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Certification of Discontinuous Composite Material Forms for Aircraft Structures

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University of Washington

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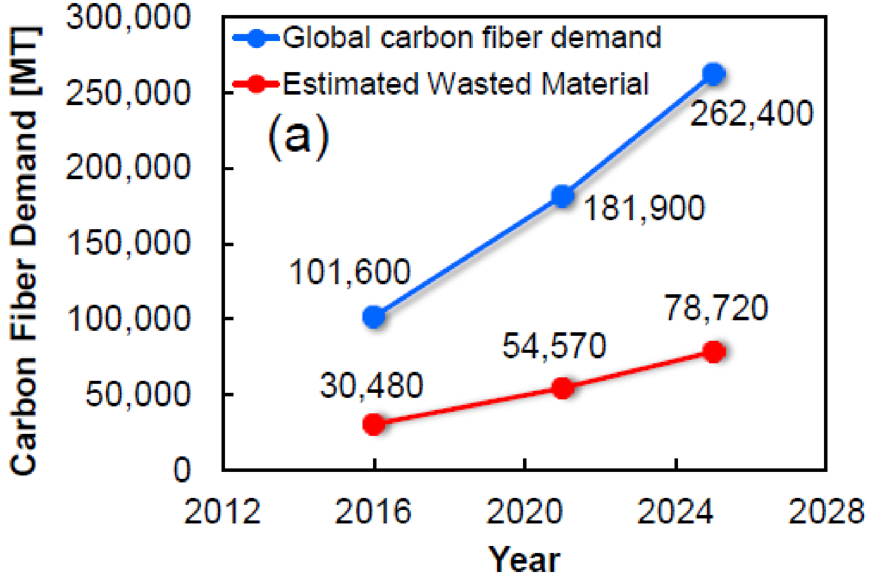
Synergistic project

Recyclability

Inside Composites



Composites Forecast and Consulting LLC

Introduction

Aviationweek.com

Avstop.com

compositestoday.com

Made of composites?

Aviationweek.com

Introduction

Large volume manufacturing

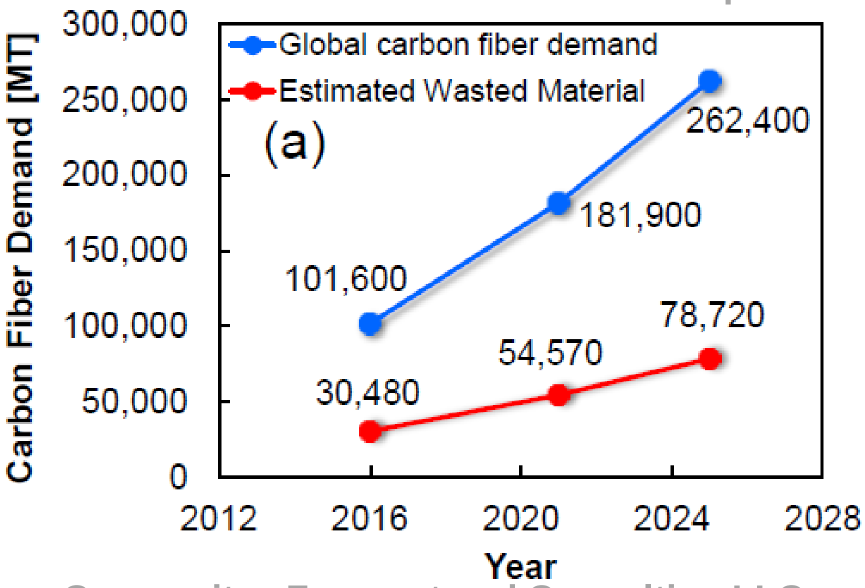
Toray

Part complexity

Tencate

Recyclability

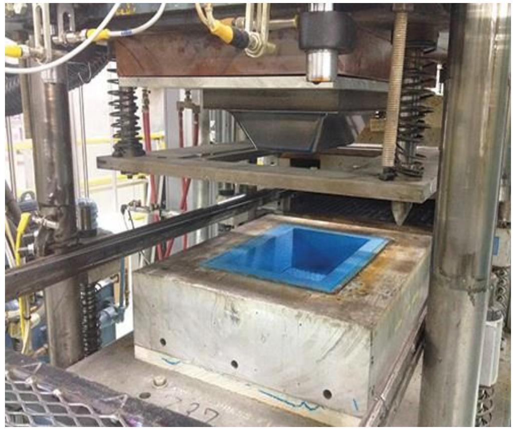
Inside Composites



Composites Forecast and Consulting LLC

Discontinuous Fiber Composites (DFCs)

Platelets-based composite



Compression molding

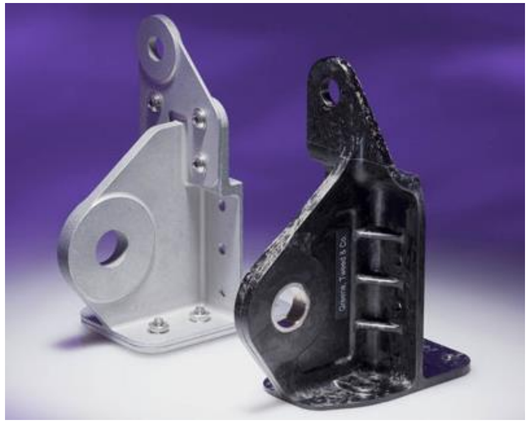
Large volume manufacturing

Hexcel

Recyclability

Nutt, 2014, CAMX

Part Complexity



Greene Tweed

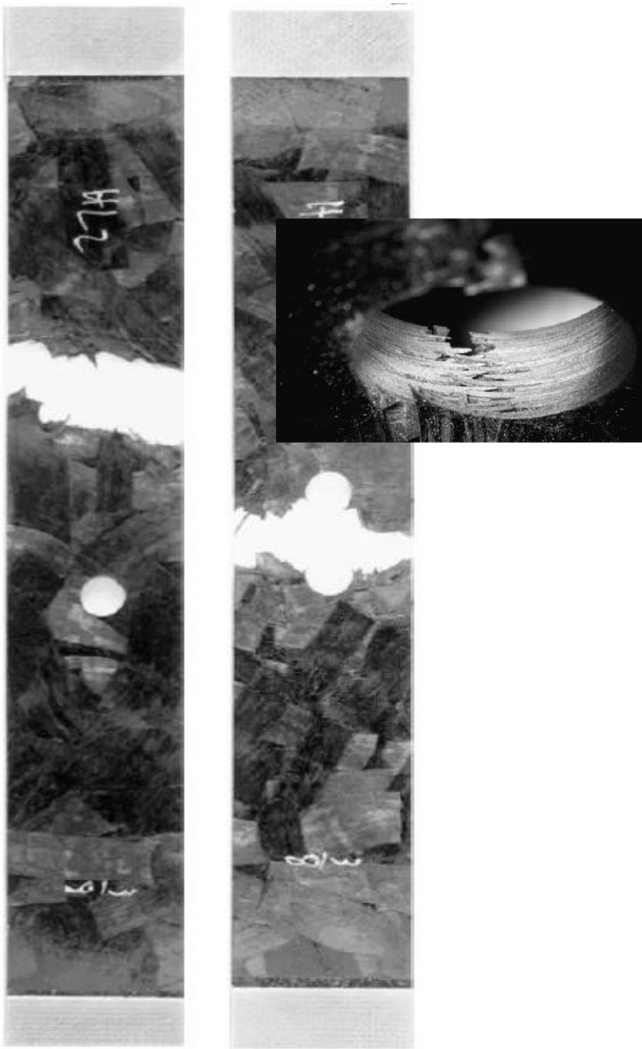
Current challenges:

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

Conventional application of DFC

Hexmc parts, Hexcel

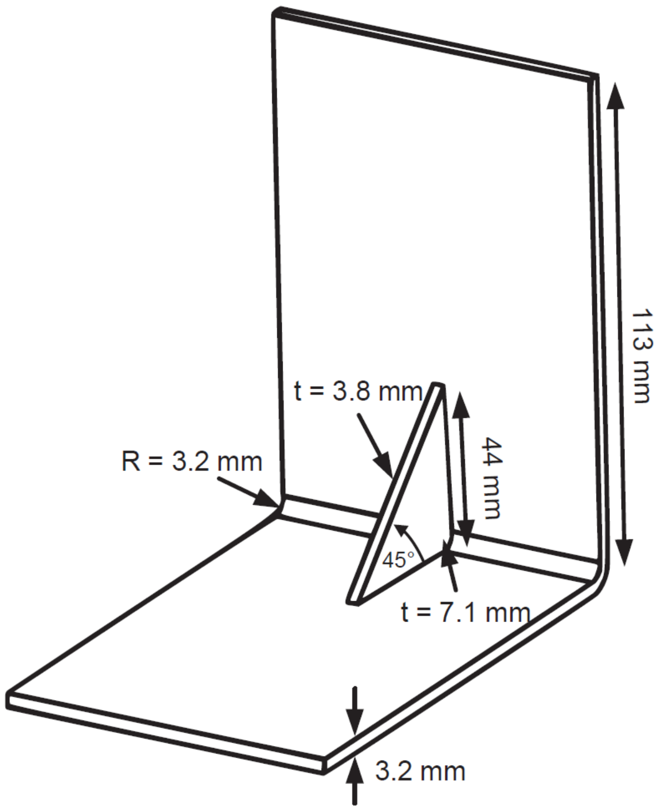
Qian, 2011



Feraboli, 2009

Current challenges:

Lack of acceptance/rejection criteria for defected DFC components

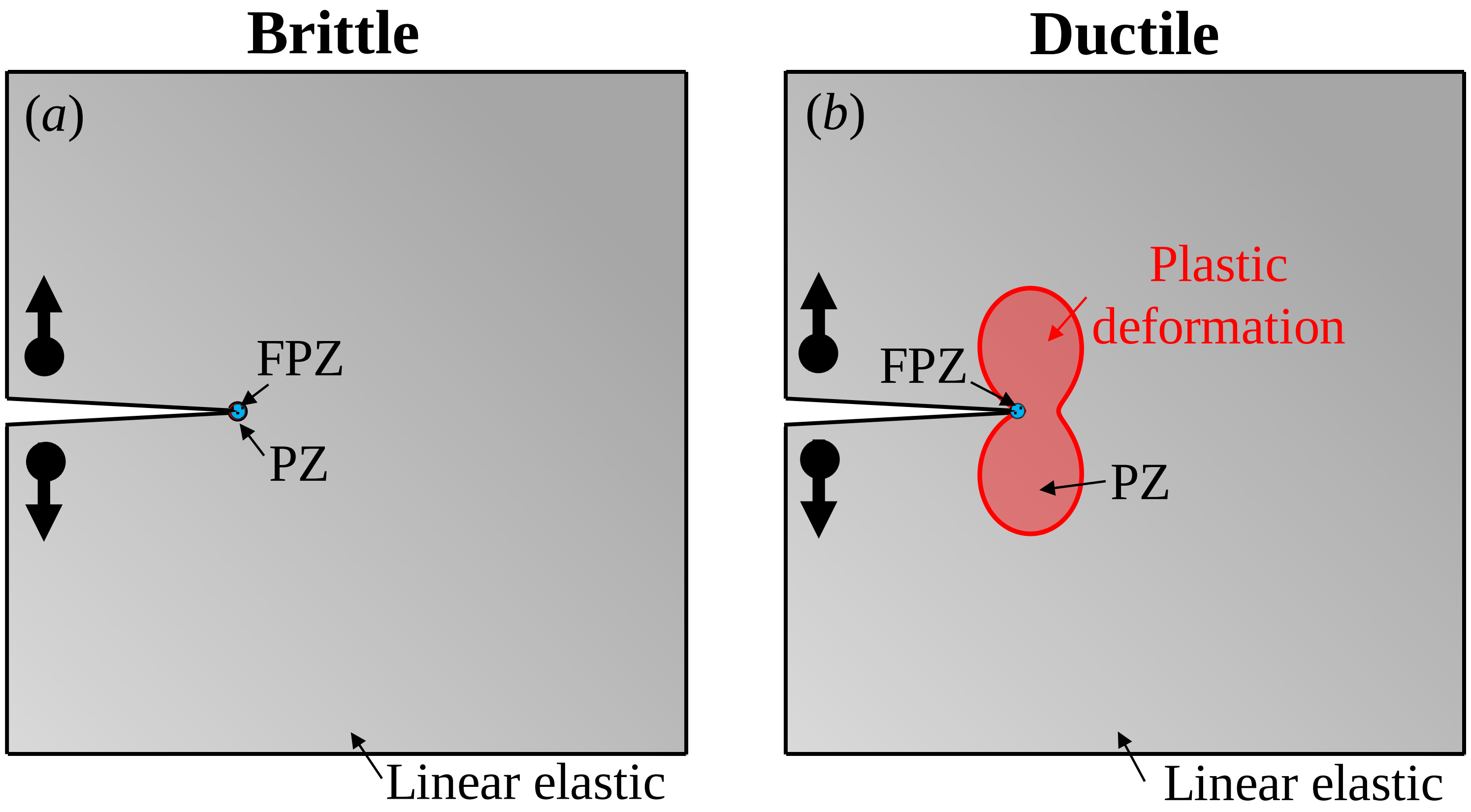


Landry, PhD dissertation, McGill, 2015

Quasi-brittle fracture behavior of DFCs

Effect of the characteristics dimension on the nominal strength

*FPZ = Fracture process zone
*PZ = Plastic zone

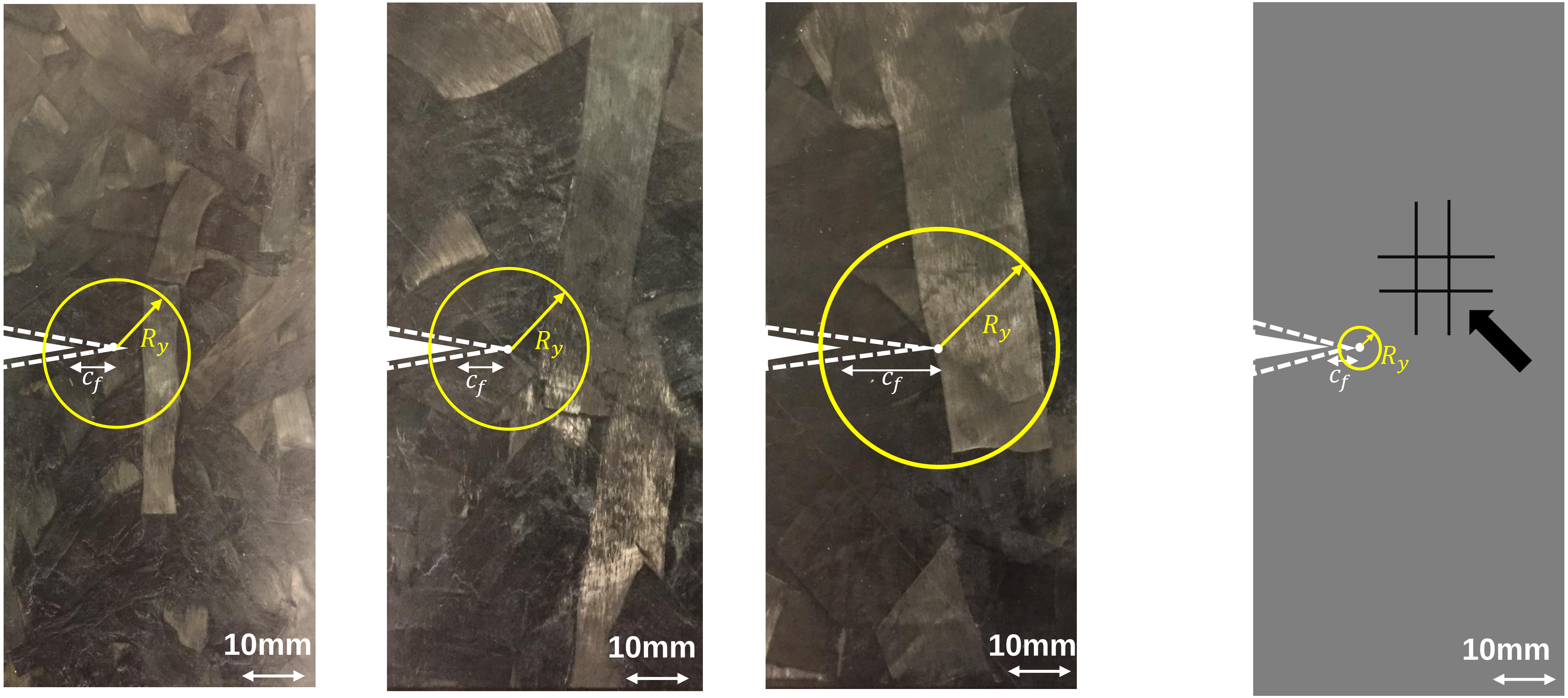


Bazant, 1998

FPZ is large in DFC

Fracture Process Zone in DFCs

Salviato et al. Comp Sci Tech, 2016



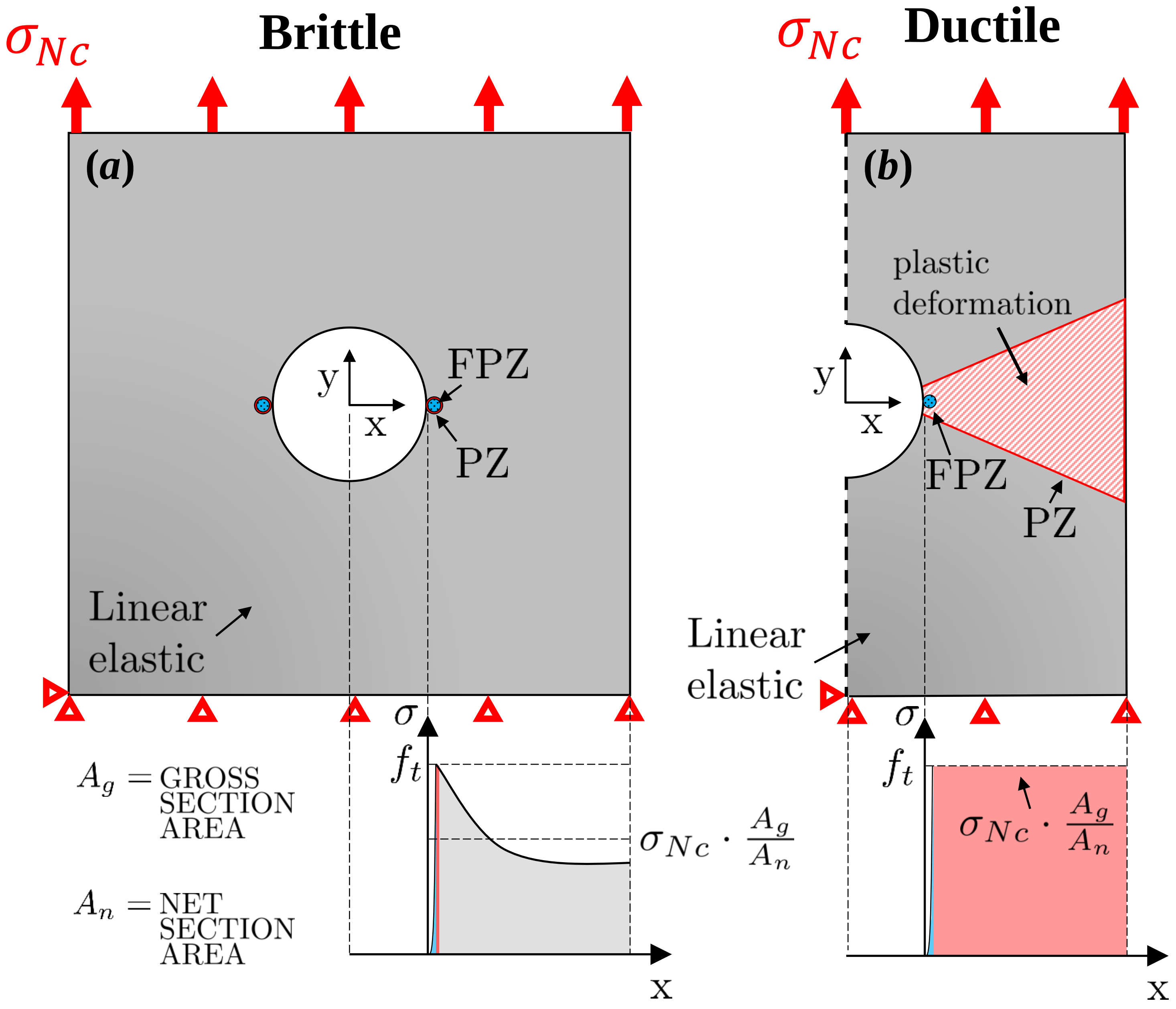
Platelet size: 25×4 mm
Thickness: 3.3 mm
c_f **= 6.55 mm,** R_y **= 8.85 mm**

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**

Quasi-brittle behavior of notched DFC structures



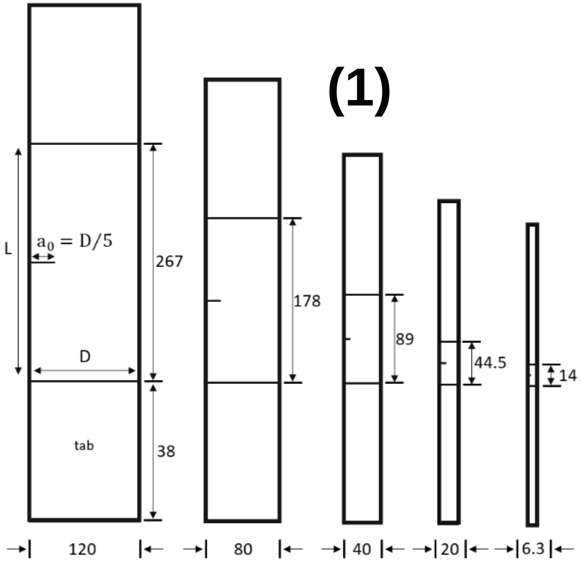
Objectives:

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

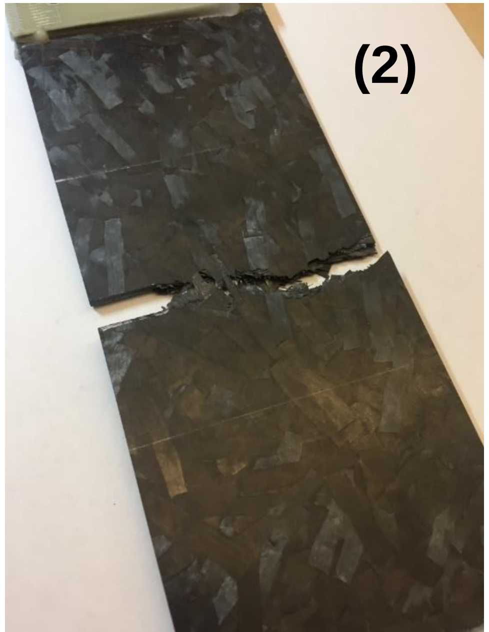
(2) To investigate the *effects of material morphology* (e.g. platelet size and distribution) and *geometrical features* (e.g. structure thickness and notch radius) *on the fracture behavior*

(3) To *develop computational tools to describe the mechanics of DFCs*

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



Size effect test, law

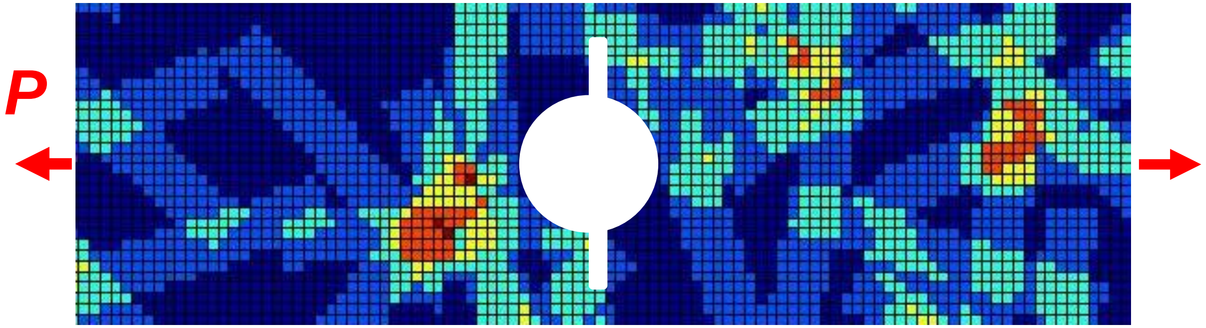


Platelet size:
75×12 mm

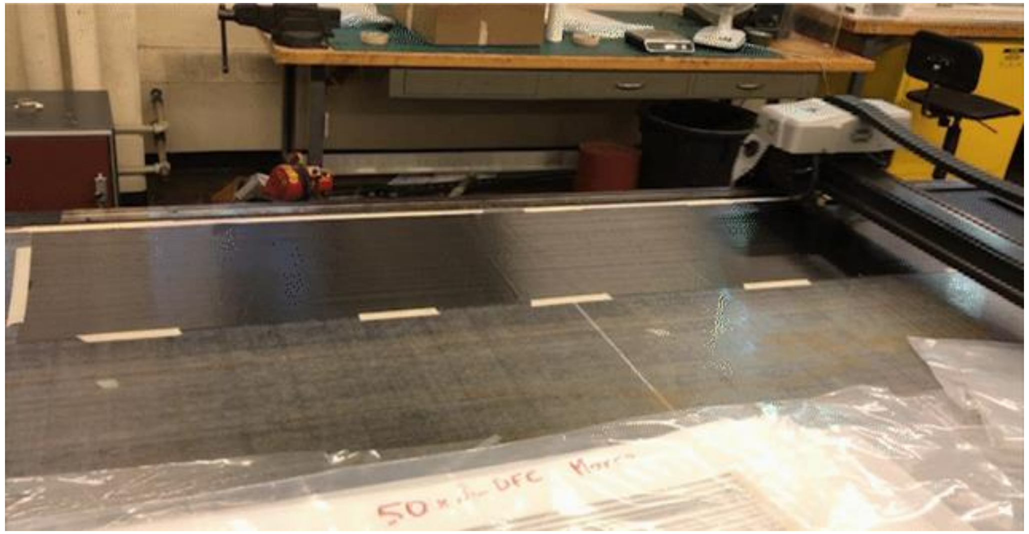
50×8 mm

25×4 mm

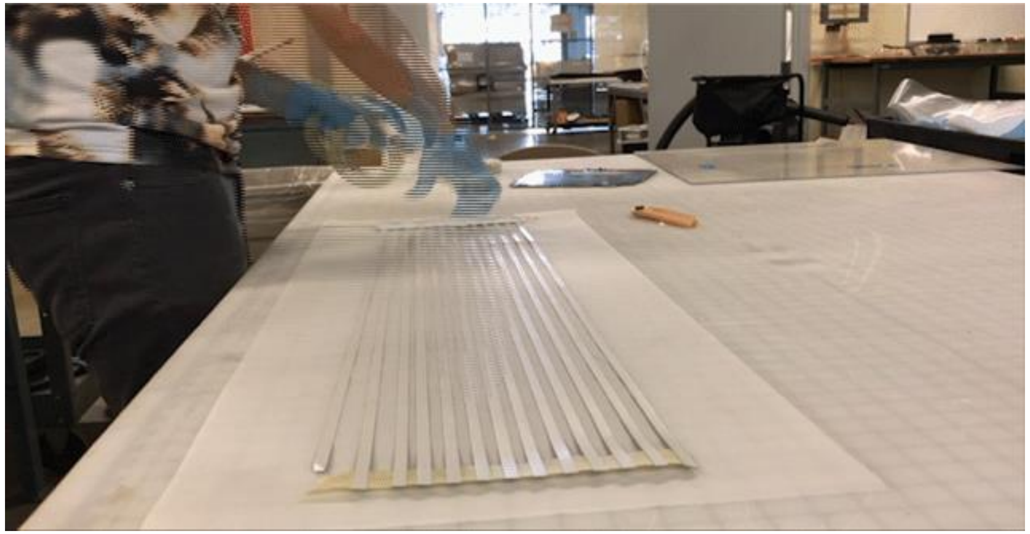
(3)



Specimen preparation



1) Cut into strips

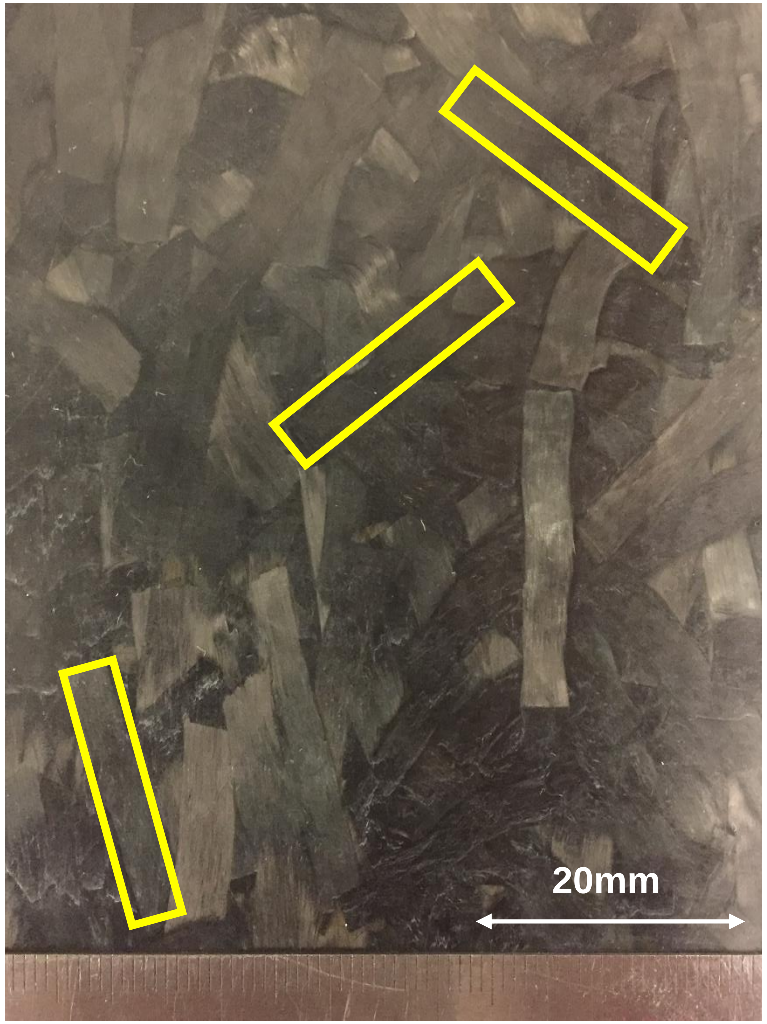


2) Remove backing tape

3) Cross-cut the strips

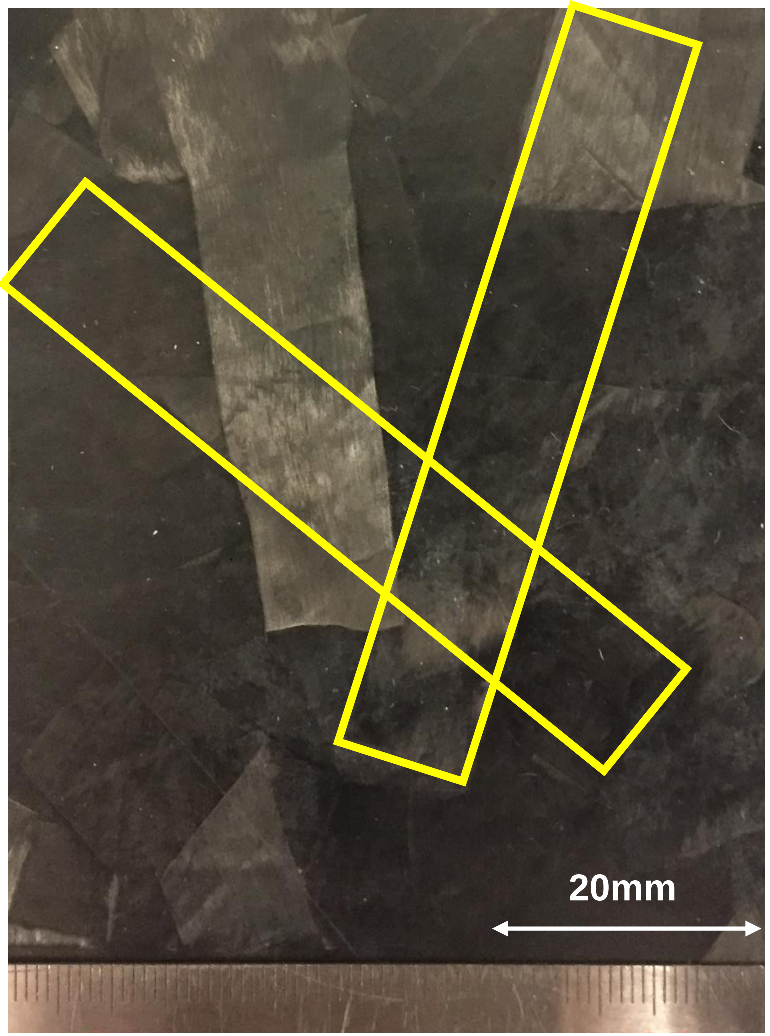
4) Distribute platelets randomly

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

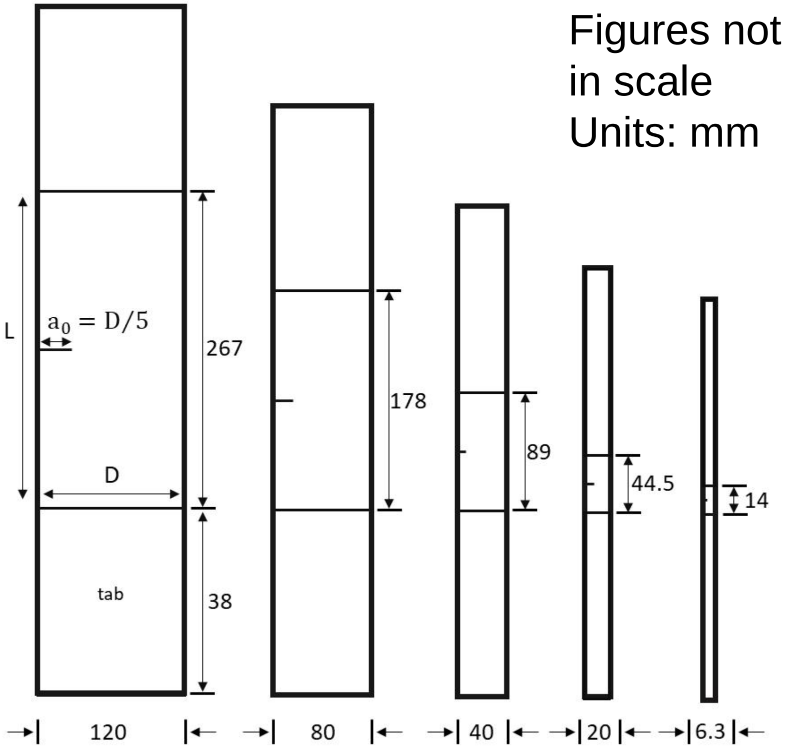
Summary of Platelets Sizes and Thicknesses Investigated

Platelet size effect study (75×12, 50×8, 25×4 mm, T = 3.3 mm) — **Thickness effect study** (50×8 mm, T = 4.4 / 2.1 / 1.1 mm) — **Platelet size effect study** (Thermoplastic)

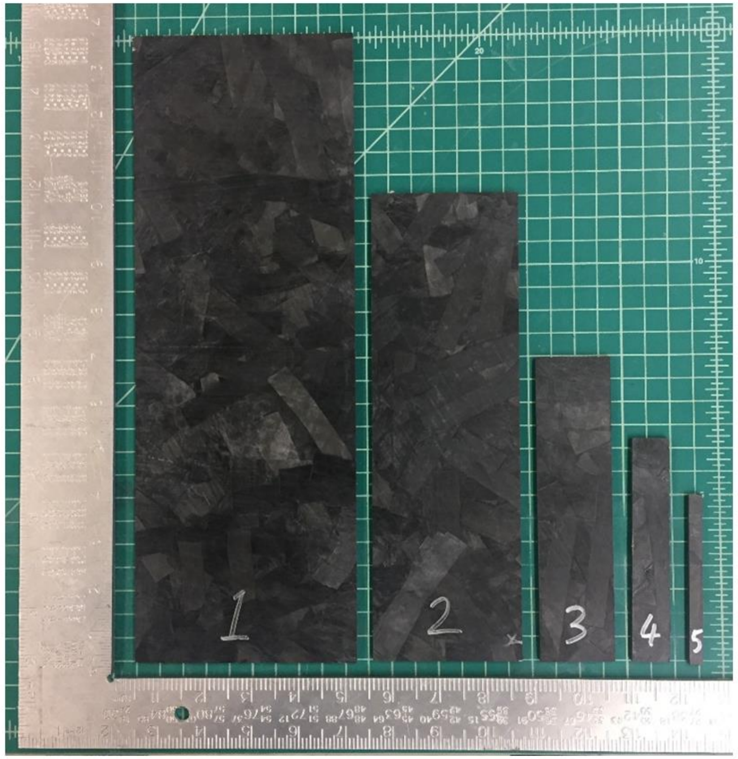
	Thermoset						Thermoplastic	
Size	75×12 mm, T = 3.3 mm	50×8 mm, T = 3.3 mm	25×4 mm, T = 3.3 mm	50×8 mm, T = 4.4 mm	50×8 mm, T = 2.1 mm	50×8 mm, T = 1.1 mm	12.7×12.7 mm, T = 3.8 mm	12.7×1.58 mm, T = 3.8 mm
1	3	2	3	*-	*-	*-	5	5
2	3	3	3	7	5	5	7	6
3	9	6	9	9	8	7	5	6
4	8	7	7	11	9	9	14	8
5	4	9	7	11	10	9	-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

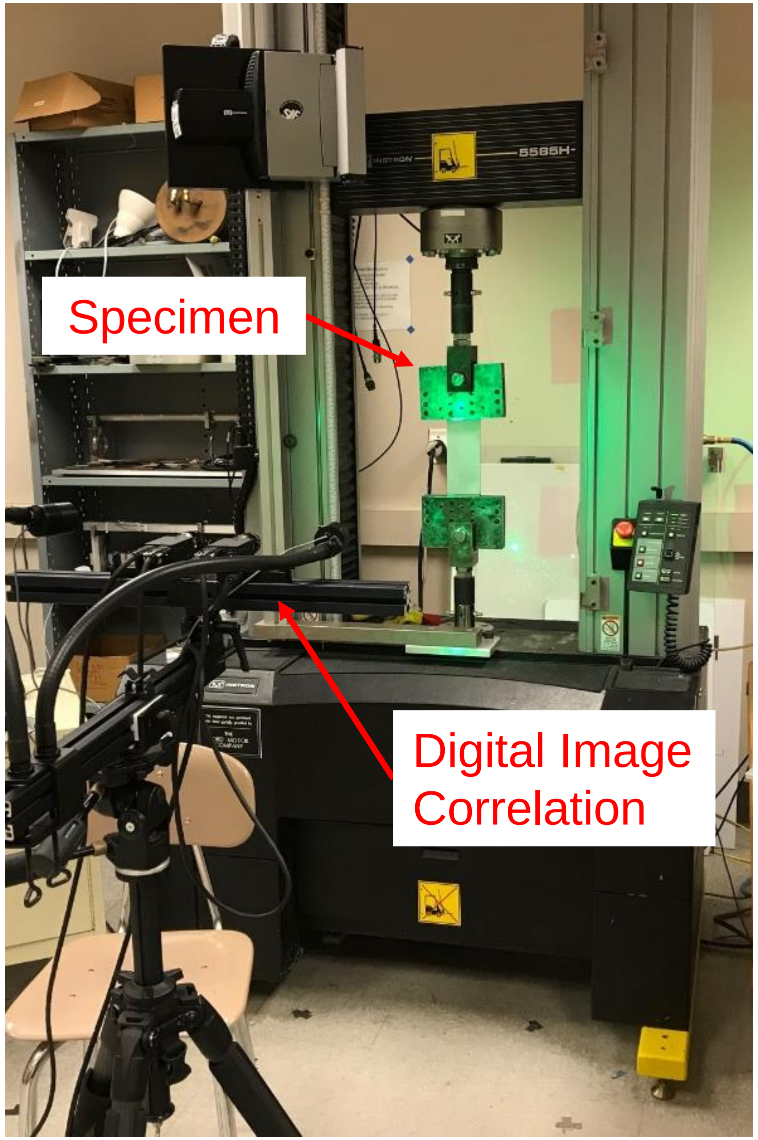
*** Coupon is well within the LEFM region, no need to test it.**

Specimen geometry



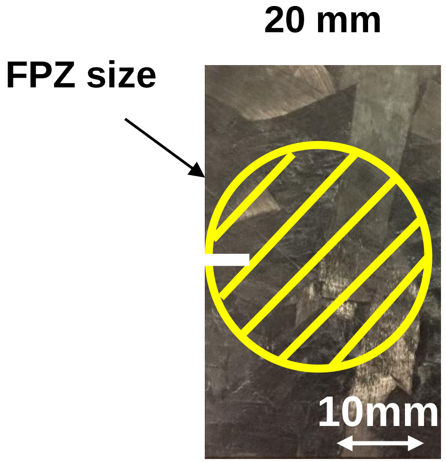
Figures not
in scale
Units: mm

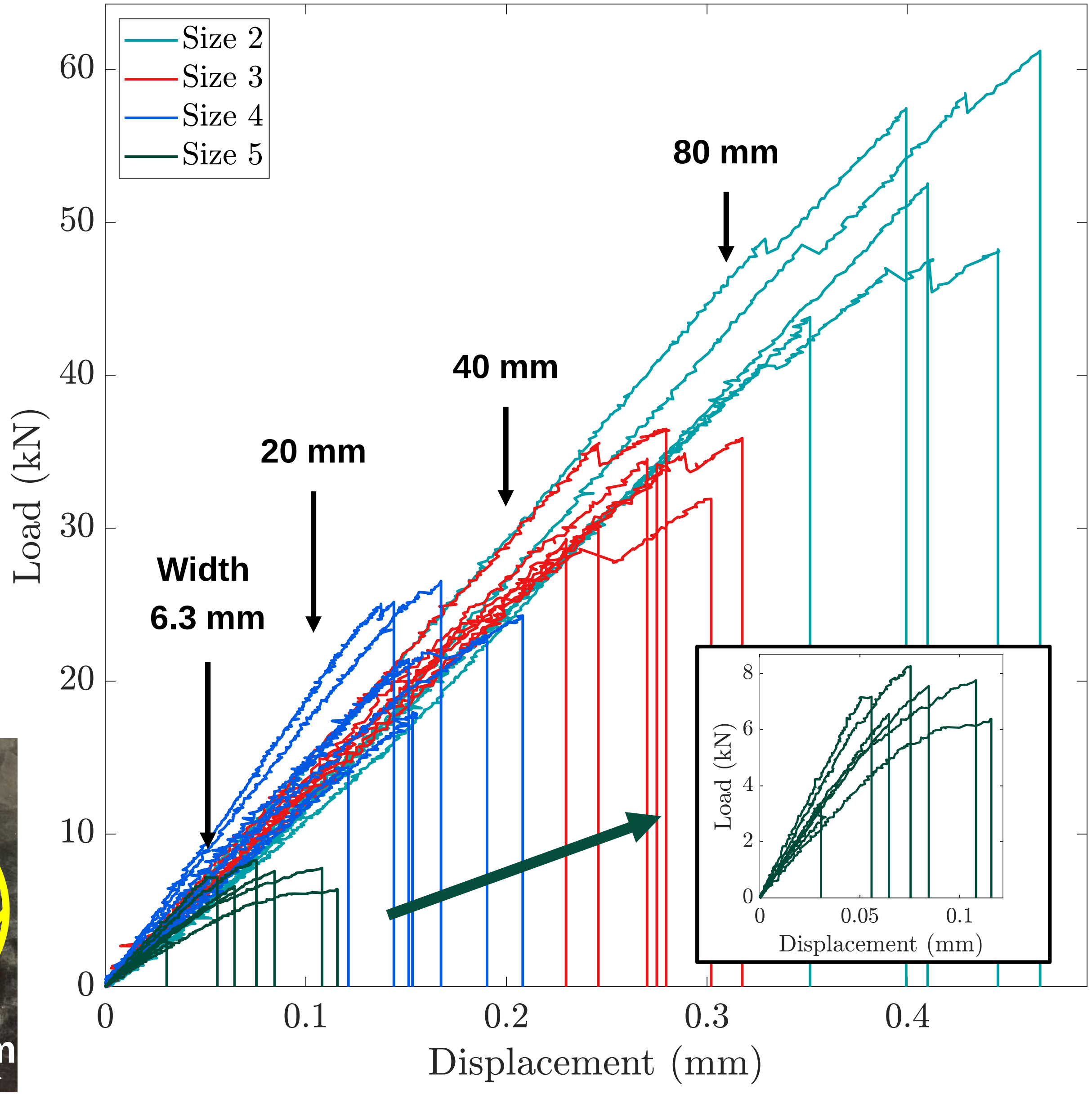


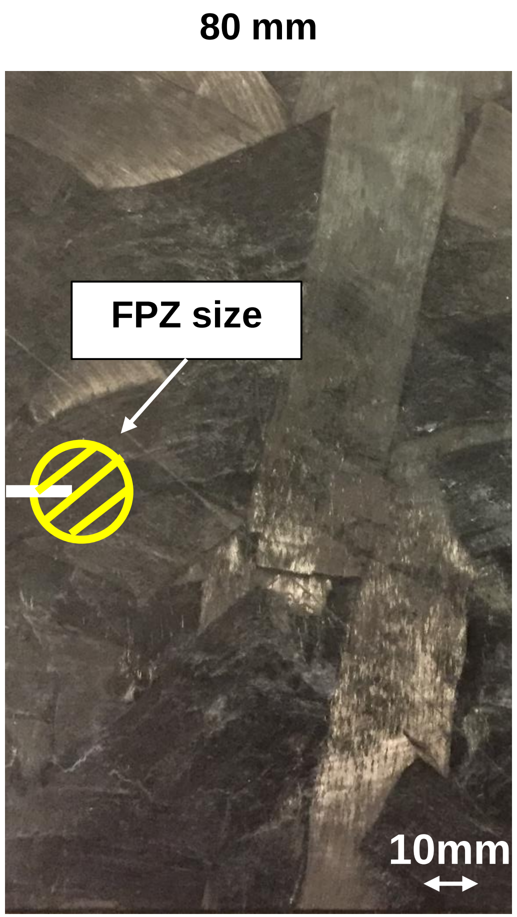


- Coupon sizes are proportionally scaled in width, gauge length, and crack length
- Thickness is constant = 3.3 mm

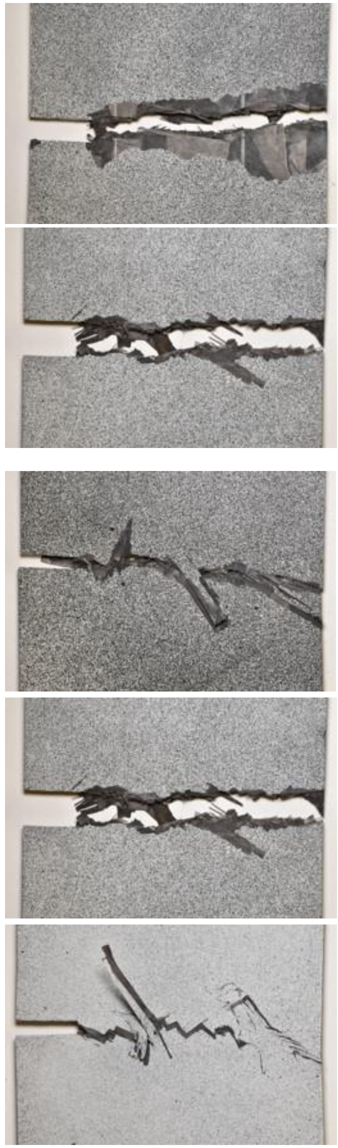
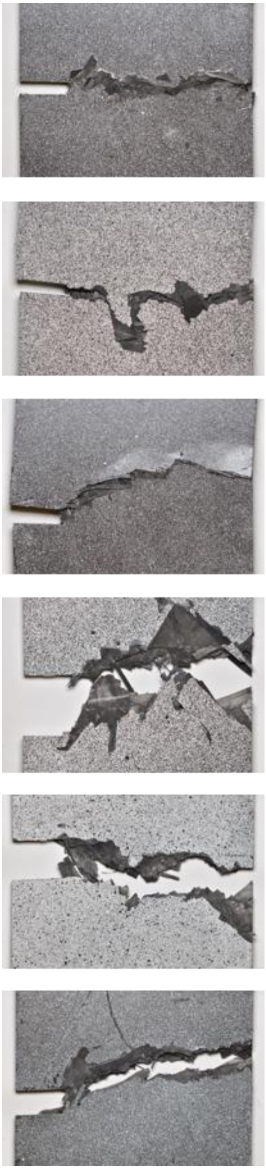
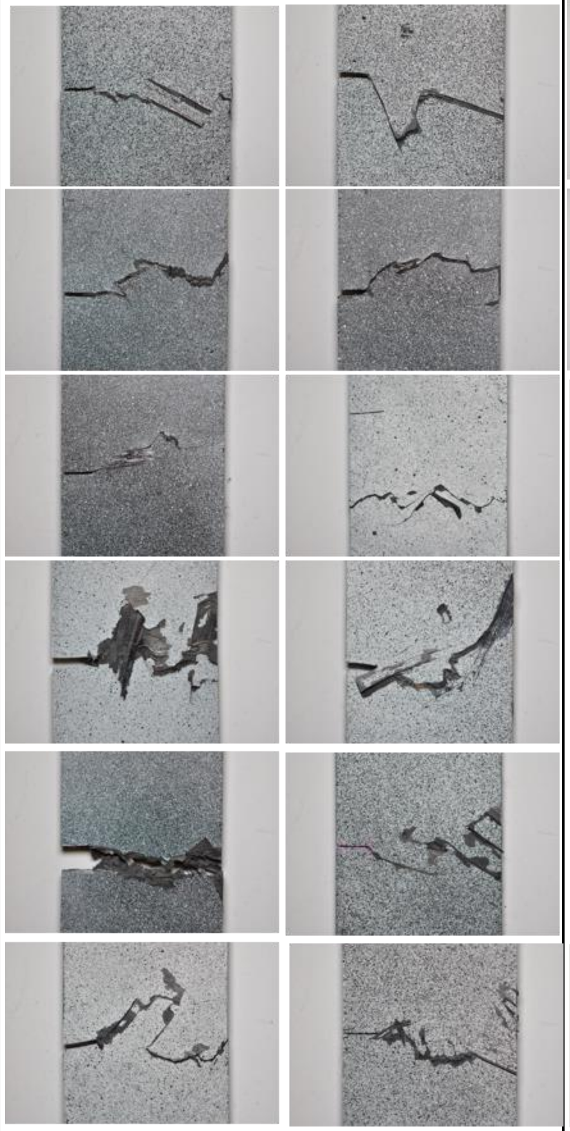
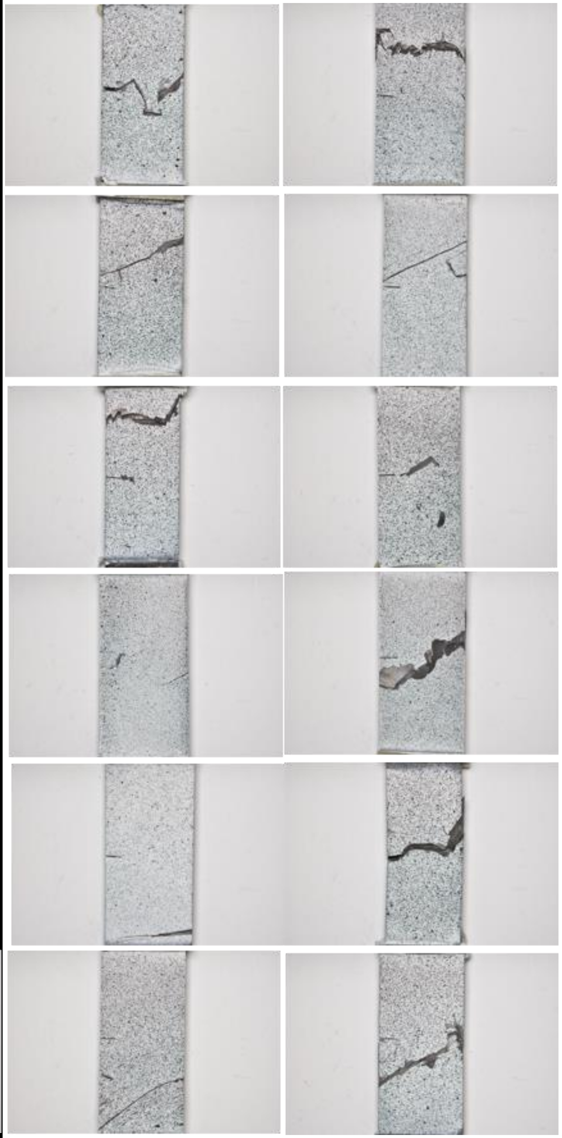
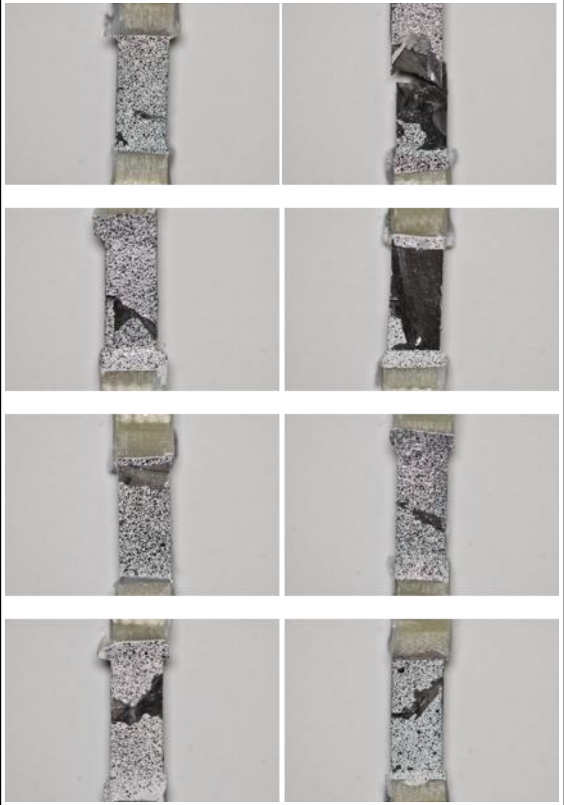
Typical Force and Displacement curves



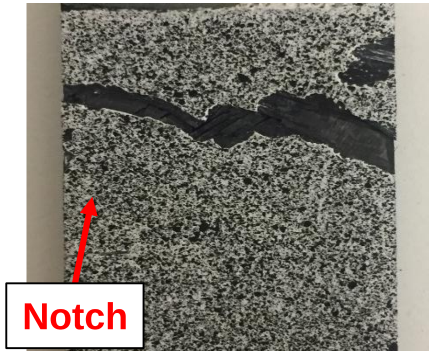
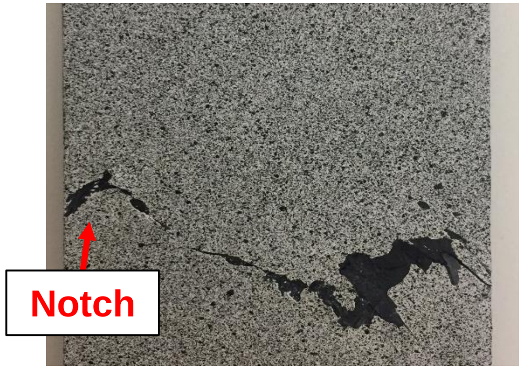
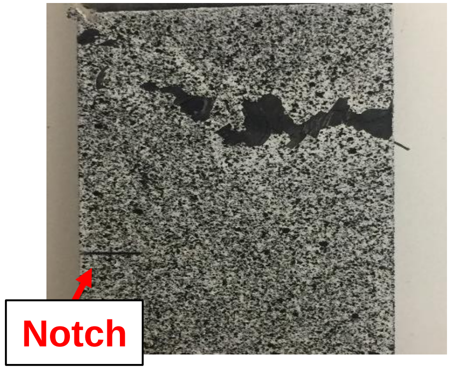
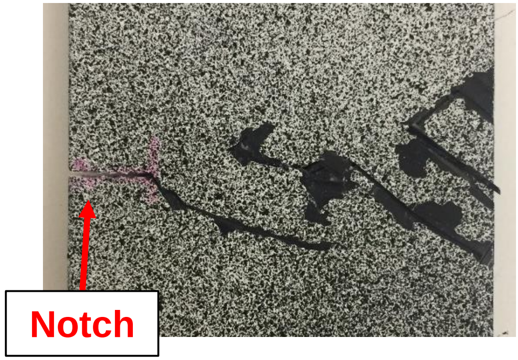
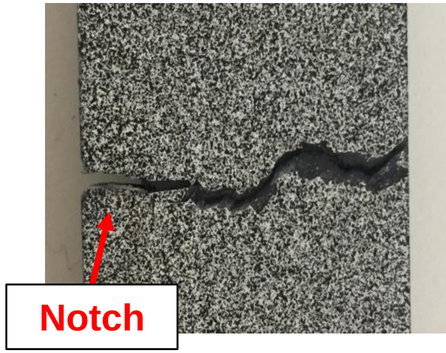
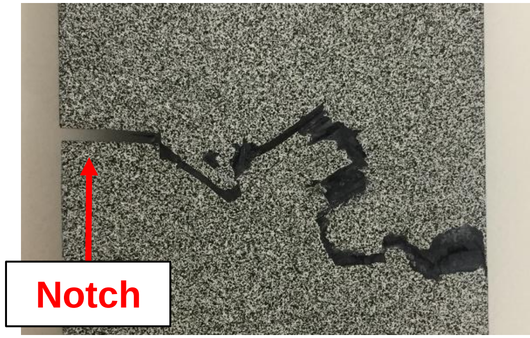




Typical Fracture Surfaces (50 x 8 mm platelets)

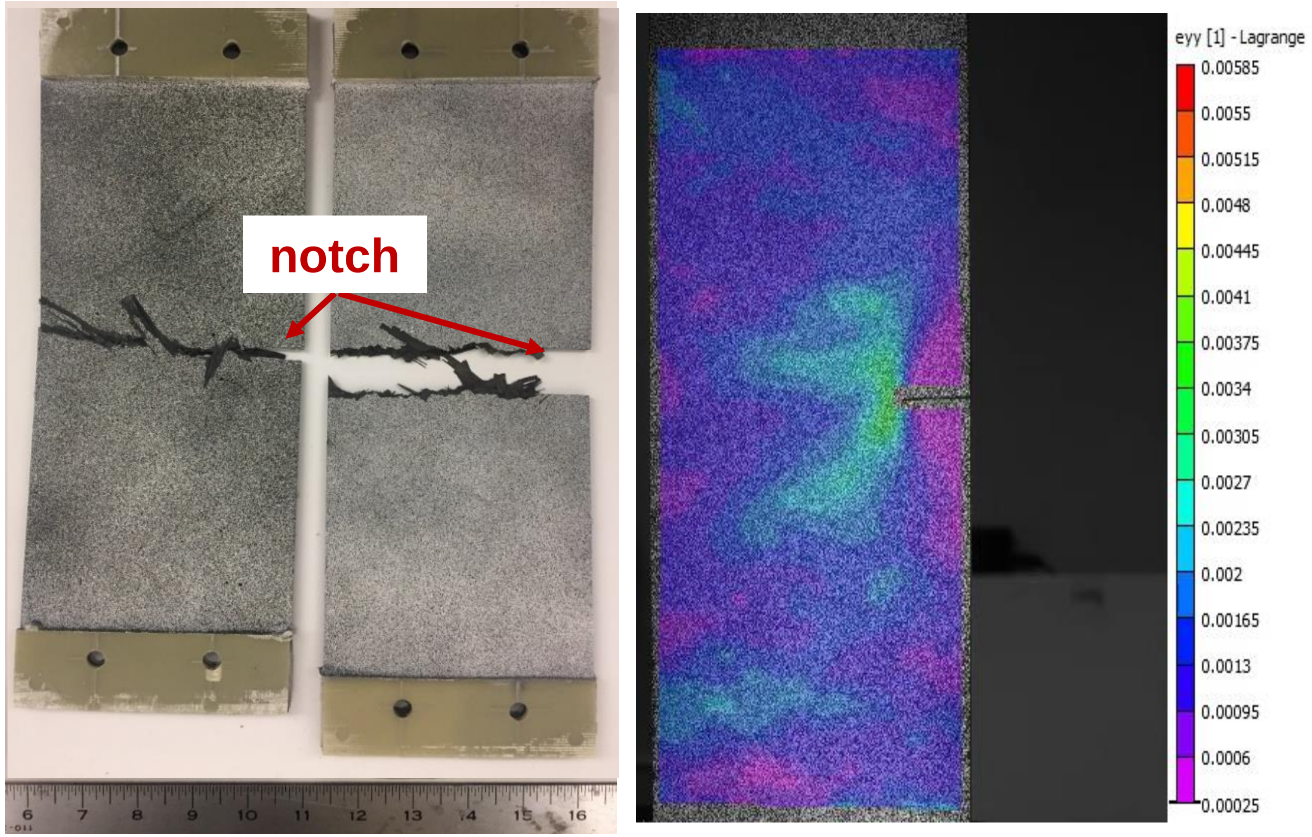
120 mm	80 mm	40 mm	20 mm	6.3 mm
				

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

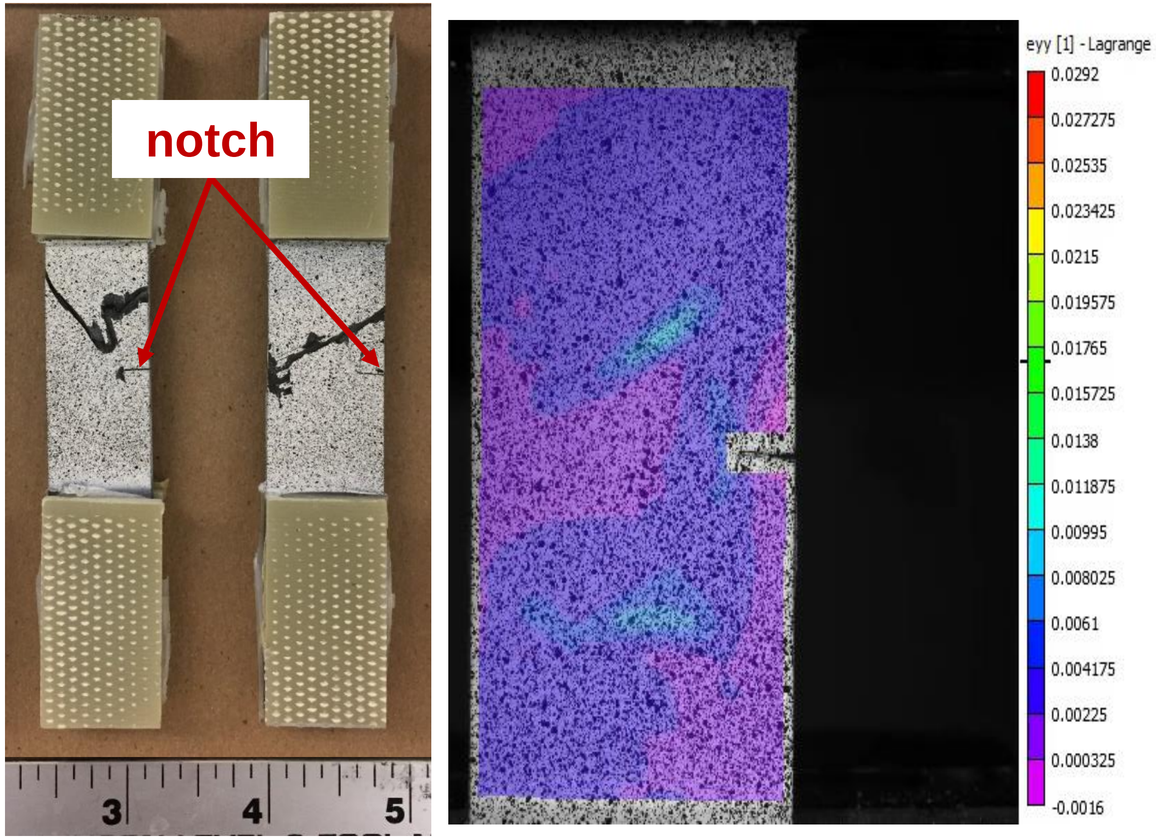
	D = 20 mm	D = 40 mm	D = 120 mm
1.1 mm			
2.2 mm			
4.1 mm			

Result 2: Fracture surfaces and DIC

Platelet size of 75×12 mm



Width = 120 mm



Width = 20 mm

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:

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

$\alpha = a/D$

E^* = **effective modulus**

g = **dimensionless energy release rate**

c_f = **FPZ length**

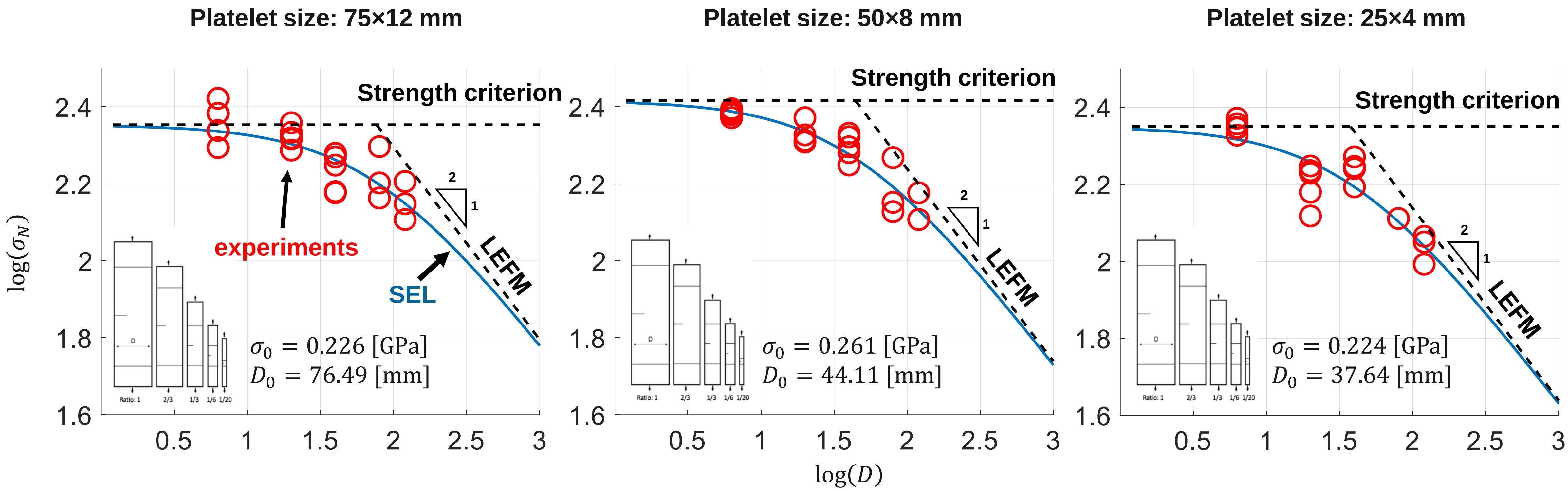
By expanding g in Taylor Series for a const D, retaining only 1st order terms and re-arranging:

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

Length scale

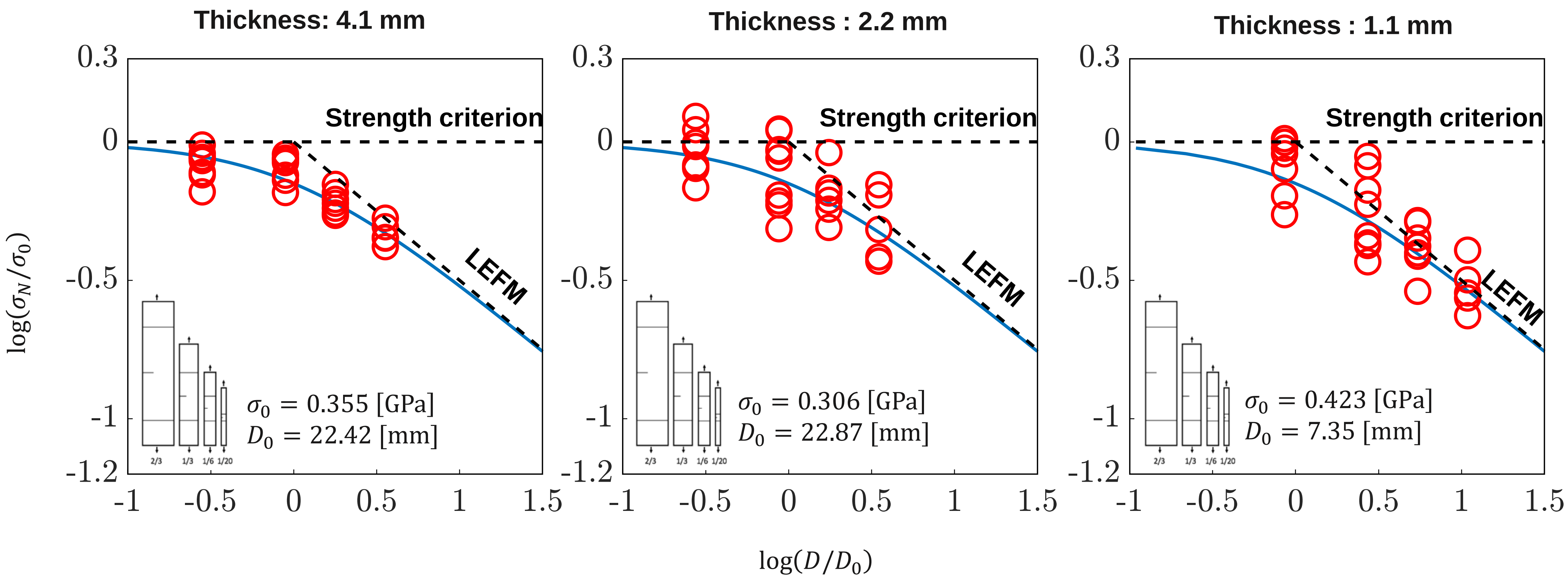
Bažant's Size Effect Law (SEL) for quasi-brittle materials

Result: Size effect curves – (varying platelet size)

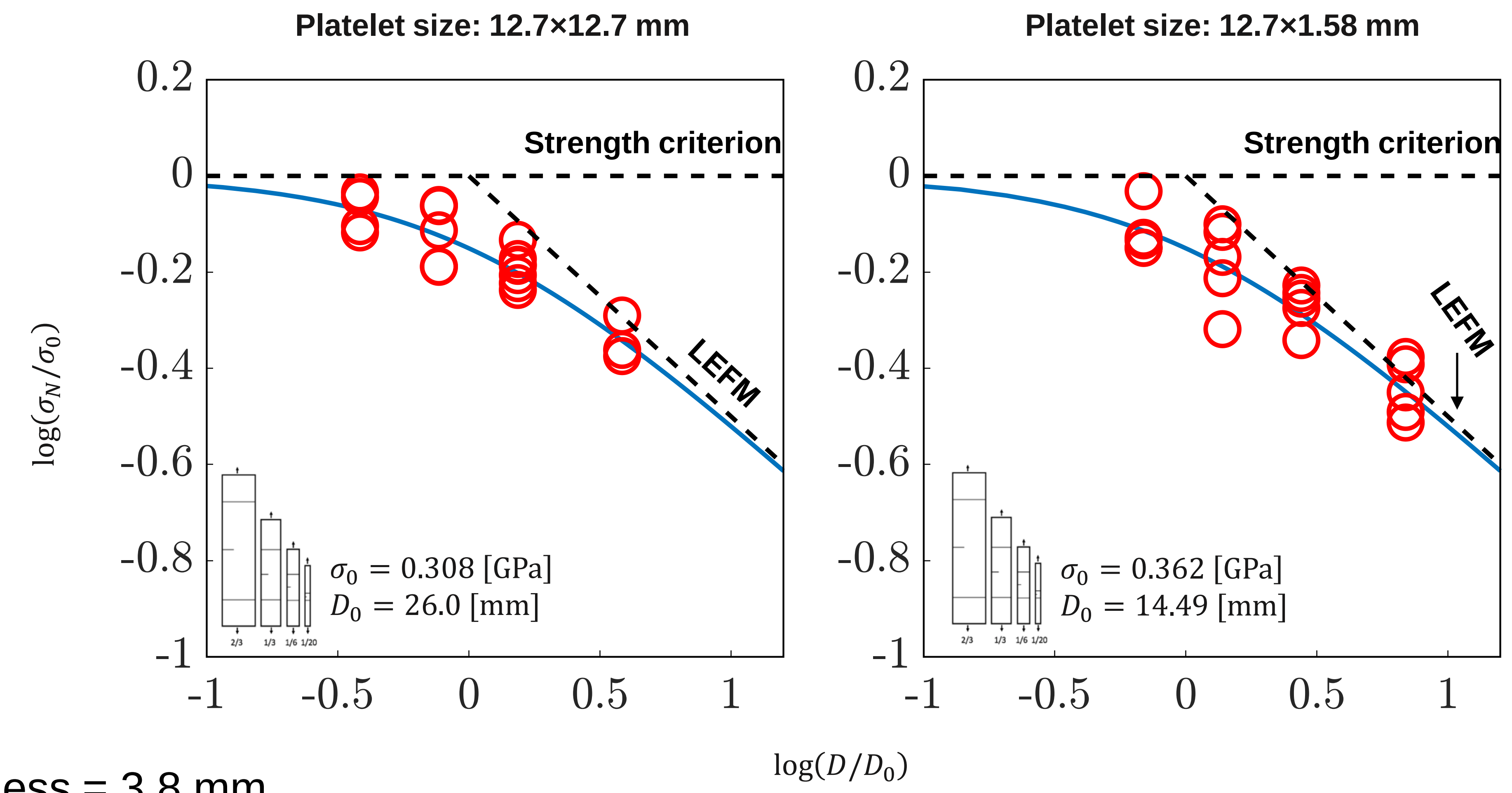


1. DFC shows a strong size effect.
   a) we can clearly observe the transition from the strength to energy driven fracture.
   b) Neither strength nor LEFM can predict the behavior of the DFC.
   c) The notch insensitivity is observed when the specimen size is moving away from LEFM region (or when the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



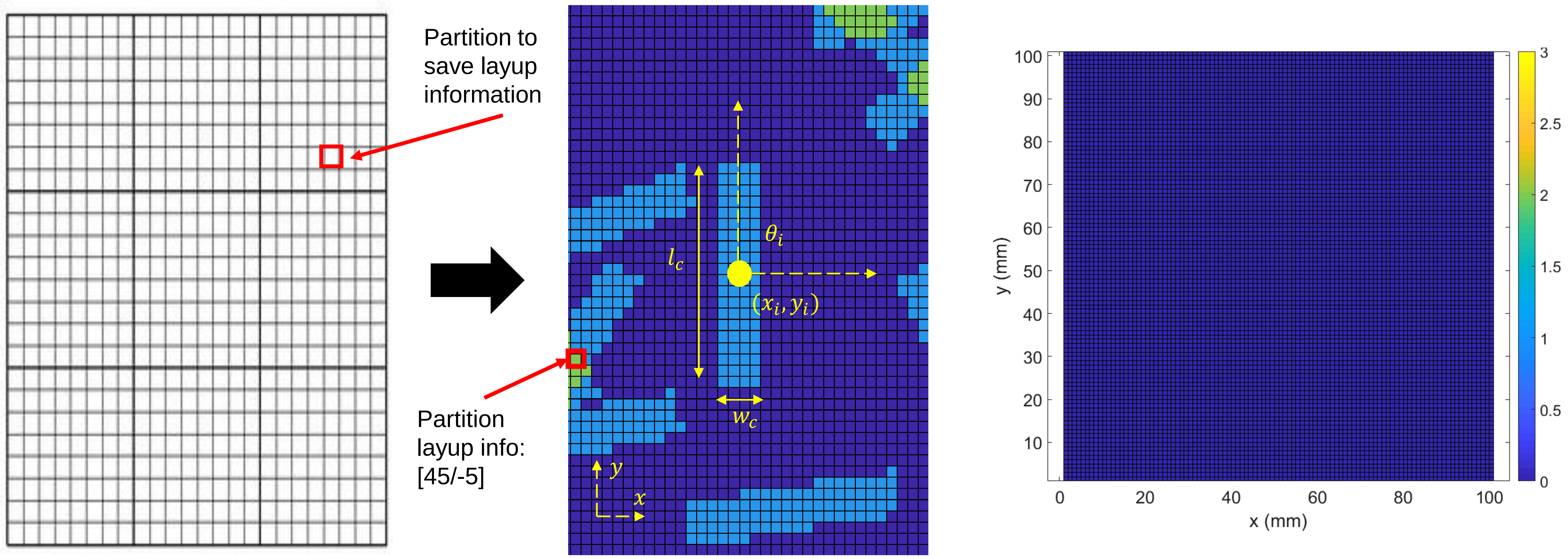
Result: Size effect curves – (thermoplastics)



*Thickness = 3.8 mm

Microstructure generation

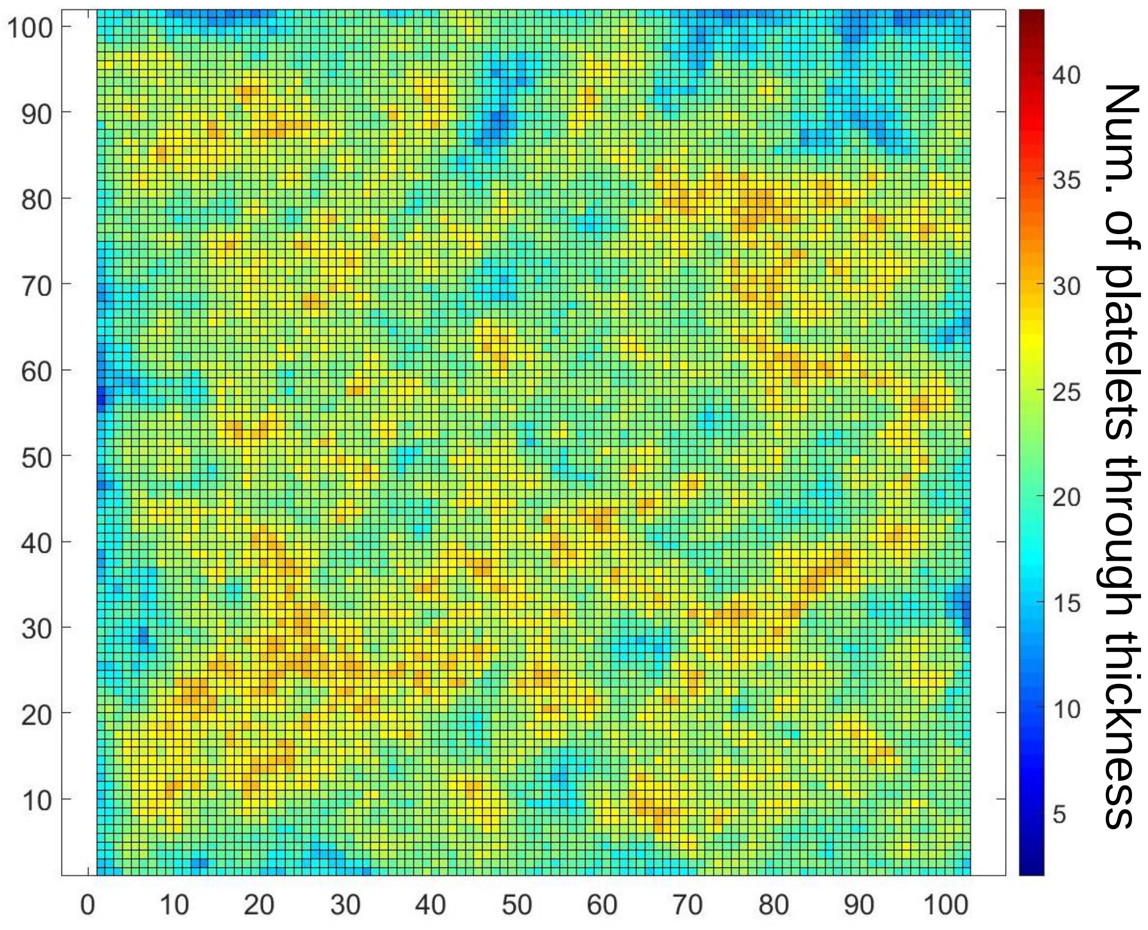
- Finite element model is based on stochastic laminate analogy [Tuttle, 2010, Selezneva, 2015]
- Platelet center point and its orientation is randomly chosen

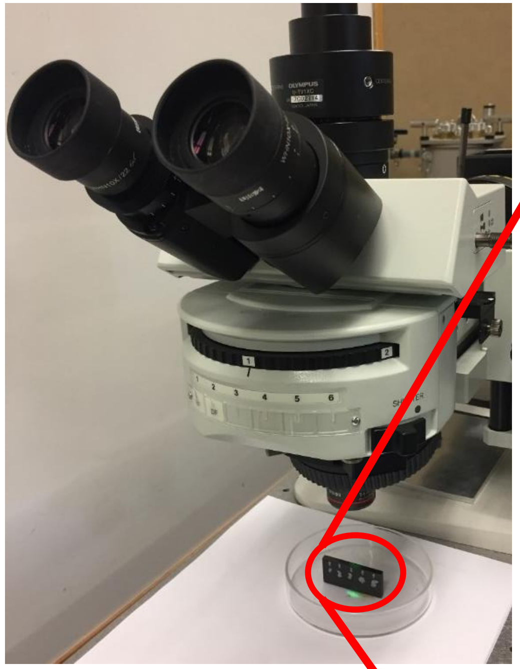


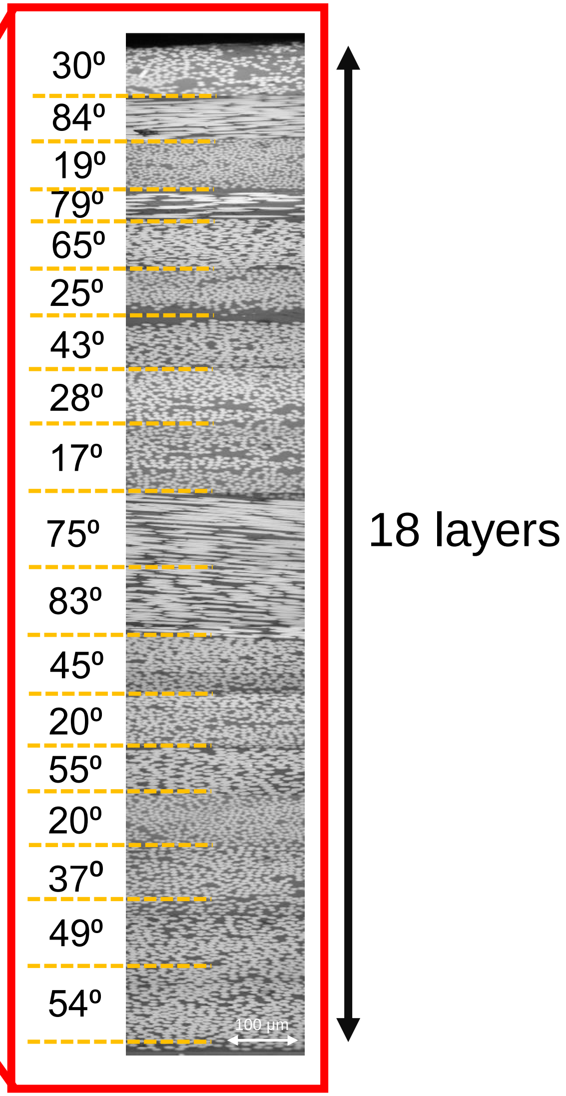
Partition generation | Random platelet generation | Example of platelet generation

Experimentally-verified morphology

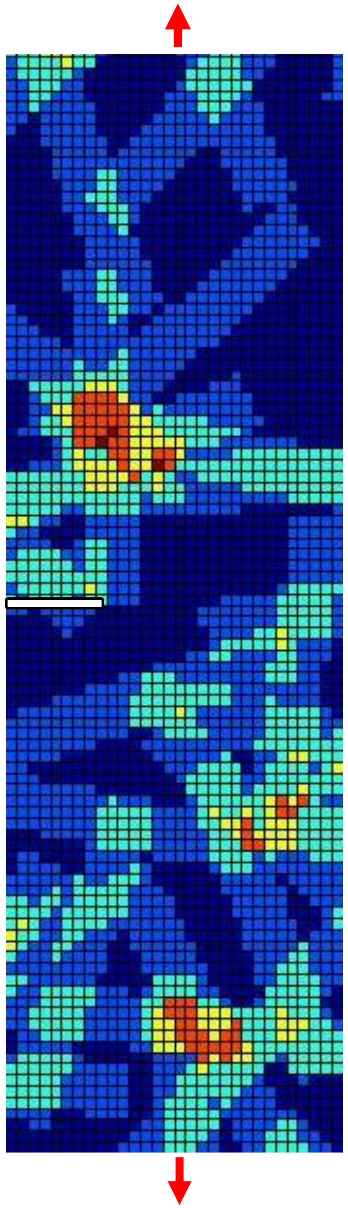
We observed total of 90 cross-sections to measure the distributions







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)

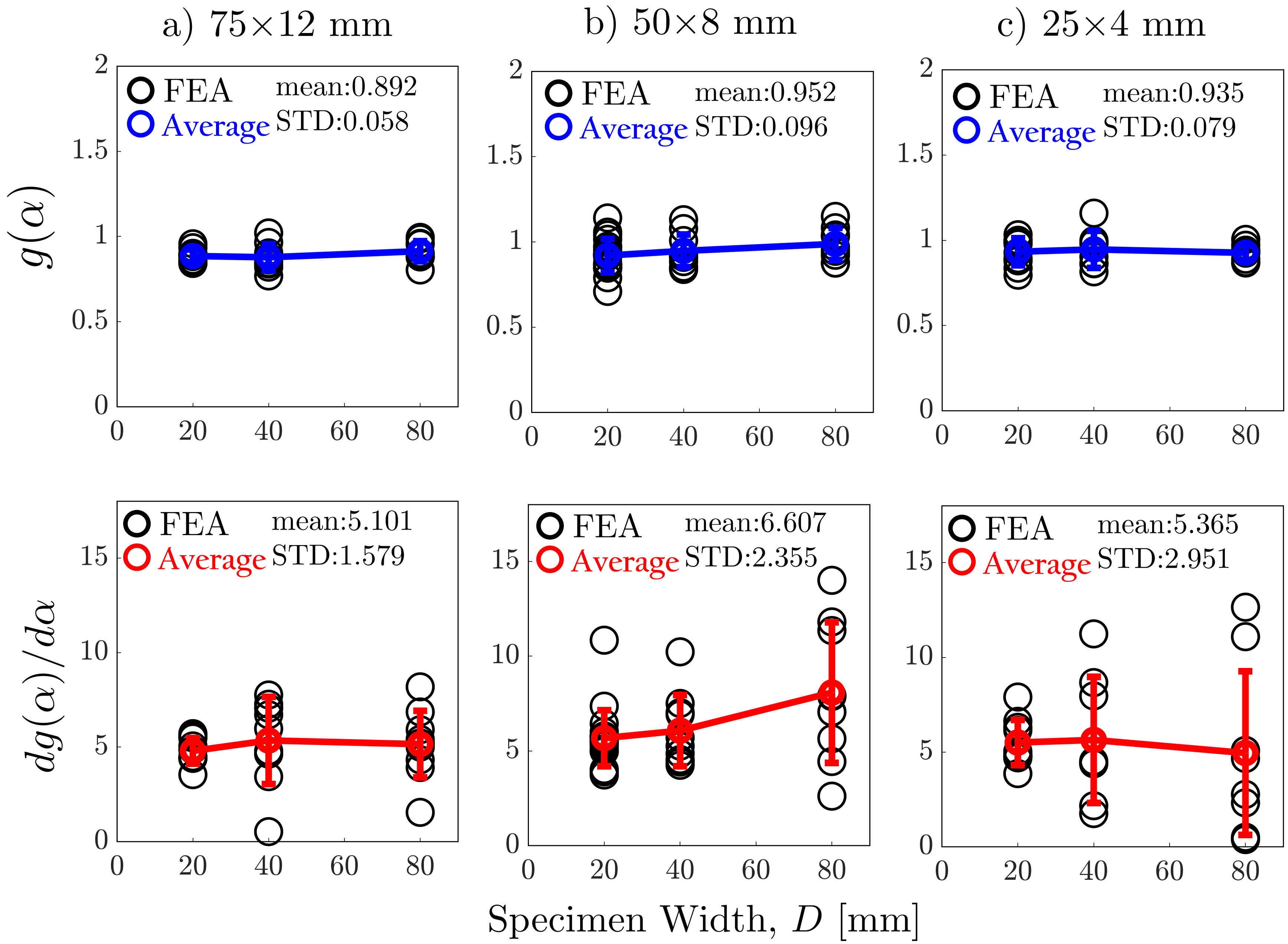
Then, $\boldsymbol{g(\alpha) = \frac{GE^*}{\sigma_N^2 D}}$, and $\boldsymbol{g'(\alpha) = \frac{dg(\alpha)}{da}}$

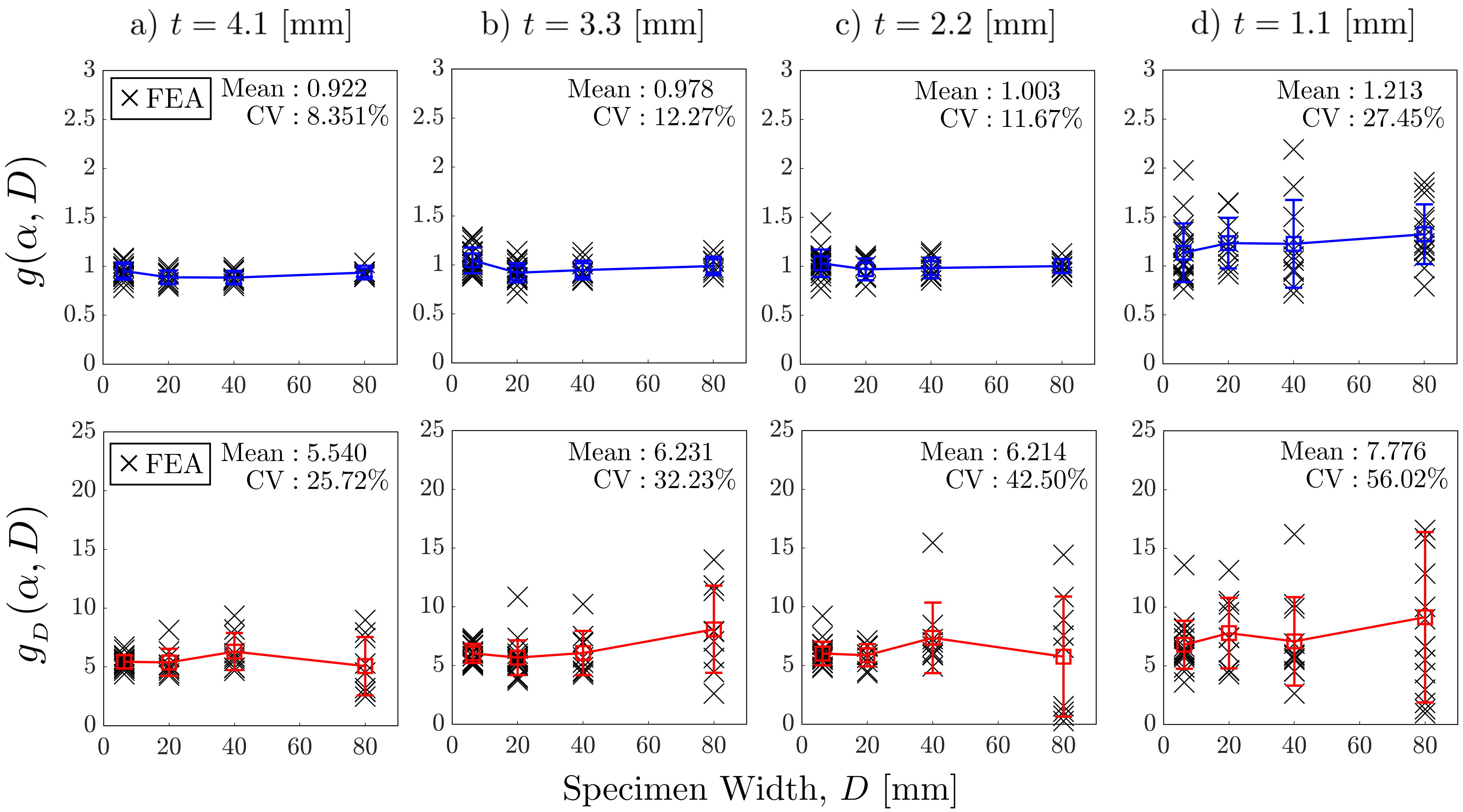
"g accounts both for the geometry and microstructural effects, therefore it is important to explicitly model the DFC's microstructure"

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



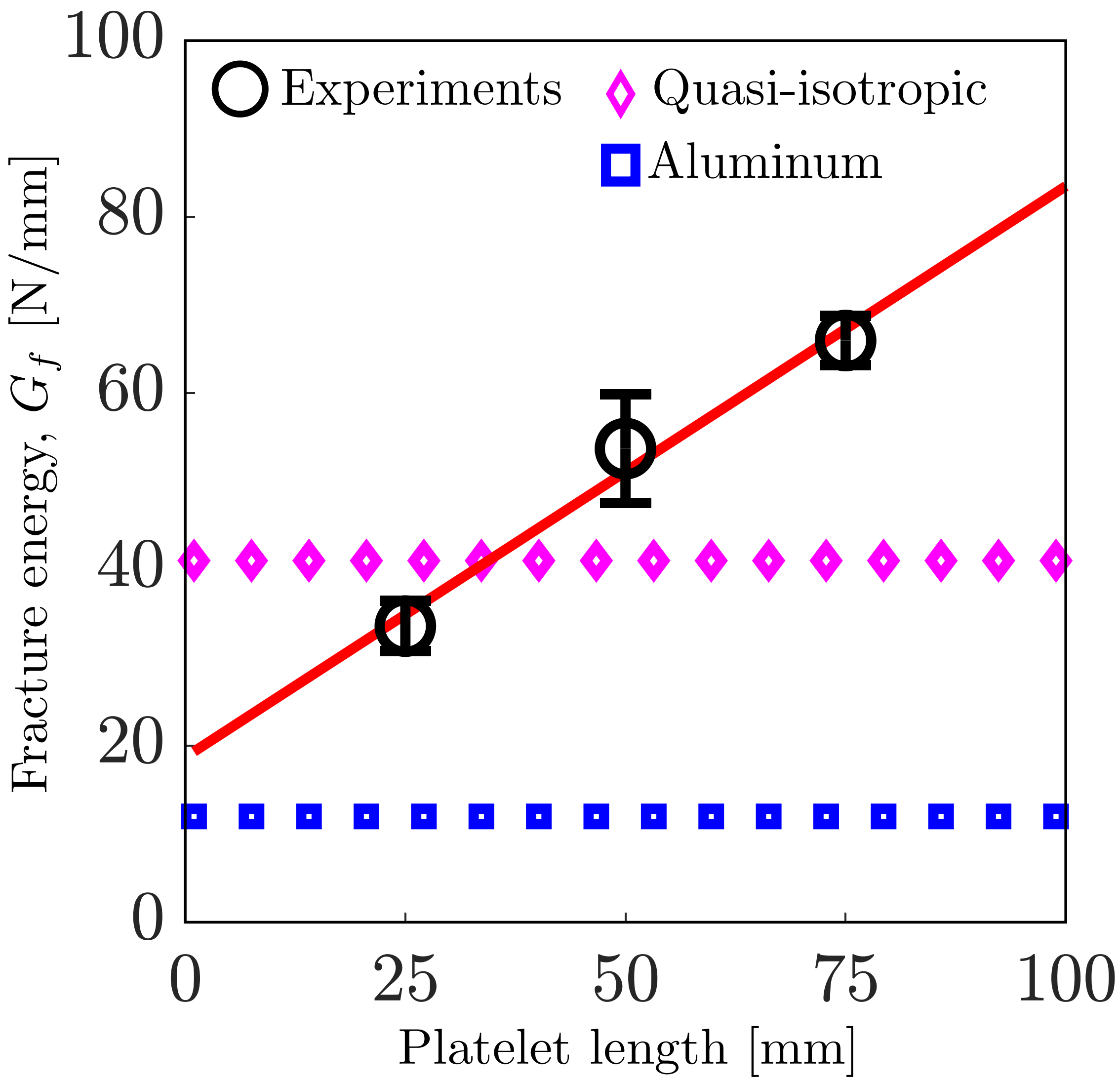


a) $t = 4.1$ [mm]
b) $t = 3.3$ [mm]
c) $t = 2.2$ [mm]
d) $t = 1.1$ [mm]
$g(\alpha, D)$
$g_D(\alpha, D)$
FEA
Mean : 0.922
CV : 8.351%
Mean : 0.978
CV : 12.27%
Mean : 1.003
CV : 11.67%
Mean : 1.213
CV : 27.45%
Mean : 5.540
CV : 25.72%
Mean : 6.231
CV : 32.23%
Mean : 6.214
CV : 42.50%
Mean : 7.776
CV : 56.02%
Specimen Width, D [mm]

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

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

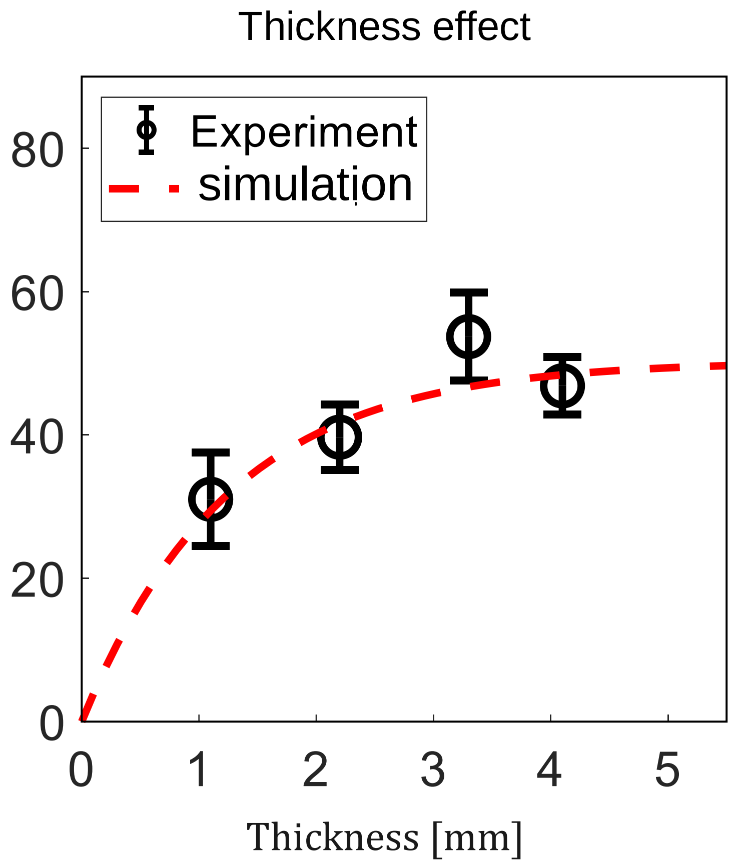
	Effective FPZ length, c_f (mm)	Fracture energy, G_f (N/mm)
25×4 (mm)	6.55 ± 1.07	33.59 ± 2.86 Δ0.0%
50×8 (mm)	7.43 ± 0.83	53.72 ± 6.14 Δ59.9%
75×12 (mm)	14.2 ± 1.85	64.98 ± 2.79 Δ93.5%



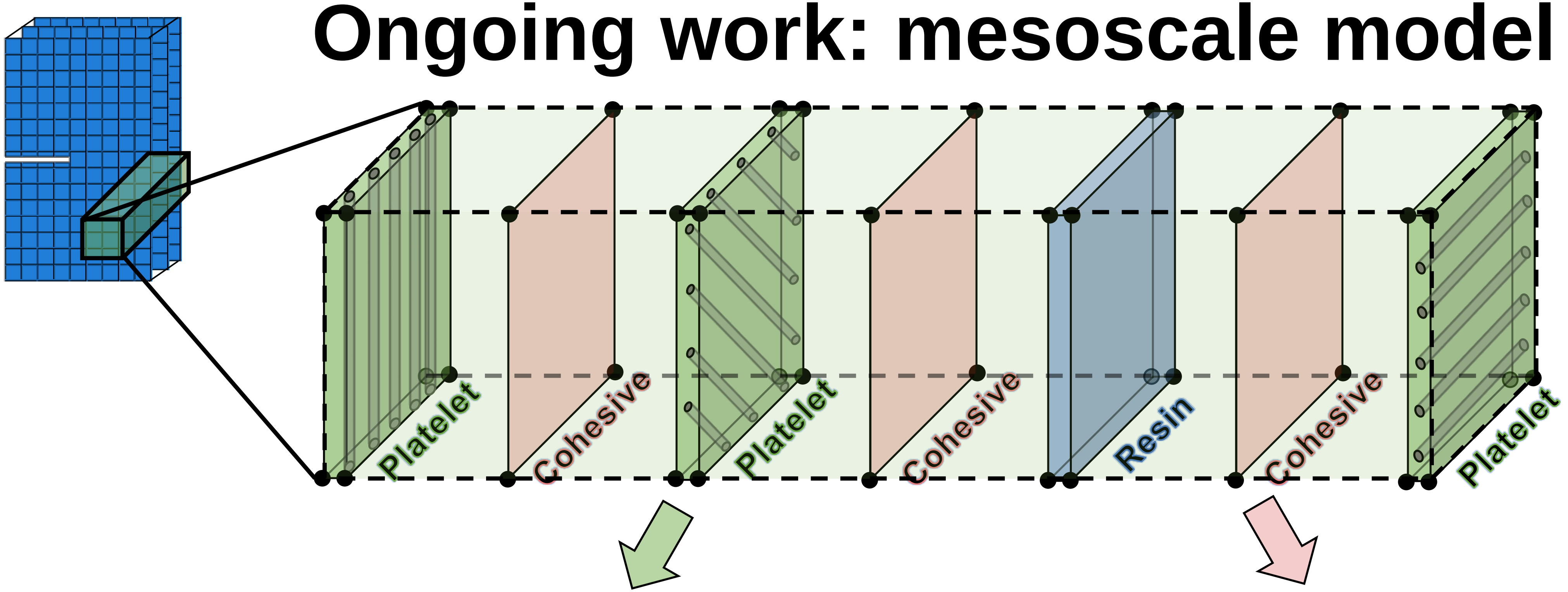
Intra-laminar mode I fracture energy of DFC (thickness effect)

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%



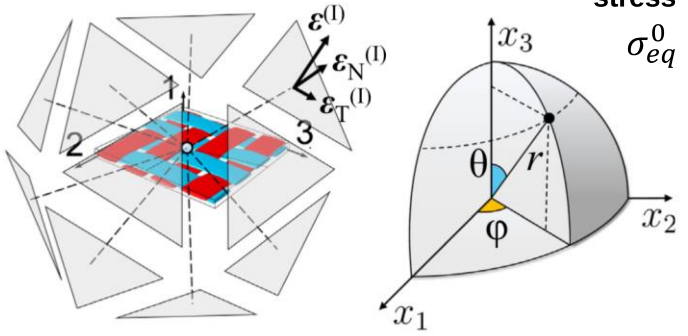
Ongoing work: mesoscale model



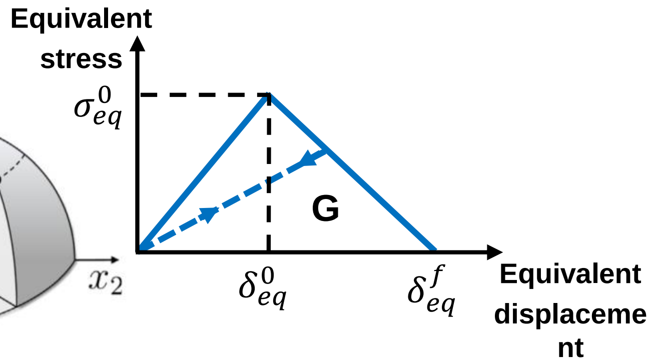
Platelet Damage/Failure

Cohesive Damage/Failure

- Spectral Stiffness Microplate model



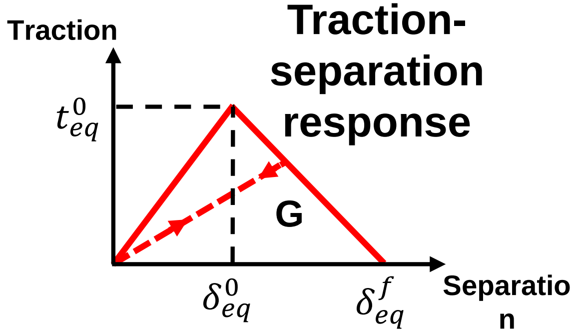
- **Linear softening damage evolution**



- **Quadratic stress Criteria**

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

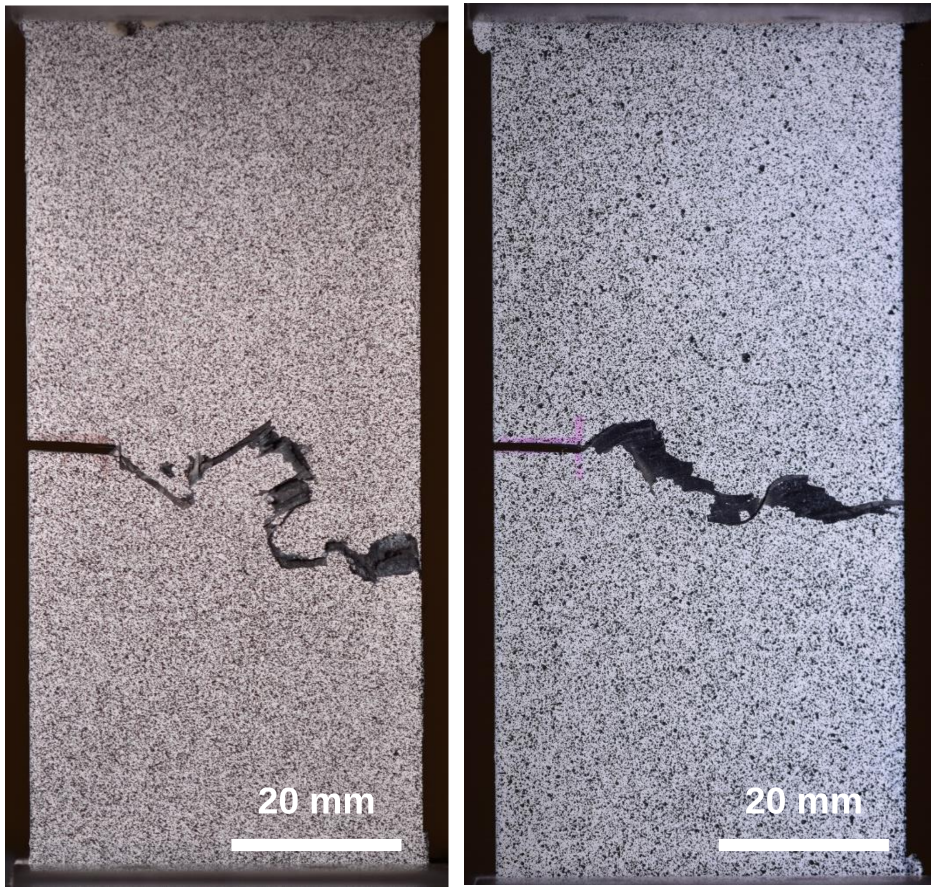
- **Linear Traction-separation response**



Salviato et al., Compos Struct, 2016

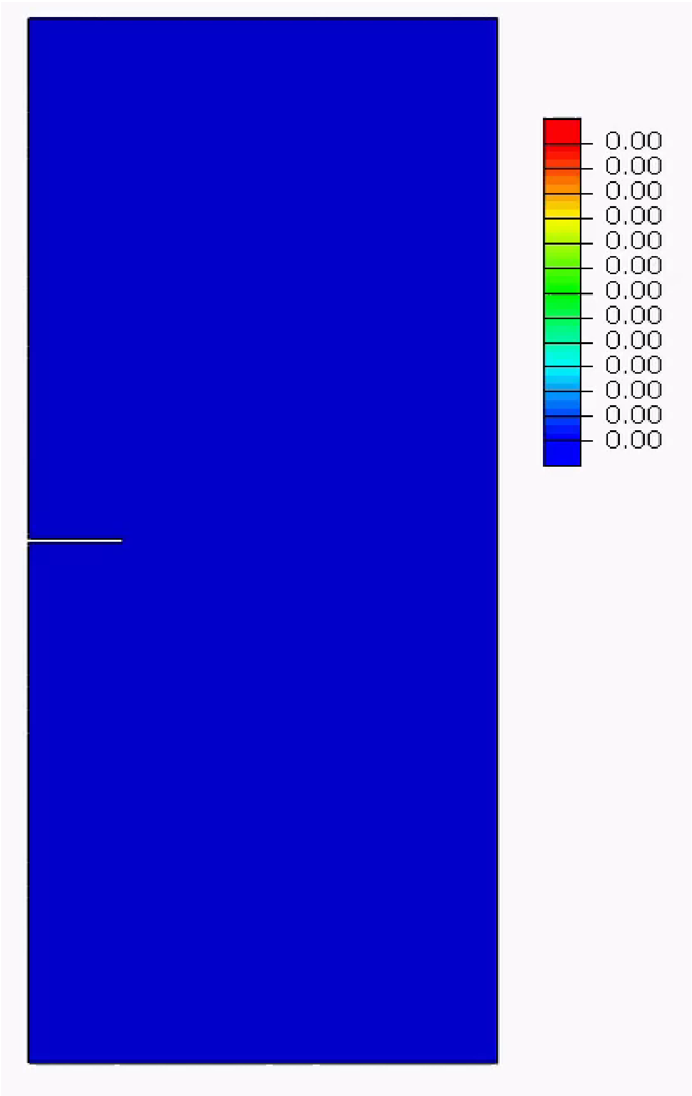
Abaqus Result Size Medium

Fracture surfaces of Medium Coupons

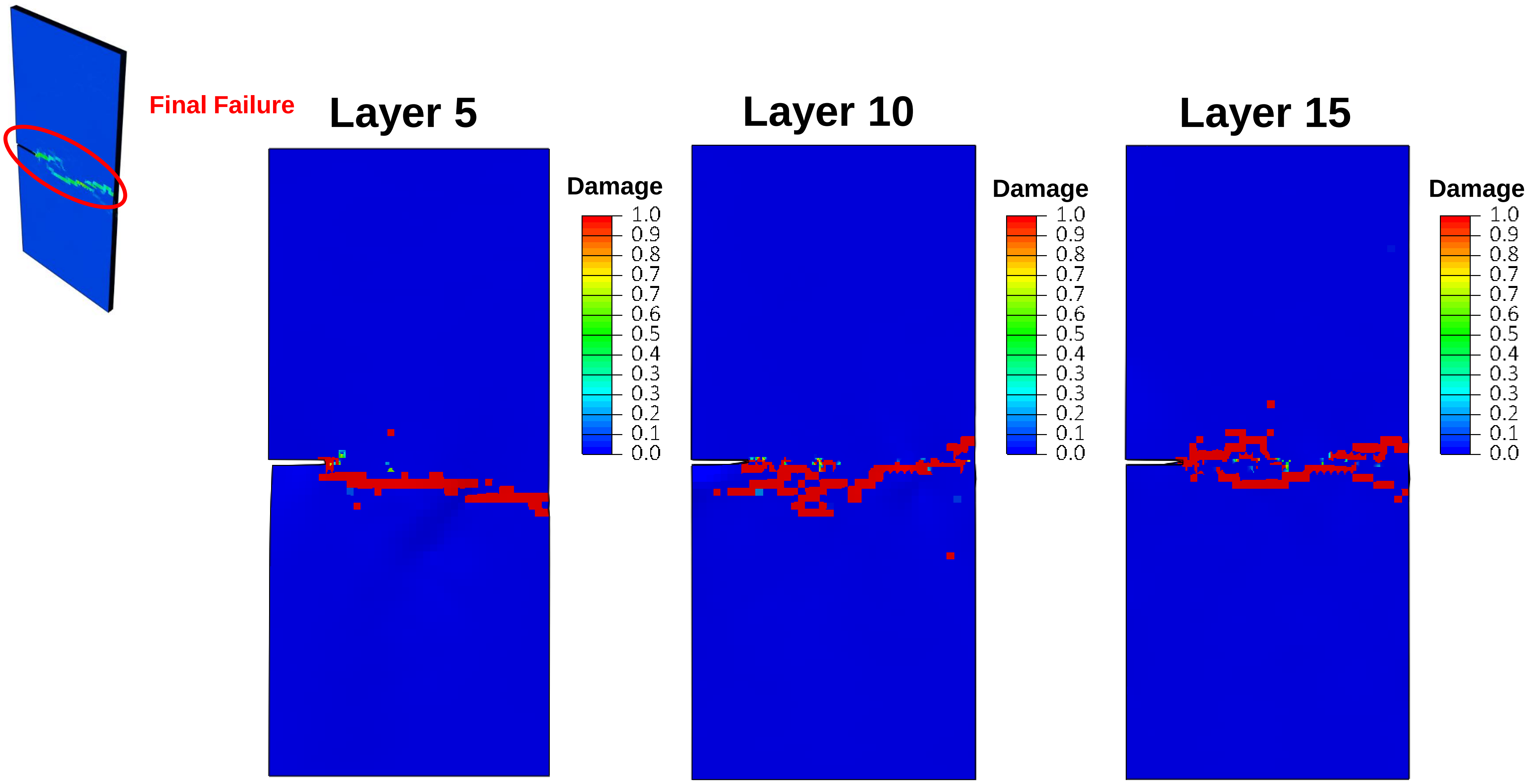


Most of fracture happens at the notch

Strain distribution in Y-dir.



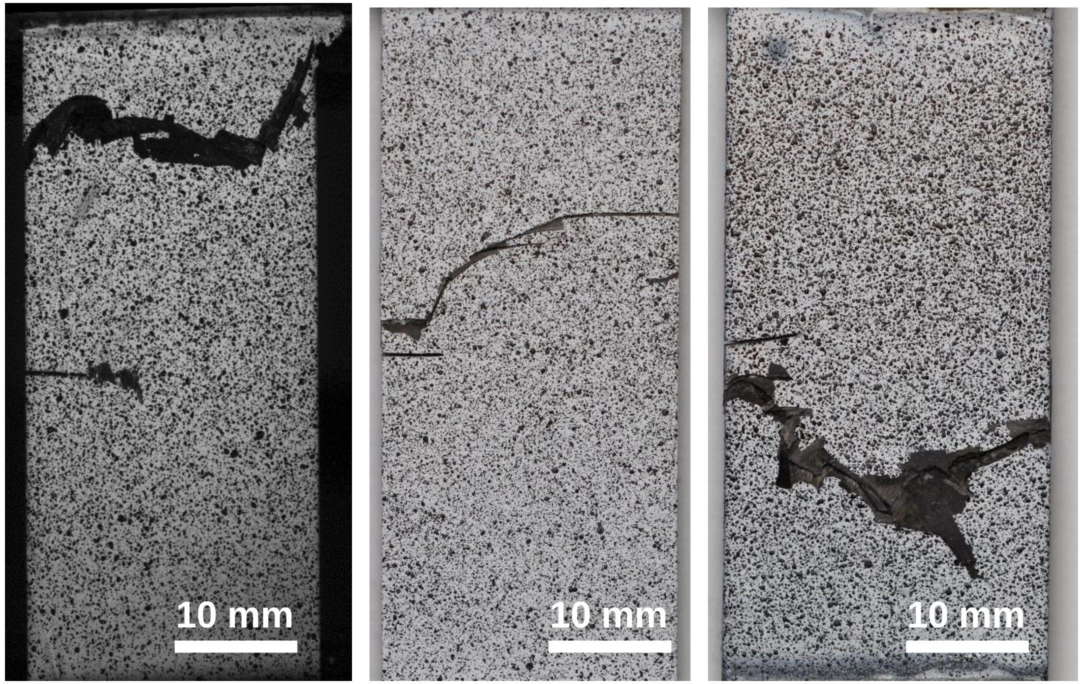
Matrix damage distributions in different layers



Localized damage at the notch

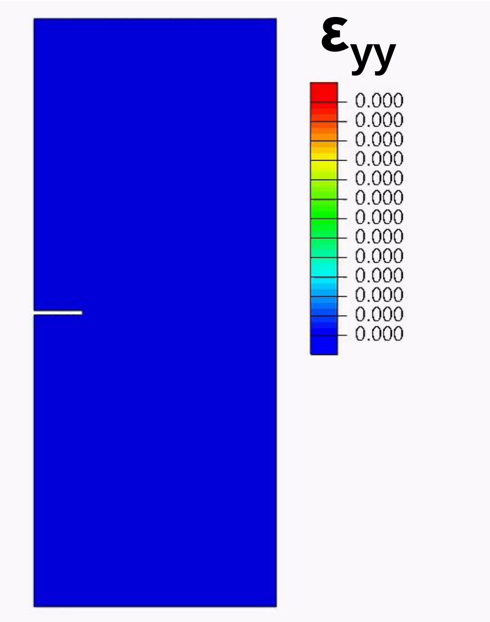
Abaqus Result Size Small Coupon

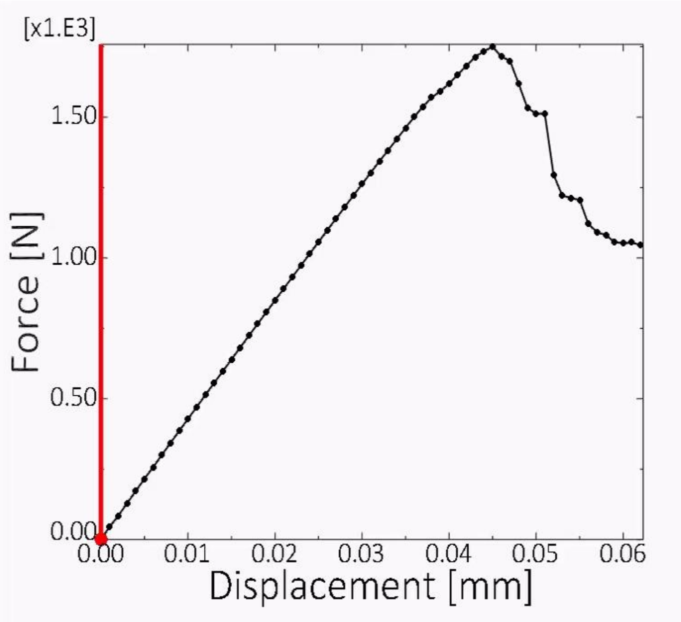
Fracture surfaces of Small Coupons



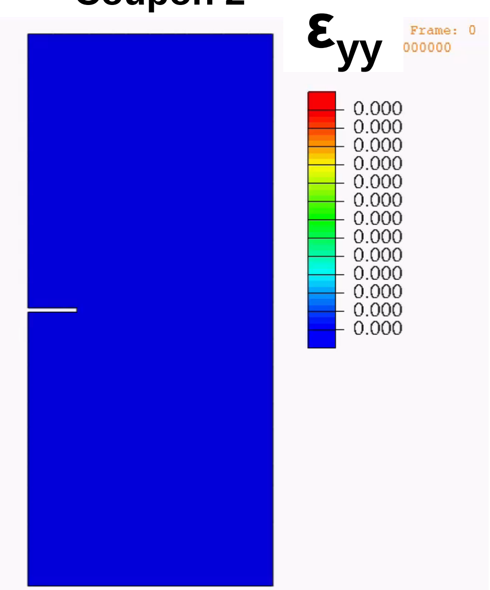
Fracture happens away from the notch

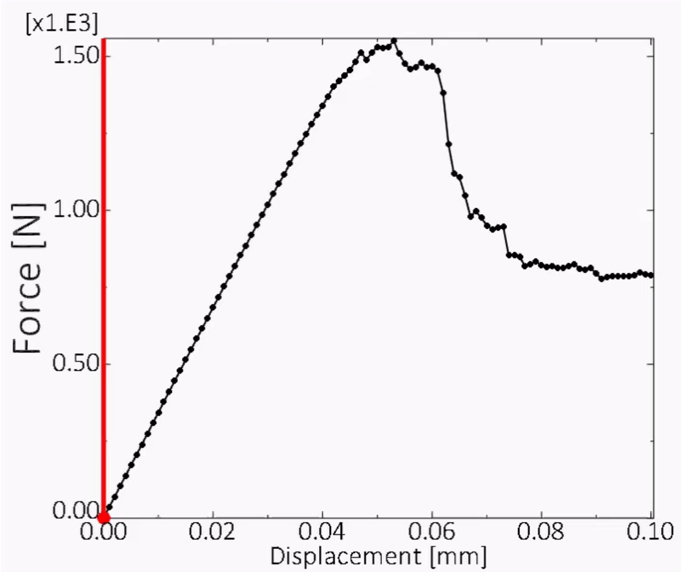
Coupon 1



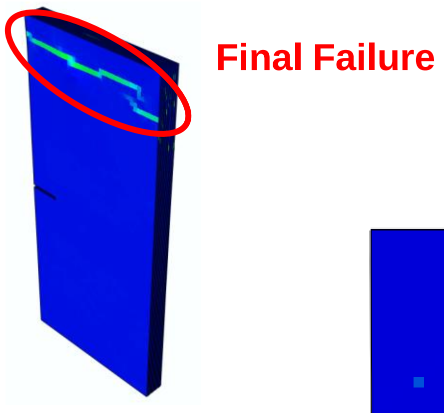


Coupon 2

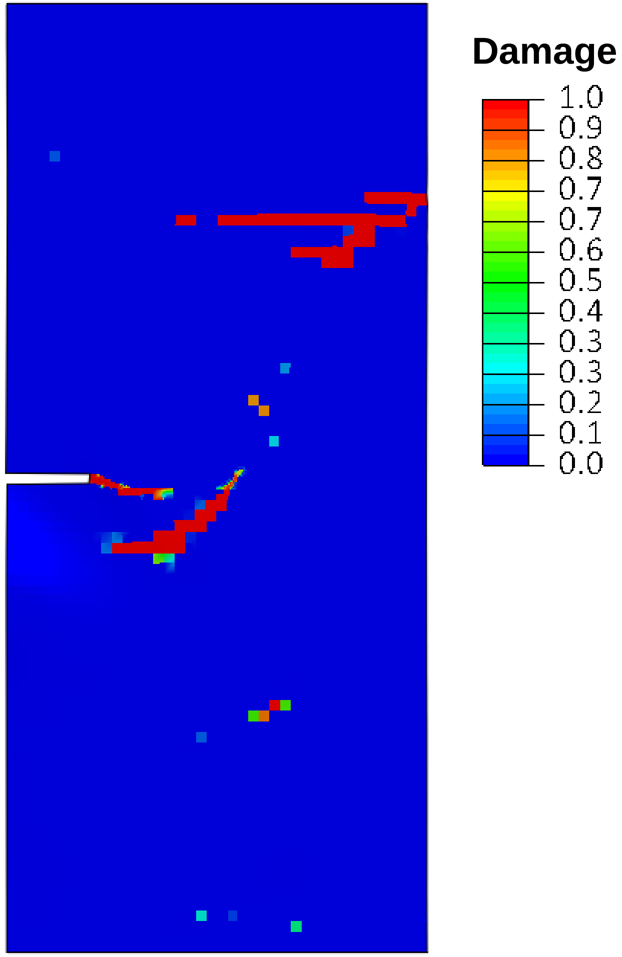




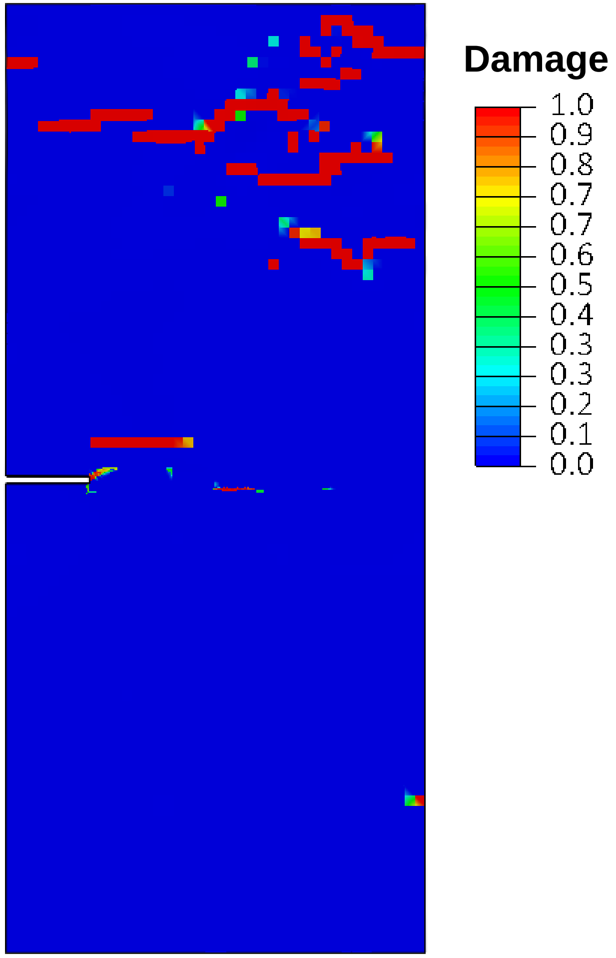
Simulated fracture morphology



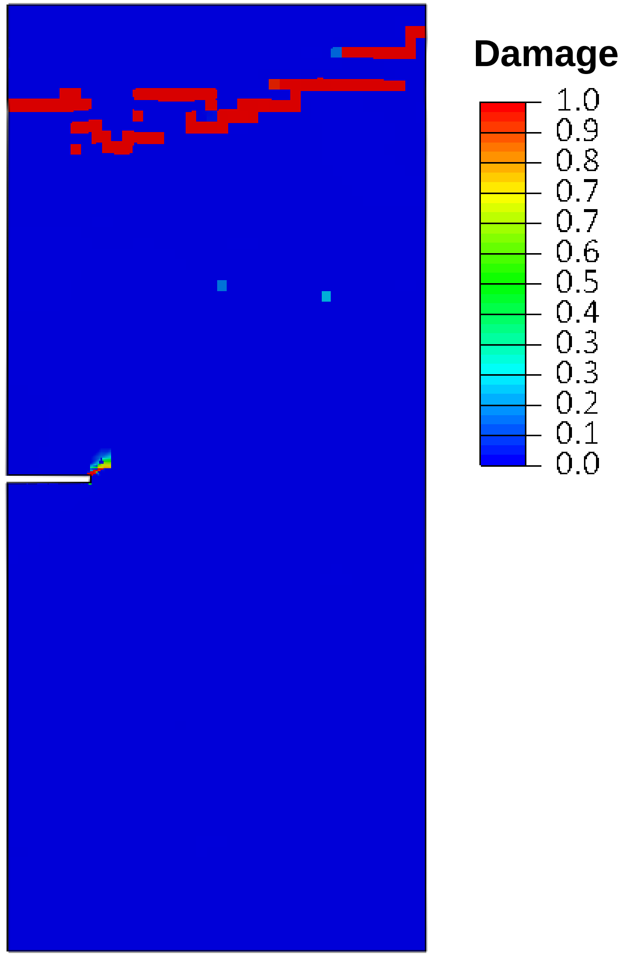
Layer 1



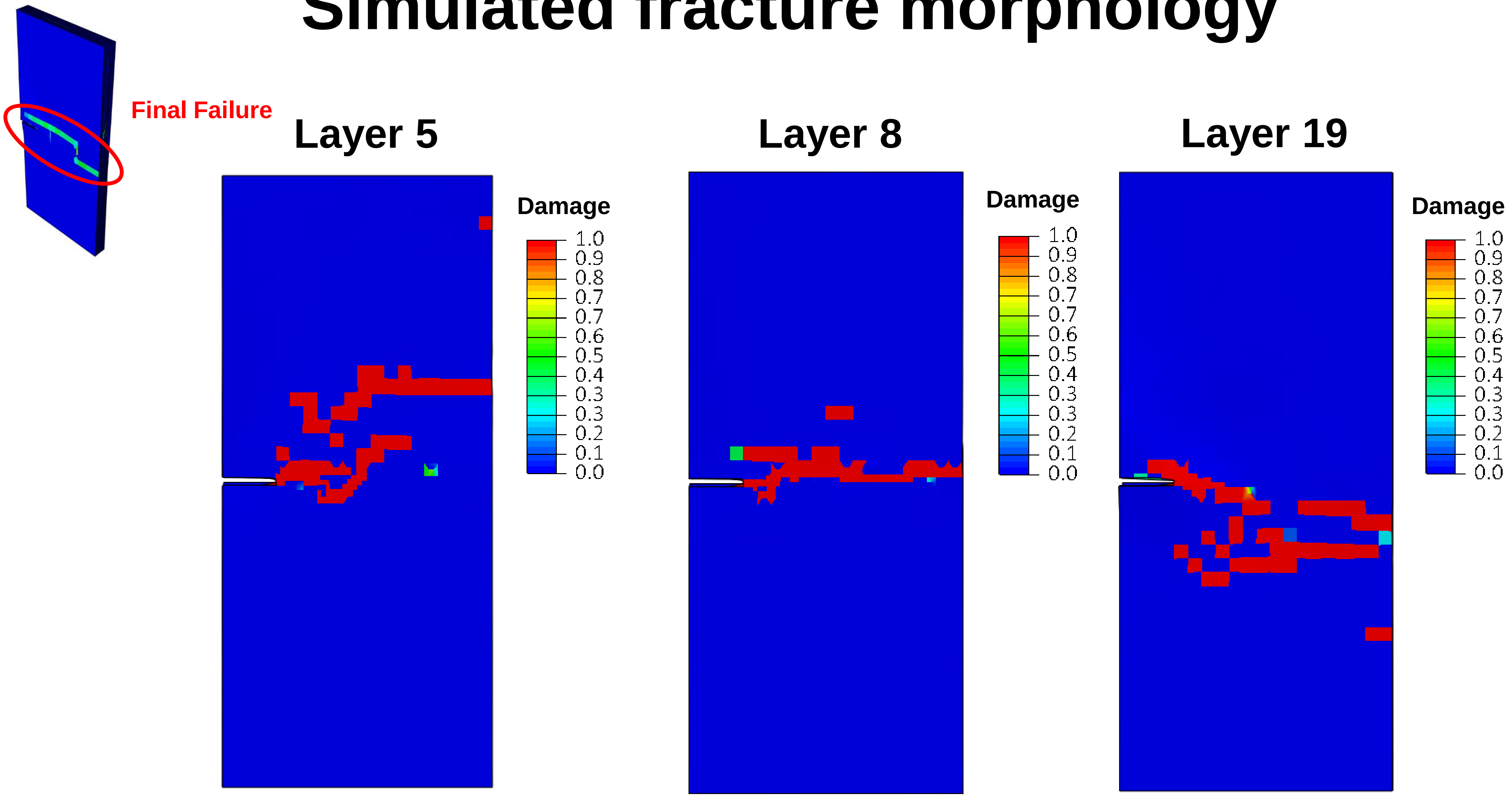
Layer 4



Layer 16



Simulated fracture morphology



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

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Certification of Discontinuous Composite Material Forms for Aircraft Structures

Marco Salviato, Jinkyu Yang, Mark Tuttle
University of Washington

JAMS 2019 Technical Review May 22-23, 2019