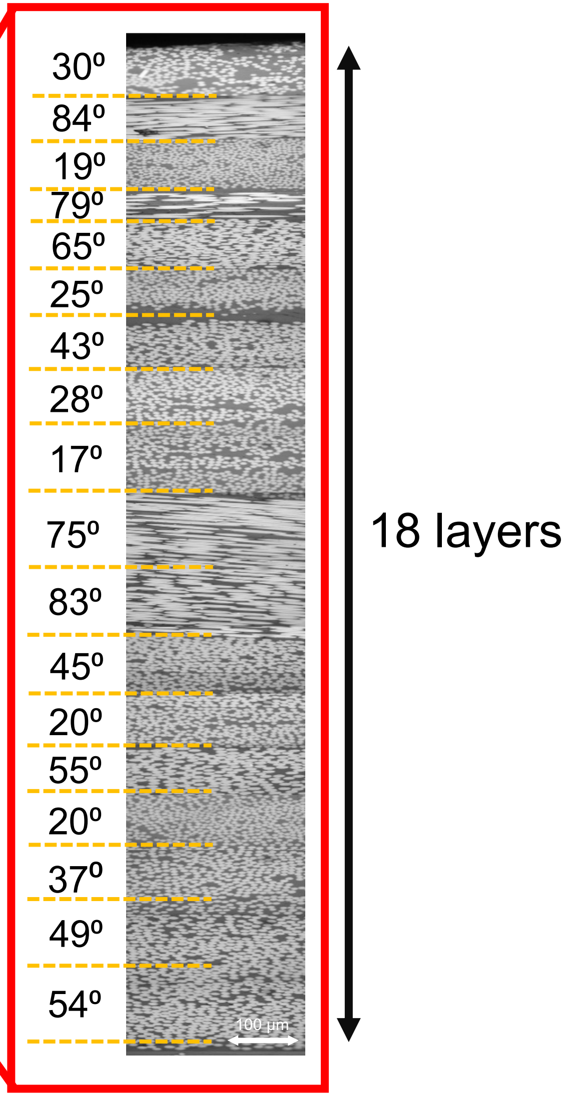
Problem with platelet distribution algorithm



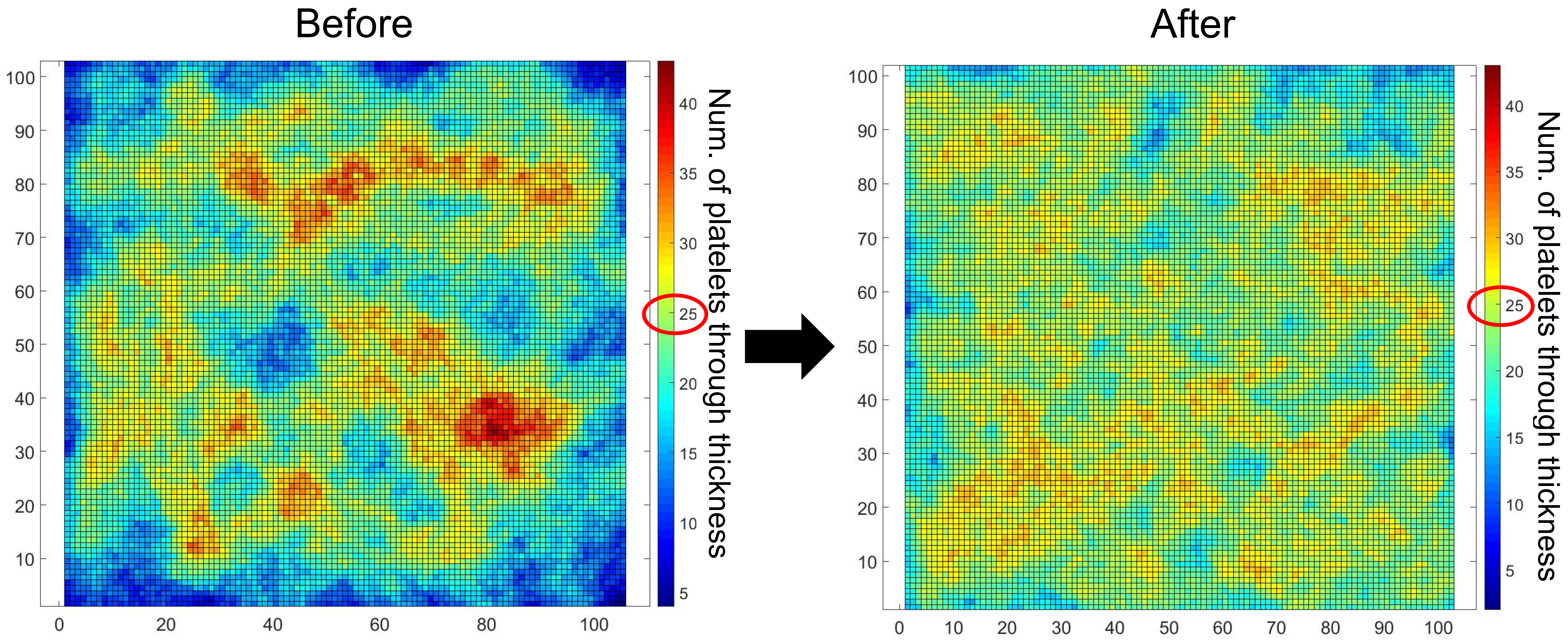
*target average number of platelets through thickness = 25

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





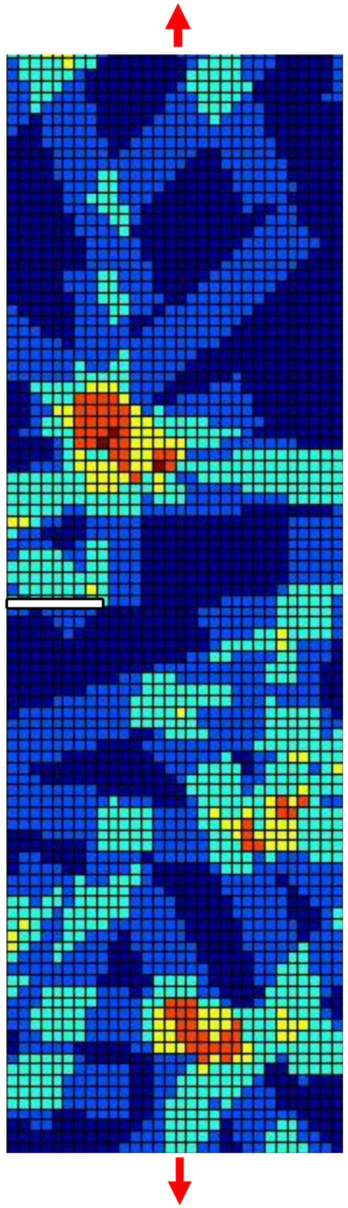
Calibrated platelet distribution algorithm



*target average number of platelets through thickness = 25

No high concentrations nor lack of platelets

Energy-Based Calculation of g and g'



Let's relate the nominal stress to the energy release rate through a dimensionless function g:

$$G = \frac{\sigma_N^2 D}{E^*} g(\alpha), \qquad \sigma_N = \frac{P(u)}{t\,D},$$ where P = load, u = applied displacement

For a given u, G can be calculated by leveraging on its definition:

$$G(u,a) = -\frac{1}{t}\left(\frac{\partial \Pi(u,a)}{\partial a}\right)_u \approx -\frac{1}{t}\frac{\Pi(u,a+\delta a/2)-\Pi(u,a-\delta a/2)}{\delta a}$$

Where Π=total strain energy in structure (= ALLIE in Abaqus)

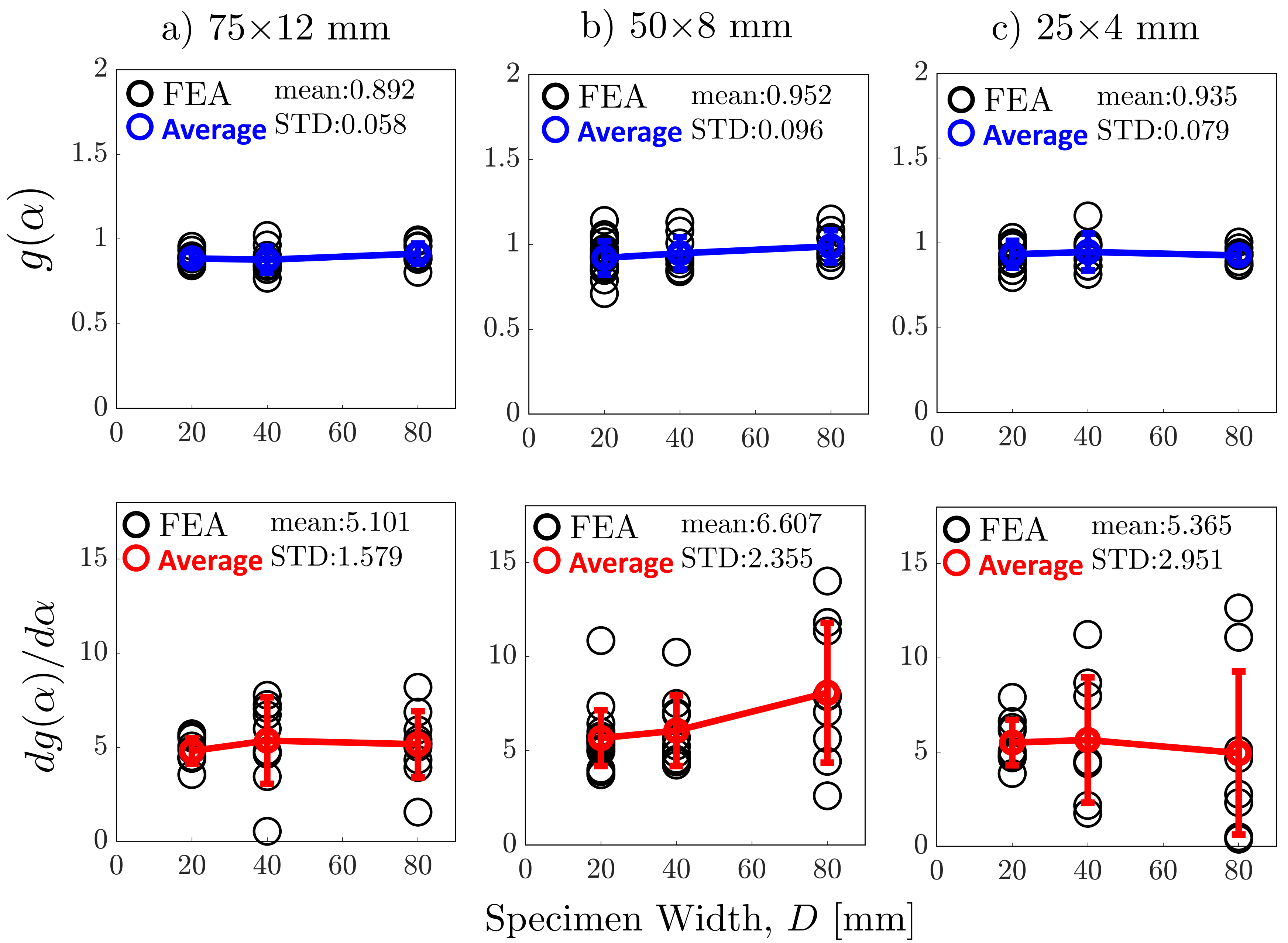
Then, $\boldsymbol{g(\alpha) = \frac{GE^*}{\sigma_N^2 D}}$, and $\boldsymbol{g'(\alpha) = \frac{dg(\alpha)}{da}}$

"g accounts both for the geometry and microstructural effects, therefore it is important to explicitly model the DFC's microstructure"

Finally,

$$G_f = \frac{\sigma_N^2 D}{E^*} g(\alpha_0), \text{ and } c_f = \frac{D_0 g'(\alpha_0)}{g(\alpha_0)}$$

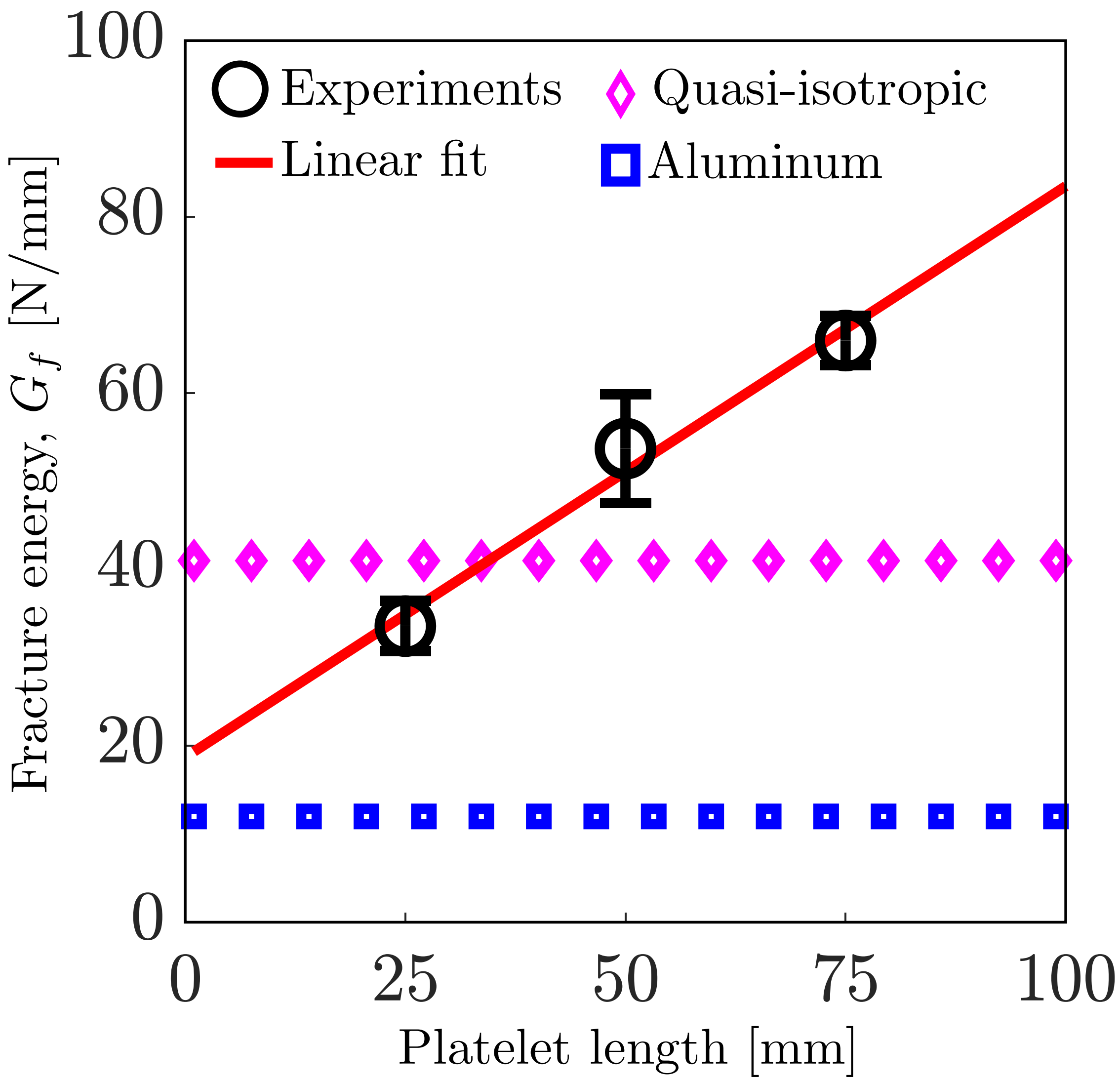
Dimensionless Energy Release Rates in DFCs



Intra-laminar mode I fracture energy of DFC (platelet effect)

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

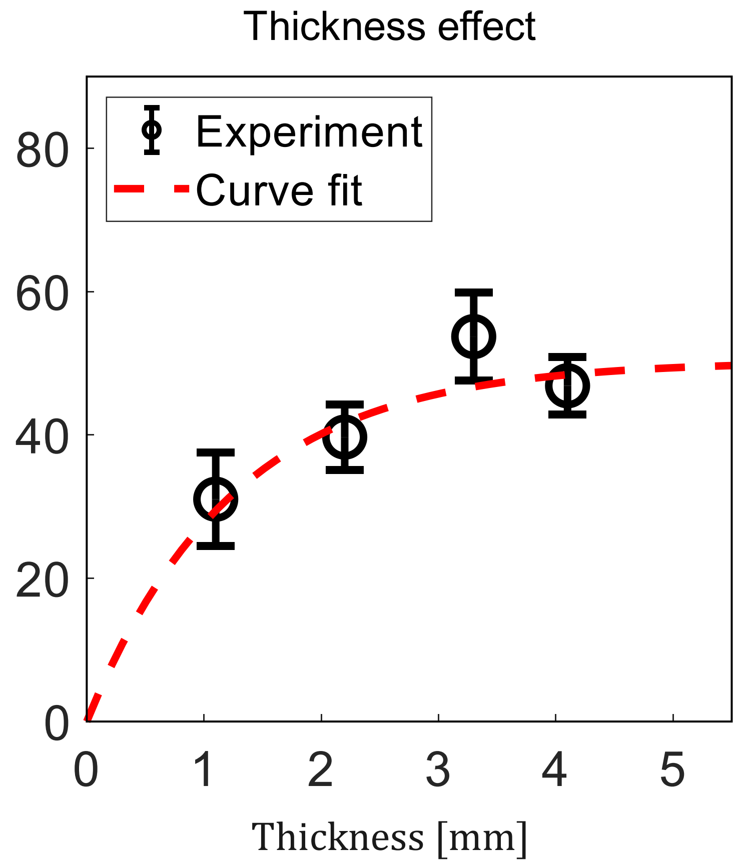
	Effective FPZ length, c_f (mm)	Fracture energy, G_f (N/mm)
25×4 (mm)	6.55 ± 1.07	33.59 ± 2.86 Δ0.0%
50×8 (mm)	7.43 ± 0.83	53.72 ± 6.14 Δ59.9%
75×12 (mm)	14.2 ± 1.85	64.98 ± 2.79 Δ93.5%



Intra-laminar mode I fracture energy of DFC (thickness effect)

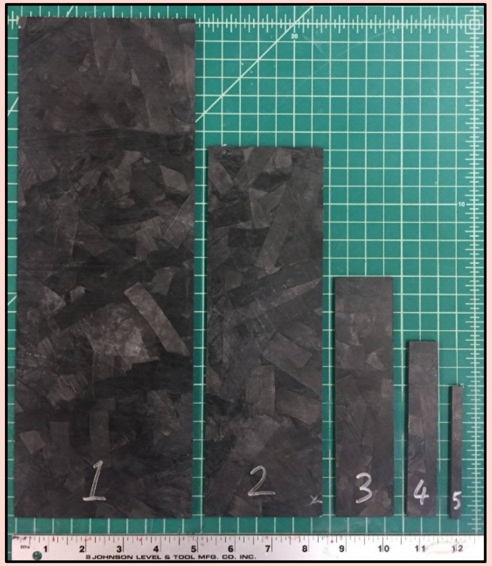
Size effect law: $\sigma_N = \sqrt{\frac{E^* G_f}{D g(\alpha_0) + c_f g'(\alpha_0)}}$

	Effective FPZ length, c_f (mm)	**Fracture energy, G_f (N/mm)**
1.1 (mm)	1.33 ± 0.63	31.02 ± 6.50 Δ0.0%
2.2 (mm)	3.84 ± 0.65	39.69 ± 4.56 Δ28.0% ↑
3.3 (mm)	7.43 ± 0.83	53.72 ± 6.14 Δ73.3% ↑
4.1 (mm)	3.70 ± 0.46	46.85 ± 3.99 Δ51.1% ↑



Material Properties:

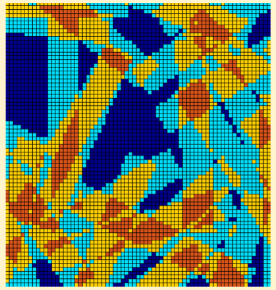
Find G_f, c_f

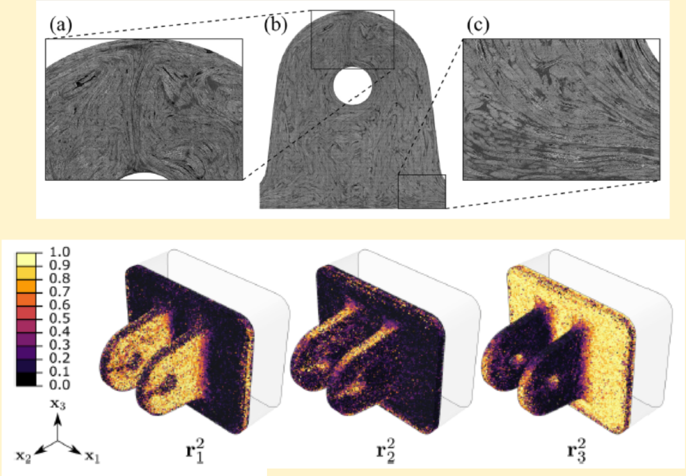


Size effect tests

Platelet Morphology Characterization:

- Computational
- µ-CT scan

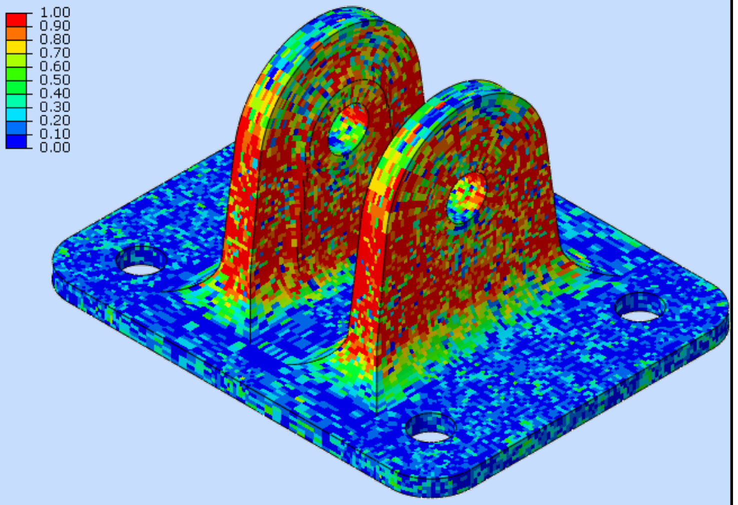




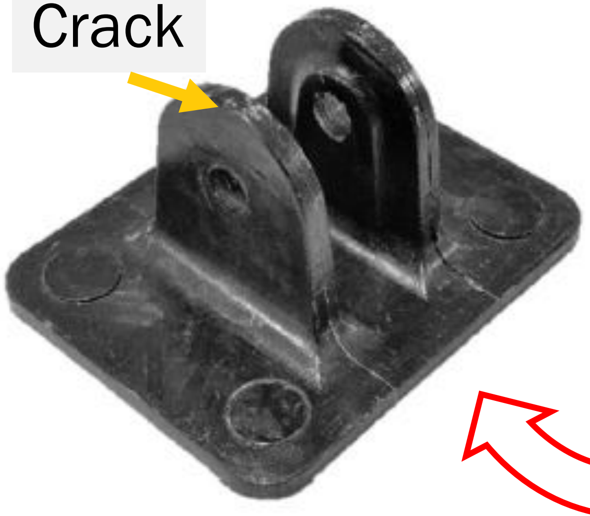
Favaloro et al. J.Rheology, 2018

Stochastic FEA:

Find g, g’



Crack



Size Effect Law

$$\sigma_N = \sqrt{\frac{E^* G_f}{D g + c_f g'}}$$

33

Looking forward

Benefit to aviation:

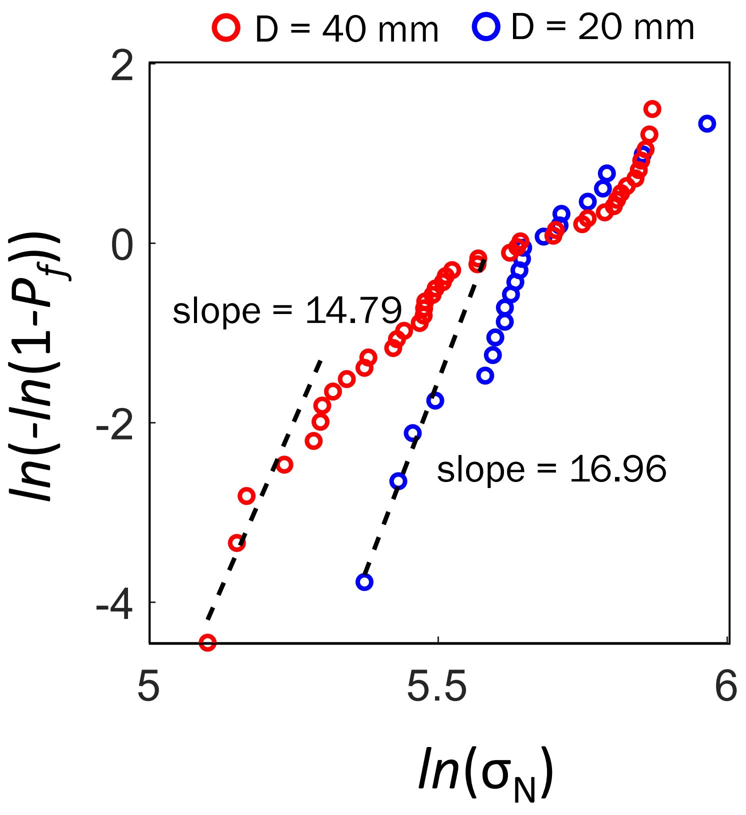
1. Novel experimental framework for characterization of the fracture toughness of DFCs;
2. Investigation of platelet size effect and thickness effect on fracturing behavior
3. Development of certification guidelines for defected DFC structures and its validation (in progress)
4. Construction of a database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

Future needs:

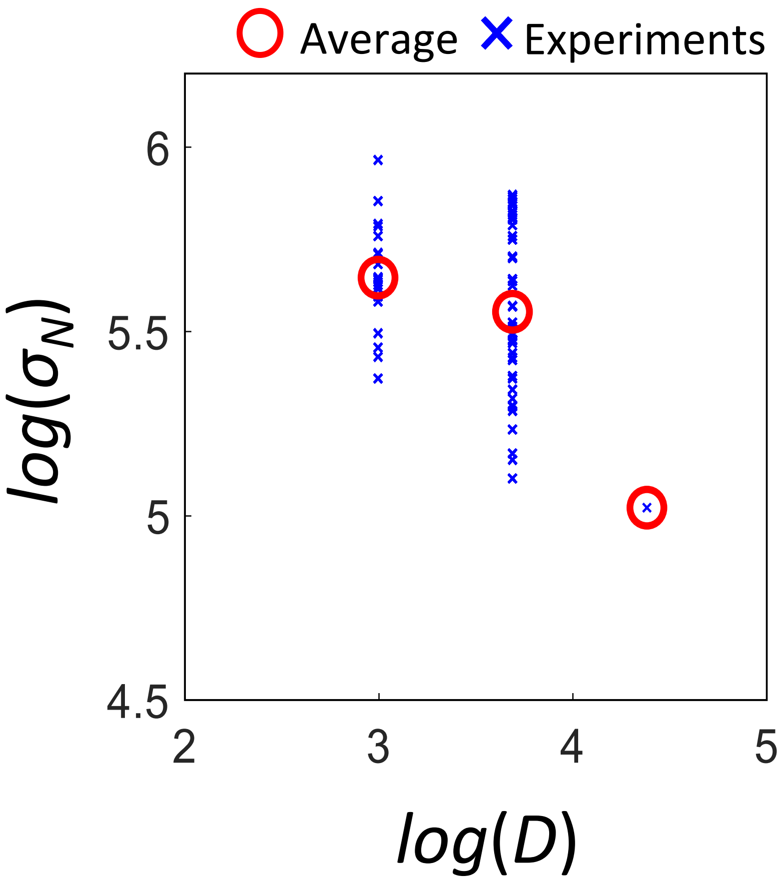
1. Better understanding on inter-laminar fracturing behavior;
2. Investigation on the use of failure probability theory to capture the significan randomness of material behavior
3. Investigation of the correlation between local platelet morphology in real components and fracturing behavior

Ongoing/future work

Statistics of strength

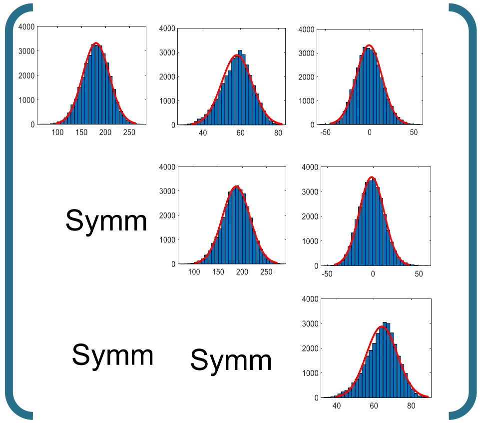


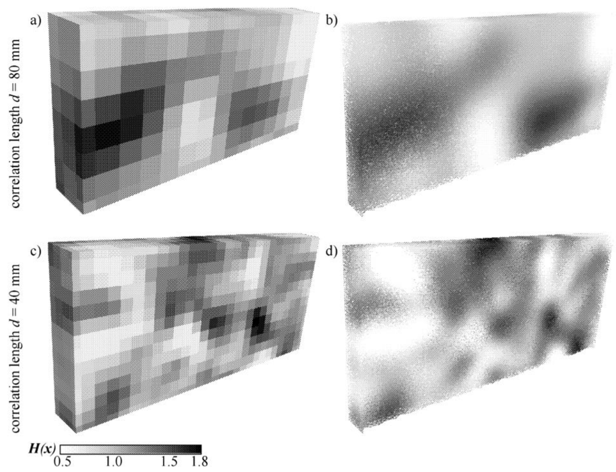
Size effect on strength



Stochastic homogenized model

$$\begin{bmatrix} A11 & A12 & A13 \\ sym & A22 & A23 \\ sym & sym & A33 \end{bmatrix} =$$





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

Acknowledgements

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

Certification of Discontinuous Composite Material Forms for Aircraft Structures

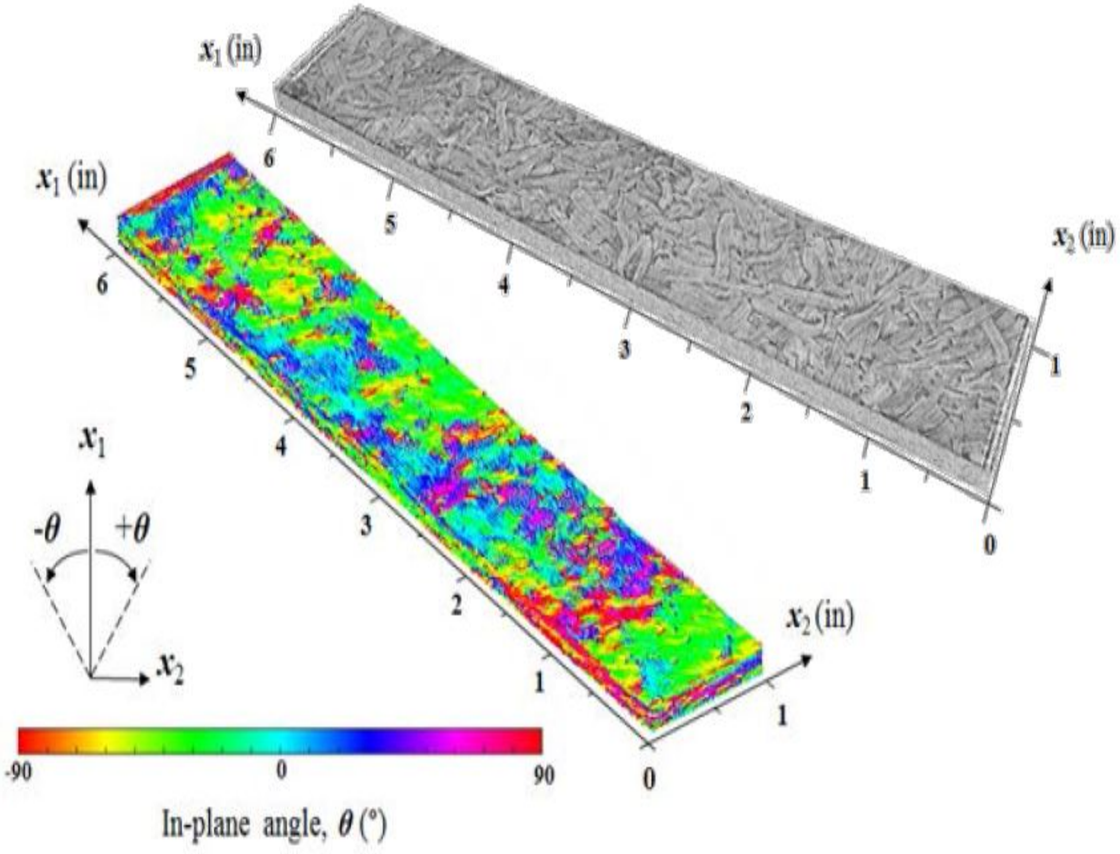
Marco Salviato, Jinkyu Yang, Mark Tuttle
University of Washington

AMTAS meeting 2018 November 7, 2018

(5) micro-CT scan and local fiber orientation

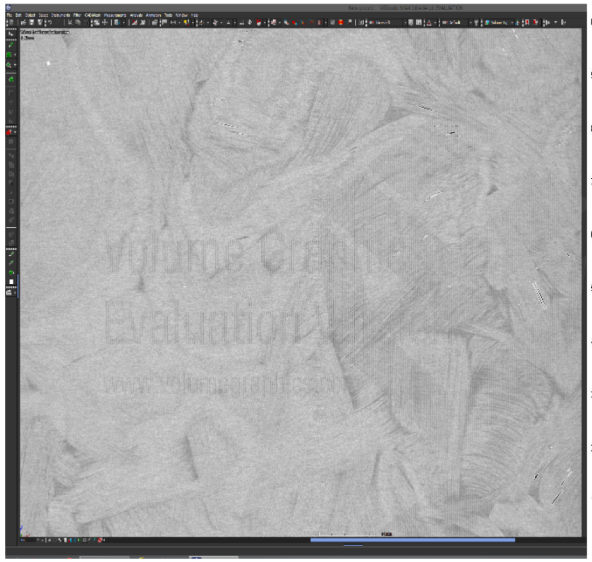
(1) Determine local fiber orientations

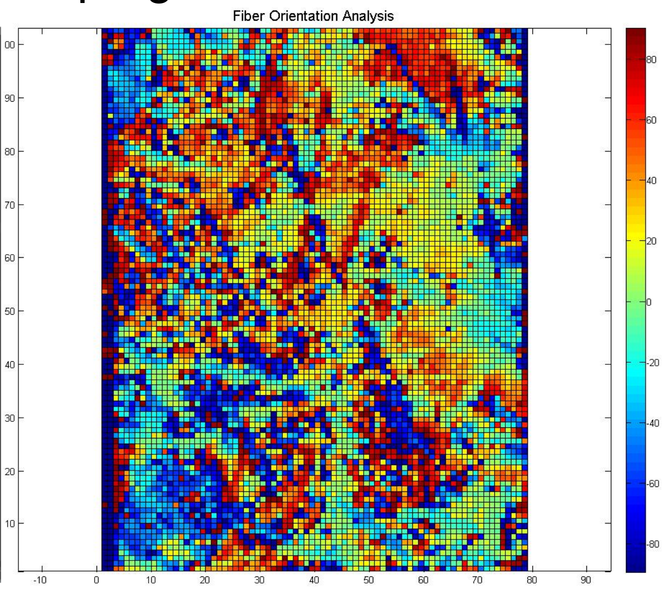
(2) Obtain defect size and locations



Denos (Purdue DFC project), 2017

Current UW progress



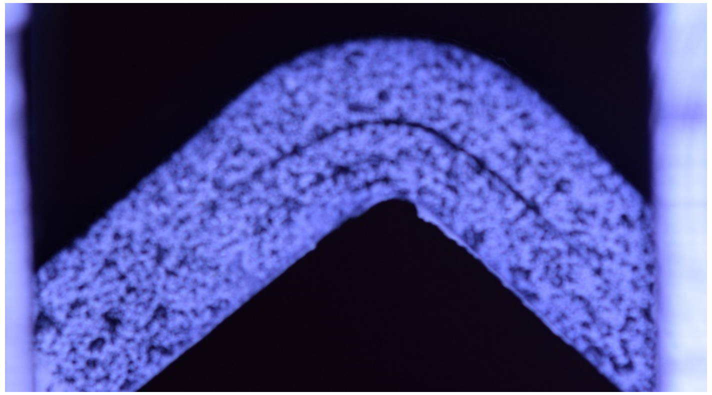


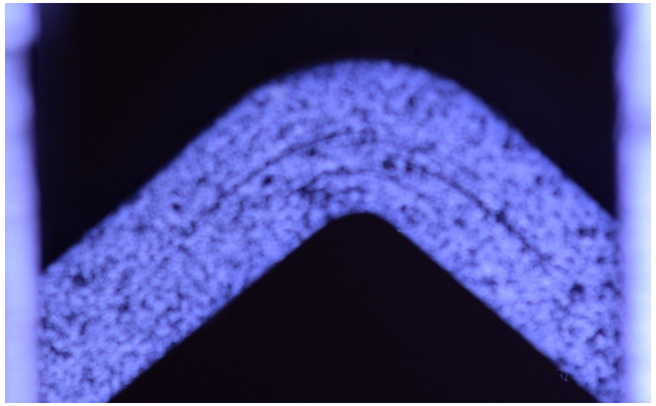
UW micro CT scan

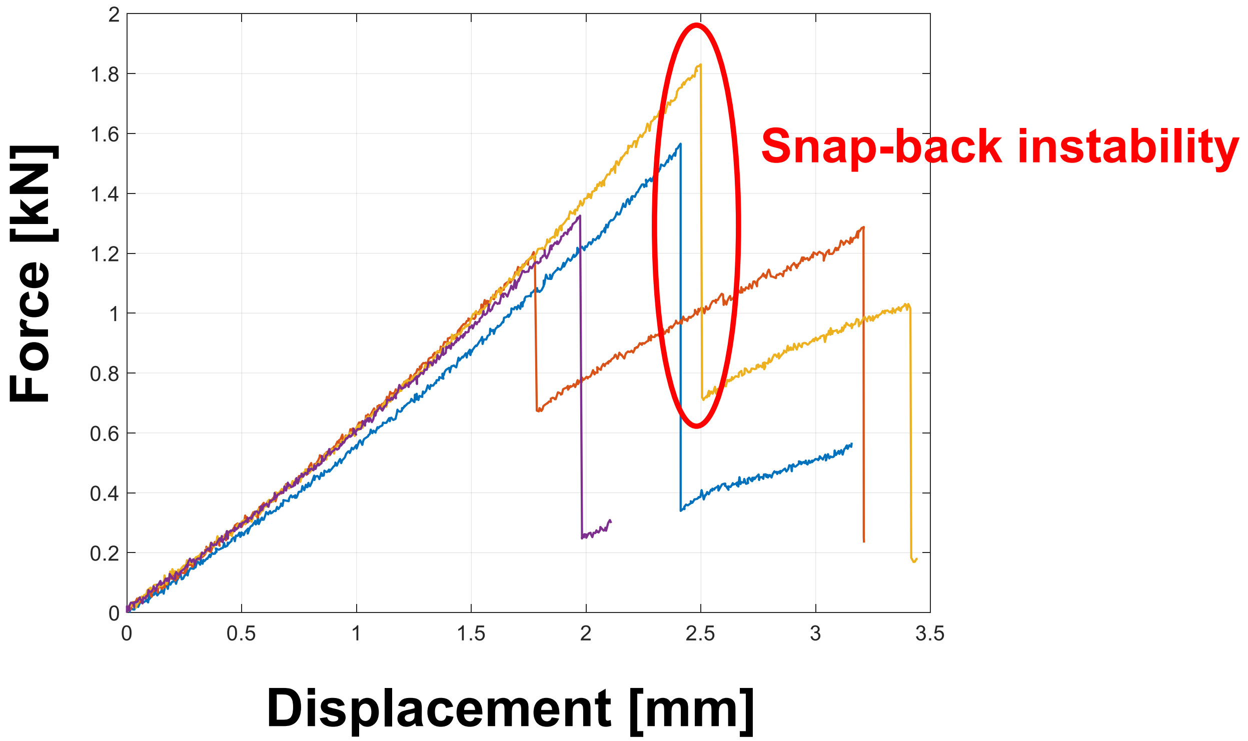
Local fiber orientation analysis in progress

- 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.

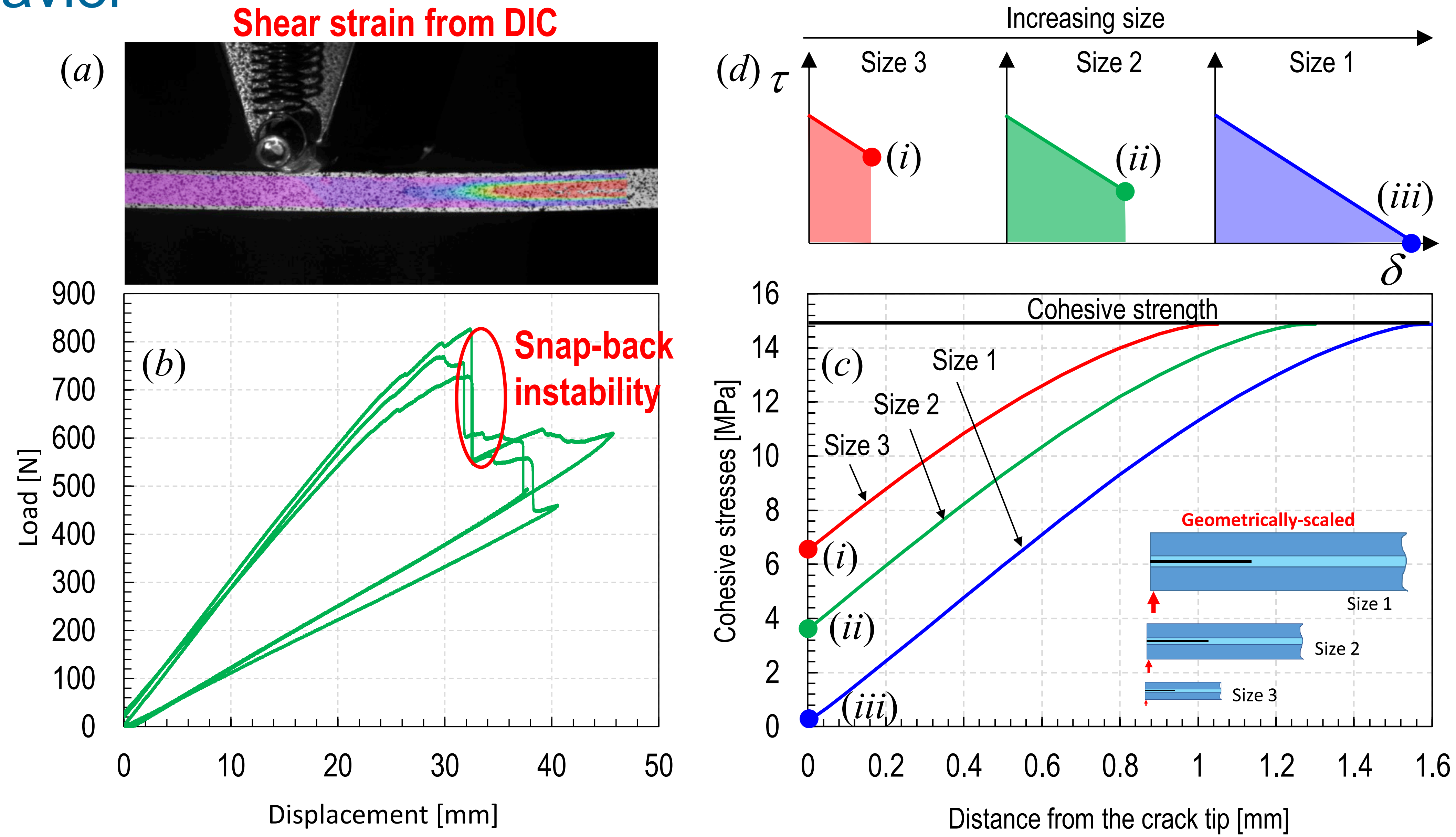
Ongoing/future work: Investigation of inter-laminar fracture behavior







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

How to obtain the fracture energy, G_f using the SEL?

Size effect law:

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

$$\Rightarrow \frac{1}{\sigma_N^2} = \frac{g(\alpha_0)}{E^* G_f} D + \frac{c_f g'(\alpha_0)}{E^* G_f}$$

$\Rightarrow Y = A * D + B$, size effect parameters from the experiments

$$\Rightarrow A = \frac{g(\alpha_0)}{E^* G_f} \text{ or } G_f = \frac{g(\alpha_0)}{E^* A}$$

$g(\alpha_0)$ is a function of total strain energy strongly related to:

1. geometry (shape)
2. microstructural effects (platelet layups)

No closed form available for the DFC material

⇨ **Need Finite Element Model**

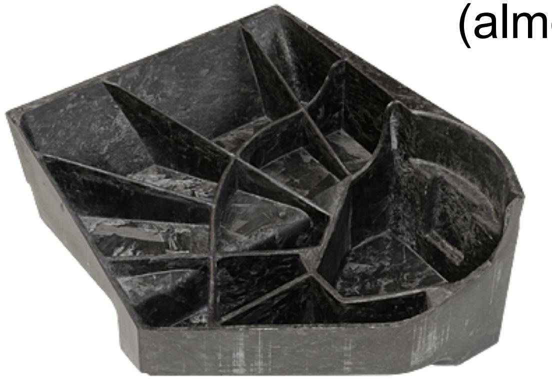
DFCs overview

HexMC Material,(450mm wide Roll),~2000 gsm,~2 mm thick

50mm x 8mm 8552/AS4 UD 150 gsm, 38% RC, Controlled Random Distribution

Source: www.hexcel.com

DFC structural components



(almost) Net shape design

Source: www.hexcel.com

Challenges for certification

- The main mechanisms of damage in the presence of multi-axial loading, notches and defects are not clearly understood;

- The multi-axial behavior of un-notched and notched DFC structures has not been characterized yet. This is key for design and certification;

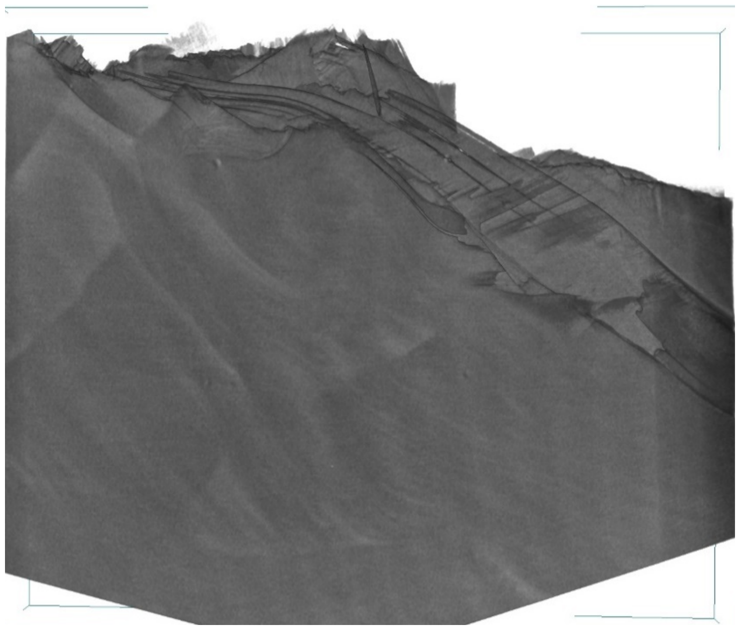
- The effects of defects on the overall structural performance has not been quantified. This is important to provide guidelines for certification and maintenance of DFC parts;

- All the above issues have to be considered keeping in mind the thickness effect which was shown to highly affect the overall mechanical behavior

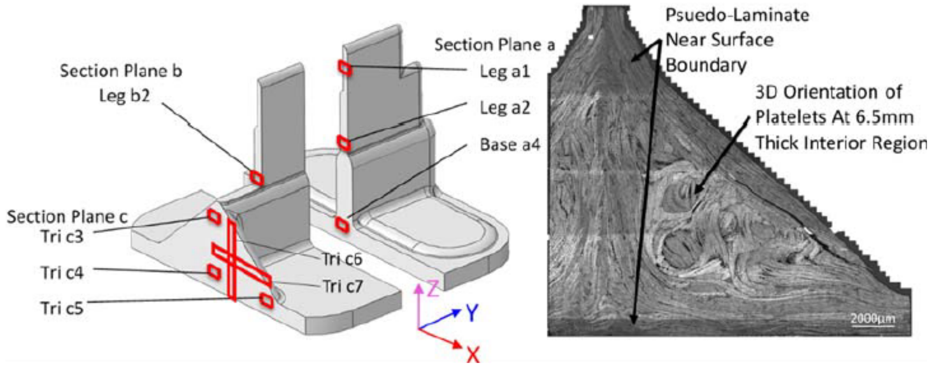
Proposed methodology and research plan

- **Damage mechanism investigation**

Extensive 3D analysis of damage progression by micro-Computer Tomography



Source: UW team



Denos, Pipes, 31st ASC conference, 2016

North Star Imaging X5000 Industrial 2D Digital X-ray and 3D Computed Tomography (CT) System: Nominal part envelope: 32' (dia.) x 48' tall, Overall system resolution: 3 µm. X-ray energy: 10-450 kV. Geometric magnification: 2000x.

Proposed methodology and research plan

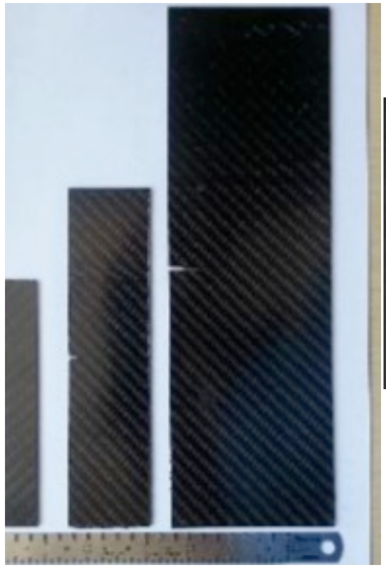
- **Defect analysis**

Experimental and computational analysis of size effect in DFC structures to find critical defect sizes keeping in mind the highly stochastic behavior

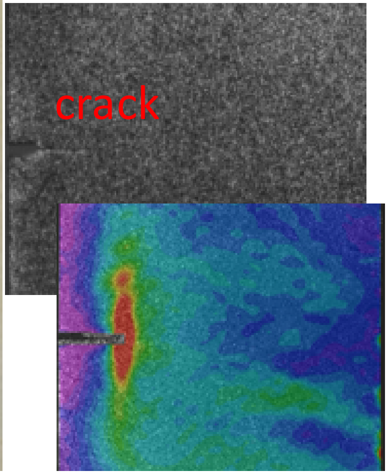
Types of defects:

- ***Molded-in defects*** **(e.g. 1.27 cm x 1.27 cm brass covered with Teflon) imbedded between HexMC plies;**
- **Visible damage from impact**
- **Incidental damage: cuts made with a saw and/or visible surface damages**

- **SENT**



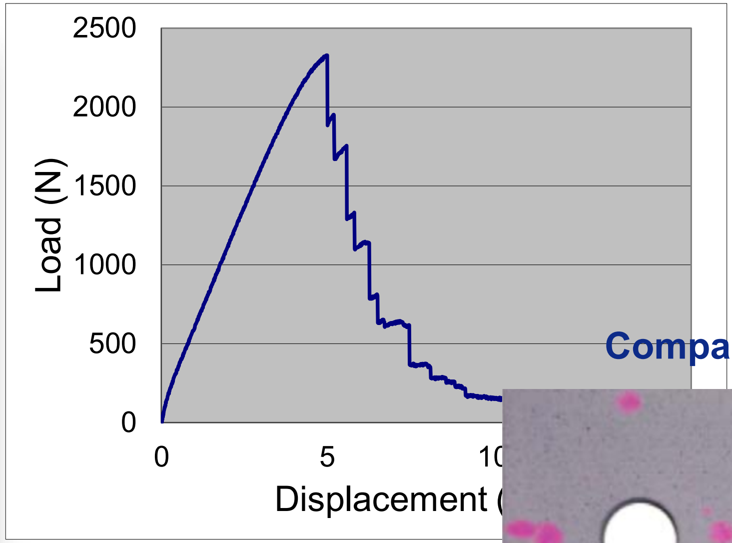
DIC investigation



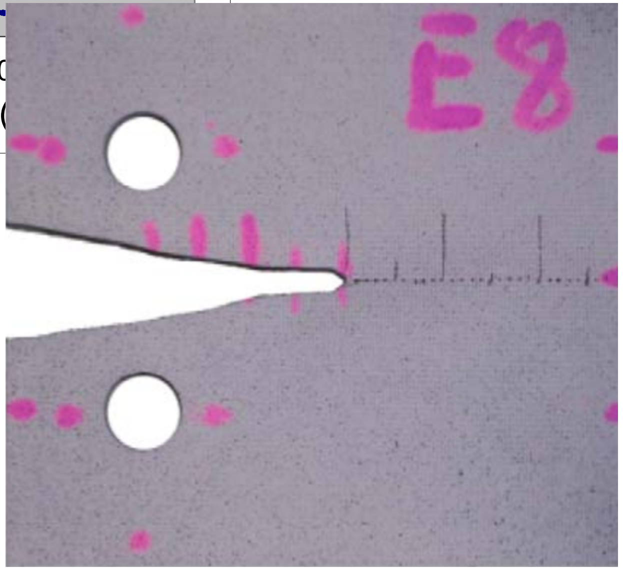
Salviato et al., Composite Science & Technology, 2016

Proposed methodology and research plan

- Compact Tension



Compact Compression



Salviato et al., Composite Science & Technology, 2016

Salviato et al., JAM, 2016

Pinho, Doctoral dissertation, London, 2005

CECAM center of excellence for composites and advanced materials

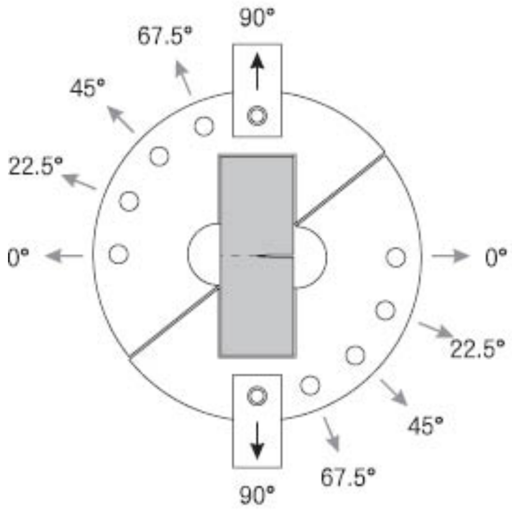
A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

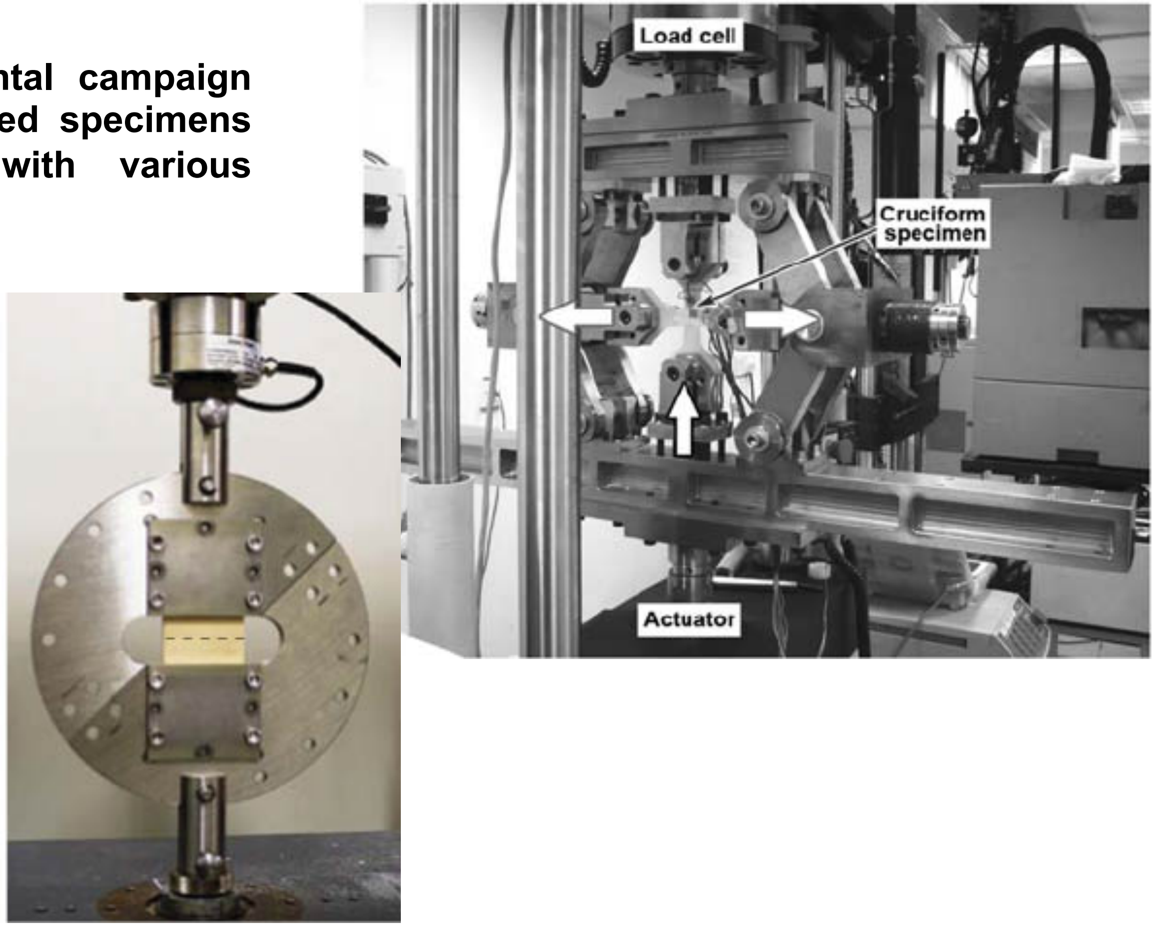
JAMS Joint Advanced Materials & Structures Center of Excellence

Proposed methodology and research plan

- **Multi-axial behavior**

Comprehensive experimental campaign on un-notched and notched specimens under biaxial loading with various thicknesses





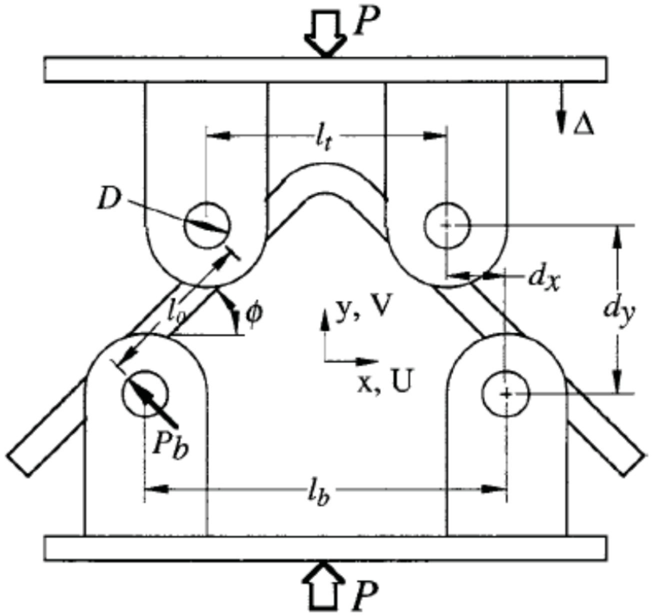
Sun et al., Journal of Composites, 2012

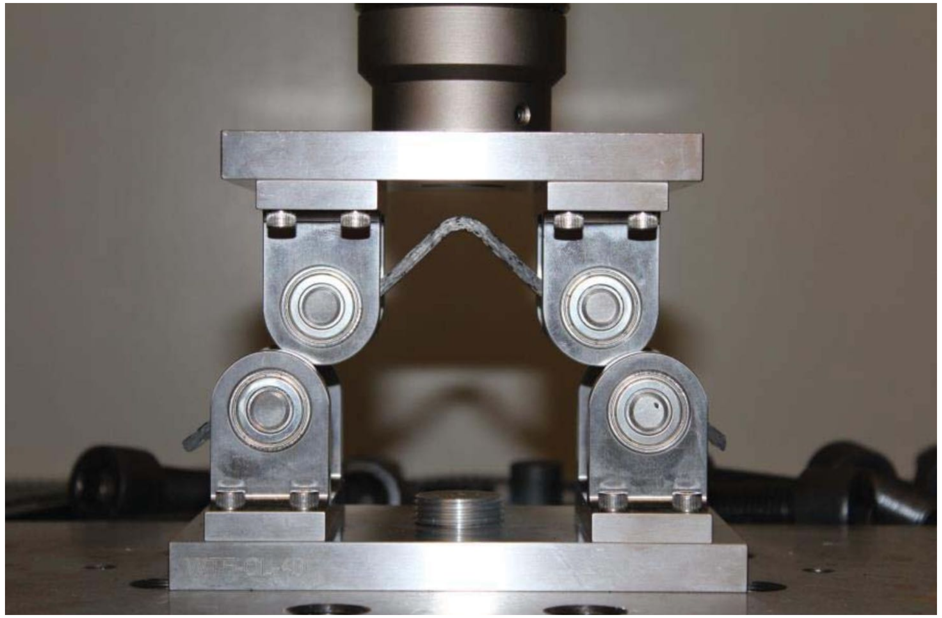
CECAM AMTAS JAMS

Proposed methodology and research plan

- **Curved beam testing**

Comprehensive experimental campaign on curved beam specimens with various thicknesses





ASTM D6415

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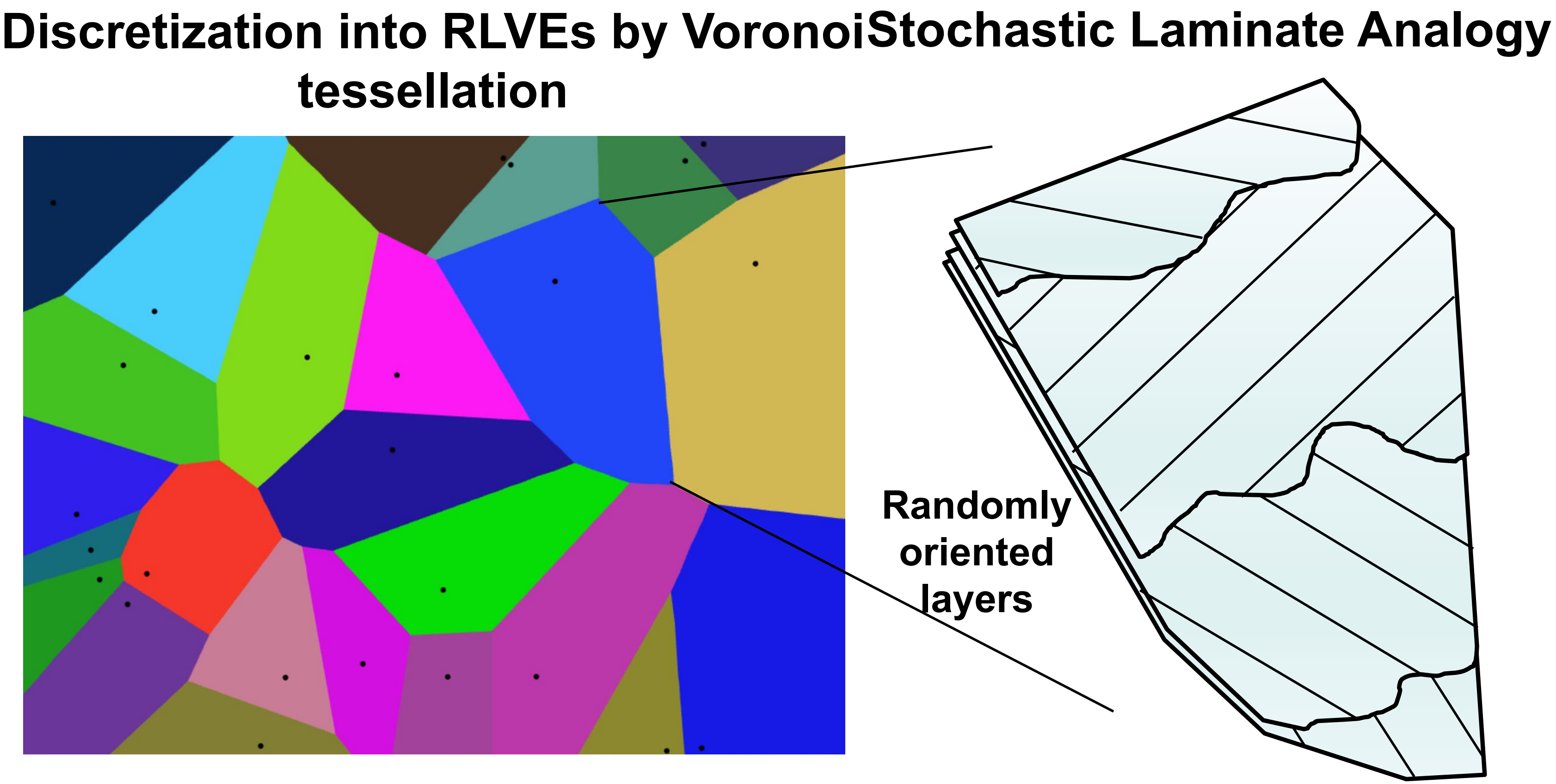
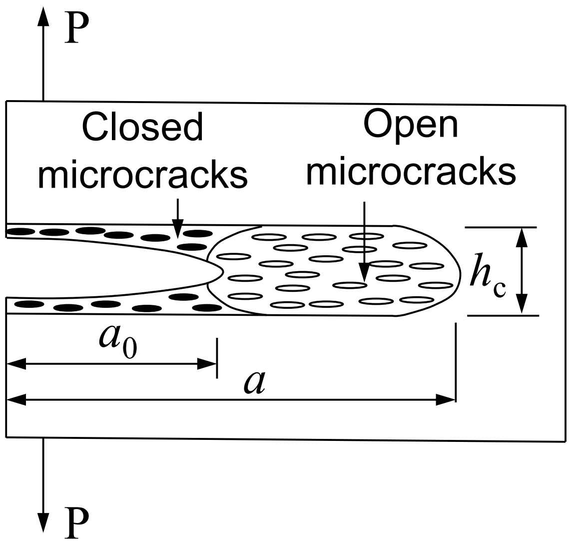
JAMS

An example of size effect study to identify the critical defect size of DFC structures

Stochastic Laminate Analogy



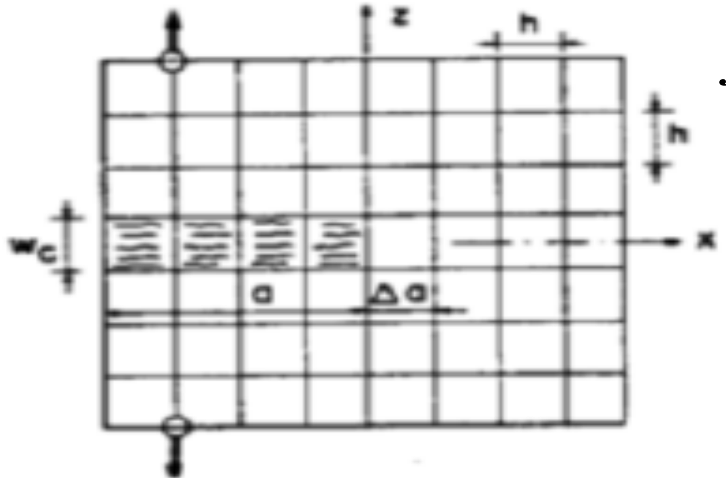
Damage progression modeling

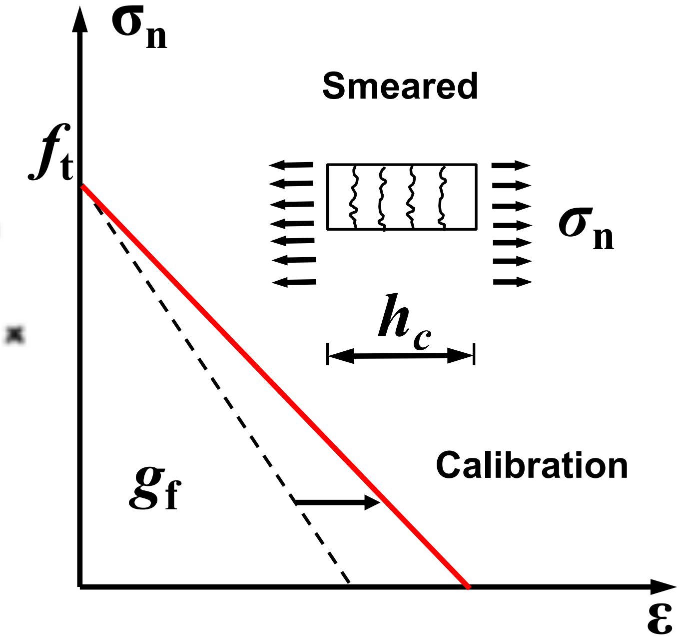


The crack is modeled as a *smeared crack band* with fixed width h_c

the crack opening, w, is calculated as the product of average strain and band width

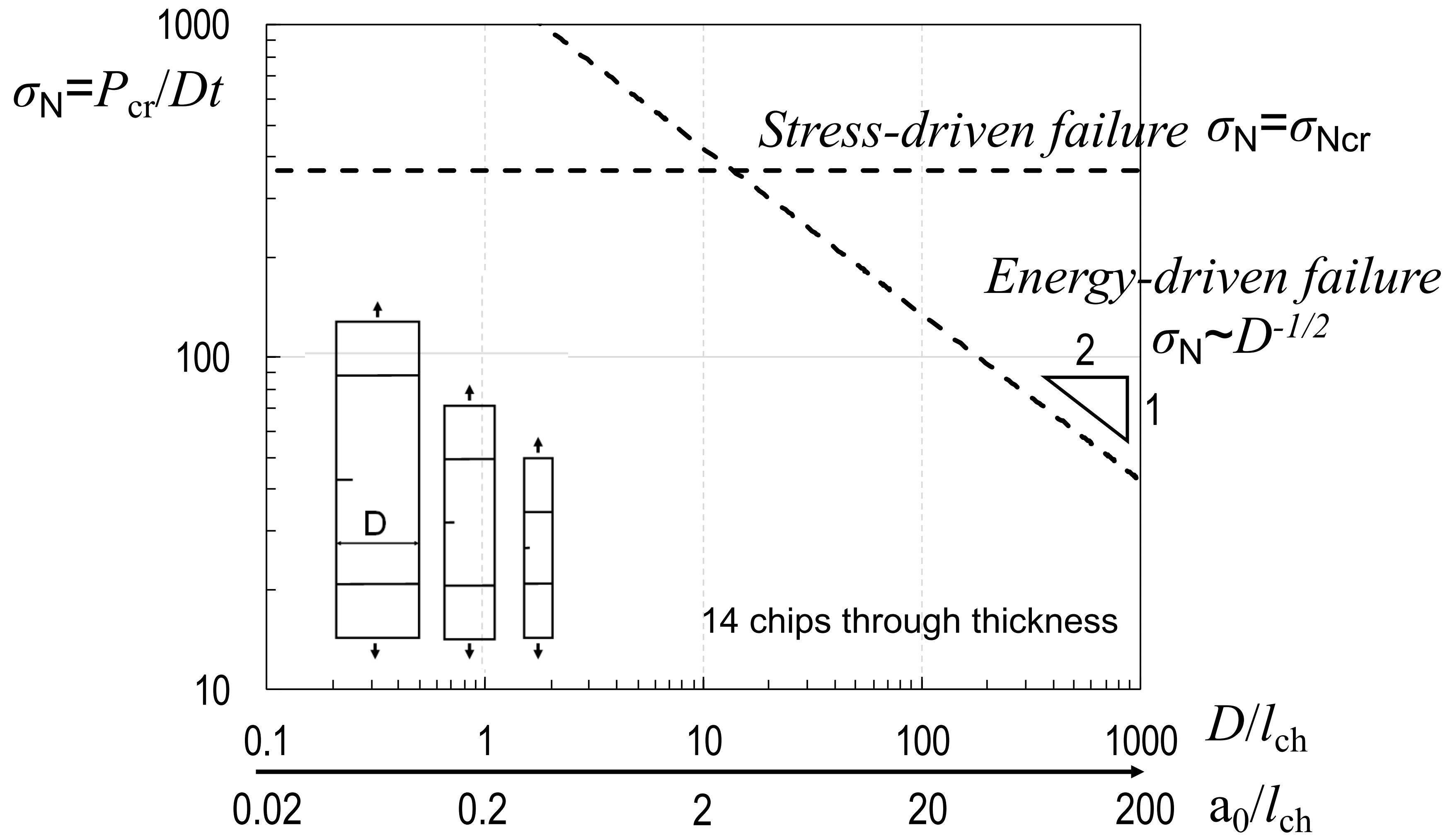
The post-peak softening response of the model is recalibrated to match the experimental fracture energy!





$$G_f = \int_{\varepsilon} \sigma(\varepsilon')h_c \mathrm{d}\varepsilon'$$

Critical defect size for DFCs



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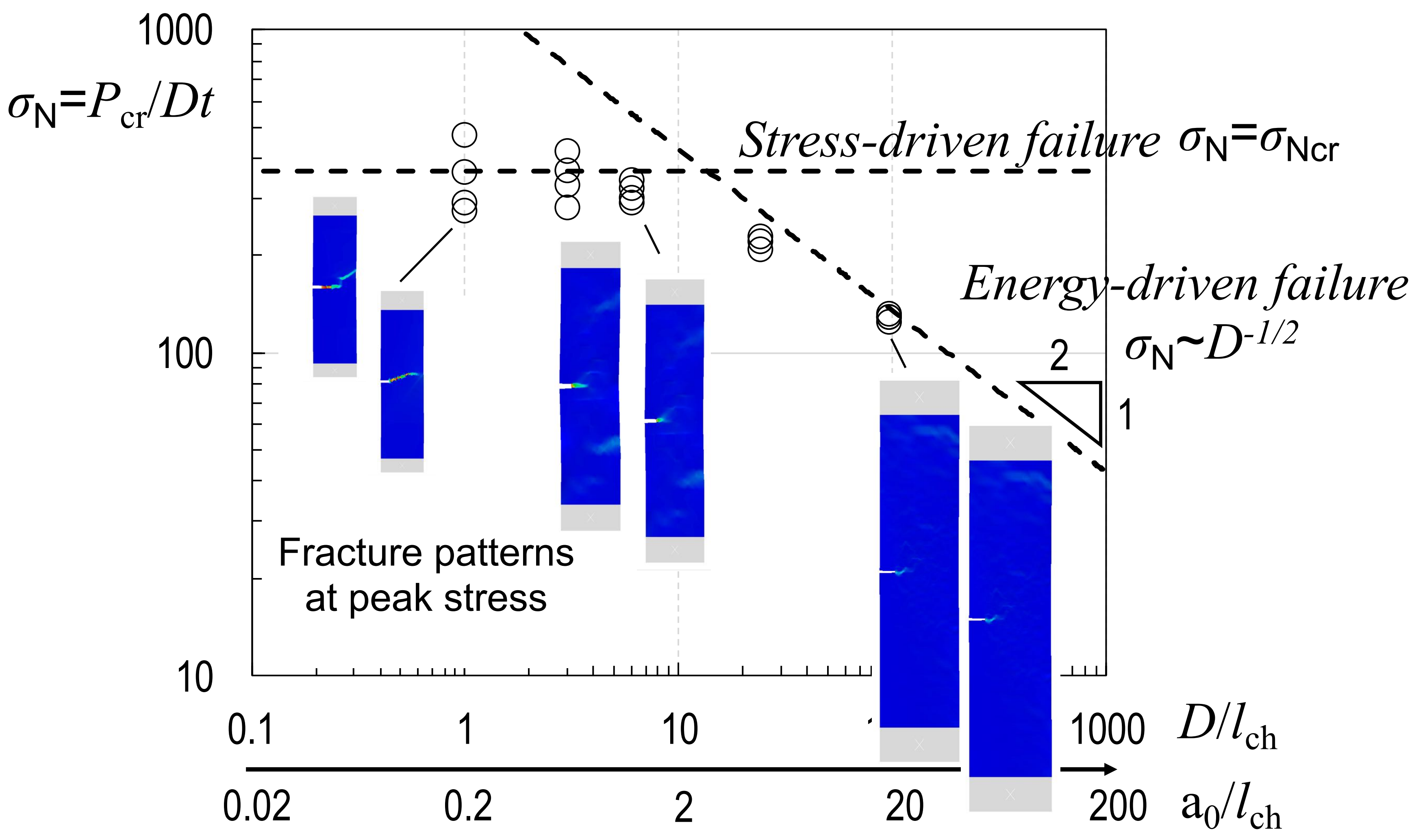


Size effect law

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

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

the following expression holds for the initial fracture energy:

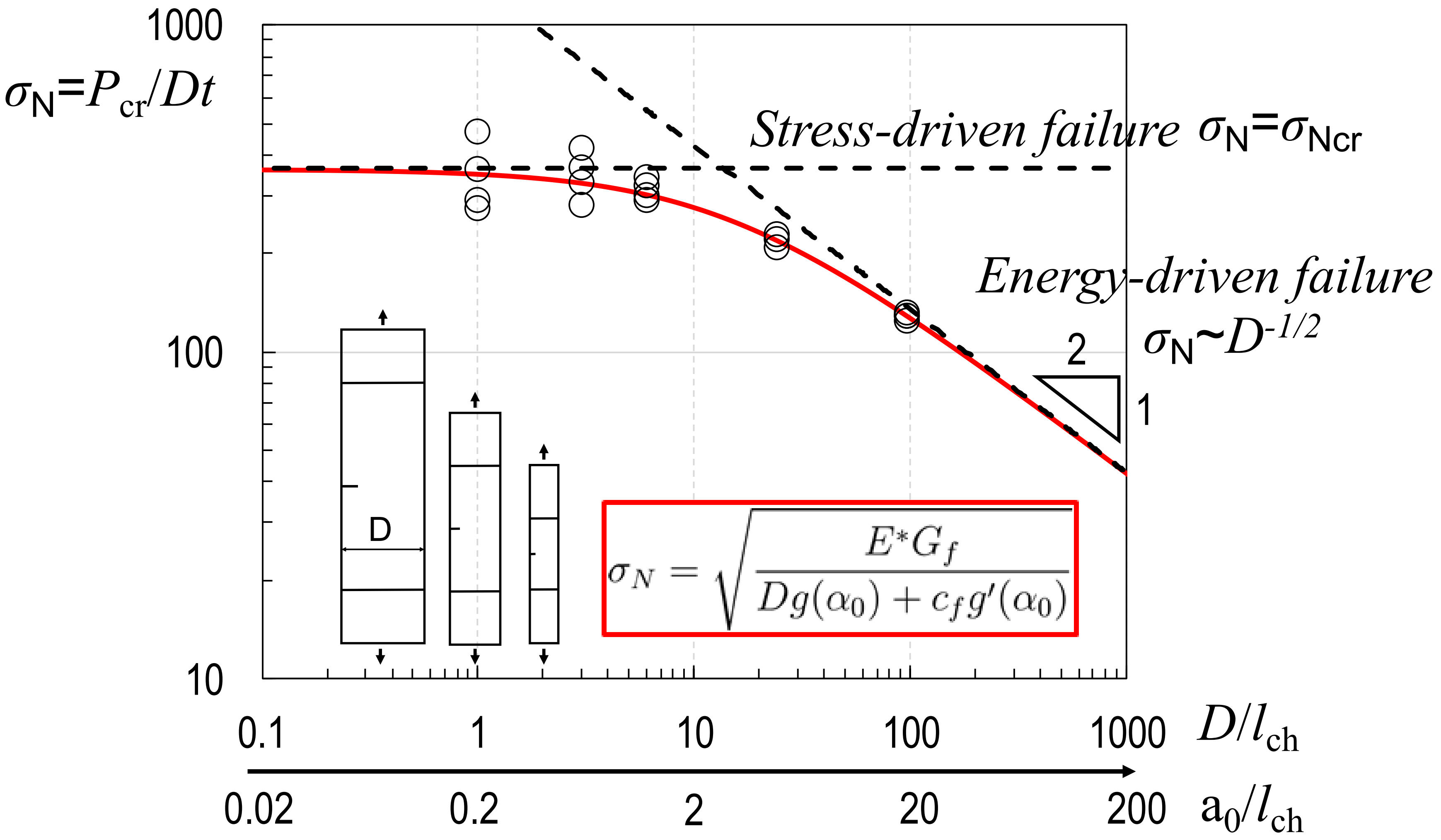
$$G_f(\alpha) = \frac{\sigma_N^2 D}{E^*} g(\alpha) = \frac{\sigma_N^2 D}{E^*} g(\alpha_0 + c_f/D) \qquad \begin{array}{l} \alpha = a/D \\ E* = \text{effective modulus} \\ g = \text{dimensionless energy release rate} \end{array} \qquad (2)$$

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

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

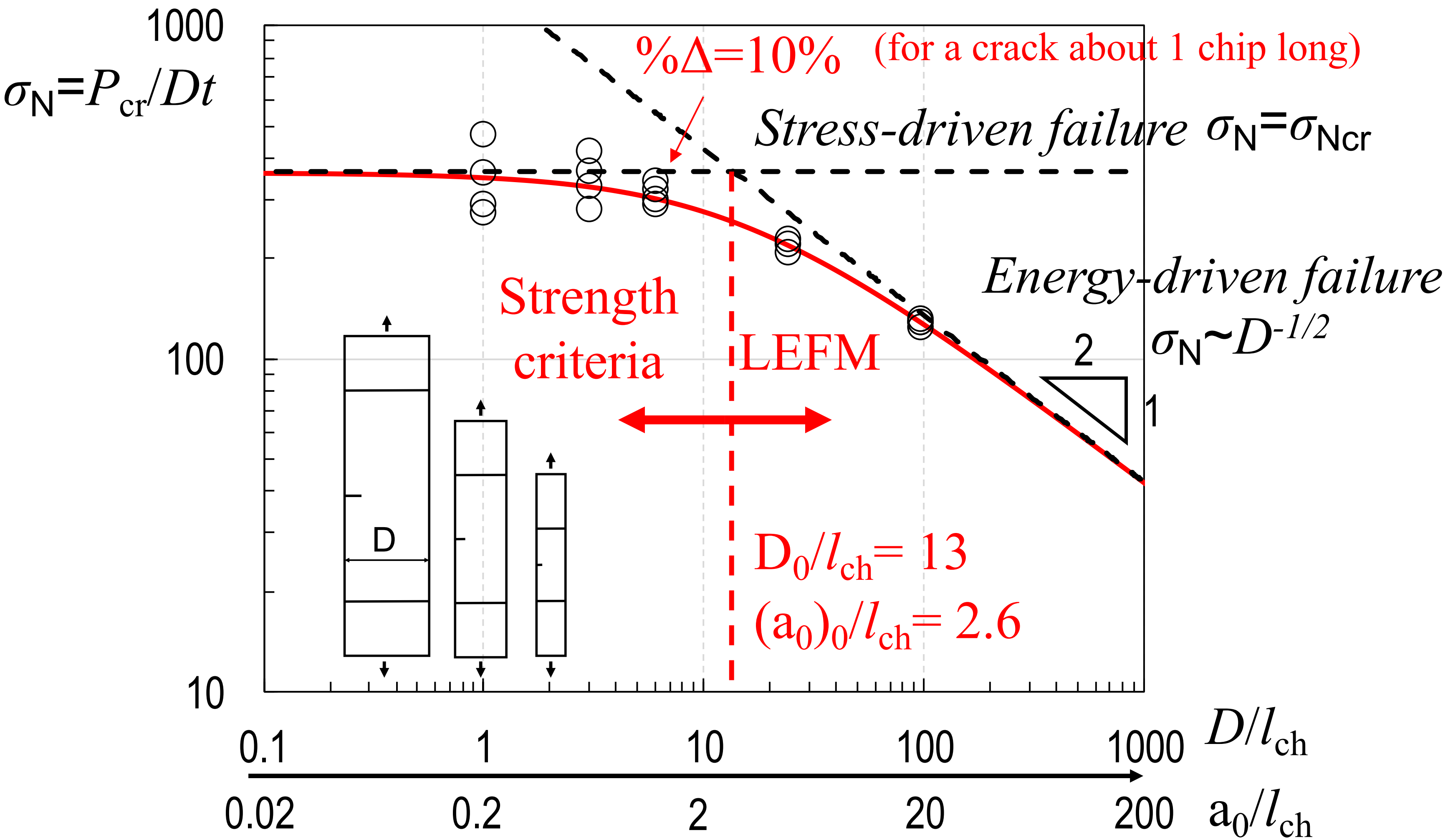
Bažant's Size Effect Law (SEL) for quasi-brittle materials (extended to DFCs)

Size effect of DFCs



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

Critical defect size for DFCs



Conclusions

- The efficient design and certification of DFC structures urges the understanding of a) the main mechanisms of damage, b) the effects of multi-axial loading and c) defects and stress concentrators

- The proposed project aims at addressing the foregoing issues by coupling computer tomography, computational modeling and multi-axial experiments on notched and un-notched DFC structures

- An example of size effect study was provided. It was shown that a) the mechanical behavior of DFC structures strongly depend on the size of the structure compared to the chip size. Small structures behaves an quasi-ductile, larger structures as brittle; b) the transition between stress-driven failure and energy-driven failure occurs at crack lengths of about 2.6 chip size; c) for a crack about 1 chip long, the structural strength decreases of 10% only; d) this information is key for certification and for maintenance scheduling.

Certification of Discontinuous Composite Material Forms for Aircraft Structures

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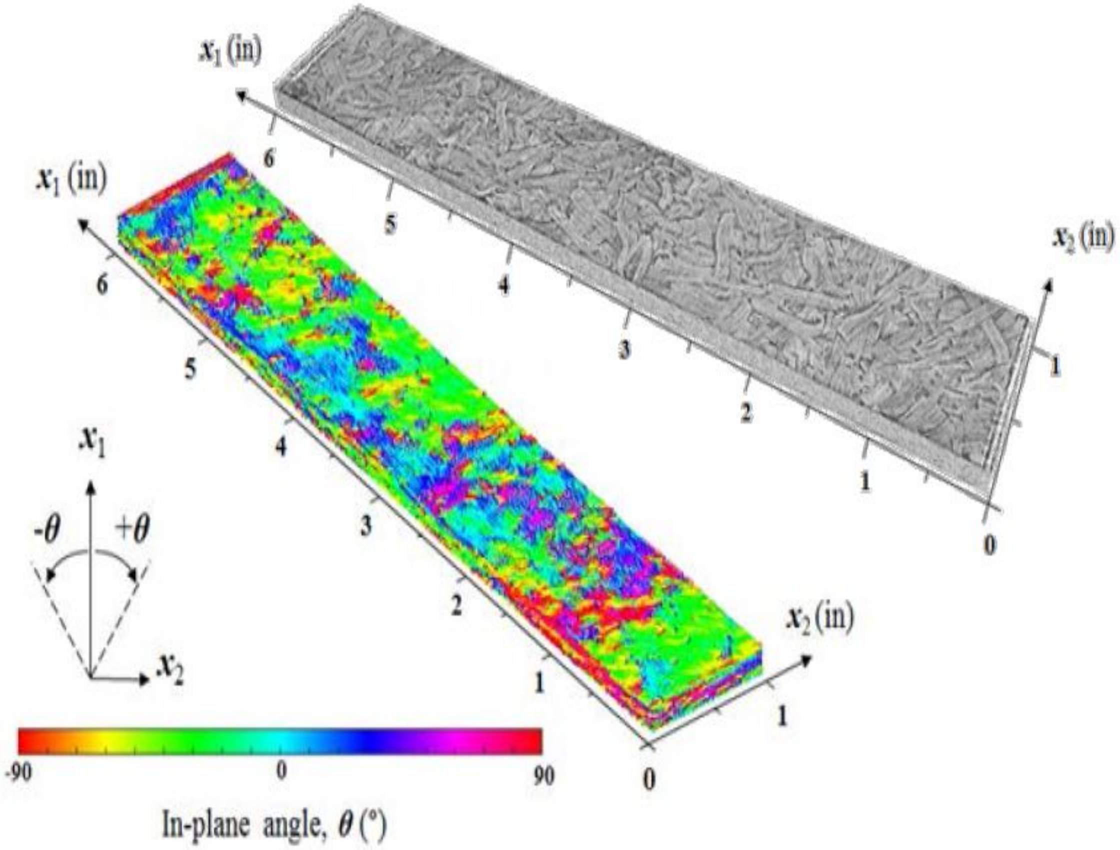
University of Washington

AMTAS meeting 2018 November 7, 2018

(5) micro-CT scan and local fiber orientation

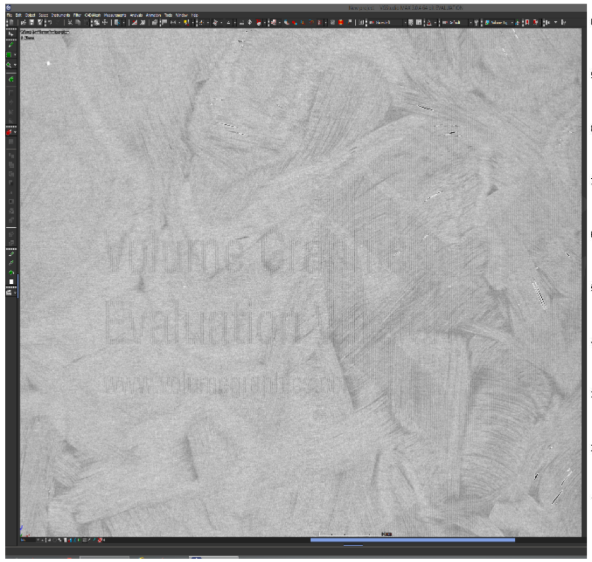
(1) Determine local fiber orientations

(2) Obtain defect size and locations

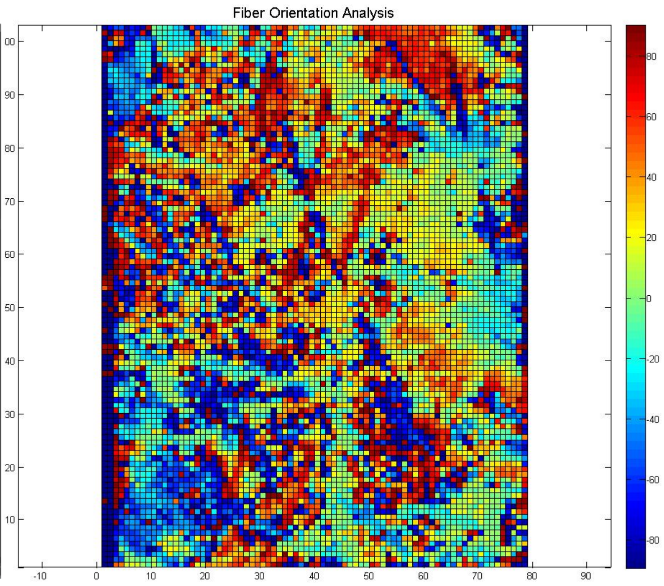


Denos (Purdue DFC project), 2017

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.**