Certification of Discontinuous Composite Material Forms for Aircraft Structures

Federal Aviation Administration

Presented by:

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JAMS

Joint Centers of Excellence for Advanced Materials

UNIVERSITY of WASHINGTON

A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

CECAM center of excellence for composites and advanced materials

JAMS Technical Review

September 29th, 2021

Research Team

UNIVERSITY of WASHINGTON

U. of Washington:

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Motivation for DFCs: Part Complexity, Productivity, & Cost-efficiency

Aviationweek.com

Avstop.com

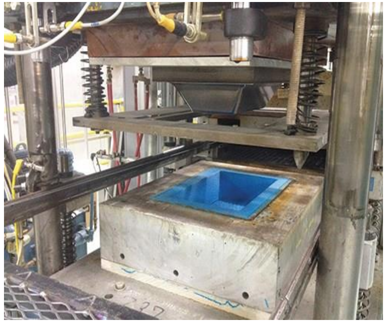
compositestoday.com

Made of composites at a cost lower than metal?

Aviationweek.com

Discontinuous Fiber Composites (DFCs)

Platelets-based composite



Compression molding

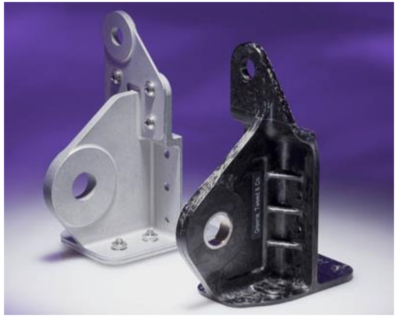
Large volume manufacturing

Hexcel

Recyclability

Nutt, 2014, CAMX

Part Complexity

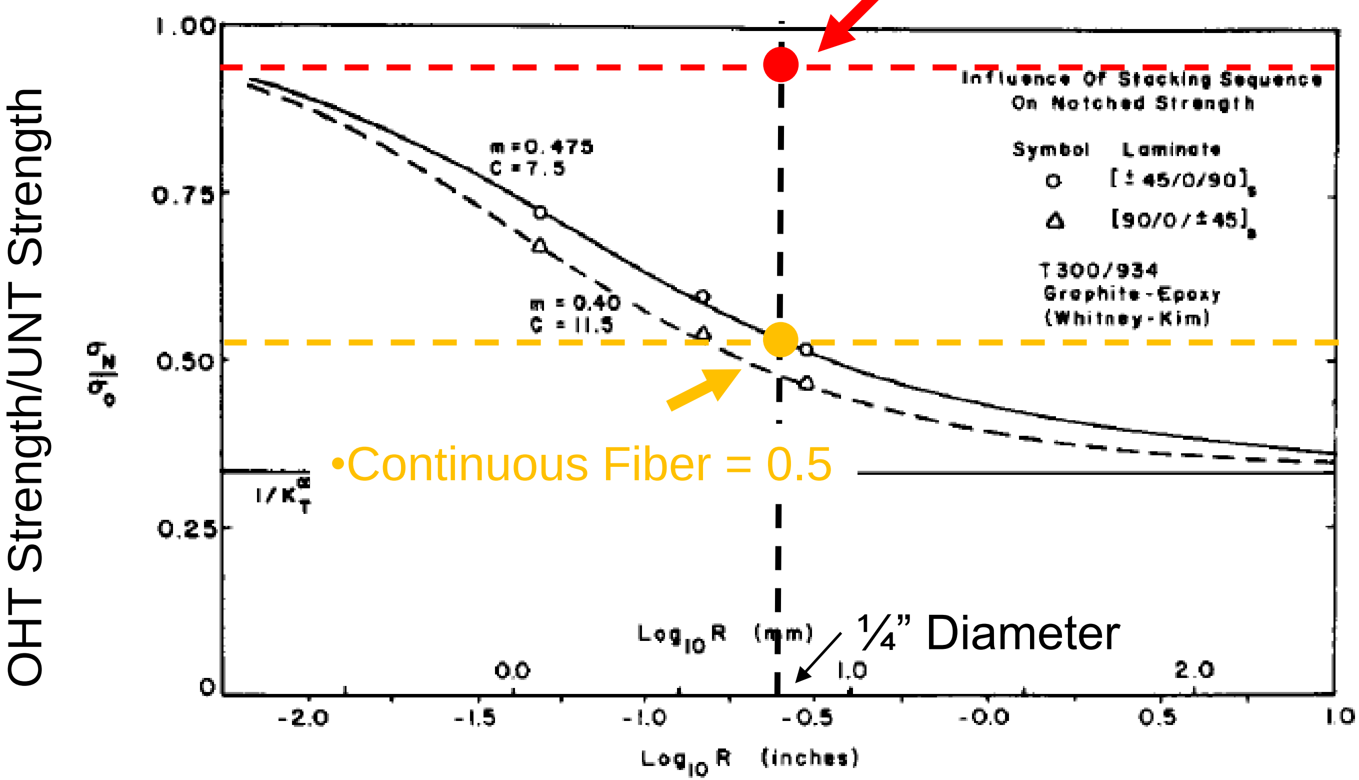


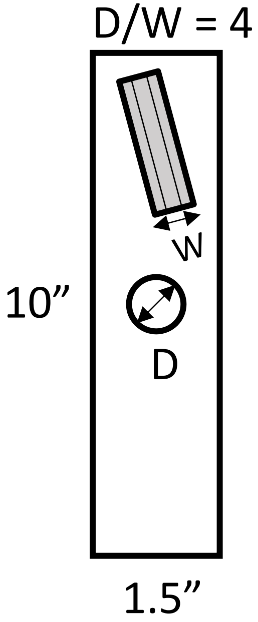
Greene Tweed

DFCs are remarkably damage tolerant

QI/T300

•[Pipes, Wetherhold, Gillespie 1978 JCompMat]





The knockdown factor for DFCs is only 8% while for UD is more than 50%

Project Goal

Enable the widespread adoption of Discontinuous Fiber Composites in the aerospace industry by formulating experimentally and computationally-driven design and certification guidelines

Challenges for DFC – Design Guidelines

Building Block Approach

Part Level

Design Guidance

Coupon Level

Analysis Tools

Proof Testing

Laminate Level

Laminate Stacking Sequence

Fiber properties

Matrix properties

Interface properties

DFC

Random platelets orientations

Platelet geometry

Structure thickness

Void contents

Experiments by UNIVERSITY of WASHINGTON NIAR

Analysis by UNIVERSITY of WASHINGTON

2023

Year 3

- 3D Load bars from Boeing
- Coupon design guidance
- Compressive behaviors

Experiments by UNIVERSITY of WASHINGTON

Analysis by UNIVERSITY of WASHINGTON

2022

Year 2

- Execute experiment plan
- Analyze using the computational tools
- Expand CT-measured platelet orientations

Experiments by BOEING

Analysis by UNIVERSITY of WASHINGTON

2021

Year 1

2020

- Utilize existing data from Boeing
- Develop computational tools
- **Identify knowledge gaps and formulate a comprehensive experiment plan**

2020

Year 1

Experiments by BOEING

Analysis by UNIVERSITY of WASHINGTON

- Utilize existing data from Boeing
- Develop computational tools
- Design 2021 experiment plan

2021

Year 2

Experiments by UNIVERSITY of WASHINGTON

Analysis by UNIVERSITY of WASHINGTON

- Execute experiment plan
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2022

Year 3

Experiments by UNIVERSITY of WASHINGTON NIAR

Analysis by UNIVERSITY of WASHINGTON

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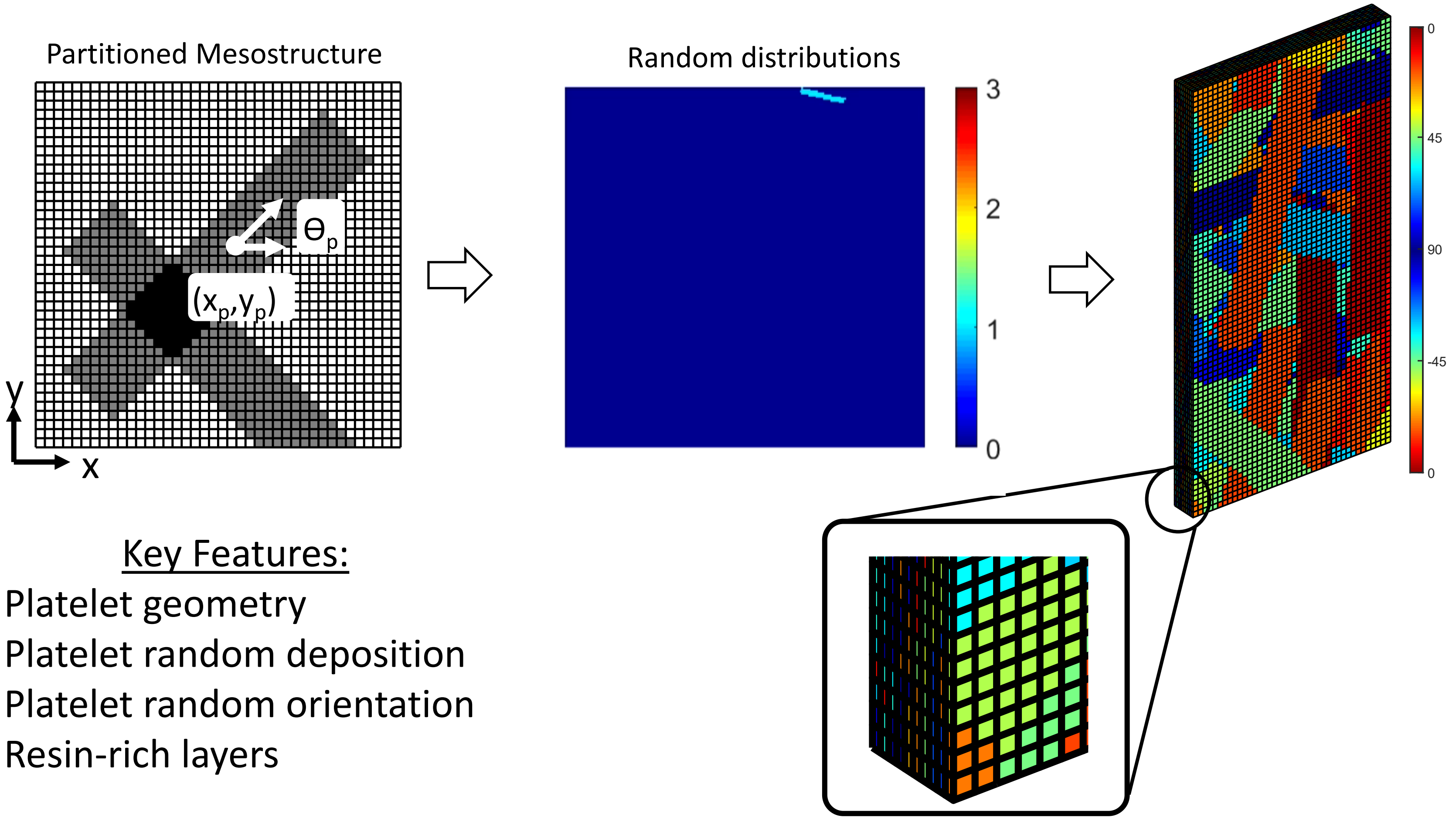
2023

Random Platelet Meso-structure Generation

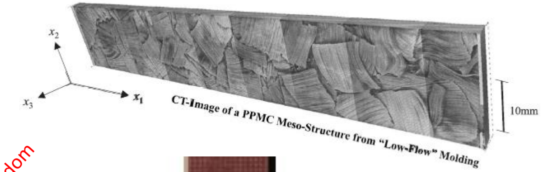


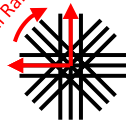
Key Features:

1. Platelet geometry
2. Platelet random deposition
3. Platelet random orientation
4. Resin-rich layers

Implemented spatial variations of the platelet orientations

Kravchenko *PhD Dissertation 2017*





$A_{11} = 0.5$

Xray μCT scan

A_{11} = 0.509

A_{11} = 0.569

A_{11} = 0.627

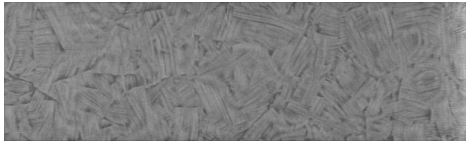
A_{11} = 0.560

A_{11} = 0.492

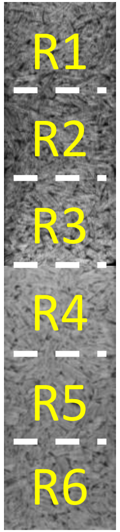
A_{11} = 0.560

A_{11} = Average platelet orientation

UW CT-measured Orientation



Xray μCT scan



A_{11} = 0.505

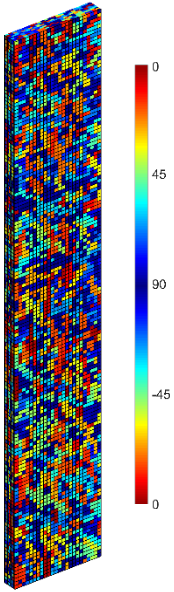
A_{11} = 0.502

A_{11} = 0.518

A_{11} = 0.530

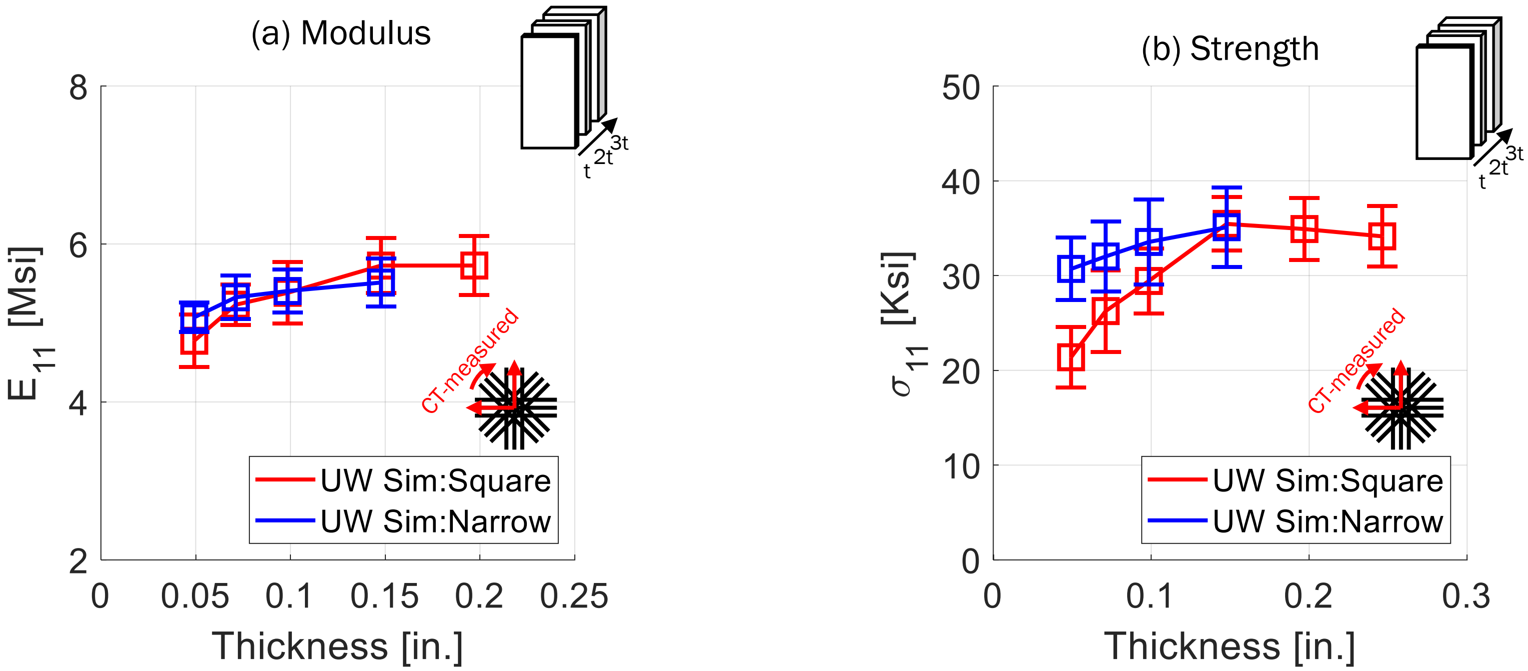
A_{11} = 0.527

A_{11} = 0.533



A_{11} is not always 0.5. They locally varies but the average is close to 0.5.

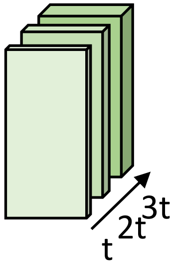
Tensile modulus and strength thickness effect



1. The modulus and thickness difference is minimum at the asymptotic thickness.
2. The thickness effect is stronger for the square platelets below 0.15” thickness.
3. Make sure to test below 0.1 and above 0.25”

Simulation Guided Experimental Plan for 2021

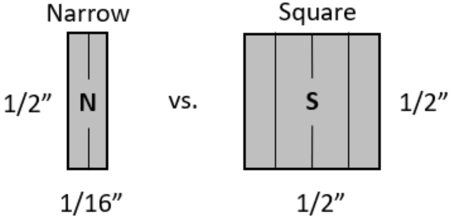
(1) Investigate the coupon thickness effect



data concentrated at thickness 0.15”

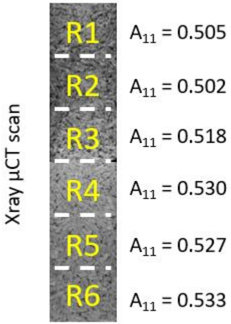
Wide range of thicknesses: 0.065” to 0.25”

(2) Investigate the platelet width effect



(Priority)

(3) Measure the platelet orientations using a µCT scan



Only at thickness 0.15”

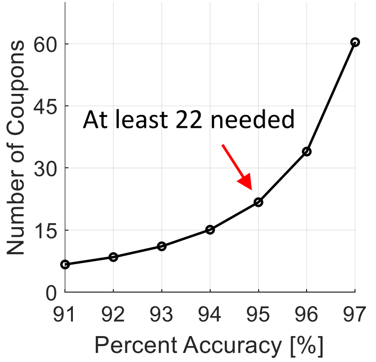
Both platelets
+
all thicknesses

(4) Investigate flow effect

Low flow (flat)

High flow (forks)

(5) Increase the number of tested coupons (up to 30 coupons)



Conclusion (Year 1)

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1. Identified the existing data set and found multiple inconsistency in the data set
    - manufacturing process
    - number of test coupons
    - data only existed for a particular platelet size or thickness.

2. Developed the computational tools
    - Create comprehensive meso-structures is important – **platelet geometry**, **platelet distribution**, **resin-rich volumes**
    - Yet, the model must be computationally efficient.

3. Performed the analysis using the computational tools
    - The thickness effect was strong below 0.25” thickness.
    - CT-measured orientations greatly improved the accuracy of the model.

4. Designed experimental plan for 2021
    - We designed the experimental plan based on computational analysis and missing knowledge gaps
    - Wide range of thickness from 0.065” to 0.25”.
    - Prioritize the narrow platelets but both platelets will be tested.
    - Take CT scans for every test case. The platelet orientations will be extracted.
    - Investigate the flow condition: low and high
    - Increase the number of test coupons up to 30.
    - Manufacturing consistency is guaranteed by Sekisui.

Experiments by UNIVERSITY of WASHINGTON NIAR

Analysis by UNIVERSITY of WASHINGTON

2023

Year 3

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- Compressive behaviors

Experiments by UNIVERSITY of WASHINGTON

Analysis by UNIVERSITY of WASHINGTON

Year 2

2022

- Execute experiment plan
- Analyze using the computational tools
- Expand CT-measured platelet orientations

Experiments by BOEING

Analysis by UNIVERSITY of WASHINGTON

2021

Year 1

2020

- Utilize existing data from Boeing
- Develop computational tools
- Design 2021 experiment plan

Experiment in progress (90% completed)

Single fracture

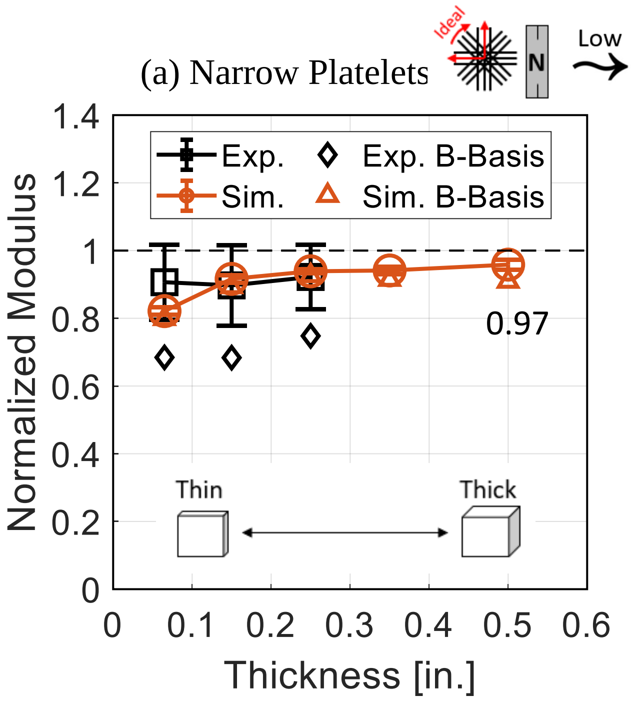
Narrow Platelets	Low Flow (Square Panels)		High Flow (Fingers)	
Thickness [In.]	UNT	OHT	UNT	OHT
0.065	17/22	-	-	-
0.15	33/33	30/35	15/15	7/12
0.25	33/33	30/35	-	-

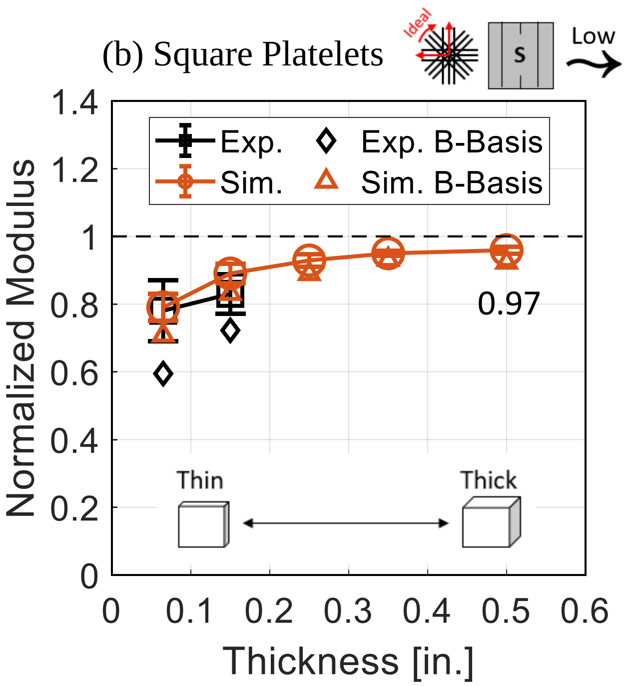
Square Platelets	Low Flow (Square Panels)		High Flow (Fingers)	
Thickness [In.]	UNT	OHT	UNT	OHT
0.065	15/20	-	-	-
0.15	30/30	30/30	15/15	7/12

Completed	Waiting for CT Scans	Boeing Data

* Current progress: 237/267 coupons = 90%

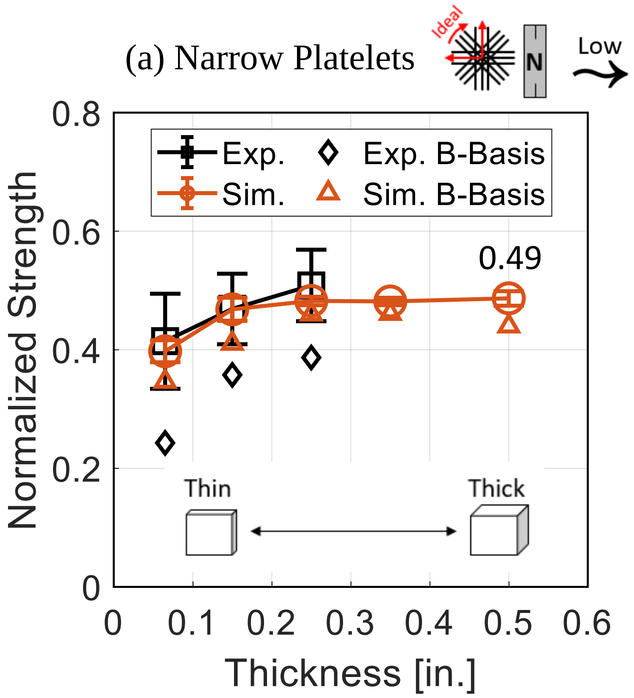
Thickness effect in low-flow coupons: Tensile modulus

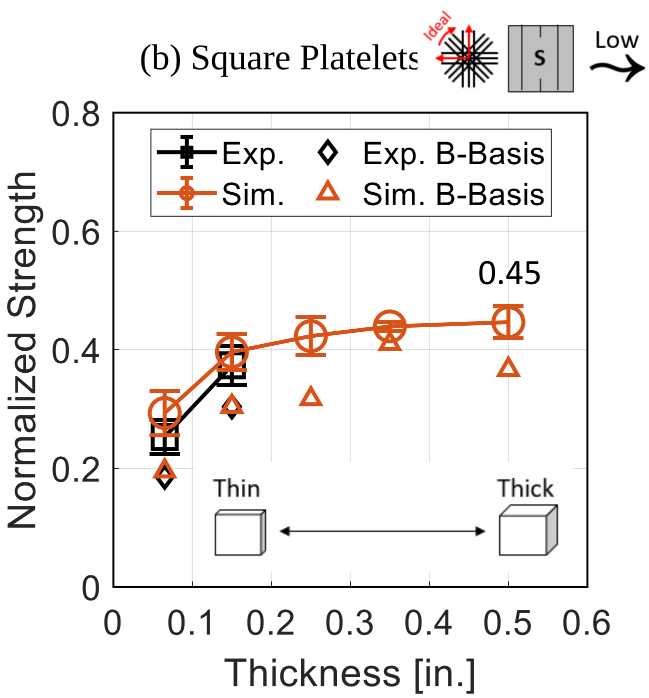




- Using the ideal random orientations, the model precisely captures the thickness effect.
- After 0.25” (45 layers) thickness, the difference between the narrow and square is negligible.
- The model underestimates the variations.

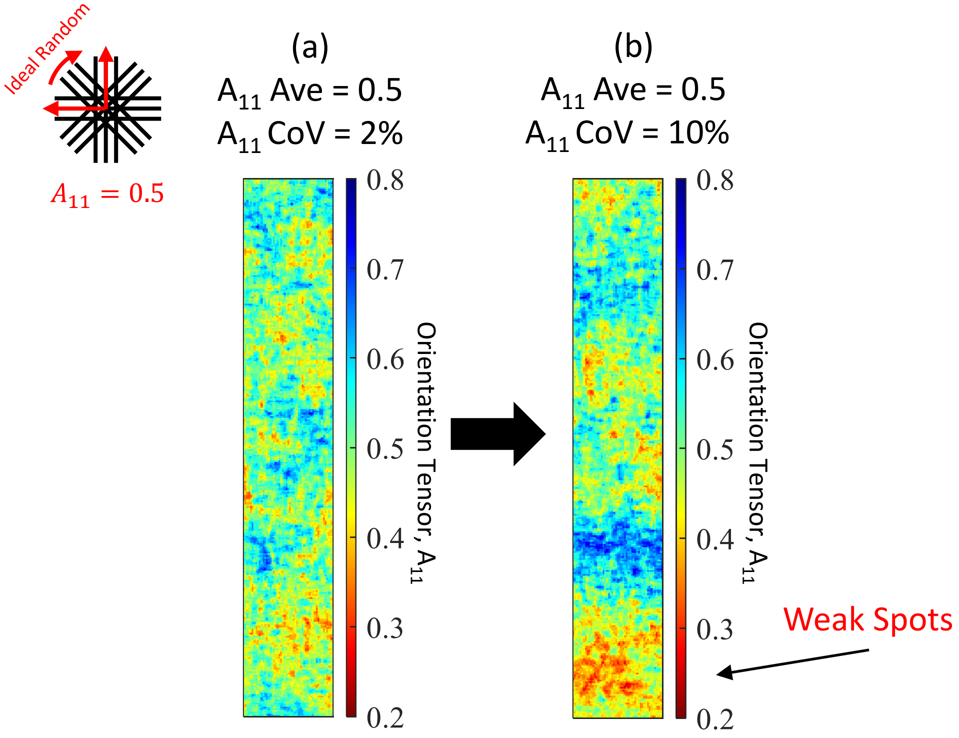
Thickness effect in low-flow coupons: Tensile strength

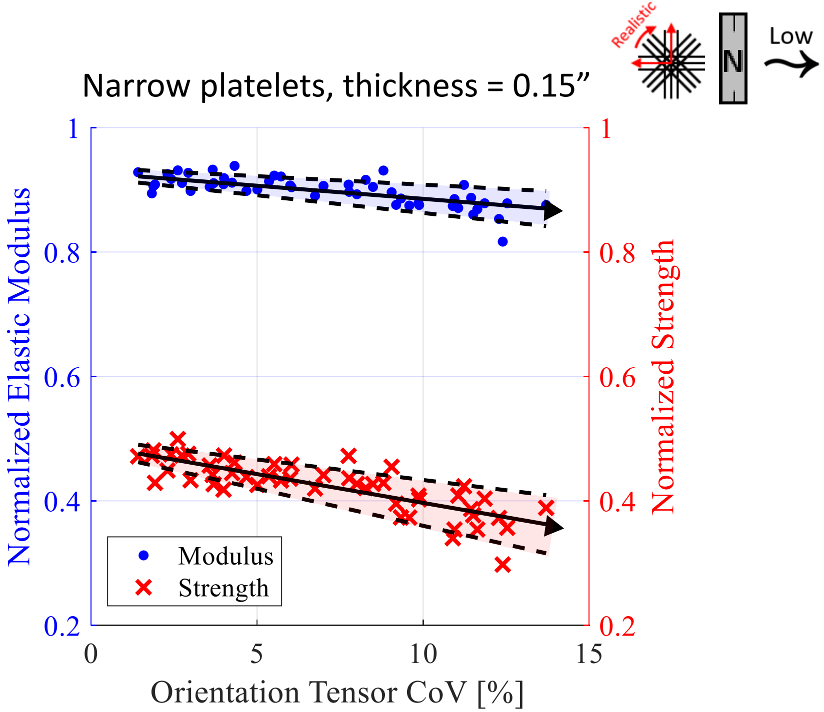




- Using the ideal random orientations, the model precisely captures the thickness effect.
- After 0.25” (45 layers) thickness, the difference between the narrow and square is only 7%.
- The model underpredicts the variations.

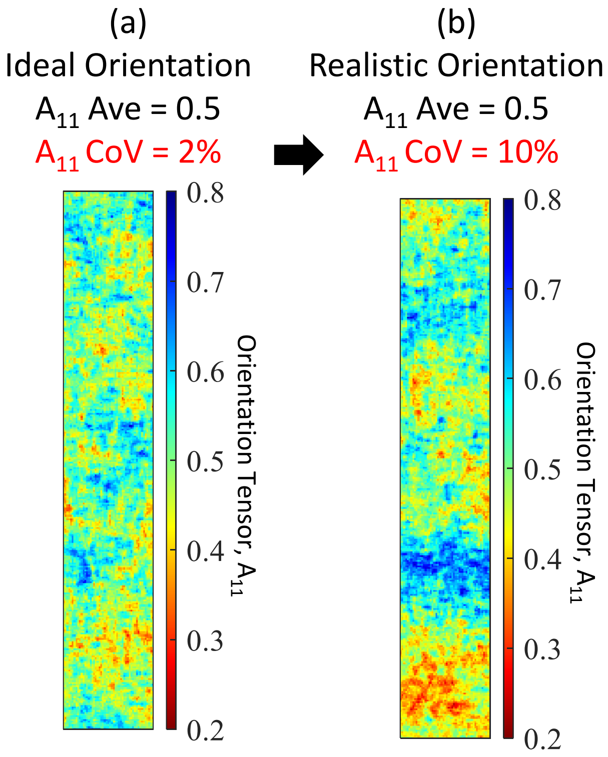
Meso-structure Characteristic 1: Orientation variations

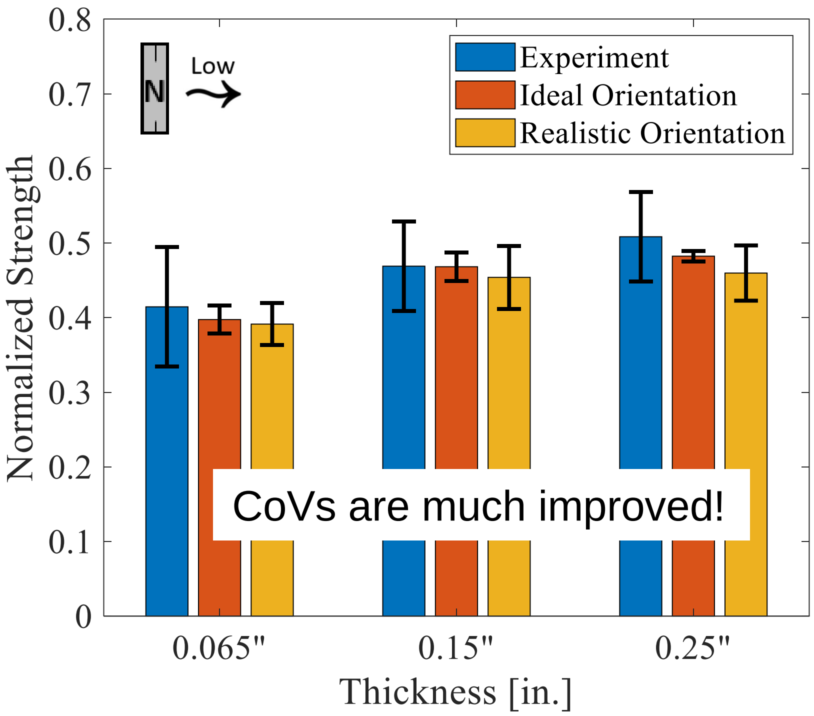




- Higher variations in the orientations decrease the average modulus and strength.
- Higher variations in the orientations increase the CoV of the modulus and strength.

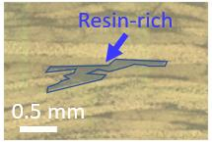
Meso-structure Characteristic 1: Orientation variations



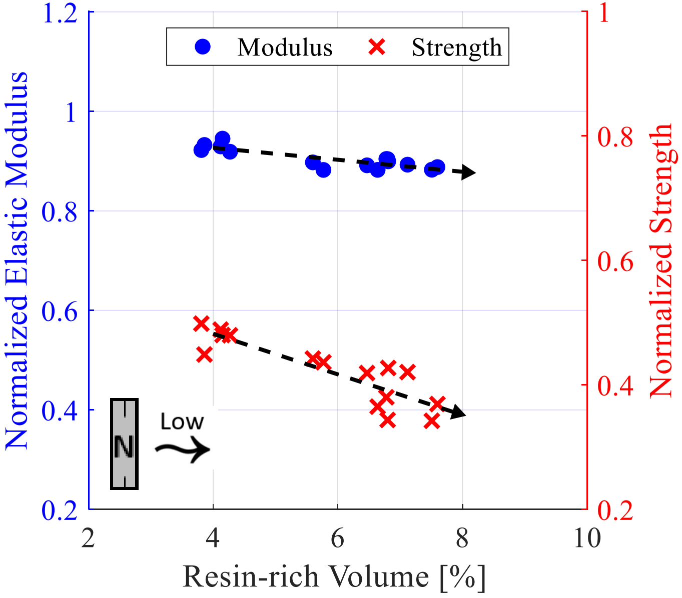


When the meso-structures are calibrated, the strength CoV is improved, closer to the experimental values (on-going work).

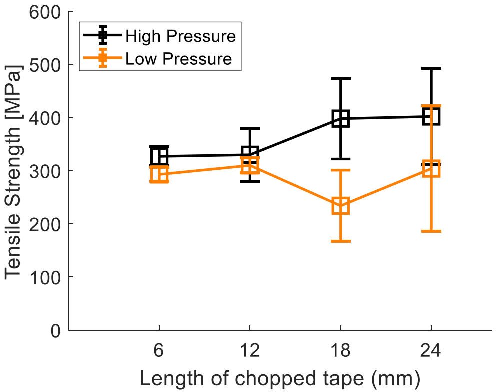
Meso-structure Characteristic 2: Resin-rich layers

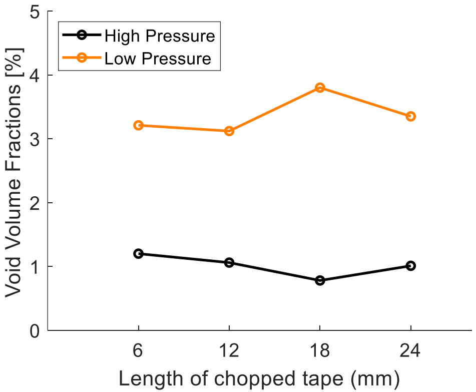


Narrow, thickness = 0.15”
Average A_{11} = 0.5



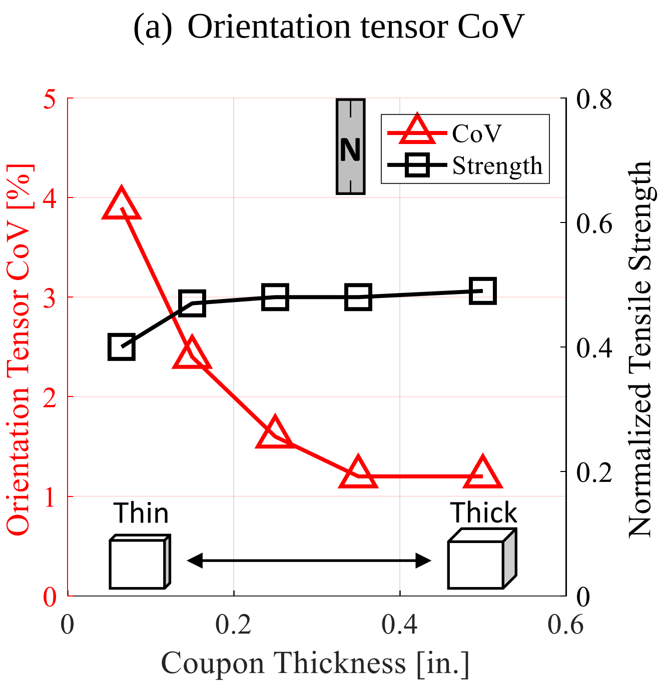
Changing manufacturing process affects the tensile strength.
↓ Pressure, ↑ Void volume, ↓ Strength [Wan, 2016, CompA]

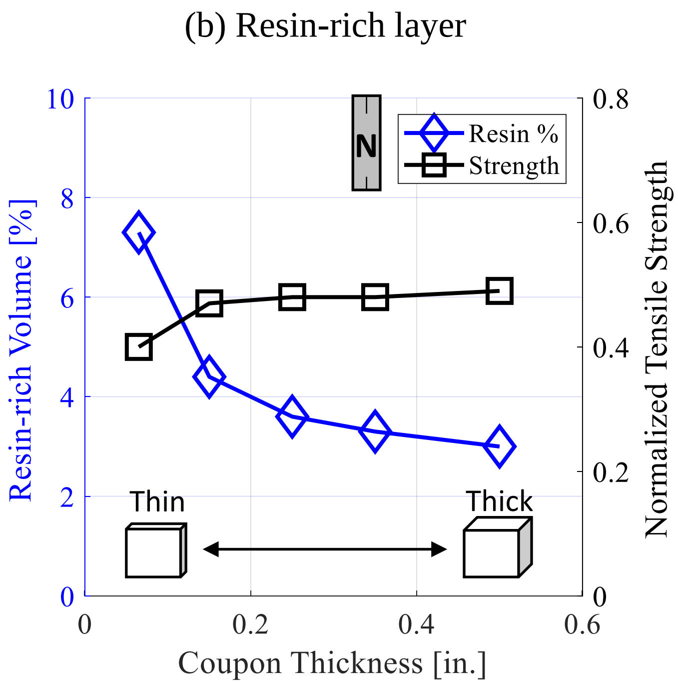




Significant effect! We must control the manufacturing process precisely, then we can reduce the effects of the resin-rich volume percentage!

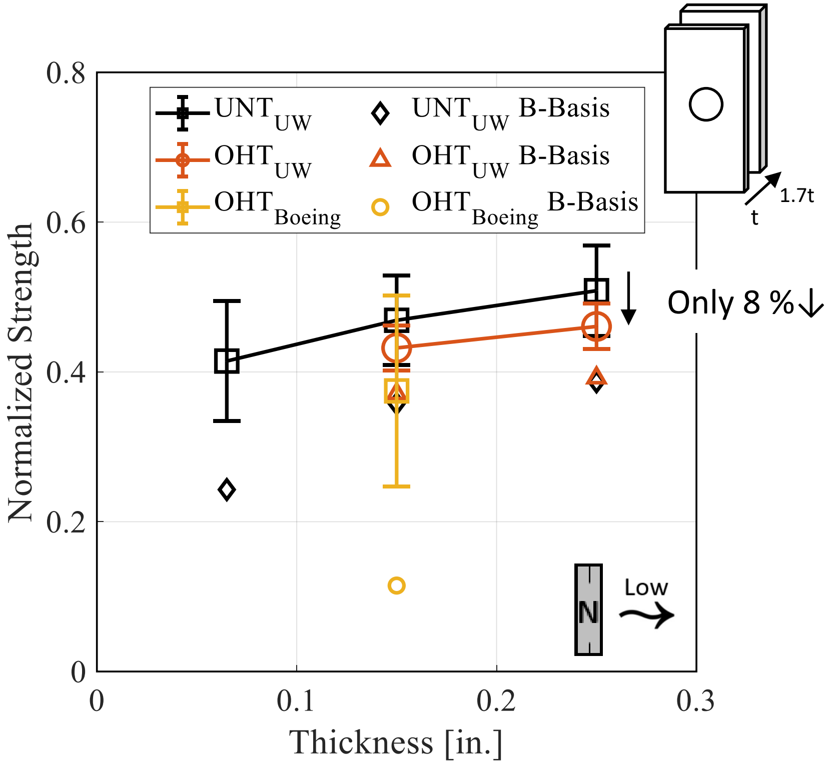
Structure thickness effect





- The thickness effect is a combination of resin-rich volume and orientation variations.
- Thicker coupons reduce both the resin-rich volume and the orientation CoV.

Open-Hole Tension (OHT) thickness effect (experimental)

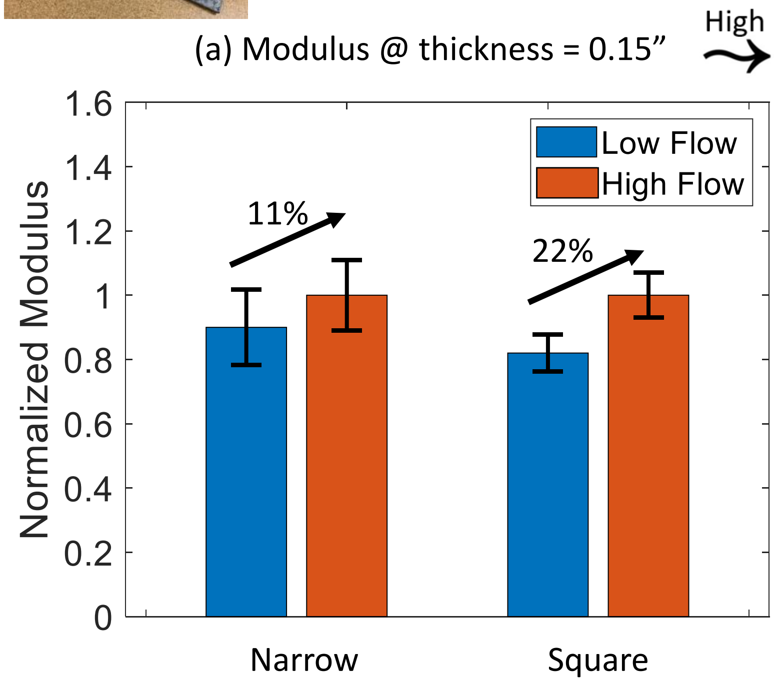


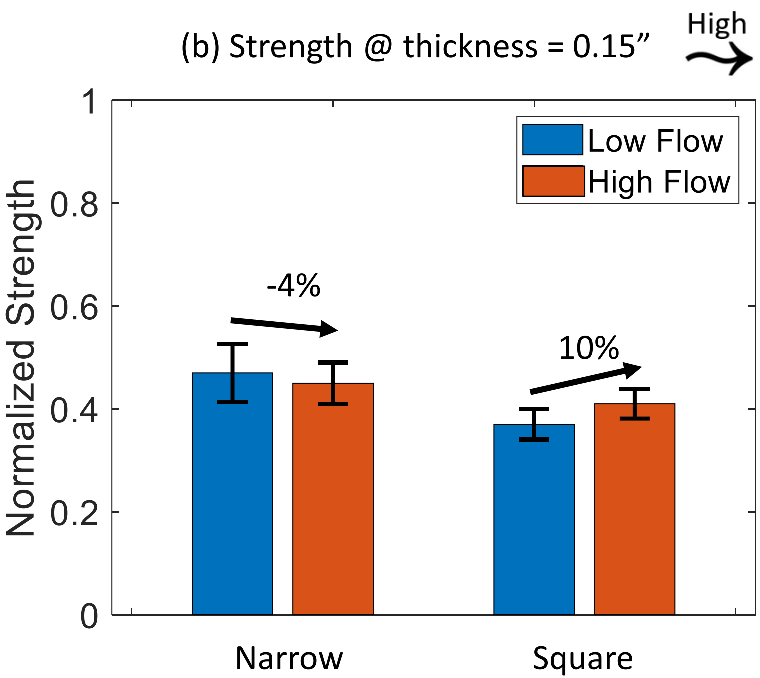
Test Type (N. of coupons)	CoV
UW – UNT (33)	13 %
UW – OHT (35)	6.9 %
Boeing – OHT (6 + 6)	34 %

CoV changes significantly with the number of test coupons

- Thickness effect exists in OHT (7% increase for the narrow platelets).
- OHT strength CoV is about a half of UNT strength CoV (13% vs. 6.7%).
- The strength reduction due to central hole is only ~ 8% for DFCs.

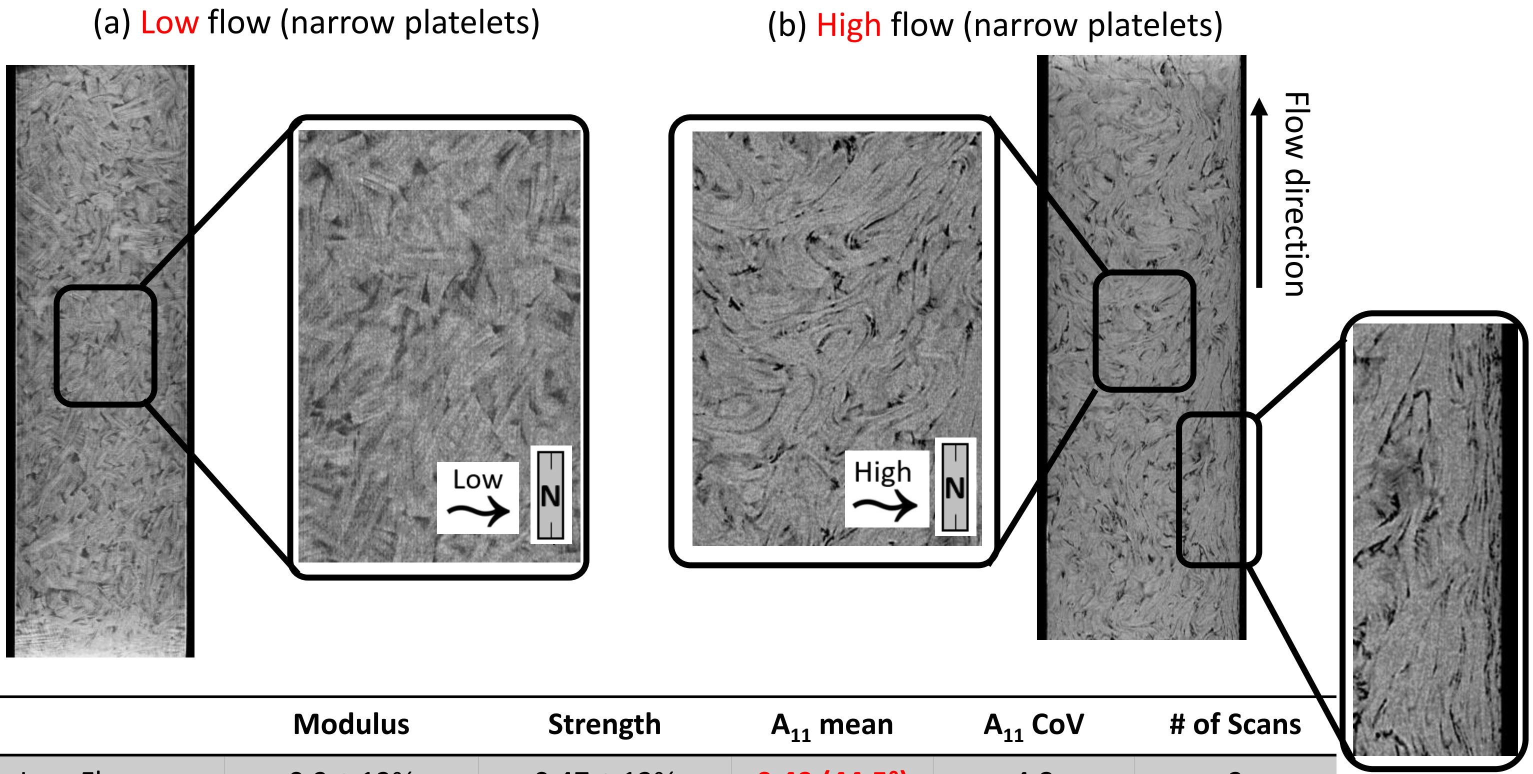
Flow effect in UNT (Experimental)





High flow condition promotes high longitudinal moduli due to favorable platelet orientations but hard to make conclusion on the strength. We may need larger number of test coupons.

Flow effects in the Narrow platelets

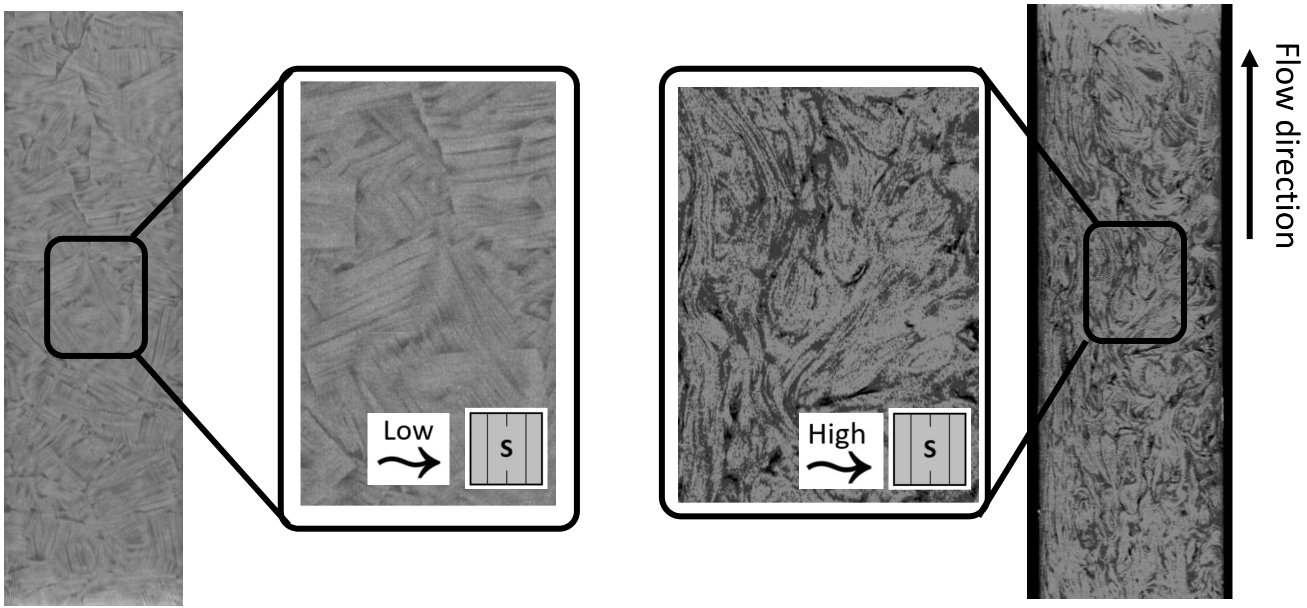


	Modulus	Strength	A_{11} mean	A_{11} CoV	# of Scans
Low Flow	0.9 ± 13%	0.47 ± 12%	**0.49 (44.5°)**	4.8	3
High Flow	1.0 ± 11%	0.45 ± 9%	**0.63 (52.5°)**	5.8	5
Perc. Increase [%]	11%	-4%	**29%**	-	-

Flow effects in the Square platelets

(a) Low flow (square platelets)

(b) High flow (square platelets)

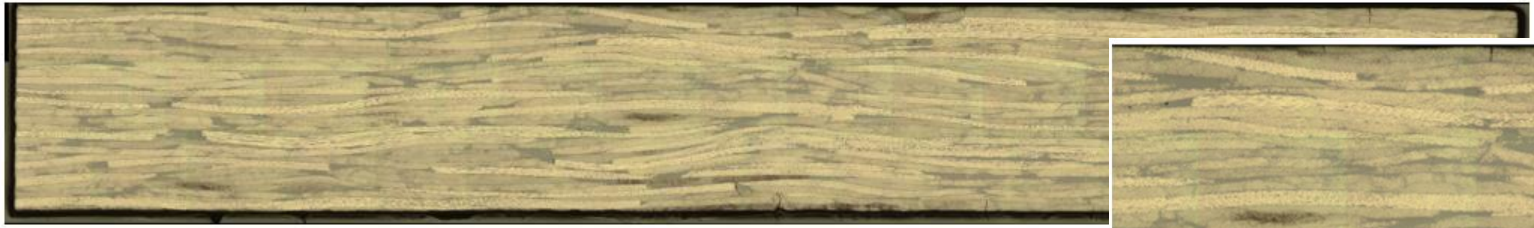


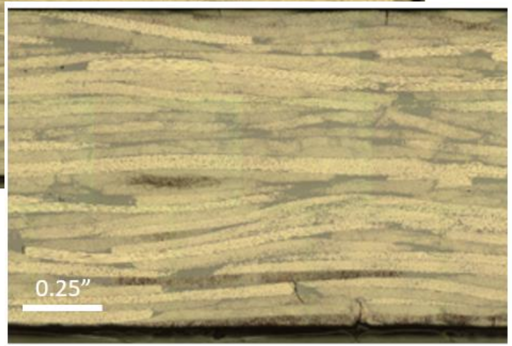
	Modulus	Strength	A_{11} mean	A_{11} CoV	# of Scans
Low Flow	0.82 ± 7.0%	0.37 ± 8%	**0.49 (44.5°)**	9.2	5
High Flow	1.0 ± 7.0%	0.41 ± 7%	**0.62 (51.9°)**	7.7	5
Perc. Increase [%]	22%	10%	**27%**	-	-

Significant increase of void contents in the high flow coupons

(a) Low flow (narrow platelets), Void contents ≈ 0.6 %

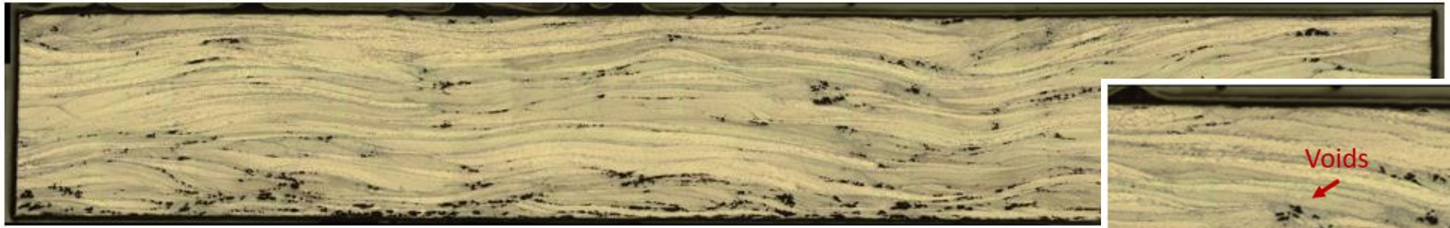
0.15”

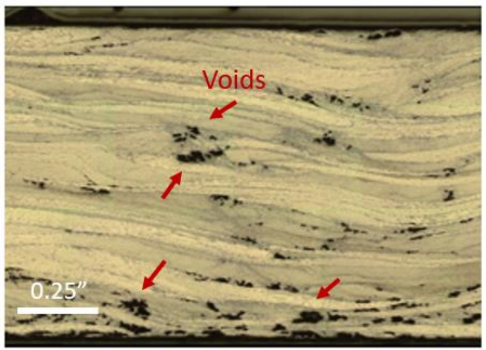




(b) High flow (narrow platelets), Void contents ≈ 3.0 %

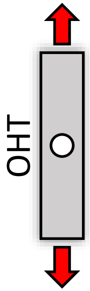
0.15”



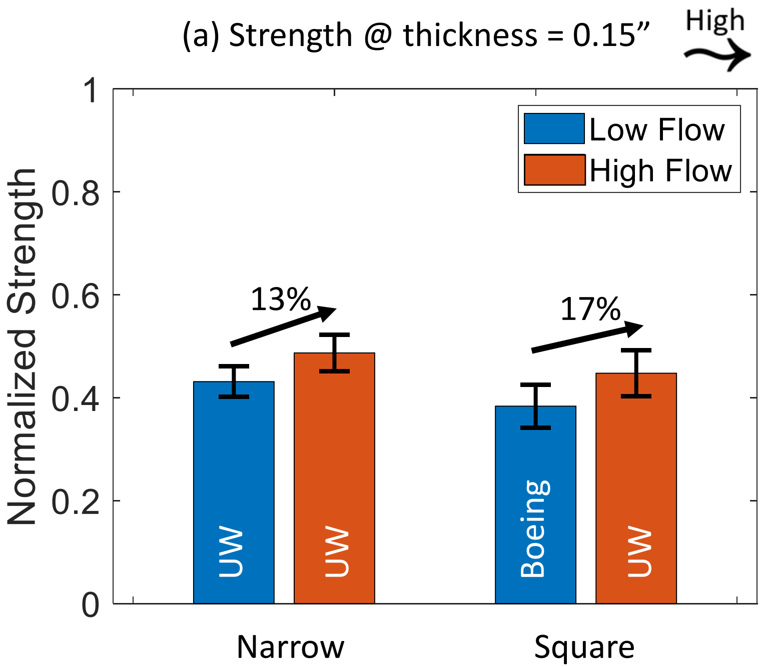


- Significantly increased void contents in high flow coupons.
- The void contents counteracts the favorable orientation tensors.

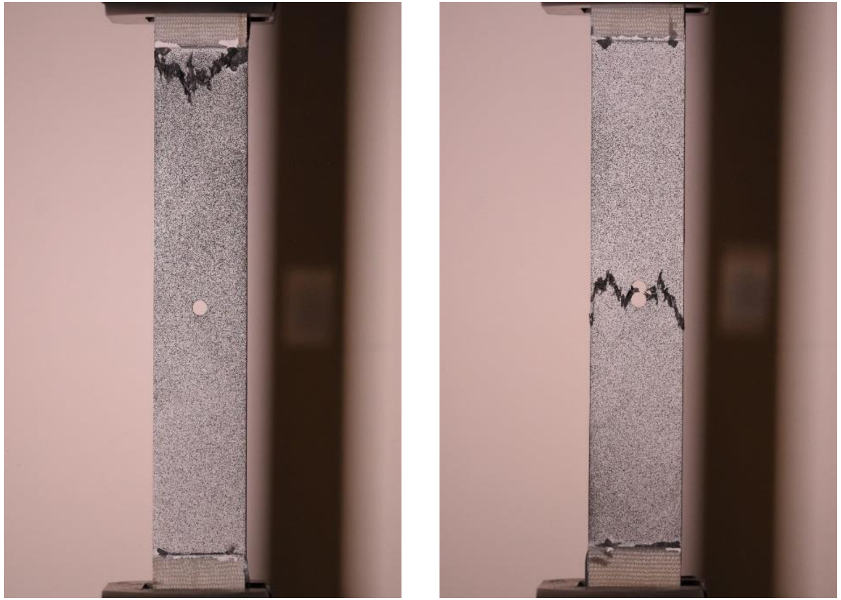
Flow effect in OHT (Experimental)



(a) Strength @ thickness = 0.15”



(b) Failure locations in OHT



Failure away from the hole

- **Narrow platelets: 16% (low flow) → 0% (high flow)**
- **Square platelets: 73% (low flow)→ 20% (high flow)**

High flow condition increases the OHT strength but also promotes deterministic failure at the central hole.

Conclusion (Year 2)

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1. Executed experimental plan
   - Large number of coupons guaranteed statistically meaningful data. Use normal distribution for the modulus and Weibull distribution for the strength.
   - The tensile strength had stronger thickness effect than the tensile modulus (24 % vs. 1% increase).
   - The narrow platelets were stronger than the square platelets (27% at thickness = 0.15”) but they also had higher variations (13% vs. 9%).
   - The strength reduction due to the central hole was significantly lower than the quasi-isotropic layup (8% vs. 50%)
   - The high flow condition increased the modulus significantly (10 - 20%) but did not affect the strength.

2. Measured platelet orientations using the CT scanner
   - We confirmed that the CT-measured orientations significantly improved the simulation results.
   - We need further investigations on taking CT scans of low thickness coupons due to high warpage.
   - The high flow condition increased the average orientation by 30% but also induced large void contents.

3. Computationally analyzed mechanisms of DFCs
   - At the asymptotic thickness (above 0.25”), the narrow and square platelets showed minimum differences in their tensile modulus and strength.
   - The platelet width effect was caused by the variations in the platelet orientations. The square platelets had higher percentage of weak spots.
   - The thickness effect was caused by (1) the variations in the platelet orientations and (2) the resin-rich volume. Thicker coupons had lower percentage of weak spots and lower volume of resin-rich area.

Experiment by BOEING

Analysis by UNIVERSITY of WASHINGTON

Year 1

2020

- Utilize existing data from Boeing
- Develop computational tools
- Design 2021 experiment plan

2021

Experiment by UNIVERSITY of WASHINGTON

Analysis by UNIVERSITY of WASHINGTON

Year 2

2022

- Execute experiment plan
- Analyze using the computational tools
- Expand CT-measured platelet orientations

Experiment by UNIVERSITY of WASHINGTON NIAR

Analysis by UNIVERSITY of WASHINGTON

Year 3

2023

- **DOE with NIAR leveraging the lesson learned in year 1 & 2**
- Investigate compression
- Analyze real 3D components

Future Plan

1) Analyze 3D Load bar structure provided by Boeing

(shown image is not the actual part)

2) Tensile coupon (UNT, OHT) design guidance

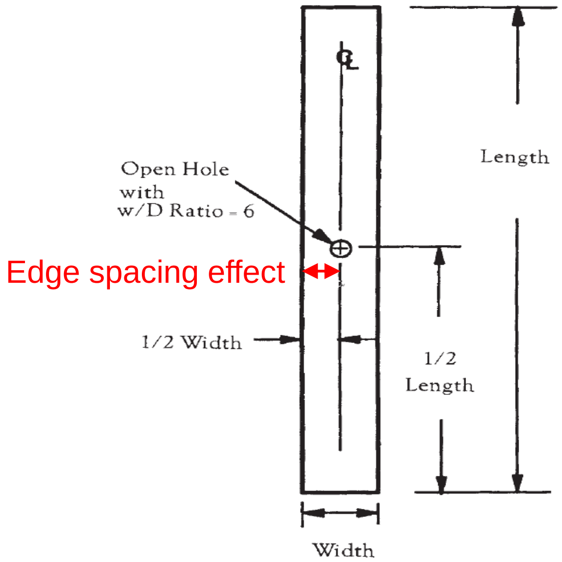


FIG. 1 Schematic of Open Hole Tension Test Specimen

ASTM D-5766 Open hole tension

Technical Publications (2021)

UNIVERSITY of WASHINGTON

Journal Publications

- S. Ko, T. Nakagawa, Z. Chen, J. Yang, M. Salviato*, “Experimental and numerical investigations of Discontinuous fiber composites Structure thickness and platelet width effect,” Composite Structures, 2021 (in preparation).
- S. Ko, S. Phenisee, J. Yang, M. Salviato*, “Understanding the Effects of Morphological Parameters on the Damage Tolerance of Discontinuous Fiber Composite Structures: A Computational Investigation,” Composite Part A, 2021 (in preparation).

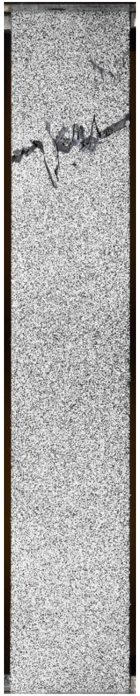
Conference Proceedings

- S. Ko*, T. Nakagawa, Z. Chen, J. Davey, T. Abdullah, L. Kuklenski, E.J. Adams, M.R. Soja, C.Y.Park, W.B. Avery, J. Yang, M. Salviato, “Experimental and numerical investigations of stochastic thickness effects in discontinuous fiber composites,” 36th American Society of Composites Conference, College Station, TX, Sep. 2021.

Thank you

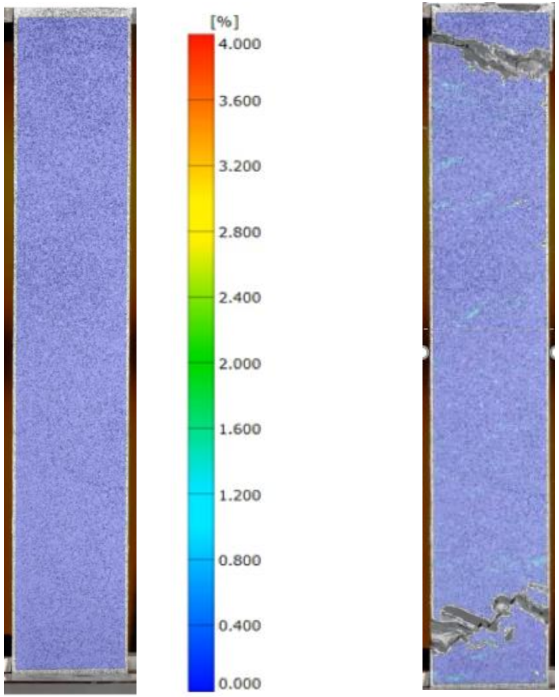
Interesting fracture surfaces

t = 0.065”



Single fracture

t = 0.065” ε_y

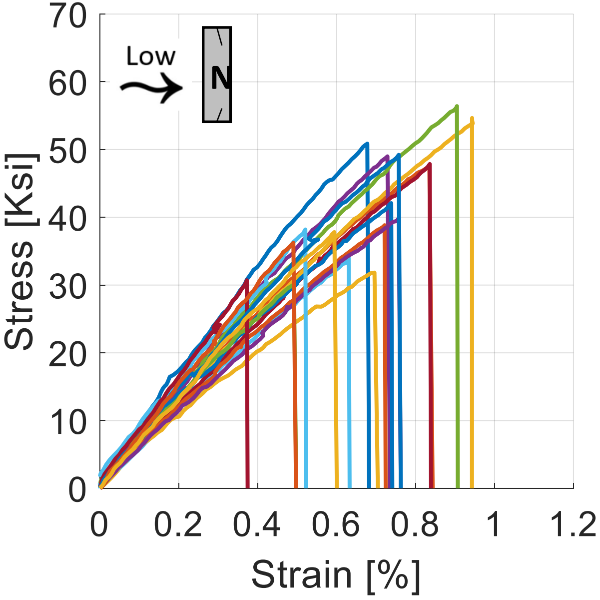


Double fractures (2 / 17 coupons)

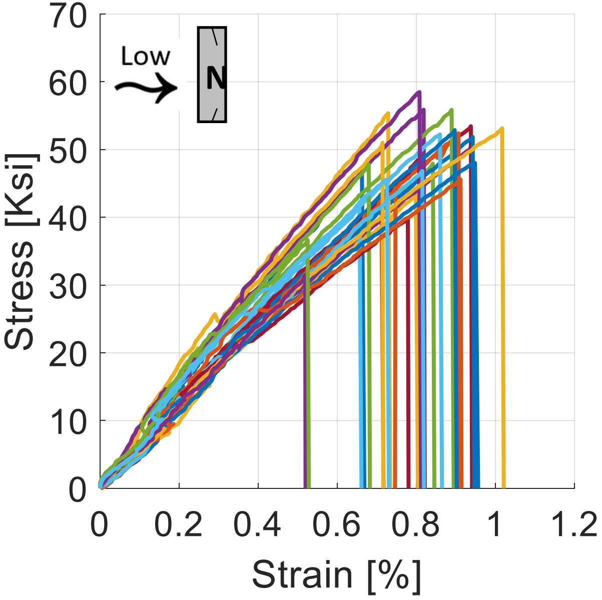
No noticeable strength reduction observed due to the double fractures.

Load-Displacement Curves (UNT) – Low flow

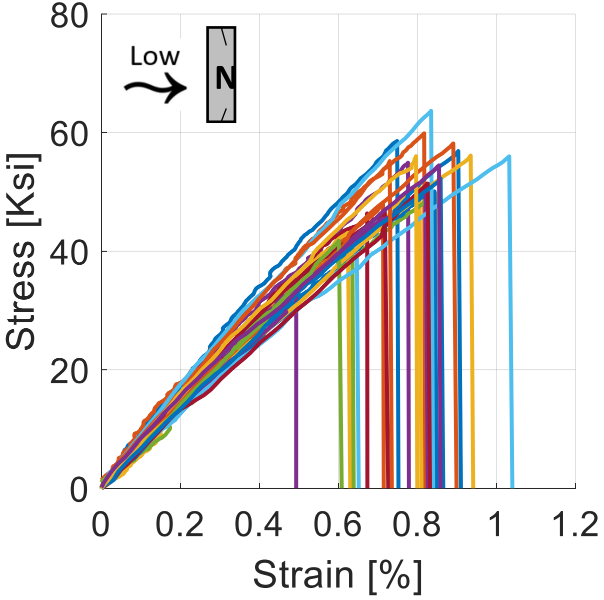
(a) Narrow Platelet, 0.065”
17 coupons



(b) Narrow Platelet, 0.15”
30 coupons



(c) Narrow Platelet, 0.25”
30 coupons

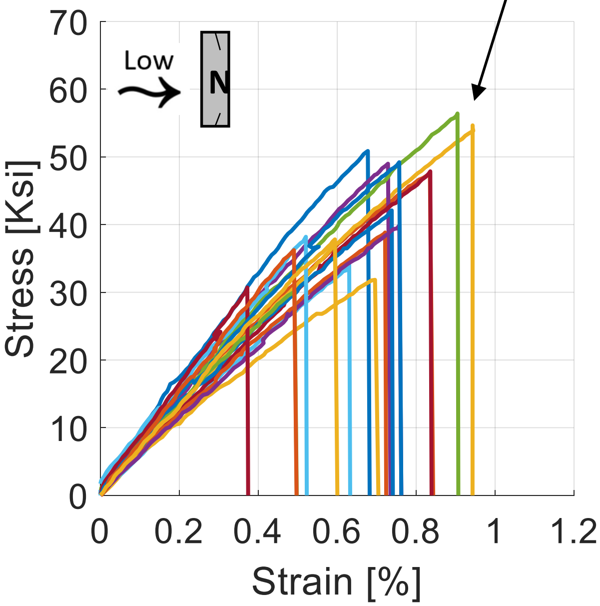


Large scatter in the data set. We need to check the outliers.

Checking the outliers (we found no outliers)

Source: CMH-17, Ch. 8-18.

Is this an outlier?



None of them are outliers!

Maximum Normed Residual (MNR) method:

Find an absolute deviation from the sample mean. Compare the deviation against the recommended significance level.

$$MNR = \max_i \frac{|x_i - \bar{x}|}{s}, i = 1,2,\ldots,n$$

x_i = data values

$\bar{x}$ = sample mean

n = sample size

s = standard deviation

$$C = \frac{n-1}{\sqrt{n}} \sqrt{\frac{t^2}{n-2+t^2}}$$

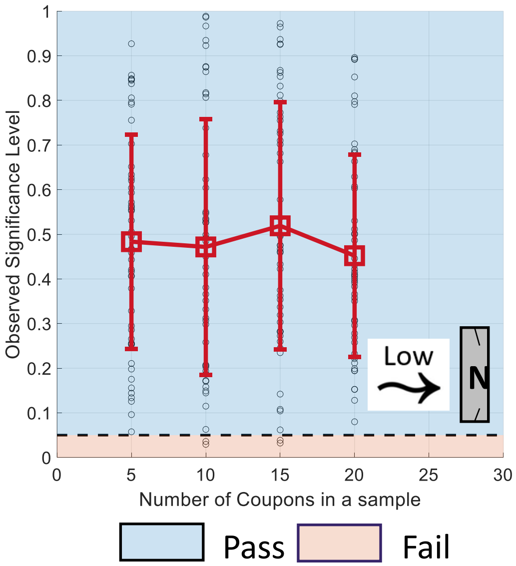
t = [1-0.05/(2n)] quantile of the t-distribution with n-2 DOF.

If MNR > C, then x_i is an outlier.

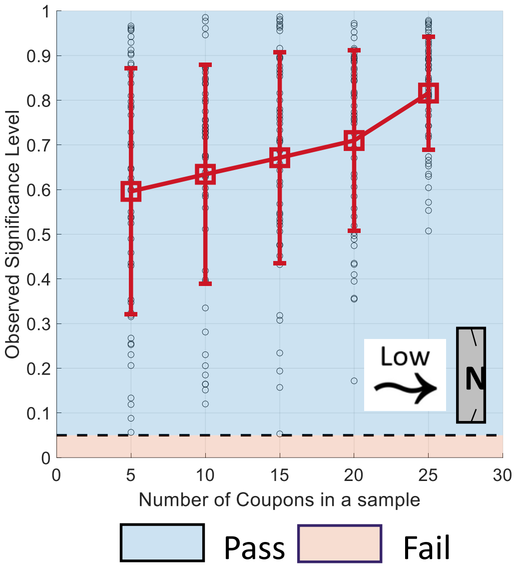
Checking the probability distributions

Use Anderson-Darling statistical analysis: CMH-17

(a) Modulus



(b) Strength



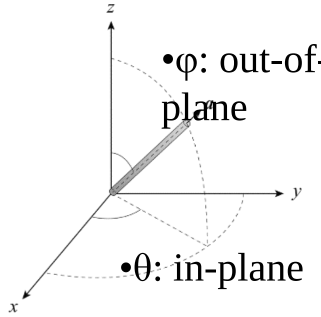
Regardless of the thickness and platelet size,

Modulus = Normal

Strength = Weibull

Quantify the random platelet orientations

- <u>Quantify the random orientation state</u>



- Definition: 3D orientation tensor

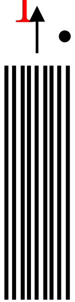
$$A_{ij} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ \dots & A_{22} & A_{23} \\ sym & \dots & A_{33} \end{bmatrix} = \begin{bmatrix} p_1p_1 & p_1p_2 & p_1p_3 \\ \dots & p_2p_2 & p_2p_3 \\ sym & \dots & p_3p_3 \end{bmatrix}$$

- Where $\begin{pmatrix} p_1 = \sin(\phi)\cos(\theta) \\ p_2 = \sin(\phi)\sin(\theta) \\ p_3 = \cos(\phi) \end{pmatrix}$

1. $A_{33} \approx 0$ (Platelets are deposited almost flat)
2. $A_{11} + A_{22} = 1$, Since 11 direction points to the loading

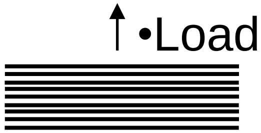
- a) Towards loading direction

$A_{11} = 1$



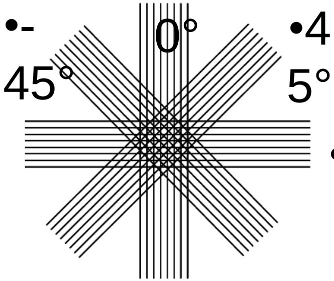
- b) Transverse to loading dir

$A_{11} = 0$



- c) Quasi-isotropic layup

$A_{11} = 0.5$



- d) Uniform random distributio

$A_{11} = 0.5$