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AMTAS
Advanced Materials in Transport Aircraft Structures
A part of the FAA Joint Advanced Materials & Structures Center of Excellence

Safety and Certification of Discontinuous Fiber Composite Structures

Marco Salviato, Jinkyu Yang, Mark Tuttle

University of Washington

Seattle, November 8th 2017

Research team

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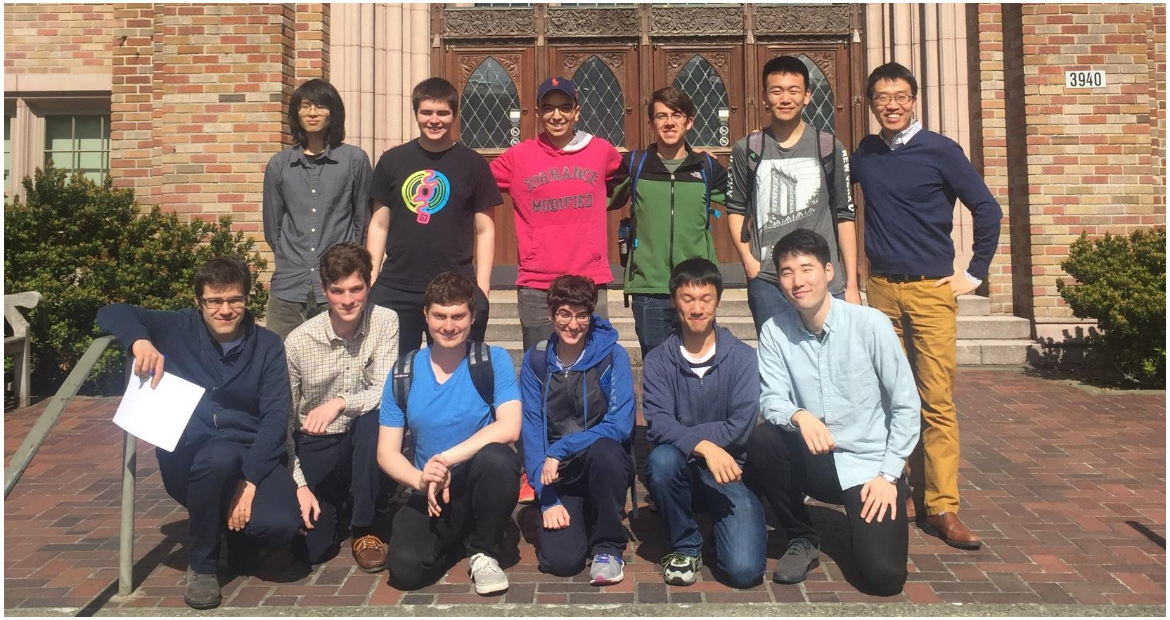


Motivation

Source: www.hexcel.com

Lamborghini Huracan

Source: www.lamborghini.com

- **Almost net-shape design of complex parts;**
- **Significant increase in volumes of production;**
- **Interesting mechanical properties;**

Source: www.toyota.com

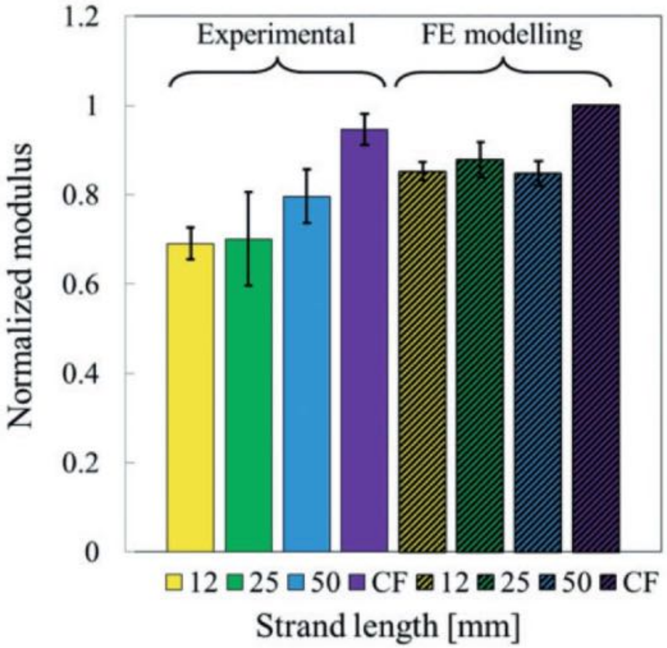
Motivation

Lamborghini Urus

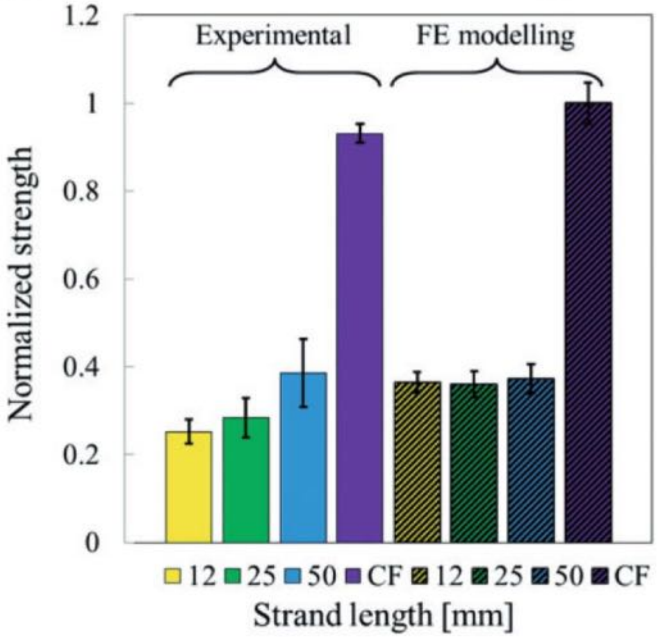
Motivation

Because the size of the main heterogeneities is significant compared to the one of typical DFC components, the mechanical behavior is strongly affected by the material mesostructure.

Elastic modulus



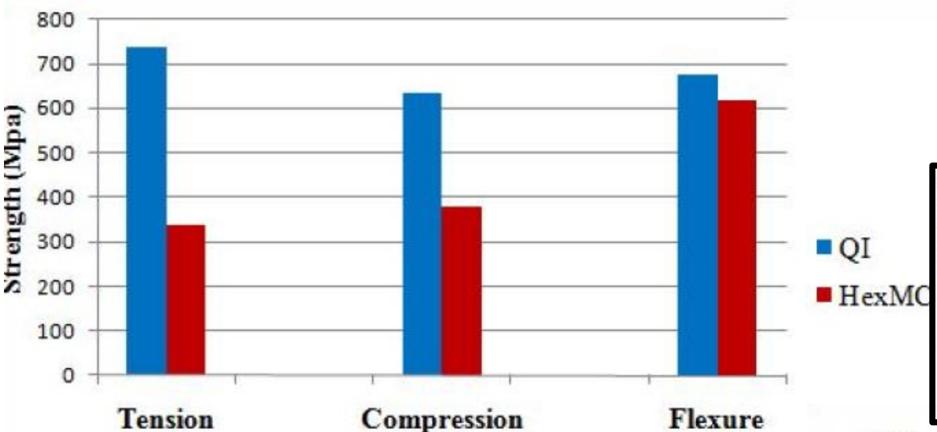
Strength

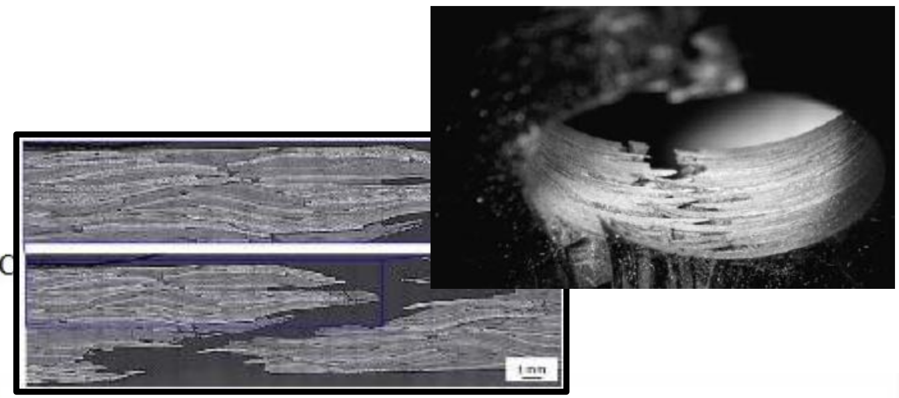


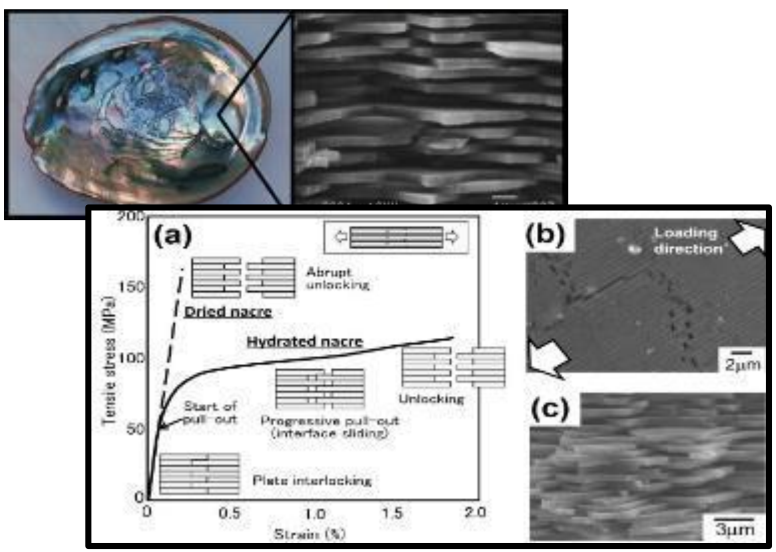
Selezneva et al., J Compos Mat, 2017

Motivation

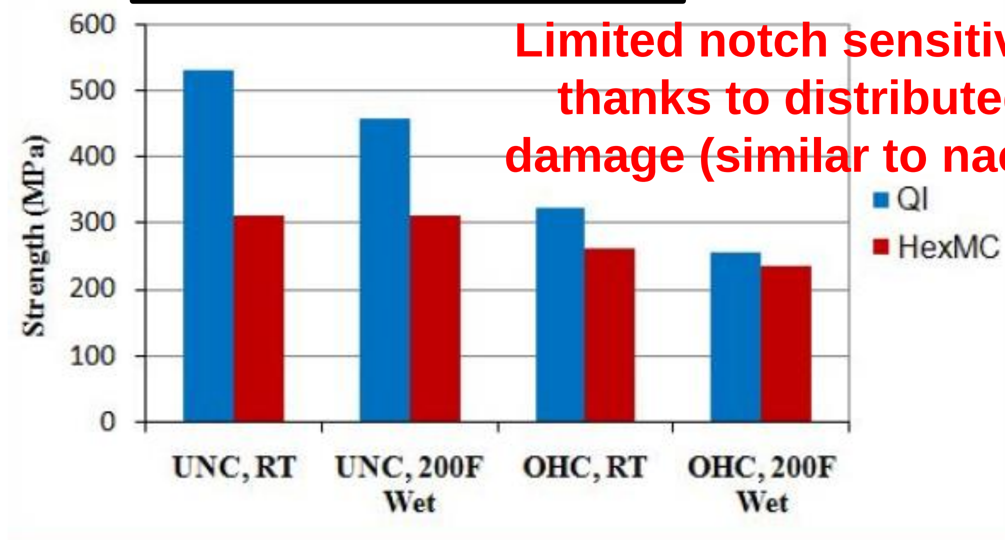
However, the complex mesostructure enables large damage progression and fracture energy dissipation.







Limited notch sensitivity thanks to distributed damage (similar to nacre)



Barthelat et al., JMPS, 2014
Boursier et al., SAMPE, 2012

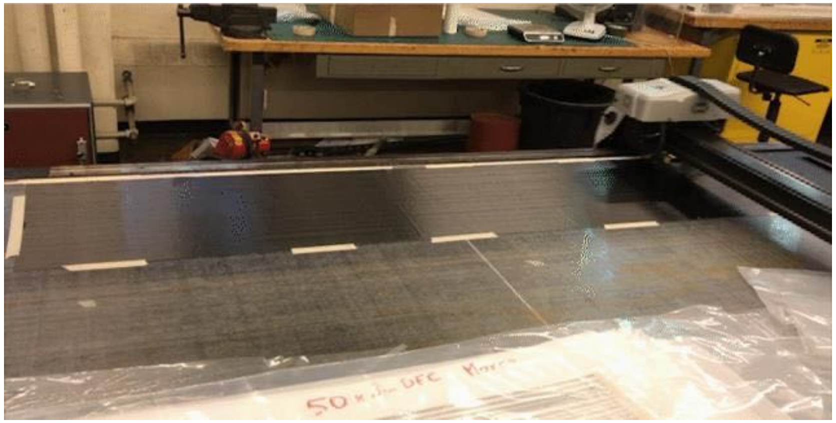
Motivation

Damage tolerance is a highly desirable property!

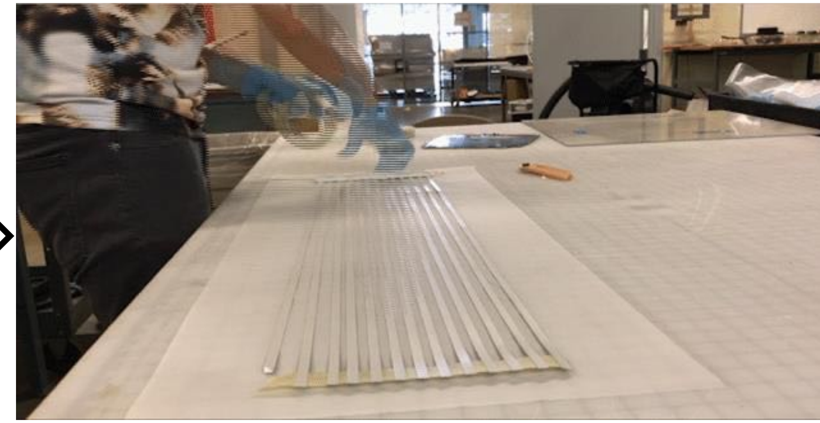
Objectives

- **Investigate the main mechanisms of damage progression and fracture in the presence of notches and defects;**
- **Clarify the role played by the platelet morphology and the mesostructure on the fracturing behavior;**
- **Develop guidelines for the experimental characterization of the fracturing behavior and for the design in the presence of stress risers;**
- **Clarify the role of *defects* such as dents and intralaminar cracks and provide guidelines for nondestructive evaluation**
- **Ultimately, the objective of this AMTAS project is to help ease the path to certification of DFC parts of aerospace structural parts.**

Methodology: DFC manufacturing with controlled platelet size



Prepreg sheets are cut into combs using CNC machine

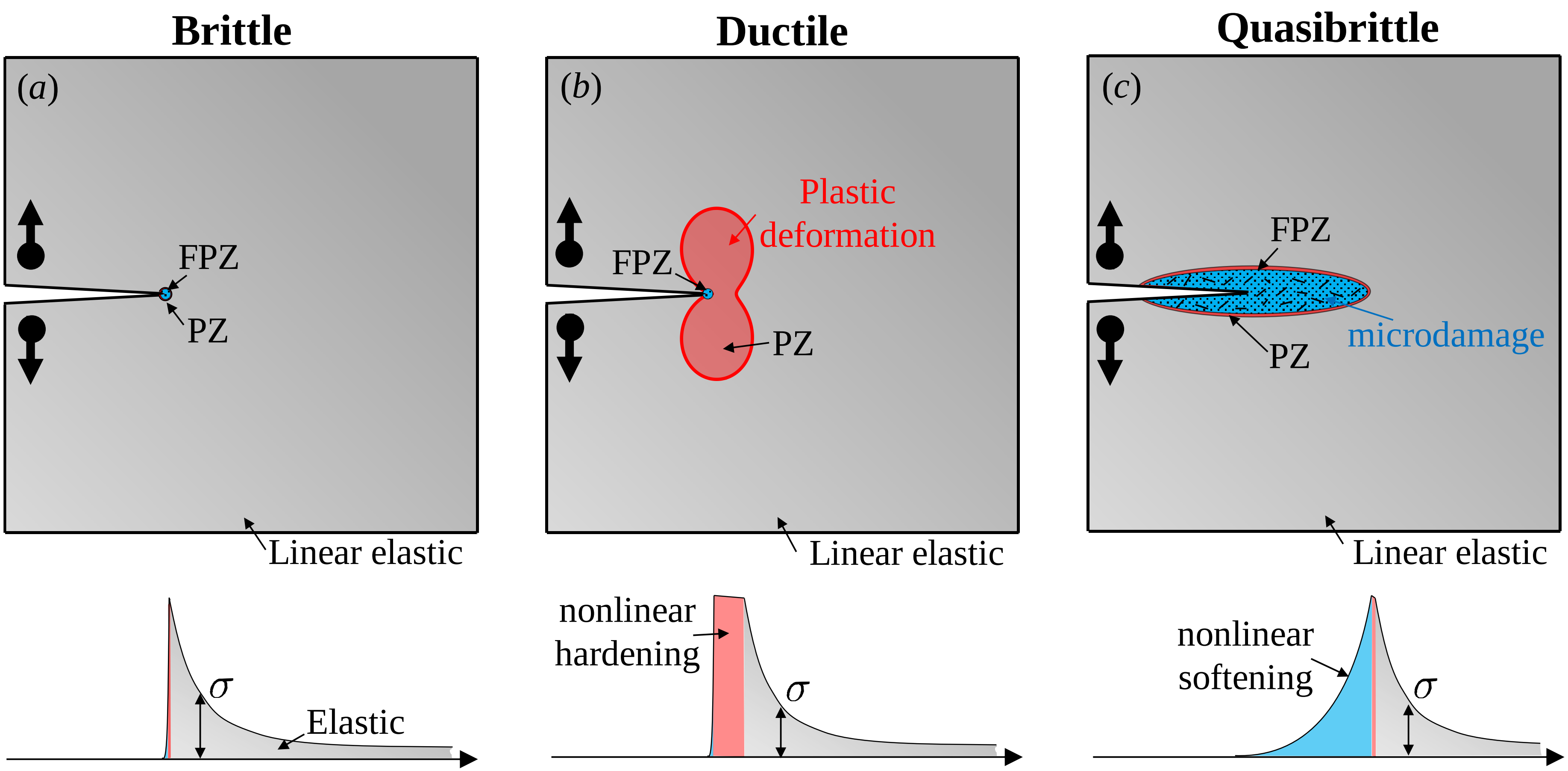


Backing tape is peeled

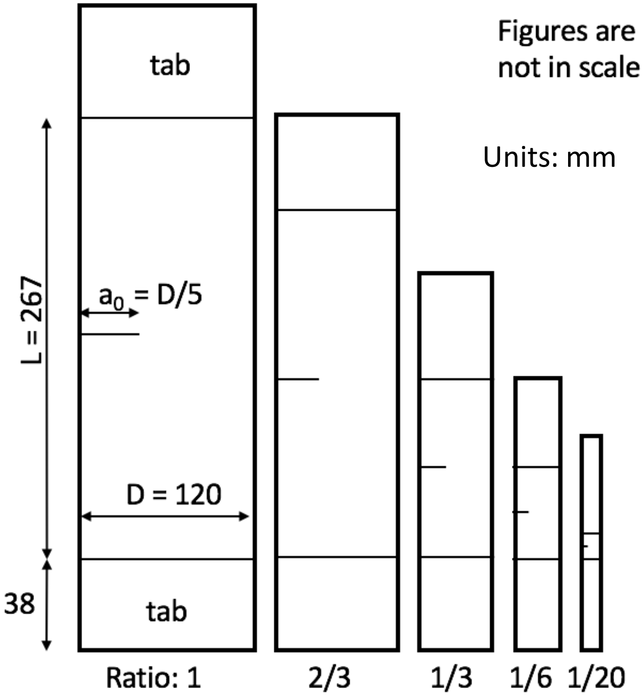
Cut across the combs to make chips in desired dimensions

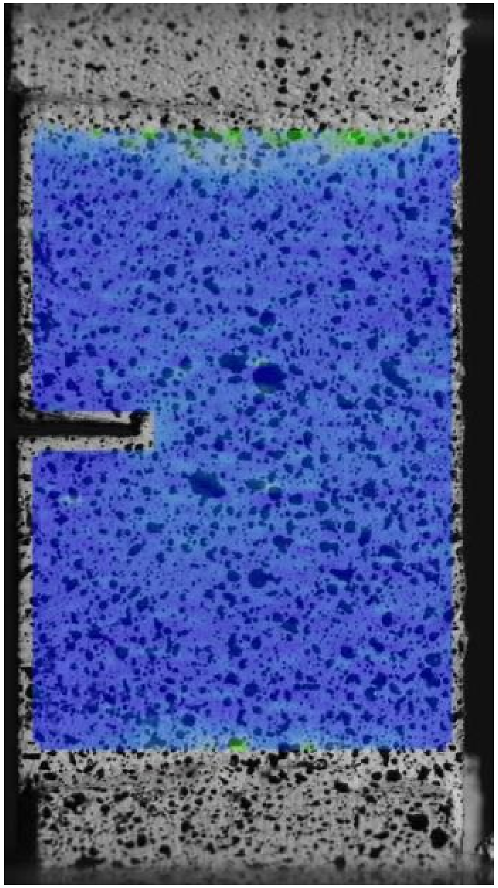
Chips are randomly distributed to form bulk material, ready for the hot-press

Methodology: Size effect test

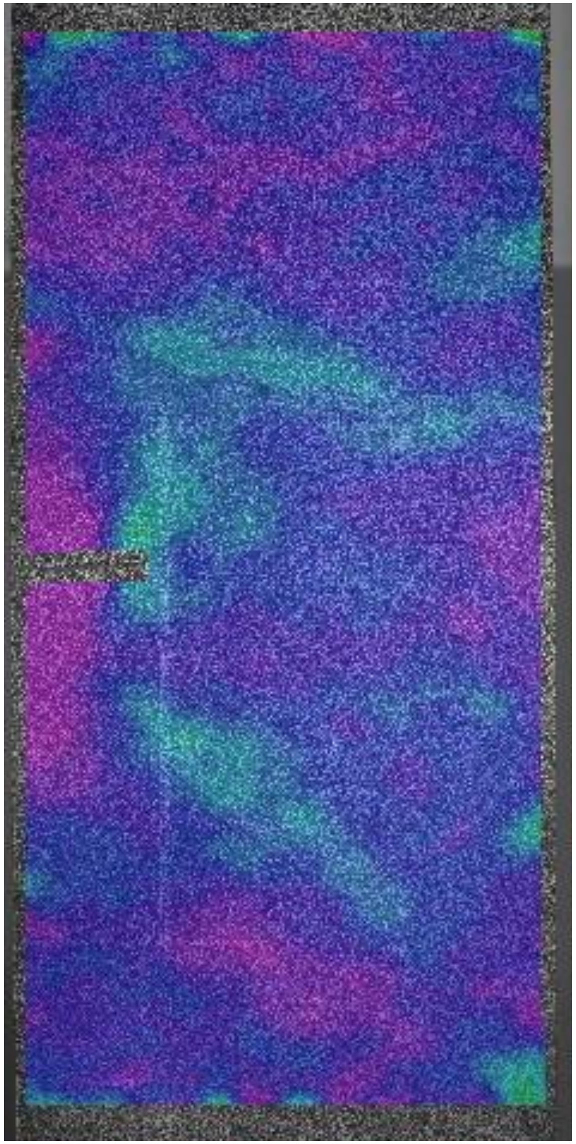


Methodology: Size effect test



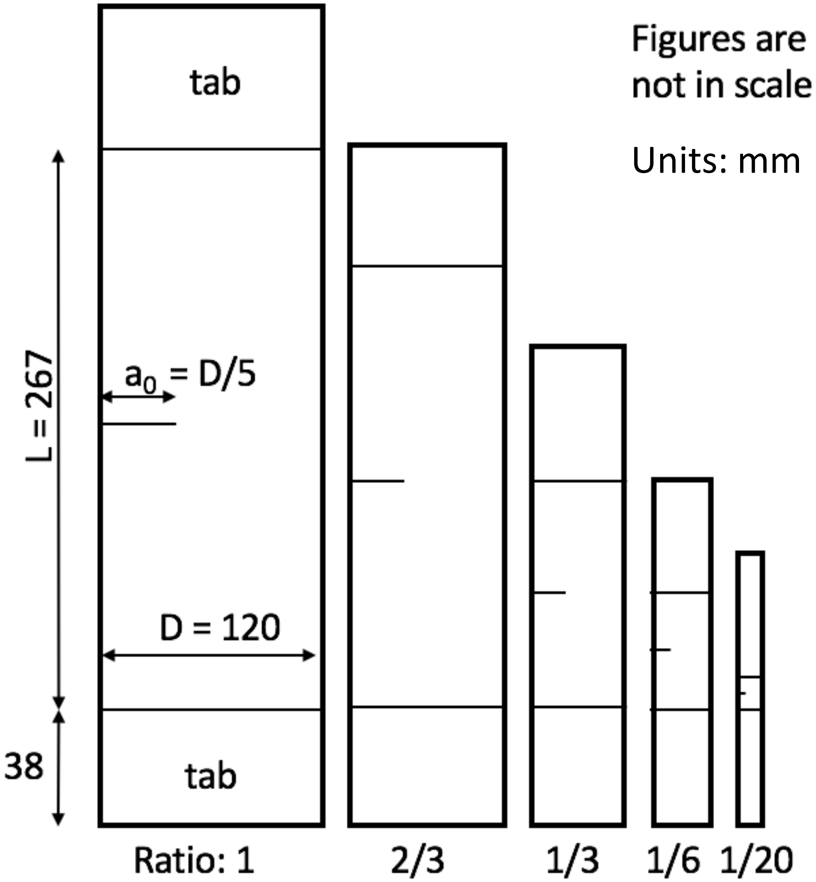


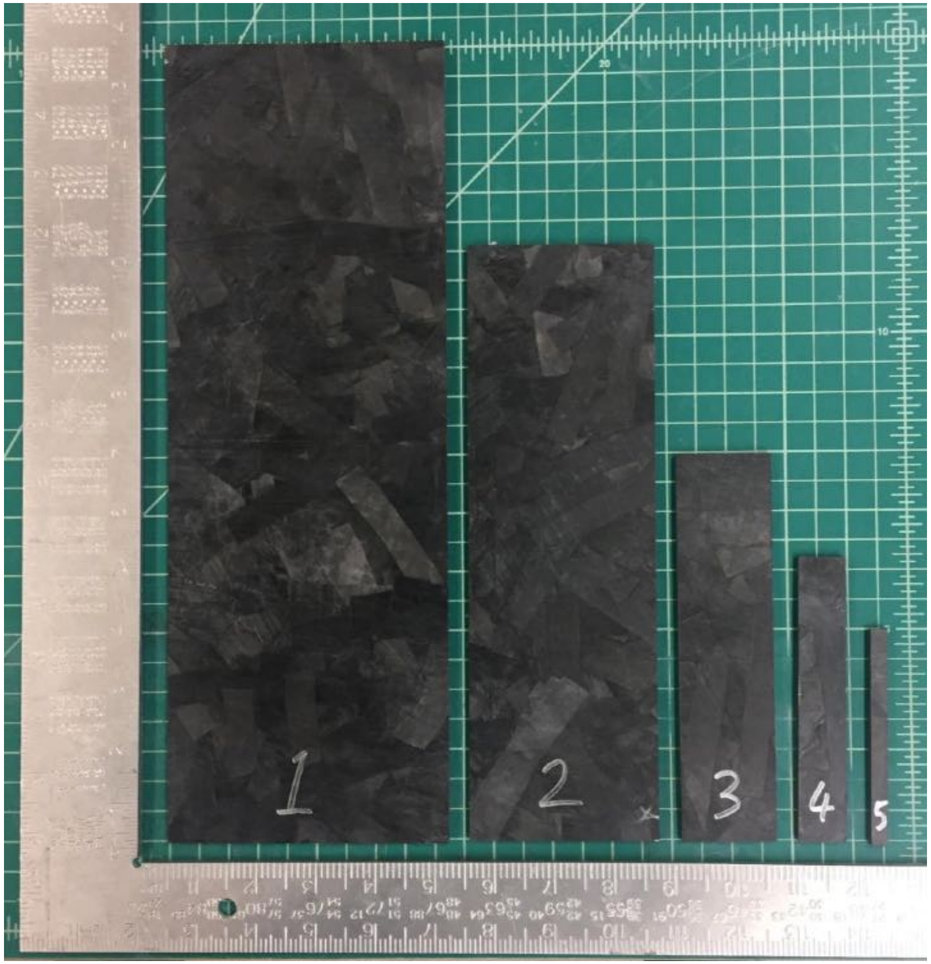
Coupon 5
(width 6.3 mm)



Coupon 1 (width 120 mm)

Methodology: Size effect test





Test plan

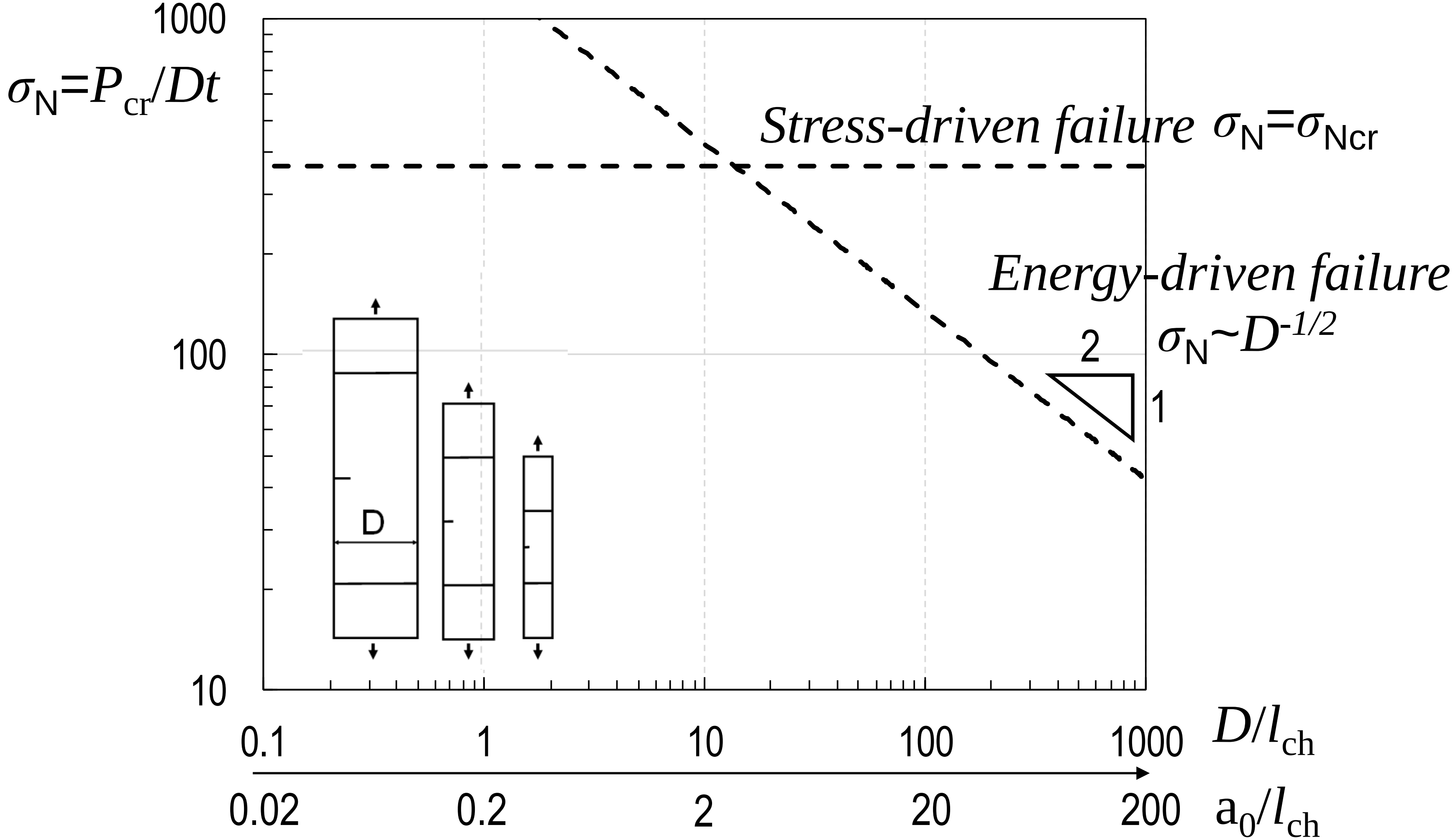
Chip size effect test:

Chip size variables	**75x12, 50x8, 25x4 (mm)**
Fixed thickness	3 (mm)
Coupon size variables	343 x 120, 254 x 80, 165 x 40, 120.5 x 20, 90 x 6.3 (mm)
Number of coupons in each variables	6
Total number of coupons	90

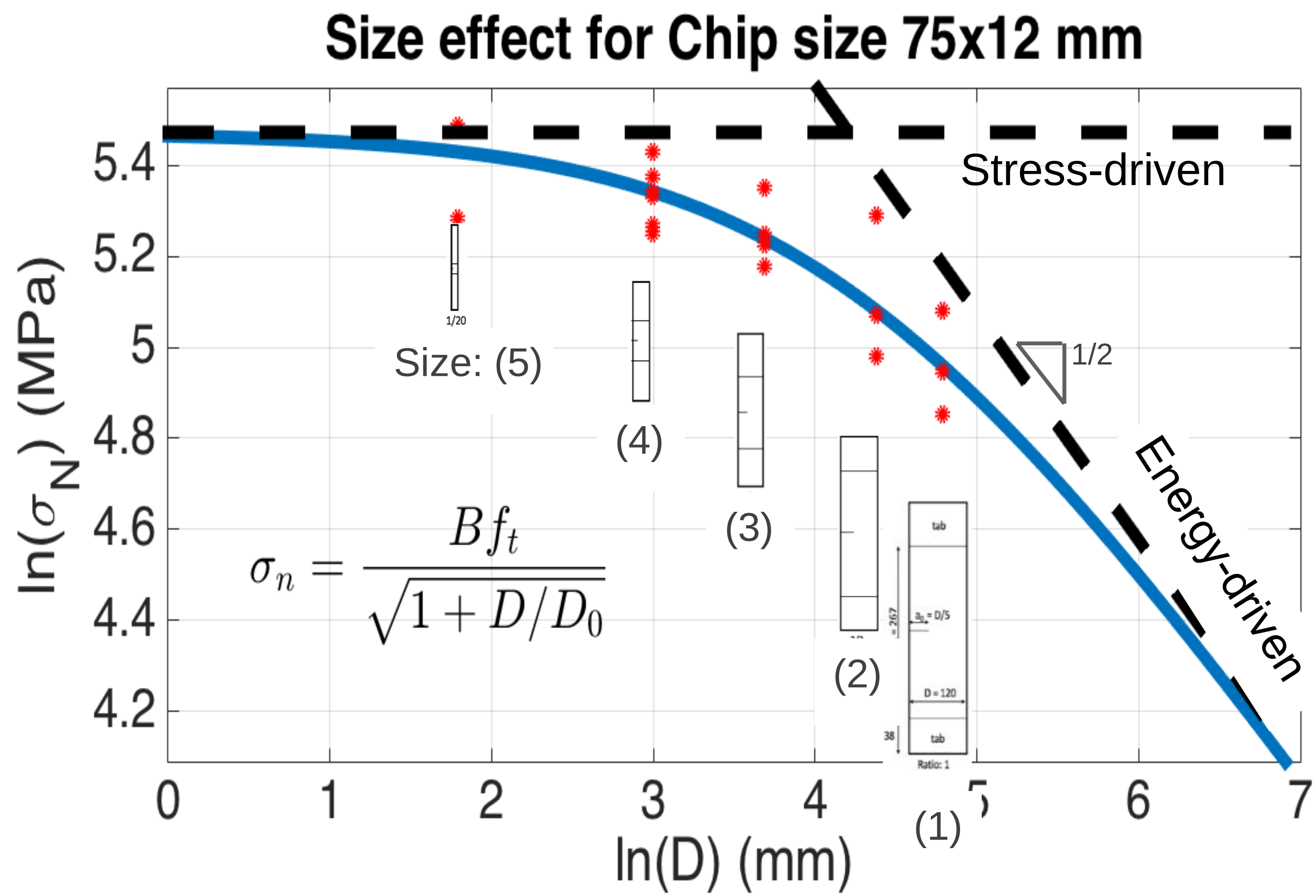
Thickness effect test:

Thickness variables	**1, 2, 4 (mm)**
Fixed chip size	50 x 8 (mm)
Coupon size variables	343 x 120, 254 x 80, 165 x 40, 120.5 x 20, 90 x 6.3 (mm)
Number of coupons in each variables	6
Total number of coupons	90

Preliminary results: size effect plot

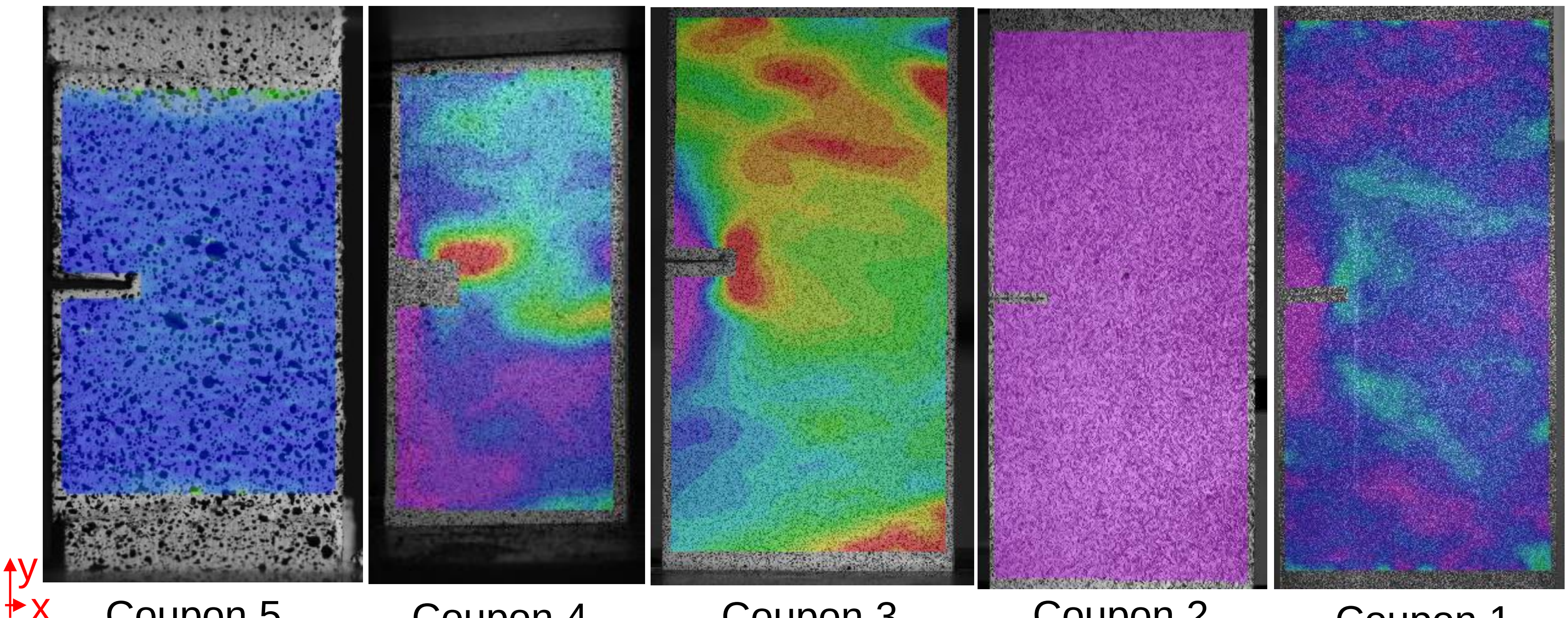


Preliminary results: 75 x 12 mm platelets



DIC data for the 75 x 12 mm case

Max principal strain



Coupon 5 (width 6.3 mm) | Coupon 4 (width 20 mm) | Coupon 3 (width 40 mm) | Coupon 2 (width 80 mm) | Coupon 1 (width 120 mm)

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:

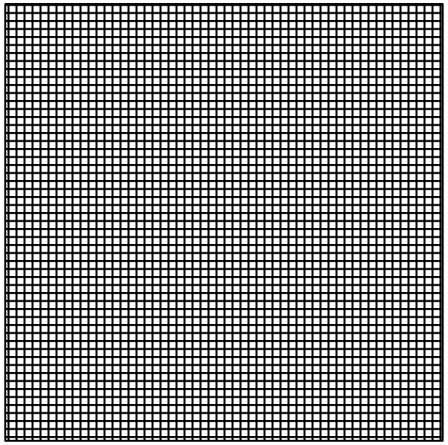
$$G_f(\alpha) = \frac{\sigma_N^2 D}{E^*} g(\alpha) = \frac{\sigma_N^2 D}{E^*} g(\alpha_0 + c_f/D) \qquad \begin{array}{r} \alpha = a/D \\ E* = \text{effective modulus} \\ g = \text{dimensionless energy release rate} \end{array} \tag{2}$$

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

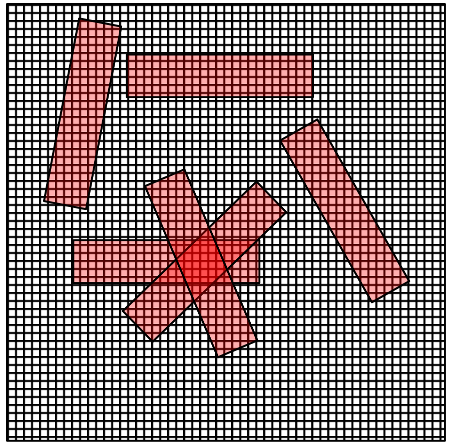
$$\boxed{\sigma_N = \sqrt{\frac{E^* G_f}{Dg(\alpha_0) + c_f g'(\alpha_0)}}} \tag{3}$$

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

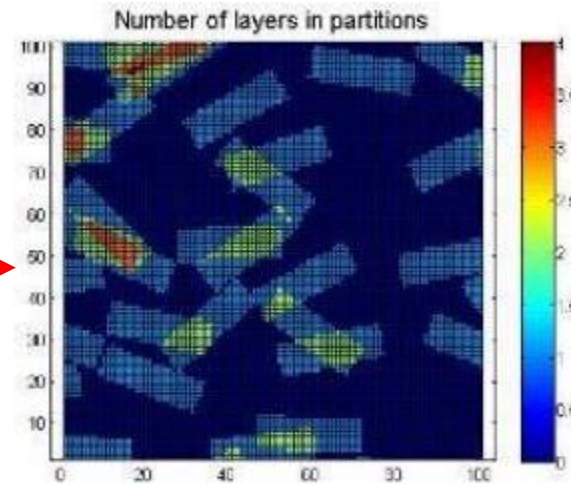
Calculation of g and g': microstructure generation



partition generation

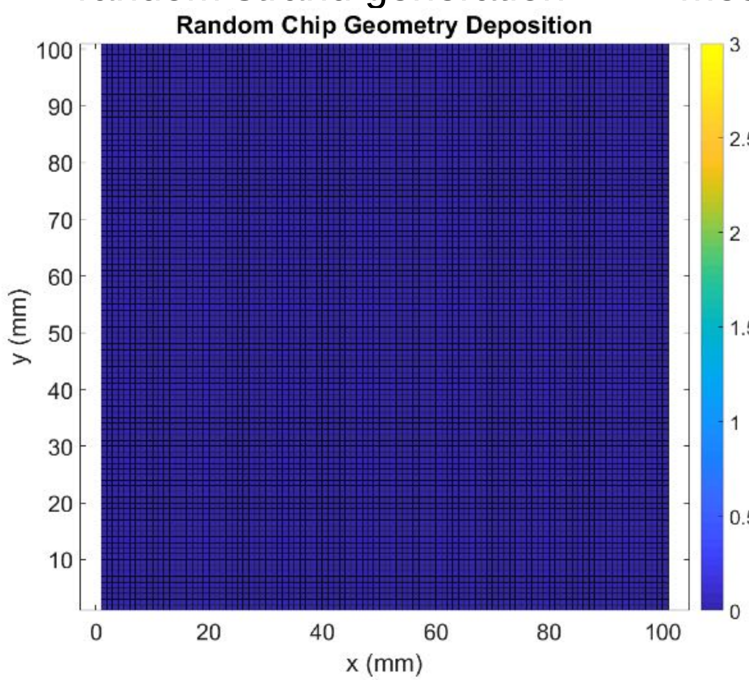


random strand generation

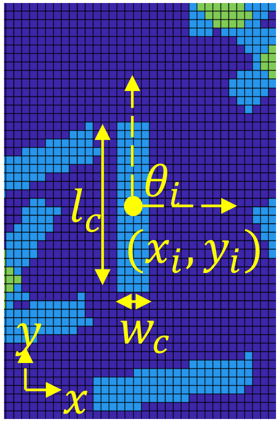


meshing with shell elements

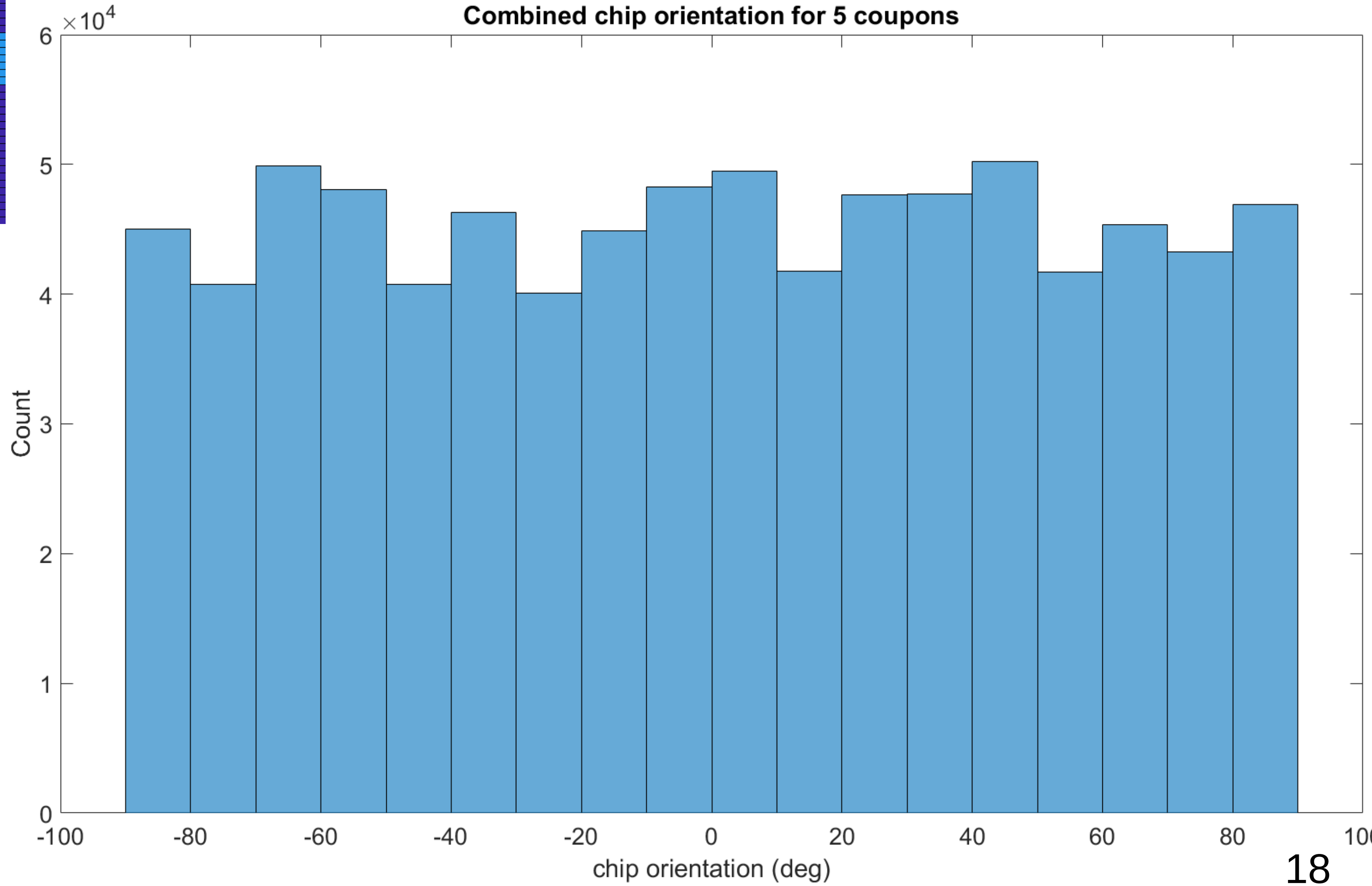
Example of typical layer distribution



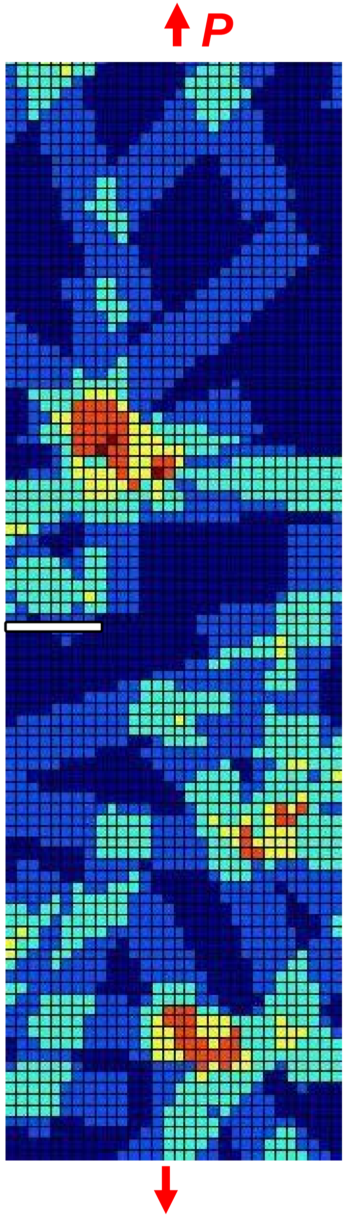
Platelet orientation distribution



Uniform or any other distribution can be assumed



Calculation of g and g'



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

$$G = \frac{\sigma_N^2 D}{E^*} g(\alpha) \qquad \sigma_N = P/(tD) \qquad \begin{array}{l} P = \text{applied load} \\ t = \text{thickness} \end{array} \qquad D = \text{width}$$

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

$$G(P,a) = \frac{1}{t}\left(\frac{\partial \Pi^*(P,a)}{\partial a}\right)_P \approx \frac{1}{t}\frac{\Pi^*(P,a+\delta a/2) - \Pi^*(P,a-\delta a/2)}{\delta a}$$

$\Pi^* =$ total complementary strain energy in the structure

Then g and g' can be calculated from G:

$$\boxed{g(\alpha) = \frac{GE^*}{\sigma_N^2 D}} \qquad \alpha = a/D$$

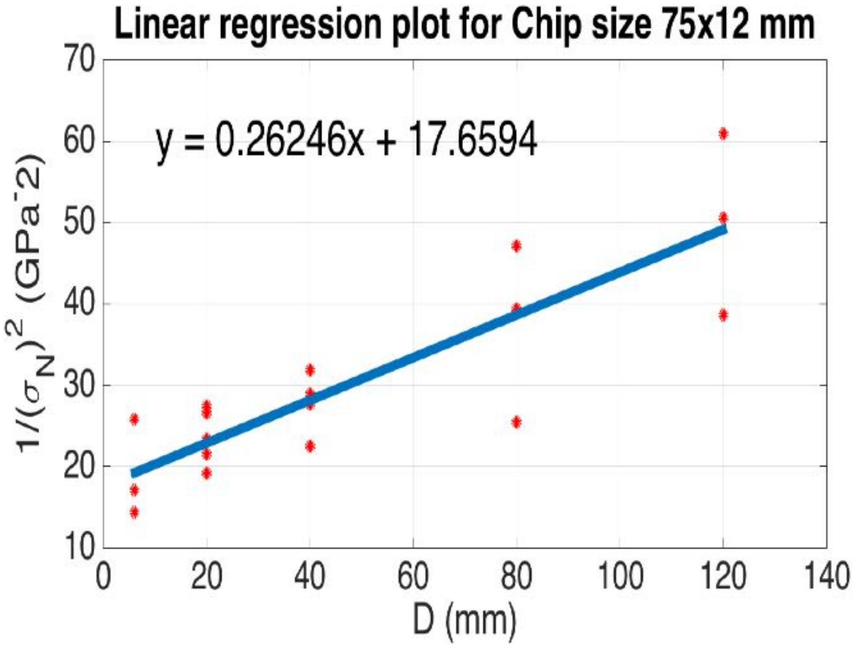
g accounts both for the geometry and microstructural effects

Estimation of Fracture Energy from Size Effect

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

Linear Regression Analysis:

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



$a_t \approx 10$ mm

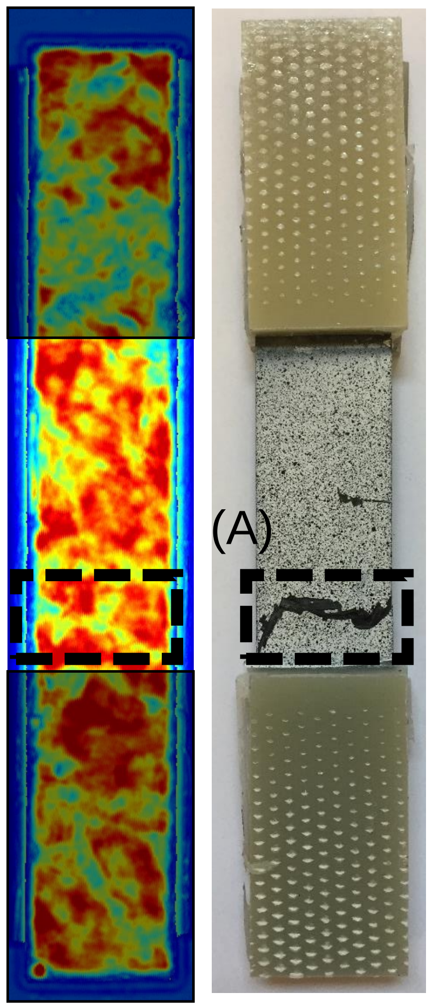
$G_f \approx 77$ N/mm

about 9 times larger than Al 7075!

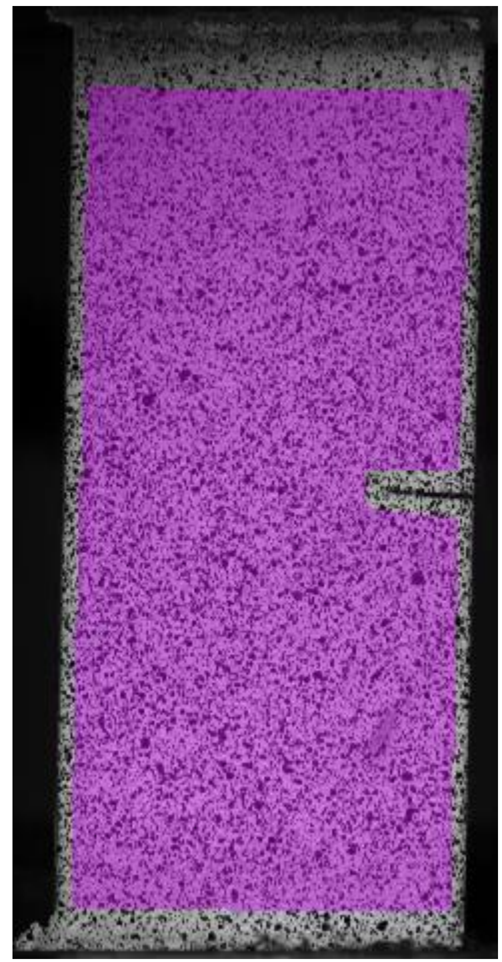
Ongoing and Future Work

Analysis of morphology and fracture analysis

C-Scan



Size 4 (width = 20mm)

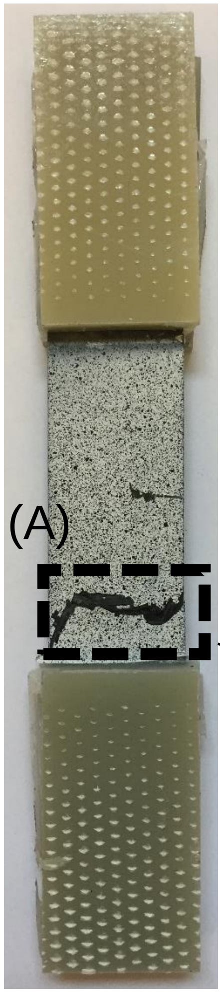


DIC in Eyy

Ongoing and Future Work

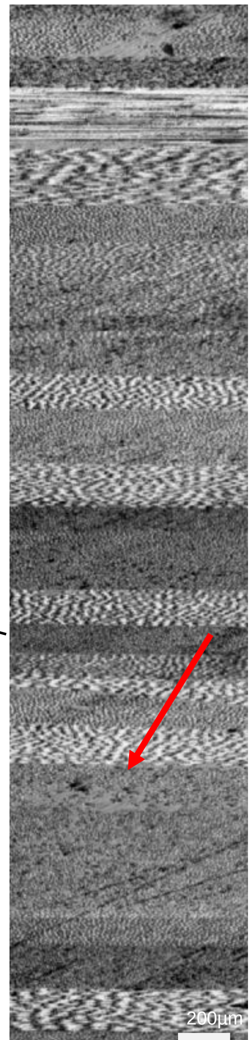
Analysis of morphology and fracture analysis

(A)



Optical microscope

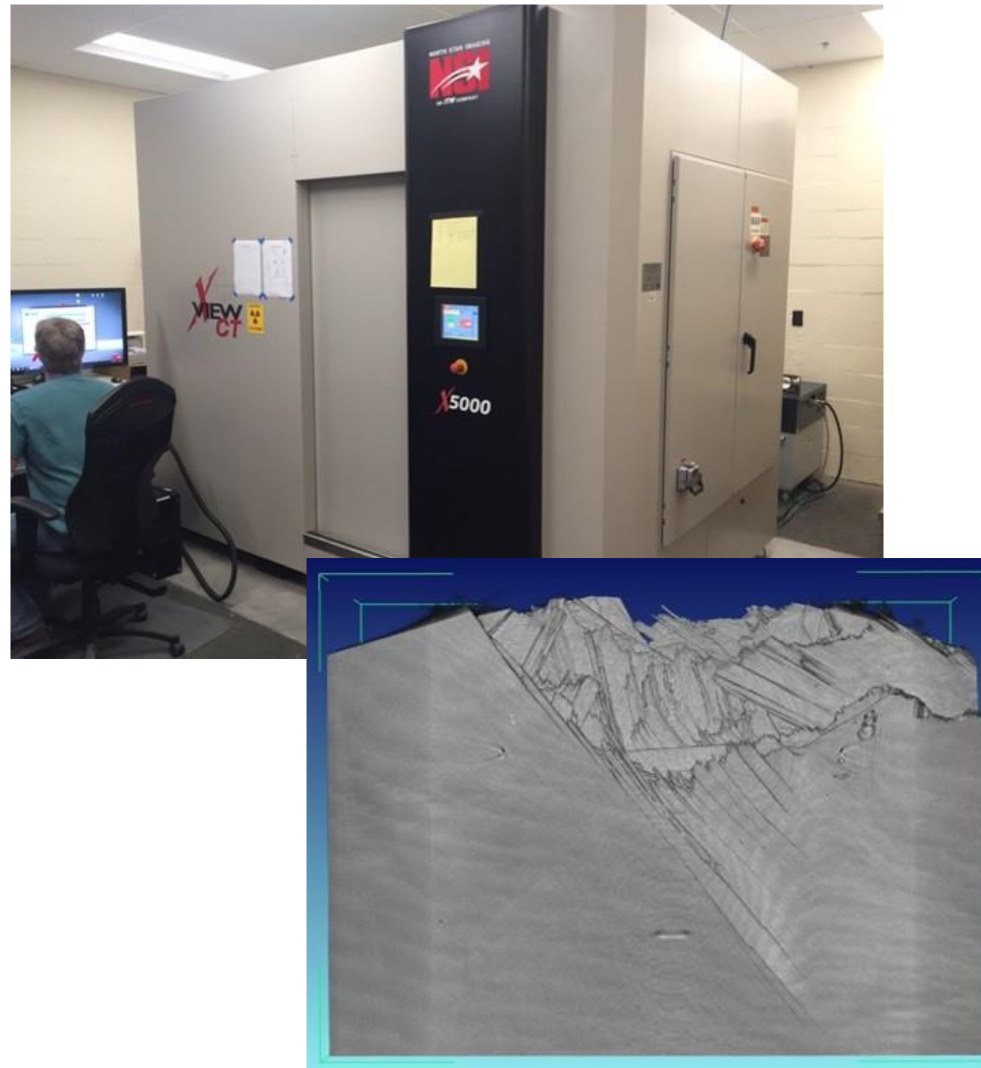
(A)



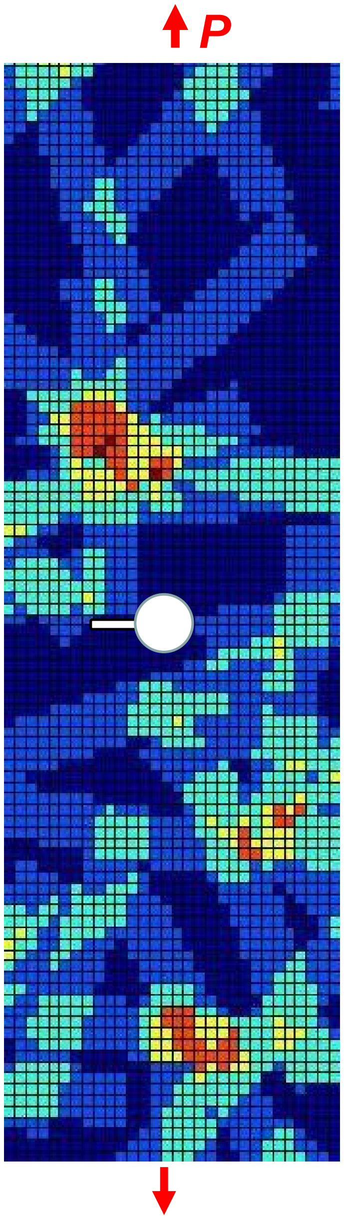
θ

Resin pocket

Micro Computed Tomography



Ongoing and Future Work



Prediction of fracture onset for other configurations

1) By Size Effect law with updated g ang g'

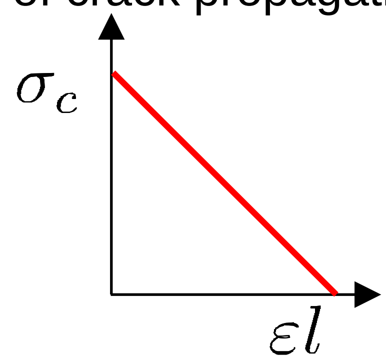
$$\boxed{\sigma_N = \sqrt{\frac{E^* G_f}{D g(\alpha_0) + c_f g'(\alpha_0)}}}$$

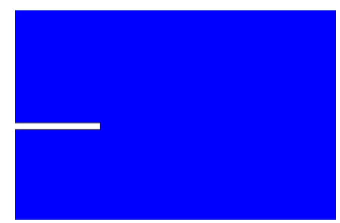
2) By Cohesive Zone Modeling of crack propagation

$$G_f = w_f / th$$

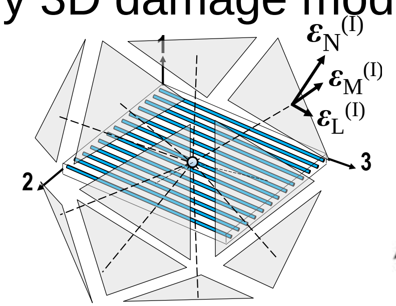
w_f = work of fracture

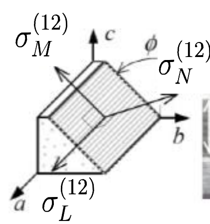
h = element width

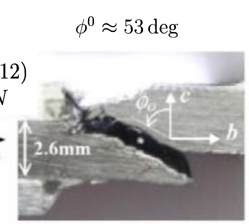


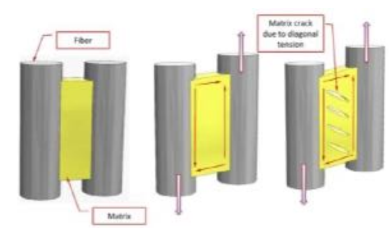


3) By 3D damage model with 3D description of the mesostructure







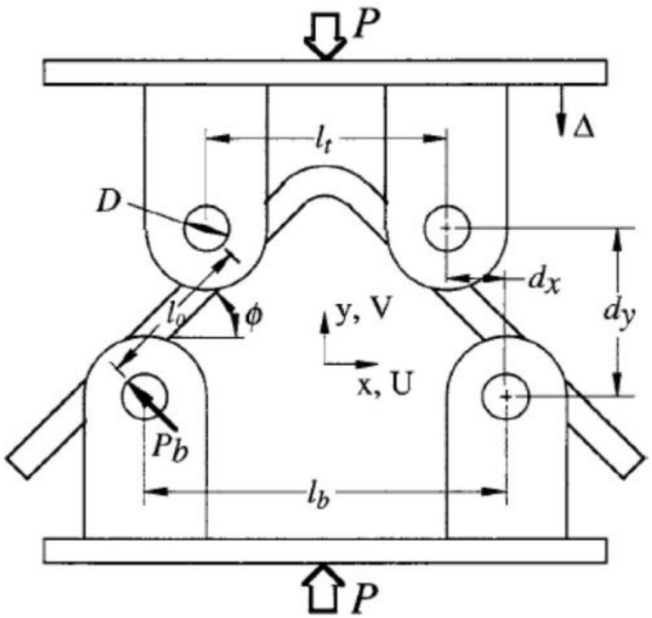


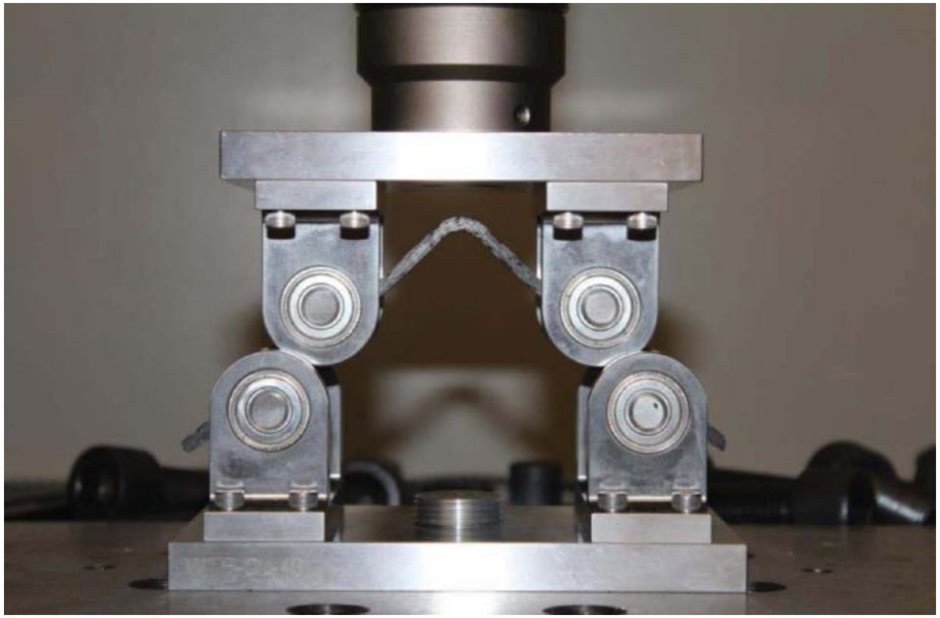
Ongoing and Future Work

Analysis of damage in curved beams

- **Curved beam testing**

Comprehensive experimental campaign on curved beam specimens with various thicknesses





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