Safety and Certification of Discontinuous Composite Structures

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Center for Urban Horticulture, University of Washington, Seattle, WA.

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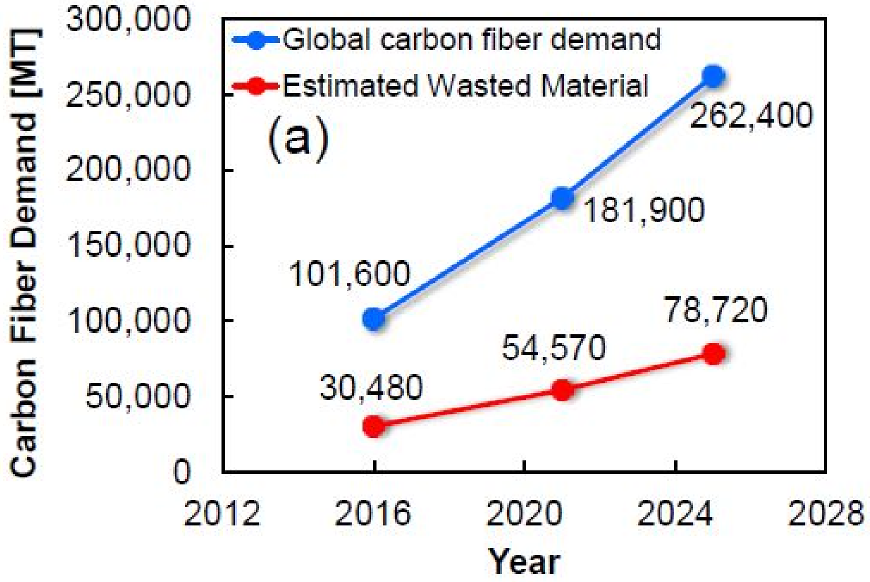
Synergistic project

Recyclability

Inside Composites



Composites Forecast and Consulting LLC

COMPOSITE RECYCLING TECHNOLOGY CENTER CRTC compositerecycling.org

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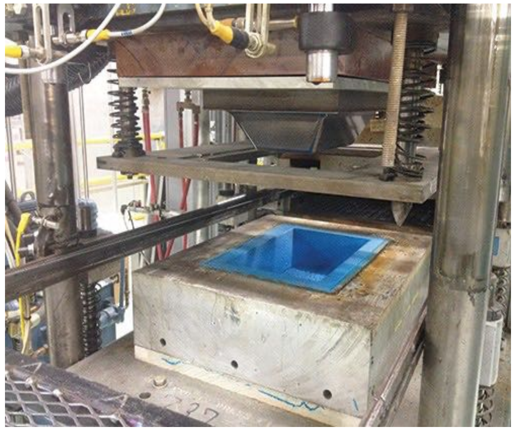
Discontinuous Fiber Composites (DFCs)

Platelets-based composite



Compression molding

Large volume manufacturing

Hexcel

Recyclability

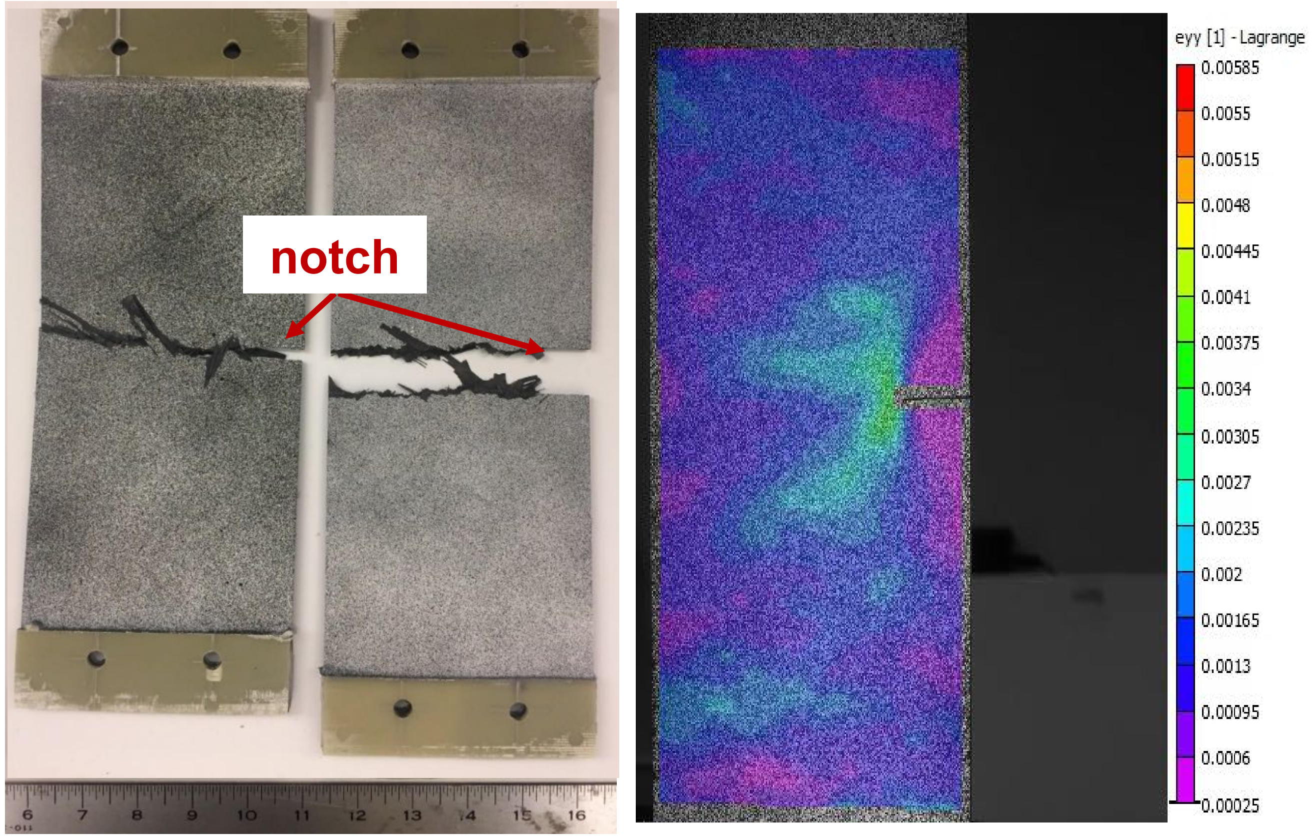
Nutt, 2014, CAMX

Part Complexity

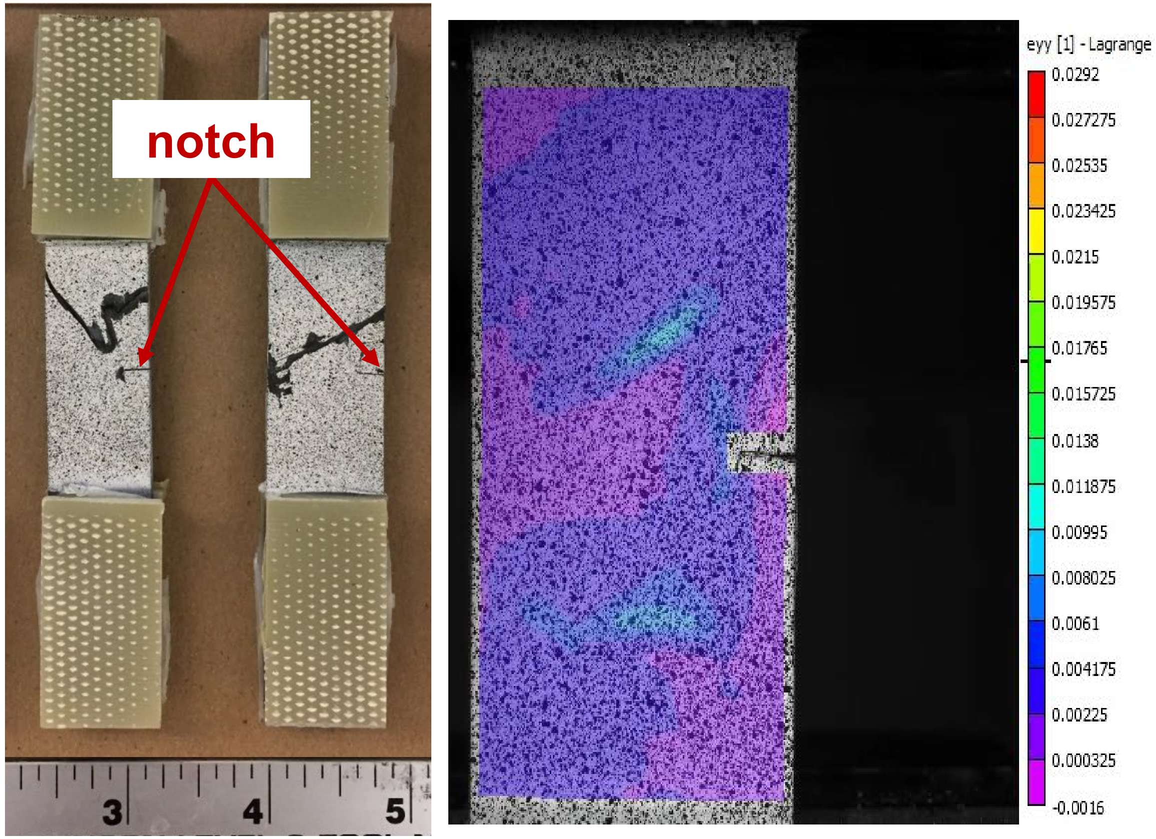
Greene Tweed

Current challenges:

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



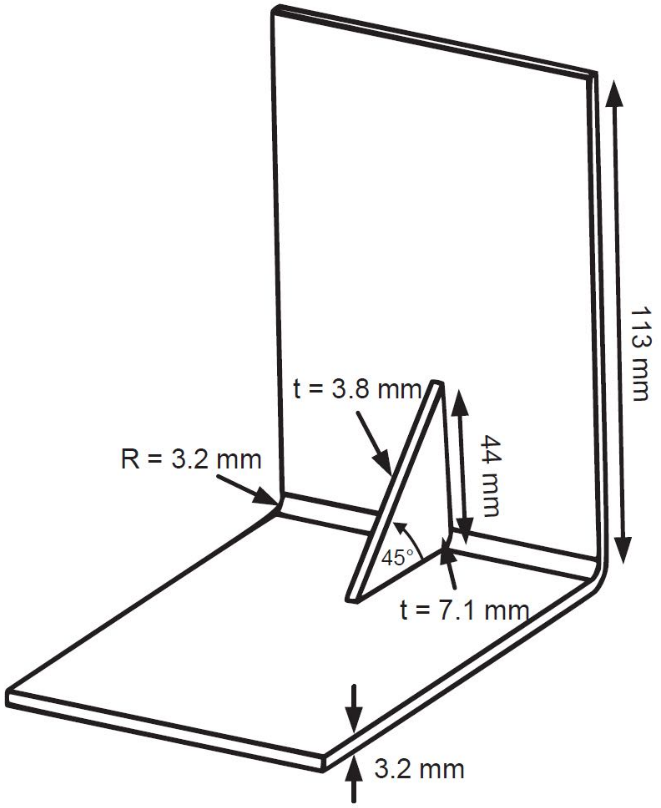
Width = 120 mm



Width = 20 mm

Current challenges:

Lack of acceptance/rejection criteria for defected DFC components



Landry, PhD dissertation, McGill, 2015

Objectives:

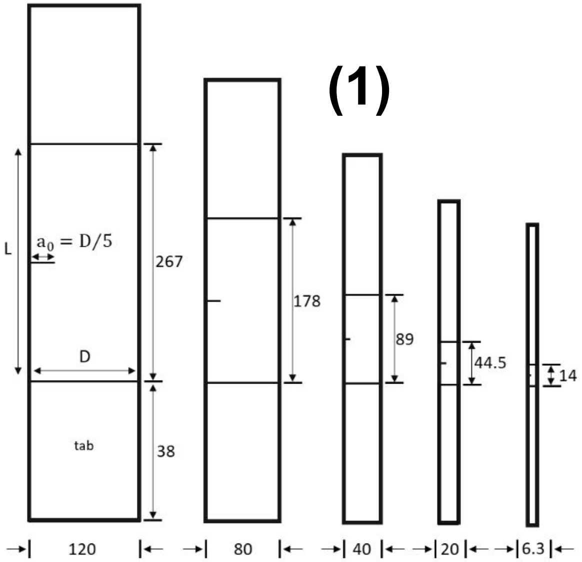
(1) To develop an *experimental protocol for the characterization of fracture toughness of DFCs*

(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 *develop computational tools to describe the mechanics of DFCs*

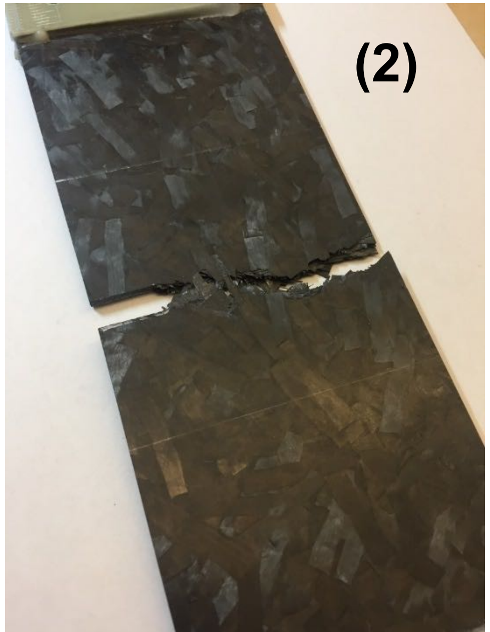
(4) To *formulate certification guidelines for DFC structures*

(1)



Size effect test, law

(2)

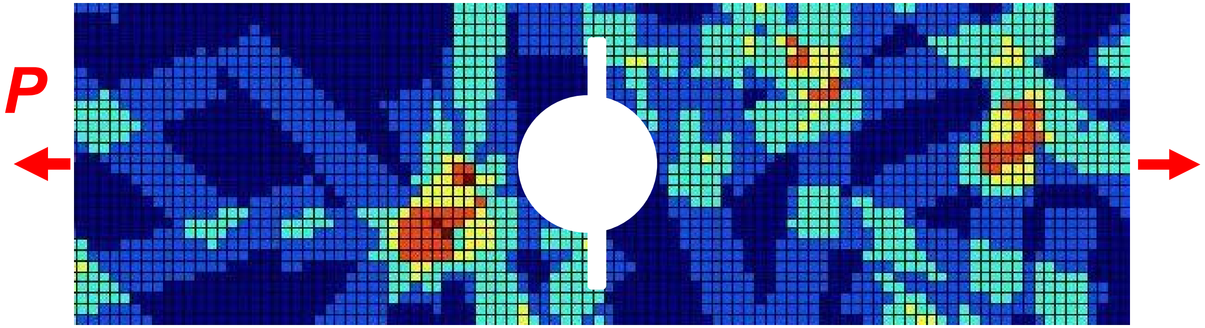


Platelet size:
75×12 mm

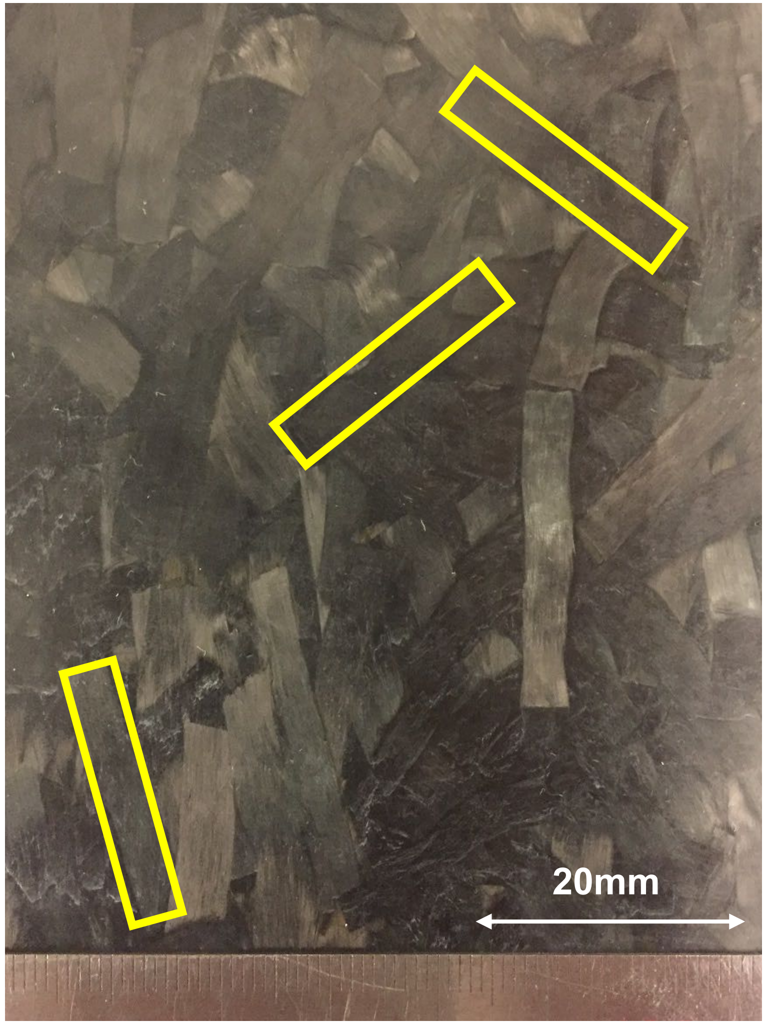
50×8 mm

25×4 mm

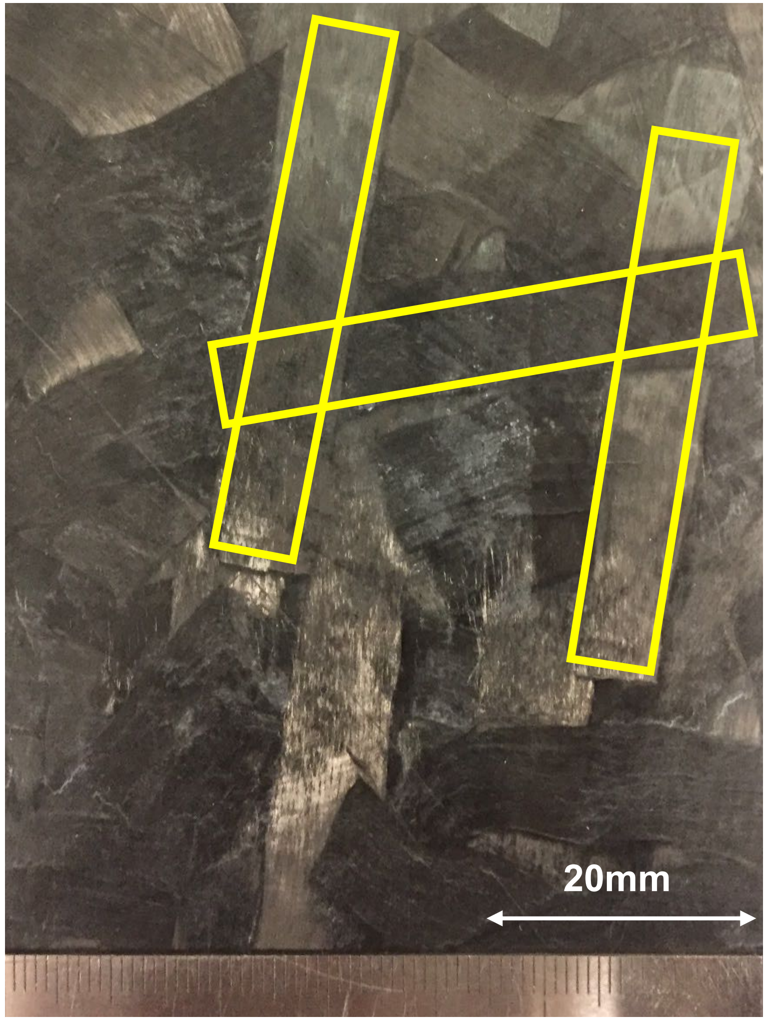
(3)



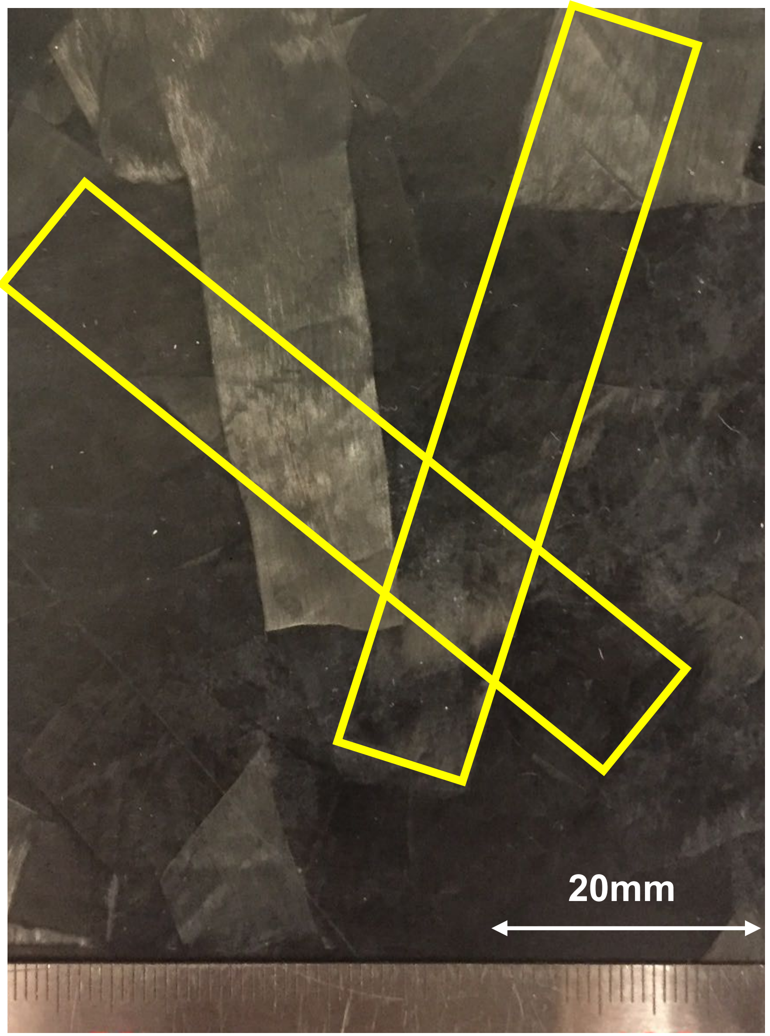
Investigated Platelet Sizes



25×4 mm



*50×8 mm



75×12 mm

*platelet size is commonly used in commercial products

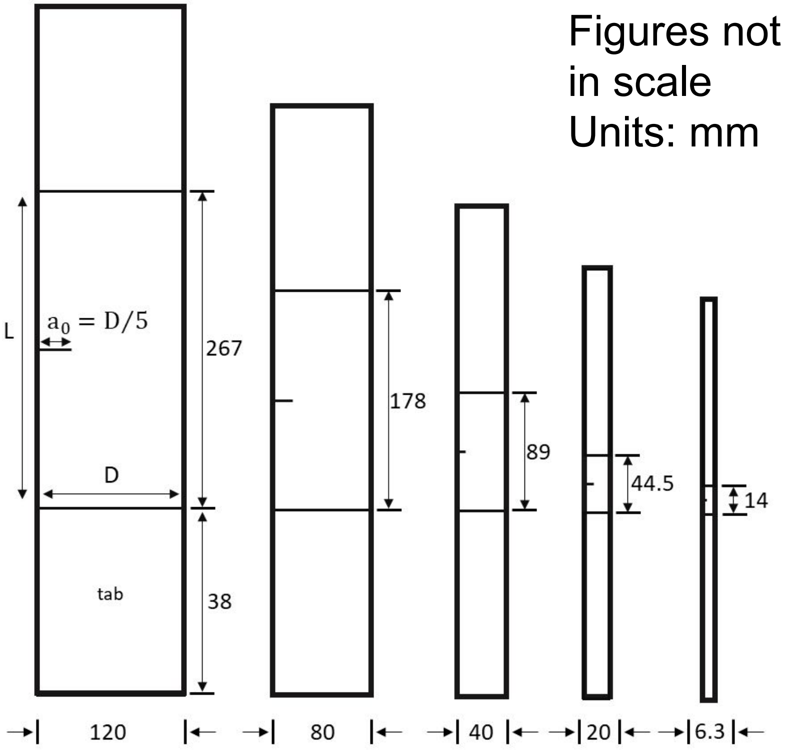
Feraboli et al. J. Reinf Plast and Comps, 2009, Boursier et al. SAMPE, 2010

Summary of Platelets Sizes and Thicknesses Investigated

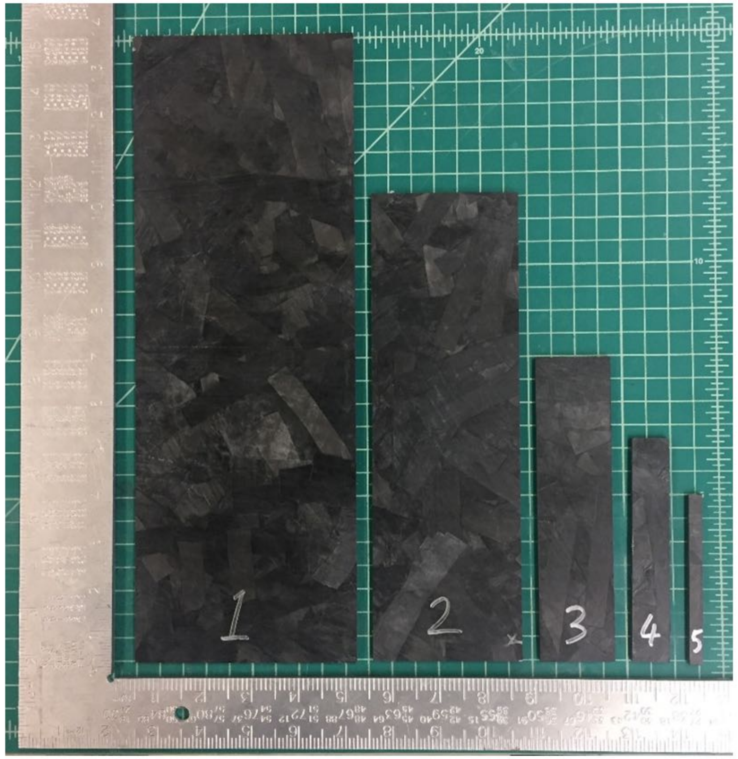
	Platelet size effect study			Thickness effect study			Platelet size effect study	
	Thermoset						Thermoplastic	
Size	75×12 mm, T = 3.3 mm	50×8 mm, T = 3.3 mm	25×4 mm, T = 3.3 mm	50×8 mm, T = 4.4 mm	50×8 mm, T = 2.1 mm	50×8 mm, T = 1.1 mm	12.7×12.7 mm, T = 3.8 mm	12.7×1.58 mm, T = 3.8 mm
1	3	2	3	*-	*-	*-	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**							

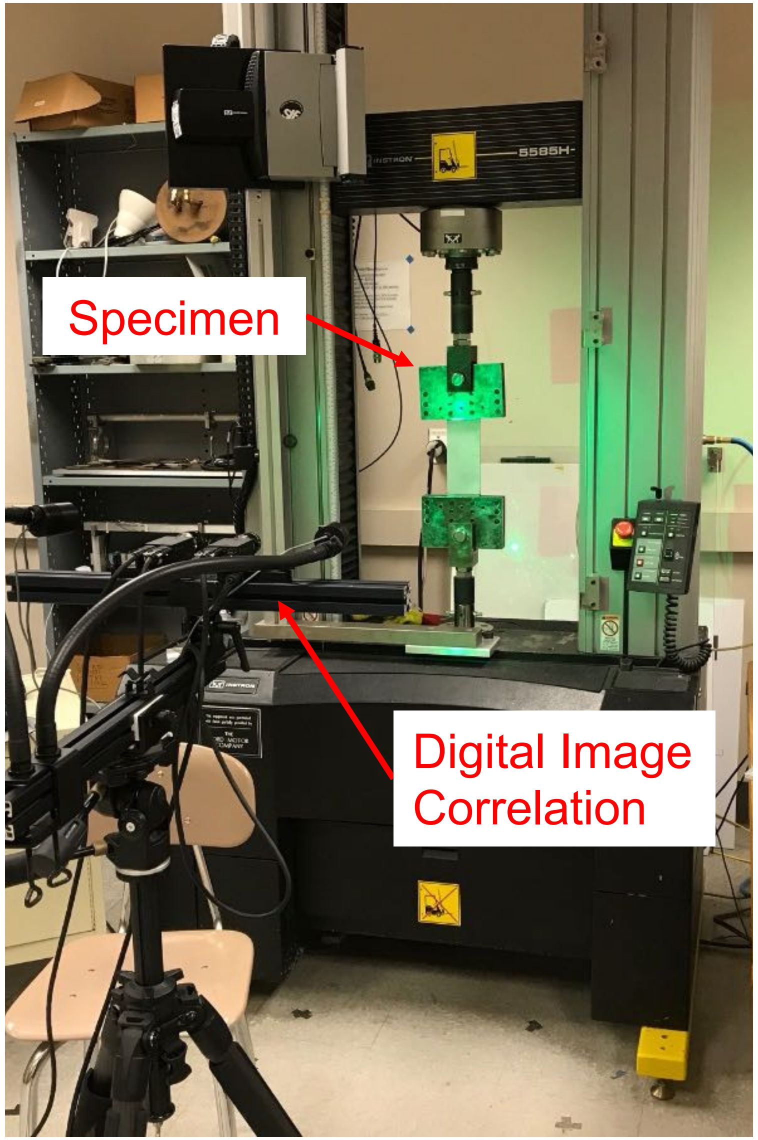
*** Coupon is well within the LEFM region, no need to test it.**

Specimen geometry



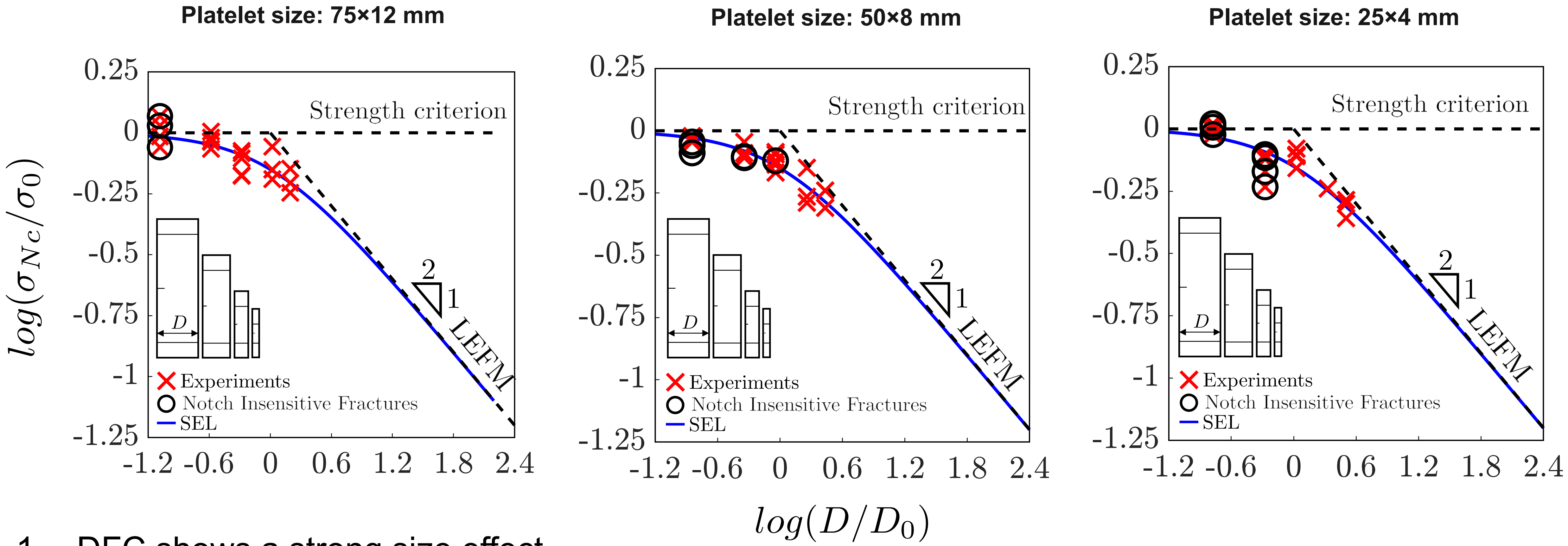
Figures not
in scale
Units: mm





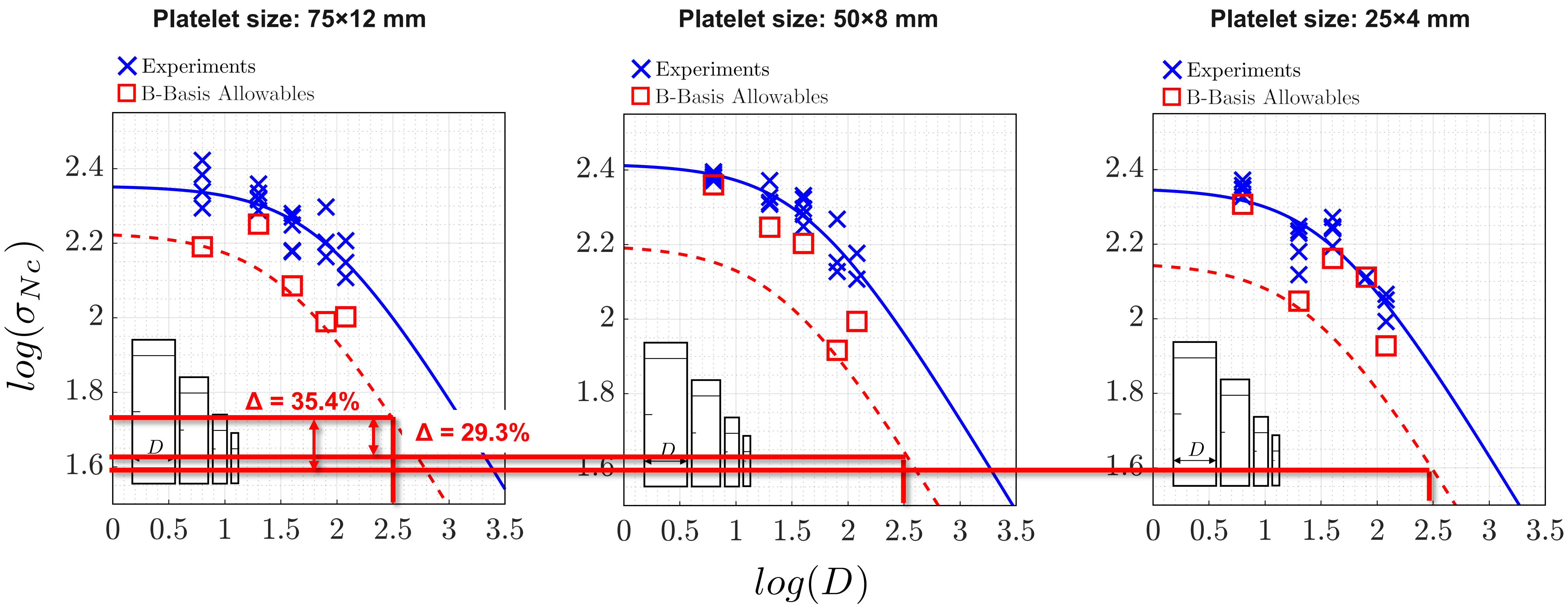
- Coupon sizes are proportionally scaled in width, gauge length, and crack length
- Thickness is constant = 3.3 mm

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, B-Basis – (varying Platelet size)

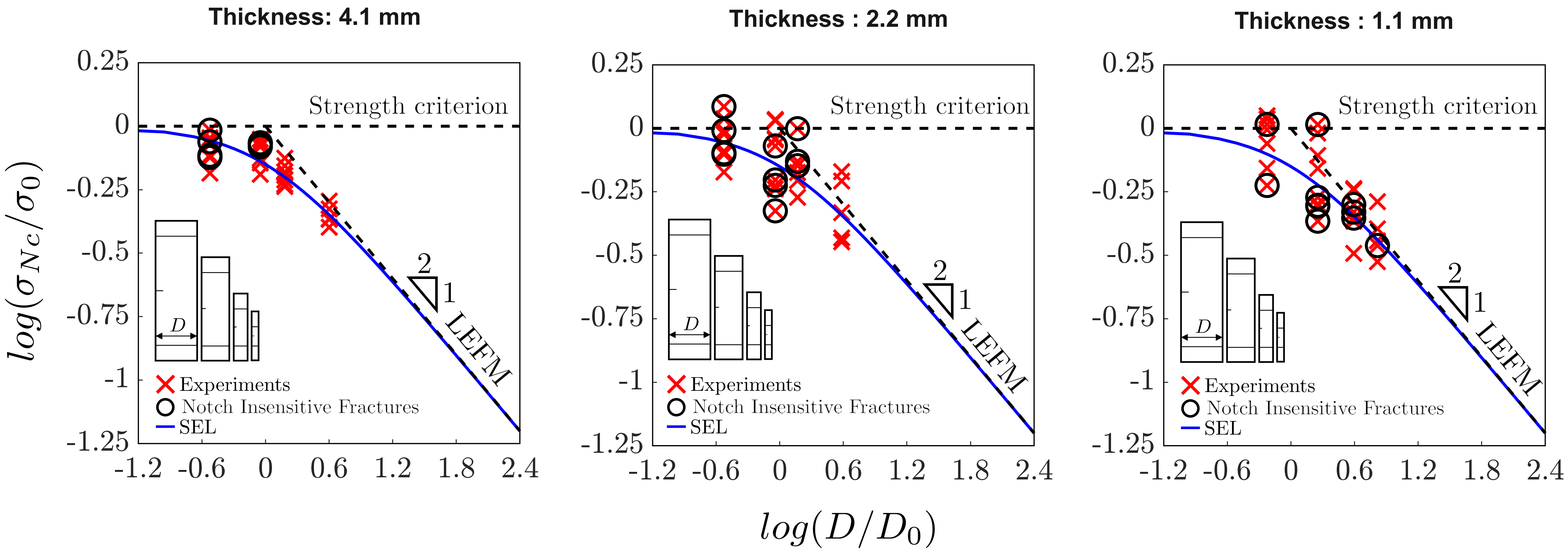


$$\sigma_{Bbasis} = Mean - K_b * STD$$ [CMH-17]

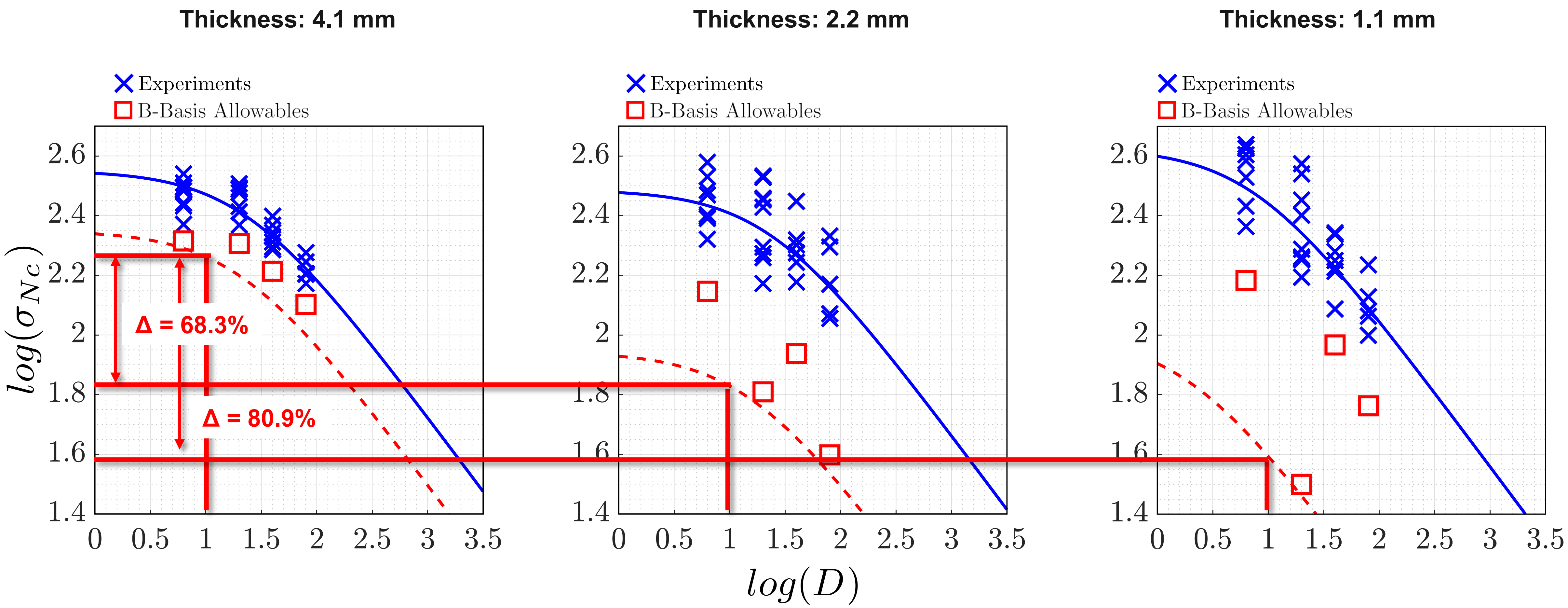
Where K_b is B-basis tolerance factor, depends on the number of tested coupons.

For simplicity, K_b = 2.583 corresponds to the 8 coupons.

Result: Size effect curves – (varying thickness)



Result: Size effect curves, B-Basis – (varying thickness)



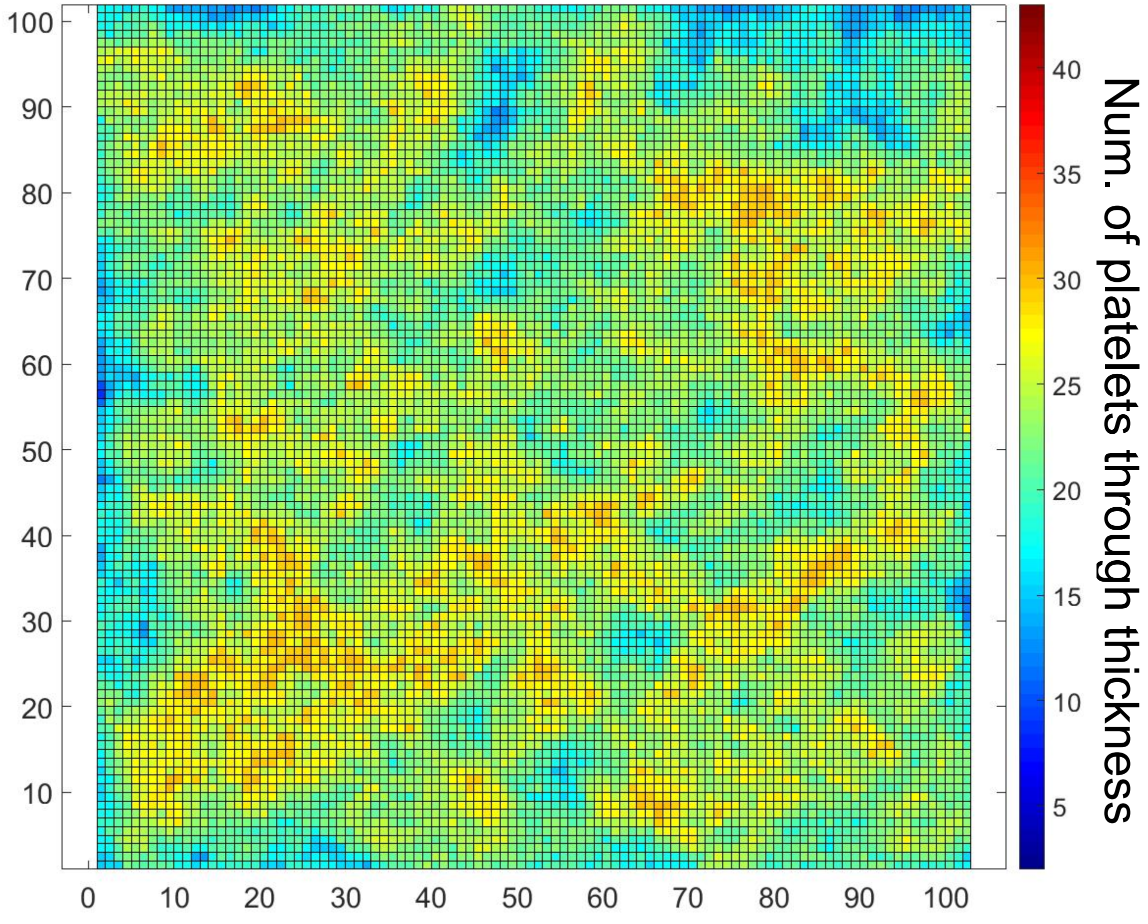
$$\sigma_{Bbasis} = Mean - K_b * STD$$ [CMH-17]

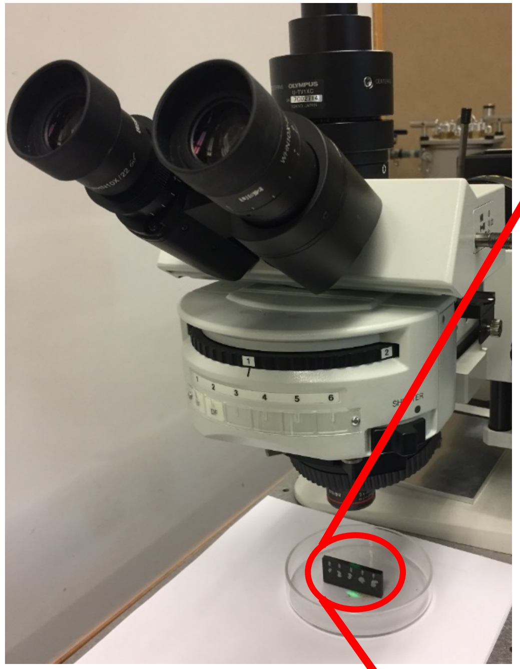
Where K_b is B-basis tolerance factor, depends on the number of tested coupons.

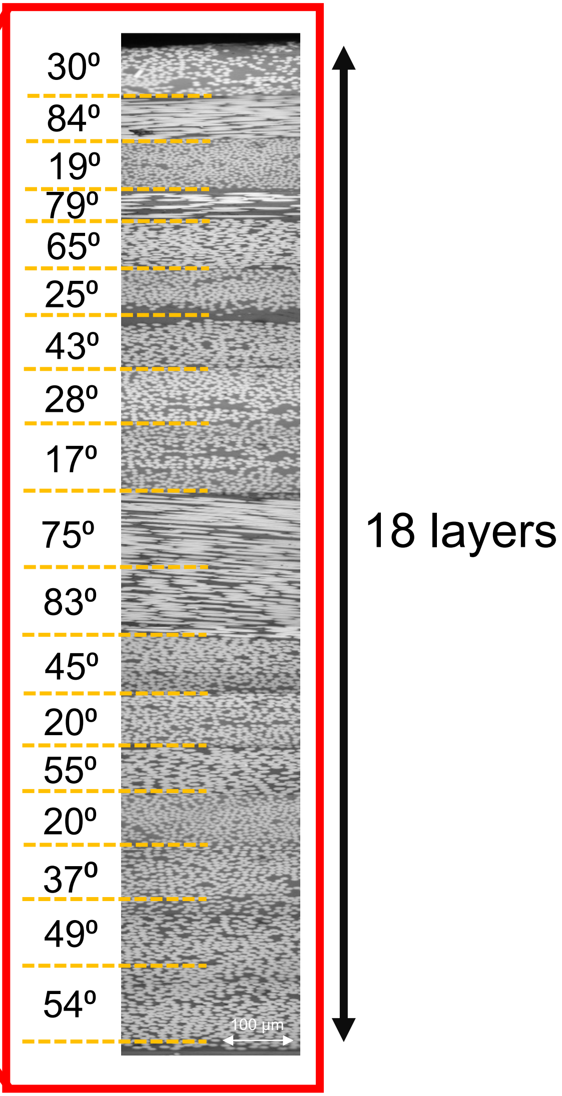
For simplicity, K_b = 2.583 corresponds to the 8 coupons.

Experimentally-verified morphology

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







Mesostructure Generation Algorithm

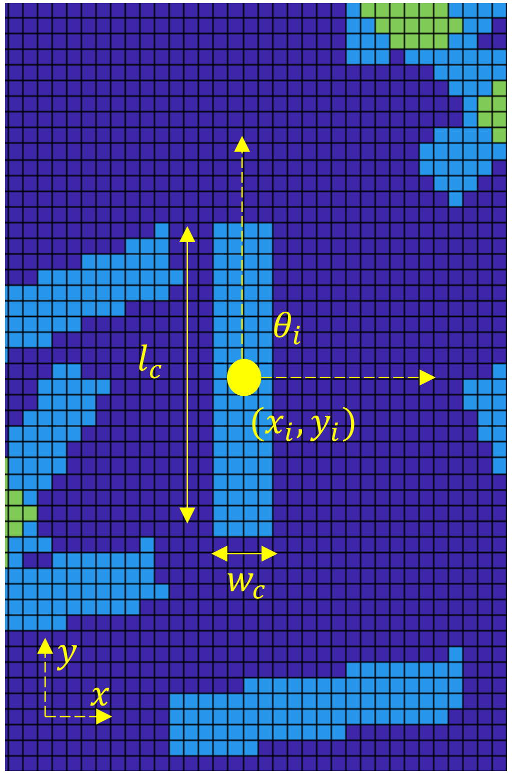
DFC In-house Manufacturing:

- **Random distributions**
- **Random orientations**
- **Platelet dimensions**
- **Structure thickness**
- **Resin pockets (< 10%)**

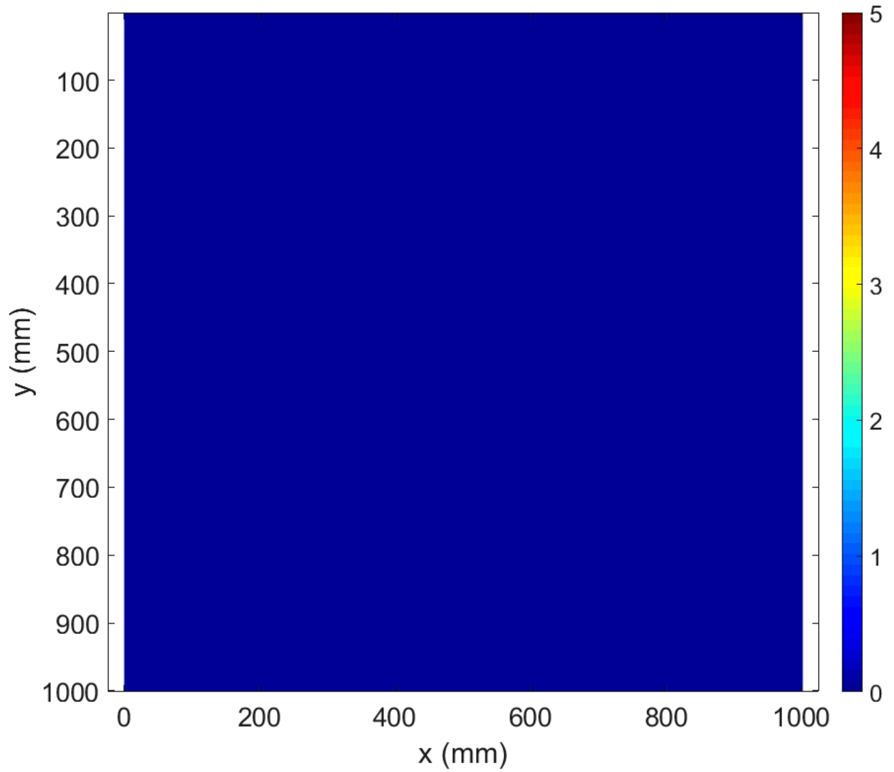
Selezneva, 2015

Extension of the Stochastic Laminate Analogy

(Harban 2017, Feraboli 2010)



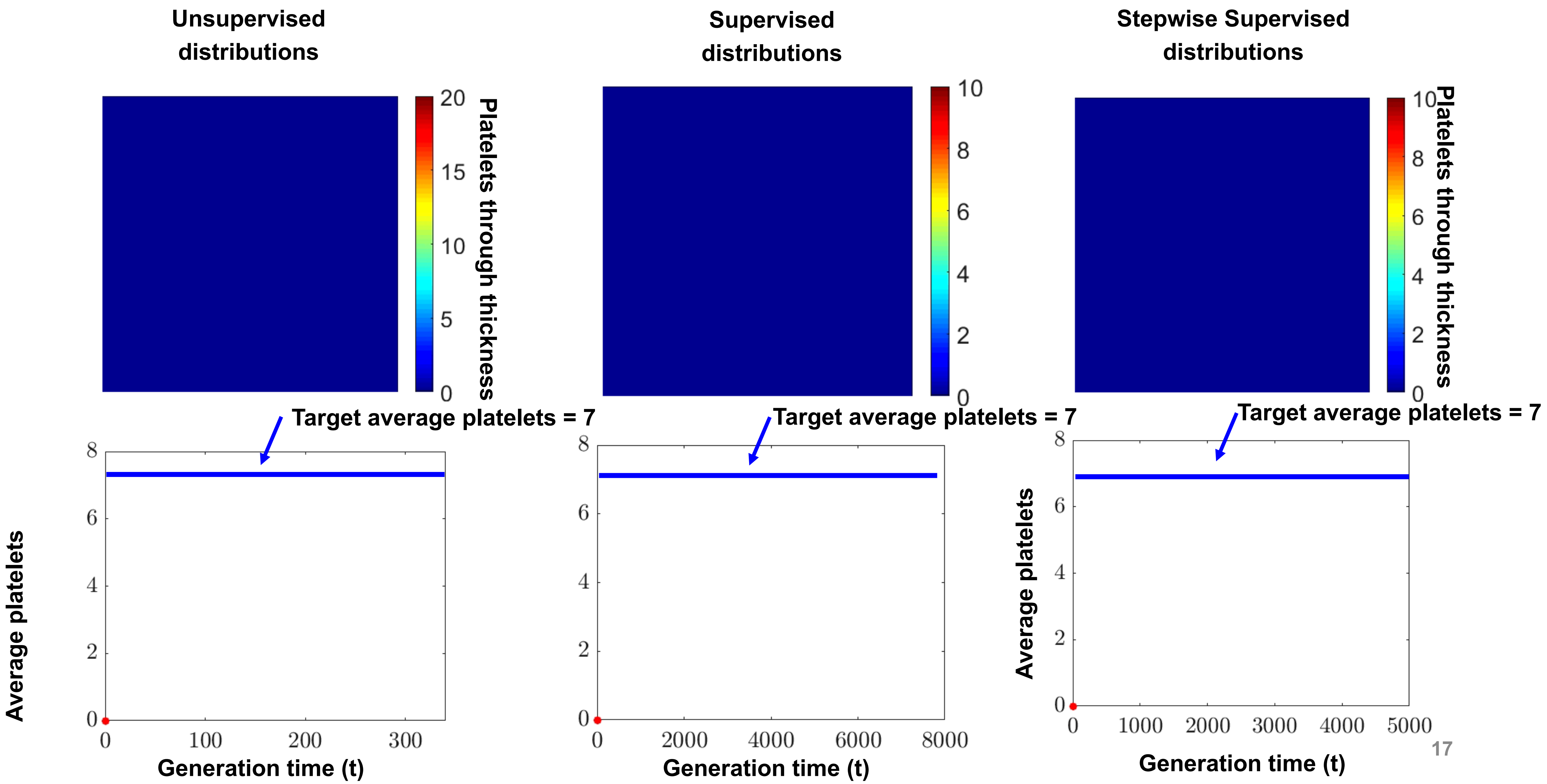
Partition-based morphology



Average platelet in the plate = 1

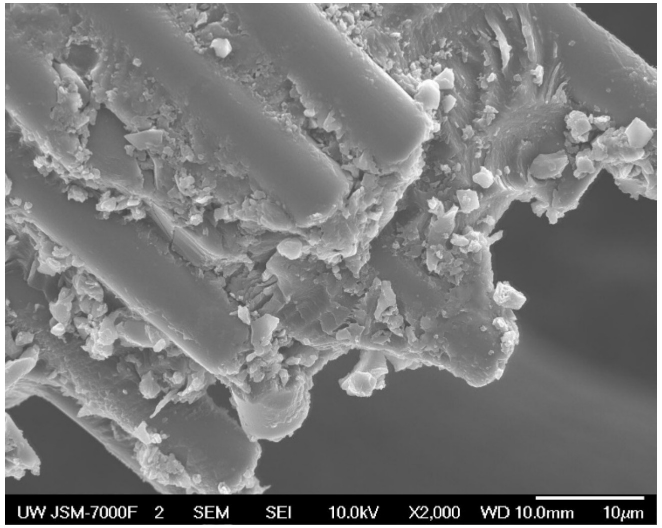
Upper limit of local platelets = 5

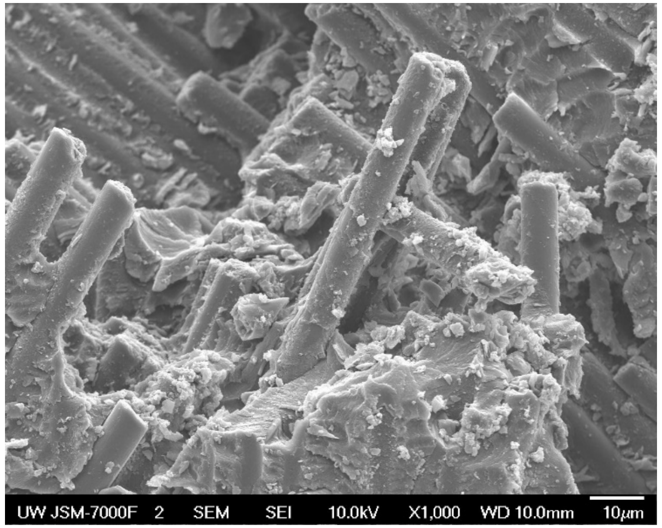
Calibration of the mesostructure



Highly Mixed Damage Mechanisms

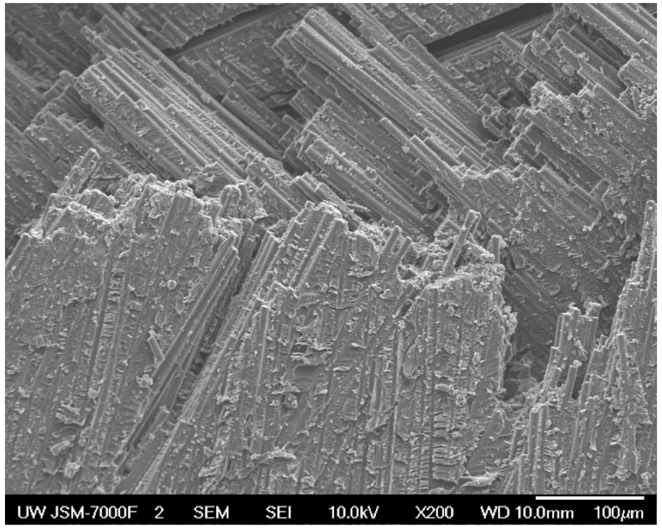
Damages within the platelets

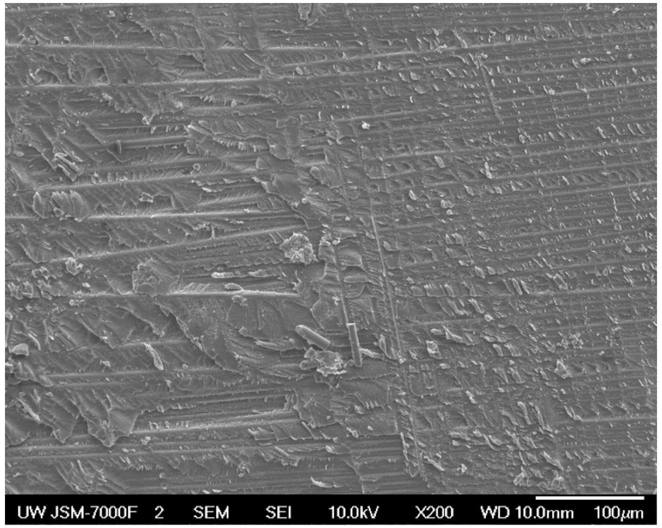




Fiber pullouts, Fiber breakages, Matrix micro-cracks

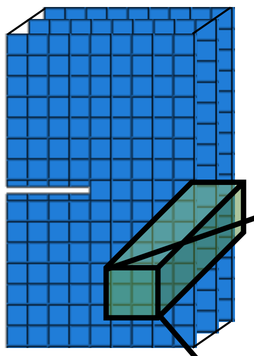
Damages in between the platelets

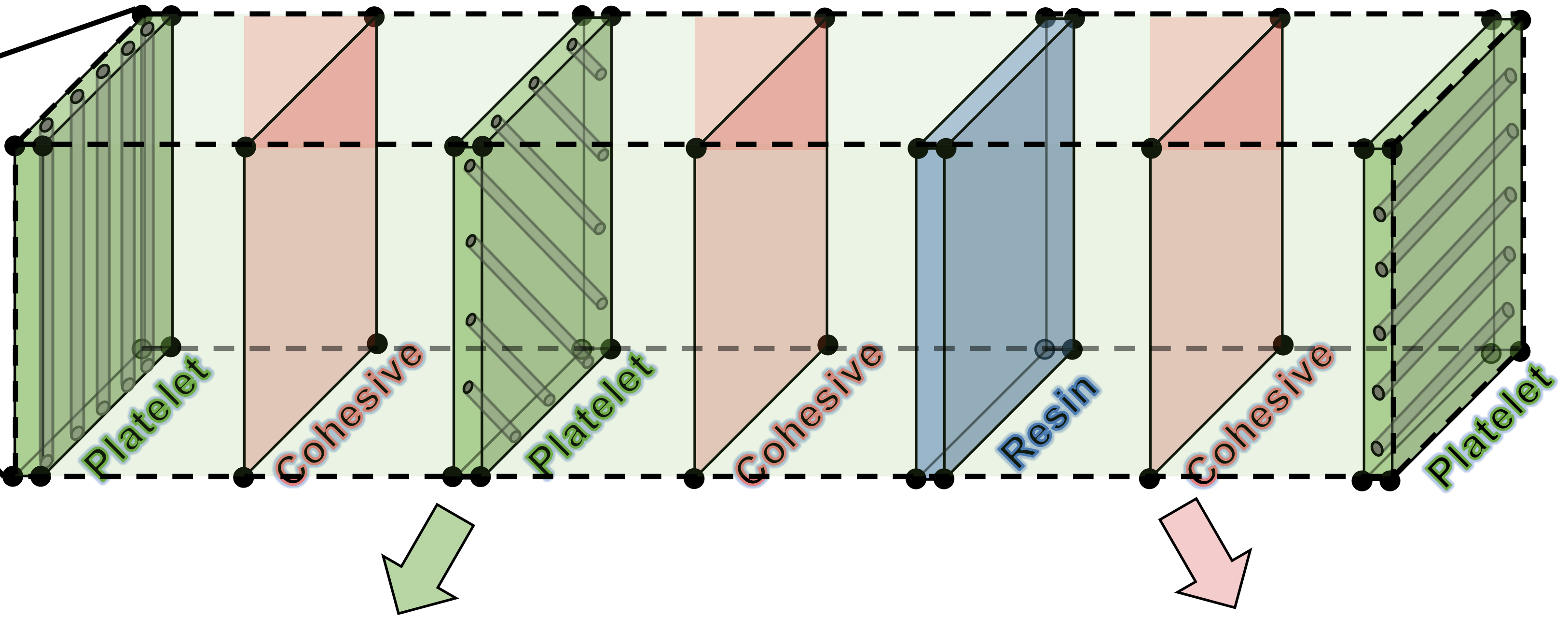




Large matrix delamination

Discrete-Mesoscale Model

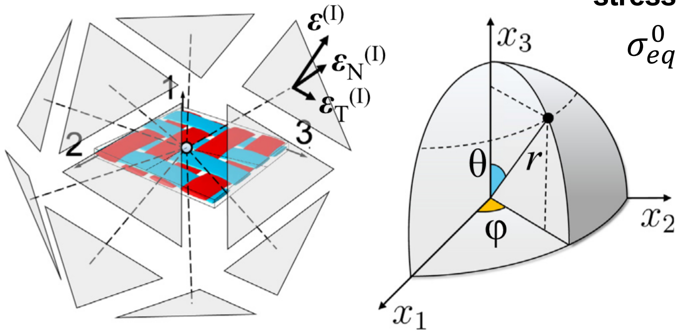




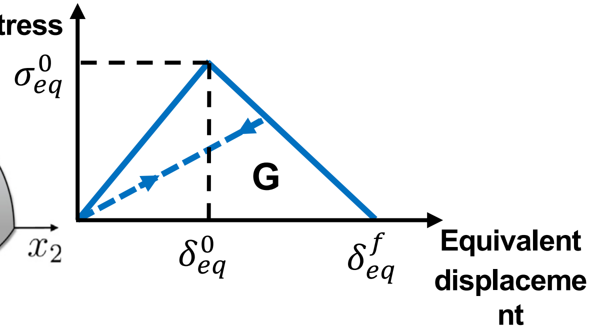
Platelet Damage/Failure

Cohesive Damage/Failure

- Spectral Stiffness Microplate model



- **Linear softening damage evolution**

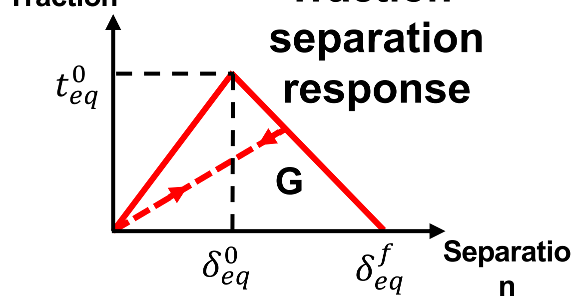


Salviato et al., Compos Struct, 2016

- **Quadratic stress Criteria**

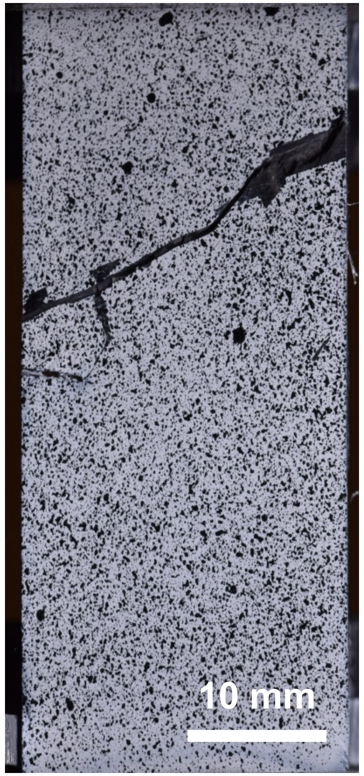
$$\left\{\frac{[t_n]}{t_n^0}\right\}^2 + \left\{\frac{t_s}{t_s^0}\right\}^2 + \left\{\frac{t_t}{t_t^0}\right\}^2 = 1$$

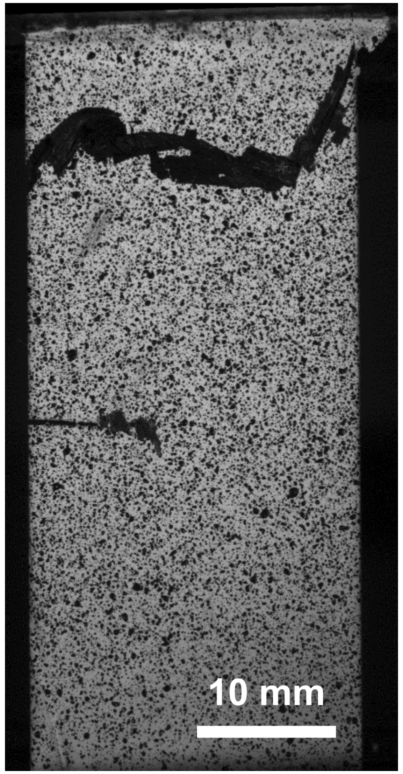
- **Linear Traction-separation response**



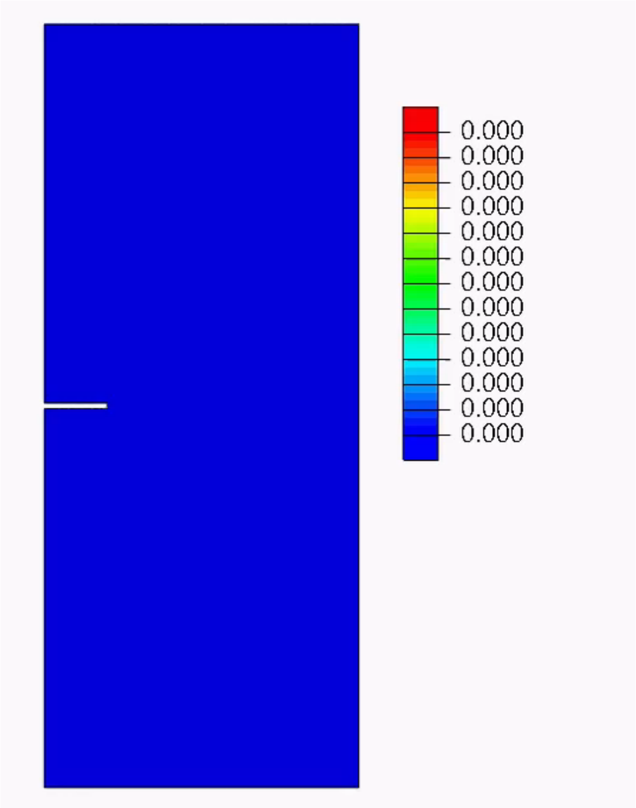
Simulations

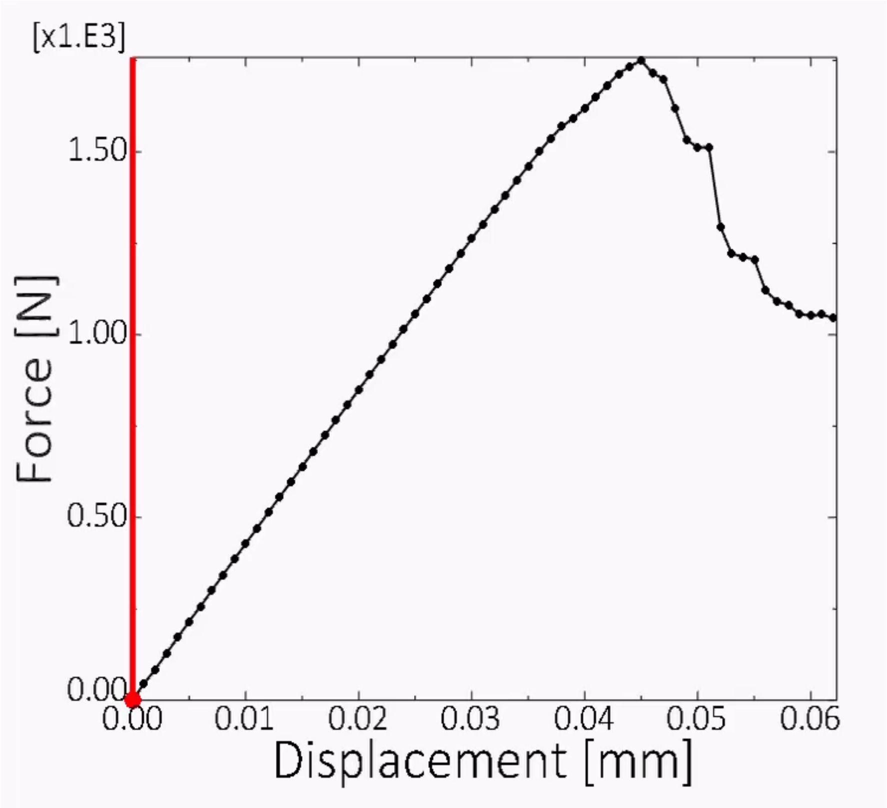
Fracture surfaces of Small Coupons



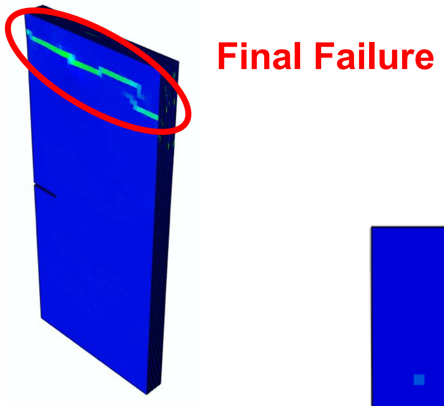


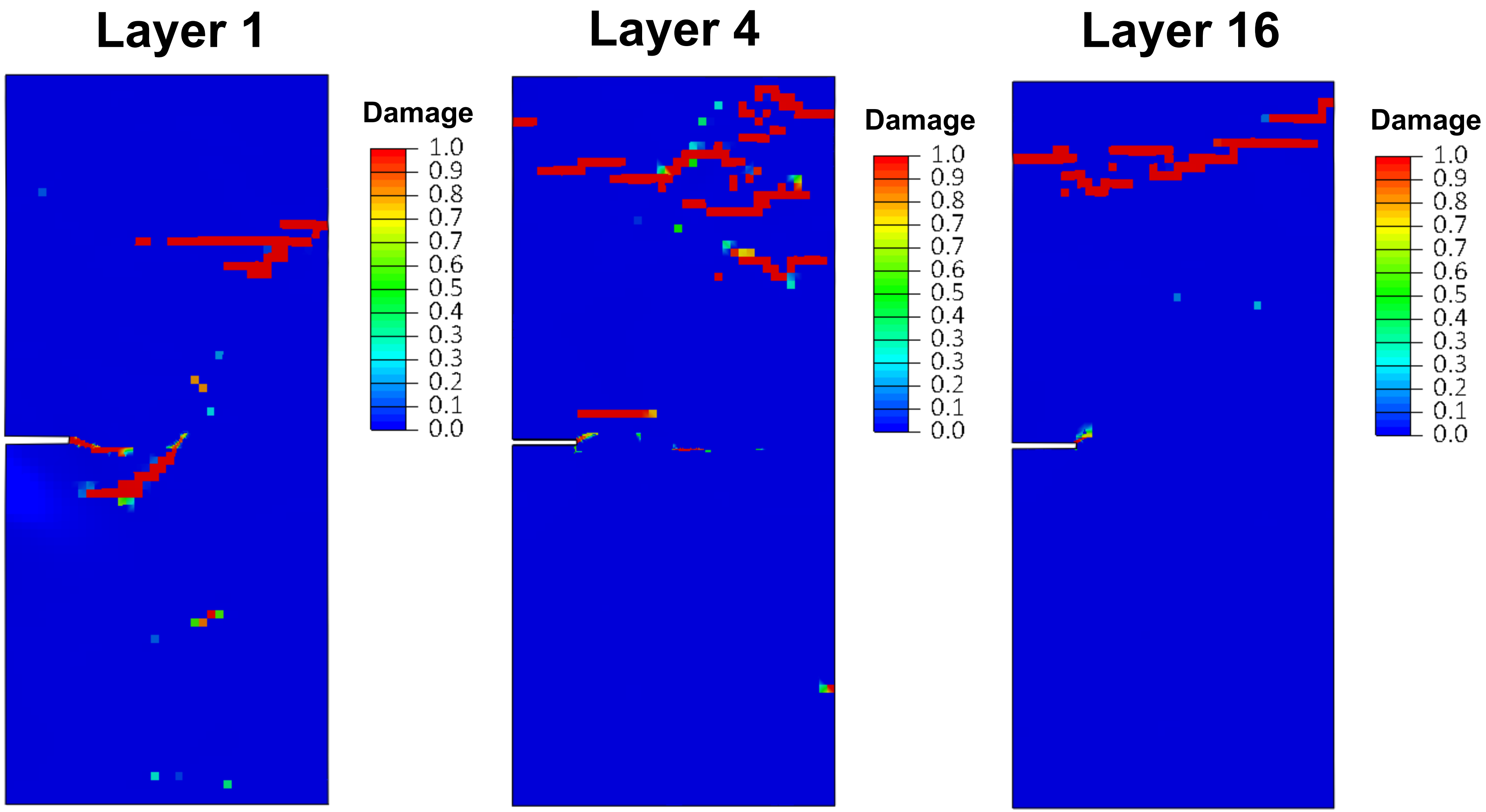
Strain distribution in Y-dir.



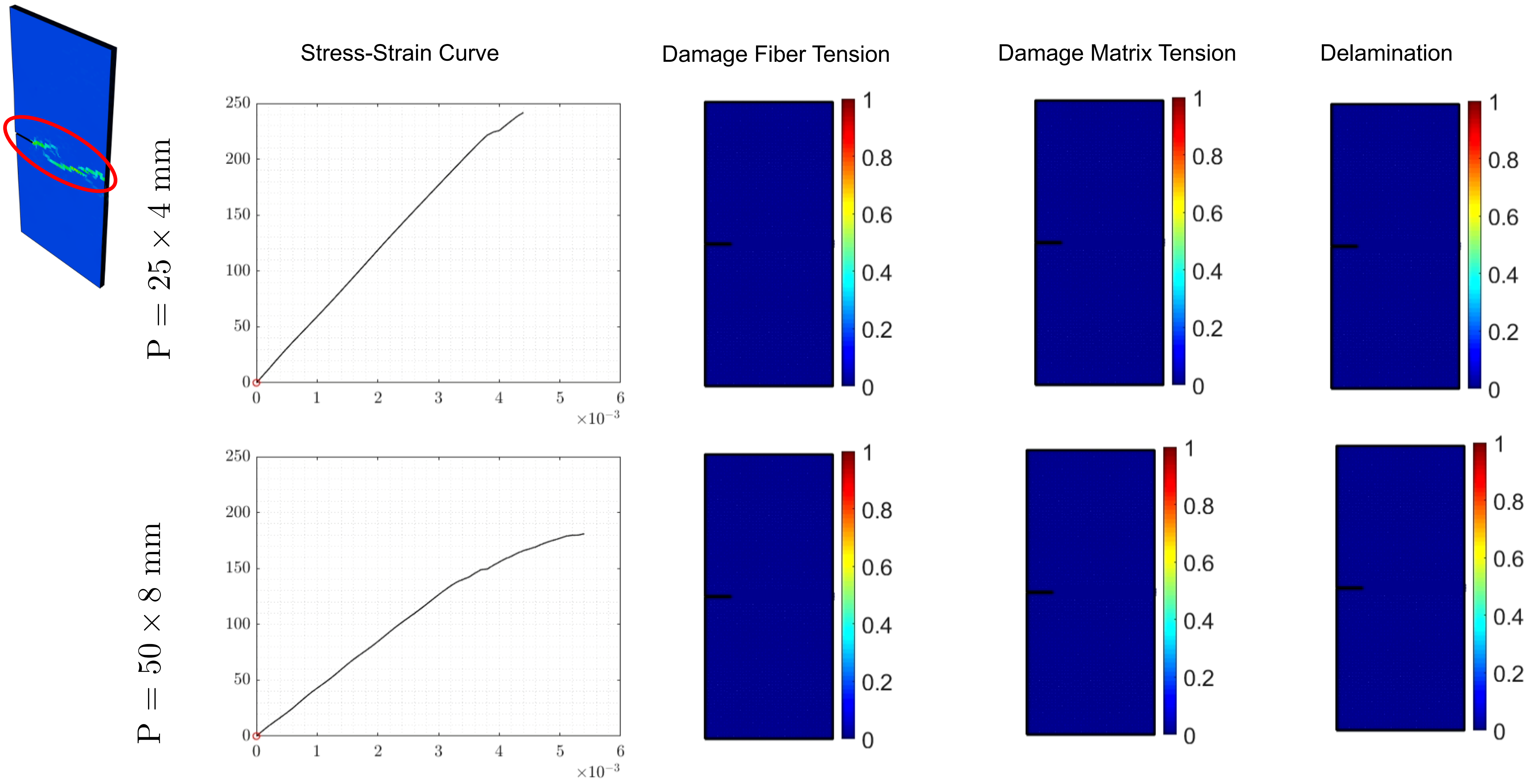


Simulated fracture morphology



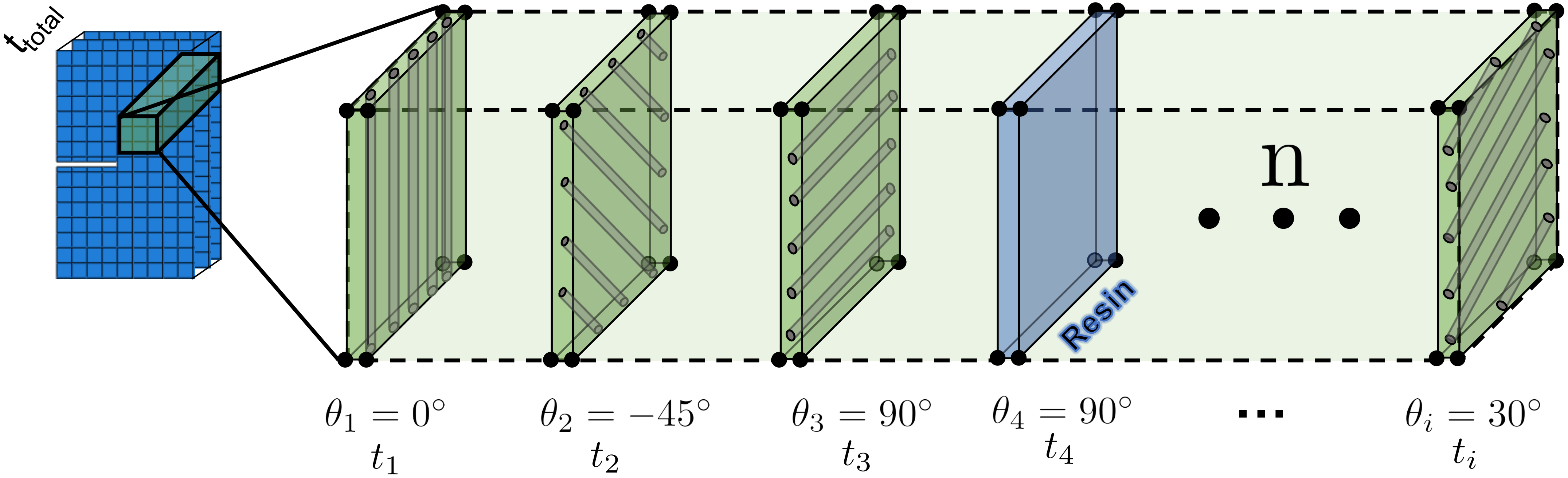


Matrix damage distributions in different layers

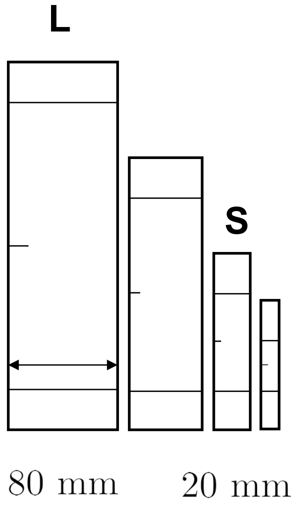


W = 40 mm, t = 3.3 mm

Stochastic distributions of the platelet orientations



$$\theta_{average} = \frac{1}{t_{total}} \sum_{i=1}^{i=n} |\theta_i| t_i$$

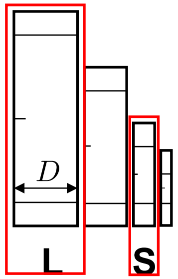


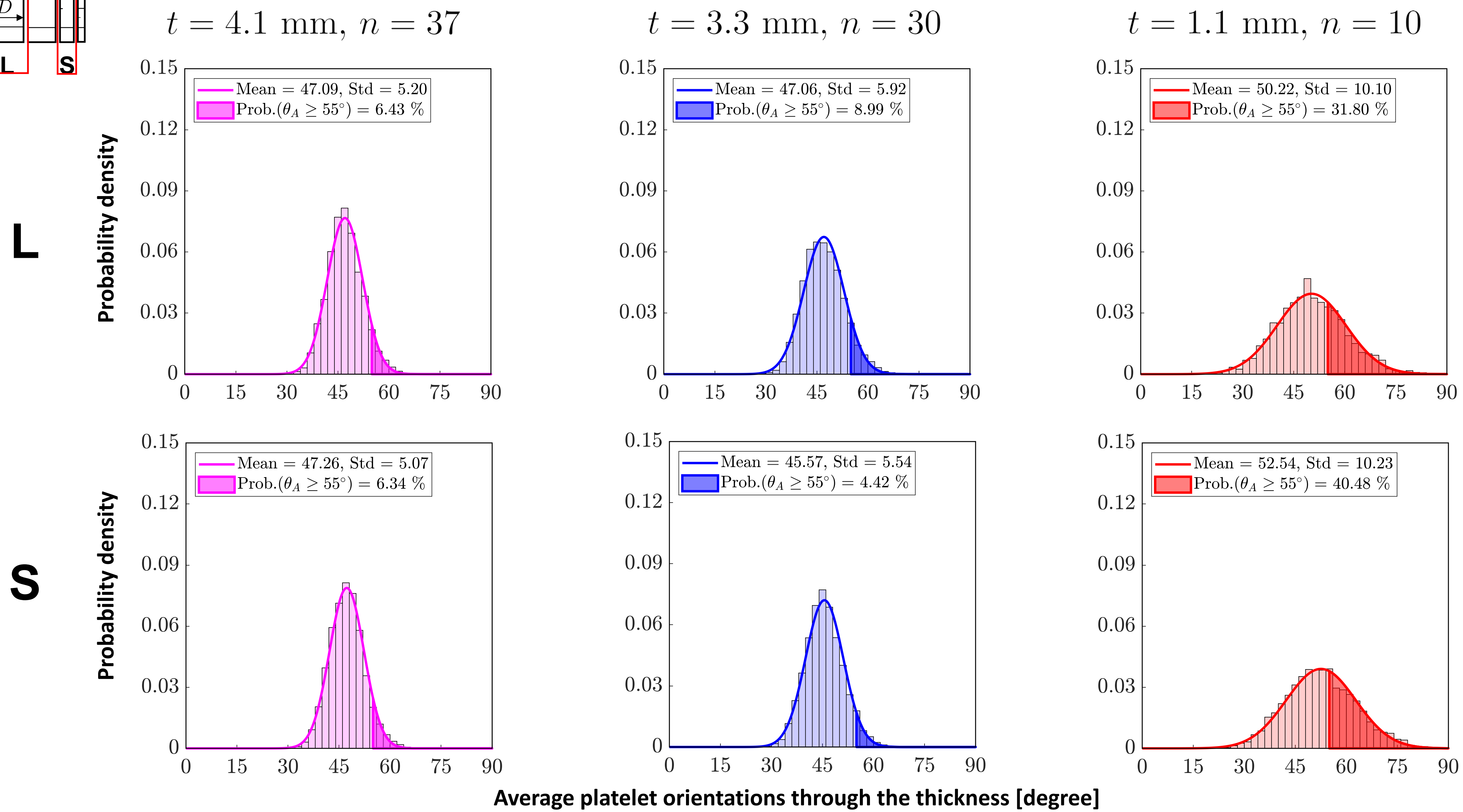
$\theta_{average}$ is calculated in each partitions.

Probability density plot is fitted using the normal distributions.

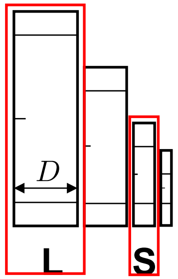
For Large size, number of partitions = 14320. For Small size, number of partitions = 900

Stochastic distributions of the platelet orientations

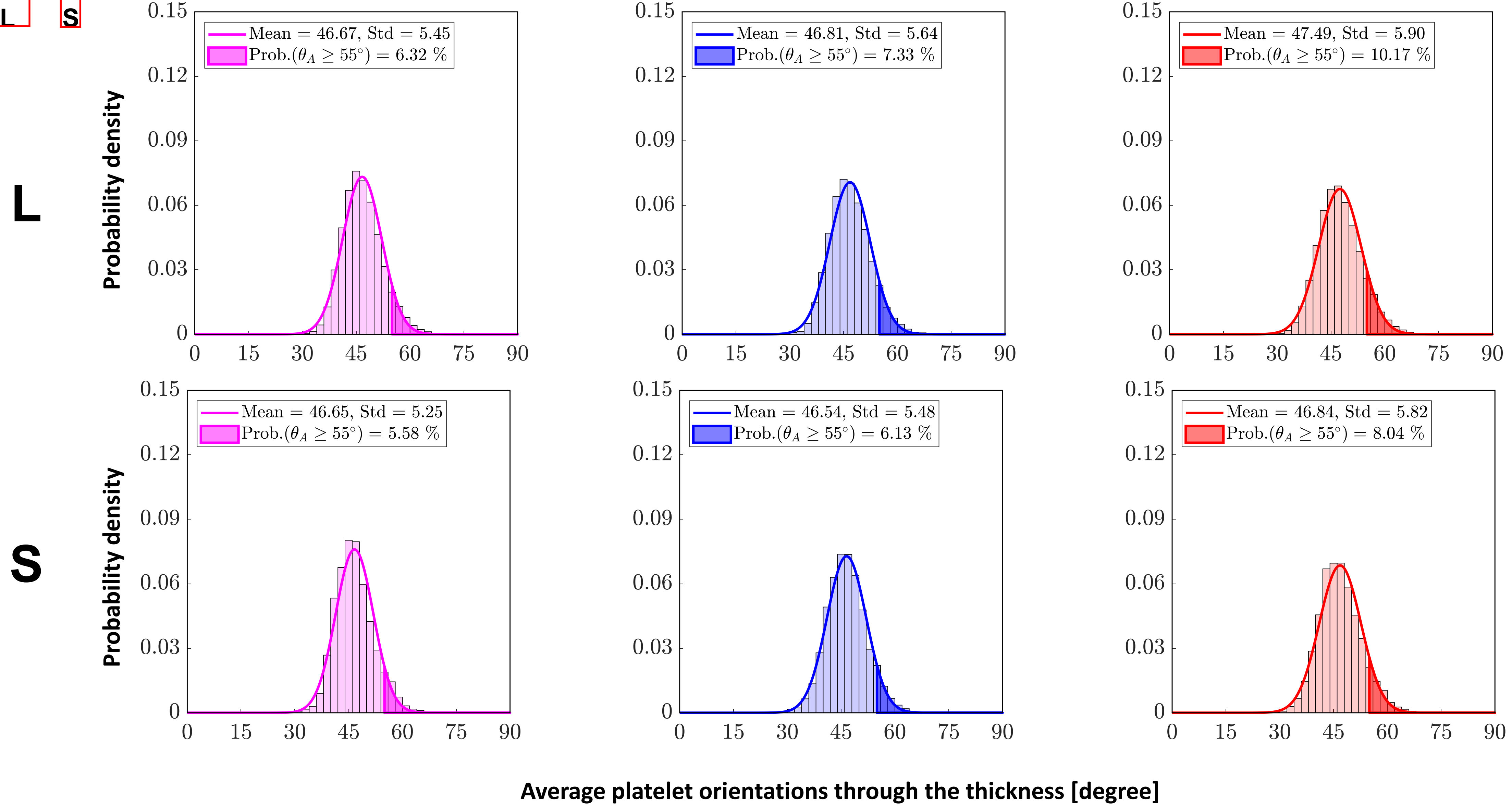




Stochastic distributions of the platelet orientations



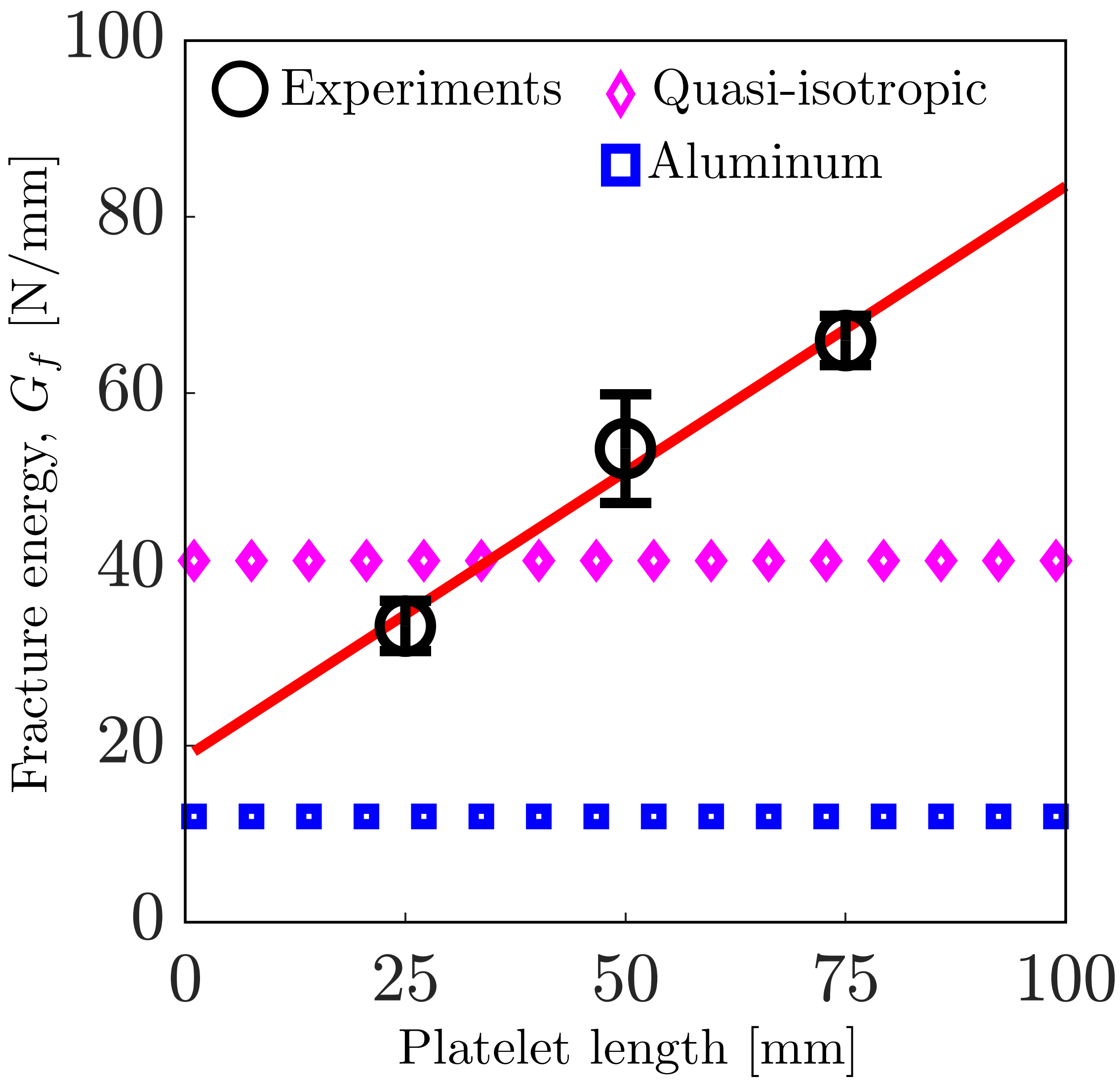
Platelet size: 100×16 mm, n = 30 | Platelet size: 50×8 mm, n = 30 | Platelet size: 25×4 mm, n = 30



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

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

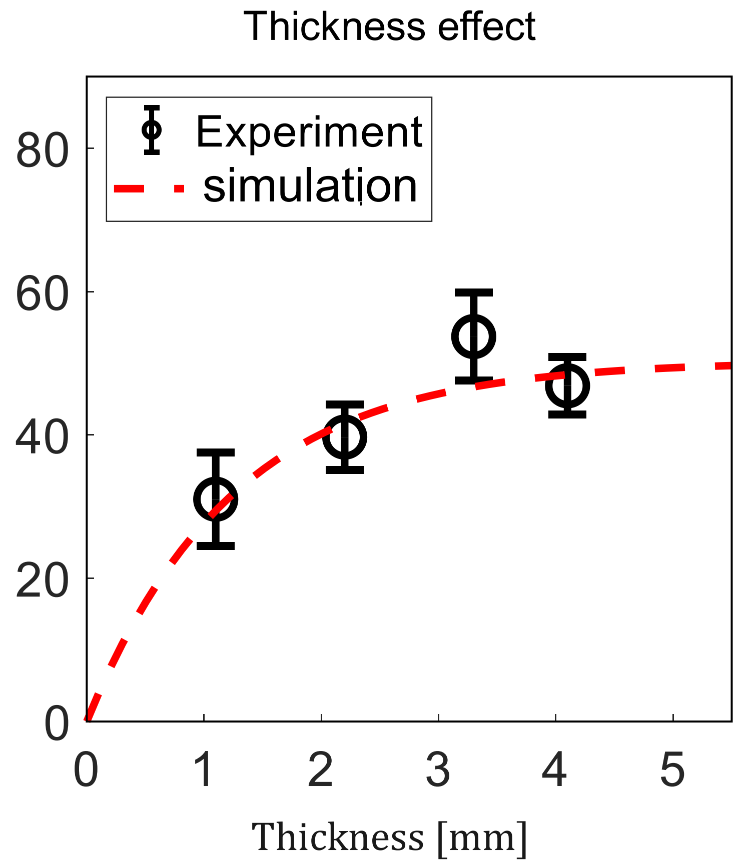
	Effective FPZ length, c_f (mm)	Fracture energy, G_f (N/mm)
25×4 (mm)	6.55 ± 1.07	33.59 ± 2.86 Δ0.0%
50×8 (mm)	7.43 ± 0.83	53.72 ± 6.14 Δ59.9% ↑
75×12 (mm)	14.2 ± 1.85	64.98 ± 2.79 Δ93.5% ↑



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% ↑



Summary

1. DFC structures feature a significant energetic (type II) size effect;
2. Depending on the platelet size and thickness relative to the structure size, the size effect may transition from energetic to energetic-statistical;
3. Combining stochastic FEA and equivalent fracture mechanics, Bažant's size effect law was extended to DFCs and shown to be in excellent agreement with the experiments;
4. Increasing the platelet size leads to higher fracture energies and improved damage tolerance;
5. A similar effect is obtained by increasing the number of platelets through the thickness;
6. Ongoing analyses suggest that stochastic mesoscale modeling can effectively capture both the energetic and energetic-statistical size effects in DFCs

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 significant 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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Safety and Certification of Discontinuous Composite Structures

Marco Salviato, Jinkyu Yang, Mark Tuttle

University of Washington

AMTAS 2019 Technical Review Nov 5-6, 2019

Center for Urban Horticulture, University of Washington, Seattle, WA.

Bažant's Size Effect Law

Define the nominal stress in the specimen as:

$\sigma_N = P/(tD)$ $P =$ **applied load,** $t =$ **thickness,** $D =$ **width** (1)

The following expression holds for the fracture energy:

$$G_f(\alpha) = \frac{\sigma_N^2 D}{E^*} g(\alpha, D) = \frac{\sigma_N^2 D}{E^*} g\left(\alpha_0 + \frac{c_f}{D}, D\right) \quad (2)$$

$\alpha = \mathrm{a/D}$

$E^* =$ **effective modulus**

$g =$ **dimensionless energy release rate**

$c_f =$ **FPZ length**

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

$$\sigma_N = \sqrt{\frac{E^* G_f}{D g(\alpha_0, D) + c_f g_{,\alpha}(\alpha_0, D)}} \quad (3)$$

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

Length scale

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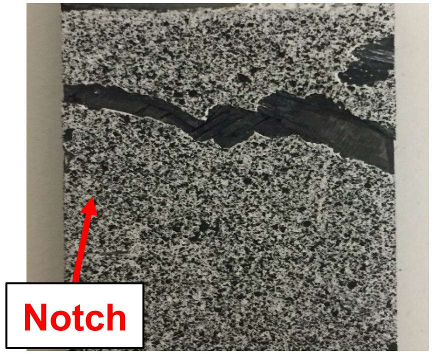
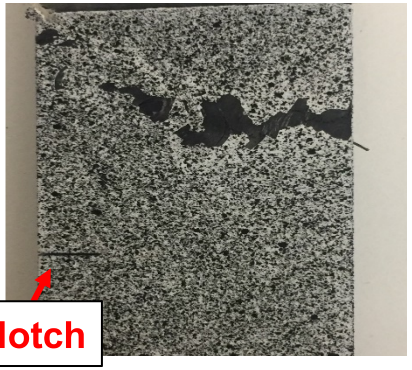
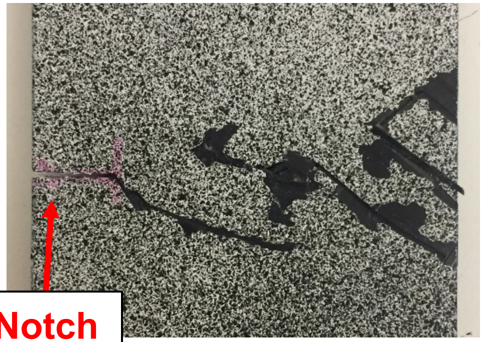
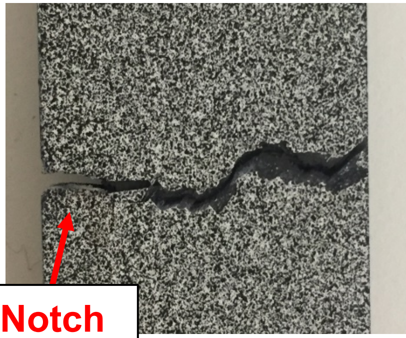
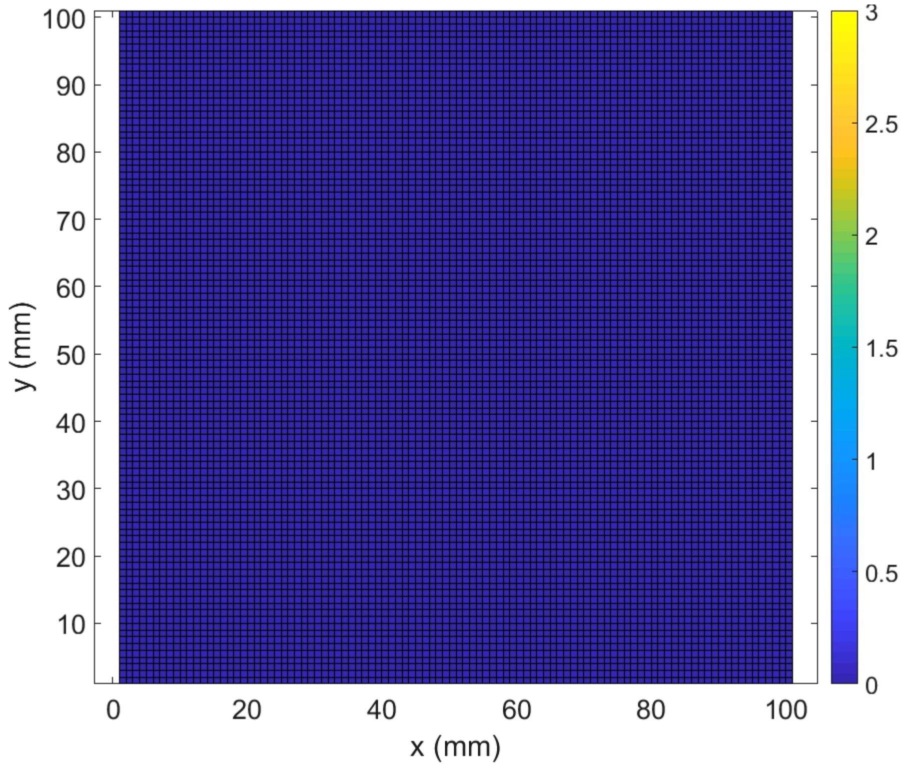
Fracture Surfaces (50 x 8 mm platelets) – thickness effect

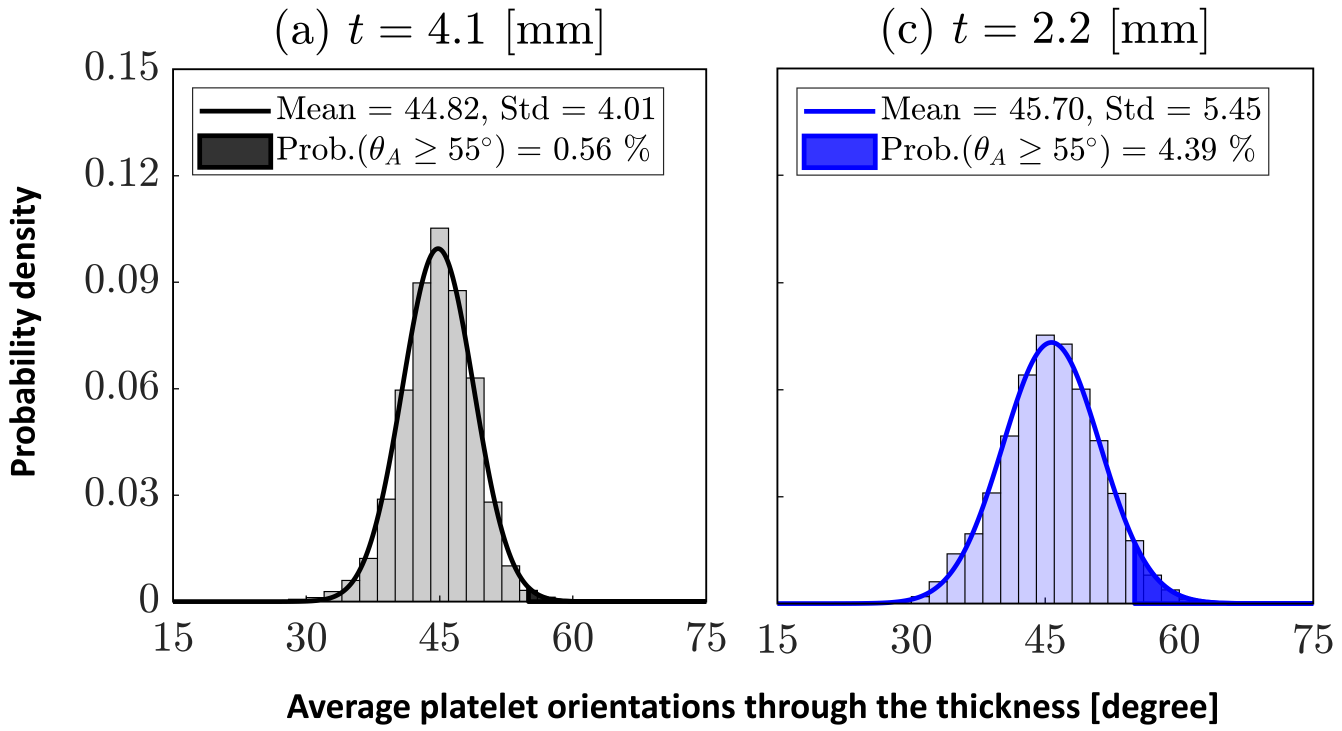
	D = 20 mm	D = 40 mm	D = 120 mm
1.1 mm			
2.2 mm			
4.1 mm			

Stochastic Finite Element Results

Mesostructure generation algorithm



Stochastic distributions of the platelet orientations



Introduction

Aviationweek.com

Avstop.com

compositestoday.com

Made of composites?

Aviationweek.com

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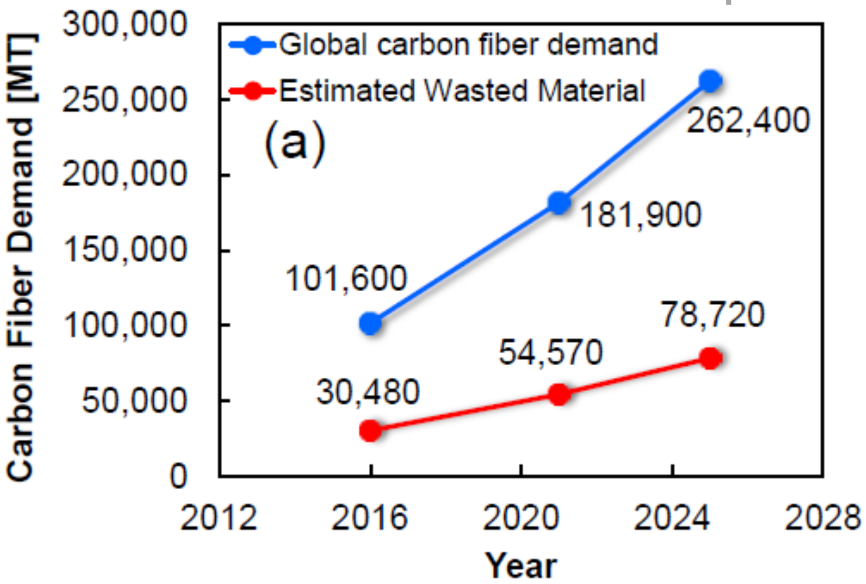
Introduction

Large volume manufacturing

Toray

Recyclability

Inside Composites



Composites Forecast and Consulting LLC

Part complexity

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Tencate

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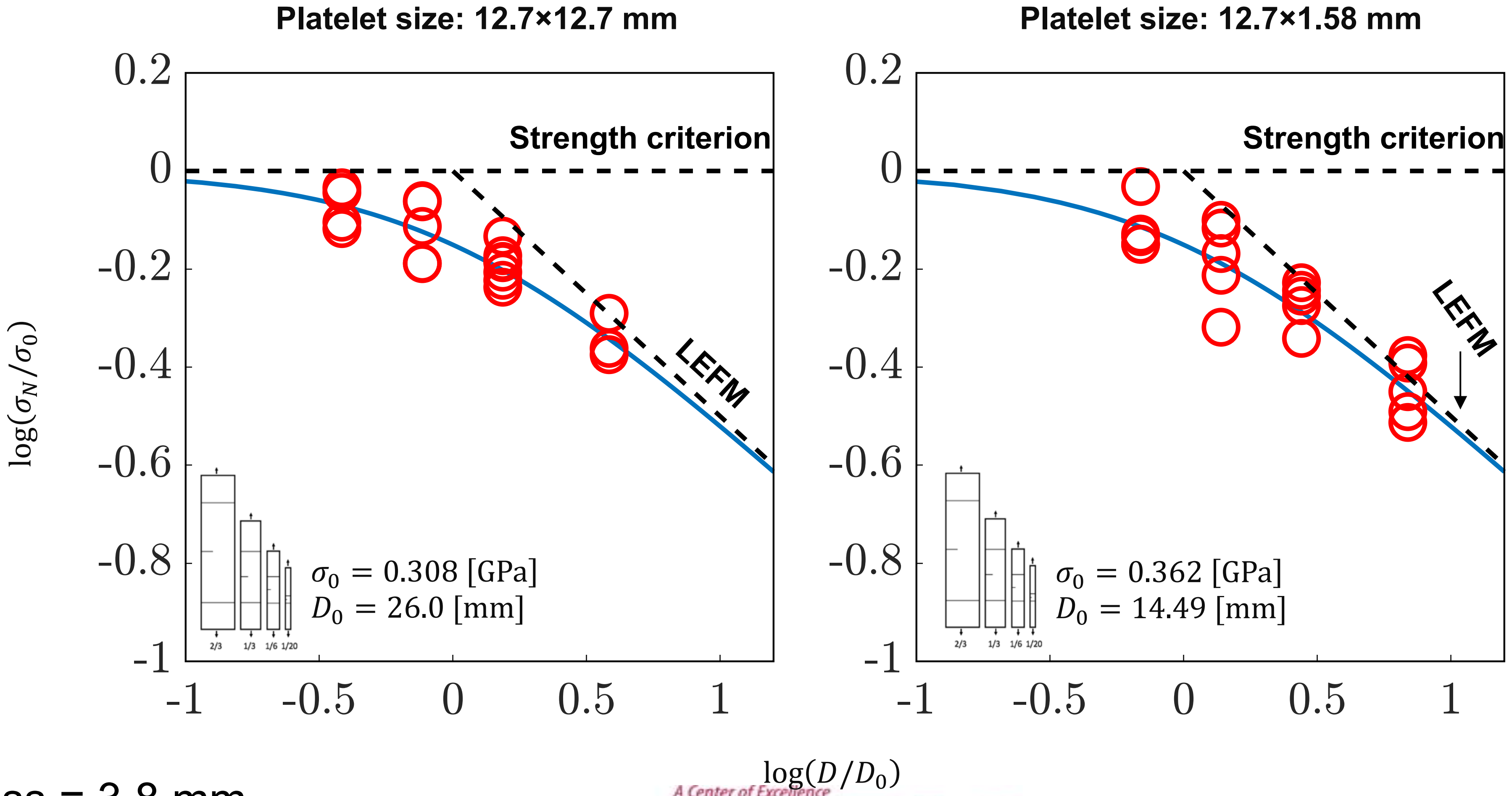
Result: Size effect curves – (thermoplastics)



*Thickness = 3.8 mm

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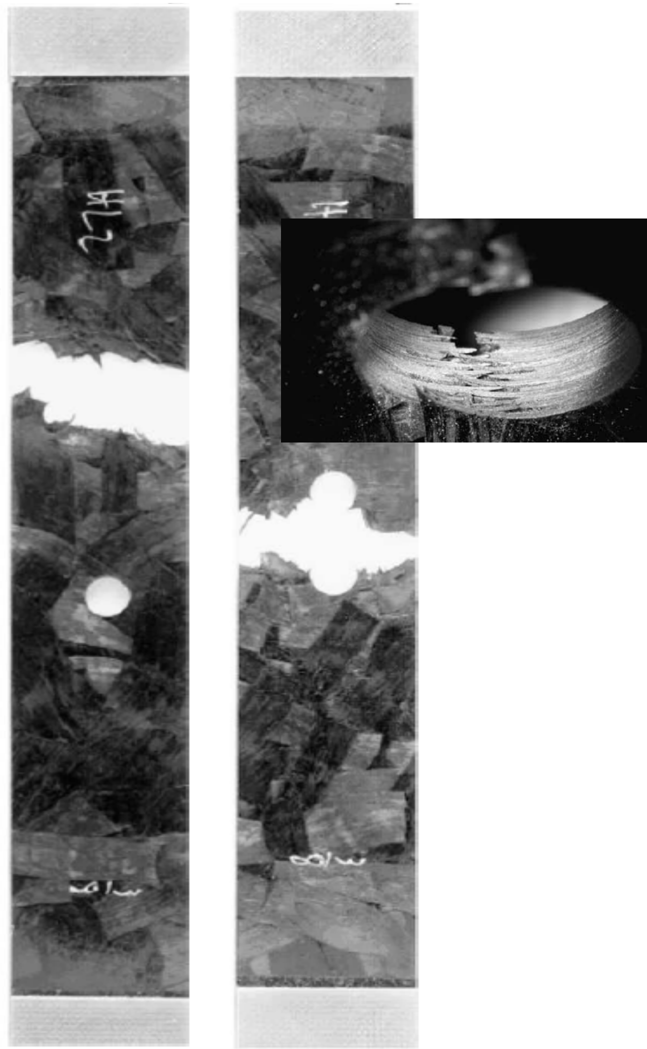
Current challenges:

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

Conventional application of DFC

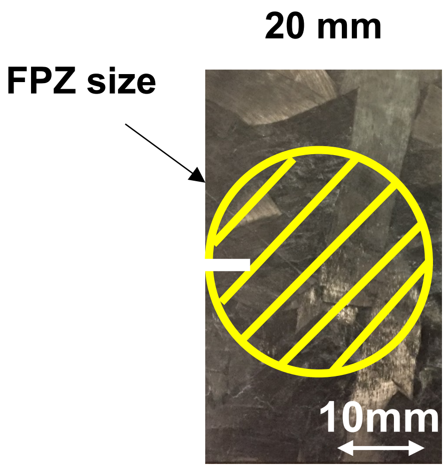
Hexmc parts, Hexcel

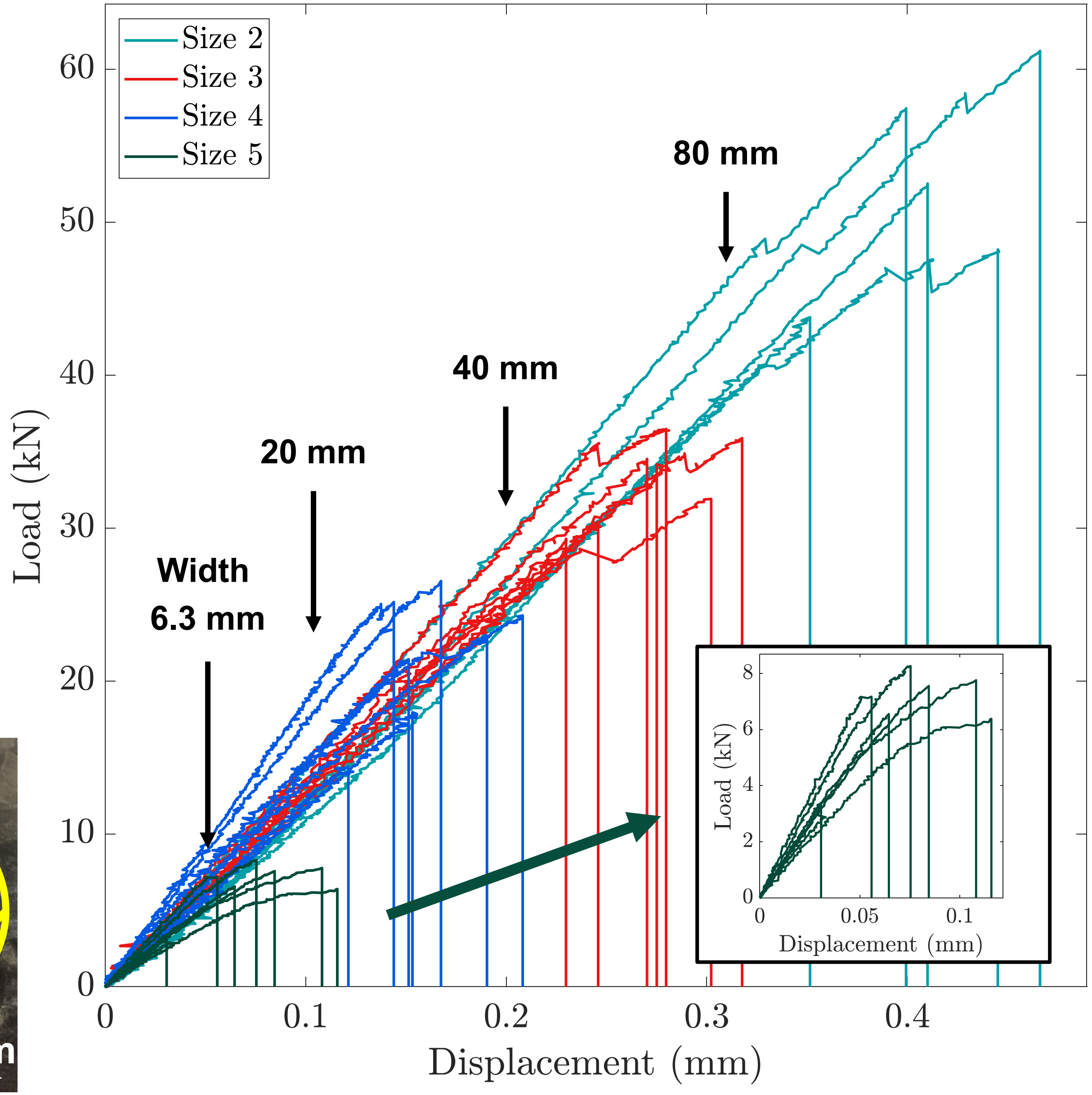
Qian, 2011

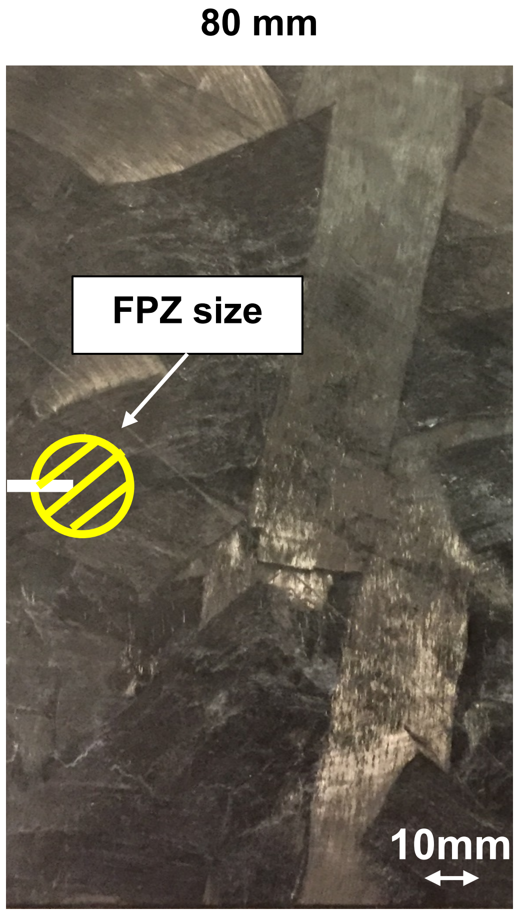


Feraboli, 2009

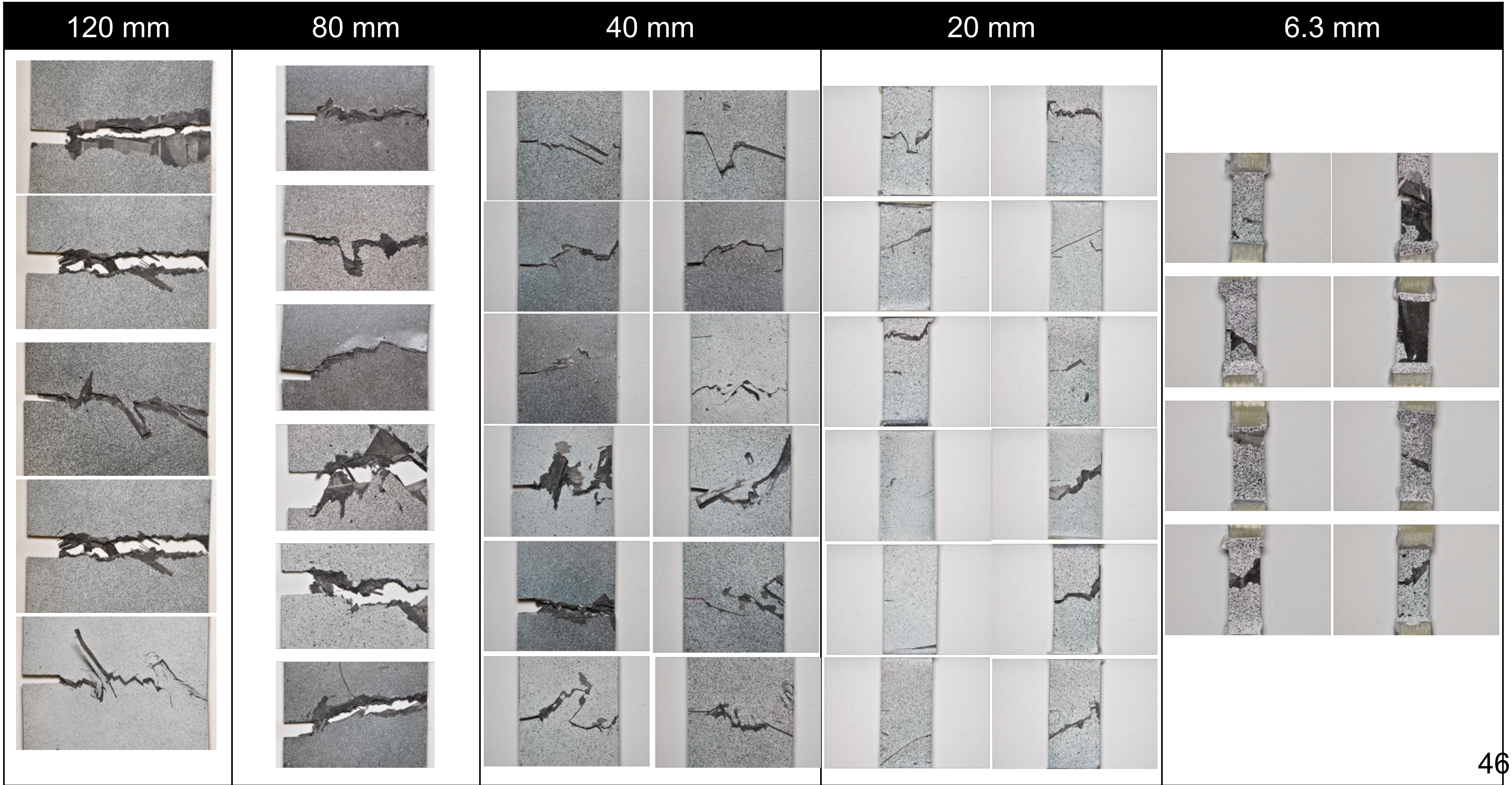
Typical Force and Displacement curves



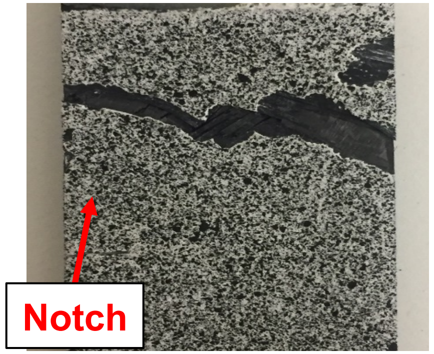
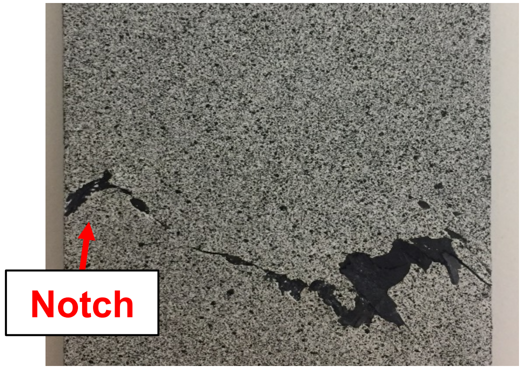
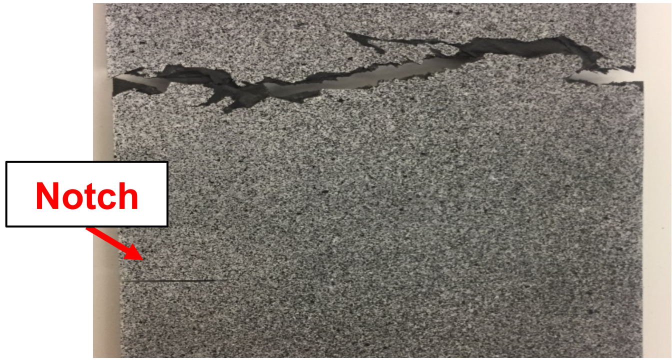
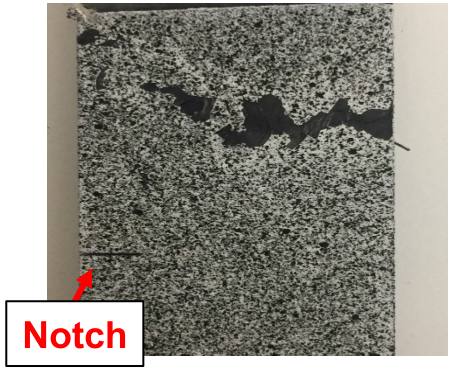
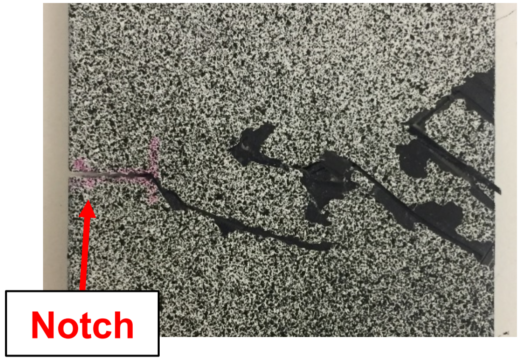
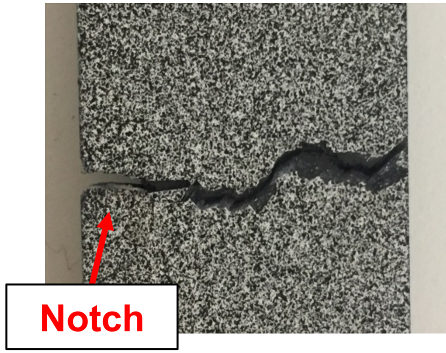
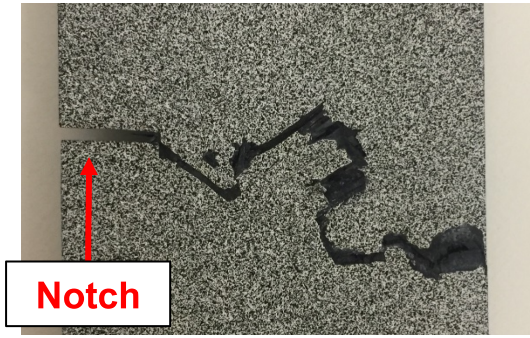




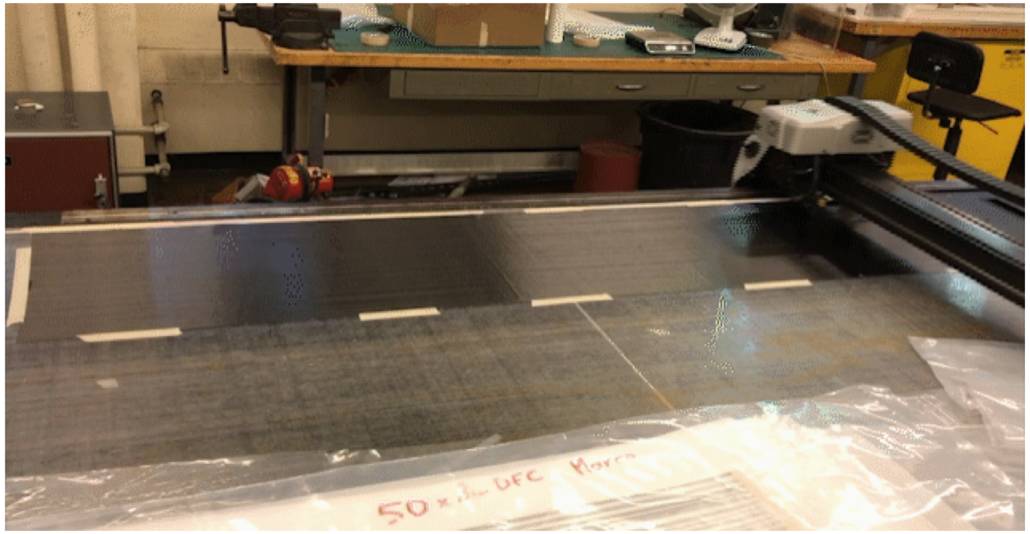
Typical Fracture Surfaces (50 x 8 mm platelets)



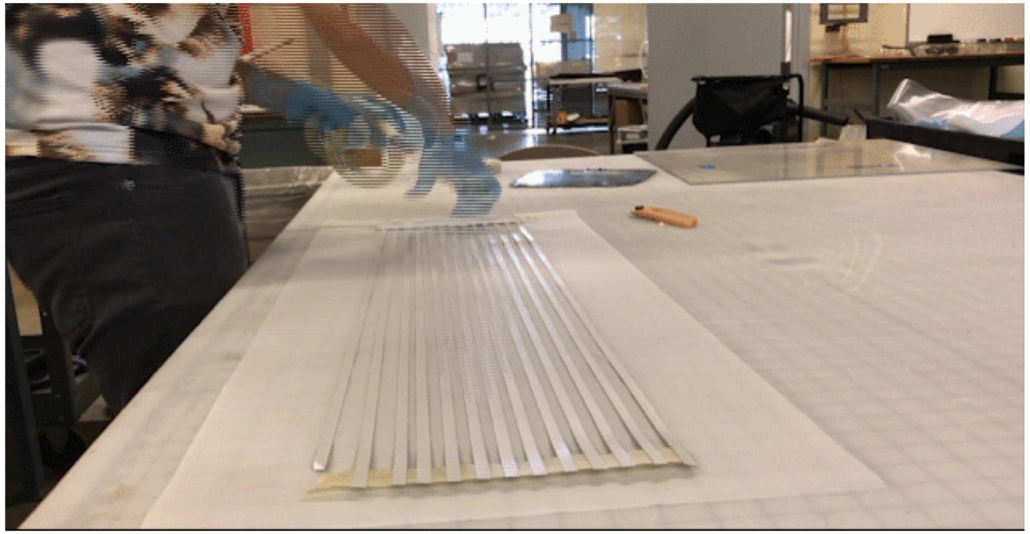
Fracture Surfaces (50 x 8 mm platelets) – thickness effect

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

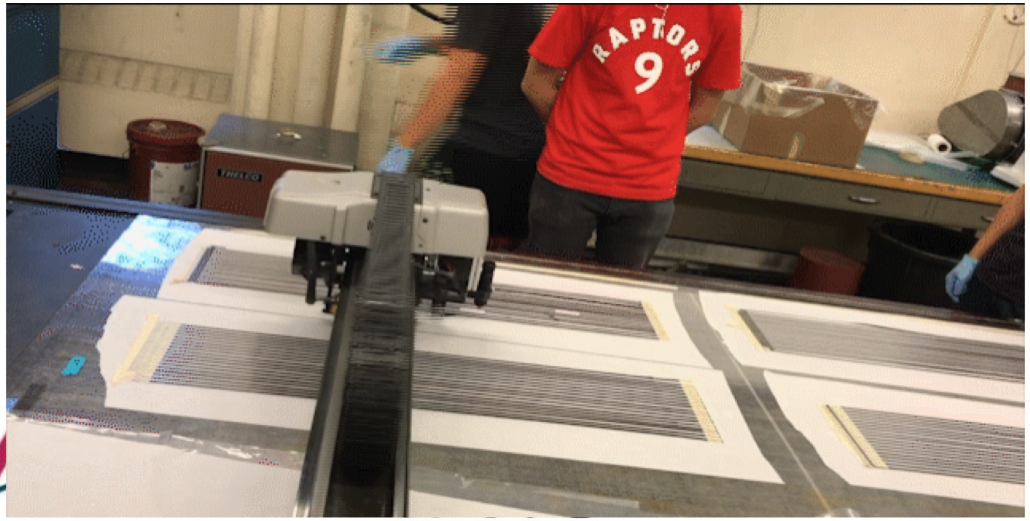
Specimen preparation



1) Cut into strips



2) Remove backing tape



3) Cross-cut the strips

4) Distribute platelets randomly

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

Size effect law:

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

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

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

➡ $A = \frac{g(\alpha_0)}{E^* G_f}$ 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

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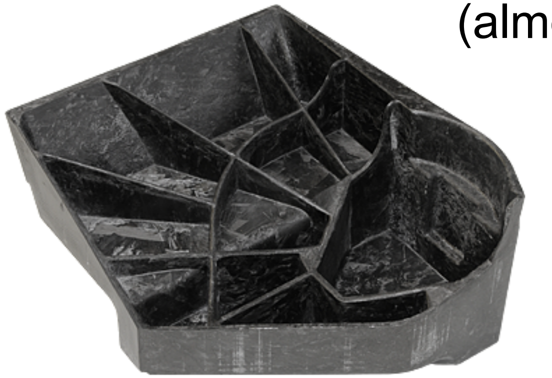
DFC structural components



(almost) Net shape design

Source: www.hexcel.com

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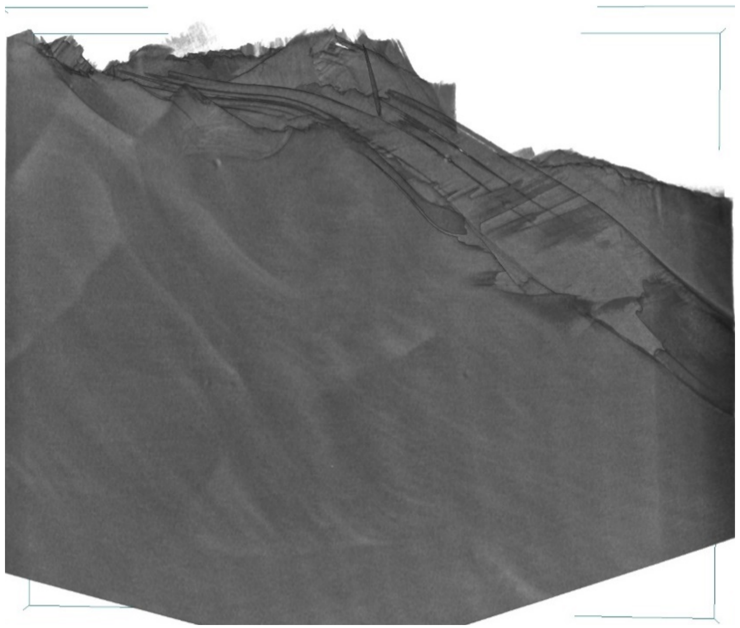
Challenges for certification

- 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

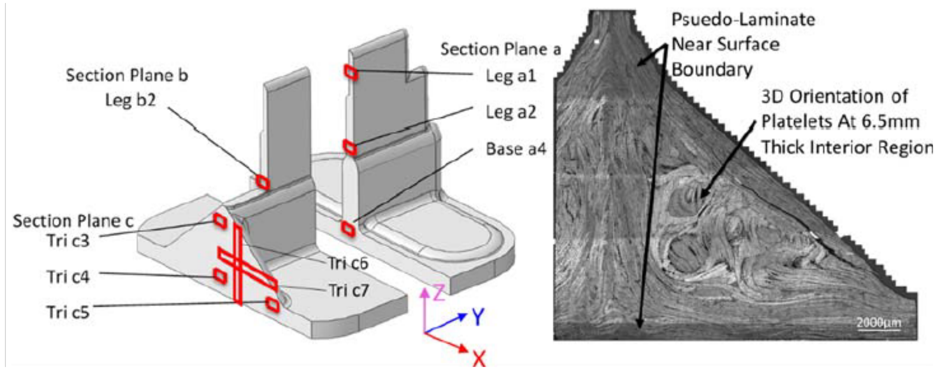
Proposed methodology and research plan

- **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.

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Proposed methodology and research plan

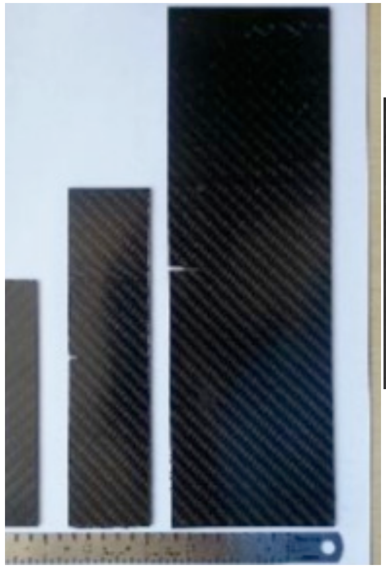
- **Defect analysis**

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

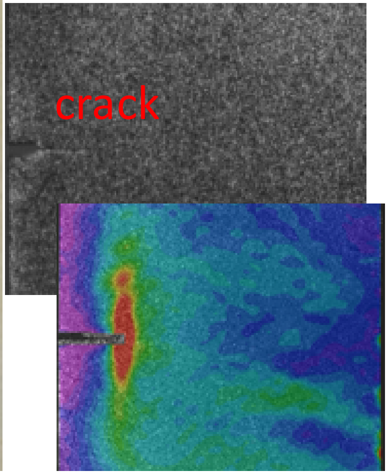
Types of defects:

- ***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**



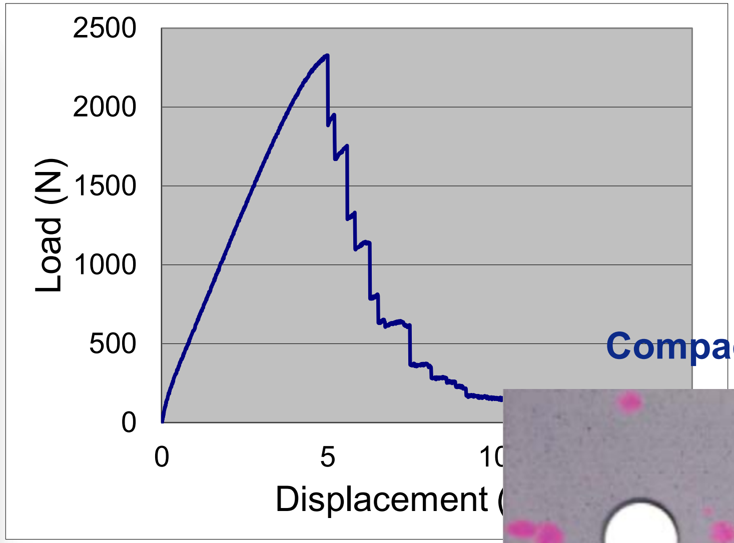
DIC investigation



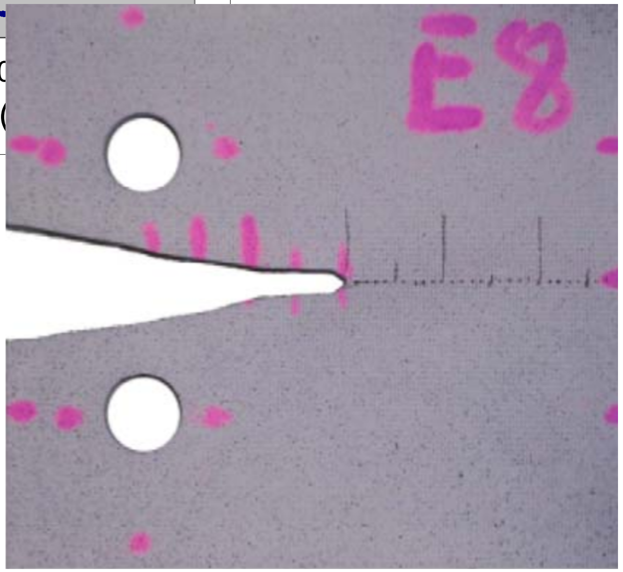
Salviato et al., Composite Science & Technology, 2016

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

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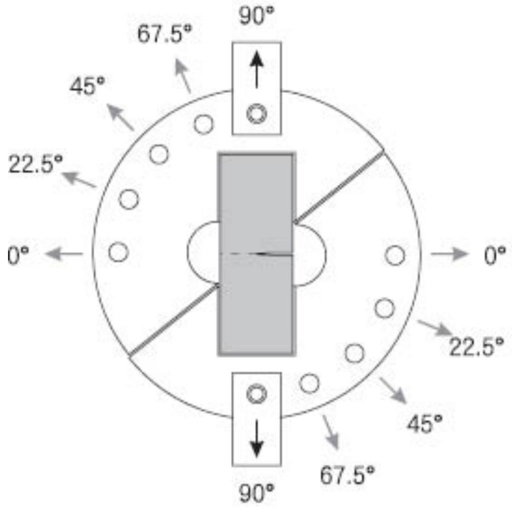
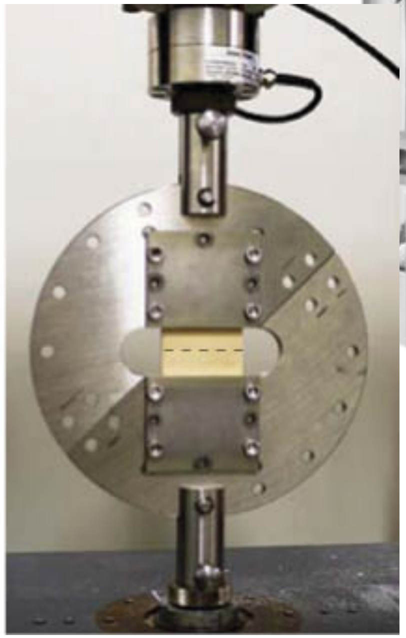
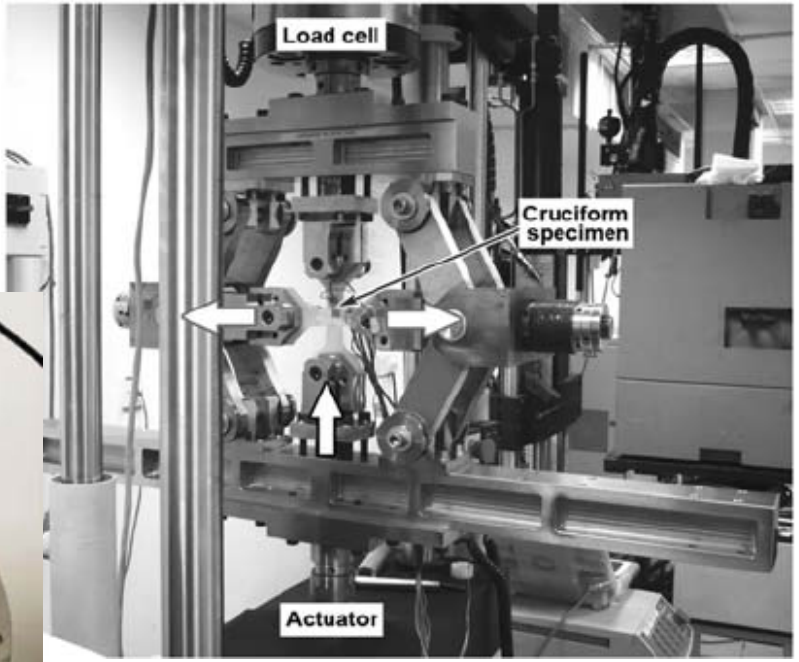
Proposed methodology and research plan

- **Multi-axial behavior**

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





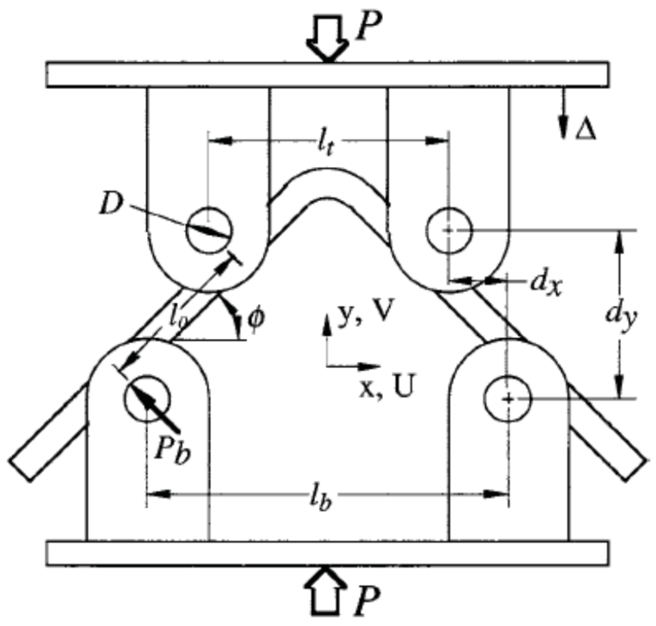


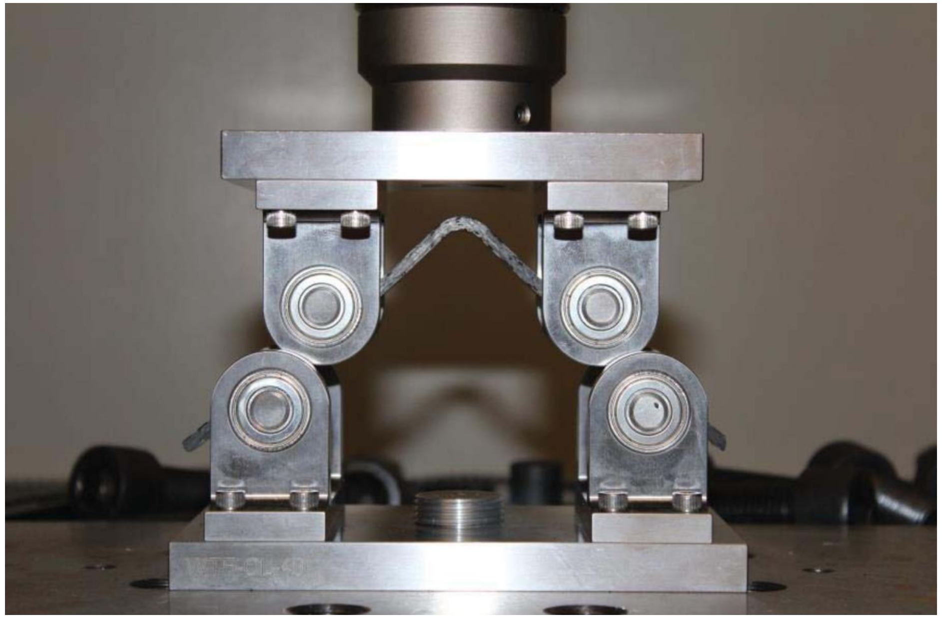
Sun et al., Journal of Composites, 2012

Proposed methodology and research plan

- **Curved beam testing**

Comprehensive experimental campaign on curved beam specimens with various thicknesses





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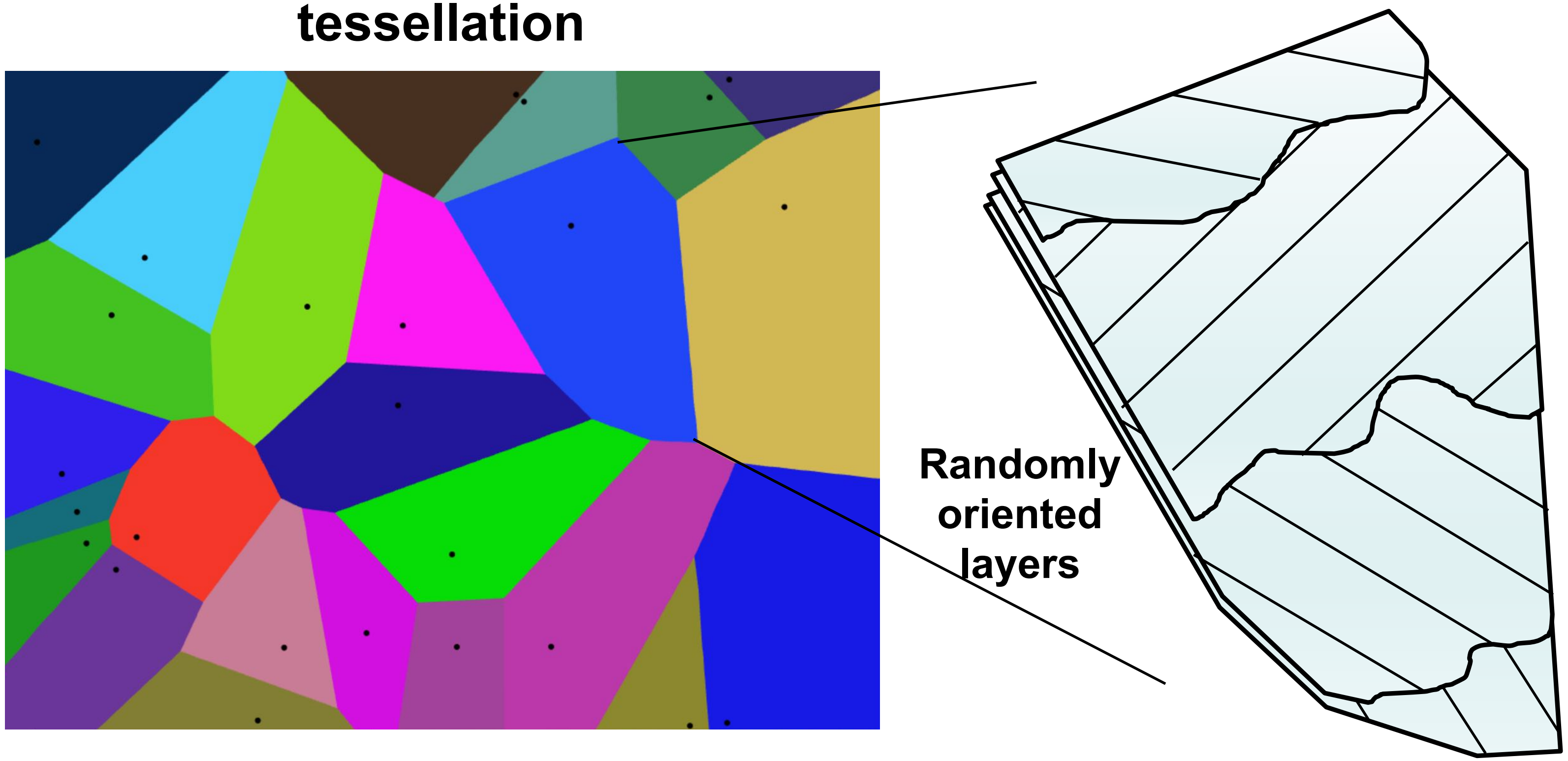
An example of size effect study to identify the critical defect size of DFC structures

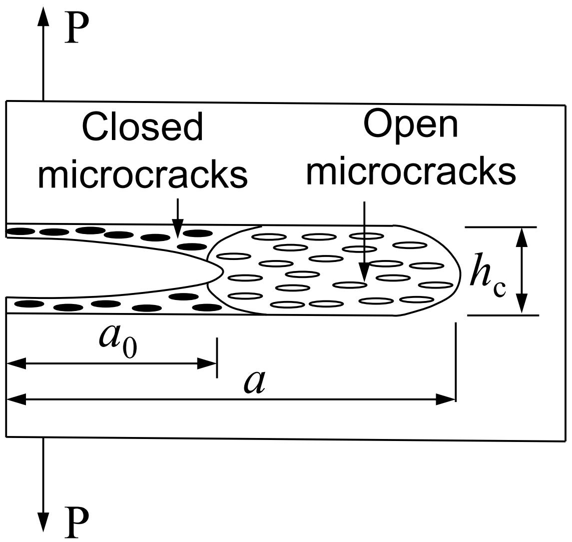
Stochastic Laminate Analogy

Discretization into RLVEs by Voronoi tessellation

Stochastic Laminate Analogy



Damage progression modeling

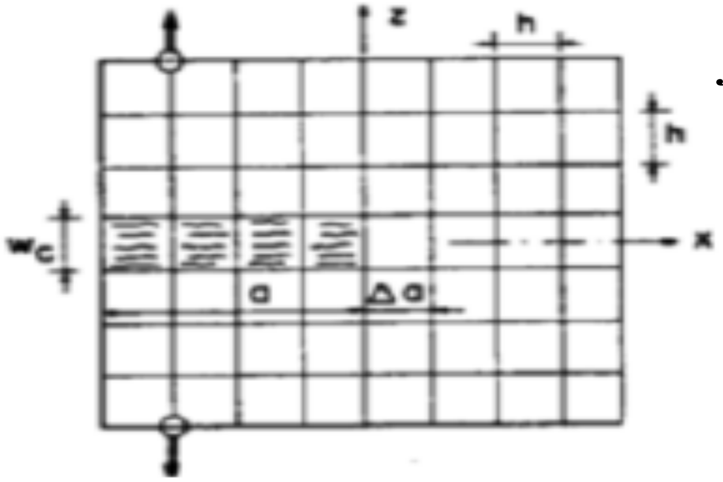


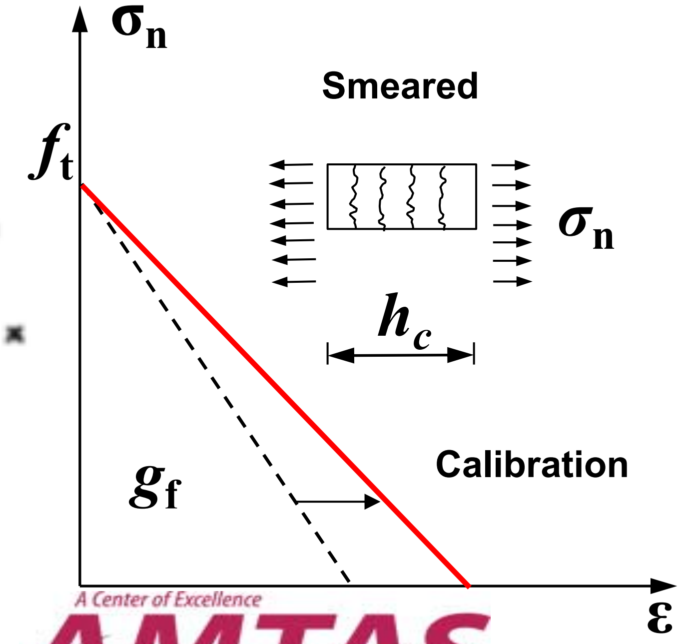
The crack is modeled as a *smeared crack band* with fixed width

$\boldsymbol{h}_{\mathrm{c}}$

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!





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

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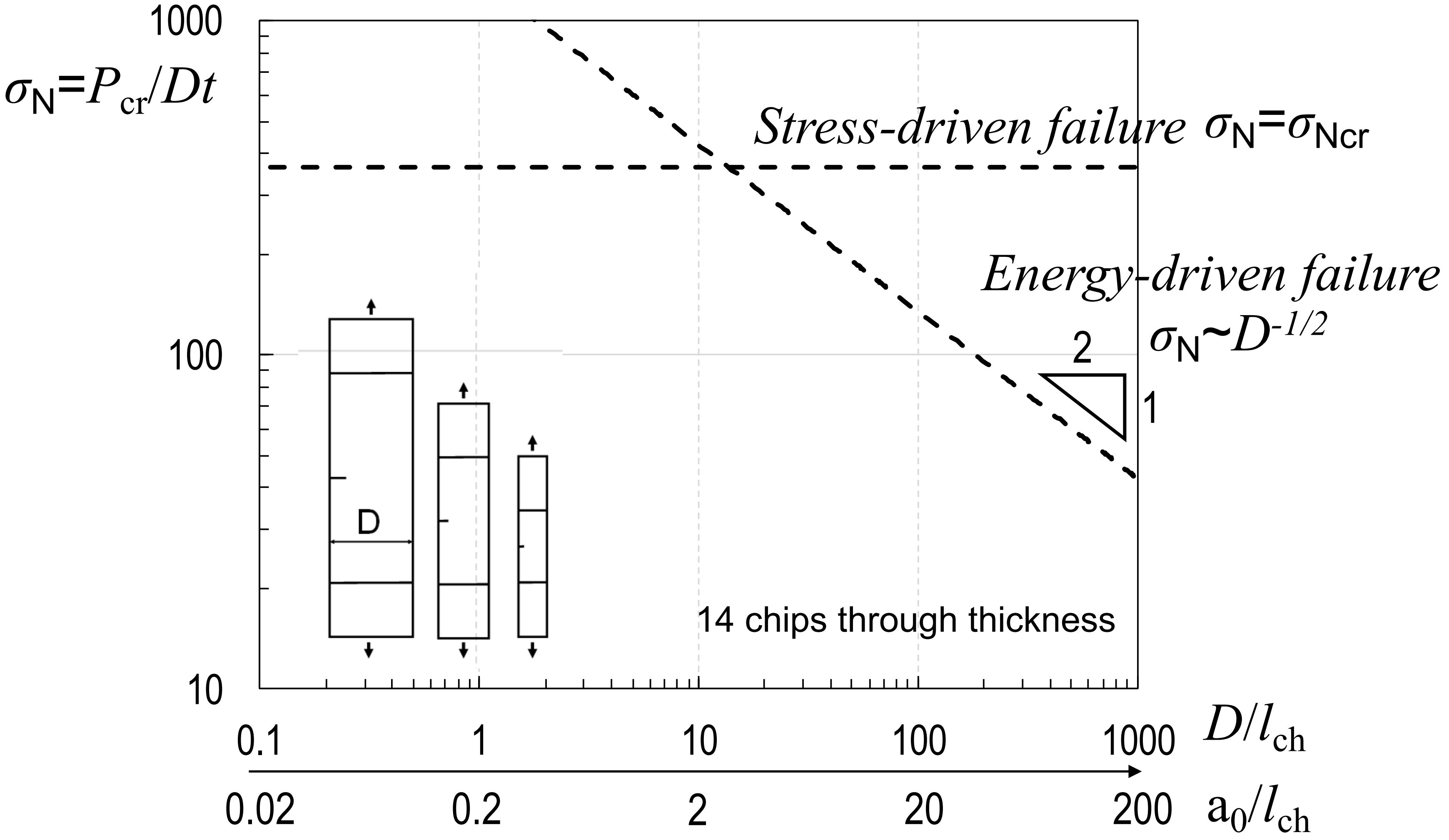
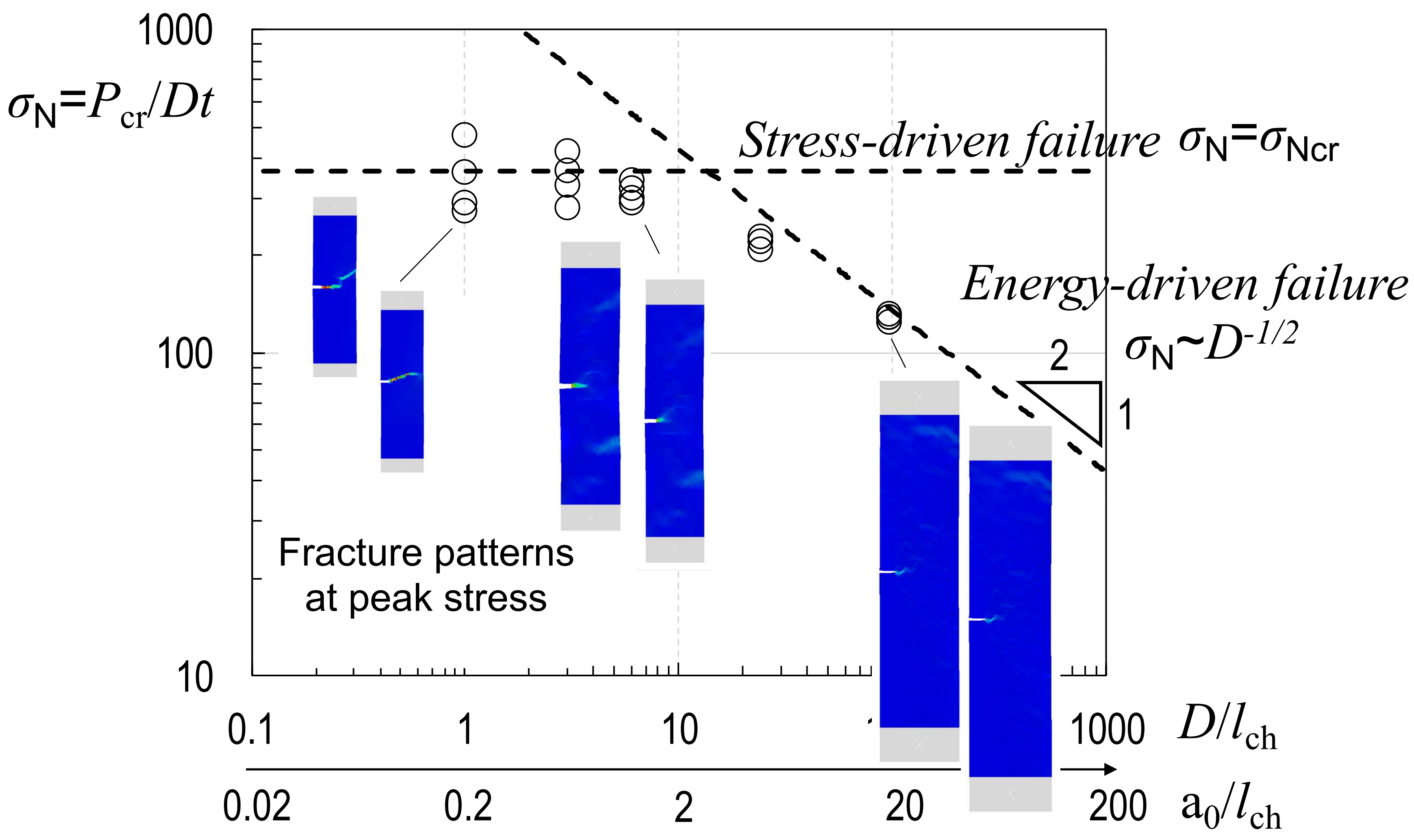
Critical defect size for DFCs



Critical defect size for DFCs



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Size effect law

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

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

the following expression holds for the initial fracture energy:

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

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)

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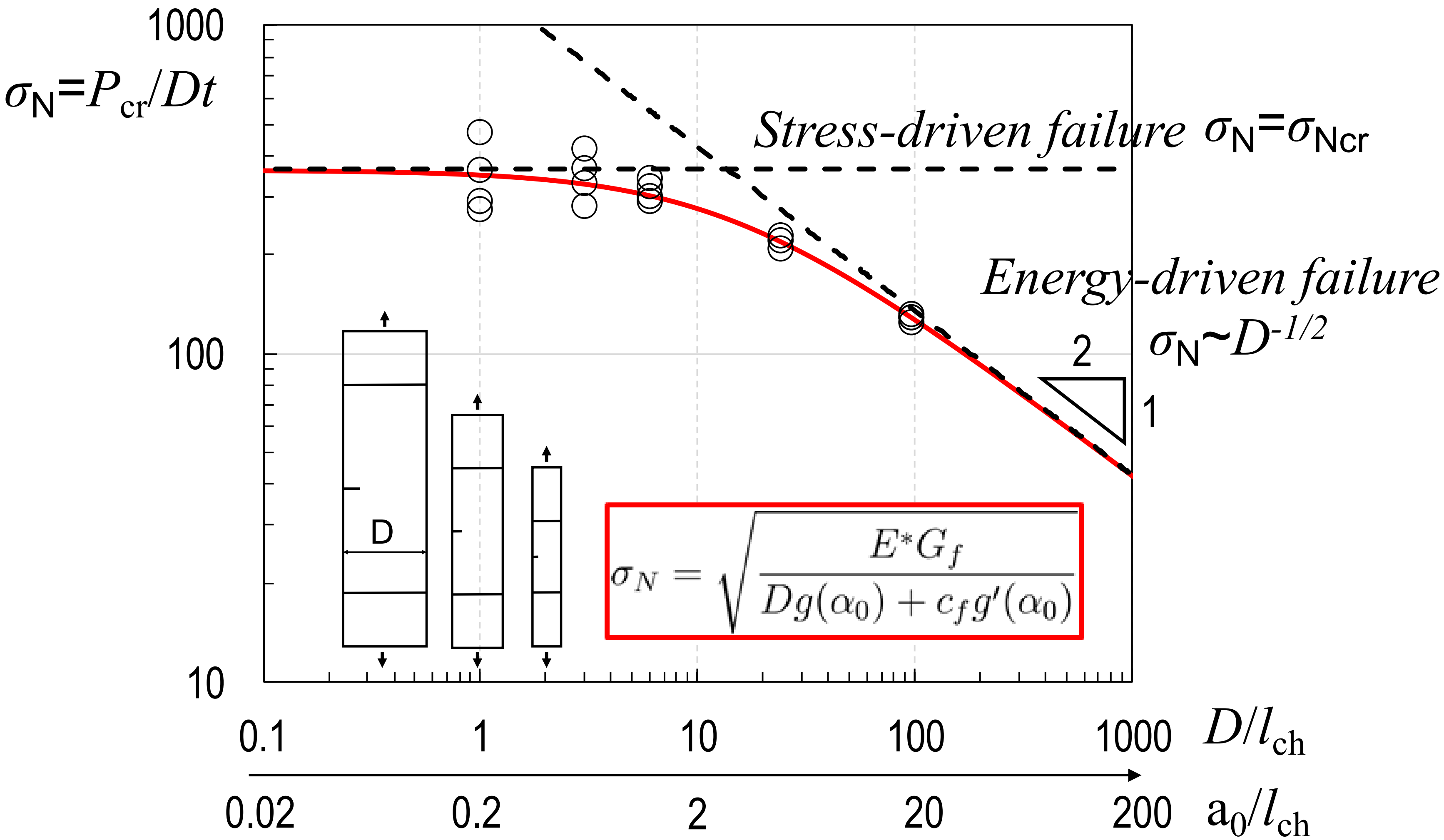
Size effect of DFCs



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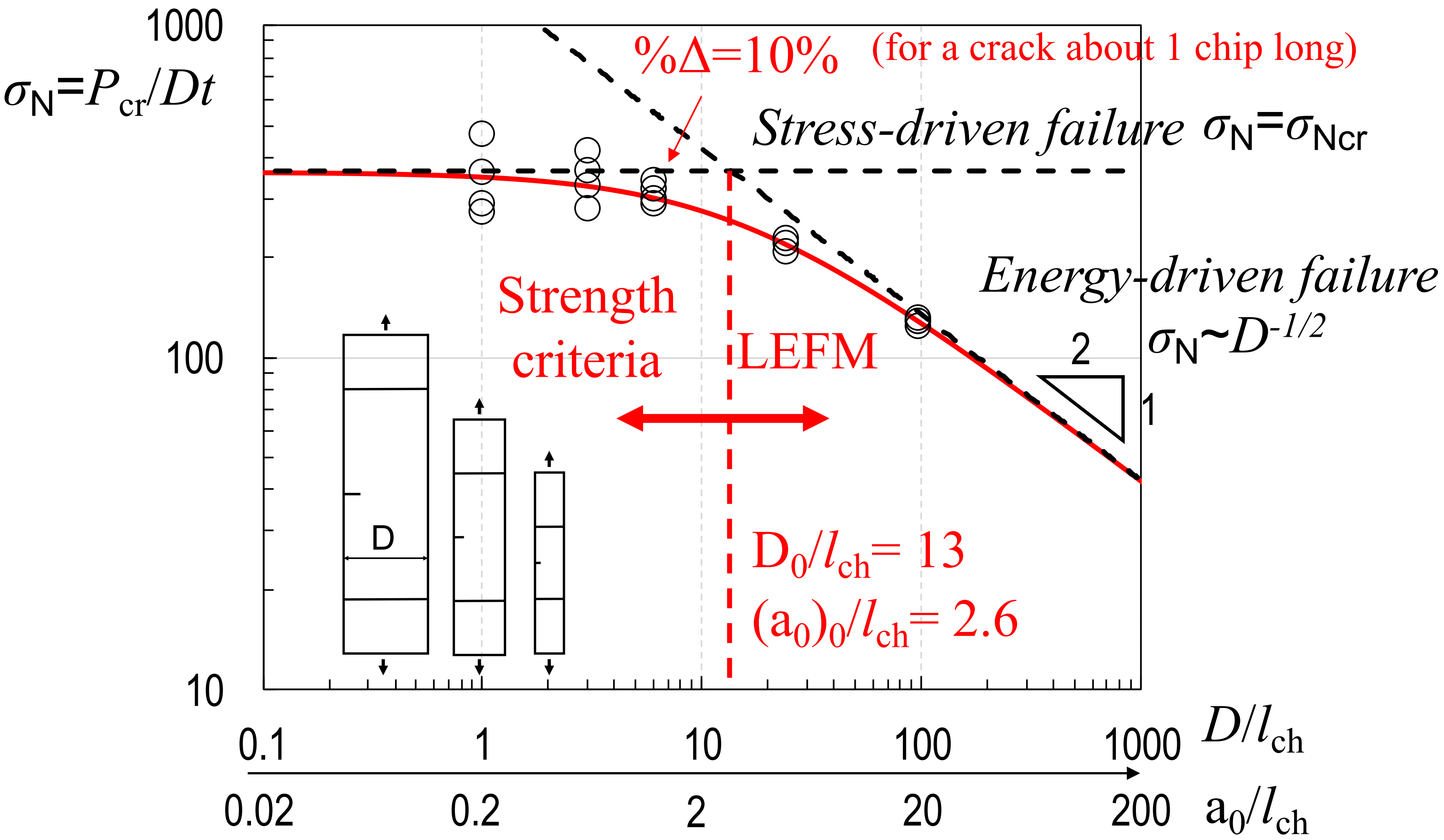
JAMS Joint Advanced Materials & Structures Center of Excellence

Critical defect size for DFCs



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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

Marco Salviato, Seunghyun Ko, Jinkyu Yang, Mark Tuttle

University of Washington

AMTAS 2019 Technical Review Nov 5-6, 2019

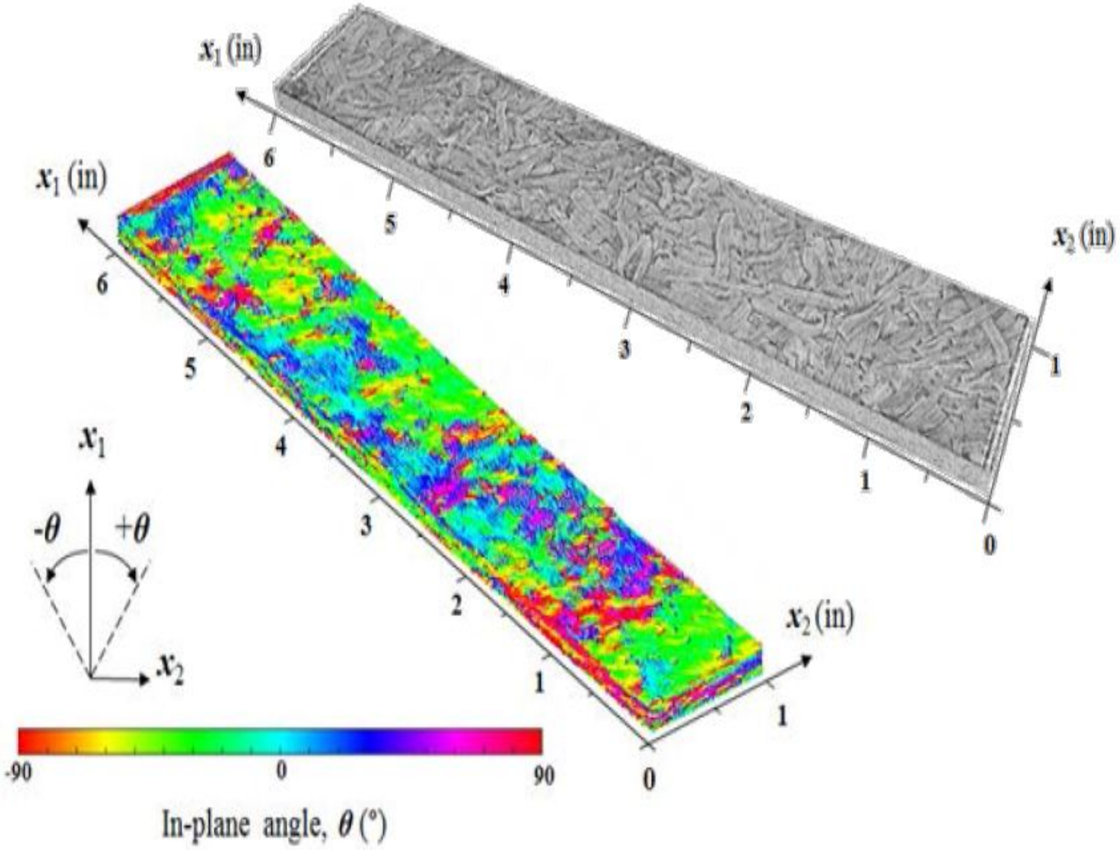
Center for Urban Horticulture, Universi[illegible]hington, Seattle, WA.

(5) micro-CT scan and local fiber orientation

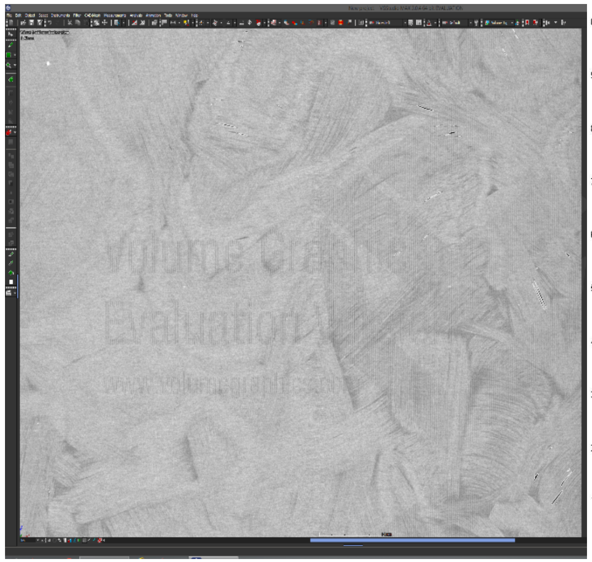
(1) Determine local fiber orientations

(2) Obtain defect size and locations

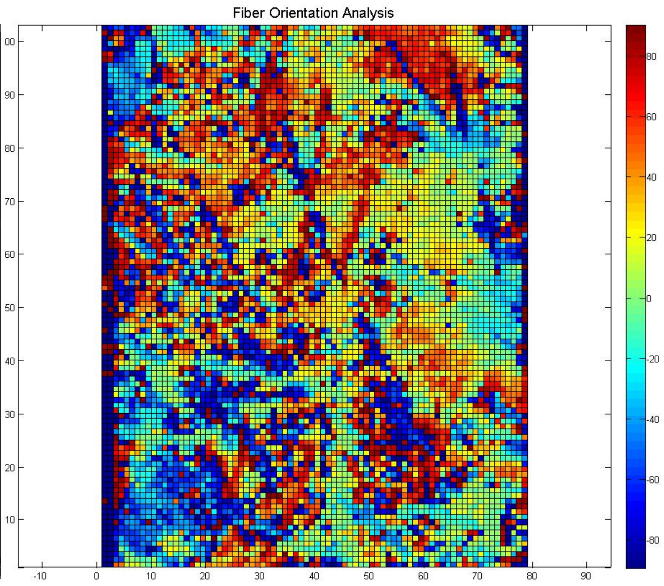
Current UW progress



Denos (Purdue DFC project), 2017



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.**